Safety Message Generation Rate Adaptation in LTE-based Vehicular Networks

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Abstract

Long Term Evolution (LTE) appears to be a practical and economical alternative to IEEE 802.11p for the rapid deployment of vehicular safety applications. Vehicles periodically broadcast messages, aka beacons, that contain their location and speed. Ideally, vehicles should have accurate knowledge of the locations of surrounding vehicles, and, if possible, have a same level of precision regardless of their speed.

The contributions of this paper are twofold. First, we propose an efficient solution for adapting the generation rate of vehicles' safety messages so that each of them experiences the same level of location precision. This fairness is attained using an analytical model, based on a queueing model that approximates the level of precision for each vehicle based on their motion speed and their generation rate of safety messages. Second, we present a solution for dynamically discovering the minimum number of resources, i.e. PRBs, that should be allocated by the LTE so as to meet a certain level of location precision for all vehicles. Our numerical results show the effectiveness of our two proposed solutions.

Keywords: LTE, safety application, beacon, vehicular, adaptation, performance

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1. Introduction

The automotive industry is expected to undergo major changes in the upcoming years. In this regard, connected cars are a key component for the development of Intelligent Transportation Systems. IEEE 802.11p is a refined version of the IEEE 802.11 standard for allowing wireless communications in vehicular environments. Despite significant technical improvements (e.g. priority, fewer overheads) to better fit the dynamic context of vehicular networks, as well as major standardization advancements, IEEE 802.11p has not yet been deployed in the real world, although there are a few pilot projects [1, 2]. One of the factors hindering its deployment are performance issues related to its scalability, as well as concerns on possible unbounded delay in message transmission [3]. At the same time, researchers and engineers have become interested in the possibility of using the already deployed cellular networks for vehicular applications. LTE (Long-Term Evolution), along with its enhancement LTE-Advanced, are one of the most prominent standards for mobile phones and terminals, providing high data rate, low latency, and a large coverage area. Because of uncertain delays in deploying IEEE 802.11p, LTE appears to be a practical and economical alternative for rapidly deploying certain vehicular applications [4].

Vehicular applications are typically categorized into three groups [5]: safety, traffic efficiency, and infotainment applications. Traffic efficiency applications are designed to reduce travel time and mitigate the effects of traffic congestion. Infotainment applications comprise classical Internet applications, as well as other emerging services. Safety applications seek to reduce the number of road fatalities by establishing some form of communication between neighboring vehicles. According to the ETSI (European Telecommunications Standards Institute), safety application communications may involve two types of messages: event-triggered and periodic messages [6]. The former are generated in response to a hazardous event encountered on the road, and are designed to notify neighboring vehicles of a specific hazard. On the other hand, periodic safety messages, aka cooperative awareness messages or beacons, are regularly broadcast by a vehicle to its neighbors. These messages are typically short, and contain only a small set of measured metrics, such as vehicle location and speed. However, their knowledge can provide vehicles with a better understanding of the other vehicles currently cruising in their environment. In our work, we focus on these types of messages.

When dealing with safety applications, knowing the precise location of surrounding vehicles is obviously a crucial matter. The actual degree of precision depends on three main factors: (i) the accuracy of the measurement revealing the vehicle's coordinates, which largely depends on the quality of the GPS device; (ii) the freshness of the measurement, which amounts to the length of time since the measurement was taken; (iii) the speed of the vehicle whose coordinates were measured. Assuming the GPS device provides accurate measurements, and because the vehicle's speed is determined by a human, we study the only controllable parameter, namely the freshness of the measurement. Clearly, even with no error in the location measurement, the accuracy of a vehicle's location degrades at the same pace as the product: freshness × speed. Hence, regardless of the quality of the GPS measurements, faster vehicles tend to experience larger levels of errors. This unfairness seems rather unsuitable for safety applications. In a more desirable situation, all vehicles would experience similar location precision, with a lack of deterioration in the average location precision of all vehicles.

We propose a solution to efficiently adapt the generation rate of safety messages based on the vehicles' speeds, so as to increase the fairness among the different vehicles. The general idea is simple: decreasing the message generation rate of the vehicles undergoing better location precision, while allowing other vehicles with worse precision to send their measurements at higher rates. However, determining the current location precision for each vehicle is not straightforward. Indeed, it is a function of both the end-to-end delay between the vehicle taking the GPS measurement and the vehicle receiving this data, and the rate at which periodic safety messages are generated. We estimate the location precision of each vehicle using an analytical model that captures the competing access of vehicles to the resources of the LTE network, as specified by the LTE scheduler. The solution to the model returns the rate at which safety messages are transmitted and received based on the current number of vehicles in the LTE cell, and on the rate at which periodic safety messages are generated. Our proposed model is conceptually simple, computationally scalable with the number of vehicles, and in general, delivers accurate results. Together with the GPS measurements and the speed of vehicles, our model provides the missing piece for evaluating the overall precision (or committed error) of the location of neighboring vehicles. Our approach is different from other adaptation techniques as we used an analytical model for predicting the expected performance of the network, while others rely on observed performance metrics such as delay and loss. Moreover, unlike other existing techniques, our solution provides fairness in location accuracy by considering the speed of vehicles in rate adaptation.

Another contribution of this paper is to help the LTE operator determine how many resources from LTE should be allocated, so as to meet some guarantees regarding the location precision experienced by the vehicles. Of course the amount of required resources highly depends on the current number of vehicles and on their speeds. We propose a simple approach for addressing this type of capacity planning issue.

Note that we designed and validated our solutions for LTE-based networks, mostly because LTE is currently the most popular cellular wireless communication standard please add the corresponding reference. LTE-Advanced, which is an enhancement of LTE, brings a number of new interesting features. However, the way LTE and LTE-Advanced share the resources of the communication channel is kept similar. Therefore, we believe that our proposed solutions can be applied without much change to this new version of LTE.

The rest of this paper is organized as follows. Section 2 presents an overview of the related works. The LTE architecture and the necessary steps in the transmission of safety messages are described in Section 3. In Section 4, we detail our solution for adapting the generation rate of safety messages in order to attain fairness in location precision for all vehicles. Section 5 presents a solution for determining the minimum number of required LTE resources to meet a given level of location precision. Section 6 concludes this paper.

