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Deadline-constrained Bursty Traffic in Random Access Wireless Networks

Nikolaos Nomikos, Nikolaos Pappas, Themistoklis Charalambous, and Yvonne-Anne Pignolet

Abstract—We consider a network of buffer-aided wireless devices having to transmit deadline-constrained data packets on a slotted-ALOHA random-access channel. While retransmission-based communication enhances reliability, the transmission of packets in the queue is delayed and as a result, they might get dropped before they are transmitted successfully. In this work, we study the performance of deadline-constrained bursty traffic with retransmissions providing a Markov chain-based analysis. The aim is to reveal the trade-off between the packet deadline and the number of retransmissions as a function of the arrival rate, and pave the way towards finding the optimal number of retransmissions, given the packet deadline and packet arrival rate. Furthermore, performance evaluation is conducted for a user with varying transmit probability and different number of retransmissions. The results reveal the effect of these parameters on the drop probability and average throughput showing the values under which, improved performance can be obtained.

Index Terms—Packet deadlines, real-time communications, deadline-constrained traffic, queueing, Markov chains.

I. INTRODUCTION

The vision for future wireless communication is that it will become the key enabler of future autonomous systems, be them connected vehicles, smart meters, or automated factories; see, for example, [1]–[3]. The wireless traffic generated by these autonomous devices, which we will refer to as machine-type communication (MTC), will be profoundly different from the wireless traffic supported by current wireless communication systems. In particular, these wireless devices may need to transmit only few bytes of information per packet and will be active only sporadically. Furthermore, a very large number of devices may seek connectivity at any time, and packets will need to be transmitted with extremely stringent requirements in terms of latency and reliability

(mission critical MTC) to enable, *e.g.*, real-time closed-loop control [4].

The proliferation of deadline-constrained information services and multimedia broadcasting over wireless networks, has led to an increasing interest in deadline-constrained broadcasting based on scheduling [5]–[9] and random access [10]–[13]. The rest of the paper concentrates on the related work that considers slotted-ALOHA random access only. The problem of improving the broadcast reliability for the deadline-constrained one-hop broadcasting based on the slotted-Aloha with retransmission was investigated in [11]. Queueing analysis of deadline-constrained broadcasting, but without retransmission was investigated in [12]. However, the analysis of deadline-constrained broadcasting with retransmission has not been analyzed yet.

This work builds on [11] and [12] to analyze the performance of deadline-constrained communication with retransmissions. The first part of the analysis does not consider buffers and it is devoted to the case that a new packet is generated when the transmission of the previous one was successful or that packet was dropped either because it reached the maximum number of allowed retransmissions or it expired. The second part is devoted to stochastic bursty traffic in which buffers are considered, we distinguish two cases: (i) first, the case that a packet can be re-transmitted until it will expire or it will be transmitted successfully. This is similar to [12], but a different Markov chain is constructed that can give the successful transmission probability directly; (ii) second, the case where there is a limited number of retransmissions, less than the deadline. We use a similar construction of the Markov chain and, hence, we analyze the performance of the system. We analyzed the system using Markov chains and numerical and simulations results are included to highlight this trade-off. From the performance evaluation, the impact of varying the transmit probability and the number of retransmissions on the drop probability and the average throughput is illustrated.

The remainder of the paper is structured as follows. In Section II we give the system model considered in this work. In Sections III and IV we provide the analysis for the successful delivery probability when a packet is generated once the previous was either successfully served or dropped and the analysis of the effect of bursty traffic and buffering, respectively. In Section V we provide the numerical and simulation results and, finally, in Section VI we conclude our work and discuss possible future directions.

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II. SYSTEM MODEL

We consider a network of N nodes, all of them in transmission range, sharing the same channel. Each node i may have its intended destination; however, without loss of generality, the results in this work consider the scenario where all the nodes have a common destination. We assume random access of the medium, where each node is transmitting with probability q_i (for simplicity of exposition we assume that q_i is the same for all nodes, *i.e.*, $q_i = q \forall i$). The time is slotted and each packet transmission takes one slot. Acknowledgements/Negative-Acknowledgements (ACK/NACK), are transmitted by the receivers over a separate narrow-band channel, and are assumed to be instantaneous and error free.

We consider the collision channel model with erasures, in which, if more than one nodes attempt to transmit during the same time slot there will be a collision and none of the packets will be received successfully. If only a node transmits at a given time slot, the transmission will be successful with a probability p due to noise, fading, attenuation, SNR threshold, etc., due to the wireless nature of the channel.

In addition, we assume that the packets have deadlines, *i.e.*, when a new packet j is generated, it has a deadline D_j (for simplicity of exposition we assume that D_j is the same for all packets, *i.e.*, $D_j = D \forall j$) and immediately enters the queue (in the bursty traffic case). If the deadline of a packet expires before it reaches its destination, then the packet will be dropped from the network. In this work, we consider two cases regarding the number of retransmissions: (a) the case in which each packet can be retransmitted until it expires (*i.e.*, retransmitted up to $D - 1$ times), and (b) the case in which the number of retransmissions of a packet is n , where $1 \leq n < D - 1$. The retransmissions are needed when the packet does not reach its destination due to either a collision or unsuccessful reception of the packet from the receiver due to the wireless nature of the channel.

