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Abstract

We consider a VoD (Video on-Demand) platform designed for vehicles traveling on a highway or other major roadway. Typically, cars or buses would subscribe to this delivery service so that their passengers get access to a catalog of movies and series stored on a back-end server. The network infrastructure comprises IEEE 802.11p RSUs (Road Side Units) that are deployed along the highway and deliver video content to traveling vehicles. In this paper, we propose a simple analytical and yet accurate solution to estimate two key performance parameters for a VoD platform: (i) the average download data rate experienced by vehicles over their journey and (ii) the average "interruption time", which corresponds to the fraction of time the video playback of a given vehicle is interrupted because of an empty buffer. Through multiple examples, we investigate the influence of several parameters (e.g., the video bit rate, the number of vehicles, the distance between RSUs, the vehicle velocity) on these two performance parameters whose outcome may help the sizing of an IEEE 802.11p-based VoD platform.

Keywords: VoD Platform, IEEE 802.11p, Vehicular Network, Performance Modeling

1. Introduction

Today, there are more than 1.25 billion vehicles worldwide and this figure is expected to rise to 2 billion by 2035. Therefore, cars and buses, be it for work or leisure, are likely to remain the most popular traveling mode in most countries and cities around the globe. However, traffic congestions and long journeys are a reality for many daily commuters and occasional passengers, potentially turning car journeys into quite unpleasant and tiring experiences. At the same time, the emergence of subscription-based VoD (Video on-Demand) services that offer access to film and television content directly to viewers over the Internet has profoundly reshaped the television market during the last decade or so. Netflix has quickly become the most popular VoD (Video on-Demand) service surpassing the cable TV on the USA market since 2017. It operates in more than 190 countries, and claims over 148 million streaming subscribers worldwide. This commercial success was made possible thanks to the availability of a large and efficient network infrastructure connecting residential units and homes with high-speed links. Analogously, given the large volume of car traffic, and assuming a ready-to-use network infrastructure for vehicles traveling along a highway or another major roadway, could a VoD service for the vehicle passengers become a commercial success too? To address this question, we first need to study the issue of designing and the feasibility of a network infrastructure able to provide a VoD service for vehicles.

Typically, a VoD platform handles unicast video streams (as opposed to broadcast traffic). Indeed, unless the considered platform is exclusively intended to deliver live streaming where multiple subscribers may watch the same content at the same time, every (subscriber) vehicle receives specific content based on its demands. In this context, designing an architecture involving V2V (Vehicle-to-Vehicle) communications where vehicles may act as relays for the delivery of video frames intended to other vehicles may incur excessive use of the radio channel bandwidth (due to the multiple transmissions of the same data), not to mention the relative complexity associated to inherent issues such as the multihop routing, trajectory prediction, etc. Nonetheless, different options are made possible for bringing connectivity to the vehicles and to deliver, over the radio channel, their requested content. Basically, the choice boils down to broadband cellular network technologies (such as 4G and 5G) and IEEE 802.11p. Unlike cellular technologies, IEEE 802.11p operates on unlicensed spectrum, eliminating the cost of acquiring licensed spectrum and allowing the VoD or highway operators to autonomously deploy their network infrastructure. This paper focuses on IEEE 802.11p but broadband cellular network technologies are arguably strong candidates too.

This paper studies the feasibility of an IEEE 802.11p-based VoD platform to stream videos to vehicles passing on a highway. In particular, we investigate the adequacy of using IEEE 802.11p for the delivery of video frames to the passing vehicles. Our contributions are threefold. First, we propose a conceptually simple and accurate analytical solution to estimate some key performance parameters with regard to the video playback at the (subscribers) vehicles. Second, through several examples, we illustrate how the proposed analytical solution can help at sizing the networking resources of an IEEE 802.11p-based VoD platform. Finally, we present a means of improving the collective experience of vehicles by temporarily blocking access to the radio channel for some vehicles.

The remainder of the paper is organized as follows. Section 2 discusses the related works. In Section 3 we present our proposed analytical solution to estimate the key performance parameters for such a VoD platform. Section 4 covers the numerical results illustrating the accuracy of our solution. In Section 5 we show examples of application of our analytical solution for the sizing of an IEEE 802.11p-based VoD platform. Section 6 concludes this paper.

2. Related work

The performance modeling of IEEE 802.11 has attracted much attention since the pioneering work by Bianchi [1]. Numerous extensions have been proposed to take into account unsaturated traffic (e.g., [2, 3, 4]) or imperfect radio channel conditions (e.g., [5, 6, 7]). Recently, several contributions such as [8, 9] have specifically addressed the case of IEEE 802.11p amendment and they consider EDCA (Enhanced Distributed Channel Access) mechanisms where frames have different priorities depending on their criticality. Typically, these works rely on mono-dimensional or two-dimensional Markov chains whose solutions may not necessarily be trivial. Aside from these fine-grained models, more macroscopic models for IEEE 802.11 that deliver estimates for the mean throughput attained by a node (for a given level of priority) have been proposed [10, 11, 12, 13]. In this paper, we too consider a general and versatile model that eases its application to the case of a VoD platform. However, the analytical model used in the present paper is simpler than the others and delivers accurate results for our metrics of interest making it an adequate choice for our purpose.

Video dissemination over vehicular networks, which consists in distributing the same video to a set of vehicles, has drawn significant interests. The video in question may pertain to roadside video emergency (e.g., warning drivers of animals crossing the roadways), video surveillance or entertainment. In several studies, vehicles are implied in the forwarding of the video. Thus, the video is transmitted over wireless multihop paths in an attempt to reach all the vehicles. For example, in [14], Fiore et al. propose an application based on broadcast transmissions to share, among vehicles, data provided by RSUs. In [15], Soldo et al. propose a solution for inter-vehicular communications exploiting a positional device (like a GPS) and the received power level. With this solution, each vehicle can dynamically select its next-hop relays. In order to limit collisions, the authors use a structured TDMA transmission thanks to the synchronization offered by the use of GPS. In [16], Maia et al. deal with the various traffic conditions by giving priority to some vehicles in the broadcasting phase and by using a rate control algorithm. In [17], Rezenda et al. suggest to select the relay nodes during a time window rather than at each single packet transmission. The proposed solution also includes an estimation of the future positions of each vehicle in the selection of the relays. In [18], Quadros et al. propose to combine a geographical dissemination routing protocol with local decisions in order to forward video frame. The proposed solution also takes into account video QoE (Quality of Experience) parameters in addition to the vehicle distance. Note that all these latter video dissemination solutions rely exclusively on V2V communications.

Other studies make use of a hybrid framework combining V2V communications and V2I (Vehicle-to-Infrastructure) communications. For example, in [19], vehicles are equipped with two network interfaces, one enabling short-range communications between vehicles and the other enabling communications with RSUs (Road Side Units). Depending on the location of the destination vehicle and on the radio link quality, the streamed video will be directly transmitted by an RSU or forwarded by intermediate vehicles to the destination vehicle. In [20], Xing et al. consider optimal paths to disseminate videos among a set of vehicles. Given the roadmap of a vehicle and the location of vehicles and RSUs, the authors cast the problem as an optimization problem that aims to minimize the delivery delay of multimedia messages (e.g., video). The authors also propose a solution to compute the best dissemination strategy. In [21], Zhou et al. consider the same scenario as in [19]. However, in their study, they introduce scalable video coding that consists in selecting the different video layers to transmit according to the radio channel quality. The V2I communications are based on the LTE-Advanced technology. These video dissemination protocols may be improved through network coding techniques (e.g., [22]) that enable to overcome packets losses at different vehicles thanks to a limited number of coded packets. Note that, unlike our work, these video dissemination studies focus on a given multimedia message or video that has to be delivered to all considered vehicles.

Other solutions make exclusively use of V2I communications. For instance, although their solution is not specifically dedicated to vehicular networks, the authors of [23] propose a solution to dynamically select the helper node (the RSU in the context of vehicular networks) from which to download the video. In this study, a user may be in the range of several helpers, and both helpers and users share the same channel bandwidth. In [24], the authors propose an auction-based channel allocation and adaptive video streaming video allocation. In their scenario, RSUs do not entirely cover the highway or road under study and videos are transmitted to a set of vehicles that are within range of the RSUs. They introduce their own time slot-based MAC (Medium Access Control) protocol to provide heuristics to select the quality level of each video as well as the allocation of time slots in order to optimize a utility function that expresses the video quality experienced at vehicles. In [25], highways are covered by 5G base stations that have short transmission range. The base stations are deployed so that they provide seamless coverage to vehicles. They are also equipped with a buffer in order to pre-load video data. In this scenario, Qiao et al. determine which bandwidth to allocate to a vehicle entering in a 5G cell. In [26], Guo et al. consider a two time-scale dynamic caching solution. They address the cache placement (by determining whether the video should be cached or not), the video quality adaptation at the application layer and the selection of the physical transmission range. Note that their scenario considers a single 5G base station.