2. Related works

Several studies have introduced and discussed the idea of using the cellular network (e.g. LTE) to run safety applications for vehicular networks [7, 8, 9, 10, 11, 12, 13]. A case in point is the technical report [7] that describes a framework for Co-operative Intelligent Transport Systems using mobile cellular networks. The report provides a preliminary performance evaluation of vehicular networks under different cellular network technologies, namely GSM/EDGE, UMTS, and LTE, aka 2G, 3G and 4G. It also includes the performance results obtained by the CoCarX project [10], which is designed to characterize the behavior of vehicular safety applications when they are run with LTE. Overall, the results of [7] demonstrate the feasibility of using LTE to run safety applications in vehicular networks. However, the authors discussed potential performance issues (e.g. long delays) when the total number of vehicles (or the generation rate of safety messages) becomes too large. Hameed and Filali [11] provided a comparative study of LTE and IEEE 802.11p for vehicular networks. Based on their results, the authors concluded that, overall, LTE outperformed the IEEE 802.11p standard, as the former provided greater network capacity and better mobility support. However, they, too, pointed out that the average transmission delay of safety messages could significantly increase if the if the load was at a high level. Finally, Park et al. [14] presented a study demonstrating the feasibility of using smartphones to run vehicular networks. Their experiments, containing measurements about latency and reliability, were made using the LTE network in three different countries. In the same work, the authors also evaluated the scalability of smartphone-based networks using a discrete event simulator [15]. Their results corroborated the aforementioned performance issues, namely the potential for transmission safety messages to be significantly hindered when the total number of transmitting vehicles becomes too large.

Overall, these latter works demonstrated the proof of concept of using LTE to run vehicular networks while discussing potential performance degradation, possibly compromising the behavior of safety applications when the network load is too high.

There are two main approaches for addressing an oversized load resulting from an excess of vehicles willing to access the LTE resources: offloading the network through clustering of vehicles, and adapting the message generation rate.

The main idea behind offloading is to gather neighboring vehicles into clusters, and letting only one vehicle, known as the cluster head, communicate with the LTE base station. Other members of the cluster transmit their messages to the cluster head that is responsible for forwarding them through LTE network. By doing so, the number of vehicles accessing the LTE can be significantly decreased, as the congestion effects. Typically, the communication between the vehicles and the cluster head may be done through IEEE 802.11p, whereas the cluster head forwards the corresponding messages using the LTE network. Several clustering algorithms have been proposed to build these clusters of vehicles [16, 17, 18].

A different approach to taming the effects of network congestion is to adapt the rate at which safety messages are generated in Vehicular Adhoc NETworks (VANETs). Schmidt et al. [19] proposed a situation-adaptive solution, in which the rate safety messages are generated is a function of the vehicle speed as well as the number and speed of vehicles in its surrounding environment. In [20], Wang et al. proposed a centralized method to determine an adequate generating rate of safety messages. Their method is based on a metric combining the current rates of safety packets and the currently observed delay experienced by messages. Feng et al. [21] proposed another solution for adapting the generation rate of safety messages. Basically, their solution monitors network performance, and whenever the performance deterioration exceeds a certain threshold, it adjusts message rates by lowering their values. Liu et al. proposed another similar rate adaptation scheme [22] that mostly depends on the estimated utilization of the cellular network resource by sensing the channel busy ratio. They then adjust the pace of safety messages accordingly. Zemouri et al. [23] proposed another way of discovering an adequate generation rate of safety messages based on a search algorithm. The idea is to iteratively adjust the generation rate in regards to the measured current collision rate and to the channel busy ratio. Finally, Egea-Lopez and Marino modeled the channel congestion with a Network Utility Maximization problem in [24, 25]. They were able to find an algorithm to set the safety message generation rate by solving (the dual of) the NUM problem, using a simple scaled gradient projection algorithm.

Based on our understanding of the state of the art, we believe that our work differs in several aspects from the existing solutions. First, despite the vast number of aforementioned works dealing with adapting the rate of safety messages, they were all designed for the case of vehicular beaconing in Vehicular Adhoc Networks. Their applicability for handling the case of cellular networks such as LTE, which is the matter of interest of our paper, is not clear.

Second, the overwhelming majority of existing solutions, if not all, rely on measurement of some network performance metrics, such as loss ratio, delay, latency and channel busy ratio. These measurements are then used to assess the current level of performance experienced by the network. Typically, if the performance is viewed as too low, it is interpreted as a congestion signal, and the safety message generation rates are lowered accordingly. Obviously, such methods are highly dependent on the availability of measurements, which must be collected, processed, transferred and analyzed. Conversely, in this paper, we propose a much simpler solution that does not need performance measurements. It is based on an analytical model, with the intention of forecasting the expected performance experienced by the safety messages.

Third, our solutions aim at leveling the fairness by providing similar location accuracy to every vehicle given their actual speed. On the contrary, other techniques tend to focus their effort on minimizing the delay (inter-reception time of the messages) so as to improve the overall location accuracy, but they do not consider the fairness explicitly.

Fourth, as far as we know, this work is the first to address the capacity planning issue in the case of an LTE-based vehicular network, i.e., determining the minimum required resources to guarantee a particular level of location precision.

3. LTE principles for transmitting safety messages

We now introduce the LTE principles involved in the transmission of a safety message, from its generation from a source vehicle to its reception by neighboring destination vehicles.

3.1. LTE architecture

LTE is an infrastructure-based network whose architecture consists of two parts: the access network and the core network, illustrated by Figure 1. The access network includes User Equipments (UEs) and base stations, which are referred to as evolved NodeBs (eNBs). On the other hand, the core network, which is typically a classic IP wired network, comprises different types of gateways such as Serving Gateway (SGW) and Packet Data Network Gateway (PGW), as well as a server to process the safety messages. In the case of a vehicular network relying on LTE, the UEs are the vehicles, and safety messages are sent from vehicles up to the server located in the core network before being sent back by eNB to the neighbor vehicles. During their journey, safety messages will experience several delays. However, given the usually oversized core networks, the bottleneck that causes most of the delays is likely to be the access part. Therefore, in our work, we will focus only on the access part in order to evaluate the impact of LTE on the freshness of the measurements of the coordinates.

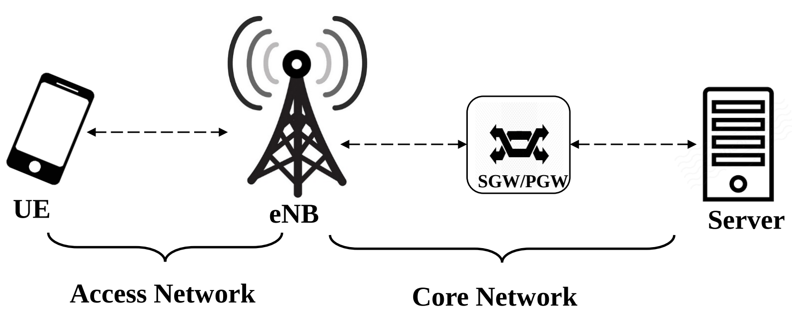


Figure 1: Simplified LTE architecture.

