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Modeling interactive real-time applications in VANETs with performance evaluation

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ABSTRACT

Vehicular Ad-Hoc Network (VANET) is an emerging technology, which provides intelligent communication between mobile vehicles. Integrating VANET with Ubiquitous Sensor Networks (USN) has a great potential to improve road safety and traffic efficiency. Most VANET applications are applied in real time and they are sensitive to delay, especially those related to safety and health. Therefore, checking the applicability of any proposed application is very important. One way to achieve that is by calculating the Round Trip Time (RTT), which is the time taken by a VANET application starting from the initiator node (source vehicle) sending a message until receiving a response from the core network. In this paper, we present a new complete analytical model to calculate the RTT of VANET applications. Moreover, we introduce a novel detailed network architecture for VANET applications using the IP Multimedia Subsystem (IMS) as a service controller in the USN environment. To the best of our knowledge, there is no previous published work that either studied the RTT of VANET applications or developed a complete architecture to implement them by integrating VANETs with USNs and IMS. The RTT is calculated by combining two analytical models. Firstly, we developed an analytical model to calculate the time needed for the communication between two nodes on a road. Secondly, we developed a queuing model using Baskett Chandy Muntz Palacios (BCMP) queuing network for the IMS servers to calculate the application's execution time in the core network. These models are general enough to be applied to any VANET application. Finally, to assess the validity and the accuracy of the proposed architecture and models, we used three different tools: C++, MATLAB, and OPNET. The analytical results were compared to the simulation results to evaluate their consistency.

1. Introduction

There is a rapid evolution of the Intelligent Transportation Systems (ITS). One of its main objectives is to improve the safety on the roads. VANET has been considered as an efficient and effective method to meet ITS's requirements by providing various applications, including collision warning, up-to-date traffic information, active navigation, and infotainment [1]. In VANETs, the vehicles communicate with each other via short-range wireless MAC protocols such as IEEE 802.11p [2].

The applications envisioned in VANET can be classified into i) safety and ii) user related applications [3].

- Safety related applications might include messages related to the safety on the road such as driver vital parameters monitoring, driver sleep control, accident alert, road conditions, weather conditions, and traffic conditions. Their communication protocols and servers should be designed to minimize delays and losses.
- User related applications are applications that provide value added services like Internet connectivity applications and peer-to-peer applications. This type can tolerate some delay and messages losses.

On the other hand, smart wearable devices [4] and USNs are emerging rapidly providing many reliable services facilitating people's lives. Those very useful small end terminals and devices require a global communication substrate to provide a comprehensive global end user service. The ITU-T recommendations for USN present the requirements for a platform to several life services and

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applications [5]. Wearable devices and USNs can have a large field of applications if they are integrated with the ITS.

To the best of our knowledge, there is no complete model, which integrates these two technologies: USN and VANET. In [6,7], we used the IMS as a service controller sub-layer in the USN environment. We extend this work here by integrating VANET and IMS. The main motive behind this integration is to leverage from the benefits of IMS [8] to support VANET applications. First, IMS is fully standardized and mature. Second, it has been chosen as the main subsystem to implement Voice over LTE (VoLTE). Consequently, IMS would probably exist in the infrastructure of telecom operators. Therefore, the idea is to reuse it instead of implementing a new subsystem for VANET applications. Third, IMS uses open standard IP protocols and is designed to easily develop and implement new services. Fourth, IMS is access independent. Consequently, the access gateway used in the proposed architecture could exploit any available access network to communicate the collected information to the core network. Finally, The ITU proposes to use the Next Generation Network (NGN) as the platform to support USN applications including vehicle communications without introducing an integration architecture. The integration between the USN controlled by IMS and VANET provides a rich environment for various critical applications especially in health and safety on the roads.

In this paper, we propose a model for a new end-to-end road safety service based on IMS as a service controller sub-layer to VANETs and wearable devices. This proposed model is general enough to be applied to any other VANET application. It combines analytical equations for the ad-hoc network and the service controller. Since safety applications are delay sensitive, the time taken by an alert to be sent until a response is received is very critical. This time is called RTT. Therefore, in this research, we study the RTT to implement safety applications based on our proposed model. This would help in calculating instantaneous parameters such as: the number of hops, the RTT needed to implement VANET applications, and the reliability of the model. The analytical results derived from the equations are compared to simulations to prove their validity. As far as we know, it is the first contribution where such a complete approach is used to model this complex architecture. The contributions of this paper can hence be summarized in the following:

- Proposing a new complete model to integrate USN and VANET platforms controlled by IMS.
- Developing a complete signaling flow to implement the proposed safety application in the IMS using the Session Initiation Protocol (SIP).
- Developing an analytical model for the vehicles link connectivity between the event initiator vehicle and the nearest RSU to calculate the reporting delay of events.
- Developing a network queuing model for the IMS servers processing functionality to provide a full estimation of the delay as a function of the alert arrival rate at the RSU.
- Calculating the total RTT starting from transmitting an event alert message until receiving a response from the IMS network. This is to evaluate the reliability of the IMS to be used as a controller for real time applications.

The rest of the paper is organized as follows: Section 2 describes the related work. Section 3 explains the proposed application algorithm and framework. Section 4 presents the mathematical model of the VANET relays on the road and the queuing model of the IMS network. Section 5 presents the evaluation of the proposed models and comparisons to simulation. Finally, Section 6 gives the conclusion of this contribution.

2. Related work

Most of the research in VANETs is focused on optimizing the data dissemination protocols, VANET link models, and security in VANET communications. Very few contributions look at the complete architecture including the VANET applications as it should be considered as a whole. As we are interested in the network modeling and its applications, we are reviewing contributions in these areas. This section presents the related work of three approaches we are working on to calculate the RTT of implementing VANET services controlled by the IMS. Part one reviews the VANET modeling related work. Part two describes the related work in modeling the IMS network servers. Finally, part three presents the integration of the VANET and the IMS platform.

Regarding the VANET modeling, when the network is sparse, the information propagation speed may depend on the vehicle speed and the network may work in a delay tolerant fashion. In [9,10], models were presented for delay tolerant networks or to investigate the impact of disconnections in vehicle networks on the information propagation. These are interesting results but in our present work, we consider only real-time applications.

The connectivity in VANETs was widely studied as in [11–13], where the connectivity probabilities were derived. In [14], authors proposed an analogy by which the ad hoc network connectivity is modeled by a $G/D/\infty$ queue. In [15], the authors used this analogy to derive the number of clients in a connected component of vehicles in a VANET and what they called the connectivity distance, which is the length of a vehicle connected component. In [16], authors investigated the effect of channel randomness on connectivity, with particular emphasis on the effect of lognormal shadowing and Rayleigh fading phenomena. The connectivity analysis had been extended to the case of a Nakagami fading channel in [17]. In [18], authors studied the minimum transmitted power necessary to ensure network connectivity in a VANET under BER requirements.

These papers provide insightful results on connectivity analysis. However, they give no detail on the number of hops in the shortest path of a vehicle connected component, which is important to estimate propagation delays. In [19], the multi-hop packet delivery was approximated through an effective bandwidth approach with the traffic parameters approximated by average ON and OFF periods. In [20,21], the connectivity and the number of hops through the shortest path were exactly modeled. Unfortunately, the results were given as recursive formula, which makes it difficult to perform the analysis as a function of network parameters. In [22], the number of hops through the shortest path in a connected component in VANETs was calculated as an explicit expression of the z-transform of its probability and was given for medium and dense networks. We will use this model to derive the access delay. This model is summarized in part IV.

For the core network modeling, the authors of [23] proposed a scheme for modeling and optimizing the IMS network design using $M/M/1/\infty$ queuing. The authors used utility functions to optimize the service rate of the IMS servers. We believe this model did not take into consideration the capacity planning of the IMS. Moreover, its evaluation experiment is not precise as it was based on two proxy servers without taking into consideration the other IMS layers' servers.

In [24], authors proposed to model and simulate the IMS network using M/M/1 network model assuming the service arrival rate is exponential. This queuing model is very theoretical and cannot simulate the real conditions of the IMS network as will be explained.

