A note on the causes degrading communication between RSUs and vehicles in overloaded conditions

Thomas Begin
LIP, CNRS - ENS Lyon - UCB Lyon 1 - Inria 5668
France
DIVA Lab, University of Ottawa
Canada
thomas.begin@ens-lyon.fr

Azzedine Boukerche
DIVA Lab, University of Ottawa
Canada
boukerch@site.uottawa.ca

ABSTRACT

Roadside units (RSUs) are a key component of future Intelligent Transportation Systems. Because of the limited capacity of RSUs, and the short lifespan of the connections initiated by passing-by vehicles, the communication resource should be used with care. In particular, unless there are some form of cooperation between RSUs or vehicles, a vehicle should start transferring its data only if the entire transfer will be complete by the time the vehicle leaves the signal range. Otherwise, not only is it useless, but it actually becomes a nuisance to the other data transfers.

In this paper, we propose a simple high-level modeling to study performance degradation affecting data transfers within an RSU signal range in overloaded conditions. Using a couple of scenarios, we show that the success rate of data transfers tend to be larger when the number of simultaneous transfers is capped at a given value, even though it comes at the expense of an immediate blocking for some transfers.

Keywords

Roadside units; Vehicular networks; Short-term connections; Performance, Modeling.

1. INTRODUCTION

The auto industry is currently undergoing considerable technological changes (e.g., electric engines, driver assistance that will eventually result in complete driverless cars). In this regard, connected cars are a key component for the development of Intelligent Transportation Systems, and they are just around the corner. Roadside units (RSUs) are typically deployed at highway roadsides and ramps, as well as road intersections. They communicate with the vehicles passing by in order to deliver data transfers regarding traffic information, emergency vehicle notifications, digital map downloads, vehicle software upgrades, infotainment, and commercial advertisements. Each RSU serves as an access point for running vehicles.

The short lifespan of the connections, hampering communication between vehicles and RSUs, occurs for two main reasons. First, the high cost for deploying and maintaining the RSUs results in an incomplete spatial coverage. It follows that running cars undergo intermittent connectivity during parts of their journey. Second, given the speed of cars, a vehicle may pass by an RSU within tens of seconds. This offers little time for completing the data transfer. In other words, there is a time deadline for completing the transfer. On the positive side, cars' trajectories are largely predictable, so that the time a running car spends within RSU range before it moves out of the signal range can be forecast.

Because communication capacity is a scarce resource both in space (due to the high cost of an RSU) and time (due to the strong mobility of cars), it should be used with care. Ideally, RSUs should cooperate so that a data transfer partially achieved in an RSU can be resumed and completed in a subsequent RSU down the road. However, the cooperation between RSUs may not be implemented so that incomplete data transfers cannot be resumed. Note that another option could consist in allowing neighboring vehicles to act as packet carriers that attempt to achieve transfer data on behalf of the original source. Although we discussed this promising alternative in the next section, it comes with its own limitations (e.g., privacy, broadcast storm issue). Hence, unless there is a form of cooperation between RSUs or vehicles, a vehicle should start transferring its data only if the entire transfer will be complete by the time the vehicle leaves the signal range. Otherwise, not only is it useless, but it actually becomes a nuisance to the other data transfers issued by vehicles within the same RSU.

In this paper, we point out the hazards of exploiting, without control, RSU communication resources in overloaded conditions. The RSU resource is shared among all running data transfers, but each must be completed within a time deadline; otherwise, the transfer fails and is no longer of use. Using simple high-level modeling, we provide insight into the potential gains resulting from the immediate blocking of data transfers that are unlikely to complete before the corresponding vehicle leaves the RSU signal range.

The remainder of this paper is organized as follows. The next section gives a brief review on the associated literature. Section 3 describes the scenario under interest and the corre-

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sponding analytical model. Numerical results are presented and discussed in Section 4. Section 5 concludes this paper.