3.2. LTE protocol stack

We now describe the main protocols and components that are involved in the transmission of a safety message from a UE to an eNodeB. At the physical layer, LTE uses the modulation format Orthogonal Frequency-Division Multiplexing (OFDM). In a nutshell, the time domain is divided into 10 ms frames, and each frame consists of 10 slots of 1 ms. In the frequency domain, the total bandwidth is divided into sub-carriers of 15 KHz each. 12 contiguous sub-carriers for a duration of one time slot is called Physical Resource Block (PRB). Figure 2 illustrates a PRB, corresponding to the smallest resource unit, aka element, that can be allocated to a UE.

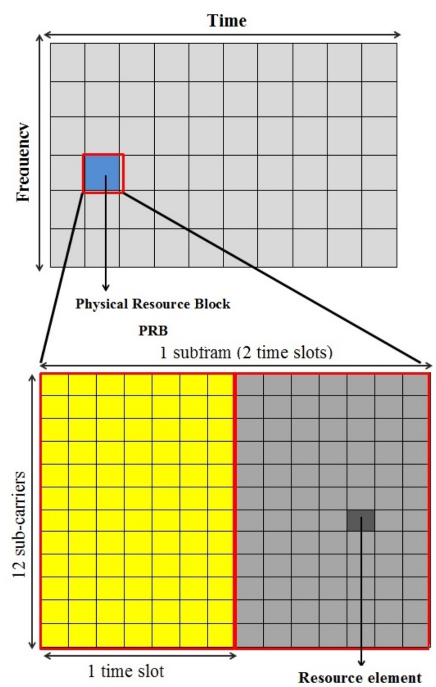


Figure 2: Physical Resource Block (PRB) within LTE.

The main function of the next layer, known as the Medium Access Control level (MAC), is the scheduler. Its goal is to share the available PRBs resources among the current UEs. There are various strategies for assigning the resources, depending on which performance parameters to optimize (e.g. throughput, fairness, QoS). In LTE, the scheduler assignments may take into account several metrics such as the channel condition of each UE, user priority, and other QoS parameters. From a practical viewpoint, unlike other technologies such as IEEE 802.11p, the LTE scheduler is centralized and implemented within the eNBs. The allocation scheme of PRBs is renewed with every Transmission Time Interval (TTI). Finally, above the physical and MAC layers, the protocols Radio Link Control (RLC) and Packet Data Convergence Control (PDCP) are responsible for tasks such as header compression/decompression of IP packets, delivery of upper layer PDUs at lower layers, segmentation, and reassembly, etc.

3.3. Transmitting safety messages

As proposed by [4], the safety message transmissions, illustrated by Figure 3, work as follows. On the uplink side, each vehicle generates periodic safety messages at a given rate. These messages contain the vehicle's current coordinates and speed. Each safety message is then fitted in an IP packet, and passes through the LTE protocol stack. The PDCP and RLC layer headers are added to the packet, and the packet is queued at the MAC layer waiting for a scheduler assignment. Once a PRB has been assigned to the vehicle, the packet is transmitted and received at eNB. Note that because of the very short size of safety messages, we assume that a single PRB is enough to complete their transmission. The packet encapsulating the safety message is then conveyed through the core network until it reaches the appropriate server that processes its content. As for the downlink, the server typically aggregates the data received from multiple vehicles into a single packet, and sends it back to the eNB. The eNB then broadcasts the corresponding message into the cell using the evolved Multicast Broadcast Multimedia Service (eMBMS). As a result, each vehicle within the cell receives the information in its entirety, but retains only the information regarding other vehicles in its vicinity, aka awareness area, filtering other irrelevant information.

As opposed to the downlink transmission, vehicles may have to compete to access LTE resources on the uplink. Therefore, additional delays, due to waiting phenomena, are likely to occur only in this direction. Hence, in our paper, we precisely study the performance attained by the vehicles on the uplink direction of LTE's access network.

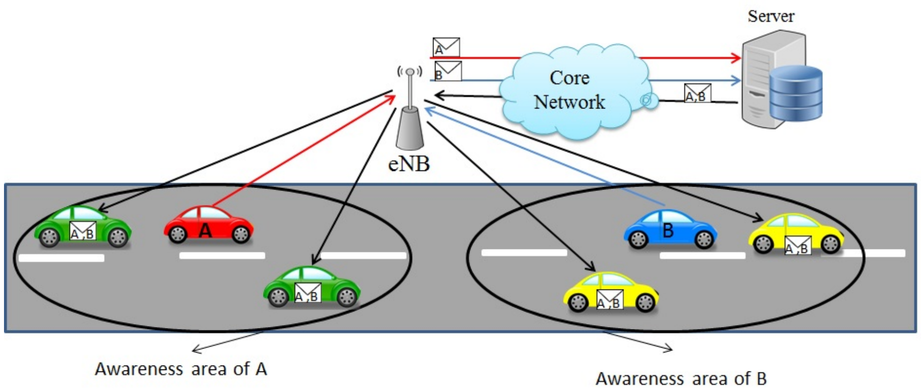
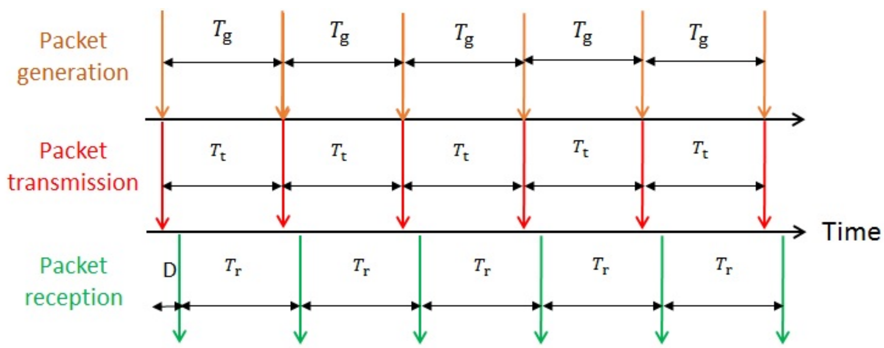


