Control-Based Scheduling with QoS Support for Vehicle to Infrastructure Communications

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Abstract

This paper is focused on data transmission scheduling in V2I communications, where a central station, the roadside beacon, decides how to allocate system resources among the vehicles under coverage. We consider non-safety applications, whose commercial appeal is expected to accelerate the deployment of VANETs. In this case, the main objective is to deliver as much information as possible during the connection lifetime of the vehicles, which is limited by their speed and by the length of the road sections under coverage. In this environment, it is especially suitable the contention-free, poll-based access mechanism of the 802.11e standard, included in current VANET specifications. The design of a scheduling mechanism is addressed in this paper from a control theory point of view with the additional novelty of using an optimal control formulation comprising resource constraints. This design strategy allows QoS differentiation, assuring a fixed amount of bandwidth for each QoS class. The resulting algorithm not only maximizes the amount of data delivered, but also reduces performance differences between users travelling along different roads.

1. Introduction

Both industry and academia have identified a wide diversity of potential applications for vehicular ad-hoc networks (VANETs). These applications are typically classified into three categories:

- Safety-related, primary aimed to avoiding car accidents.
- Transport-efficiency, focused on improving road traffic flow and providing driving assistance.
- Comfort-related, allowing the access to informative and entertainment contents.

These services are provided by means of two different communications modes:

- Vehicle to Vehicle (V2V). In this case, vehicles communicate exclusively among them.
- Vehicle to Infrastructure (V2I). In this case, vehicles exchange information with fixed stations generally referred to as roadside beacons. These stations may connect the vehicle network with other data networks.

In this paper, we focus on V2I communication for non-safety-applications, especially those that require the delivery of large amounts of data. Examples of these types of applications are the following:

- Download audio/video programs, e.g. podcast subscriptions. Probably the most resource-intensive service and potentially the most popular one.
- Digital map downloading and updating. Access to touristic information.
- Internet-based services: e-mail service, cached web pages access.
- Traffic information and weather forecasts.
- Advertising and other commercial applications.
- Delay-Tolerant-Network applications: To carry information from one point (roadside-beacon or user) to another point (roadside beacon) by using vehicles as temporal storage nodes.

Although less critical, we consider that these applications may have a significant impact on the commercial success of VANETs, contributing to accelerate its implementation and deployment.

Considering these applications, this paper studies the design of scheduling algorithms within the framework of the V2I communication mode defined by the IEEE 802.11p task group [1] in their amendment to the IEEE 802.11 standard. This amendment is known as wireless access in vehicular environments (WAVE) and its MAC layer is based on the 802.11e standard [2]. 802.11p foresees the presence of one control channel, reserved for system control and safety channels and one or several service channels that support the applications considered. The proposed scheduling mechanism operates in the contention-free, poll-based access mode of 802.11e and decides, at the beginning of each MAC frame, how to allocate the available contention-free time of the MAC frame among the traffic streams in the system.

In contrast to safety-related services, where the main objective is to deliver small data packets with short delays and high reliability, in our case, the main objective is to maximize the amount of data that each vehicle receives before leaving the coverage area of the roadside beacon. Several characteristics of the system hinder this objective, especially those related to the vehicle speed: the rapidly changing propagation conditions of the V2I links and the shortened connection lifetime. However, the fact that movement trajectories (paths) are determined by the roads under coverage can be exploited in the design of effective scheduling policies.

We discuss how the scheduling problem can be formulated from the perspective of control theory. Although control theory has been previously applied to develop 802.11e scheduling algorithms in [3], we present a novel approach based on optimal control combined with constrained optimization and especially adapted to V2I communication. In addition, our formulation can be easily extended to incorporate QoS differentiation and, with a suitable configuration, it can also mitigate performance differences between users traveling along different routes and with different speeds.

This paper is organized as follows. We briefly summarize the characteristics of interest in the 802.11e standard and overview related work in V2I and 802.11e scheduling. We then present our control-based approach, detailing relevant aspects such as computational complexity, vehicle position detection and QoS differentiation. Our proposal is evaluated by means of simulation experiments. We finally conclude highlighting the main contributions of our work.

2. The IEEE 802.11e MAC

The IEEE 802.11e standard [2] was developed by the Task Group E in order to include a set of QoS enhancements to the IEEE 802.11 MAC specifications. One of the main features of the 802.11e is the definition of a MAC layer function called hybrid coordination function (HCF). This function allows two access methods to operate concurrently. One is a contention-based method, called enhanced distributed channel access (EDCA) and the other one is a contention-free, polling-based mechanism. Its name is HCF-controlled access channel (HCCA), and has attracted a notable research attention since the first draft of the standard was released. Researchers have mainly focused on the design of effective scheduling mechanisms for HCCA considering variable bit rate traffic [3], [4], [5]. In V2I communication we are dealing with a different type of traffic. Nevertheless, the HCCA framework is very useful to exploit several characteristics of the vehicular system in the design of a V2I scheduler, as shown later in this paper.