Another work proposed modeling the IMS servers using BCMP networking [25] for an authentication method. The solution considers an open queuing network model and hence is too simple.

Moreover, this work does not take into consideration the messages reply in calculating the servers delay.

Regarding the use of the IMS as the platform for implementing the VANET application, there is very little literature in that area. In [26], authors proposed an integration between the ITS and the IMS. They proposed the integration based on a design for a gateway on the vehicle onboard device. The work in [27] extended the idea in [26]. It presented an IMS based platform for the deployment of services in vehicular network. They integrated two service enablers to enrich presence and instant messaging and two customized IMS clients. They aimed to provide a service platform of a control mechanism enabling the vehicular terminals to operate these services efficiently regardless of the access technology.

In these articles, authors did not present a detailed functional model for the proposed integration and their service enablers. Their work concentrated on developing a real service platform. However, they did not mention the parameters they used in their scenarios as well as the road traffic load and its distribution. Therefore, these results are limited in scope.

The authors of [28] proposed an integrated architecture for the VANET with the IMS in the presence of WSNs. They proposed a design for a gateway, which is the central point of the integration. The integration was proposed in terms of how to access the IMS network. All the previous work shares the same problem. They focused on developing a design of the gateway required for that integration without mentioning the requirements of the integration of the middleware layer in the USN as defined in the ITU recommendations [5].

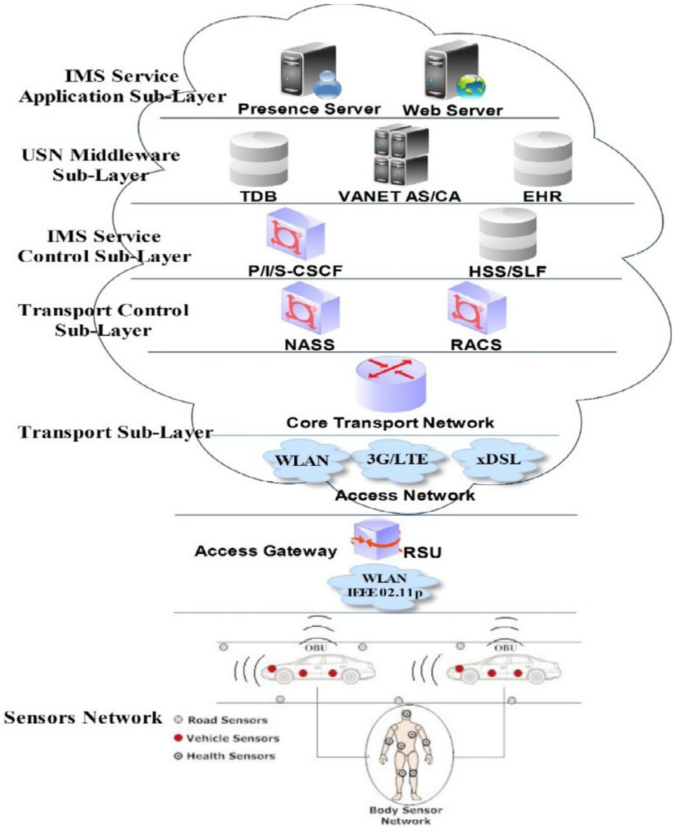

Fig. 1. Next generation VANET network architecture.

3. Application framework

3.1. Architecture model

This subsection presents our model architecture. We propose a complete architecture that complies with the ITU requirements [5] and follows the proposed model in [6,7] based on using the IMS as a controller for VANET applications. The proposed architecture consists of two layers: transport layer and service layer as shown in Fig. 1.

The Sensor network contains different types of wearable devices or sensors with wireless capability. The basic difference between these two terms is that a wearable device is usually not capable of routing or forwarding but only reporting information to a gateway, while sensors can organize themselves in more complex connected graphs. These two kinds of nodes observe the vehicle driver, the vehicle itself, and the surrounding atmosphere as well. Additionally, mechanical sensors fixed on the car can detect failure or warnings within the car. Data is then aggregated using the On Board Unit (OBU) fixed in the vehicle.

The Access Gateway layer in Fig. 1 contains the Road Side Unit (RSU) which provides the access and connectivity requirements between VANET and IMS infrastructures. It interacts with the OBUs using Dedicated Short Range Communication (DSRC) based on IEEE 802.11p. On the other hand, it interacts with the IMS network using SIP.

The Transport layer provides transfer functionalities and comprises access network, core transport network, and transport control sub-layer as defined in the standards [29]. The access network functions take care of end users' access to the network as well as collecting and aggregating the traffic towards the core network. The transport control sub-layer is further divided in two subsystems: the Network Attachment Subsystem (NASS) and the Resource and Admission Control Subsystem (RACS) to provide the QoS, privacy, security, and authorization as required for the USN applications.

The Service layer provides the platform for enabling services to the user. It includes registration and session control functions. It contains three sub-layers: the Control sub-layer, USN middleware sub-layer, and the Application sub-layer. The service control sub-layer is based on the standard IMS [30] and controls the authentication, routing, and database of the subscribers. This sub-layer provides the USN requirements needed including service profile, open service environment, security, and authorization.

The USN middleware sub-layer consists of a set of logical functions to support USN and VANET applications. It contains the Application Servers (ASs) providing the different services. It is responsible of executing the different applications. The AS is integrated with a Context Awareness server (CA) to automatically adapt an application or service depending on the user's current situation. This integration eases services control and reduces the signaling required between both of them.

It contains also a private database for the e-Health services' subscribers. We call it the Electronic Health Record (EHR). It contains the initial sensors configuration settings, the collected monitored vital signs, emergency contacts, medical supervisors, medical history, and any other information related to the e-health service. Moreover, the layer comprises a Traffic Data Base server (TDB). It contains the general safety rules, weather information, roads conditions and rules, etc. The TDB server contents are updated regularly.

The Service Application Sub-layer contains a Presence Server (PS), which is used to follow and publish the vehicles status in real-time as will be explained later in details. This sub-layer contains also a Web Server (WS), which can publish roads events, status, and any updates that could be useful for the passengers.

Other facilities and services that cover the sensor network management, user service profiling and personalization, open service

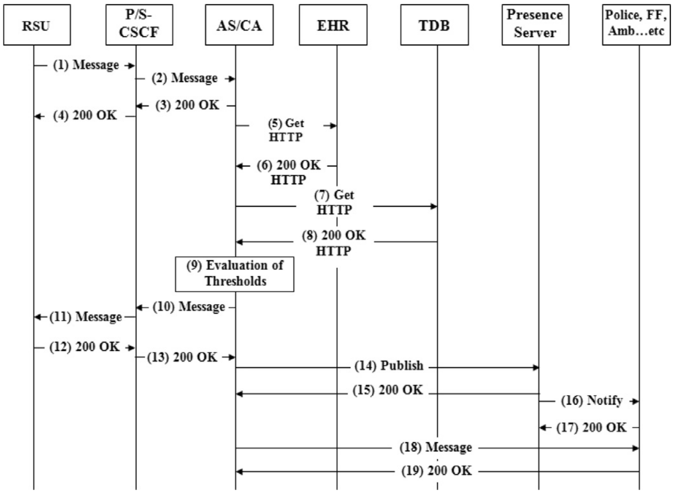

Fig. 2. Application signaling flow in the IMS.

environment, location based service support, and service privacy of the USN requirements are used. However, we have not included them in this description for the paper clarity.

3.2. VANET communication model

In this subsection, we describe the new SIP signaling flow used to implement the proposed model. We consider that there are different types of vehicles on the road. These vehicles are equipped with OBUs to communicate with each other and with the RSUs. Drivers put wearable devices to monitor their vital signs and health status.

