Computer Networks 000 (2016) 1–13

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

A joint active time and flow selection model for cellular content retrieval through ITS

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ARTICLE INFO

Article history:
Received 15 July 2015
Revised 22 March 2016
Accepted 27 March 2016
Available online xxx

Keywords:
cellular 4G network
offload
modeling
analytic study
performances
vehicular network

ABSTRACT

Operators need to address increased data demands to meet subscribers' growing requirements by offloading a portion of cellular traffic onto other types of networks. In this paper, we investigate the possibility of using vehicular ad hoc networks (VANETs) for this purpose. We study joint data flow selection and contention resolution in a hybrid VANET-cellular system. We formulate the problem as an optimization problem called FOSAA, which considers vehicle-to-vehicle and vehicle-to-infrastructure link quality, channel access, inter-nodal interference and node active time. The problem is solved through an iterative approach. FOSAA is compared to other proposed schemes. The performance results show that offloading fraction is significantly affected by the data volume, vehicle density and number of hops from the infrastructure to the downloader vehicles.

1. Introduction

Recent studies have confirmed that, in the near future, cellular networks will most likely become overloaded and congested, especially in hot zones and urban areas. Moreover, tablet subscriptions are expected to grow from 250 million in 2012 to approximately 850 million in 2018, exceeding the number of fixed broadband subscriptions [1]. The average smartphone usage increased by 81% in 2012 [2]; in addition, the total number of smartphone subscriptions will be tripled and is expected to increase to 3.3 billion by the end of 2018 [1]. The growing number of such mobile devices results in an increase in data demand and Internet queries, which become the dominating traffic request of wireless cellular network users. By the end of 2018, it is estimated that a smartphone will generate approximately 2GB of data per month, and a mobile PC will generate over 10GB of data [1]; moreover, by 2017, two-thirds of the world's mobile data traffic will be video data [2]. Data traffic has doubled in only one year, between 2011 and 2012, in contrast to mobile voice traffic, which continues to grow at a steady rate [1]. According to [3], this increase in mobile data traffic demand is expected to continue to increase at a rate of more than 100% annually. Operators need to address this increase in data traffic demand and ensure sufficient RAN (Radio Access Network) capacities to meet this growing demand.

Numerous works have studied systems for offloading cellular traffic via FemtoCells or Wi-Fi hotspots [4]. Accordingly, it will also be interesting to consider and investigate possible offloading through mobile ad hoc networks formed by opportunistic communications between intelligent vehicles, wherein vehicles are wirelessly connected and form a Vehicular Ad hoc Network (VANET). In this context, this work provides analysis and a comparison of analytical models proposed for cellular traffic offloading. We discuss and evaluate the capacity and ability of VANETs to offload a portion of cellular traffic while considering the constraints related to the intermittent vehicular nodes' connectivity in I2V and V2V links and to the data volume. We propose a cooperative traffic transmission problem formulation in a joint 4G LTE Advanced cellular infrastructure and VANET network where VANET nodes cooperate with the LTE infrastructure by offloading a portion of the cellular traffic.

This solution is very promising and motivated by many reasons. A dedicated frequency band, i.e., 5.86–5.92 GHz, has been allocated for Intelligent Transportation System (ITS) communications. In addition, according to the ETSI 102 638 technical report, by 2027, almost 100% of vehicles will be equipped with On Board Units (OBUs), therein providing V2V (vehicle-to-vehicle) and I2V (infrastructure-to-vehicle)/V2I (vehicle-to-infrastructure) communications, thereby forming ITS [5]. Thus, with the increasing

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http://dx.doi.org/10.1016/j.comnet.2016.03.015
1389-1286/

number of vehicles equipped with OBU devices, several related applications are emerging such as safety-related applications (e.g., collision warning, emergency information, assistance for safe driving, and remote vehicle diagnostics), automobile high-speed Internet access, and multimedia content sharing. Moreover, most subscribers currently use their smartphones and tablets during transit. Vehicles are where citizens spend a substantial portion of their time during a day, with more time being spent only in homes and offices. According to [6], commuters spend 500 million hours per week in a car. Thus, opportunistic contacts between vehicles offer high capacity for data transmission.

In summary, traffic offloading using VANETs is a promising solution for partially supporting the exponential growth of mobile data traffic, which otherwise could not be supported even by 4G cellular networks [2] for two main reasons. First, the dedicated frequency band allocated for VANET communications represents an attractive capacity potential compared to the freely shared band used for Wi-Fi. Second, subscribers use their mobile devices during most of the time that they are using modes of transportation. According to the Alcatel-Lucent's study performed in 2009 [6], 22 % of interviewed consumers would be willing to pay from 30$ to 65$ per month for services proposed while traveling on the road. Therefore, using VANETs to offload a portion of cellular traffic seems to be an attractive solution to investigate.

The remainder of this paper is structured as follows. In Section 2, we present related works. In Section 3, we describe the system model. In Sections 4 and 5, we present the FOSAA model and its resolution procedure. In Section 6, benchmarking schemes are detailed. Finally, a performance evaluation and conclusions are presented in Sections 7 and 8.

2. Related works

The most popular proposed offloading solutions include femtoCells for indoor offloading and Wi-Fi for outdoor offloading. Numerous analytical models and studies have been conducted in this context [4,7,8]. However, very few works have focused on cooperation between cellular infrastructure and opportunistic communications between vehicles whereby the cellular network is offloaded through VANETs. Most of these works study the I2V link for the purpose of improving the performance of VANETs by addressing challenges related to data dissemination to mobile users (e.g., gateway selection and the number of copies of a message) rather than content downloading through heterogeneous networks and without considering the interaction between the vehicular network and the cellular infrastructure.

Moreover, most modeling efforts are directed at predicting opportunistic communications rather than at the capacity of VANETs to support additional cellular traffic. For example, Ref. [9] establishes a mathematical framework to study the problem of coding-based mobile data offloading wherein mobile data traffic is characterized by heterogeneous sizes and a limited storage capacity of the offloading participants. The problem formulation is based on maximizing users' interest satisfaction with multiple linear constraints on limited storage. The output of the proposed formulation provides a solution that decides when to use the coding and how to allocate the network resources in terms of contact rate and offloading storage. In Ref. [10], the authors present an analytical study of content offloading through VANETs. The problem formulation is based on maximizing a cost function that represents the fraction of content that vehicular nodes might download through VANETs. The considered constraints include channel access and flow conservation. However, in this paper, the authors do not consider inter-RSU roaming/handover and the quality of the link between the infrastructure and the VANET network. In Ref. [11], the authors present a graph-based model that decides which data should be scheduled to vehicles. They formulate a non-integer LP problem, solved at each RSU, to form transmission scheduling decisions. Ref. [12] proposes a mechanism for selective IP traffic offload (SIPTO) for vehicular communication networks under the context of providing IP flow mobility for users in vehicles. The proposed solution has been prototyped. The system presented in [13] is called "Thedu", which proposes access to Web search from moving vehicles. The system is proposed for interactive web applications in a delay-tolerant network (DTN) composed of access points and buses where the objective is to achieve routing between mobile nodes. Experimental and analytical results show that V2V and I2V communications enhance the performance of applications.

The author in [14] proposes an approach aimed at injecting the correct amount of content copies into the network. Similarly, in Ref. [15], the scope is the same as in Ref. [14] but considers smartphones instead of vehicular nodes. The authors propose to deliver the information to only a small fraction of selected users, called target users, to reduce mobile data traffic by considering the delay-tolerant nature of non-real-time applications. The work is based on opportunistic communications among mobile users and studies how to select a target set of only k users, which will later help to further propagate the information among all the subscribers through their social participation, when their mobile phones are within the transmission range of each other and can communicate opportunistically. Such an offloading approach is attractive because it does not require any additional costs. However, this approach faces several challenging issues, such as battery and storage limitations of mobile devices, non-predictable user mobility, and heterogeneity of data traffic, that have to be overcome.

Very few references have considered the case wherein cellular infrastructure is offloaded through a VANET network. Refs. [16–19] focus on content downloading. Ref. [16] studies content downloading from the infrastructure in a vehicular environment. However, only I2V direct transfers are considered wherein the cellular infrastructure is only used for signaling transmissions. The focus of this paper is on the prefetching of content at road side units (RSUs) through the optimization of the usage of the links while estimating the amount of traffic that the vehicles will be able to download from each RSU. Ref. [17] considers the fact that neighboring vehicles have a high probability to request the same content when deciding on data to be downloaded. The work presented in [20] proposes a scheduling scheme for content downloading in vehicular networks using a simplistic mobility model and without considering the existence of a cellular network. Ref. [21] also considers DTN for cellular offloading.