2. RELATED WORKS

In this paper, we study the hazards of exploiting, without control, RSU communication resources in overloaded conditions. Although extensive literature exists on performance analysis of vehicular ad hoc networks (VANETs), only a handful of papers have specifically addressed communication performance between an RSU and the vehicles passing by. In what appears to be a pioneering study, Yu and Xu [1] introduced a new metric expressing the amount of data that can be transmitted to a vehicle before it leaves the RSU signal. The authors used this metric instead of a time deadline to formulate an admission control algorithm for IEEE 802.11p based networks as a linear programming problem. Later, Rawashdeh and Mahmud [2] described an admission control and resource allocation algorithm, based on an estimation of the physical expected time for completing the data transfers. For the sake of safety, their estimates include a margin of security. More recently, Bejaoui [3] proposed a new scheme combining a novel scheduling policy and an admission control for VANETs with IEEE 802.11p communications. In the context of vehicle-to-vehicle (V2V) communications, Luan, Shen and Bai [4] developed an analytical framework for IEEE 802.11p to evaluate the likelihood of successful data transfers, based on the mobility statistics of vehicles. Based on its predictions, the authors proposed an admission control scheme that filters data transfers with a low likelihood of accomplishment. Campolo et al. [5] derive closed-form expressions for a couple of metrics related to the transmission of a service announcement message in a multichannel VANETs. The proposed approach takes account of collisions and independent channel-induced bit errors, but does not capture additional delays resulting from queueing effects. These works are primarily focused on the development of methods to avoid the performance degradation occurring in overloaded conditions. To do so, their analysis and solutions are tightly coupled with a set of protocols (e.g., IEEE 802.11p) and assumptions (e.g., vehicle mobility).

More recently, efforts have been made to design vehicular networks that are more scalable and cooperative so that vehicles experience a larger connectivity. This can be particularly useful in situations where the network signal of RSUs is sparse. Vehicular Delay-Tolerant Networks (VDTN) are precisely developed to allow the completion of data transfers over longer periods of time, typically using other vehicles as packet carriers. Indeed, when an end-to-end path is unlikely to exist between a vehicle and the nearest road side unit (RSU), VDTNs allow vehicle-to-vehicle communications so that data packets are gradually forwarded towards the RSU. VDTNs have attracted a lot of attention in recent years. A recent overview of this subject was provided by Pereira et al. in [6]. Because the data packets are conveyed through multihop communications, their delivery delay is more uncertain. Abdrabou and Zhuang propose a mathematical framework to characterize the maximum packet delivery delay [7]. In a separate work, Abdrabou et al. study mathematically the delivery delay and reliability of packets when vehicles can act as packet carrier for others. However, as often pointed out, VDTNs are exposed to the broadcast storm problem (combinatorial growth of duplicated packets). Zhang et al. present a scheme to circumvent this issue [8].

3. SCENARIO AND ANALYTICAL MODEL

Notation

We consider the communications between an RSU and passerby vehicles as illustrated in Fig. 1. We denote with L the communication range of the RSU, with V the average speed of vehicles, and with T the average sojourn time of a vehicle within the RSU communication range. It follows that:

$$T = \frac{2L}{V}.$$

Note that T also stands for the time deadline applying to the data transfers.

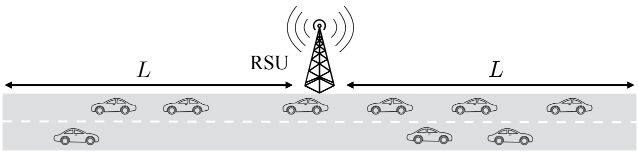


Figure 1: A roadside unit serving multiple by-passing vehicles.

The size of the data transfers issued by the vehicles follows a probability density function with mean μ. We denote by C the actual communication capacity of the RSU that remains following the subtraction of the protocol overheads.

Let λ be the average rate at which the vehicles enter in the RSU signal range. Then, the traffic intensity A is simply given by:

$$A = \lambda.\mu. \tag{1}$$

By denoting with N the average number of vehicles within the RSU signal range, we have:

$$\lambda = \frac{N}{T}. \tag{2}$$

In this paper, we focus primarily on overloaded conditions, which means that the utilization of the communication resource is high. Let U reflect the utilization factor of the resource ($U \in [0, 1]$).