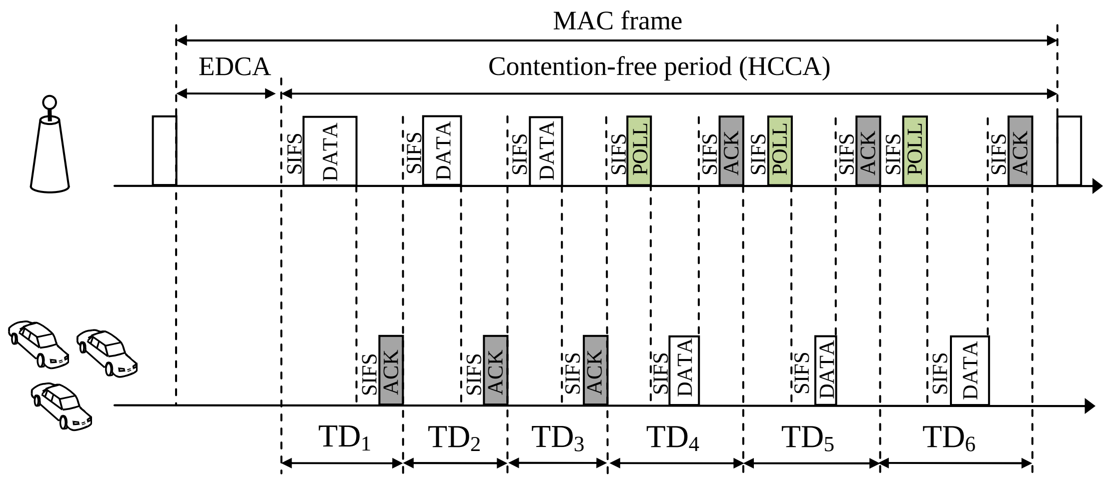

Figure 1. *Simplified temporal diagram of a MAC frame allocating 3 downlink and 3 uplink TXOPs.*

One of the main features of HCCA is the concept of transmission opportunity (TXOP), which refers to the time duration during which a station is allowed to transmit a burst of data frames. The hybrid coordinator (HC) entity, which is typically located at the access point, assigns TXOPs to each station. The HC starts an uplink TXOP by issuing a poll request frame to the station. A downlink TXOP is simply started by the HC with the transmission of a MAC service data unit (MSDU). The TXOP duration (TD) is explicitly set by the HC in the poll request frames. Contention-based periods are required to allocate other services. Therefore, the duration of a contention-free period is limited to a maximum value, and is given by the system's variable *CAPLimit*. Figure 1 shows a diagram of the HCCA access method, where three downlink and three uplink traffic streams receive TXOP allocations. The small period of time that always appears between two successive transmissions is called the shortest interframe space (SIFS). The SIFS, the poll frames and the ACK frames constitute a protocol overhead that is taken into account in the scheduling mechanism. ACK frames can acknowledge a set of MSDUs by means of the block ACK option.

Related Work in V2I Scheduling.

Very few works focused on data transmission scheduling in roadside to vehicle systems have been published so far. One of the few papers fully devoted to this issue is [6]. Their proposal assumes that the roadside beacon knows the connection lifetime of each vehicle in advance. Therefore, users with less data to transmit or to receive and whose remaining time in the system is smaller are given higher priority. This scheme, although pioneering in exploiting some characteristics of V2I networks, is not specifically compatible with the 802.11p standard and foresees the link quality factor, which is typically considered essential in wireless scheduling schemes [7]. Our approach to the problem is completely different in many ways, especially in the application of the 802.11e framework, the use of an optimal control policy, and the support of QoS differentiation.

Related Work in 802.11e Scheduling

The reference scheduler proposed by the Task Group E in the 802.11e standard, as well as its later enhancements, is mainly focused on real-time traffic streams. In the reference scheduler, each station is assigned a fixed TXOP duration (TD) which is mainly determined by typical real-time traffic descriptors, like the average bit rate, and the lowest delay bound.