Obviously, there are several ongoing efforts focused on predicting future vehicular contacts given the current position and vehicle trajectories [22,23]. There are two main approaches: modeling the vehicle location through a Markovian process and studying the time and duration of contacts. In Ref. [24], vehicular movement prediction is leveraged for data prefetching at RSUs and for handoff between the RSUs. The experimental results demonstrate the practical viability of exploiting mobility prediction to fully utilize I2V contacts. In Ref. [11], a probabilistic representation of inter-node contacts called fog-of-war is proposed. Based on the exact knowledge of vehicular mobility and inter-node contacts, the authors add noise to the contact presence, duration and rate. By varying the noise level, the fog-of-war model can reflect different degrees of prediction accuracy. The authors show that there is an order of magnitude difference in accuracy between the output of the fog-of-war model and the forecasts obtained through Markovian techniques.

In this work, we consider the impact of the VANET capacity as well as the I2V and V2V link qualities for traffic offloading decision making. We also consider the role of a gateway that assists a downloader vehicle in retrieving content from the infrastructure. Our system can use any of the aforementioned VANET prediction techniques for determining V2V and I2V contacts. The objective of this paper is to provide a comparison of analytic models used for mobile data offloading via VANETs. We also propose an offloading model, called FOSAA, that represents an original contribution compared to other works [10,11] in numerous aspects: first, we use variable data flow volumes, in contrast to simulations in reference [10], which only consider 10 Mbytes of data. Second, in our MAC model, in addition to the channel access contention, we consider interference from hidden nodes. Moreover, the node active time is carefully adjusted to increase the network capacity. Finally, our proposed problem formulation is performed in a decentralized manner. To the best of our knowledge, this is the first time that the VANET traffic offloading problem has been studied in the context of hybrid cellular infrastructure and ITS networks considering hidden terminals.

3. System modeling

The system model is based on a hybrid network architecture composed of two systems: an LTE cellular infrastructure and a VANET network. The cellular infrastructure is composed of eNodeBs connected via an S1 interface to the LTE Evolved Packet Core (EPC) [25]. The ITS system is composed of fixed Road Side Units (RSUs) deployed over a road (e.g., highway) and vehicular nodes traveling along this road. Only intelligent vehicles that have wireless communication capabilities are considered in this study. We call the Region of Interest (ROI) the geographical region of an RSU within which vehicles send and receive information from this RSU. Intelligent vehicles are equipped with OBUs that utilize two interfaces: an IEEE 802.11p-based interface tuned on one service channel (SCH) for V2V communications and another interface, based on Wi-Fi, that is used for the I2V connection. I2V and V2V communications occur on different channels. Vehicles that do not integrate communication interfaces are not visible to the RSU; thus, they are not considered in the problem formulation. Each vehicle can be attached to only one RSU.

Vehicles may periodically send their identity and velocity/position to the RSU using floating car data (FCD) transmissions [6]. Moreover, due to the high dynamicity of vehicular nodes, numerous clustering methods have been proposed for grouping homogeneous vehicles into stable sets, called clusters. Each cluster is composed of vehicles that ensure stable V2V links. Many references have proposed clustering methods performed in a centralized [26] or decentralized manner. Based on such information, the RSU is aware of vehicles in each cluster within its ROI. The system model is based on considering vehicles moving along a multi-lane road without intersections. The RSU can thus determine the I2V and V2V connectivity in its ROI based on FCD and clustering information. Snapshots of the vehicular network topology are then built, thus providing V2I and V2V link specifications. The vehicle connectivity graph is periodically updated as FCD information is received using a graph connectivity manager (GCM) unit. The GCM module is installed in each RSU, and the module's role is to build and update the connectivity graph of vehicles belonging to the module's ROI using location information. The graph is composed of vertices and edges, where a vertex represents one vehicular node. An edge is located between two vertices and has a weight related to its corresponding V2V link quality, herein called P_{QoS} in formula (3), (5) and (10). The parameter P_{QoS} reflects the achievable data rate related to the V2V link quality ratio between the two vehicular nodes. It is set based on the V2V distance, as specified in Fig. 2.

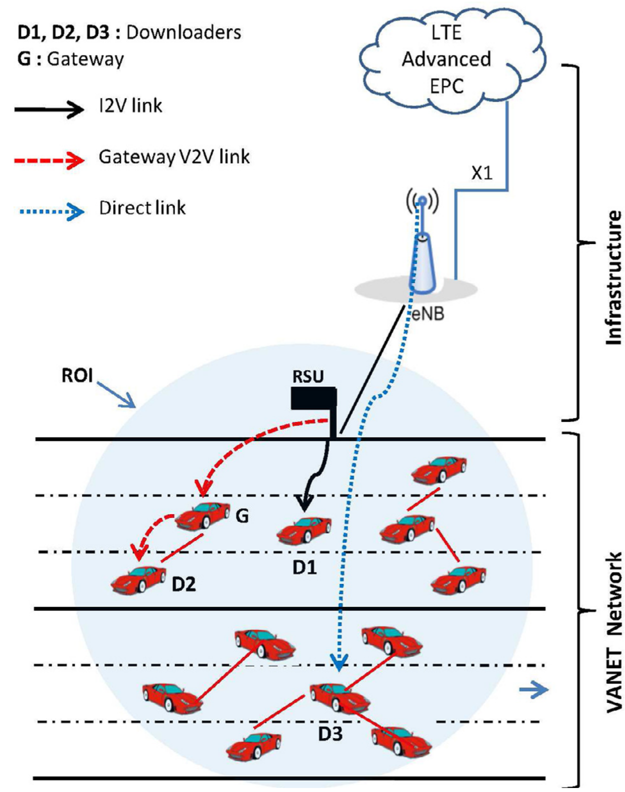


Fig. 1. Content downloading types.

A vehicle user wishing to download content from the cellular network is herein called a *downloader*vehicle. More concretely, the *downloader* vehicle receives queries containing requests from an Application Program Unit (APU) to download content from the cellular network. The APU is an interactive application that might be uploaded to the smartphone of a user traveling in the vehicle or built into the vehicle itself.

Downloading content from the infrastructure could be performed through three mechanisms (c.f. Fig. 1): (1) via a direct I2V link from the RSUs, (2) via V2V links rooted at a gateway that receives content from the RSU, and (3) via an eNodeB based on a direct cellular link. We assume that the RSU is aware of the V2V contacts and routing path from the RSU via relays to the *downloader*. As vehicles participate in the offloading, these participating vehicles can be awarded by operators by offering a reduced cost for a service, by guaranteeing a specific QoS level, etc. [27]. Basically, these vehicles will receive the data content from the RSU and will route this content through the V2V links of the vehicular network to the *downloader* vehicle.

The goal of this work is then to define a method that decides upon of the amount of data that can be offloaded through the VANET network either through a direct link or via V2V multihop links. We notice here that, compared to other previous works, we study traffic downloading in a VANET while simultaneously considering the I2V and the V2V communications and the data volume. We jointly investigate the selection of the data flow to offload and the possible supported data volumes and the time activities of vehicular nodes.

4. Problem formulation

We present a multi-constraint optimization problem to evaluate the maximum data content that can be downloaded via the VANET network through either direct I2V downloading or V2V

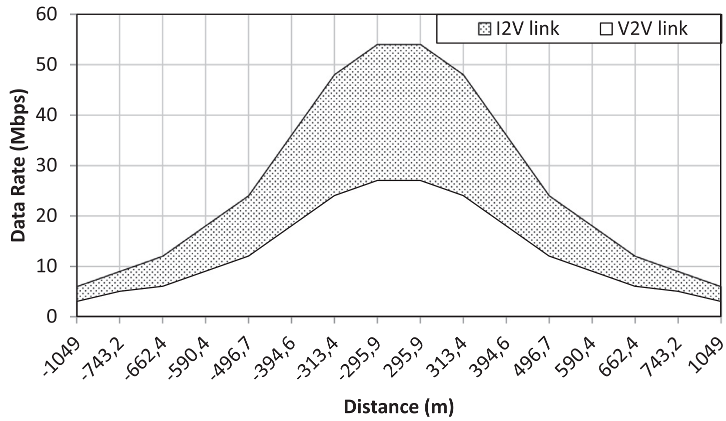


Fig. 2. I2V/V2V achievable data rate.

relayed links. The proposed problem formulation is called the Flow Offloading Selection and Active time Assignment problem (FOSAA).