Assuming that all data transfers are completed, we have:

$$U = \frac{A}{C} \tag{3}$$

Combining equations (1), (2) and (3), it follows:

$$\lambda = \frac{U.C}{\mu}. \tag{4}$$

Equation (4) allows us to adequately set the value of λ so as to reflect a degree of congestion on the RSU resource.

Modeling the general performance

We now describe how we model the multiplexing of the existing data transfers, so as to determine wether a transfer will be fully completed before the corresponding vehicle leaves the signal range.

Data transfer scheduling between vehicles and the RSU is primarily ruled by the Media Access Control (MAC) layer used in the architecture. The RSU multiplexes packets (aka frames, time slots, Physical Resource Blocks) from all current data transfers, typically using a variant of FDMA (e.g.,

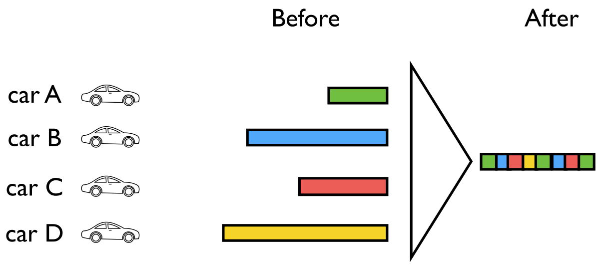


Figure 2: Multiplexing several flows on a single channel.

LTE [9]) or CSMA/CA (e.g., IEEE 802.11p [10]) approaches. Figure 2 illustrates how several data transfers originated by different cars are multiplexed over a single radio channel.

However, from a higher perspective, we may consider that the RSU simultaneously processes multiple data transfers. Hence, we believe that the data transfer processing by the RSU can be modeled as a single-server queue with the processor sharing discipline. Under a processor sharing policy, the requests are all served simultaneously, each receiving an equal fraction of the service capacity available. Fig 3 depicts the proposed model in the event of 6 competing data transfers, each processed by the RSU at the speed of $C/6$. Note that several variants of the service policy have been proposed to account for multiple classes with different priorities, which could correspond to different data rates of transmission. It is worth mentioning that, under Poisson arrivals, the average performance of a single-server queue with processor sharing depends only on the first moment, namely the mean, of the size of the data transfers.

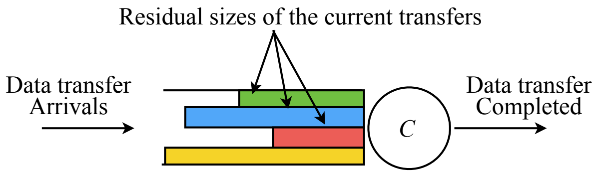


Figure 3: High-level performance modeling of the data transfer times.

The steady-state analysis of a single server queue with processor sharing policy and Poisson arrivals is well documented [11]. The mean sojourn time can be obtained by:

$$\mathbb{E}[R] = \frac{1}{C/\mu - \lambda}.$$

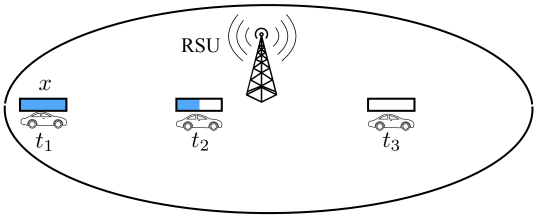
The expected sojourn time of a request of size x, $R(x)$ is given by:

$$R(x) = \frac{x}{C(1-\rho)}, \tag{5}$$

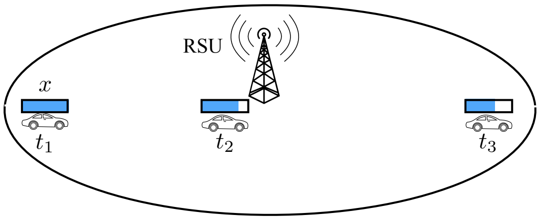
with $\rho = A/C = \lambda.\mu/C$. Equation (5) simply states that the time for transferring data of size x is equal to its processing time as if it had an exclusive access to the RSU resource, x/C, scaled down by an adjustment factor, $1/(1-\rho)$, reflecting the impact of the other competing data transfers.