The messages exchanged between the vehicles or between them and the RSUs are entirely composed of elements determined by the sender, allowing for flexible data exchange. There are different types of messages. The basic safety message contains vehicle safety-related information that is periodically broadcasted to surrounding vehicles. The emergency vehicle alert message is used to broadcast warnings to surrounding vehicles that an emergency vehicle is operating in the vicinity. The probe vehicle data message contains status information about the vehicle to enable applications that examine traveling conditions on road segments. The traveler advisory message provides congestion, travel time, and signage information, etc.

Once a vehicle detects an event such as an accident or driver health risk, it sends an alert message to the neighbor vehicles to be relayed to the nearest RSU. This message contains all the available data including the vehicle's ID, location, lane, speed, etc. The VANET architecture forwards the message in a V2V mode until it reaches the nearest RSU. We use the Wireless Access in Vehicular Environments (WAVE) protocol family for this communication. It is based on directional relaying of information.

Once the RSU receives the message from vehicles' OBUs, it forwards it to the Proxy/Severing-Call Session Control Function (P/S-CSCF) of the IMS as shown in step 1 of Fig. 2. The information is formulated in the SIP "MESSAGE" body as in [7]. The P/S-CSCF forwards this message to the Application Server/Context Awareness (AS/CA) (step 2). The AS/CA acquires the current health record of the vehicle's driver from the EHR server and/or the current road information from the TDB server using HTTP "GET" request as in steps 5–8. All this information is used by the AS/CA to perform a comparison and a situation analysis of the event that occurred (step 9). Based on the result of the analysis, the AS/CA sends its decision as a SIP "MESSAGE" (step 10) to the RSU. The RSU relays it (step 11) to the vehicle which detected the event and/or its surrounding vehicles according to the instructions received from the AS/CA. Subsequently, the AS/CA sends a SIP "PUBLISH" request (step 14) to the PS to update the status of the road/vehicle/driver. Afterwards, the PS notifies in step 16 the interested parties of this change. These parties could be drivers' relatives, cars owners, cars rental agencies, police departments, fire brigades, ambulances, or passengers intending to travel on the road where the event occurred. This would allow them to handle the situation accordingly. It is assumed that these parties had already subscribed with the PS to track such events. This subscription is not shown in the Figure. Moreover, the AS/CA sends a SIP "MESSAGE" (step 18) to any interested website such as emergency websites and traffic websites, which might publish that there is a traffic jam on that road.

The context created for each event at the operator side would formulate the event conditions. According to that, it would decide which actions should be taken to alleviate the worst cases. The feedback taken by the AS/CA could be different types of reactions or alert messages sent to the source vehicle and/or to the surrounding vehicles.

As mentioned earlier, it is very important to calculate the RTT starting from the moment when an event is detected by a vehicle and a message is transmitted until a response is received from the core network to be able to evaluate the validity of the proposed network architecture model. This is not a simple problem. Therefore, we decompose it into two parts. First, we need to model the VANET link connectivity in order to calculate the communication delay between the event detecting vehicle and the nearest RSU. Second, we model the IMS servers' processes to implement the proposed service. The next section is dedicated to the models derived for these two parts.

4. Modeling the VANET link connectivity and IMS servers

This section describes the mathematical models used along with their derivations. The Vehicle to Vehicle (V2V) communication is firstly presented followed by the core network.

4.1. V2V connected set model

In order to calculate the time delay expected between the vehicle that detects an event and the nearest RSU, we need to calculate the number of hops between this vehicle and the nearest RSU. Note that assuming a shortest path routing the number of hops is not the number of nodes: only the farthest node under the coverage of another sending node retransmit a packet. To achieve this goal, we use our own model of link connectivity between vehicles on a road presented in [22].

The model is an extension of [14] where the authors calculate the connectivity probability between two nodes as a function of the inter-distance between them. We extend this model to calculate the number of nodes in the shortest path between two nodes that is the number of hops. Our approach consists of estimating the hop density on a connected set to estimate the number of nodes in the shortest path between two vehicles separated by a certain distance. We define the hop density as the number of hops in a connected component of vehicles divided by the spread (in space) of this connected component. For this goal, we calculate the number of hops in the largest shortest path in the connected set, which is the number of hops in the shortest path from the start of the connected component to its end divided by the spread of the connected set. In order to calculate the number of hops in the largest shortest path and as in [14], we use the same analogy presented in [31] where the idea is to notice that the number of vehicles in a VANET connected component is equal to the number of clients in a busy period of the M/D/∞ queue. The method to calculate the probability distribution of the number of clients in a busy

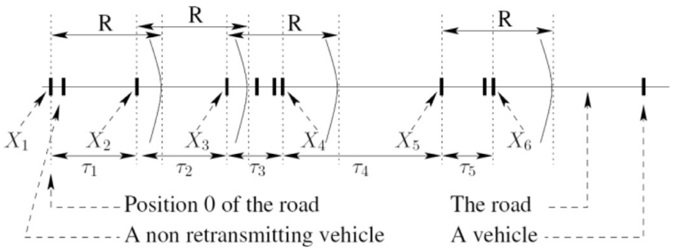

Fig. 3. Vehicles connected component according to the shortest path.

period of $GI^X/D/\infty$ queue (of which $M/D/\infty$ queue is a particular case) is given in [15].

Similar to [14], we consider free flow vehicles traffic on a straight road with speeds distributed according to a truncated normal distribution. The minimum and maximum speeds are V_{min} and V_{max}. Their mean and standard deviation are μ and σ respectively. Note that if the vehicle transmission range R is sufficiently large compared to the road width L, the commonly used assumption of modeling a multiple lane road by a straight line with spread vehicles is highly acceptable. The vehicles arrive at position 0 of the road according to a Poisson process with a rate λ_a. As proved in [14], the inter-distance of the vehicles at any given time is exponentially distributed with the following rate:

$$\lambda = \lambda_a \int_{V_{min}}^{V_{max}} \frac{1}{\upsilon} \frac{\frac{2}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\upsilon-\mu}{\sigma}\right)^2}}{\operatorname{erf}\left(\frac{V_{max}-\mu}{\sigma\sqrt{2}}\right) - \operatorname{erf}\left(\frac{V_{min}-\mu}{\sigma\sqrt{2}}\right)} d\upsilon \tag{1}$$

To calculate the inter-distance between the retransmitting vehicles on the road, we assume a shortest path between them as in Fig. 3. Let $X_1, X_2, \ldots, X_n$ be the retransmitting vehicles. X_{n+1} is either the farthest vehicle under X_n's coverage, or the next vehicle after X_n if the distance between X_n and X_{n+1} is larger than R. If X_{n+1} is the farthest vehicle under X_n coverage, there may be other vehicles between X_n and X_{n+1}. However, we assume they do not retransmit the packets sent by X_n. The X_{n+1} vehicle is assumed to be the next hop for the X_n's as it is within its coverage range.

Let τ_n be the distance between node X_n and node X_{n+1}. Let $N[a; b]$ be the number of vehicles between positions a and b. When $x_1 \le R$, the probability function of τ_1 is given by:

$$\begin{aligned} F_{\tau_1}(x_1) &= P(\tau_1 \le x_1) \\ &= P(N[x_1; R] = 0 \cap N[0; x_1] \ge 1) \\ &= e^{-\lambda(R-x_1)}\left(1 - e^{-\lambda x_1}\right) \end{aligned} \tag{2}$$

When $x_1 > R$, it is:

$$F_{\tau 1}(x_1) = 1 - e^{-\lambda x_1} \tag{3}$$

The probability function of τ_n knowing $\tau_{n-1} = x_{n-1}$ in the case of $\tau_{n-1} > R$ is the same as τ_1. When $x_n \le R$, the probability function of τ_n knowing $\tau_{n-1} = x_{n-1}$ and $\tau_{n-1} \le R$ is given by:

$$\begin{aligned} F\tau_n/\tau_{n-1}(x_n, x_{n-1}) &= P\left(\tau_n \le \frac{x_n}{\tau_{n-1}} = x_{n-1} \cap \tau_{n-1} \le R\right) \\ &= e^{-\lambda(R-x_n)} - e^{-\lambda x_{n-1}} \end{aligned} \tag{4}$$

and in the case $x_n > R$:

$$F_{\tau_n/\tau_{n-1}}(x_n, x_{n-1}) = 1 - e^{-\lambda[x_n-(R-x_{n-1})]} \tag{5}$$

If the inter-distance between the hops was Poisson, the solution would be straightforward. It is not the case as shown in Eqs. (2)–(5).We conclude that the distance between the retransmitting vehicles on the shortest path is a Markovian process. In the rest of this section, we assume without loss of generality, the first retransmitting vehicle X_1 is located at the beginning of a connected component.