4.1. Notations and assumptions

We first define symbols and notations used in the model:

- i is the vehicle index, $i \in V$, where V is the set of *downloader* vehicles. The index 0 in the formulas represents the RSU.
- $\varphi_{i,f}$ is the flow f of the *downloader* vehicle i.
- F_i is the set of requested flows of *downloader* vehicle i.
- L_i is the set vehicle indexes constituting the path of intermediate nodes between the RSU and vehicle i.
- B_i is the set of nodes that are exposed to vehicle i, where an exposed node is a node visible to vehicle i.
- I_{ij} is the set of hidden nodes interfering with vehicle i when i transmits to vehicle j, in which a hidden node is a node that is visible to vehicle j but not to vehicle i.
- G is the set of vehicles playing the role of gateways between the RSU and the VANET network for other vehicles.
- S_i is the set of vehicles that have vehicle i as relay.
- C_i is the set of direct children of node i.
- $\vartheta_{i,f}$ is the traffic volume of the flow f of the vehicle i.
- In this work, we assume that the data flow is the basic data unit to be offloaded.

4.2. FOSAA formulation

The objective function for the FOSAA is

$$\max \sum_{i} \sum_{f} \varphi_{i,f} \tag{1}$$

where $\varphi_{i,f}$ is binary and represents whether the flow f of the *downloader* vehicle i is offloaded (1) or not (0). The objective of FOSAA is to guarantee fairness between different vehicles. To this end, the objective function maximizes the number of offloaded flows rather than the amount of data in offloaded flows. FOSAA is a max flow formulation problem that considers the following constraints.

4.2.1. Gateway capacity

Gateway-RSU links are bottlenecks of the communication from vehicles to RSU. Thus, all traffic through gateway nodes will be less than their link capacity, which is

$$\vartheta_{g,max} - \sum_{i \epsilon S_g} \sum_{f \epsilon F_i} \vartheta_{i,f} \cdot \varphi_{i,f} \geq 0, \quad g \in G, \tag{2}$$

where S_g is the set of vehicles that have vehicle g as a gateway and $\vartheta_{i,f}$ is the traffic volume of flow f in vehicle i. The link capacity $\vartheta_{g,max}$ is expressed as

$$\vartheta_{g,max} = P_{QoS,(0,g)} \cdot DR_I \cdot \alpha \cdot LCD_g, \tag{3}$$

where $P_{QoS,(0,g)}$ is the link quality probability between the RSU and the gateway vehicle g, DR_I is the maximum achievable data rate on the I2V channel, α $(0 \leq \alpha \leq 1)$ is a predetermined fraction of content that we attempt to offload, and LCD_g represents the Link Connectivity Duration between the RSU and the gateway vehicle g. According to the definition in [28], this duration is

$$LCD_g = \frac{\sqrt{(\alpha^2+\gamma^2)R_I^2 - (\alpha\delta - \beta\gamma)^2} - (\alpha\beta + \gamma\delta)}{\alpha^2+\gamma^2}, \tag{4}$$

where $\alpha = V_g cos\theta_g$, $\beta = x_g - x_0$, $\gamma = V_g sin\theta_g$, and $\delta = y_g - y_0$. (x_g, y_g) is the Cartesian coordinates of vehicle g, and (x_0, y_0) is the Cartesian coordinates of the RSU. V_g is the velocity of vehicle g, which has an inclination θ_g, $(0 < \theta_g < 2\Pi)$ with respect to the x-axis. R_I is the RSU wireless transmission range.

4.2.2. Channel capacity

This constraint is related to the potential of the intermediate nodes to relay the traffic to a destination vehicle. This constraint limits the amount of flows through the vehicle link $i-j$ by considering link quality, node active time, and collision in the MAC layer, which is

$$b_i \cdot P_{mac,(i,j)} \cdot P_{QoS,(i,j)} \cdot DR_{v2v} \cdot LCD_{(i,j)} - \psi_{i,j} \geq 0, \quad (i,j) \in V \tag{5}$$

where j is the direct relay of i and $LCD_{(i,j)}$ is the Link Connectivity Duration between the two vehicles i and j. This reflects the stability of the link between these two vehicles and the link's lifetime. b_i is the normalized active time of vehicle i, and $\psi_{i,j}$ is the capacity through the vehicle $i-j$ V2V link defined in (7). The normalized active time is the ratio of vehicle i's transmission time to the total time (transmit + wait):

$$b_i = \frac{T_i}{W_i + T_i} = \frac{\rho_i}{1+\rho_i},$$

Due to the high mobility of vehicular nodes, the first and second constraints are expressed to guarantee that the *downloader* vehicle can retrieve all the data flow content from the RSU before leaving its coverage area.

4.2.3. Saturation limit

Similar to the argument in [29], the active times of neighboring nodes must satisfy the following:

$$1 - \sum_{k \epsilon B_i \cup \{i\}} b_k \geq 0. \tag{6}$$

4.2.4. Aggregation

The aggregation constraint defines the ability of the vehicle i-to-vehicle j V2V link to support the relayed traffic. This constraint is expressed as

$$\psi_{i,j} - \sum_{k\epsilon S_j}\sum_{f}\vartheta_{i,f}\cdot\varphi_{k,f} = 0 \quad (7)$$

4.2.5. Path availability

'The path availability constraint attempts to evaluate the link quality between the RSU and the *downloader* vehicle i. This constraint is the probability that a single-hop or multi-hop path exists between the vehicle i and the RSU. This is expressed as

$$PA_i - PA_{th}\cdot\varphi_{i,f} \geq 0, \quad f \in F_i, \quad (8)$$

where $PA_{th} > 0$ and F_i is the set of flows of vehicle i. The path availability (PA_i) between the vehicle i and the RSU is

$$PA_i = \prod_{\{j,k\}\epsilon L_i} LA^i_{j,k}, \quad (9)$$

$LA^i_{j,k}$ represents the link availability (LA) of the vehicle j-to-vehicle k intermediate link composing the RSU to vehicle i link, which is defined as

$$LA^i_{j,k} = P_{cov,(j,k)}\cdot P_{QoS,(j,k)}\cdot P_{mac,(j,k)}, \quad \{j,k\}\epsilon L_i, \quad (10)$$

where $P_{QoS,(j,k)}$ is the link quality probability and $P_{cov,(j,k)}$ is the probability of having a reliable V2V link by maintaining a link above a target SNR γ_0 at the receiver node. According to [30],

$$P_{cov,(j,k)} = \exp\left(-\frac{\gamma_0\cdot N_0\cdot d^{\alpha}_{(j,k)}}{K\cdot P_j}\right), \quad (11)$$

where N_0 is Gaussian noise, $d_{(j,k)}$ is the distance between vehicle j and vehicle k, α is the path loss exponent, P_j is the transmission power of vehicle j, K is the path loss constant, and γ_0 is the target SNR. When $j = 0$, $P_{cov,(0,k)}$ evaluates the I2V link (between the RSU and the gateway), $d_{(0,k)}$ is the distance between the base station and vehicle k, and P_0 is the transmitting power of the base station.

$P_{mac,(j,k)}$ is the probability of having a successful transmission according to the IEEE 802.11p protocol when considering interference from hidden nodes. This probability is expressed as

$$P_{mac,(j,k)} = 1 - P^{MaxTrials}_{coll,(j,k)}, \quad \{j,k\}\epsilon L_i, \quad (12)$$

where *MaxTrials* is the maximum allowable number of attempts to access to the medium according to the IEEE 802.11p standard [31]. The collision probability of vehicle j while attempting to access the common medium to send traffic to vehicle k and while considering interference from hidden nodes is expressed according to [29] as follows:

$$P_{coll,(j,k)} = 1 - \prod_{p\epsilon I_{jk}}\left[\frac{1}{1+\rho_p}\left(1-\frac{\rho_p}{T_p}\right)^{H_p}\right]\prod_{p\epsilon B_j}\left(1-\frac{\rho_p}{T_p}\right), \quad (13)$$

where ρ_p is expressed as

$$\rho_p = \frac{T_p}{W_p}$$

in which W_p is the back-off time, which is the average waiting time before each transmission from vehicle p, and T_p is the transmission time of the entire data frame. $T_p = H_p + T_{SIFS} + T_{ACK} + T_{DIFS}$, including the transmission time of the header and the payload H_p, the Short Inter-frame Space T_{SIFS}, the ACK T_{ACK}, and the DCF Inter-frame Space T_{DIFS}.