Overall, the work that comes closest to ours is that of Sun et al. in [24]. The authors consider a similar scenario to the ones considered in this paper where videos are distributed to a set of vehicles, and where RSUs do not entirely cover the highway or road under study. Note that their work differs from ours for two main reasons: (i) their approach assumes a TDMA scheme and does not rely on existing standardized MAC protocols (e.g., IEEE 802.11p), and (ii) they aim to optimize resources and the selection of video quality layers for each vehicle in real time whereas the goal of our study is to provide an help for dimensioning the networking resources of an IEEE 802.11p-based VoD platform.

The current paper is an extended version of a previous paper by the same authors [27]. It contains additional scenarios as well as another real-life

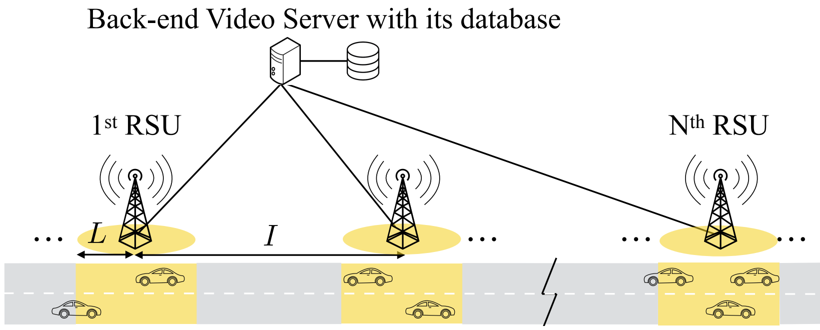

Figure 1: Considered VoD architecture for vehicles along a highway.

video trace to validate the accuracy of the proposed model in the case of vehicles with different velocities and of a constant influx of vehicle arrivals. Furthermore, this paper studies the influence of the video bit rate on the vehicle performance and shows that performance improvements can be made by temporarily blocking access to the radio channel for the vehicles with the smallest transmission rates.

3. System model considered and its analytical solution

3.1. System description

We describe the networking aspects of a VoD (Video on Demand) platform designed for vehicles traveling on a highway or other major roadway. Typically, cars or buses would subscribe to this delivery service so that their passengers get access to a catalogue of movies and series stored on a back-end server. Along the highway, RSUs (Road Side Units) are deployed and serve as APs (Access Points) to the passing vehicles using IEEE 802.11p [28]. Figure 1 illustrates the outline of the considered VoD platform. We now discuss each of the components involved in a possible architecture designed to provide the VoD service on a highway.

RSUs

RSUs are network equipments that are deployed along a road. Each RSU is linked through a high-speed wired link to a back-end video server that stores, possibly in an external database server, all available videos. Additionally, RSUs have another wireless interface that serves as an access point to passing vehicles. We denote by N the total number of RSUs along the studied section of highway and by L the length of the signal range of an RSU. We assume that RSUs are placed uniformly along the highway with distance I from each other. In practice, to limit the number of RSUs and so the cost of deployment, we expect I to be larger than L. Therefore, the coverage of consecutive RSUs will not overlap and portions of the highway will be left without network access.

Vehicles

Assuming that only vehicles that have subscribed to the VoD service interact with the RSUs, we can restrict our description to the subset of these subscribers. Each (subscriber) vehicle i is characterized by its velocity v_i. Vehicles are equipped with IEEE 802.11p interfaces to enable communication with RSUs. Provided a vehicle is within an RSU signal range, it attempts to download as much as possible the content of its video. Downloaded data correspond to video frames. Whenever a vehicle downloads frames at a faster rate than it plays frames (on its media player), it stores the surplus in a buffer building up a queue with received but not yet played frames. We assume that there is no upper limit on the buffer size. As soon as a vehicle leaves an RSU signal range and ends up in a portion without network access, it keeps playing frames drawn from the buffer until the queue exhausts. A vehicle will experience an interruption of the video playback unless it reaches the next RSU before its buffer becomes entirely depleted.

IEEE 802.11p

The communications between the RSUs and the passing vehicles operate on IEEE 802.11p [28]. Note that the described architecture involves no V2V (Vehicle-to-Vehicle) communications. It is also worth noting that by doing so the vast majority of the traffic is sent from the RSUs towards the vehicles. It follows that chances of interferences (colliding frames) are close to zero since RSUs do not overlap. Note also that there is no MAC contention between RSUs since they do not belong to each other's detection range.

IEEE 802.11p belongs to the class of CSMA/CA-based protocols (Carrier-Sense Multiple Access with Collision Avoidance). We now describe briefly how the transmission of a frame proceeds over 802.11p according to the principles of DCF (Distributed Coordination Function). Each RSU maintains a queue with frames ready to be sent to vehicles passing in its signal range. The RSU pulls the first-in-line frame from its buffer and verifies that the radio channel is sensed empty during an AIFS period. If not, it waits until the radio channel becomes free. Then, either way, the RSU postpones its transmission for a random delay (derived from the size of contention window), which is commonly referred to as the backoff period. Once the backoff period expires, the RSU starts the actual transmission of the frame to the destination vehicle. The latter waits for a SIFS period before returning an ACK frame to the RSU to acknowledge the good reception of the frame. In case a frame is not properly received, the RSU starts over the same procedure but with a larger contention window that increases the expected length of the backoff period. The duration for transmitting a frame also depends on the size of the frame and on the transmission rate negotiated for the radio communication between the RSU and the passing vehicle. Indeed, 802.11p allows 8 different transmission rates ranging from 3 Mbps to 27 Mbps. In practice, an RSU regularly assesses the quality of the radio channel towards each of its destination vehicles. Based on these quality assessments it selects the highest transmission rate that still maintains a low probability of errors.

Since the RSUs are fixed in space and operating in an outdoor environment, we assume that the transmission rates selected by the WiFi manager, which is responsible for selecting the transmission rate based on the assessed quality of the radio channel, may be expressed as a function of the distance separating the RSU to the destination vehicle. In the numerical evaluation, we consider the Ideal WiFi manager of ns-3 [29] but any other manager could be used instead. Figure 2 reports the transmission rates chosen by an RSU as a function of the distance to its destination vehicle using this particular WiFi manager. Note that this WiFi manager skips two possible transmission rates so that six possible transmission rates (instead of eight) appear in Figure 2.

Because vehicles associated with an RSU typically have different transmission rates, their communications are exposed to the performance anomaly [30]. All the vehicles associated to the same RSU obtain (approximately) the same throughput despite having different transmission rates. This is because DCF of 802.11p provides equal treatment in the channel access.

Note that IEEE 802.11p provides multiple independent channels so that multiple communications on different channels occur at the same time without collision. Without loss of generality, we study the case of only one radio channel but all the following discussion can easily be extended to the case of multiple channels. Note also that, in the described VoD platform, all IEEE 802.11p frames used for the video transmission have the same level of priority.

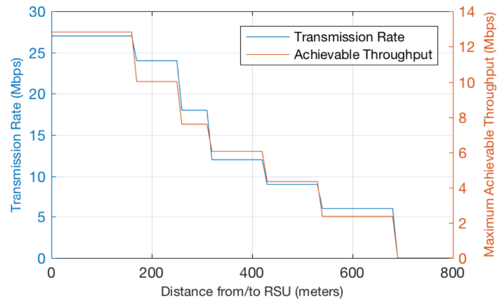

Figure 2: Transmission rates and their corresponding maximum achievable throughputs for packets of 1500 bytes as a function of the distance between an RSU and its destination vehicle. Note that the two y-axes have different scales.

Videos

Movies and series available at the back-end server are compressed using a codec that produces videos encoded at a variable bit rate. We denote by c the mean bit rate of a given video averaged over its whole duration. Video frames are transmitted from the video server to the destination vehicles over TCP (Transmission Control Protocol)[1] (or over new Transport Layer protocols such as QUIC (Quick UDP Internet Connections)). We assume that RSUs always have frames waiting to be transmitted to each of their associated vehicles. In practice, when a vehicle enters into the signal range of the first RSU along the highway, the vehicle associates to the RSU. In return, the RSU updates its forwarding table and so is the forwarding table of the video server. Hence, the video server gets a path to the vehicle in question. Then, a TCP connection is open and the server can start the transfer of the video. When the vehicle leaves the RSU signal range, the TCP connection is shortly closed (due to an inactivity timeout) causing the data transfer to stop. As soon as the vehicle enters into the signal range of the next RSU, Link layer/routing information will be updated on this RSU, and the data transfer will resume, potentially with a new TCP connection.