However, when the total number of data transfers being processed is limited to K, the analysis becomes complex. Hence, we rely on discrete-event simulations to handle the cases limiting the number of simultaneous transfers. For the sake of clarity, we assume that the RSU provides a fair share between the multiple data transfers, so that each data transfer is processed at the same pace (regardless of size, priority, location or any property).

4. NUMERICAL RESULTS



(a) Transfer is completed in time



(b) Transfer is not completed in time

Figure 4: Request of size x is initiated by the vehicle at time t_1. In the above figure, the data transfer is completed by time t_3 and is thus regarded as a success. In the below figure, it is considered as a failure because by time t_3 the data transfer is not yet complete whereas the vehicle is on the brink of leaving the signal range.

We now use our proposed model to study the overall communication behavior between the RSU and the vehicles passing by. Our metric of interest is the proportion of data transfers that meet their time deadline. In our scenarios, a transfer may fail because it is not completed by the time the corresponding vehicle leaves the RSU signal range, or because it is directly blocked by the RSU. Figures 4a and 4b represent an example of success and failure, respectively. The rate of success is computed as follows:

$$\text{Rate of success} = 100 \times \frac{\#\text{ transfers completed in time}}{\text{total }\#\text{ transfers}}.$$

We evaluate this rate for several values of K, including $K = \infty$, which indicates no limit on the total number of data transfers that are processed simultaneously by the RSU.

In our first two scenarios, arrivals occur according to a Poisson process. This assumption allows us to make use of equation (5) to calculate the rate of successful data transfers when there is no restriction on the total number of data transferts queued in the buffer. Modeling arrivals by a Poisson process is a fair choice when arrivals occur one-at-a-time, the probability of an arrival is close to constant and there is little dependence between arrivals. Li et al. studied the mobility of vehicles in Beijing and Shanghai, and they conclude that "the contact rate between vehicles and RSUs exhibits strong Poisson property" [12]. However, in the last scenario, we release the Poisson assumption and resort instead to another distribution for the inter-arrivals.

Scenario 1: a perfect scalability

First, we assume that the multiplexing scheme provides a perfect scalability. In other words, if n denotes the current number of data transfers, each transfer is served at the rate C/n. Table 1 reports the selected values for the parameters. All data transfers are of equal size, μ. Figure 5 shows the corresponding results (solid curve with triangle markers, Δ). We observe that the maximal value for the success rate is attained when the total number of data transfers being processed simultaneously is limited to $K = 10$. The deviation between the peak value and the asymptotic value is close to 10%.

Table 1: Parameters used for Scenarios 1, 2 and 3.

Symbol	Value
L	750 meters
V	30 meters/sec
T	50 sec
μ	1 MB
C	2 Mbps
λ	0.2375 vehicles/sec
N	11.875 vehicles
U	0.95

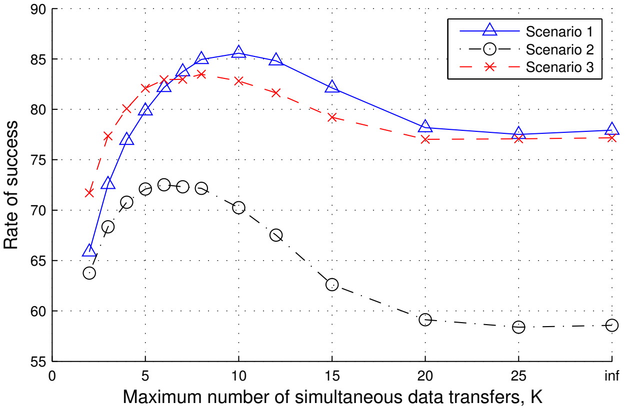


Figure 5: Rate of data transfers successfully completed for different K.