In [4], Grilo *et al.* pointed out the convenience of adding some flexibility to the duration of the TXOPs in order to accommodate traffic bursts, which are common in real-time traffic types like MPEG-4 video. They propose a token bucket algorithm to allow variations of the TDs while assuring a fixed average value. Their scheduling scheme issues polls according to the classical earliest due date discipline. The due date is given by the maximum service interval, defined as the maximum allowed time between the start of two successive TXOPs allocated to a station. This proposal was later improved in [8], where the maximum and minimum service intervals were also adapted according to the traffic characteristics and the instantaneous buffer occupancy.

Flexibility and adaptability, especially in TD, is a common feature in most of the works addressing 802.11e scheduling. Qiang Ni describes in [5] a scheduling algorithm that uses the queue length information, which is a feature supported in 802.11e, to adjust the TXOP allocation such that an ideal queue length is pursued. Although not explicitly stated, this algorithm is in essence, a control system. The feasibility of the control theoretic approach is fully recognized in [3], where the computation of the TD is derived from a discrete-time control formulation of the system. We develop this approach further using an optimal control formulation that incorporates the resource constraint imposed by the maximum duration of the contention-free period of the MAC frame, which is a feature that has been generally overlooked in previous works.

In contrast to typical 802.11e scenarios, V2I communications are not characterized by rate-varying applications, but by batch download sessions. In consequence, it is not required to adapt TDs to variations in the rate of the traffic streams. In our case, the goal is to maximize the amount of data delivered to each vehicle before it leaves the coverage area, and to do it as independently of the vehicle's route as possible. Therefore, TDs are adapted to the amount of data buffered per vehicle, to their estimated routes and to the positions of the vehicles, which are associated to the average quality of the links. Moreover, our scheme can easily incorporate QoS differentiation allowing bandwidth reservations for lower priority traffic streams.

3. The scheduling problem as an optimal control problem

In essence, scheduling refers to allocating system resources to multiple connections. In 802.11e HCCA, the resource to be allocated is the available contention-free time within the MAC frame. The scheduling algorithm should decide what data streams should transmit and the duration of their transmission periods within the frame. For several years, and especially during the last decade, resource allocation problems have been formulated as convex optimization problems [7], where the aim is to maximize or minimize an objective function, which represents mathematically the main goal of the system, *e.g.* to maximize the rate, to minimize the delay or to maximize power efficiency. Sometimes, the objective is formulated by means of utility functions, which represent the relative importance given to the magnitude of the parameter of interest. In some situations, it may be useful to assign quadratic costs to certain variables, *e.g.* to the queue length, because this policy penalizes large differences between users, which can be exploited to pursue fairness.

If the dynamics of the system's variables, including the ones in the quadratic cost function, is governed by a set of linear equations, the resulting formulation corresponds to a quadratic optimal control problem [9]. In this section we show how the scheduling problem can be formulated in this way.

The decisions of the scheduler are reflected in the evolution of the queue lengths of each data stream (buffer process) at the link layer. Let $x_i(k)$ denote the queue length, in bits, of the *i*-th traffic stream at the beginning of the k-th frame. The state of the system is then given by the vector $\mathbf{x}_k = (x_1(k), x_2(k), \ldots x_N(k))$, where N is the total number of nonzero queues in the system. Note that each vehicle can be associated to more than one traffic stream, given that each component in $\mathbf{x}_k$ corresponds to a transmission direction (uplink or downlink) and one QoS class.

The state changes after each MAC frame according to the TD allocation and the propagation conditions of each wireless link. From a dynamic system perspective, the control vector $\mathbf{u}_k$ at the *k*-th frame, is given by the set TXOP durations (without protocol overheads) allocated to each traffic stream. The control vector $\mathbf{u}_k = (TD_1(k), TD_2(k), \ldots TD_N(k))$ is the scheduling decision at each MAC frame.

Let us assume that, during its assigned transmission time, the *i*-th traffic stream transmits *m* MAC service data units (MSDU) of the nominal size, *L*, i.e. $m = TD_i(k)\cdot R/L$, where *R* is the transmission rate (MSDU fragmentation is obviated for the sake of clarity). Given the propagation conditions of the link between the access point and the vehicle associated to the i-th component of $\mathbf{x}_k$, only *n* out of the *m* transmitted MSDUs are correctly decoded at the receiver. Let $PER_i(k) = 1- n/m$ denote the packet error ratio of the i-th link at frame *k*. The state of the *i*-th queue at the beginning of frame *k*+1 is then given by: $x_i(k+1) = x_i(k) - (1- PER_i(k))\cdot R\cdot TD_i(k)$. We can now formulate the system equations in matrix notation as:

$$\mathbf{x}_{k+1} = \mathbf{A}_k\, \mathbf{x}_k + \mathbf{B}_k\, \mathbf{u}_k \qquad (1)$$

where, according to the terminology of dynamic systems theory, $\mathbf{A}_k$ is referred to as the system matrix, which in our case is an identity matrix, and $\mathbf{B}_k$ is the distribution matrix which in our system is a diagonal matrix such that the *i*-th diagonal element is equal to $-(1-PER_i(k))\cdot R$. Note that what allows us to use linear equations to describe the buffer process is the fact that, at the link layer, the consequences of the changing propagation conditions in the radio channel can be modeled as a PER. The PER values at each point of the road should be obtained in advance either by experimental measures or by offline computations.