Performance parameters of interest

To evaluate the behavior of the described VoD platform, we study two performance parameters that can be computed for each vehicle.

[1]A modified version of TCP as discussed in Section 4.1.

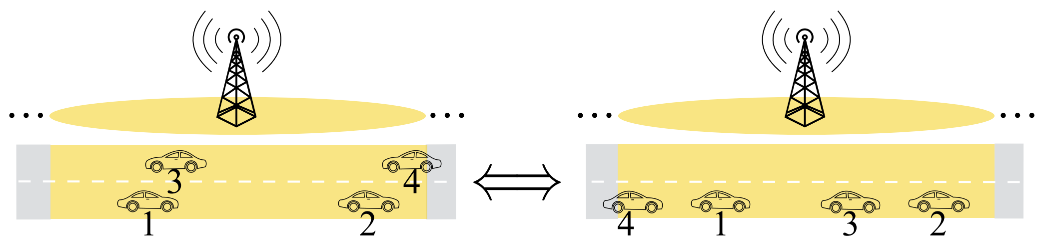

Figure 3: Substituting a two-way highway scenario by a one-way highway scenario.

First, we consider the average download data rate experienced by a vehicle over its journey. It is simply computed as the sum of data received from each RSU divided by the time of the journey.

The second parameter is referred to as the "interruption time". It corresponds to the fraction of time a vehicle spends with the playback of its video interrupted because of an empty buffer. Recall that a vehicle must buffer enough data so that it can keep playing its video during its stay in the non-covered areas between RSUs.

3.2. Analytical solution

At the level of each RSU

Let us consider a given RSU along with its associated vehicles at a given time. To begin with, it is worth noting that the current state of this two-way highway scenario can be viewed as an one-way highway scenario. It suffices to remove vehicles in one direction and to reposition them in the other direction at the same distance from the RSU. Note that this equivalence holds because of the symmetry around an RSU. Figure 3 illustrates this process. Although our analytical solution works for two-way highways, having all vehicles moving in the same direction eases its description. Therefore, in the remainder of the paper, we will consider that all the vehicles associated to a given RSU are moving in the same direction.

Let n be the current number of vehicles associated with the considered RSU. Given their distance to the RSU, each vehicle negotiates and determines its transmission rate (cf. Section 3.1). We denote by T_i $(i = 1, \ldots, n)$ the transmission rate of the i-th vehicle. Because IEEE 802.11p involves transmission overheads (e.g., AIFS, Backoff, ACK), we introduce the definition of maximum achievable throughput that corresponds to the throughput a vehicle would attain if left alone with its RSU (no competing vehicles).

We use A_i to indicate the maximum achievable throughput of the i-th vehicle. Note that maximum achievable throughputs are easily derived from the transmission rates given the size of frames (e.g., [31]). Figure 2 indicates the found values for A_i given T_i and frames of length 1500 bytes.

Knowing the maximum achievable throughput of each vehicle, we aim at estimating their attained throughput while taking into account the CSMA/CA-based sharing of the radio channel between vehicles, which mostly ensures fairness in the number of channel accesses among the vehicles (and not so much the duration of those access). To do that we rely on the formula proposed by Amer et al. [10], which is derived from previous works [11, 12, 13]. Denoting the attained throughput of vehicle i by B_i, and assuming that RSUs have always frames waiting to be sent to their associated vehicles, we have:

$$B_i = \frac{1}{\sum_{j=1}^{n} \frac{1}{A_j}} \qquad \text{for } i = 1, \ldots, n. \tag{1}$$

Note also that Equation 1 implies that all the vehicles associated to the same RSU receive the same attained throughput, which is in line with the performance anomaly (cf. Section 3.1, [30]). To account for the time dependency of B_i, we use $B_i(t)$ to denote the attained throughput of vehicle i at time t.

To compute how much data a vehicle i downloads from the RSU, we need to introduce a vector whose elements correspond to the time where either the current number of vehicles associated to this RSU changes or the (negotiated) transmission rate of any of these vehicles, including vehicle i itself, changes. Let e be this vector, $|e|$ its length, and e_k its k-th element. Denoting by D_i the amount of data downloaded by vehicle i, it follows that:

$$D_i = \sum_{k=1}^{|e|} B_i(e_{k-1}).(e_k - e_{k-1}). \tag{2}$$

At the level of the N RSUs

The derivation of the download data rate of a vehicle i along the N RSUs is straightforward. It suffices to sum up the amount of data downloaded on each RSU and to divide it by the duration of its journey.

The computation of the interrupted time for a vehicle is more complicated. To begin with, we need to keep track of the current number of video frames queued in each vehicle buffer and waiting to be played. Let us consider a vehicle i. We denote by f the vector comprising all the times where the vehicle transmission rate varies, including 0's when the vehicle is not associated with an RSU. Recall that these times may correspond to a change of the distance between this vehicle and its associated RSU but may as well correspond to a change of the distance between the RSU and another of its associated vehicles. The vector f is a sub-vector of e that contains only times where there is a change impacting the vehicle i. We use f_k to refer to the k-th element of f. It follows that during the interval $[f_{k-1}, f_k]$, the amount of data received by vehicle i is equal to:

$$B_i(f_{k-1}).(f_k - f_{k-1}). \tag{3}$$

During this time interval, provided vehicle i has enough data to be played, the playback of its video plays, on average, an amount of data equal to:

$$c.(f_k - f_{k-1}). \tag{4}$$

If the quantity computed in Equation 3 is larger than that of Equation 4, then the buffer of vehicle i fills over the duration $f_k - f_{k-1}$. Otherwise, it depletes. We use $Q_i(t)$ to denote the current length (in time units) of the queue buffered on vehicle i at time t. $Q_i(t)$ can be computed as follows. Posing $Q_i(f_0) = 0$ (buffer is initially empty), we have:

$$Q_i(t) = (Q_i(f_{k-1}) + (B_i(f_{k-1}) - c)(t - f_{k-1}))^+ \quad \text{for any time } t \text{ in } [f_{k-1}, f_k] \tag{5}$$

The interrupted times experienced by vehicle i over each period $[f_{k-1}, f_k]$ can now be evaluated. Let $J_i(k)$ denote the interrupted times experienced by vehicle i over the period $[f_{k-1}, f_k]$. Note that the playback of the video of vehicle i is interrupted whenever its queue length comes to 0. Hence, we can derive $J_i(k)$ as follows:

$$J_i(k) = \int_{f_{k-1}}^{f_k} \mathbb{1}_{Q_i(t)=0} \, dt \tag{6}$$

Finally, the interruption time for vehicle i along the N RSUs is simply obtained as the quotient of summing up the $J_i(k)$ for all k's over the duration of the vehicle journey. The result is a real number in the interval $[0, 1]$ expressed as a percentage in the next section. Table 1 summarizes the main notations used in this paper.

N	Number of RSUs
I	Distance between two successive RSUs (meters)
L	Signal range of RSUs (meters)
v_i	Velocity of the i-th vehicle (meters/sec)
c	Bit rate of the codec (Mbps)
n	Current number of vehicles associated to a given RSU
T_i	Transmission rate of the i-th vehicle in a given RSU (Mbps)
A_i	Maximum achievable throughput for the i-th vehicle in a given RSU (Mbps)
B_i	Attained throughput for the i-th vehicle in a given RSU (Mbps)
e	Vector of times where the transmission rate of a vehicle is susceptible to change within an RSU signal range
f	Vector of times where the transmission rate of vehicle is susceptible to change during its whole journey
D_i	Amount of data downloaded by the i-th vehicle in a given RSU
$Q_i(t)$	Queue length in the buffer of vehicle i at time t (sec)
$J_i(k)$	Interrupted time in the playback of the video of the i-th vehicle over the period $[f_k, f_{k-1}]$

Table 1: Main notation.