5. FOSAA resolution procedure

The FOSAA problem is difficult to solve directly because it contains nonlinear constraints and integer variables. Thus, we propose to solve it approximately via an iterative approach. In each iteration, one algorithm, namely, FOSAA-φ, determines flow assignments, and another algorithm, namely, FOSAA-a, determines contention resolution.

The goal of FOSAA-φ-n, where n is the iteration index, is to determine the $\varphi_{i,f}$ that maximizes the objective function (1). Initially, b_i is fixed and set to $b_i = \frac{1}{\max_{j\epsilon B_i}|B_j|}$, $\forall i \in V$. FOSAA-a-n, i.e., FOSAA-a performing at the n^{th} iteration, optimizes node time activities in an attempt to obtain higher offloading fractions. It takes $\varphi_{i,f}$ from FOSAA-φ-n as an input to determine the optimal ρ_i, which reflects the contention level of the vehicles i, $\forall i \in V$. Next, through an iterative process, we determine the highest offloading fraction that can be reached with adequate values of ρ_i. Details of the solution to the FOSAA are given in Algorithm 1.

Algorithm 1 FOSAA Problem Resolution Pseudo Algorithm.

Initialization
- $\varphi_{i,f} = \{\}, \quad \forall i \in V, \forall f \in F_i$
- $b_i = \frac{1}{\max_{j\epsilon B_i}|B_j|}, \quad \forall i \in V$
- FOSAA-φ-1 $\Rightarrow \varphi^1_{i,f}, \quad \forall i \in V, \forall f \in F_i$
- $S^1 = \sum_i\sum_f \varphi^1_{i,f}$ & $S^n = 0$ & $n = 2$

Offloading and Contention Optimization Loop
- while $S^n \neq S^1$
- FOSAA-a-(n-1) $\Rightarrow \rho^n_i, \quad \forall i \in V$
- FOSAA-φ-n $\Rightarrow \varphi^n_{i,f}, \quad \forall i \in V, \forall f \in F_i$
- $S^1 = S^n$ & $S^n = \sum_i\sum_f \varphi^n_{i,f}$ & $n = n+1$
- end

The FOSAA-φ-n formulation represents an integer linear programming problem, where $\varphi_{i,f}$ varies and b_i is fixed. Thus, the considered constraints are Path Availability (8), Gateway Capacity (2), Channel Capacity (5) and Aggregation (7) constraints. The problem is solved using a binary optimization module that determines whether the data flow can be routed through the VANET network ($\varphi_{i,f} = 1$) or not ($\varphi_{i,f} = 0$). FOSAA-φ-n is solved using optimization tools in Matlab.

The FOSAA-a-n problem formulation and resolution are as follows.

5.1. Details of FOSAA-a-n

FOSAA-a-n's objective is to determine an adequate contention level of the vehicular nodes by determining ρ_i. When $\varphi_{i,f}$ is fixed, we transform the problem into a convex programming problem and solve it via standard optimization tools.

5.1.1. FOSAA-a-n problem formulation

The objective of the FOSAA-a problem is to allocate to each vehicular node a maximum amount of resources required to send related data flows, aiming to increase vehicles' offloading potential. Thus, the FOSAA-a objective function emphasizes the active times by maximizing the contention level of each vehicular node:

$$\max\sum_i \rho'_i, \quad \forall i \in V \quad (14)$$

Because $\varphi_{i,f}$ is fixed, the FOSAA-a formulation is based on the FOSAA problem and considers the following constraints:

5.1.1.1. Link availability. We simplify the path availability to link availability as $LA^i_{j,k} \geq LA_{th}$, i.e.,

$$LA_{th} - P_{cov,(j,k)} \cdot P_{QoS,(j,k)} \cdot P_{mac,(j,k)} \leq 0, \quad \{j,k\}\epsilon L_i, \; i \in V, \tag{15}$$

Successful medium access. This constraint is expressed using the successful transmission probability ($P_{suc,(j,k)}$), defined later in (17):

$$P_{mac,(j,k)} - 1 - \left(1 - P_{suc,(j,k)}\right)^{MaxTrials} \leq 0, \tag{16}$$

$\{j, k\}\epsilon L_i$, $i \in V$,

where *MaxTrials* is the maximum number of attempts to access to the medium, as defined in the standard [31].

One medium access attempt. The successful transmission probability must satisfy

$$\prod_{p\epsilon I_{jk}}\left[\frac{1}{1+\rho_p}\left(1-\frac{\rho_p}{T_p}\right)^{H_p}\right]\prod_{p\epsilon B_j}\left(1-\frac{\rho_p}{T_p}\right) - P_{suc,(j,k)} \leq 0 \tag{17}$$

$\{j, k\}\epsilon L_i$, $i \in V$

Channel capacity constraint. This constraint is related to the potential of intermediate nodes to relay the traffic.

$$\psi_{i,j} - b_i \cdot P_{mac,(i,j)} \cdot P_{QoS,(i,j)} \cdot DR \leq 0, \quad \forall (i,j) \in V \tag{18}$$

Saturation limit. The active times of all vehicles exposed to vehicle i must satisfy

$$\sum_{k\epsilon B_i \cup \{i\}} b_k - 1 \leq 0, \quad \forall i \in V \tag{19}$$

Aggregation.

$$\psi_{i,j} - \sum_{k\epsilon S_j}\sum_{f} \vartheta_{k,f} \cdot \varphi_{k,f} \leq 0 \tag{20}$$

5.2. FOSAA-a convex transformation

We first invoke a logarithmic change to the variables as follows: $\rho'_i = \log(\rho_i)$, $b'_i = \log(b_i)$, $P'_{mac,(j,k)} = \log(P_{mac,(j,k)})$, $\psi'_{i,j} = \log(\psi_{i,j})$.

For the path availability constraint, because $P_{cov,(j,k)}$ and $P_{QoS,(j,k)}$ are fixed for (j, k), $P_{mac,(j,k)} \geq \frac{LA_{th}}{P_{cov,(j,k)} \cdot P_{QoS,(j,k)}}$. This constraint becomes

$$\log\left(\frac{LA_{th}}{P_{cov,(j,k)} \cdot P_{QoS,(j,k)}}\right) - P'_{mac,(j,k)} \leq 0 \tag{21}$$

Moreover, let $\log(P_{suc,(j,k)}) = P'_{suc,(j,k)}$, and notice that $log(1 - (1 - exp(x))^m)$ is a concave function. The Successful Medium Access constraint becomes

$$P'_{mac,(j,k)} - \log(1 - (1 - \exp(P'_{suc,(j,k)}))^{MaxTrials}) \leq 0 \tag{22}$$

On the other hand, we approximate $\left(1 - \frac{\rho_p}{T_p}\right)^{H_p}$ and $\left(1 - \frac{\rho_p}{T_p}\right)$ using their continuous form $\exp(-\frac{\rho_p H_p}{T_p})$ and $\exp(-\frac{\rho_p}{T_p})$. Thus, with a log transformation, the One Medium Access Attempt constraint is expressed as

$$\sum_{p\epsilon I_{jk}}\left[\log(1+\exp(\rho'_p)) + \exp(\rho'_p) \cdot \frac{H_p}{T_p}\right] + \sum_{p\epsilon B_j}\frac{\exp(\rho'_p)}{T_p} \tag{23}$$

$$-P'_{suc,(j,k)} \leq 0$$

Let $C_{i,j} = \frac{\psi_{i,j}}{DR \cdot P_{QoS,(i,j)}}$. After the transformation, we obtain a convex Channel Capacity constraint expressed as

$$\log(C_{i,j}) - b'_i - P'_{mac,(i,j)} \leq 0 \tag{24}$$

where $b'_i = \rho'_i - \log(1 + \exp(\rho'_i))$. The saturation limit and the aggregation constraints become

$$\sum_{k\epsilon B_i \cup \{i\}} \exp(b'_k) - 1 \leq 0 \tag{25}$$

$$\exp(\psi'_{i,j}) - \sum_{k\epsilon S_j}\sum_{f} \vartheta_{k,f} \cdot \varphi_{k,f} \leq 0 \tag{26}$$

Therefore, FOSAA-a is transformed into a convex programming problem. The goal is to maximize (14) under constraints (21), (22), (23), (24), and (25). As a result of this transformation, FOSAA-a can be easily solved by optimization tools in Matlab. The solution provides active times of vehicular nodes relative to the offloaded flows.