According to the characteristics of the applications supported by a V2I system, the typical situation is that the traffic streams of each vehicle entering the system start with an initial backlog of data. Therefore, the objective of the scheduling algorithm is to minimize the residual backlogs of each vehicle leaving the system, which is equivalent to throughput maximization. This objective can be incorporated into a quadratic cost objective function by simply adding the quadratic values of each state component, $\alpha_i\cdot x_i^2(k)$, where α_i is a weighting factor that balances the relative importance of each queue size. This factor can be used, for instance, to assign different weights to vehicles according to their estimated connection lifetime, avoiding that vehicles spending very few time under coverage receive much less data than vehicles that remain longer in the system.

The contention-free time of the MAC frame is a limited resource, especially considering that each vehicle spends a limited number of MAC frames under coverage. Therefore, the cost function should reflect the link quality, in the sense that the cost of allocating resources to a station with better propagation conditions should be lower than the cost associated to a vehicle with a high PER. In consequence, the cost function incorporates factors of the form $\beta_i(k)\cdot u_i^2(k)$, where $\beta_i(k)$ is a weighting factor associated to the control value of the *i*-th traffic stream at the *k*-th frame. A suitable value for $\beta_i(k)$ is $PER^2_i(k)$. We can now formulate the cost function to be minimized at the *k*-th scheduling stage:

$$\mathbf{x}^T_{k+1}\, \mathbf{Q}_{k+1}\, \mathbf{x}_{k+1} + \mathbf{u}^T_k\, \mathbf{R}_k\, \mathbf{u}_k \qquad (2)$$

where the matrices $\mathbf{Q}_{k+1}$ and $\mathbf{R}_k$ are diagonal matrices whose diagonal elements are the weighting factors α_i and $\beta_i(k)$ respectively and ^{T} denotes the transpose operation. Note that, because of the characteristics of

V2I communication, when a user enters the system its state variable has its highest value, and its propagation conditions are generally poor, given that the vehicle is detected at the edge of the coverage area, far from the roadside antenna. As time passes, its link quality improves and, after certain instant, this quality will start to degrade as the vehicle moves away from the roadside antenna. Every vehicle circulating on the same road will experience the same link quality evolution. However the evolution will be faster for vehicles traveling at higher speed.

Previous discussion allows us to set the weighting factors for $x_i^2(k)$ as $\alpha_i = t^2_{max} / (t^2_i \cdot B^2_i)$, where t_{max} is the maximum time that a vehicle is expected to spend under coverage, t_i is the expected sojourn time for the vehicle associated to the *i*-th data stream and B_i is its initial data backlog. This definition of α_i has a twofold objective. First, to normalize the cost of the elements in $\mathbf{x}_k$ in order to prevent large backlogs from neutralizing the cost of the elements in $\mathbf{u}_k$. Second, to mitigate the differences in the amount of data delivered to vehicles traveling at different speeds and roads, by adjusting the relative cost accordingly to the estimated sojourn time in the system.

The control vector that minimizes the cost function can be obtained by applying the system equation (1) into the cost expression (2) and equating to zero the derivative of the resulting equation. What we obtain is a feedback-based control law consisting of a simple linear expression, $\mathbf{u}_k = \mathbf{L}_k \mathbf{x}_k$, where $\mathbf{L}_k$ is known as the gain matrix [9] and is given by the following matrix operation:

$$\mathbf{L}_k = -(\mathbf{R}_k + \mathbf{B}^T_k \mathbf{Q}_{k+1} \mathbf{B}_k)^{-1} \mathbf{B}^T_k \mathbf{Q}_{k+1} \mathbf{A}_k \qquad (3)$$

Because of the diagonal structure of the matrices in (3), the resulting gain matrix is also diagonal and its computation reduces to a set of N operations, *i.e.* its complexity is O(N). The name for a linear feedback control optimizing a quadratic cost is linear quadratic regulator (LQR). Figure 2 illustrates the feedback structure of the LQR-based V2I scheduler and summarizes its main features. The location estimator block is explained later in this paper.