Using Theorem 2 in [22], the probability to have k vehicles in a connected component is:

$$\begin{aligned} P(N_b = k) = &\int_{x_1=0}^{R} \cdot \int_{x_2=R-x_1}^{R} \cdots \int_{x_{k-1}=R-x_{k-2}}^{R} P(\tau_k > R/\tau_{k-1} = x_{k-1}) \\ &\times \prod_{i=2}^{k-1} dP(\tau_i = x_i/\tau_{i-1} = x_{i-1}) dP(\tau_1 = x_1) \end{aligned} \tag{6}$$

Let us denote $\lambda' = \lambda R$, $\rho = \lambda' e^{-\lambda'}$, and $\rho' = e^{-\lambda'}$.

From (2)–(6), the probability of the number of connected vehicles becomes with a simple change of variables:

$$P(N_b = k) = \rho^{k-1} \times \int_{u_1=0}^{1} \int_{u_2=1-u_1}^{1} \cdots \int_{u_{k-1}=1-u_{k-2}}^{1} \prod_{i=1}^{k-2} e^{\lambda' u_i} \prod_{i=1}^{k-1} du_i \tag{7}$$

By denoting

$$\mathfrak{M}_{\alpha,k} = \rho^k \times \int_{u_1=0}^{1} \int_{u_2=1-u_1}^{1} \cdots \int_{u_k=1-u_{k-1}}^{1} u_k^{\alpha} e^{\lambda' u_k} \prod_{i=1}^{k-1} e^{\lambda' u_i} \prod_{i=1}^{k} du_i \tag{8}$$

We have

$$P(N_b = k) = \rho \mathfrak{M}_{1,k-2} \tag{9}$$

In [22] the following recursive system is easily proved:

$$\begin{cases} \mathfrak{M}_{0,k} = \mathfrak{M}_{0,k-1} - \rho \mathfrak{M}_{1,k-2} \\ \mathfrak{M}_{\alpha,k} = \mathfrak{M}_{0,k-1} - \frac{\alpha}{\lambda'} \mathfrak{M}_{\alpha-1,k} - \frac{\rho \mathfrak{M}_{\alpha+1,k-2}}{\alpha+1} \end{cases} \tag{10}$$

Let $Q(z)$ be the z-transform of N_b, and $M_1(z)$ be the z-transform of $\mathfrak{M}_{1,k}$:

$$Q(z) = \sum_{k=1}^{+\infty} P(N_b = k) z^k \tag{11}$$

$$M_1(z) = \sum_{k=1}^{+\infty} \mathfrak{M}_{1,k} z^k \tag{12}$$

Then, the z-transform of N_b is:

$$Q(z) = \rho' z + \rho z^2 (1 + M_1(z)) \tag{13}$$

Assuming a special case where $\lambda R \ge Ln(4)$, the z-transform $M_1(z)$can be expressed as (cf. Theorem 3 in [22]):

$$M_1(z) = \frac{h_1(z) + h_2(z) + h_3(z)}{\rho z^2 \left[1 + \sqrt{1 - 4\rho' z^2} - 2z e^{\frac{1}{2}\lambda'\left(\sqrt{1-4\rho' z^2}-1\right)}\right]} \tag{14}$$

where

$$\begin{aligned} h_1(z) = &\sqrt{1 - 4\rho' z^2}\left[\left(1 - \rho' - \rho\right) z^3 - \left(1 - \rho'\right) z^2 - z(1 - \rho) \right. \\ &\left. + 2 - \rho' - \rho\right] \end{aligned} \tag{15}$$

$$\begin{aligned} h_2(z) = &e^{\frac{1}{2}\lambda'\left(\sqrt{1-4\rho' z^2}-1\right)}\left[2\rho z^3 + 2\rho' z^2 - z - 1 + (z - 1)\right. \\ &\left. \times \sqrt{1 - 4\rho' z^2}\right] \end{aligned} \tag{16}$$

$$h_3(z) = z^3\left(\rho' + \rho - 1\right) + z^2\left(1 - 3\rho' - 2\rho\right) + z(1 - \rho) + \rho' + \rho \tag{17}$$

Concretely, to calculate the probability of the total number of hops in the largest shortest path, the z-transform in Eq. (14) can be used if $\lambda R \ge Ln(4)$ and the recursive formula in Eq. (10) must be used for a small value of λR. The recursive calculation is difficult since numerical truncation and round up problems occur for large k. This is because small quantities are subtracted many times. Using the z-transform allows to avoid this truncation problem. Fortunately, when λR is small, only a small number of probabilities needs to be calculated because the numbers of hops in connected components are small. Conversely, when λR is large, a large number of probabilities must be calculated but it can be done through the z-transform. Note that the z-transform exists in theory for $\lambda R \geq Ln(4)$. However, it may be more careful to use it for λR slightly larger than $Ln(4)$ as the z-transform is diverging in $Ln(4)$, and the numerical differentiation near $Ln(4)$ is not very stable.

Based on the above, the average number of hops $E(no.of hops)$ in the connected component for an infinite road length can be calculated by differentiating (14) with respect to z as follows:

$$\begin{aligned} E(no.of\ hops) &= \sum_{k=1}^{+\infty} kP(N_b = k) = \left(\frac{\partial Q(z)}{\partial z}\right)_{z=1} \\ &= P(N_b = 1) + 3P(N_b = 2) + 2P(N_b = 2)M_1(1) \\ &\quad + \rho\left(\frac{\partial M_1(z)}{\partial z}\right)_{z=1} \\ &= \rho' + 2\rho + 2\rho M_1(1) + \rho\left(\frac{\partial M(z)}{\partial z}\right)_{z=1} \end{aligned} \tag{18}$$

The average size (in terms of length or spread, not number of hops) of the connected component can be calculated as in [14] as:

$$E(size) = \frac{1}{\lambda e^{-\lambda R}} - \frac{1}{\lambda} \tag{19}$$

Finally, we can calculate the number of hops in terms of the average road length L as:

$$E(no.of\ hops)_L = \frac{E(no.of\ hops)}{E(size)} \times L \tag{20}$$

Using this result, the delay for transmitting a message between two nodes on a road is directly calculated by multiplying Eq. (20) by the delay taken by a vehicle to transmit its message (T_H).

4.2. Note on the generality of the V2V connected set model

4.2.1. V2V multi-segment model

In real life, the traffic flow changes along the road due to traffic lights, traffic jams, road curves, etc. Therefore, real V2V communication cannot be modeled using a simple linear relaying scenario.

In order to match the real scenarios in roads, we propose a new assumption within the model. We assume that each road is divided into separate segments (indexed by B), and that each of them has a specific vehicle density, a specific length L_B, and different arrival rates. This assumption allows adapting our results to the real roads scenarios. Therefore, the total number of hops in the road will be the summation of each segment's hops as follows:

$$E(no.\ of\ hops)_{Total} = \sum\nolimits_{B=1}^{\infty} E(no.\ of\ hops)_{L_B} \tag{21}$$

Accordingly, the time delay between two nodes on the road using the segmentation assumption is calculated using:

$$D_{total} = \sum\nolimits_{B=1}^{\infty} \frac{E(no.\ of\ hops)_{L_B}}{E(size)} \times L_B \times T_H \tag{22}$$

We show later that the complete model with multi-segments gives very satisfactory results compared to the simulation scenarios as will be discussed in Section 5.