4. Performance and accuracy of the proposed solution

We explore a number of scenarios to study the accuracy of our proposed analytical solution. The considered scenarios include the following ranges of parameter values: the number of vehicles varies from 1 to 20 (reflecting low, average and high traffic densities), the distance between RSUs lies in between 1400 to 8000 meters (representing close and distant RSUs), and the velocity of the vehicles varies from 14 to 36 meters/sec (corresponding to slow and fast vehicles, viz. approx. 50 and 130 km/h respectively). Because a long portion of a highway can be viewed as the concatenation of shorter portions, we keep the number of RSUs set to 3 through this validation section. With these settings, on any scenario, each vehicle undergoes connected periods, in which its attained throughput depends on the number and positions of the other vehicles, and disconnected periods whose lengths depend on its velocity.

We now discuss the videos being played by vehicles in our scenarios. We consider that all vehicles are watching videos encoded at the same average bit rate and we use c to denote this bit rate. Although our approach can handle scenarios in which vehicles are watching videos encoded at different codecs, having the same value of c for all vehicles will ease the understanding of the interplay between the two considered performance parameters, namely the average download data rate and the average interruption time. For the sake of comparison, we consider three different videos: a CBR (Constant Bit Rate) flow that generates frames of constant size as well as two real traces, namely Star Wars Episode 4 and Harry Potter (codec H265 [32]), that produce frames of different sizes.

We implemented the proposed model in Matlab and measured its execution times on a machine with a 2 GHz Intel Core i5 with 2 cores processor. Based on the execution times for more than 300 examples with a number of vehicles ranging from 5 to 20 and different values for the distance between RSUs, the average execution time of our analytical solution was found to be 27.2 ms.

4.1. Simulation details

Besides the proposed analytical solution, we perform realistic simulations using ns-3 [29]. The simulator implements a wireless physical layer with possible transmission errors, the IEEE 802.11p standard, and the TCP-IP stack. At the MAC (Medium Access Control) layer, we use the Ideal WiFi manager of ns-3 that determines the IEEE 802.11p physical transmission rate (ranging from 3 to 27 Mbps) according to the SNR (Signal-to-noise Ratio). Figure 2 depicts the behavior of this manager as a function of the distance between an RSU and a vehicle. The y-axis on the left represents the 802.11p physical transmission rates while that on the right expresses the corresponding maximum achievable throughput taking into account the different overheads and times to access the medium (AIFS, Backoff, ACK, etc.).

The transfer of video frames between the back-end server and the passing vehicles is performed using a modified version of Transport protocol TCP. The use of TCP guarantees an appropriate sending rate while ensuring reliability (by retransmitting lost packets). Note that only one TCP connection is open between the back-end server and a vehicle. Depending on the current position of a vehicle (within or out of the signal range of an RSU), its TCP connection may be active or inactive. If active, the server reads the video frame by frame and attempts to transfer them as fast as possible. If inactive, the transfer is automatically stopped and whenever the associate vehicle re-enters in an RSU signal range, its TCP connection will be re-opened and its data transfer will resume. Note that, whenever a vehicle is outside the transmission range of an RSU, all its TCP segments are lost. With the default

TCP algorithm [33], the RTO (Retransmission Timeout) doubles for each segment retransmission until it reaches its maximum value set to 60 seconds. This may lead to a very long period without retransmission attempt so that vehicles entering in the coverage of an RSU do not resume their video transfer right away. Consequently, in our simulations, we changed the maximum RTO (clause 2.5 in [33]) to a value of 3 seconds instead of 60. Let us note that although modifying the setting of TCP may suffice for the purpose of a proof of concept, designing an appropriate Transport protocol for an IEEE-based VoD platform is an important issue that lies beyond the scope of the present paper.

On top of the TCP-IP stack, we coded a video player which is instantiated on each vehicle, and an application running on the back-end video server that distributes videos to the vehicles. Note that we use a 1 Gbps wired LAN to interconnect the back-end server with the RSUs. Each video stored at the back-end server is described by a trace file that indicates the video frame sizes and the times they are played. As mentioned earlier we consider Star Wars Episode 4 and Harry Potter where the video frame sizes vary from 13 bytes to 30 kB as well as a CBR video where the video frame sizes are constant (3125 bytes). Therefore, depending on the video frame sizes, an IP packet may contain only a part of a single video frame or several video frames. The CBR video trace file has been set to obtain the same video bit rate as Star Wars, which is approximately $c = 750$ kbps. This allows us to assess the impact of the video frame sizes on the performance parameters of the VoD platform. On the other hand, the Harry Potter trace delivers a lower video bit rate close to $c = 580$ kbps.

On each vehicle, the video player collects and stores the received data into a buffer and plays the video frames according to the video trace. The video begins when the first video frame is received. Each video player counts the total amount of downloaded data as well as the interruption time (corresponding to the amount of time a player is not able to play its video by lack of video frames into its buffer).

Note that we repeated each simulated experience 10 times with different seeds. Simulated results depicted in the following figures correspond to their mean values along with their confidence interval at a degree of 95%. The ns-3 code is made available [34] with the scripts that generate the simulations and process ns-3 output.

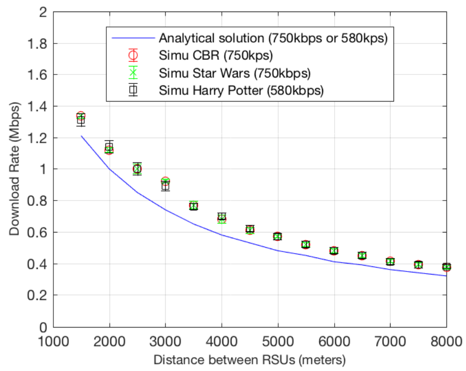

Figure 4: Scenario 1: Average download data rate as a function of the distance between RSUs.

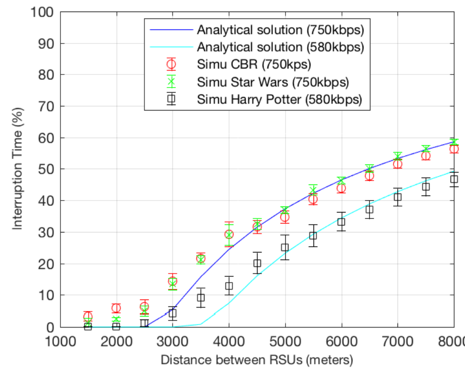

Figure 5: Scenario 1: Average interruption time as a function of the distance between RSUs.

4.2. Scenario 1

In our first scenario, we consider a set of 5 vehicles, each with a velocity of 30 meters/sec and spaced from each other by 200 meters. Therefore, the 5 vehicles are spread over 1000 meters and, because the signal range of an RSU goes up to 700 meters on each direction (see Figure 2), the number of vehicles connected to a given RSU may vary from 0 to 5. We consider several possible distances between adjacent RSUs ranging from 1500 to 8000 meters leading to disconnected periods of 3 and 220 seconds, respectively. We run the simulator ns-3 for each video (CBR, Star Wars, Harry Potter) as well as our analytical solution on this scenario using a value for c of 750 and then of 580 kbps. Figures 4 and 5 present the corresponding performance parameters.

Figure 4 reports the average download data rate (in Mbps) computed over all vehicles. First, let us note that the download data rates returned by our analytical model are identical to each other for both values of c since the video bit rate c is only taken into account when computing the interruption time. Second, regardless of the specific video used by the simulator, the average download data rates are much alike. Indeed, although video frames may come at different sizes, they are encapsulated within IP packets whose sizes is fit to the link MTU (Maximum Transmission Unit), namely 1500 Bytes so that the actual video trace in use does not affect much the download data rates. Third, the analytical solution delivers accurate results with a relative error close to 10%. More precisely, the analytical solution exhibits a constant negative bias. This discrepancy probably results from the delay in establishing a connection (forwarding table, TCP setup) when a vehicle enters into the signal range of an RSU. Indeed this delay, which exists only in the simulator, postpones the association of distant vehicles with low data rates to the RSU and hence lessens the effect of the IEEE 802.11 performance anomaly (which was discussed in Section 3.1). We will further investigate this phenomenon in the next section.

In Figure 5, we represent the interruption time experienced by vehicles for different distances between adjacent RSUs. We observe that, in the case of a video of 750 kbps and up to a distance of 2000 meters, vehicles move along the highway with virtually no interruption in their video playback. For larger distances between RSUs, the average interruption time increases steadily. Besides, unlike the download data rate, there is a difference, though small, when passing from the CBR video to Star Wars (despite having the same bit rate c). On the other hand, Figure 5 clearly illustrates that having a lower video bit rate (like Harry Potter) helps mitigate the video playback interruptions. Finally, the predictions delivered by the analytical solution are close to the values delivered by the simulation with absolute errors generally lying under 10%.