Scenario 2: a workload-dependent contention

In our second scenario, the communication capacity C of the RSU remains equally split between data transfers. However, its efficiency decreases with an increasing number of simultaneous data transfers. We represent this scalability cost by serving each of the n current data transfers at the speed C/n^{α} with $\alpha = 1.1$. Furthermore, the size of the data transfers are drawn from a Pareto distribution with a scale factor of 3 and a mean value kept to 1 MB. The other parameters are set as shown in the former scenario. The corresponding results are reported in Figure 5 (dash-dotted curve with circle markers, $\bigcirc$). Aside from being lower, the found values for the success rate also exhibit a maximal value at a certain value of K. The asymptotic value of the success rate when $K = \infty$ is almost 15% less than the highest discovered value for $K = 7$.

Scenario 3: releasing the Poisson assumption

In our third scenario, the instant of arrivals for data transfers are no more drawn from a Poisson process. Instead, the inter-arrival times follow a Normal distribution with a standard deviation equal to the mean. Note that negative values are unlikely to be drawn, but are automatically set to zero. As for the communication capacity of the RSU, we keep the same setting as in the former scenario with $\alpha = 1.1$. All data transfers are of size μ. The remaining parameters are reported in Table 1. Figure 5 (dotted curve with cross markers, $\times$) depicts the obtained results for the rate of success under these circumstances. While the rate of success peaks when the total number of active data transfers is restricted to 8, this rate is lower if no control is performed.

Similar results were obtained for many other scenarios (not shown in this paper) with other values of L, V, μ, C, λ and N.

Discussion

Through these three scenarios, we observe that the outcome of data transfers competing for the communication resource of an RSU may exhibit a significant performance collapse if the number of simultaneous data transfers is not limited. Indeed, beyond a saturation point an increase of the load (i.e., number of data transfers) leads to a decrease in performance. This overload phenomenon, aka thrashing effect [13], has been first observed by Denning in multiprogramming systems. Since then it has been observed and documented in multiple and various domains, including queueing systems with a service time elongation (e.g., [14]), database systems (e.g., [15]), wired packet-switched networks (e.g., [16, 17]) and CSMA/CA-based wireless networks (e.g., [18, 19, 20]).

5. CONCLUSIONS

Unlike the works cited above, we proposed a simple high-level modeling to study performance degradation affecting data transfers within an RSU signal range. The proposed model does not aim to capture the specific details of a case study, and therefore its use must be restricted to a high-level analysis of the RSU communications. In this regard, it is clearly not applicable to study the performance of a specific case study. However, despite its simplicity, the proposed model captures declining performance in overloaded conditions; because of its simplicity, it clearly identifies the key reasons undermining the rate of successful data transfers.

We present a couple of scenarios that illustrate, using the proposed model, that the success rate of data transfers is generally larger when the number of simultaneous transfers is capped at a given value, even though it comes at the expense of an immediate blocking and failure for some transfers. Therefore, developing and deploying new management policies in the RSUs may significantly improve efficient use of resources. Note that the expected gains may be larger than those of a "simple" threshold on the number of simultaneous transfers, as we performed in this paper.

Finally, we believe that the proposed model may also be useful when prototyping a new solution, such as admission control, to rapidly obtain a glimpse of its performance instead of using a detailed and thorough network simulator, which may be hard to implement, long to run, and misleading to analyze.

Our future works will focus on extending our proposed modeling approach to handle the case where several RSUs cooperate so that incomplete and interrupted data transfers can be resumed and fully completed in subsequent RSUs. New scheduling policies can be developed to decide which data transfer requests must be prioritized in each RSU composing the path of vehicles so that ultimately the overall rate of successful transmissions is improved.