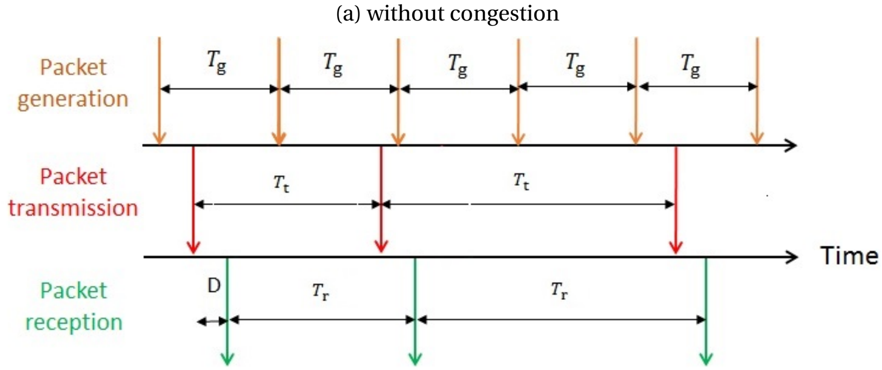
Figure 3: LTE transmission of safety messages.

3.4. Location precision and safety message periods

We now discuss the relations between the generation, transmission, and reception rates of safety messages, and the precision of vehicle location. Let T_{g_i}, T_{t_i} and T_{r_i} denote the corresponding periods for the message generation, transmission, and reception of vehicle i, respectively. Note that, for the sake of simplicity, we temporarily assume that all vehicles generate safety messages at the same rate, so that we can drop the index i. The rate at which safety messages are effectively transmitted over the wireless channel depends on the degree of contention. If there is no congestion, safety messages are scheduled by the eNB at the next TTI immediately after their generation. It follows that T_g and T_t match as shown by Figure 4a (in fact, they may differ at most one TTI). On the other hand, if LTE resources are not enough, some safety messages may have to wait before being assigned to a PRB, and eventually, a packet may be overwritten (dropped) by newer one if its waiting time exceeds T_g. Figure 4b illustrates this situation, in which T_t exceeds T_g. Once safety messages have been transmitted over the access part, they are conveyed through the core network of LTE up to the server. The delay associated with the core network, denoted by D, is typically small and, more importantly, close to deterministic. Under this deterministic assumption, T_t and T_r coincide. Now, from the server point of view, the freshness of information, which contributes the determination of the overall accuracy of the vehicles' coordinates, is a function of both T_r and D. As a reminder, we refer to freshness as the length of time since the measurement was taken. Clearly, from Figure 4, it follows that the freshness value is at least equal to D and is bounded above by $D + T_r$.



(a) without congestion



(b) with congestion

Figure 4: Generation, transmission and reception times.

For any given vehicle, we define the location precision for a given vehicle i as being the distance that the vehicle has traveled since the last measurement at the server disposal was taken. We denote by e_i the location precision of vehicle i. Recall that the freshness of measurements precisely denotes the time period between the measurement generation at the vehicle and the current time at the server. It follows that the location precision of each vehicle i, can be calculated as follows:

$$e_i = (T_{r_i} + D).v_i \quad (1)$$

where v_i is the speed of vehicle i whose value is embedded in the safety messages, and is hence known by the server. Of course, Eq. 1 obeys that the greater the speed of a vehicle, the larger its error on its location and worse location precision.

Assuming that the error on the location for a set of vehicles is deemed too large (or equivalently, their precision is too low), a tempting solution could consist of increasing their safety message rates, i.e. decreasing their generation periods T_g. This simple solution will work as long as the LTE access network is not congested. Otherwise, it may actually worsen the situation, because increasing the safety message rates of vehicles may, in fact, lead to more congestion. Therefore, in the next section, we propose an adaptive solution that increases the message generation rate for some vehicles while reducing it for others, so that vehicles experiencing the worst precision get a better location precision and the overall strain on the network resources is kept to a moderate level.

4. Adapting the generation rate of safety messages

Setting vehicles' safety message rates so that vehicles all experience the same level of location precision is not an easy task. Indeed, if every vehicle generates safety messages at the same rate, then their safety messages should undergo, on average, the same level of freshness. However, because vehicles run at different speeds, they will experience various degrees of precision on their location. This unfairness seems rather unfit for safety applications. A more desirable situation would be that all vehicles undergo the same (good enough) level of precision on their location.

In this section, we propose a solution to adapt generation rates of safety messages, so that each vehicle ultimately experiences a similar degree of precision on their location. However, our solution assumes that the freshness of safety messages are known. Hence, prior to the solution description, we come up with an analytical model to calculate these freshness values.

4.1. Analytical model to approximate the freshness of safety messages

Computing the freshness of safety messages is not a straightforward matter, because they are not a linear function of the aggregated generation rate of safety messages of all vehicles (representing the workload) and of the available LTE resources. To derive their values, we introduce an analytical model that captures the way that safety messages generated by vehicles compete to gain access to the radio channel. We decided to make use of the queueing theory to model the interactions between safety messages. Alternately, Petri nets could be applied, provided that the more complex timed Petri nets are considered in order to take into account the timing.

The model comprises a set of N queues representing the N vehicles, and a set of C servers representing the C PRBs allocated by LTE. Each queue i ($i = 1, \dots, N$) is fed according to the generation rate of the corresponding vehicle i whose period is given by T_{g_i}. For the sake of simplicity, we refer to $\lambda_i = 1/T_{g_i}$ as being the message generation rate at node i. The size of queues is limited to 1, because newer messages overwrite unsent messages. Each server requires exactly one time slot, i.e. 1 ms, to complete the transmission of a safety message. Finally, the C servers (which are shown as $PRB_1, \dots, PRB_C$) are simultaneously exhaust the N queues in a way that is determined by the LTE scheduler. Therefore, we represent the entire system architecture by a polling model, as depicted in Figure 5.

The solution to a polling system has been vastly documented in the literature [26],[27]. However, even under simplifying assumptions (e.g. Poisson arrivals and exponential distributed service times), the exact solutions to polling system remain complex, involving typically numerical Laplace transforms, and become unscalable with a growing number of queues (N here) and of servers (C here) due to the exponential growth in the number of states within the associated Markov chain.