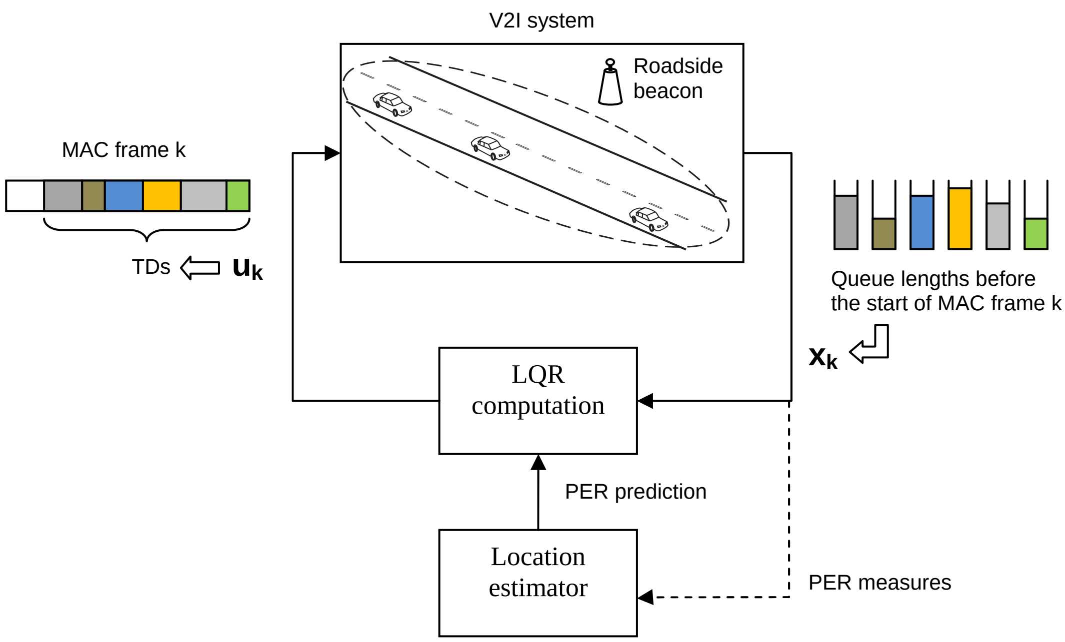

Figure 2. *Diagram of the feedback structure of a LQR-based V2I scheduler and the variables involved.*

However, the classical LQR computation does not take into account any constraints for the resulting control. As explained before, the scheduler in the V2I system must allocate the available contention-free time within the 802.11 MAC frame, bounded by *CAPLimit*. Therefore the sum of the elements of $\mathbf{u}_k$ and the overheads involved cannot exceed this value (the control must be feasible). A similar problem is pointed out in [3], where a feedback strategy is also investigated. The strategy in that case was to multiply each TD by a proportional reducing factor. However, in an LQR, this policy would, in general, move the control vector to an operation point far from the optimum. The most rigorous approach is to reformulate the problem as a constrained quadratic optimization problem, where the cost function (2) must be minimized subject to the following constraint: $\sum TD_i + \sum OH_i =$ *CAPLimit*, where OH_i is the overhead associated to the *i*-th traffic stream. This condition will only be applied if the control obtained with gain matrix (3) is unfeasible.

Because the optimization problem is only subject to an equality constraint, it can be transformed into a system of N+1linear equations by means of the Lagrange multipliers technique [10]. Once again, because of the diagonal structure of the system, its solution can be obtained by means of N+1 scalar operations, and thus the cost is O(N+1). However, it is possible for some of the resulting TD values to be negative (or to be below a given minimum value, in general). In this case, these elements will be set to 0 and the system will be solved again for the remaining elements of $\mathbf{u}_k$. This algorithm will proceed iteratively until all the components of $\mathbf{u}_k$ have feasible values. Computational experiments have shown that the optimum solution is attained in no more than 3 or 4 iterations. The resulting control scheme is a constrained LQR (cLQR). In general, obtaining the expression of an optimal control of this type is computationally cumbersome and therefore is only practical when offline computation is possible, which is not the case of our system because of the changing propagation conditions of the links. However, the structure of the problem allows a simple, iterative and fast computation of the solution, being feasible for a real-time system where the scheduler have to decide in a time-scale of milliseconds.