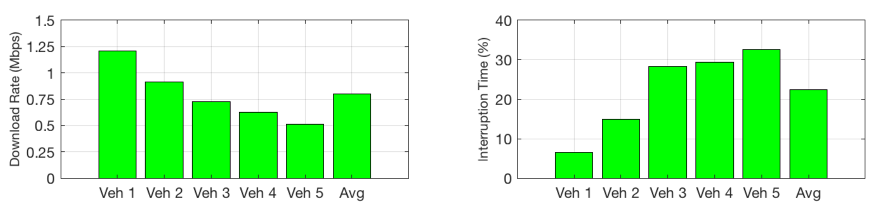

Figure 6: Scenario 1: Performance experienced by each vehicle in the case of Star Wars video and a distance of 3500 meters between RSUs.

This scenario clearly shows that considering only the average download data rate (and not the average interruption time) could be misleading when analyzing the results. For example, let us consider a video bit rate of 750 kbps and a distance between RSUs of 3500 meters. Then, Figure 4 shows that the simulator forecasts an average download data rate around 800 kbps, (a rate that is slightly higher than that of the video). However, in these same conditions, the simulator calculates that the average interruption time will near 20% (see Figure 5). To better understand this phenomenon, we represent in Figure 6 the performance attained by each vehicle. It appears

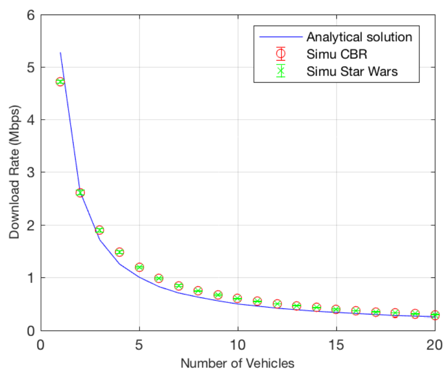

Figure 7: Scenario 2: Average download data rate as a function of the number of vehicles.

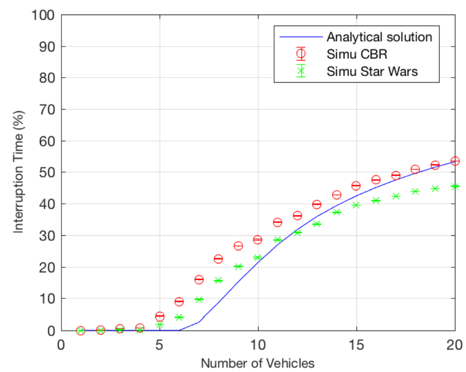

Figure 8: Scenario 2: Average interruption time as a function of the number of vehicles.

that the performance of vehicles may largely differ depending on their specific position (e.g., the first vehicle benefits from meeting less competition in accessing the radio channel when being in the vicinity of the RSUs).

4.3. Scenario 2

Our second scenario studies the accuracy of the analytical solution for different vehicle densities. To do that we let the number of vehicles vary from 1 up to 20 while the distance between consecutive vehicles is set to $\frac{1000}{\text{(number of vehicles)}}$ meters. The distance between RSUs is kept to 2000 meters and the velocity of vehicles is set to 30 meters/sec. For the sake of readiness, we represent only the results obtained for a video bit rate of c=750 kbps.

Figure 7 reports the associate results for the average download data rate computed over all vehicles. As expected, the download data rate decreases quickly as the number of vehicles grows. Our analytical solution is able to accurately capture this trend and provides accurate estimate of the average download data rate.

The results for the interruption time experienced by vehicles are given in Figure 8. First, we observe that, depending on the video being used (CBR or Star Wars), the simulator results may fairly differ. However, in any case, virtually no interruption times occur up to a number of vehicles of 4. Second, we notice that the analytical solution (which only considers the average video bit rate) tends to slightly overestimate the cut-off value of the number of vehicles where the video playback starts to experience interruption

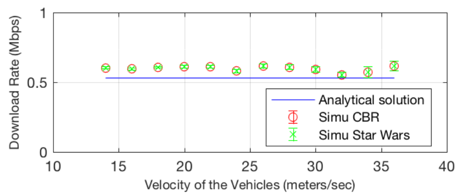

Figure 9: Scenario 3: Average download data rate as a function of the velocity of vehicles.

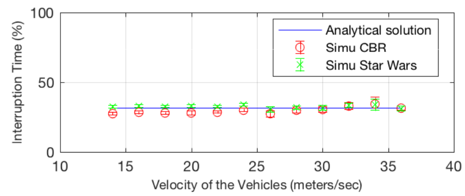

Figure 10: Scenario 3: Average interruption time as a function of the velocity of vehicles.

time. More generally, Figure 8 shows that our analytical solution may over- or underestimate the interruption times depending on the number of vehicles and the video in use. Nonetheless, its estimates appear to be generally fair and in agreement with those delivered by the simulator.

4.4. Scenario 3

In our third scenario, we evaluate the accuracy of our analytical solution for different vehicle velocities. We let their velocities vary from 14 up to 36 meters/sec (approx. 50 and 130 km/h, respectively) while maintaining the distance between RSUs to 4500 meters and the number of vehicles to 5 (spaced by 200 meters).

Figure 9 reports the corresponding results for the average download data rate. As expected, we observe that this value holds constant regardless of the actual velocity of the vehicles. Note that the simulator results may slightly vary though due to changed circumstances regarding the update of forwarding tables and timeout of TCP connections. Similarly to Scenario 1, the results returned by our analytical solution tend to slightly underestimate those delivered by the simulator. However, the mean relative error stays within 10%.

In Figure 10 we represent the found values for the interruption times. We notice that the proposed analytical solution also manages to deliver accurate estimates for this performance parameter.

4.5. Scenario 4

Our fourth scenario handles the case of vehicles having heterogeneous velocities. Similarly to Scenario 1, we consider a set of 5 vehicles initially spaced from each other by 200 meters. However, unlike Scenario 1, vehicles 1, 3 and 5 travel at a speed of 36 meters/sec while vehicles 2 and 4 move at

28 meters/sec. Note that we refer to the vehicles 1, 3 and 5 as the "fast vehicles" and to the vehicles 2 and 4 as the "slow vehicles". We let the distance between RSUs vary from 1500 to 8000 meters. For each RSU inter-distance, we run the simulator for each video (CBR and Star Wars) as well as our analytical solution using a value of $c = 750$ kbps. Note that the simulated results were obtained by averaging over 50 independent runs.

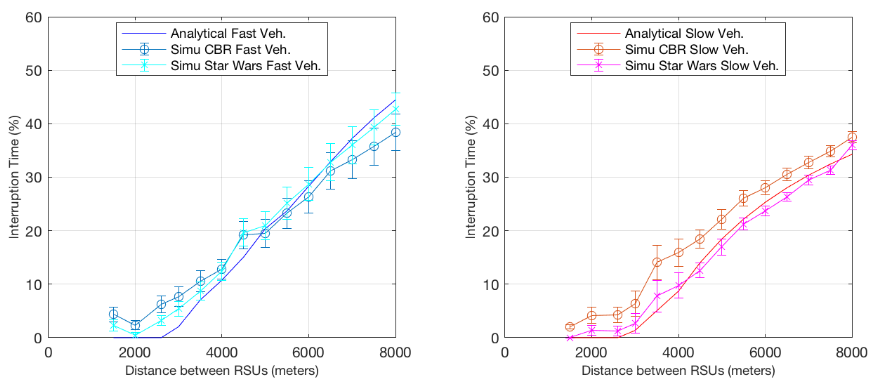

Figure 11: Scenario 4: Average interruption time as a function of the distance between RSUs. Left plot shows results for fast vehicles while right plot presents those for slow vehicles.

Figure 11 reports the interruption time experienced by fast vehicles as well as that experienced by slow vehicles using the simulator and our proposed analytical model. First, we observe that slow vehicles tend to experience just as many interruptions in their video playback than fast vehicles regardless of the distance between RSUs. In fact, Figure 11 suggests that although vehicles may travel at a different velocity, their actual velocity has virtually no effect on their performance. We also notice that the proposed analytical solution is able to fairly capture the interruption times for vehicles traveling at different velocity.