4.2.2. On the Poisson traffic assumption

The above Poisson traffic assumption is valid in free flow condition, but it is questionable elsewhere. In real conditions, it is often more general. In this part, our goal is to present an integrated V2V plus infrastructure model, which requires presenting a model of the road part (the V2V model). For simplicity, we present only the Poisson case. In fact, our method is more general. The reader is referred to [22] for details and demonstrations. We give here just a summary of the insights of the generalization.

Eq. (6) is always valid whatever the traffic assumption. However, the cumulative distribution of the distance between hops must be adapted depending on the vehicles process that is Eqs. (2)–(5) are no more valid if the vehicle traffic is not Poisson anymore. If it is assumed that the cumulative distribution of the distance between vehicles is *F(x)* and f(x) is its density, then it can be proved (cf. [22], Theorem 1) that:

When $R - x_{n-1} \leq x_n \leq R$

$$\begin{aligned} F_{\tau_n/\tau_{n-1}}(x_n, x_{n-1}) &= \frac{1}{1 - F(R - x_{n-1})} \int_{u=R-x_{n-1}}^{x_n} \mathrm{L}^{-1} \\ &\times \left[\frac{\mathrm{L}[\mathrm{f}(\mathrm{x} + \mathrm{R} - \mathrm{x}_{\mathrm{n}-1})]}{1 - \mathrm{L}[f(x)]}\right]_{(u-(R-x_{n-1}))} [1 - F(R - u)]du \end{aligned}$$

Where L(*f*) is the Laplace transform of function *f* and L^{-1} its inverse.

$$F_{\tau_1}(x_1) = \int_{u=0}^{x_n} \mathrm{L}^{-1}\left[\frac{\mathrm{L}[\mathrm{f}(\mathrm{x})]}{1 - \mathrm{L}[f(x)]}\right]_{(u)} [1 - F(R - u)]du$$

When $x_n \geq R$, the cumulative distribution function of τ_n knowing τ_{n-1} and $\tau_{n-1} \leq R$ is

$$F_{\tau_n/\tau_{n-1}}(x_n, x_{n-1}) = \frac{F(x_n) - F(R - x_{n-1})}{1 - F(R - x_{n-1})}$$

$$F_{\tau_1}(x_1) = F(x_1)$$

Then, this hop distribution depending on F can be injected into (6).

This model has been validated with traces provided by the University of Catalunya (cf. [37,38]): cf. [22].

4.3. IMS performance modeling

This subsection presents the modeling of time taken to implement the service in the core network. For this goal, we use the BCMP network queuing. It is helpful for modeling protocol interactions and servers behavior.

The queuing network consists of service centers/stations. Each of them has a scheduling discipline. This scheduling could be one of four service disciplines: First Come First Served (FCFS), Last Come First Served (LCFS), processor sharing, and infinite servers. Each class of customers may have a distinct service time distribution and the customers' messages are of different classes (q).

The BCMP queues network could be open, closed, or mixed for each type of the mentioned scheduling disciplines. In our model, we will use a mixed queuing network, which consists of N $(N \geq 1)$ service centers/stations. The model can give a good approximation of complex protocol interactions, which is considered as a compromise between complicated solutions and precision.

Fig. 4 shows a queuing representation model of the IMS and middleware servers according to the proposed signaling flow in Fig. 2. There are six servers/stations (P/S-CSCF, AS/CA, EHR, TDB, PS, and Interested Sites).

The system state can be defined as the number of each customer's class in each service center. The state S of the system is given by $(s_1,\ s, \ldots, s_N)$ where $s_i = (n_{i1}, n_{i2}, \ldots, n_{iq})$ denotes the

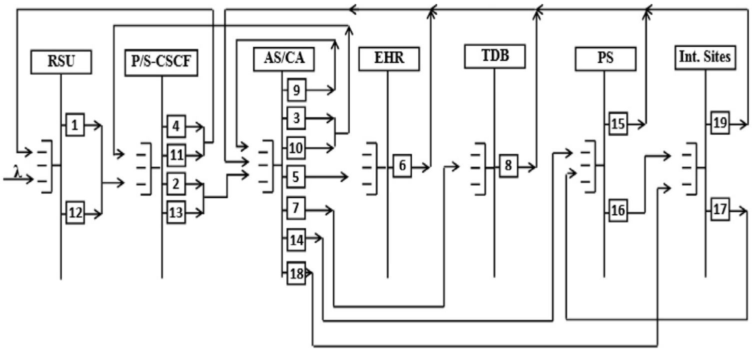

Fig. 4. Queuing model for the proposed architecture.

state of each service center i and n_{iq} is the number of customers of class q in service center i. According to the BCMP theorem [32], the probability distribution state in a BCMP network has the following form:

$$p(S) = cd(S)g_1(y_1)g_2(y_2)\ldots g_i(y_i) \tag{23}$$

Where c is a normalizing constant chosen to make the equilibrium state probabilities sum to 1, *d(S)* is a function of the number of customers in the system, and each g_i is a function that depends on the type of service center i.

$$g(y_i) = \begin{cases} \dfrac{n_{i!}}{\mu_i^{n_i}}\left[\prod\limits_{q=1}^{Q} \dfrac{\lambda_{i,q}^{n_{i,q}}}{n_{i,q}!}\right] & \text{Service Centers of Type 1} \\ n_i!\prod\limits_{q=1}^{Q} \dfrac{\lambda_{i,q}^{n_{i,q}}}{\mu_{i,q}^{n_{i,q}} n_{i,q}!} & \text{Service Centers of Type 2\&4} \\ \prod\limits_{q=1}^{Q} \dfrac{\lambda_{i,q}^{n_{i,q}}}{\mu_{i,q}^{n_{i,q}} n_{i,q}!} & \text{Service Centers of Type 3} \end{cases} \tag{24}$$

Where in our model n_i is the number of messages at server i, μ_i is the service rate by server i to handle an incoming message, $\mu_{i,\,q}$ is the service rate at server i of the message class q, and $\lambda_{i,\,q}$ is the arrival rate at server i of the message class q.

The servers of the model are assumed to be of the processor-shared type and the distribution of the arrival rate of messages is Poisson. There are nineteen messages in the signaling flow, and they are supposed to be of the same class for simplicity (i.e. $\lambda_i = \lambda_{i,q}$). According to that, (23) can be simplified as in [32] to:

$$p_i(n_i) = (1-\rho_i)\rho_i^{n_i} \tag{25}$$

Where

$$\rho_i = \sum \frac{\lambda_i}{\mu_i} \tag{26}$$

For a stable system, this condition ($\lambda_i < \mu_i$) must be conformed for each server i. Additionally, the transmission failure probability of each message is assumed to be zero ($p=0$). Hence, there is no message retransmission. Therefore, it can be ignored. Accordingly, we can calculate the utilization of each server from Fig. 4 as follows:

$$\rho_{CSCF} = \lambda_{CSCF}\left(\frac{1}{\mu_2}+\frac{1}{\mu_4}+\frac{1}{\mu_{11}}+\frac{1}{\mu_{13}}\right) \tag{27}$$

$$\rho_{AS/CA} = \lambda_{AS/CA}\left(\frac{1}{\mu_3}+\frac{1}{\mu_5}+\frac{1}{\mu_7}+\frac{1}{\mu_9}+\frac{1}{\mu_{10}}+\frac{1}{\mu_{14}}+\frac{1}{\mu_{18}}\right) \tag{28}$$

$$\rho_{EHR} = \frac{\lambda_{EHR}}{\mu_6} \tag{29}$$

$$\rho_{TDB} = \frac{\lambda_{TDB}}{\mu_8} \tag{30}$$

$$\rho_{PS} = \lambda_{PS}\left(\frac{1}{\mu_{15}}+\frac{1}{\mu_{16}}\right) \tag{31}$$

$$\rho_{Contacts} = \lambda_{Contacts}\left(\frac{1}{\mu_{17}}+\frac{1}{\mu_{19}}\right) \tag{32}$$

Assuming the system is to be stable, the average arrival rate of messages λ_i for each server i is different and is calculated according to the messages flow in each server queue, which is decomposed into two parts:

- Messages coming from outside with arrival rate λp_{0i}, where p_{0i} is the probability that a client message arrives to the system at server i.
- Messages from server j with arrival rate $\lambda_j p_{ji}$ for all servers $j=1$, 2,…M, where p_{ji} is the probability that a customer completes his service at server i and goes to server j.