The preceding procedure allows the concurrence of EDCA-based services (mainly car-to-car communication) with HCCA. In this case, the frame time assigned to EDCA may be decided by the HCF in a frame-by-frame basis and, therefore, the available time for HCCA (*CAPLimit*) may change at each stage. The proposed scheme is still valid since its main goal is to optimally allocate the existing resources at each frame. Even though the amount of resources differed from one frame to another, the computation of the TDs requires the same steps.

A note on the computational complexity

Many works make a considerable effort to develop scheduling algorithms with O(N) computational cost [3] or lower, [6]. In contrast, other researchers argue that, given the state of the art in microprocessors and firmware for networking devices, the time required to perform much more complex operations, of the order of $O(N^3)$ or higher, is short enough to allow its use in real-time operation. This fact opens the door to solving more complex problems by means of more powerful techniques. In consequence, many previous works [7] [11], formulate scheduling and resource allocation problems as convex optimization problems with inequality constraints. These kind of problems are generally solved by means of iterative algorithms like the Newton method [10], consisting of solving a system of linear equations, which has a cost of $O(N^3)$, at each iteration. Typically, the number of iterations required for convergence ranges from 10 to 35. Sometimes, it is possible to exploit the structure of the problem to reduce the cost of each iteration to $O(N^2)$ or even O(N), like in our proposal, which, in addition, achieves the optimal solution in up to 4 iterations.

4. Vehicle´s location estimation

According to the definition of the distribution matrix $\mathbf{B_n}$ in (2), the computation of the control vector requires an estimation of the PER of each vehicle in the upcoming MAC frame (see Figure 2). In this section we propose a strategy to generate a prediction of the PER that each vehicle would experience during MAC frame *k* before the beginning of that frame. This forecast is associated to an estimation of the sojourn time of each vehicle in the system, which is also necessary in order to compute the weighting factors in the cost function.

Because data transmission is collision-free in the HCCA scheme, the PER of each wireless link is only determined by its propagation errors. These errors depend on the average signal power received which is related to the distance between the vehicle and the roadside antenna, the transmission power, the radiation diagram of the antennas, and the obstacles in the line-of-sight of the link. In contrast to a cellular mobile network, the motion of a terminal station in V2I is constrained to a limited and generally small number of paths, corresponding to the roads under coverage. Each path can be characterized by the average PER at each of its points. These values can be obtained from the average power received at each point or by experimental measuring in the system. We will refer to the set of average PER values of a path as the error pattern of this path. The error pattern, in combination with the speed information, facilitates the estimation of the vehicle's position within its path, its expected average PER in upcoming frames and its sojourn time under coverage. However, it is required to identify foremost the path followed by the vehicle.

This identification can be based on comparing the error patterns with the PER measurements obtained after each TXOP period.