6. Benchmarking schemes

6.1. Greedy scheme

With the Greedy offloading and active time assignment scheme, both the node active time computation and the selection of offloaded traffic flows are performed step by step in an iterative process until reaching network capacity saturation.

Let us define H^k to be the set of nodes that are at k hops from the RSU and A_i to be the set of active nodes that are exposed to vehicle i. For traffic flow selection, the Greedy approach is applied by first checking the data flows of first-hop nodes ($\in H^1$). The approach selects in each iteration the flow whose *downloader* vehicle is at one hop from the RSU and that satisfies the following channel limit constraint:

$$\sum_{f} \vartheta_{i,f} \leq V^I_{i,max}, \quad i \in H^1 \tag{27}$$

where

$$V^I_{i,max} = b_i \cdot P_{QoS,(0,i)} \cdot DR_I \cdot LCD_i$$

If the flow does not satisfy the channel limit constraint, it will not be offloaded, and the iterative process is completed; otherwise, one-hop-flow checking is continued. For the node active time assignment, we assume equity between neighboring active nodes by setting $b_i = \frac{1}{|A_i|}$. Notice that the priority of nodes at the same hop could be randomly set or be based on the position of the *downloader* vehicles. If all one-hop flows satisfy the channel limit constraint, the Greedy approach checks the two-hop flows. With the two-hop flows, two constraints must be satisfied to offload the flow:

$$\begin{cases} \sum_{f} \vartheta_{i,f} \leq V^V_{i,max}, \quad i \in H^2 \\ \sum_{j\epsilon J_g}\sum_{f} \vartheta_{j,f} \leq V^I_{g,max} \end{cases} \tag{28}$$

where g is the gateway of vehicle i to the RSU and J_g is the set of nodes that have vehicle g as a gateway to the RSU and for which flows have been selected to be offloaded. $V^V_{i,max}$ evaluates the maximum capacity of the V2V channel when accessed by vehicle i and is defined as follows:

$$V^V_{i,max} = b_i \cdot P_{QoS,(g,i)} \cdot DR_{v2v} \cdot LCD_{(g,i)}$$

For node active time assignment, we assume equity between neighboring nodes, i.e., $b_i = \frac{1}{|A_i|}$. We affect active times to vehicles that have already verified offloading constraints. b_i must satisfy the following constraint:

$$\sum_{k\epsilon B_i \cup \{i\}} b_k \leq 1 \tag{29}$$

Please cite this article as: G.e.m. Zhioua et al., A joint active time and flow selection model for cellular content retrieval through ITS, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.03.015

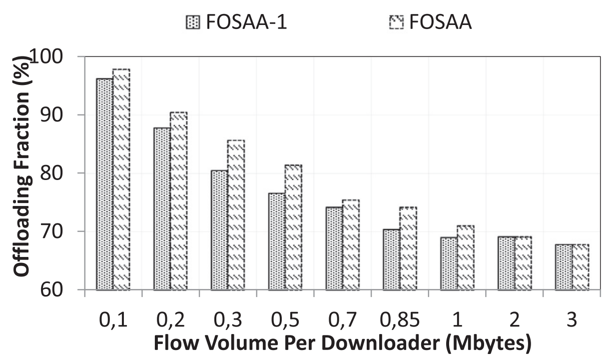


Fig. 3. Impact of data volume.

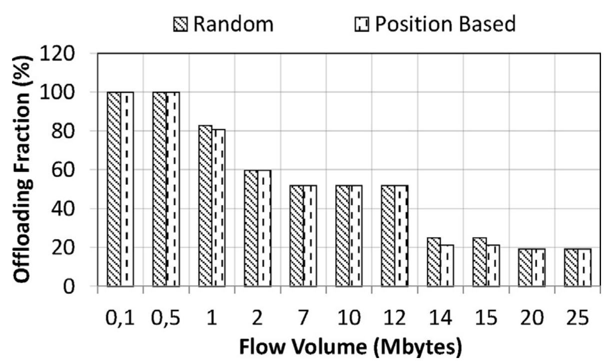


Fig. 4. Greedy approach evaluation.

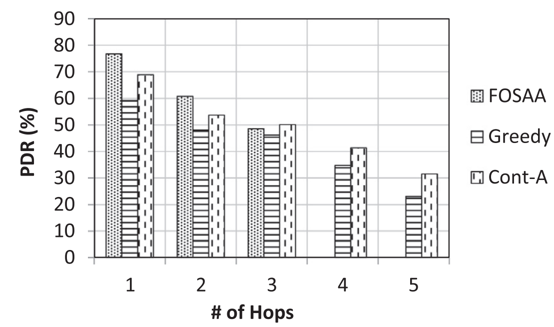


Fig. 5. Average PDR of flows routed through the VANET.

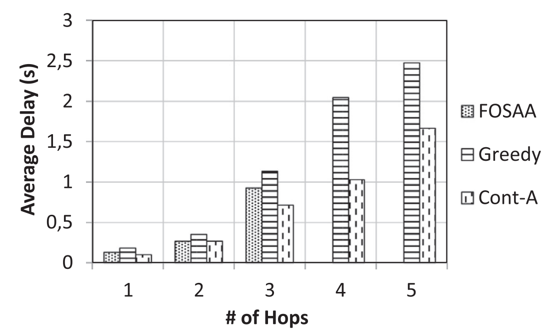


Fig. 6. Average delay of flows routed through the VANET.

Table 1
Vehicular network simulation parameters.

Parameters					*Values*			
Vehicular mobility					IDM_LC			
Acceleration (a)					0.3 ms^{-2}			
Deceleration (b)					0.3 ms^{-2}			
Min speed					11.2 ms^{-1}			
Max speed					39.2 ms^{-1}			
Road topology					Grid			
Step for recalculating movement parameters					1 s			
No. lanes/road					2			
Topology #	Symmetric topology				Non-symmetric topology			
	1	3	5	6	2	4	7	8
No. nodes	18	42	9	21	13	26	18	24
No. gateways	6	6	3	3	3	6	3	3
Max hops	2	3	2	3	3	3	4	5
No. children	{2}	{2}	{2}	{2}	{0, 1, 2, 3}			

The two-hop flows that do not satisfy theses constraints will not be offloaded, and the iterative process is completed. If all two-hop flows satisfy the constraints, the Greedy approach checks the three-, four-, ..., k-hop flows with the same approach as the one- and two-hop flows, where k is the highest number of hops from the RSU to vehicles in the VANET topology.

With the Greedy approach, the offloading decision and active time assignment stopping criteria are reached when at least one of the three constraints (27), (28) and (29) is not satisfied.

6.2. Neighboring-Aware Greedy scheme

We define a Neighboring-Aware Greedy (Nei-A) scheme, which represents an approximation of the FOSAA scheme. Nei-A is based on a Greedy scheme formulation with b_i being set as defined by the $[b_i]_{FOSAA}$ formula. The node active time assignments play an important role in optimizing the offloading capacity of the vehicular nodes because they affect the amount of data that can be retrieved and relayed through the nodes. To this end, defining a heuristic for the FOSAA scheme by approximating b_i assignments of FOSAA represents an interesting approach.

Based on data collected from several simulation scenarios and depicted later in Figs. 8(a) and 7, we determine that, with the FOSAA scheme, b_i assignments could be approximated using the function defined in (30). $[b_i]_{FOSAA}$ is formulated based on detection and estimation theory. Moreover, according to Fig. 8(a), b_i presents a multiple-regression shape related to the number of neighbors and sons. Sons of vehicle i are the set of vehicular nodes that have vehicle i as relay (defined by the set S_i). Thus, based on these observations, we collect a set of observations of b_i related to FOSAA assignment for different and heterogeneous simulation scenarios; see Table 1. Then, we inject this set of observation data, i.e., b_i, into a regression function (defined in a Matlab tool) to determine the regression coefficient related to the two parameters, i.e., the number of neighbors and the number of sons, to predict the behavior of b_i. Moreover, through simulations and approximation result analysis, we believed and found out later that, in addition to the number of neighbors and sons, b_i is also closely dependent on the vehicular environment specificity. This is why the parameter Ω was added. Ω characterizes the VANET topology, which is highly distinguished by the number of vehicular nodes and the max hops, as specified in Table 1. Therefore, we determine that b_i assignments of the FOSAA scheme can be approximated as follows:

$$[b_i]_{FOSAA} = min(1\ ,\ -0.0895|B_i| - 0.0118|A_i| + \Omega) \tag{30}$$

where $|B_i|$ is the number of active neighbor nodes to node i, $|A_i|$ is the number of sons of node i, and Ω is a dynamic parameter that is determined by the vehicular environment and that is generic for adaptation to the simulation scenario. Similarly, we found out that Ω can be approximated using the following relation:

$$\Omega = 0.0642|NbNde| - 0.1165|NbHop| \tag{31}$$

To prove the validity of this approximation, we perform simulations and comparisons with FOSAA and Greedy schemes presented in Figs. 8, 9 and 10.