So, the average arrival rate at each server i can be calculated as:

$$\lambda_i = \lambda p_{0i} + \sum_{j=1}^{M} \lambda_j p_{ji} \tag{33}$$

where $\lambda_i = e_i\lambda$ and e_i is the rate of visiting server i or the average number of passing by server i. So, (33) can be written as follows:

$$e_i = p_{0i} + \sum_{j=1}^{M} e_j p_{ji} \tag{34}$$

Now, we can deduce a system of equations that satisfies the visit rate for each server i. As we can see, the model considers the averages of messages types in the different servers. It does not respect the time sequence of each procedure. It is however very sufficient and does not affect the evaluation of the overall performance.

Based on the last equation and according to Fig. 5, the distributions of messages for each server (P/S-CSCF, AS/CA, EHR, TDB, PS, and Interested Sites) can be represented by the following equations:

$$e_1 = 1 + \frac{2}{7}e_2 \tag{35}$$

$$e_2 = \frac{2}{4}e_1 + e_3 + e_4 + \frac{1}{2}e_5 + \frac{1}{2}e_6 + \frac{1}{7}e_2 \tag{36}$$

$$e_3 = \frac{1}{7}e_2 \tag{37}$$

$$e_4 = \frac{1}{7}e_2 \tag{38}$$

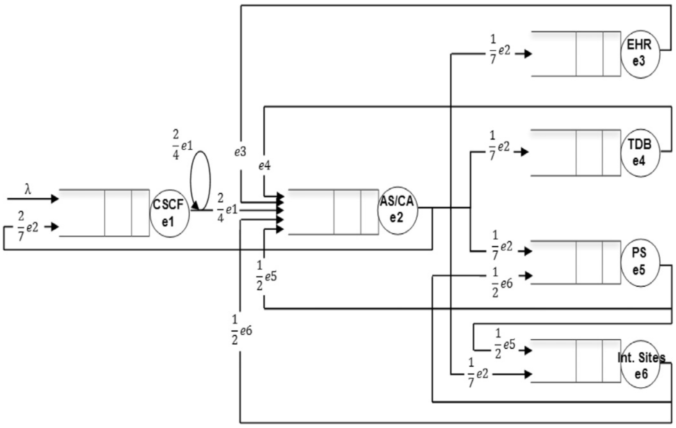

Fig. 5. Calculations of arrival rate for each server.

$$e_5 = \frac{1}{7}e_2 + \frac{1}{2}e_6 \tag{39}$$

$$e_6 = \frac{1}{7}e_2 + \frac{1}{2}e_5 \tag{40}$$

Solving the above equations produces the arrival rate at each server in terms of the arrival rate at the AS/CA as it has the highest arrival rate ($\lambda_{AS/CA}$). The solution is as follows:

$$\lambda_{CSCF} = \frac{4}{7}\lambda_{AS/CA} \tag{41}$$

$$\lambda_{EHR} = \lambda_{TDB} = \frac{1}{7}\lambda_{AS/CA} \tag{42}$$

$$\lambda_{PS} = \lambda_{Contacts} = \frac{2}{7}\lambda_{AS/CA} \tag{43}$$

From (25), the mean queue size corresponding to the average number of clients waiting on servers is calculated as:

$$E(n_i) = \sum_{n_i=1}^{\infty} n_i p_i(n_i) = \frac{\rho_i}{1-\rho_i} \tag{44}$$

where i stands for the servers: (P/S-CSCF, AS/CA, EHR, TDB, PS, and Interested Sites).

Using the Little's Law, the service processing time at each server is as follows:

$$T_i = \frac{E(n_i)}{\lambda_i} = \frac{1}{(1-\rho_i)\mu_i} = \frac{1}{\mu_i - \lambda_i} \tag{45}$$

In order to calculate the total processing time D of the service implementation in the IMS network, we sum the time spent by the RSU (T_C) to create its messages (1 and 12 in Fig. 2), the service processing time (T_i) at each server (P/S-CSCF, AS/CA, EHR, TDB, PS, and Interested Sites), the waiting time at each server's queue and the transmission time (T_t) of each message.

$$\begin{aligned} D &= T_C + T_t + \sum_i T_i \\ &= T_C + T_t + \sum_i \frac{1}{\mu_i - \lambda_i} \end{aligned} \tag{46}$$

Assuming there is no queuing in the RSU, its waiting time can be approximated to zero. Therefore:

$$T_C = \sum_{q \epsilon Q_{RSU}} \frac{1}{\mu_q} \tag{47}$$

Where $Q_{RSU} = (message\ 1,\ message\ 12)$

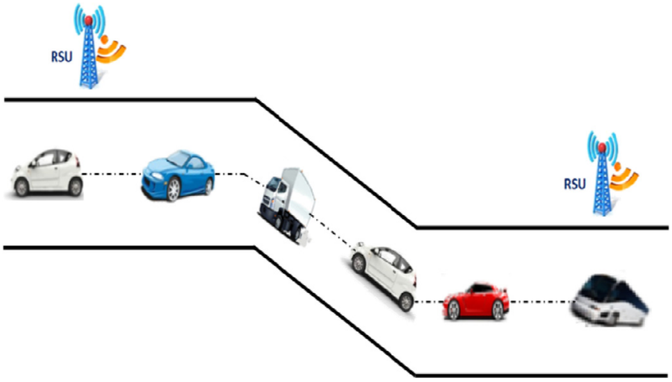

Fig. 6. V2V link model.

So, $T_C = \frac{1}{\mu_1} + \frac{1}{\mu_{12}}$. The final form of (46) is:

$$D = \frac{1}{\mu_1} + \frac{1}{\mu_{12}} + T_{CSCF} + T_{\frac{AS}{CA}} + T_{EHR} + T_{TDB} + T_{PS} + T_{Contacts} + T_t \tag{48}$$

It is to be noted that, although not explicitly indicated, (48) includes the fact that some messages revisit the same server more than one time as indicated in Eqs. (27)–(32).

5. Performance evaluation

In this section, we validate the proposed analytical models of the V2V link connectivity and the IMS queuing model. This section is divided into three parts. In part one; we calculate the delay between the vehicle that detects the event and the nearest RSU. In part two, we calculate the average processing time of the VANET application in IMS network. In the last part, the average RTT of the proposed application is calculated starting from the initiator node (source vehicle) sending a message until receiving a response from the core network.

Dividing the entire system into two subsystems and simulating them individually to calculate the total delay by summing the simulation results does not affect the accuracy of the simulation. The technique to divide complex systems into smaller modules (or subsystems) and to build the modules separately is a well-known approach to study complex systems [33,34].

5.1. V2V link model validation

In this part, we test the maturity of the analytical model in calculating the number of hops between two nodes on a road and hence the delay between them. The link model used is shown in Fig. 6. The analytical results are calculated using C++ and the simulation results are obtained using MATLAB (2012a). The studies are decomposed into several experiments for the ease of surveying. First, the following network design assumptions as follows were made:

- We assume the vehicle that detects the event is the same vehicle that transmits the alert message and that the destination node is the nearest RSU.
- The total road length between these two nodes L=2, 3, and 4 Km.
- The vehicles density range is from 0.01 to 0.1 vehicles per meter in step of 0.01 and the distribution on the road is assumed to be Poisson.
- The mobility of the vehicles is neglected since nodes remains almost stationary within message transmission time [35].