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6. REFERENCES

[1] B. Yu and C.-Z. Xu, "Admission control for roadside unit access in intelligent transportation systems," in *Quality of Service, 2009. IWQoS. 17th International Workshop on.* IEEE, 2009, pp. 1–9.

[2] Z. Y. Rawashdeh and S. M. Mahmud, "Admission control for roadside units based on virtual air-time transmissions," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE.* IEEE, 2011, pp. 1–6.

[3] T. Bejaoui, "QoS-oriented high dynamic resource allocation in vehicular communication networks," *The Scientific World Journal*, vol. 2014, 2014.

[4] T. H. Luan, X. Shen, and F. Bai, "Integrity-oriented content transmission in highway vehicular ad hoc networks," in *INFOCOM, 2013 Proceedings IEEE.* IEEE, 2013, pp. 2562–2570.

[5] C. Campolo, A. Molinaro, A. Vinel, N. Lyamin, and M. Jonsson, "Service discovery and access in vehicle-to-roadside multi-channel VANETs," in *2015 IEEE International Conference on Communication Workshop (ICCW).* IEEE, 2015, pp. 2477–2482.

[6] P. R. Pereira, A. Casaca, J. J. Rodrigues, V. N. Soares, J. Triay, and C. Cervelló-Pastor, "From delay-tolerant networks to vehicular delay-tolerant networks," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4, pp. 1166–1182, 2012.

[7] A. Abdrabou and W. Zhuang, "Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 129–139, 2011.

[8] L. Zhang, B. Hassanabadi, and S. Valaee, "Cooperative forwarding for vehicular networks using positive orthogonal codes," in *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC).* IEEE, 2013, pp. 1935–1940.

[9] C. Lottermann, M. Botsov, P. Fertl, R. Müllner, G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "Lte for vehicular communications," in *Vehicular ad hoc Networks.* Springer, 2015, pp. 457–501.

[10] "IEEE 1609 - Family of Standards for Wireless Access in Vehicular Environments (WAVE)," January 2006.

[11] M. Harchol-Balter, *Performance Modeling and Design of Computer Systems: Queueing Theory in Action.* Cambridge University Press, 2013.

[12] Y. Li, D. Jin, P. Hui, and S. Chen, "Contact-aware data replication in roadside unit aided vehicular delay tolerant networks," *IEEE Transactions on Mobile Computing*, vol. 15, no. 2, pp. 306–321, 2016.

[13] H.-U. Heiss, "Overload effects and their prevention," *Performance evaluation*, vol. 12, no. 4, pp. 219–235, 1991.

[14] J. E. Shore, "The lazy repairman and other models: Performance collapse due to overhead in simple, single-server queuing systems," in *ACM SIGMETRICS Performance Evaluation Review*, vol. 9, no. 2. ACM, 1980, pp. 217–224.

[15] Y. C. Tay, N. Goodman, and R. Suri, "Locking performance in centralized databases," *ACM Transactions on Database Systems (TODS)*, vol. 10, no. 4, pp. 415–462, 1985.

[16] D. Davies, "The control of congestion in packet-switching networks," *IEEE Transactions on Communications*, vol. 20, no. 3, pp. 546–550, 1972.

[17] M. Gerla and L. Kleinrock, "Flow control protocols," in *Computer Network Architectures and Protocols.* Springer, 1989, pp. 273–328.

[18] P. C. Ng and S. C. Liew, "Throughput analysis of IEEE802.11 multi-hop ad hoc networks," *IEEE/ACM Transactions on Networking (ToN)*, vol. 15, no. 2, pp. 309–322, 2007.

[19] S. Razak, V. Kolar, N. B. Abu-Ghazaleh, and K. A. Harras, "How do wireless chains behave?: the impact of mac interactions," in *Proceedings of the 12th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems.* ACM, 2009, pp. 212–220.

[20] T. Abreu, N. Nguyen, T. Begin, I. Guerin-Lassous, and B. Baynat, "Substitution networks: Performance collapse due to overhead in communication times," in *International Conference on Ad Hoc Networks.* Springer, 2012, pp. 1–16.