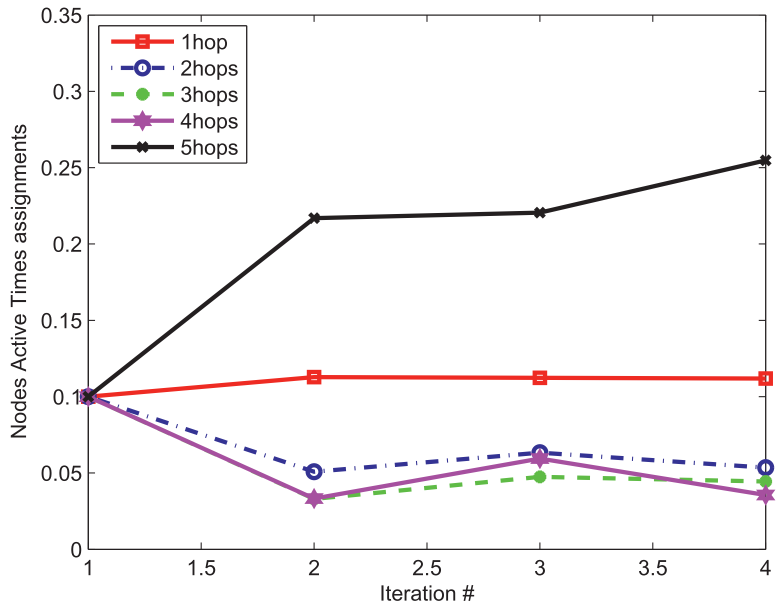
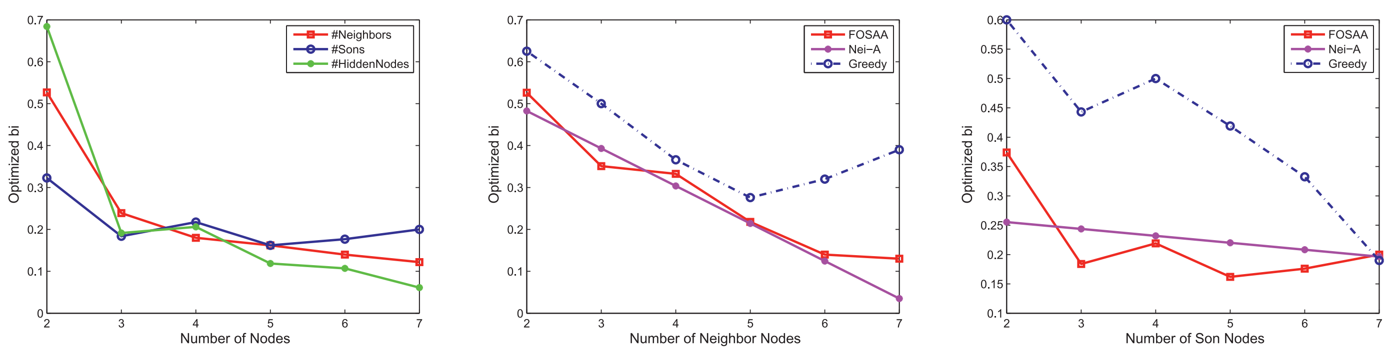


Fig. 7. Active times (b_i) assignments after successive iterations of FOSAA-a.



(a) with FOSAA (b) Impact of No. of Neighbor Nodes (c) Impact of No. of Son Nodes

Fig. 8. Node active time (b_i) assignments and dependencies.

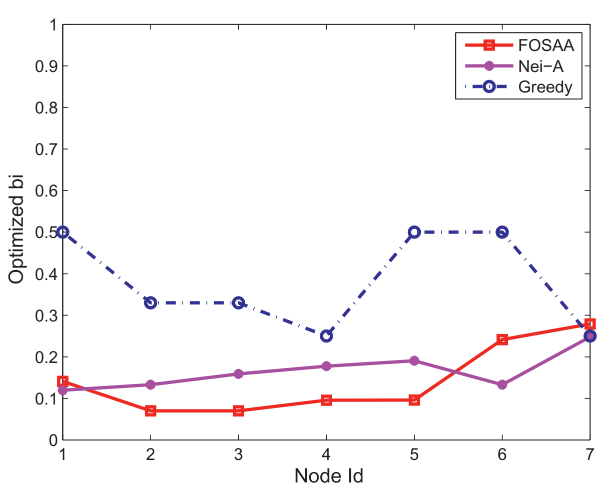


Fig. 9. Node active time (b_i) assignments for the FOSAA, Greedy and Nei-A schemes.

6.3. Contention-Aware Greedy scheme

The goal of the Contention-Aware Greedy (Cont-A) offloading and active time assignment scheme is to select the flows that will have the minimum bottleneck impact on the VANET capacity. The Cont-A scheme chooses to offload the gateway and its sons having the minimum channel occupation requirement by evaluating the maximum ratio of the volume through I2V links to able to handle the capacity of all its sons' V2V links. More precisely, Cont-A chooses the set of nodes to offload such that

$$\min_{i \in H^1}\{M_i\}$$

where

$$M_i = \max_{j \in S_i}\{m_j\}$$

where

$$m_j = \frac{\sum_{k \in S_j} \sum_{f} \vartheta_{k,f}}{V_{j,max}}$$

and

$$V_{j,max} = b_g \cdot P_{QoS,(g,i)} \cdot DR_{v2v} \cdot LCD_{(g,i)}$$

For the node active time assignment, we assume equity between neighboring nodes, were $b_i = \frac{1}{|B_i|}$. The set of B_i only includes nodes that are involved in traffic offloading in the current step. b_i must satisfy the channel saturation constraint defined by

$$\sum_{k \in B_i \cup \{i\}} b_k \leq 1 \quad (32)$$

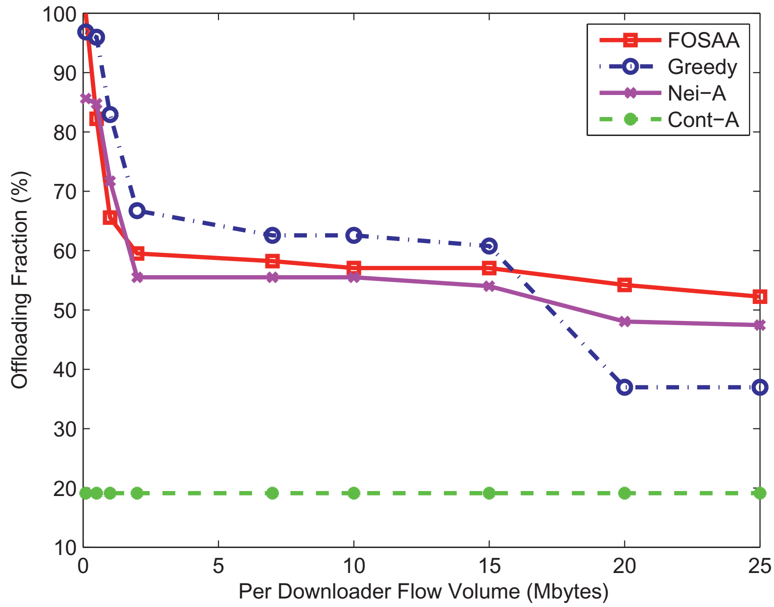


Fig. 10. Impact of data volume on FOSAA, Greedy and Cont-A offloading approaches.

7. Performance evaluation

In this section, we evaluate the effectiveness of the FOSAA scheme to determine the capacity of a vehicular network to support additional traffic originating from the cellular infrastructure. We compare the FOSAA scheme to the Greedy and Cont-A schemes. Very few works have studied the potential of using vehicular nodes for offloading LTE base stations. The originality of this paper is that it goes beyond existing works by including several additional major parameters such as channel contention, interference from hidden nodes, V2V link quality and availability, heterogeneous content size and node active times. These parameters are inherent in ad-hoc-based networks. Moreover, based on the FOSAA evaluation results, we have deduced a heuristic for the FOSAA scheme, called here the Nei-A scheme, and proved its validity through simulations.