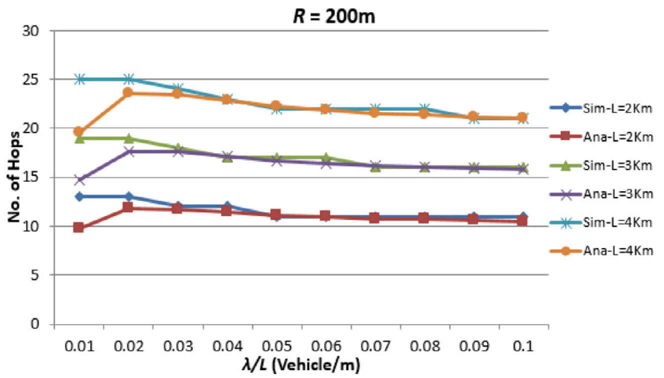

Fig. 7. Comparison of number of hops of different road lengths at a transmission range ($R = 200$ m).

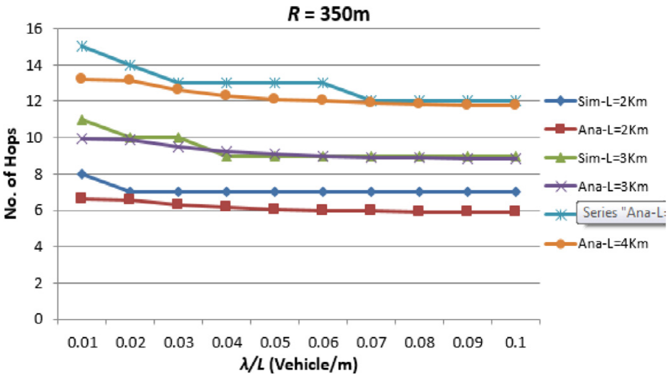

Fig. 8. Comparison of number of hops of different road lengths at a transmission range ($R = 350$ m).

- The number of hops is obtained versus the λ/L vehicles per meter.

Experiment 1: in this experiment, we calculate the number of hops between the vehicle that detects an event and the nearest RSU versus the vehicles density (λ/L: vehicles/m). We assume the transmission range $R = 200$ m, and the vehicles density varies from 0.01 to 0.1 vehicle/m in steps of 0.01. The experiment was repeated for different distances between the vehicle that detects the event and the nearest RSU, specifically: $L = 2$, 3, and 4 Km respectively. Fig. 7 shows he results of the analytical model along with those obtained from the simulation. As shown in the Figure, the results from both the model and the simulation are very close. Moreover, the increase of the distance between the source and the destination yields to an increase of the number of hops as expected. The number of hops at the different distances ($L = 2$, 3, and 4 Km) settles almost at 11, 16, and 21 hops respectively with the increase of the vehicles density. The Figure clearly shows that the stability points are reached at high vehicles density. This means that the number of hops approaches a fixed value with the increase of vehicles number on the road until reaching a saturation point where any further increase of the of the number of vehicles has no effect. This is due to that the model is based on the shortest path between the source and destination. Therefore, it is not affected by the increase of the vehicles density on the road.

Fig. 8 and Fig. 9 show the results of the same experiment with the same assumptions but at different transmission ranges: $R = 350$, and 500 m respectively. As shown in these Figures, the number of hops is inversely proportional to the transmission range assuming the same vehicles density and speed. Additionally, as the transmission range increases, a minor difference appears between the analytical and the simulation results if the distance between the vehicle that detects the event and the nearest RSU is not much larger than the transmission range. It is very clear in Fig. 8, when the transmission range $R = 500$ m, and the distance between the vehicle that detects the event and the nearest RSU: $L = 2$, 3, and 4 Km. This is because the value of the distance between the two proposed nodes L is close to the value of the transmission range R.

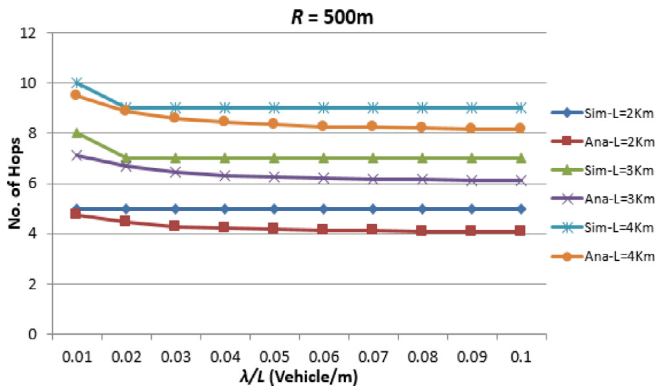

Fig. 9. Comparison of number of hops of different road lengths at a transmission range ($R = 500$ m).

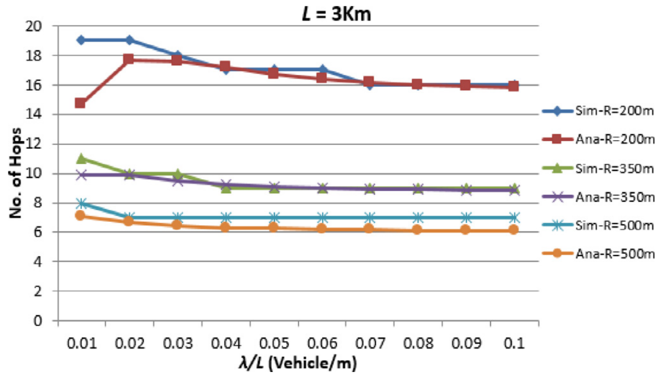

Fig. 10. Comparison of number of hops of different transmission ranges ($R = 200$, 350, and 500 m) at distance between the vehicle that detects the event and the nearest RSU ($L = 3$ Km).

Using the results of the previous simulation, the effect of the transmission range R on the number of hops when the distance between the vehicle that detects the event and the nearest RSU $L = 3$ Km is studied. The results are drawn for transmission ranges of $R = 200$, 350, and 500 m. Fig. 10 shows the results of the analytical model along with those obtained from the simulation. The Figure confirms that a saturation of the hops number is reached at high vehicles densities. On the other hand, the increase of the transmission range speeds up reaching the saturation value at lower vehicles densities for both the analytical and the simulation results.

Experiment 2: we calculate the communication delay between the vehicle that detects the event and the nearest RSU versus the vehicles density at different transmission ranges of $R = 200$, 350, and 500 m respectively. The vehicles speed is assumed to be 100 Km/h and the distance between the vehicle that detects the event and the nearest RSU $L = 3$Km. Since modeling the IEEE 802.11p is out of scope, we use the results of [35] to obtain the analytical and simulation values per hop of the IEEE 802.11p broadcast performance in terms of time. The authors of this work developed a Markov chain model for the IEEE 802.11p broadcast. As mentioned in their work, there are two main types of safety messages: emergent safety messages and routine safety messages. The emergent safety messages have the highest priority that matches

Table 1
IEEE 802.11p MAC access delay.

Density (Vehicle/m)	Min delay (ms)	Max delay (ms)	Average delay (ms)
0.01	1.5373	3.9954	2.76635
0.02	1.5377	5.3343	3.436
0.03	1.5371	8.6794	5.10825
0.04	1.5376	11.4207	6.47915
0.05	1.5373	25.1149	13.3261
0.06	1.5371	45.4646	23.50085
0.07	1.5372	62.9478	32.2425
0.08	1.5371	75.341	38.43905
0.09	1.537	86.0945	43.81575
0.1	1.5371	98.7202	50.12865

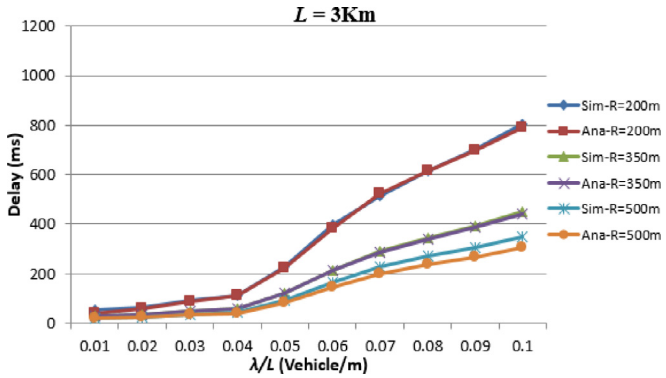

Fig. 11. The delay comparison of different vehicle density at different transmission ranges ($R = 200$, 350, and 500 m) at distance between the vehicle that detects the event and the nearest RSU ($L = 3$ Km).

our proposed safety algorithm. The same model assumptions mentioned in [35] used for the analytical and simulation of the IEEE 802.11p broadcast. These results are listed in Table 1 showing the minimum, maximum, and the average delay for the emergent safety messages at vehicles densities of 0.01 to 0.1 in steps of 0.01. Authors in [35] proved that there is a good agreement between analytical values and simulation results.