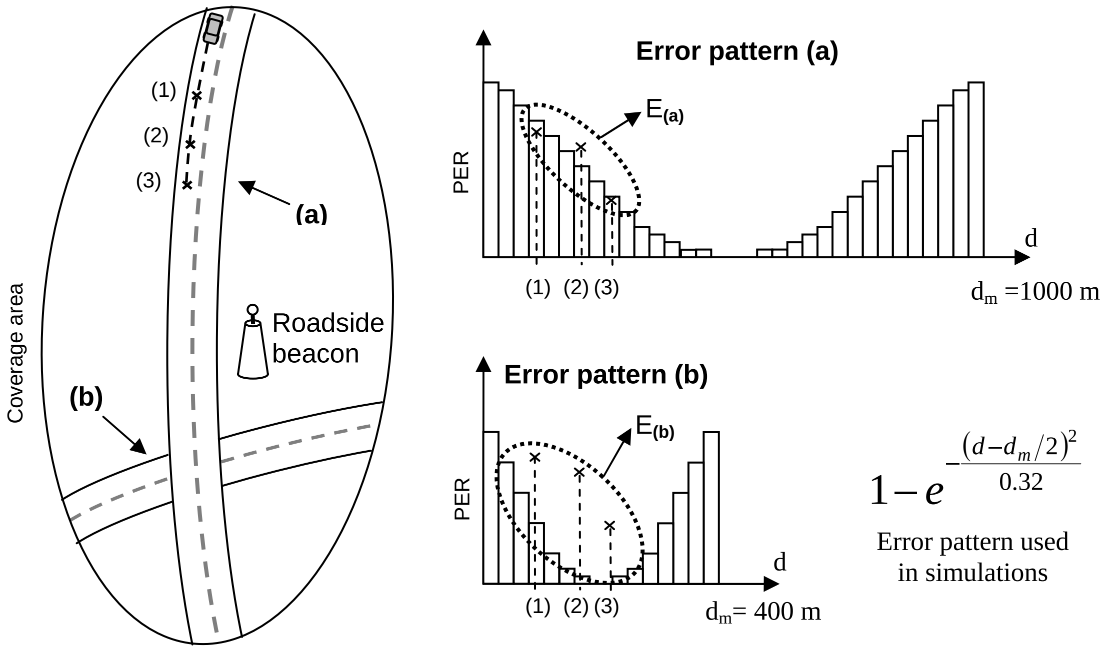

Figure 3. *Example scenario with a roadside beacon covering two road segments of different lengths. The system obtains PER measurements for a vehicle when it transmits or receives a burst of MSDUs. The system compares these measures with the stored error patterns of each route. In this case, the system detects very fast that the vehicle moves along route (a).*

Figure 3 shows a V2I system where a roadside beacon (RB) provides radio coverage over two roadway segments of 1000 and 400 meters each. Each segment is characterized by its error pattern, denoted by (a) and (b) respectively. When a user is detected by the system, it must inform the RB of its speed. If the vehicle provides its position as well, the path identification is straightforward. If the station is unable to provide its location, the system should make a hypothesis about the path that, in principle, should be the worst case, *i.e.* the shortest one (b). Then the access point starts allocating TXOPs to this user accordingly to the error pattern (b). The PER measures are obtained at each MAC frame from the MSDUs received with error (uplink) and from the ACKs (downlink). The system can compute the quadratic errors ($E_{(a)}$ and $E_{(b)}$) between the PER measures and each error pattern. Then, each vehicle will be assigned the path whose error pattern presents a smaller difference with the PER measures.

5. Simulation Results

The proposed scheduling scheme (cLQR) has been evaluated by means of MATLAB simulations in the scenario of Figure 3 and compared with the following feasible scheduling mechanisms:

1. System State Minimizer Proportional (SMP): In this scheme the TXOP durations are proportional to the components of the $\mathbf{u}_k$ vector that minimizes the value of the state vector ($\mathbf{x}_k$) in the system equation (1).
2. State Proportional (SP): A classical approach in which the TDs are proportional to the queue length of each traffic stream.
3. Link Quality Proportional (LQP): Another classical scheme in which the resources are allocated proportionally to the link quality of each user. In our case, the quality metric for the links is the transmission success ratio (1−PER).

The error patterns for each route are given by the function shown in Figure 3. Because at vehicular speeds only fast fading is present, errors in MSDU transmissions can be assumed to be uniformly distributed during a TXOP. These patterns, jointly with the parameter configurations of Table 1, fully describe the simulated scenario and allow the replication of the results shown in this paper.

The initial backlog of every traffic stream is configured to 15 Mbit, resulting in a saturation regime operation, a very usual condition in the evaluation of scheduling algorithms. The traffic flow on each segment is 1 vehicle per second (3600 vehicles per hour), which is relatively high considering usual estimations for highways.

Simulation parameter	**Value**
MAC frame length	30 ms
Collision-free time (*CAPLimit*)	25 ms
Nominal transmission rate (uplink and downlink)	10 Mbit/s
MSDU length	1000 bits
Poll overhead	100 μs
Downlink traffic streams per vehicle	1
Uplink traffic streams per vehicle	1
Initial backlog per traffic stream	15 Mbit
Average vehicle speed	110 Km/h
Deviation of the vehicle speed	10 Km/h
Vehicle speed probability distribution	gaussian
Vehicle arrival rate per route	1 vehicle/s
Vehicle inter-arrival time distribution	exponential
Length of route a	1000 m
Length of route b	400 m
Error pattern granularity	1 m

Table 1. *Parameters setting.*

Table 2 shows, for each scheduling algorithm, two performance figures: the average amount of data transferred per vehicle and the ratio between the average amount of data delivered to vehicles of route b and the average amount of data delivered to vehicles of route a. These figures are obtained by averaging the results of 20 simulation runs of 10 minutes of system operation each. The resulting confidence intervals are less than 1% with a confidence degree of 95% according to a t-student distribution. The first metric constitutes the main goal of a scheduling algorithm in the considered scenario, and the second one gives an idea of how much the performance perceived by the user depends on the length of the road segment under coverage. Obviously, the optimum ratio would be 1, meaning that the performance is completely independent of the route. Note that the delivery ratios obtained by the reference algorithms (SMP, SP, LQP) are very close to the ratio between the lengths of the routes (0.4), while the cLQR obtains a ratio of almost 0.9, showing the effectiveness of the weighting policy applied in the cost function.