Table 2
IEEE 802.11p simulation parameters.

Parameters	*Values*
Physical/Mac protocols	IEEE 802.11p
Preamble length	144 bits
PLCP header length	48 bits
Beacon interval	100 ms
CW min/max	15 / 1023
Interface queue type	DropTail/PriQueue
Interface queue length	50 packets
V2V transmission range	$R = 300$ m
Vehicular mobility generator	VanetMobiSim
CBR data rate	0.3 Mb/s
Packet size	500 bytes
Flow priority (AC)	2

7.1. Vehicular mobility generator (mobility model)

Compared to mobile ad hoc networks, vehicular mobility's special characteristics include acceleration and deceleration in the presence of other traffic, queuing at intersections, traffic congestion, and bursts caused by traffic lights. Thus, we need to employ realistic mobility models that reflect as closely as possible the characteristic behavior of the vehicular nodes moving through the roads. The VanetMobiSim tool [32] is used for vehicular mobility generation in these simulations. We based our car-following model on Intelligent Driver Model-Lane Changing (IDM-LC) with collision avoidance. The basic idea of IDM is that there is a safe following distance between vehicles. No two vehicles in the same lane can be within the safe distance of each other. The LC provides the possibility for a vehicle to change lane and overtake another vehicle based on the MOBIL overtaking model, which allows a vehicle to change lanes if this change minimizes the overall nodes' braking. IDM-LC parameters are listed in Table 1. Once vehicular mobility is generated, the trace is fed to the network simulator (here, NS2). Snapshots of the VANET topology (node positions and velocities) are then performed periodically and fed to the optimization problem resolution tool (here, Matlab). As detailed in Section 5, FOSAA resolution has been performed based on a convex problem transformation. The Greedy and Cont-A schemes are easily directly solved with Matlab. The FOSAA, Greedy and Cont-A schemes select the data flows that could be retrieved through the vehicular network. Then, these data flows are injected into the network simulator, and the network performances are evaluated. Network performance simulations are performed using the Network Simulator NS2.33 [33]. We implement an IEEE 802.11p package in our testbed to enable VANET communications among high-speed vehicular nodes. The Table 2 presents the VANET simulation parameters, inspired from [34].

The performances evaluation is based on using scenarios presenting different vehicle topologies, whereby each scenario is characterized by its number of vehicular nodes and the maximum number of hops to the infrastructure; see Table 1. These scenarios represent different snapshots of the vehicular node movements, therein offering heterogeneous topology features based on a variable number of vehicular nodes ([1-42] nodes) and number of hops from the RSU to the *downloader* vehicle ([1-5] hops) for evaluating the impact of vehicle density and the number of hops on the offloading fraction. The simulation time of the scenarios is 300 s, with a step of 1 s for each recalculation of the vehicles' movement parameters. We limit the maximum radio range of any vehicular node to 300 m to enable the establishment of reliable communication. Moreover, it is clear that the overhead induced by VANET routing protocol is not an issue because we use a dedicated SCH

Table 3
Data traffic simulation parameters.

Traffic assignment	
Distribution	Uniform
Number of flows	[1-5]
Flow size	[0.1-20] Mbytes
QoS class	Best Effort
Parameters	
H_p	$27 \cdot T_s$
$T_s/T_{SIFS}/T_{ACK}/T_{DIFS}$	9/10/30/28 μs
R_I/R_{v2v}	1000/300 m
LA_{th}	0.001
MaxTrials	2

channel for data transmission. For the cellular network, we assume that full cellular coverage of the area is available.

7.2. Traffic demand generator (traffic model)

We formulate the FOSAA optimization problem with the goal of maximizing the set of data flows (1) that are retrieved through the vehicular nodes under several constraints. The *downloader* vehicle can always perform its download through the cellular infrastructure if it cannot retrieve its requested content through the ITS.

It is shown in [4] that most mobile data traffic is data and video streaming traffic. Thus, we made an assumption that all data flows under consideration are mapped to the best effort access category. The remaining traffic is sent through the cellular network.

In previous evaluations in [35], we studied the impact of traffic flow distributions on the offloading fraction. The traffic flow distribution represents the number of flows that each vehicle requests from the infrastructure. Three distributions have been considered: uniform, Gaussian and exponential. With a uniform distribution, the number of requested flows of each *downloader* vehicle is in the range [1–5]. The Gaussian distribution presents a standard deviation of $\sigma = 1$ and a mean of $\mu = 2$. The exponential distribution is characterized by $\mu = 2$. Simulations have shown that traffic flow distributions do not affect the offloading fraction [35]; thus, in this work, we consider a uniform distribution as specified in Table 3. On the other hand, two flow volume distributions are studied: homogeneous and heterogeneous. In the homogeneous case, all flows for all *downloader* vehicles have the same size. In the heterogeneous case, the flow size follows a uniform distribution in the interval [1-20] Mbytes; see Table 3.

7.3. Simulation results

In this section, we present the simulation results of the evaluation of the evolution and improvement of the offloading fraction and the node active times (b_i) from the first iteration of the FOSAA scheme until convergence and its dependencies. We compare the FOSAA approach to the Greedy and Cont-A-based Greedy approaches and evaluate the impact of the data traffic volume, the vehicle density and the number of hops on the offloading fraction. The configuration of the network, such as the set of flows to be offloaded and the node active time, is computed by Matlab for each scheme. Then, the configuration is injected into NS2. We find that it it takes at most only a few seconds for the FOSSA resolution scheme to obtain the results in Matlab, even when there is a large number of vehicles (the settings of the simulation scenario are shown in Table 1). For the FOSAA numerical evaluation, we assume that I2V and V2V communications are based on IEEE 802.11 standards and occur on two different bands.

To evaluate the impact of data volume on the offloading fraction of the FOSAA scheme, we injected different data flow volumes for the same given network topology. We collected results of each per-downloader flow volume. We then varied the network topologies and averaged the results. Moreover, the mobility of the nodes and changes in the topology are treated in the simulation for the purpose of evaluating the impact of the network topology on the FOSAA performances. Snapshots of the VANET network are performed periodically; one snapshot is performed after sending all the data traffics through the I2V link. The topology, vehicles' positions and velocity and V2V links change in each snapshot.

In Fig. 3, we plot the impact of increased flow volumes on the offloading fraction of the first (i.e., FOSAA-1) and last iteration of the FOSAA approach for scenario#2. We notice an average improvement of 5% of the offloading fraction from the first iteration, i.e., FOSAA-1, until the last iteration, i.e., FOSAA, due to the optimal b_i that are set to the vehicular nodes, c.f. Fig. 7. Moreover, it is clear that, for FOSAA and FOSAA-1, the traffic offloading percentage decreases when increasing the flow volume because a higher data volume requires a higher channel capacity, and because the channel capacity is limited, the V2V channel would only support a smaller portion of the traffic with increasing content volume. Finally, FOSAA offloads 97.79% of the data flows of low data volumes, which represents all 1- and 2-hop flows and a fraction of 3-hop flows.

In Fig. 4, we present the performances of the Greedy approach with increasing per-flow data volume and compare two Greedy offloading strategies: a random priority assignment and a position-based priority assignment. With the random priority assignment, the Greedy scheme first checks the data flows of the first hop nodes by randomly selecting one-hop nodes. Under the position-based priority assignment, the Greedy scheme first checks the first node, then the second, then the third, … etc, moving in the same direction. We can see from Fig. 4 that the Greedy offloading fraction is clearly independent of the priority of nodes at the same hop. In the remaining simulations, we use the position-based priority assignment for the Greedy approach.

In Fig. 5, we plot the packet delivery ratio (PDR) of offloaded flows at 1-2-3-4-5 hops from the RSU. It is clear that, under the FOSAA approach, 4- and 5-hop flows are not offloaded, which is why the PDR is zero in such cases. The 4- and 5-hop flows are offloaded under the Greedy and Cont-A approaches because these schemes select the flows based on the gateway capacity rather than the nodes' position. FOSAA presents the highest PDR. In general, PDR decreases when the number of hops increases. Notice that, here, PDR is defined as the percentage of flows allocated, which is different from the end-to-end hop packet successful probability. Because the packet is allowed to retransmit multiple times (7 times according to the default DCF setting) before success, the packet loss probability after all retries is quite small. For example, even when there is a high packet loss probability (50%), the packet loss probability after 7 retries is $0.5^7 = 0.0078125$, which is negligible. Therefore, in practice, we can assume that all allocated flows can be totally disseminated to corresponding vehicles.