4.6. Scenario 5

In our last scenario, we study the case of a non-stop influx of vehicles. We consider several possible distances between successive vehicles so that the average number of vehicles per RSU ranges from 1 up to 20. The RSU inter-distance is set to 2000 meters and vehicles travel at a velocity of 30 meters/sec. We run the simulator for the CBR and Star Wars video as well

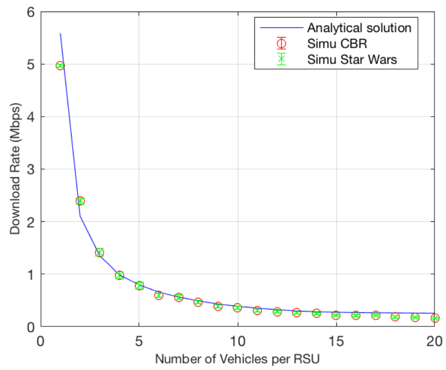

Figure 12: Scenario 5: Average download data rate as a function of the number of vehicles per RSU.

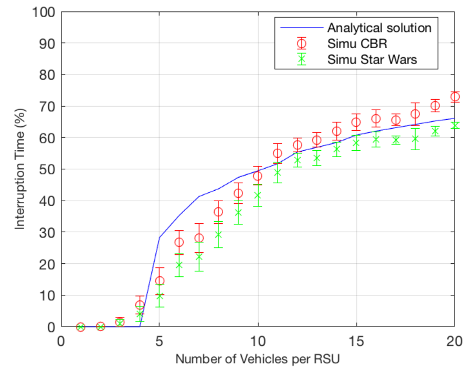

Figure 13: Scenario 5: Average interruption time as a function of the number of vehicles per RSU.

as our analytical solution with a video bit rate of c=750 kbps, and we collect the corresponding results. Note that we did not include the first vehicles in our computations as these vehicles undergo a non-representative behavior due to their leading position. Let us also underline that, though similar, Scenarios 2 and 5 address two different types of traffic arrivals. Indeed, while Scenario 2 handles the case of a finite number of vehicles that may vary from 1 to 20, Scenario 5 deals with a non-stop influx of vehicles with different densities.

Figure 12 represents the average download data rate experienced by vehicles as a function of the number of vehicles per RSU. Not surprisingly, we observe that the larger the density of vehicles, the less each vehicle can download.

In Figure 13, we represent the average interruption time as a function of the number of vehicles per RSU. We observe that vehicles tend to experience no interruption in their video playback as long as their density remains below a value of 5 vehicles per RSU. Beyond this value, the average interruption time grows quickly and can exceed 50% if the number of vehicles per RSU nears 15.

5. Applications

To illustrate the application of our analytical solution, we study the problem of dimensioning an IEEE 802.11p-based VoD platform. Application 1

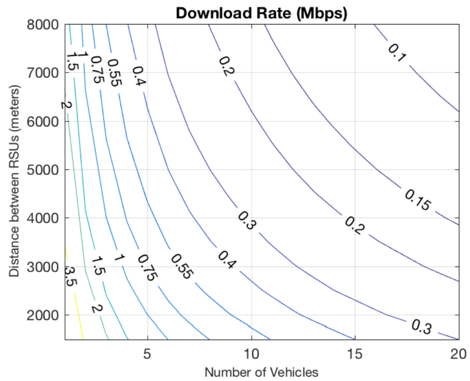

Figure 14: Application 1: Average download data rate against the number of vehicles and their velocity.

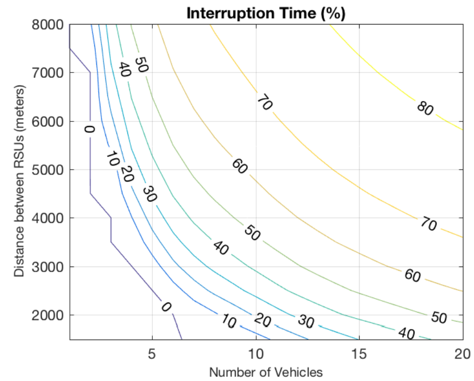

Figure 15: Application 1: Average interruption time against the number of vehicles and their velocity.

relates to the design and sizing phases of a VoD platform while the two others illustrate strategies to improve the quality of experience of subscribers by either adapting the video bit rate (Application 2) or by temporarily blocking the download for vehicles with low transmission rates (Application 3).

5.1. Application 1

Our first scenario analyzes the joint effect of the distance between RSUs and the number of vehicles on the performance of a 802.11-based VoD platform. We use the same settings than in Scenario 2 except that we let the distance between RSUs vary from 1500 meters up to 8000 meters. The video bit rate is set to c=750 kbps.

The results of our analytical solution for the average download data rate per vehicle are shown in Figure 14. As expected, this figure indicates that as the number of vehicles and the distance between RSUs grow, the average download data rate tends to decrease. In particular, Figure 14 suggests that, for a distance between RSUs of 3000 meters and a total of 5 vehicles, the average download data rate experienced by vehicles will lie at 750 kbps (just as the video bit rate).

Figure 15 reports the values found by our analytical solution for the interruption time. We observe that both the number of vehicles and the distance between RSUs significantly affect the value found for the interruption time. The region to the left of the zero-valued contour line is of particular interest since this represents conditions wherein vehicles should experience no interruption time in their video playback. First, we notice that the zero-valued contour line of Figure 15 does not coincide with that of 0.75 Mbps[2] depicted in Figure 14. This clearly underlines the need to consider both performance parameters (and not only the average download data rate) when studying the performance of such a VoD platform. Second, the maximum number of vehicles while maintaining no interruption in their video playback varies from 1 up to 7 depending on the actual distance between RSUs. For instance, for a distance between RSUs of 1500 meters, up to 6 vehicles can watch their video without experiencing interruptions.

Note that our analytical solution can easily deliver its forecasts as a function of the highway capacities and of the market penetration of a VoD service (i.e. the percentage of passing vehicles having subscribed to the VoD service) instead of the number of subscribed vehicles. Indeed, given a length and capacity for a highway as well as a mean velocity for the vehicles, one can easily derive the average number of vehicles on this portion of the highway using Little law [35]. For example, assuming a market penetration of 5%, an average vehicle velocity of 30 meters/sec, and a highway sustaining a capacity of 4800 vehicles/hour [36] and of length 6380 meters (corresponding to 3 RSUs spaced by 2500 meters and transmitting up to 690 meters each), it follows that the total number of subscribed vehicles can be estimated to $0.05.\frac{7200}{3600}.\frac{6380}{30} = 14.17$.

As a final note, let us remark that the predicted interruption time can also be used to size the length of the video to be buffered before the video playback starts (to avoid video interruptions). Indeed, Hossfeld et al. have shown that users tend to be extremely sensitive to interruptions and that services should be designed accordingly e.g., by increasing initial delay for prebuffering [37]. In our example, Figure 15 suggests that, for a distance between RSUs of 1500 meters and a total of 11 vehicles, the videos will be stalled (interrupted) for about 10% of time. Therefore, if each vehicle prebuffers 10% of the videos before starting their playback then the VoD platform could possibly accommodate those 11 vehicles without any interruption at the cost of initial delays for filling up the video buffers. Note that the time for filling up buffers can be computed in advance. Indeed, vehicles spend a total of 146 seconds between their connection to the first RSU and their disconnection from the third RSU (they travel the 690 + 1500 + 1500 + 690 = 4380 meters at a

[2]Remind that the video has a bit rate of 750 kbps.

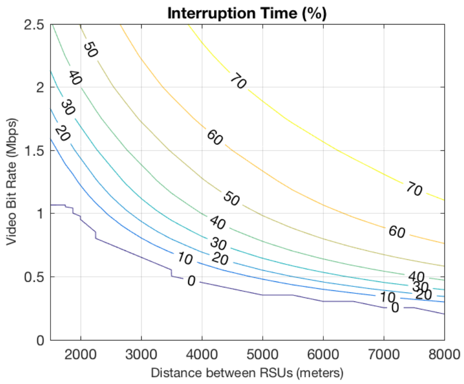

Figure 16: Application 2: Average interruption time against the distance between RSUs and the video bit rate.

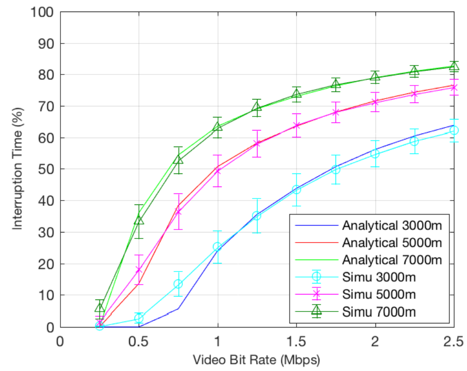

Figure 17: Application 2: Average interruption time as a function of the video bit rate for three distances between RSUs.

speed of 30 meters/sec). Thus, each vehicle needs to prebuffer 14.6 seconds of video which will take around 19.9 seconds since the average download rate for 11 vehicles is close to 0.55 Mbps (see Figure 14). In the case of a longer scenario, the prebuffering period can become larger and may appear too long. A solution can consist in reducing the video bit rate as discussed in the next section.