Fig. 11 shows the delay comparison at different vehicles densities and for different transmission ranges $R = 200$, 350, and 500 m. The distance between the vehicle that detects the event and the nearest RSU is assumed to be $L = 3$ Km. As shown in the Figure, the delay increases with the increase of the vehicles density at each mentioned transmission range. The reason for this is that the increase of the vehicles density yields to more transmission demands and channel accessing. In conclusion, the communication delay is directly proportional to the vehicles density if the transmission range is fixed. As for the transmission range, the number of relays between a source and a destination decreases with the increase of the transmission range since the vehicle communication coverage increases.

It can be concluded from the previous results that the analytical model gives very satisfactory results compared to the simulation scenarios.

5.2. IMS queuing modeling validation

In this part, we validate the IMS analytical model by comparing its performance with the simulation results. We calculate the IMS servers' processing time of the proposed VANET application according to the signaling flow of Fig. 2. The signaling flow starts when the RSU forwards the received alert message to the CSCF servers. We used MATLAB (2012a) to implement the analytical model and OPNET Modeler (V.14.0) to simulate the IMS servers' functionalities. We used the values of the IMS servers processing time mentioned in [36] as in Table 2.

Table 2
IMS servers' parameters used.

Parameters		Duration
Process time (microsecond)	UE	200
	P/S/I-CSCF	200
	HSS	10
Propagation delay (microsecond)	UE/P-CSCF	5000
	other links	200

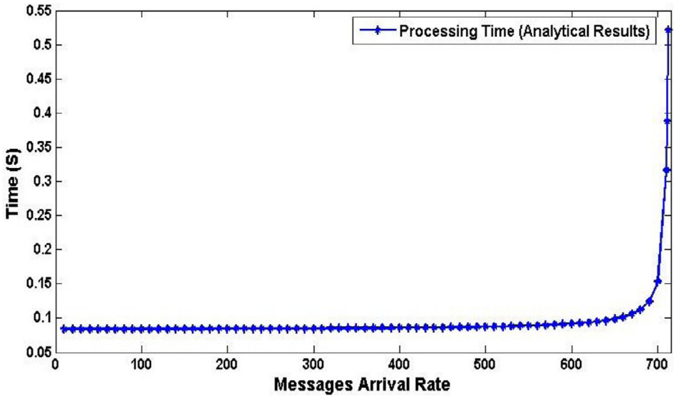

Fig. 12. The processing time of VANET applications on the IMS servers.

Table 3
Average processing time of VANET application.

Analytical versus simulation	
MATLAB	112.3 (ms)
OPNET	124.2 (ms)

Fig. 12 shows the processing time of the proposed VANET application using the IMS as a sub-layer controller versus the messages arrival rate at the servers for the analytical model. As expected, the processing time of the proposed application increases with the increase of the messages arrival rate. The average processing time is obtained over all the possible message arrival rate as shown in Table 3.

The OPNET simulator gives its results according to these parameters: processing time, transmission time, number of users, and background utilization. We used the same processing and transmissions times used in the analytical model to match the results of both. However, in OPNET we do not have the facility to match between the number of users/server utilization parameters and the arrival rate of messages as in the mathematical model. Therefore, we compared the average processing time of the mathematical model with the average processing time of the OPNET as in Table 3.

5.3. RTT calculation

In this last part, we calculate the RTT, which is the time taken by a VANET application starting from the vehicle that detects the event sends a message until it receives a response from the core network. In order to obtain this total time, we need to sum the averages of the following timers:

- Time required to send an alert message from the vehicle that detects the event until reaching the nearest RSU.
- Time necessary to execute the proposed application in the IMS servers according to the messages signaling flow of Fig. 2.

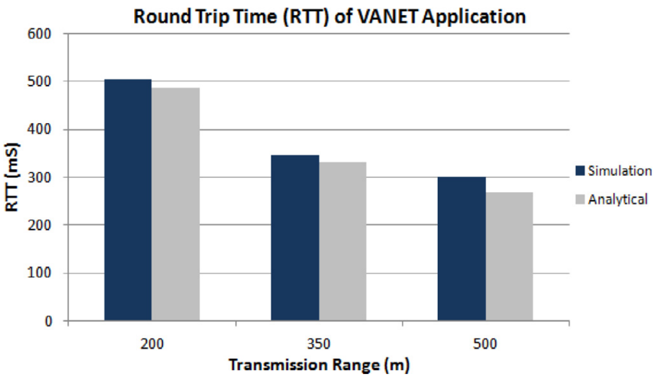

Fig. 13. Round trip time comparison between the analytical and simulation results of the proposed VANET application.

- Time needed to send the IMS feedback message to the interested sites and to broadcast it to the vehicles in the event vicinity.

Following our VANET model, we calculated the average time (analytically and by simulation) taken by the alert message to be sent between the two proposed nodes of distance $L = 3$ Km. For the IMS network, we used the average processing time of the proposed VANET application as in Table 3. Finally, as the RSU is responsible of broadcasting the feedbacks of the core network, we sum the average time required to broadcast the feedback of the IMS. As shown in Fig. 13, the analytical and simulation results are very close. It is obvious from the RTT results that the major factor contributing to the RTT is the VANET specially when using a low transmission range. The Figure shows that the RTT is inversely proportional to the transmission range. The IMS processing time has less effect on the RTT compared to the vehicular communication delay, which is more influential. The VANET network is the major factor in the RTT as the communication delay between vehicles suffers of three main factors: vehicles density, collisions, and connection intermittent. These factors yield to a higher delay than in the IMS network. The average IMS processing time is less than the VANET delay by 3.06 times if the transmission range is 200 m and is 1.41 times less if the transmission range is 500 m. Consequently, the IMS can be used in real time applications without affecting the system stability. This is because the average processing time introduced by the IMS servers has less effect on the VANET application RTT than the delay due to the VANET communication.

6. Conclusions

In this paper, we proposed a complete model, including signaling flows, which uses the IMS as a service controller sub-layer for VANET applications due to its benefits and features. Additionally, the use of IMS provides the ITU-T service requirements of USN applications and services. On the other hand, safety applications are time sensitive. Therefore, there is a need to test the validity of the proposed model. One way to achieve this is by calculating the Round Trip Time (RTT), which is the time taken by a VANET application starting from the initiator node (source vehicle) sending a message until receiving a response from the core network. For the validity of our proposal, we developed two analytical models for the proposed architecture. First, we modeled the vehicles link connectivity on roads to estimate the reporting delay of events until reaching the closest RSU using the connectivity queuing model $GI^X/D/\infty$. The analytical model validity is proved in the performance section. It achieves a perfect performance when comparing its results with those obtained from the simulation. Second, we modeled the behavior of the IMS servers using BCMP networking. The performance of the developed model is validated and it shows to be more accurate when compared with the simulation results. These models are general enough to be applied to any VANET application.

Finally, we calculated the RTT to test the reliability of the proposed application model. As a conclusion from the results, the average RTT of the proposed model is less than a second, which proves the applicability of using the IMS as a sub-layer controller for VANET applications.

This work will be used as a base for further work. We plan to derive models for more sophisticated vehicular communication scenarios and to incorporate beam-forming based broadcast technique.

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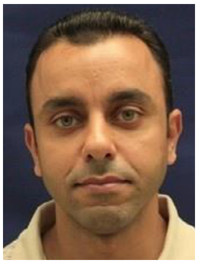

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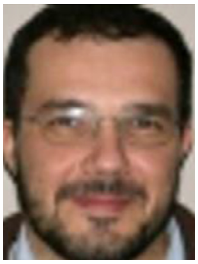

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