Algorithm	**Data delivered per vehicle**	**Per-route delivery ratio**
SMP	2.59 Mb	0.44
SP	2.78 Mb	0.44
LQP	2.77 Mb	0.43
cLQR	3.60 Mb	0.86

Table 2. *Performance results of different scheduling algorithms.*

6. QoS differentiation and minimum bandwidth reservation

One of the main advantages of the cLQR-based scheduling scheme is that it allows a relatively simple differentiation among QoS classes. This differentiation is parametric, which means that each QoS class is assured a fixed value of each QoS parameter. In our case, the scheduling mechanism can assure a percentage of the available throughput to each class.

The bandwidth reservation scheme consists of decomposing the TD assignation problem into several sub-problems, one per each QoS class. The resource constraint of each sub-problem is determined by the bandwidth reservation and by the resources that higher QoS classes leave unused. As an example, let us consider a V2I system with two QoS classes. The highest priority and the lowest priority classes are granted 90% and 10% of the total resources respectively. The resource constraints are, in principle $0.9\times$*CAPLimit* and $0.1\times$*CAPLimit*, but if any of the classes requires less time than its initial bound, the remaining collision-free time will be added to the time available to the other class. In order to know the amount of unused resources, the system only needs to perform the linear operation $\mathbf{u}_k = \mathbf{L}_k\ \mathbf{x}_k$ once per class. In the worst case, the QoS differentiation requires one additional O(N) iteration compared to the single-class system.

Figure 4 shows a trace of the instantaneous throughput per QoS class in the V2I system described above. The throughput is defined as the amount of data correctly delivered per MAC frame. In this simulation experiment each vehicle is associated to four traffic streams operating at saturation regime: QoS1 uplink, QoS1 downlink, QoS2 uplink and QoS2 downlink. The rest of the parameters are configured according to Table 1. The traces show how the bandwidth is accurately distributed to each class according to the QoS guarantees.

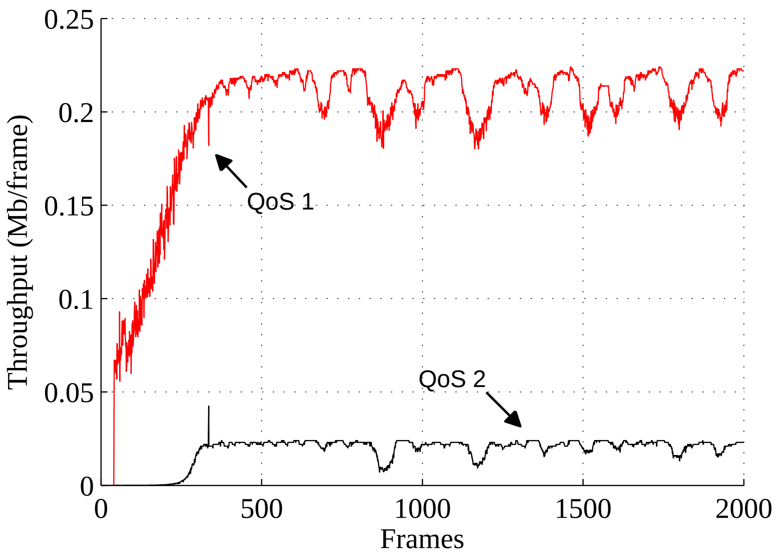

Figure 4. *Trace of the throughput per MAC frame for each QoS class. QoS1 and QoS2 are granted 90% and 10% of the resources respectively.*

7. Conclusions

This paper presents a scheduling strategy for V2I communications (cLQR), suitable for non-safety applications where the objective is to deliver as much data per user as possible. Our scheme relies on the polling-based, contention-free access mode of the IEEE 802.11e standard, included in the WAVE specifications. The design of a scheduling algorithm is formulated as an optimal control problem where the controller has to distribute the available contention-free time of the IEEE MAC frame. The main contributions of the strategy presented in this paper are:

- The formulation comprises resource constraints.
- Given the characteristics of the applications considered, our scheduling algorithm adapts the resource allocation to the queue lengths and to the estimated link qualities, while previous proposals are focused on variations of the data traffic rate.
- Our strategy exploits special characteristics of the vehicular environment:
    - Restricted movement trajectories determined by the roads under coverage.
    - Feasible prediction of the packet error rate based on the estimated location and movement.
    - Limited and predictable connection lifetime that is determined by the road section under coverage and the vehicle speed.
- The framework presented can be easily extended to incorporate QoS differentiation based on bandwidth reservation for different QoS classes.

Simulation results show that, apart from increasing the amount of data delivered per vehicle, our scheduling algorithm reduces performance differences between users traveling along different roads.

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