Instead, we propose a simple and approximate solution that relies on the use of servers with vacation [28] to capture the involved interactions between queues and servers. We decompose the original polling system into a set of N separated queueing models with server vacation, as illustrated in Figure 6. Upon its processing by a server, queue i becomes and remains empty until the next message generation, at most T_{g_i}. It may then have to wait until a server serves it again. This waiting time,

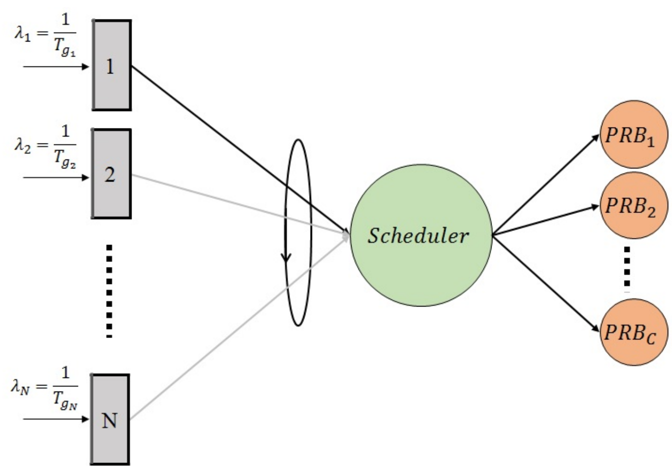


Figure 5: Model of transmission of safety messages through LTE.

corresponding to the processing of packets by servers at other queues, is denoted as the vacation time.

Thus, we are now dealing with N separate queues, each with constant inter-arrivals (aka deterministic), a queueing room restricted to one, constant service times, and a single server that leaves in vacations upon completing message processing. Let T_{v_i} denote the expectation of the duration of a vacation for queue i. We express it as:

$$T_{v_i} = \frac{\sum_{j=1:j\neq i}^{N} p_j^{\text{full}}}{C}.\tau + \tau \tag{2}$$

where p_j^{full} is the probability that queue j has a message to send when one of the C servers arrives, and τ is the duration one PRB, which represents the transmission time of one message and is equal to 1 ms. Note that the first term in Eq. 2 reflects the ratio of the mean number of vehicles that have a message to be sent over the number of servers C, leading to an estimation of the waiting time a message has to be kept before getting processed. The computation of T_{v_i} involves p_i^{full} which can be calculated as follows:

$$p_i^{\text{full}} = \begin{cases} \dfrac{T_{v_i}}{T_{g_i}}, & T_{g_i} > T_{v_i} \\ 1, & T_{g_i} \leq T_{v_i} \end{cases} \tag{3}$$

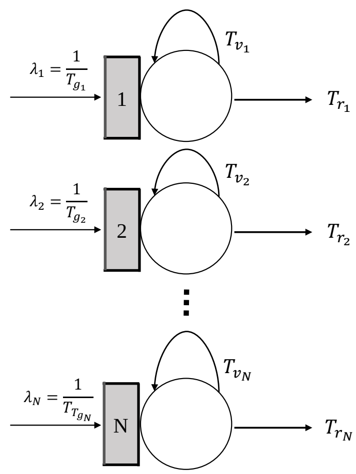


Figure 6: Decomposition of the polling system into N queues with server vacation.

Indeed, if the message generation period of a queue is smaller than its vacation time, i.e. $T_{g_i} \leq T_{v_i}$, then at least one safety message will be generated during the vacation time, and the corresponding queue is sure to be found full when the server will return from its leave. On the other hand, if the message generation period is larger than the vacation time, Eq. 3 simply states that the probability that the queue is found full when the server returns from its leave increases linearly with its generation period.

The time between two successive transmissions for node i can be viewed as a geometric random variable with parameter p_i^{full} re-drawn every T_{v_i} time unit. Therefore, its expectation, i.e. T_{t_i}, can be computed as follows:

$$T_{t_i} = \sum_{n=1}^{\infty} n T_{v_i} (1 - p_i^{\text{full}})^{n-1} p_i^{\text{full}} = \frac{T_{v_i}}{p_i^{\text{full}}} \tag{4}$$

Finally, because we assume that potential delays beyond the LTE uplink are negligible, we have:

$$T_{r_i} \simeq T_{t_i} \tag{5}$$

Note that Eq. 2 (resp. Eq. 3) expresses T_{v_i} (resp. p_i^{full}) as a function of p_j^{full} ($j = 1, \ldots, N : j \neq i$) (resp. T_{v_i}). Therefore, we first resort to a fixed-point iteration to discover the values of T_{v_i}, and then apply Eq. 4 and 5 to obtain T_{r_i} (as shown by Algorithm 1 in Appendix).

We now evaluate the accuracy of the proposed approximate solution in obtaining the mean inter-reception time between 2 successive messages of a vehicle i, i.e. T_{r_i} ($i = 1, \ldots, N$). This validation step is carried out by comparing the results provided by our solution with those delivered by a discrete-event network simulator (NS-3). We set the length of each simulation to 60 seconds and the size of safety messages to 50 Bytes.

To begin with, we consider a scenario with 200 vehicles, categorized into two groups of 100 vehicles each. Vehicles belonging to group 1 (resp. 2) generate safety messages at a period of $T_g = T$ (resp. $T_g = 1.5T$). The number of PRBs available in each time slot is set to $C = 3$. In order to carefully investigate the behavior of our approximation under various levels of workload, we introduce a new parameter, Λ, that represents the total workload of the network. Because each vehicle generates a single safety message every T_{g_i}, Λ can be calculated as:

$$\Lambda = \sum_{i=1}^{N} 1/T_{g_i} \tag{6}$$

Then, we can derive a new parameter, ρ, which is intended to reflect the level of congestion on the LTE resources by normalizing the total workload by the available resources:

$$\rho = \Lambda/C = \left(\sum_{i=1}^{100} 1/T + \sum_{i=101}^{200} 1/1.5T \right) /3 = 55/T \tag{7}$$

We refer to ρ as the normalized workload. Note that a value of ρ less than 1 indicates a network capable of handling the workload, while a value larger than 1 corresponds to an overloaded network.

Figure 7a represents the values of T_{r_i} of Group 1 obtained by our approximate solution and those delivered by the simulator for a wide range of values of T, varying from 25 to 175 ms. Note that the corresponding values of the normalized workload ρ ranges from 0.3 to 2.1. The found results exhibit an interesting pattern. For low values of ρ, the network is far from congested, so increasing ρ (or equivalently the message generation rates of vehicles) results in decreasing the inter-reception time.