5.2. Application 2

In our second application, we conjointly study the influence of the distance between RSUs and the bit rate of the videos played on each vehicle on the performance of the considered VoD platform. To do that we consider a portion of a highway equipped with 3 RSUs. We let the number of vehicles vary from 1 to 20 and we include video bit rates ranging from 0.3 Mbps up to 2.5 Mbps. Vehicles travel at a velocity of 30 meters/sec and are spaced from each other by 200 meters.

Figure 16 represents the corresponding results for the average interruption time. It suggests that, for the considered setting of the VoD platform, selecting a lower video bit rate can greatly reduce (if not removing altogether) the interruption time. For example, for a distance between RSUs of 3000 meters, decreasing the video bit rate from 1.2 Mbps to 0.6 Mbps causes the interruption times to reduce from 30% to 0%.

Note that in order to validate the general correctness of Figure 16, we compare in Figure 17 the analytical results of our model with those delivered

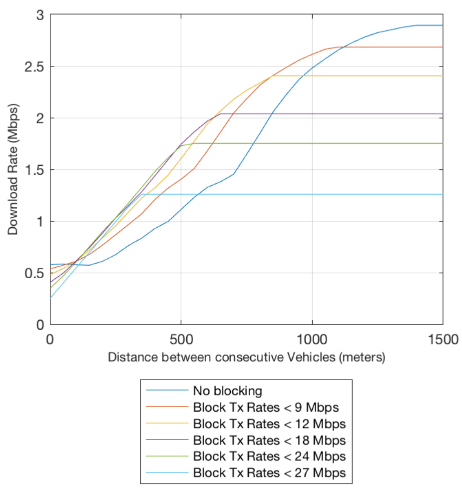

Figure 18: Application 3: Average download data rate as a function of the inter-vehicle distance for different blocking policies with a video bit rate of 0.75 Mbps.

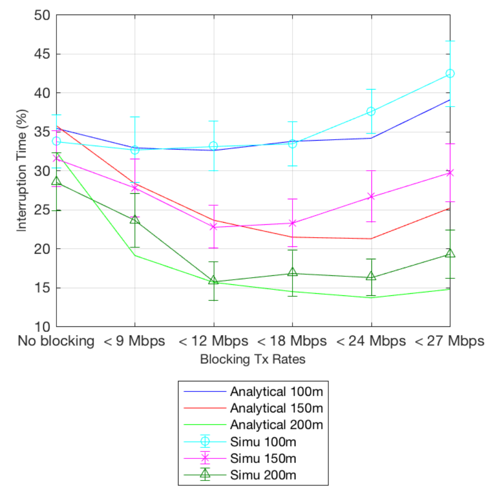

Figure 19: Application 3: Average interruption time as a function of the inter-vehicle distance for different blocking policies with a video bit rate of 0.75 Mbps.

by the simulator for three possible distances between RSUs and ten video bit rates. We observe that the outcomes of both approaches are typically in agreement.

5.3. Application 3

Our last application explores a means of improving the collective experience of vehicles by temporarily blocking access to the radio channel for some vehicles. Let us consider a set of three RSUs spaced by 4500 meters and a set of 5 vehicles traveling at a velocity of 30 meters/sec. We let the space between each vehicle vary from 0 up to 1500 meters. Using our analytical solution we can easily evaluate the average values for the download data rate and interruption time for each inter-vehicle distance. Then, we run the same experiment again but this time we apply a blocking policy to the vehicles. Specifically, we block the radio channel access for the vehicles that are the furthest from the RSUs starting with those having a negotiated transmission rate below 9 Mbps. We then move the cut-off value to higher values of the transmission rate, blocking vehicles having less than 12 Mbps, 18 Mbps, 24 Mbps, and 27 Mbps.

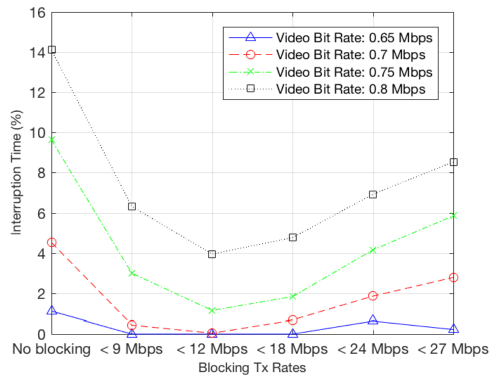

Figure 20: Application 3: Average interruption time as a function of the video bit rate for different blocking policies with an inter-vehicle distance of 150 meters.

Figure 18 shows the corresponding results for the average download data rate. First, when the distance between vehicles is small (say, an inter-distance of less than several meters), there is no gain at blocking the network access to certain vehicles. Indeed, because all vehicles have more or less the same transmission rate, temporarily blocking one of them equals blocking them all. Second, for vehicles spaced from 100 meters up to 1000 meters, there is a significant gain at preventing vehicles with the lowest transmission rates to access the radio channel. For example for an inter-distance of 500 meters between vehicles, the average download data rate grows from 1.25 to nearly 1.75 Mbps by simply blocking vehicles with a negotiated rate less than 18 Mbps. This improvement results from the well-established performance anomaly (discussed in Section 3) where vehicles with the lowest transmission rates tend to penalize all the others. Finally, as expected, when the distance between vehicles nears 2 $\times$ signal range of the RSU (viz. around 700 meters), each vehicle gets exclusive access to the RSU so that there is no interest at blocking any vehicles.

In Figure 19 we represent the average interruption time as a function of the selected blocking policy for three possible inter-distances between vehicles. This figure clearly demonstrates that the potential gain in terms of download data rate (observed in Figure 18) results in a clear decay in the average interruption time. Note that simulation results are included in Figure 19 to validate that this gain also occurs in the simulator.

Interestingly, video bit rate adaptation and blocking low transmission rates can be combined to further improve the quality of experience of subscribers. Figure 20 illustrates this gain when the 5 vehicles are spaced from each other by 150 meters with a distance between RSUs of 3000 meters. In the absence of a blocking policy, vehicles experience interruptions in their video playback as soon as the video bit rate reaches 0.65 Mbps. However, by blocking transmissions with a rate lower than 12 Mbps, interruption times are virtually removed, even if the video bit rate is increased to 0.7 Mbps. Similarly, for a video bit rate of 0.8 Mbps, blocking the lowest transmission rates helps lower the average interruption time from 14% to 4%.

Overall, Figures 18, 19 and 20 indicate that simple optimization policies can help improve collectively the experience of individual vehicles. It is worth mentioning that, since vehicles are mobile and heading towards the same direction, each of them will at some point reach the largest transmission rate. Therefore, concerns about unfairness are less prevalent in this case than in other wireless networks where nodes are far from experiencing statistically similar conditions.

6. Conclusions

In this paper, we explore the feasibility of implementing an IEEE 802.11p-based network infrastructure to build a VoD platform for the highway traffic. The network infrastructure comprises IEEE 802.11p Road Side Units that are deployed along the highway and deliver video content to traveling vehicles. We propose a conceptually simple and fast analytical solution to estimate two key performance parameters for a VoD platform: (i) the average download data rate experienced by vehicles over their journey and (ii) the average "interruption time", which corresponds to the fraction of time the video playback of a given vehicle is interrupted because of an empty buffer. We run realistic simulations on several scenarios to evaluate the accuracy of the analytical solution. Despite its simplicity, the analytical solution provides fair estimates for the two considered performance parameters. Through multiple examples, we investigate the influence of several parameters (e.g., the video bit rate, the number of vehicles, the distance between RSUs, the vehicle velocity) on these two performance parameters whose outcome may help the sizing of an IEEE 802.11p-based VoD platform. Our examples also highlight the need to consider both performance metrics as the average download data rate may lead to wrong conclusions regarding the quality of experience (interruption times) for the subscribers. At last, we show that, by taking advantage of the rate adaptation mechanism of IEEE 802.11p, collective performance improvements can be made for example by temporarily blocking access to the radio channel for the vehicles with the smallest transmission rates.

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References

[1] G. Bianchi, Performance analysis of the IEEE 802.11 distributed coordination function, IEEE Journal on Selected Areas in Communications 18 (3) (2000) 535–547. doi:10.1109/49.840210.