Fig. 6 predicts the average delay of offloaded traffic at 1-2-3-4-5 hops from the RSU. Under FOSAA, the 4- and 5-hop flows are not offloaded, leading to an average delay of zero. The 4- and 5-hop flows are offloaded with and Greedy and Cont-A approaches. Obviously, the delay increases as the number of hops increases, and the FOSAA scheme presents the smallest delay.

Fig. 7 depicts the variations and convergence of the node active times ($b_i, \forall i \in V$) for 5-hop scenarios after performing successive iterations of FOSAA. In the first iteration, equity among nodes is assumed, and thus, FOSAA-φ-1 generates an output that represents the lowest offloading bound. In the second iteration of FOSAA, FOSAA-a sets the b_i while satisfying the channel capacity saturation limit and time sharing between exposed nodes. The offloading fraction is improved but could be further improved in the next iterations. In the third and fourth iterations, the $b_i, \forall i$

∈ V values converge, and the upper bound of offloading fraction is reached. In these scenarios, a maximum of four iterations are required for FOSAA to converge and for FOSAA-a to set the adequate active times (b_i) offering the highest offloading fraction. We also notice that intermediate nodes present low active times and that border nodes (at 1 and 5 hops) present higher b_i. More precisely, we believe that b_i depends mostly on the number of exposed nodes (neighbor nodes) and son nodes. This predication is proved in Fig. 8, where we plot the b_i settings while considering the number of sons, neighbor nodes, hidden nodes and other nodes.

In Fig. 8(a), we evaluate the node active time dependencies and settings according to the surrounding neighbors, sons and hidden nodes. We notice that b_i increases when the numbers of neighboring nodes and hidden nodes decrease. b_i is small for a large number of active neighboring nodes and for two-hop nodes. Moreover, we notice that the number of neighbor nodes and son nodes most strongly affects b_i. Thus, and based also on Fig. 7, we deduce that intermediate nodes, which are characterized as presenting a large number of neighbors, will suffer from low active times. However, border nodes, especially one-hop nodes, obtain large b_i because they will play the role of gateways to the infrastructure for all their son nodes. In addition, under the FOSAA scheme, b_i assignments could be approximated using (30) and (31), which depends on the number of active neighbor nodes, the number of son nodes, and a dynamic parameter related to the vehicular node topology. Moreover, according to Fig. 8(a), b_i presents multiple-regression shape related to the number of neighbor and son nodes. Thus, based on these observations and on the predictor variable b_i, a Matlab regression function determined the regression coefficient related to each parameter. $[b_i]_{FOSAA}$ is formulated based on detection and estimation theory. To prove the validity of Nei-A, we perform the simulations and comparisons presented in Figs. 8, 9 and 10.

In Fig. 8(b) and (c) , we plot the variations in b_i for the FOSAA, Greedy and Nei-A schemes for increasing number of neighboring and son nodes. In Fig. 9, we plot the b_i assignments of some nodes for the FOSAA, Greedy and Nei-A schemes. It is clear from these figures that, with the FOSAA and Nei-A schemes, the b_i values overlap when the number of neighbor and sons nodes increased and for different node ids. The Greedy scheme presents heterogeneous values. To go further extend the Nei-A and FOSAA analysis, we also evaluate the corresponding offloading fractions.

In Fig. 10, we present the impact of data volume on the offloading fraction for the FOSAA, Greedy, Nei-A, and Cont-A schemes. The presented results are the average of all simulation scenarios presented in Table 1. It is clear that the offloading fraction decreases when the flow volume increases because a higher capacity is required to support more data offloading. Thus, a channel capacity constraint is mandatory in FOSAA model because it will indicate whether the channel can support additional traffic. Moreover, the FOSAA and Nei-A schemes present similar offloading fractions even for high data flow volumes. The Greedy scheme presents an approximately 5% higher offloading fraction compared to FOSAA for data flow volume $<$ 15 Mbytes and decreases considerably by approximately 25% compared to FOSAA for data flow volume $>$ 15 Mbytes. We deduce that Nei-A presents a mix of the features from the FOSSA and Greedy schemes because it can operate in both light load ($<$ 15 Mbytes) and high load cases. The Cont-A scheme presents the lowest offloading fraction, i.e., only 20% of data flows are offloaded. As a conclusion, Fig. 10 clearly confirms that Nei-A could approximate the FOSAA scheme and could be its heuristic model.

In Fig. 11, we predict the impact of the number of hops on the offloading fraction for the FOSAA-1, FOSAA-2, FOSAA, Greedy and Cont-A schemes. For data traffic demand, one data flow of 0.5 Mbytes is requested for each vehicular node. According to Fig. 10,

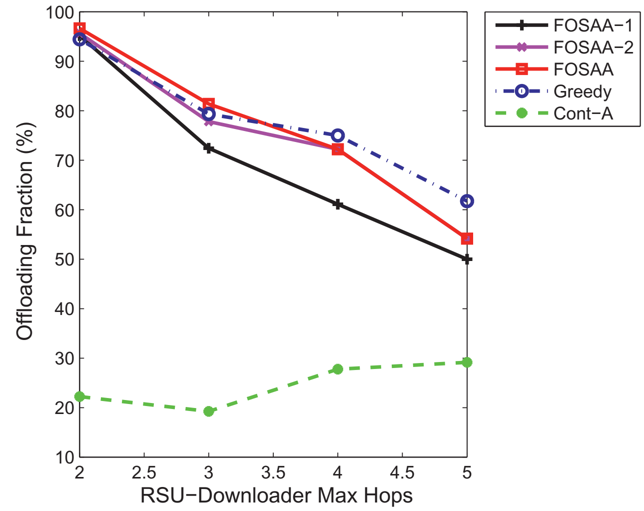


Fig. 11. Impact of number of hops on offloading fraction for FOSAA, Greedy and Cont-A approaches.

with these 0.5 Mbyte flows, the Greedy and FOSAA schemes present similar performances. The offloading fraction is improved from FOSAA-1 to FOSAA-2 and converges to that of FOSAA. The fraction decreases considerably when the number of hops increases, especially to more than 3 hops. We notice that, for 4- and 5 hop-flows, the offloading fraction with the Greedy scheme is higher than that of FOSAA because a fraction of 4- and 5-hop flows are offloaded under the Greedy scheme. With the Cont-A scheme, a maximum of 30% of the traffic could be offloaded.

Therefore, based on Figs. 10 and 11, we can deduce that, for the light data traffic case, with a data flow volume $<$15 Mbytes, and with 2- and 3-hop VANET topologies, the FOSAA, Greedy and Nei-A schemes present similar offloading fractions. For the high data traffic case, with a data flow volume $>$15 Mbytes, the FOSAA and Nei-A schemes continue to obtain equivalent performances, therein presenting a greater than 50% offloading fraction. However, the Greedy and Cont-A schemes could not handle the high data traffic and suffer a decrease of greater than 25%. These results follow from the fact that the FOSAA and Nei-A schemes optimize the node active time assignments according to the surrounding environment (numbers of neighbor, son, and hidden nodes). As a conclusion, despite FOSAA presenting sensibly higher offloading fractions compared to Nei-A, the Nei-A scheme is most suitable beause it can be adopted for both light and heavy load cases and presents lower computational complexity than does FOSSA.

8. Conclusions

In this work, we presented FOSAA, an analytical model that determines the potential of using vehicular nodes for cellular traffic offloading. We studied joint data flow selection and contention resolution in a hybrid VANET and cellular infrastructure system, where the objective is to maximize the set of data flows offloaded through the vehicular nodes. The evaluation results show that FOSAA prioritizes the offloading of 1- and 2-hop flows and that the adequate node time activity assignment ensures a higher offloading fraction. FOSAA also obtains a higher offloading fraction compared to the Greedy and Cont-A approaches and converges after a maximum of 4 iterations. We concluded that the node active times are closely related to the number of active neighbor and son nodes and to the vehicular environment. The Nei-A scheme was proposed to approximate the FOSAA scheme. The simulations results show that the FOSAA and Nei-A schemes present similar performances and that they are adaptable to both light and heavy load cases.

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Please cite this article as: G.e.m. Zhioua et al., A joint active time and flow selection model for cellular content retrieval through ITS, Computer Networks (2016), http://dx.doi.org/10.1016/j.comnet.2016.03.015