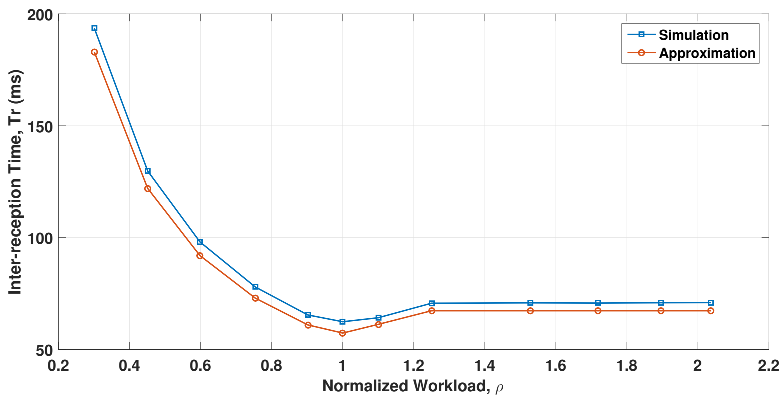
This tendency holds until the tipping point where the network begins to be overloaded due to a workload that is too large. Vehicles must then wait before transmitting their messages, which in turn increases the inter-reception times. Finally, for the highest levels of workloads, in which every vehicle has always a packet waiting to be sent, the inter-reception times come close $\frac{N}{C}\tau$. We observe that the proposed approximation successfully captures the pattern exhibited by T_{r_i}, and furthermore, that its values are very close to those of the simulation.

Figures 7b shows similar results for groups 2. Here, we also notice that the discrepancy between the approximation and the simulation results is small, usually less than 6%.

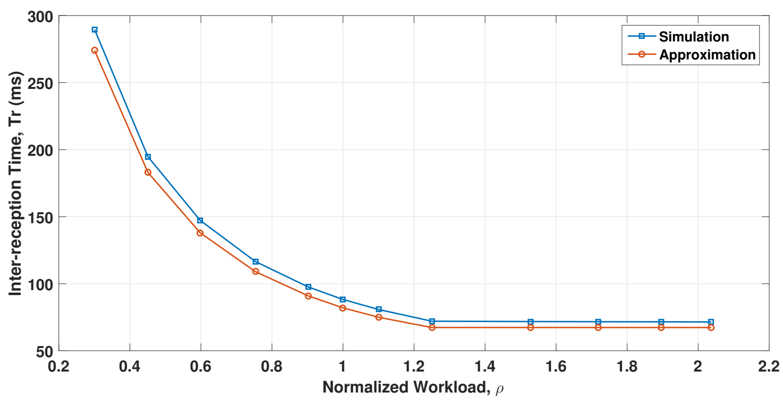
To provide a better outlook on the accuracy of our approximation, we perform hundreds of other scenarios with different values for the number of vehicles, N ranging from 100 to 300, for the number of available PRBs, C between 1 and 6, as well as for the message generation periods of each vehicle, T_{g_i}, randomly selected between 20 and 200 ms. The corresponding results are reported in Table 1. This table indicates that with a total number of 100, 200 and 300 vehicles, and only a single PRB, the maximum error is less than 10%, and the average error is less than 7%. For larger numbers of vehicles, the accuracy of the approximation seems to deteriorate slightly. However, interestingly, its accuracy tends to improve with increasing values of C. For example, considering 300 vehicles, the average error committed by our approximation is close to 7% when there is only 1 PRB, while this average error decreased to less than 5% with 6 PRBs. Finally, it is worth noting that over the hundreds of scenarios that we explored, we never met a case where our approximation committed an error more than 10%.

4.2. Adapting the rates of safety message generation

We now describe the proposed iterative algorithm that the server can run in order to unify the location precision experienced by vehicles moving at different speeds. At each iteration, given the current values of λ_i (recall that $\lambda_i = \frac{1}{T_{g_i}}$), the algorithm determines the corresponding values of T_{r_i} and e_i for all vehicles using the previously described modeling application. The algorithm then calculates the



(a) 1st group generating safety message every $T_g = T$



(b) 2nd group generating safety message every $T_g = 1.5T$

Figure 7: Accuracy of the proposed solution to approximate T_r with N=200 and C=3.

Table 1: Average and maximum errors committed by the proposed approximation over hundreds of examples.

N	C	Average error (%)	Maximum error (%)
100	1	4.3	6.3
200	1	5.4	7.9
300	1	7.1	9.8
100	3	3	5.1
200	3	4.2	6.6
300	3	5.9	8.4
100	6	1.4	2.5
200	6	2	4.3
300	6	4.9	7.6

average location precision computed over all vehicles, i.e. $\overline{e} = \sum_{i=1}^{N} e_i$. Based on these values, the algorithm updates the values of λ_i. It decreases λ_i for vehicles having a lower value of e_i (i.e. better location precision) than the average value of vehicles by a multiplicative factor, α ($\alpha < 1$). On the other hand, it increases λ_i for vehicles experiencing worse precision than the average value by another multiplicative factor, β ($\beta > 1$). Therefore, the new value of the total workload is as follows: $\Lambda = \sum_{i:e_i \leq \overline{e}} (\alpha\lambda_i) + \sum_{i:e_i > \overline{e}} (\beta\lambda_i)$. In order to keep its value constant once the values of λ_i have been updated, it suffices to set a given value for α (e.g. 0.99), and select β so that:

$$\beta = 1 + \frac{(1-\alpha)\sum_{i:e_i \leq \overline{e}} \lambda_i}{\sum_{i:e_i > \overline{e}} \lambda_i} \quad (8)$$

This iteration is repeated until convergence is found, namely when the values of e_i are sufficiently close to $\overline{e}$. Then, the server can request vehicles to modify their generation period of safety messages according to the values of T_{g_i} found at the convergence. Figure 8 depicts the corresponding block diagram, while the associated algorithm is given in the Appendix (see Algorithm 2).

Note that although we have no mathematical proof that our algorithm converges, it never failed to converge within typically several dozens of iterations in the thousands of scenarios (not show in this paper) that we have explored.

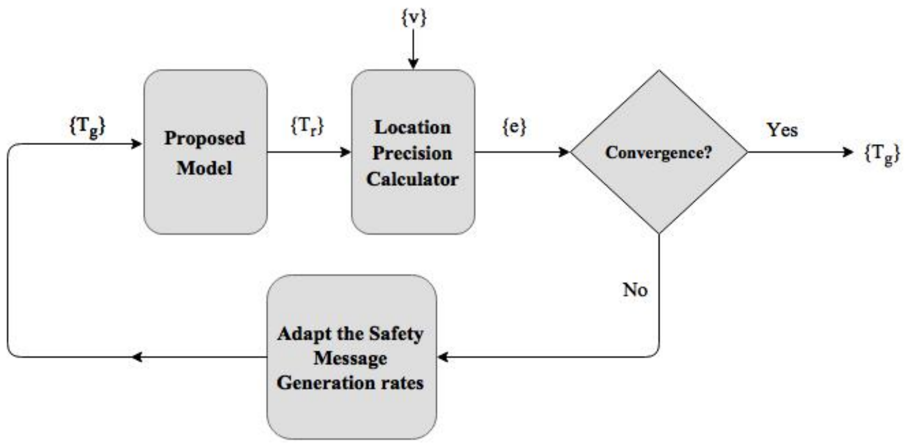


Figure 8: Block diagram for adapting the rates of safety messages.