[2] O. Tickoo, B. Sikdar, Modeling queueing and channel access delay in unsaturated IEEE 802.11 random access MAC based wireless networks, IEEE/ACM Transactions on Networking 16 (4) (2008) 878–891. doi:10.1109/TNET.2007.904010.
URL `http://dx.doi.org/10.1109/TNET.2007.904010`

[3] E. Felemban, E. Ekici, Single hop IEEE 802.11 DCF analysis revisited: Accurate modeling of channel access delay and throughput for saturated and unsaturated traffic cases, IEEE Transactions on Wireless Communications 10 (10) (2011) 3256–3266.

[4] M. Stojanova, T. Begin, A. Busson, Conflict graph-based model for ieee 802.11 networks: A divide-and-conquer approach, Performance Evaluation 130 (2019) 64–85.

[5] F. Daneshgaran, M. Laddomada, F. Mesiti, M. Mondin, Unsaturated throughput analysis of IEEE 802.11 in presence of non ideal transmission channel and capture effects, IEEE Transactions on Wireless Communications 7 (4) (2008) 1276–1286. doi:10.1109/TWC.2008.060859.

[6] B. Nardelli, E. W. Knightly, Closed-form throughput expressions for csma networks with collisions and hidden terminals, in: 2012 Proceedings IEEE INFOCOM, IEEE, 2012, pp. 2309–2317.

[7] J. Lee, H. Lee, Y. Yi, S. Chong, E. W. Knightly, M. Chiang, Making 802.11 DCF near-optimal: Design, implementation, and evaluation, IEEE/ACM Transactions on Networking (TON) 24 (3) (2016) 1745–1758.

[8] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, X. Shen, Analytical study of the IEEE 802.11p MAC sublayer in vehicular networks, IEEE Transactions on Intelligent Transportation Systems 13 (2) (2012) 873–886. doi:10.1109/TITS.2012.2183366.

[9] J. Zheng, Q. Wu, Performance modeling and analysis of the IEEE 802.11p EDCA mechanism for VANET, IEEE Transactions on Vehicular Technology 65 (4) (2016) 2673–2687. doi:10.1109/TVT.2015.2425960.

[10] M. Amer, A. Busson, I. Guérin Lassous, Association optimization in Wi-Fi networks: Use of an access-based fairness, in: Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM '16, ACM, 2016, pp. 119–126.

[11] L. Li, M. Pal, Y. R. Yang, Proportional fairness in multi-rate wireless LANs, in: INFOCOM, Proceedings IEEE, IEEE, 2008, pp. 1004–1012.

[12] O. B. Karimi, J. Liu, J. Rexford, Optimal collaborative access point association in wireless networks, in: INFOCOM, Proceedings IEEE, IEEE, 2014, pp. 1141–1149.

[13] W. Li, S. Wang, Y. Cui, X. Cheng, R. Xin, M. A. Al-Rodhaan, A. Al-Dhelaan, AP association for proportional fairness in multirate WLANs, IEEE/ACM Transactions on Networking 22 (1) (2014) 191–202.

[14] M. Fiore, C. Casetti, C.-F. Chiasserini, On-demand content delivery in vehicular wireless networks, in: Proceedings of the 8th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM '05, ACM, 2005, pp. 87–94. doi:10.1145/1089444.1089461.
URL `http://doi.acm.org/10.1145/1089444.1089461`

[15] F. Soldo, C. Casetti, C. Chiasserini, P. A. Chaparro, Video streaming distribution in vanets, IEEE Transactions on Parallel and Distributed Systems 22 (7) (2011) 1085–1091. doi:10.1109/TPDS.2010.173.

[16] G. Maia, C. Rezende, L. A. Villas, A. Boukerche, A. C. Viana, A. L. Aquino, A. A. Loureiro, Traffic aware video dissemination over vehicular ad hoc networks, in: Proceedings of the 16th ACM International Conference on Modeling, Analysis & Simulation of Wireless and Mobile Systems, MSWiM '13, ACM, 2013, pp. 419–426. doi:10.1145/2507924.2507962.
URL `http://doi.acm.org/10.1145/2507924.2507962`

[17] C. G. Rezende, A. Boukerche, H. S. Ramos, A. A. Loureiro, A reactive and scalable unicast solution for video streaming over vanets., IEEE Trans. Computers 64 (3) (2015) 614–626.

[18] C. Quadros, A. Santos, M. Gerla, E. Cerqueira, QoE-driven dissemination of real-time videos over vehicular networks, Computer Communications 91-92 (2016) 133 – 147. doi:https://doi.org/10.1016/j.comcom.2016.07.008.
URL `http://www.sciencedirect.com/science/article/pii/S0140366416302651`

[19] M. Xing, L. Cai, Adaptive video streaming with inter-vehicle relay for highway vanet scenario, in: Communications (ICC), 2012 IEEE International Conference on, IEEE, 2012, pp. 5168–5172.

[20] M. Xing, J. He, L. Cai, Utility maximization for multimedia data dissemination in large-scale vanets, IEEE Transactions on Mobile Computing 16 (4) (2017) 1188–1198. doi:10.1109/TMC.2016.2582482.

[21] H. Zhou, X. Wang, Z. Liu, Y. Ji, S. Yamada, Resource allocation for svc streaming over cooperative vehicular networks, IEEE Transactions on Vehicular Technology 67 (9) (2018) 7924–7936. doi:10.1109/TVT.2018.2847325.

[22] F. Jamil, A. Javaid, T. Umer, M. H. Rehmani, A comprehensive survey of network coding in vehicular ad-hoc networks, Wireless Networks 23 (8) (2017) 2395–2414. doi:10.1007/s11276-016-1294-z.
URL `https://doi.org/10.1007/s11276-016-1294-z`

[23] D. Bethanabhotla, G. Caire, M. J. Neely, Adaptive video streaming for wireless networks with multiple users and helpers,

IEEE Transactions on Communications 63 (1) (2015) 268–285. doi:10.1109/TCOMM.2014.2378774.

[24] L. Sun, H. Shan, A. Huang, L. Cai, H. He, Channel allocation for adaptive video streaming in vehicular networks, IEEE Transactions on Vehicular Technology 66 (1) (2017) 734–747. doi:10.1109/TVT.2016.2535659.

[25] J. Qiao, Y. He, X. S. Shen, Improving video streaming quality in 5g enabled vehicular networks, IEEE Wireless Communications 25 (2) (2018) 133–139.

[26] Y. Guo, Q. Yang, F. R. Yu, V. C. Leung, Cache-enabled adaptive video streaming over vehicular networks: A dynamic approach, IEEE Transactions on Vehicular Technology.

[27] T. Begin, A. Busson, I. Guérin Lassous, A. Boukerche, Video on demand in ieee 802.11 p-based vehicular networks: Analysis and dimensioning, in: Proceedings of the 21st ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM '18, ACM, 2018, pp. 303–310.

[28] IEEE standard for information technology-local and metropolitan area networks-specific requirements-part 11: Wireless LAN medium access control and physical layer specifications amendment 6: Wireless access in vehicular environments, IEEE Standard 802.11p.

[29] The Network Simulator ns-3, https://www.nsnam.org/.

[30] M. Heusse, F. Rousseau, G. Berger-Sabbatel, A. Duda, Performance anomaly of 802.11 b, in: INFOCOM, Proceedings IEEE, Vol. 2, IEEE, 2003, pp. 836–843.

[31] A. Duda, Understanding the performance of 802.11 networks, in: PIMRC, Proceedings IEEE, Vol. 8, 2008, pp. 2008–1.

[32] Video trace library, `http://trace.eas.asu.edu/`, arizona State University.

[33] M. Sargent, J. Chu, D. V. Paxson, M. Allman, Computing TCP's Retransmission Timer, RFC 6298 (Jun. 2011). doi:10.17487/RFC6298. URL `https://rfc-editor.org/rfc/rfc6298.txt`

[34] Ns-3 simulations: Video on demand in a ieee 802.11p network, http://www.anthonybusson.fr/index.php?option=com_content&view=article&id=18:ns-3-vod&catid=2:uncategorised.

[35] A. O. Allen, Probability, Statistics and Queueing Theory with Computer Science Applications, Second Edition, Elsevier, 1990.

[36] J. Laufer, Freeway capacity, saturation flow and the car following behavioural algorithm of the vissim microsimulation software, in: 30th Australasian Transport Research Forum, Vol. 25, 2007.

[37] T. Hoßfeld, S. Egger, R. Schatz, M. Fiedler, K. Masuch, C. Lorentzen, Initial delay vs. interruptions: Between the devil and the deep blue sea, in: Proceedings of the International Workshop on Quality of Multimedia Experience (QoMEX), IEEE, 2012, pp. 1–6.