4.3. Numerical results

In this section, we introduce two scenarios to illustrate the behavior of our proposed solution to adapt the generation rates of safety messages.

In scenario A, we consider a total of $N = 320$ vehicles and $C = 1$ available PRBs per time slot. We categorize the vehicles into four groups, each comprising 80 vehicles, and with a moving speed of 5, 10, 25 and 30 m/s, respectively. We initialize the generation period of safety messages, T_{g_i}, at the same value for all vehicles, and we run our proposed algorithm. Figure 10 shows the corresponding results. It depicts the evolution of the location precision for each group, e_i, as well as the average location precision as a function of the number of iterations. Because all vehicles initially have the same value for T_{g_i}, the values of e_i start with higher values for the fast vehicles than for the slower ones. Initially, the fastest vehicles (group 4) have a location precision close to 10 meters, while that of the slowest vehicles (group 1) are around 2 meters. However, after several dozens of iterations and changes of the generation periods of safety messages, our algorithm ultimately converges to a solution wherein all vehicles, regardless of their speed, share the same level of precision, which is around 5.5 meters.

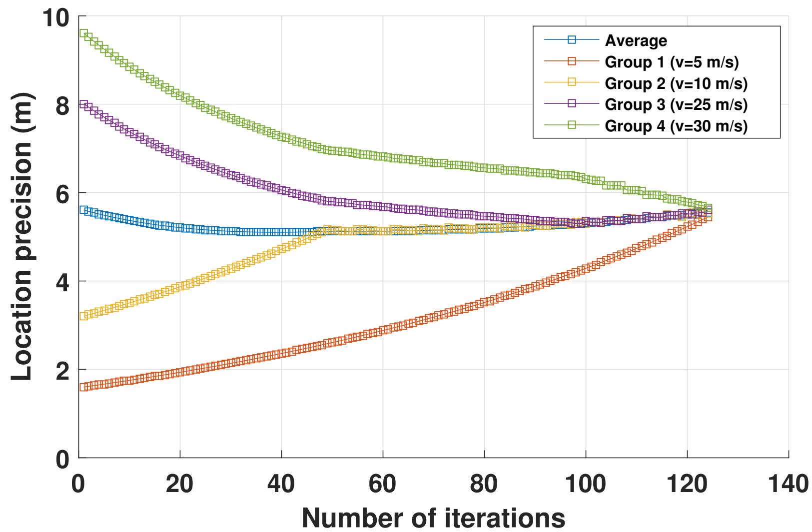


Figure 9: Scenario A: Location precision vs. number of iteration with $N = 320$ vehicles, $C = 1$ PRB.

In scenario B, we consider $N = 250$ vehicles with a total of $C = 2$ PRBs available in each slot. Unlike scenario A, each vehicle has its own speed, which is randomly selected between 5 to 35 m/s. We run our proposed algorithm and represent the found results in Figure 9. We show the average, maximum and minimum location precision of the vehicles. Initially, the worst location precision (which corresponds to the fastest vehicle) is 4.5 meters, while the best location precision (which corresponds to the slowest vehicle) is only 0.5 meters. Once the algorithm is done, the generation periods of safety messages have been modified in a way that all vehicles experience a location precision of around 2.5 meters.

These two scenarios, and many others, demonstrate the ability of our proposed solution to efficiently and automatically set the generation rates of safety messages so that every vehicle undergoes the same level of location precision despite their different speeds. This kind of fairness between vehicles is a nice feature for road security.

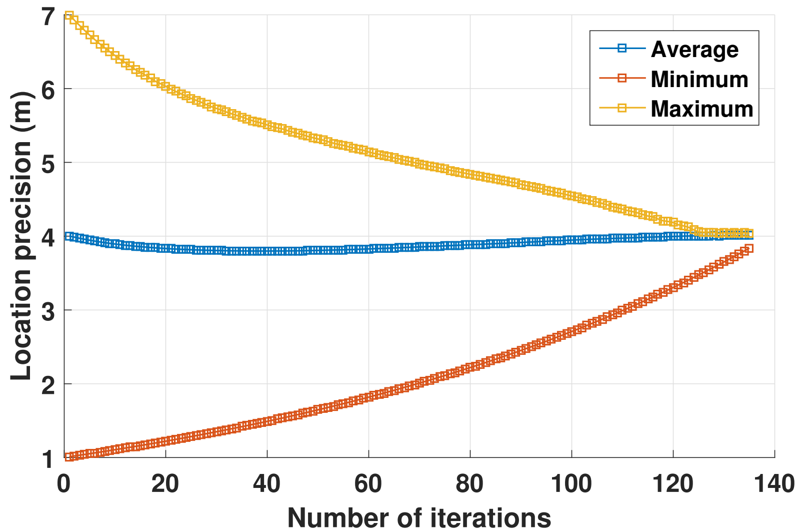


Figure 10: Scenario A: Average, minimum and maximum location precision vs. number of iteration with $N = 250$ vehicles, $C = 2$ PRBs.

5. Sizing the number of PRBs

In the previous section, we addressed the issue of unfairness by proposing an algorithm to let vehicles with different speeds experience the same level of precision on their location by differently tuning their generation rate of safety messages. However, even though all vehicles experience the same location precision, the found solution may be regarded as inadequate. Such a situation is likely to occur in cases with overloaded networks, because the number of allocated PRBs is too low in regard to the aggregated demands of vehicles. On the other hand, it may be possible for a good level of precision to be obtained with fewer PRBs than currently allocated, so that the network could assign more resources for other vehicular applications without affecting the safety message transmissions. More generally, because the number of vehicles and their current speeds are quantities that vary with time, the required number of PRBs is also likely to vary with time. Fortunately, as discussed in Section 3.2, the LTE scheduler is capable of dynamically (de)-allocate PRBs.

In this section, we present a solution for discovering the minimum number of

PRBs needed to meet a given level of precision on the vehicles' location. The proposed solution makes use of the algorithm described in Section 4, and works as follows. Initially, the current numbers of vehicles together with their speed are known. We also determine an objective in terms of location precision (expressed in meters). Starting with a number of PRBs equal to 1, we will iteratively increase the number of allocated PRBs until the solution delivered by message generation adaptation (see Section 4) satisfies the desired location precision. Figure 11 sketches the main step of our algorithm.

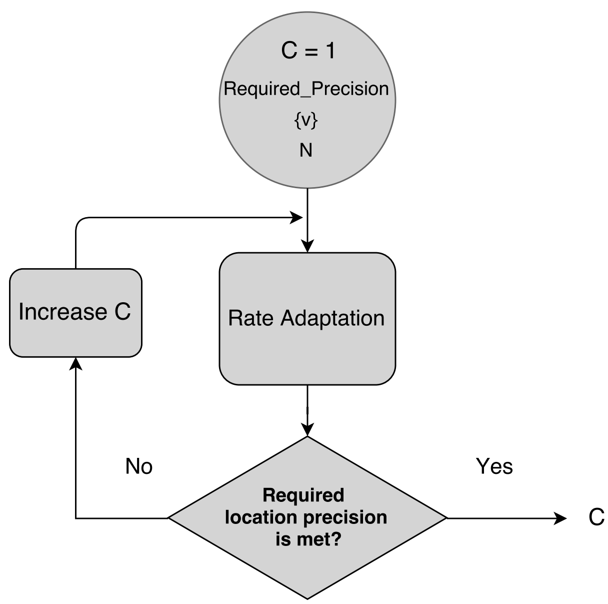


Figure 11: Block diagram for dynamically provisioning LTE resources.

We now present an example that illustrates how to exploit our algorithm. We assume that vehicles are uniformly distributed within 4 groups, with respective speeds of 10, 20, 30 and 40 m/s. We set the objective for the location precision to 1.5 meters. We now run our algorithm to properly size the number of PRBs for 3 different sizes for the vehicle fleet, namely 100, 200 and 300 vehicles. The corresponding results are reported in Figure 12. If the total number of vehicles is around 100, then 2 PRBs are sufficient for providing the desired level of precision. However, for a number of vehicles close to 200, it becomes necessary to provision 4 PRBs and even 6 PRBs if the number of vehicles grows to 300. We also include similar results for a different value of targeted location precision. Not surprisingly, when the location precision is less stringent, the number of needed PRBs is less. Indeed, a total of 1, 2, and 3 PRBs are sufficient for handling a fleet of 100, 200, and 300 vehicles, respectively.

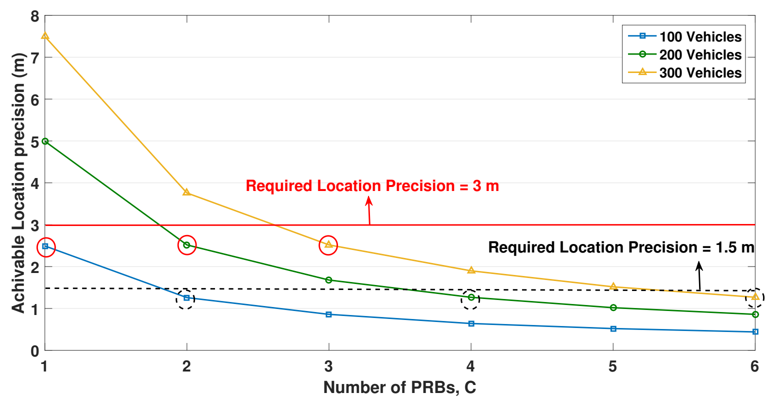


Figure 12: Sizing the number of required PRBs.

Finally, note that because the procedure involves little computational complexity, it can be periodically re-executed to take into account new numbers and speeds of vehicles.

6. Conclusion

Safety applications have an important role to play in forthcoming vehicular networks. They aim to make streets and roads more secure. However, their efficiency is tightly tied to a good and controlled level of precision regarding vehicles' location. Though GPS devices embedded in vehicles provide accurate estimates of current vehicle positions, potential contention on the upload channel of the network and the different speeds of the vehicles make the resulting precision unclear.

In this paper, we consider a situation in which the transmission of safety messages is carried out through LTE. First, we propose an efficient solution for adapting the generation rate of vehicles' safety messages, so that each of them experiences the same level of location precision. This fairness is attained using an analytical model, based on a queueing model that approximates the level of precision for each vehicle based on their motion speed and their generation rate of safety messages. Second, we present a solution for dynamically discovering the minimum number of resources, i.e. PRBs, that should be allocated by LTE, so as to meet a certain level of location precision for all vehicles. Our numerical results show the effectiveness of our two proposed solutions.

Appendix

Algorithm 1 Computing Inter-reception time, T_r

procedure COMPUTE_T_R($\{T_g\}$)
    for each `node i` **do**
        $T_{v_i} \leftarrow \frac{N}{C}\tau$
    end for
    repeat
        for each `node i` **do**
            if $T_{g_i} > T_{v_i}$ **then**
                $P_{\mathrm{i}}^{full} \leftarrow T_{v_i} / T_{g_i}$
            else
                $P_{\mathrm{i}}^{full} \leftarrow 1$
            end if
        end for
        for each `node i` **do**
            $T_{v_i} \leftarrow \tau * \left(1 + \frac{\left(\sum_{j \neq i} p_j^{\mathtt{full}}\right)}{C}\right)$
        end for
    until Convergence
    for each `node i` **do**
        $T_{r_i} \leftarrow \frac{T_{v_i}}{P_i^{full}}$
    end for
    `return(`$\{T_r\}$`)`
end procedure

Algorithm 2 Rate adaptation algorithm

procedure RATE_ADAPTATION($N, \{v\}, C$)
  Initialize α
  $\{T_g\} \leftarrow \frac{N}{C}\tau$
  repeat
    $\{T_r\} \leftarrow COMPUTE\_T\_R(\{T_g\})$
    for each `node i` **do**
      $e_i \leftarrow T_{r_i} * v_i$
    end for
    $\{\lambda\} \leftarrow \frac{1}{T_g}$
    $\beta = 1 + \frac{(1-\alpha)\sum_{i:e_i \le \overline{e}} \lambda_i}{\sum_{i:e_i > \overline{e}} \lambda_i}$
    for each `node i` **do**
      if $e_i \le \overline{e}$ **then**
        $\lambda_i \leftarrow \lambda_i * \alpha$
      else
        $\lambda_i \leftarrow \lambda_i * \beta$
      end if
    end for
  until Convergence
  `return`($\{\lambda\}, \{e\}$)
end procedure

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