The arrival process of packets at a node is assumed to be Bernoulli with an average probability λ . Let μ denote the probability that a packet at the head of the line of the queue of a node will be transmitted successfully to the destination in a given time slot. Then, when $b - 1$ nodes are backlogged where $b \leq N$, μ is given by $\mu = pq(1 - q)^{b-1}$. The transmission from the queue takes place at the beginning of the slot and the arrivals are entering the queue at the end of the slot.

III. ANALYSIS - PART I: SUCCESSFUL DELIVERY PROBABILITY

In this section we consider the analysis regarding the successful delivery probability of a packet that is at the head of the queue. Here, a new packet is generated when the previous one is delivered successfully or it is dropped. Recall that a packet can be dropped either because it is expired or the number of retransmissions reached the allowed number of attempts n . We consider two cases, where $n = 0$ and also the case where $0 < n \leq D - 1$.

When the traffic has deadlines, a relevant metric is the successful delivery probability of a packet, given the packet

is at the head of the buffer, $p_s(n, D)$, which is the probability that a packet will be successfully delivered at the destination before its expiration or before reaching the allowed number of transmissions n .

A. The case where $n = 0$

Here we consider the case where no re-transmissions are allowed. Thus, when the allowed number of attempts m is $m = 1$ (*i.e.*, $m = n + 1$), then $p_s(m, D)$ becomes

$$\begin{aligned} p_s(1, D) &= \mu + (1 - q)\mu + \dots + (1 - q)^{D-1}\mu \\ &= \mu \sum_{k=1}^D (1 - q)^{k-1} = \frac{\mu[1 - (1 - q)^D]}{q}. \end{aligned} \quad (1)$$

Let $\nu \triangleq p(1 - q)^{N-1}$, then $\mu = q\nu$ and (1) becomes

$$p_s(1, D) = q\nu \sum_{k=1}^D (1 - q)^{k-1} = \nu[1 - (1 - q)^D]. \quad (2)$$

B. The case where $0 < n \leq D - 1$

In this part we will derive the successful delivery probability when the number of attempts to transmit a packet is m . Let S denote the event that a packet will be transmitted successfully within the delivery deadline, and let X denote the event of the first transmission attempt. Then, $p_s(m, D)$ is given by [11]

$$p_s(m, D) = \sum_{k=1}^D \mathbb{P}(S, m | X = k) \mathbb{P}(X = k).$$

Therefore, the value of $p_s(m, D)$ can be computed by:

$$\begin{aligned} p_s(m, D) &= q[\nu + (1 - \nu)p_s(m - 1, D - 1)] \\ &\quad + (1 - q)q[\nu + (1 - \nu)p_s(m - 1, D - 2)] \\ &\quad + (1 - q)^2q[\nu + (1 - \nu)p_s(m - 1, D - 3)] \\ &\quad + \dots \\ &\quad + (1 - q)^{D-1}q[\nu + (1 - \nu)p_s(m - 1, 0)] \\ &= \sum_{k=1}^D (1 - q)^{k-1} q[\nu + (1 - \nu)p_s(m - 1, D - k)]. \end{aligned}$$

A closed-form expression for $p_s(m, D)$ cannot be computed, but its value can be computed recursively.

IV. ANALYSIS - PART II: THE EFFECT OF BURSTY TRAFFIC AND BUFFERING

In the previous section, we considered the case that a packet is generated directly after the successful transmission or the drop of the previous one. In this section we go a step further and we consider the effect of bursty traffic and buffering on the performance of the system. More specifically, a packet will be generated in a time slot with a given deadline according to a probability λ and will enter the queue. We focus our analysis by considering a single node; this node has bursty traffic and the rest $N - 1$ nodes are assumed always backlogged, *i.e.*, they always have at least one packet in their queues. This scenario is considered as the worst-case one, since it overestimates the number of

Fig. 1. Markov Chain when the number of retransmissions is $D = 3$, $n = 2$.

transmitting nodes and thus the number of collisions in a time slot. We use a Markov chain model of the system with bursty traffic and the arriving packets are stored in a buffer. We consider two cases, based on the number of allowable retransmissions: first, we consider that each packet can be retransmitted as many times as needed, as long as it is in the system (*i.e.*, number of retransmissions $n = D - 1$); second, we consider that each packet has a limited number of retransmissions (*i.e.*, $n < D - 1$).

A. Number of retransmissions $n = D - 1$

In this case, the number of possible retransmissions is the same with the deadline. For a deadline D , the Markov chain has $D + 1$ states, the states from 0 to D model the passed time. In our constructed Markov chain we include 2 additional *virtual* states (*i.e.*, states S and U) to model the successful and the unsuccessful delivery, respectively. The state S is to capture the success in a packet transmission before its expiration or dropping. The transition probabilities from state S to any other state depends on the state prior to S . The state U , models the case where a packet either expires or it is dropped. An illustrative example of the Markov Chain for deadline $D = 3$ is depicted in Fig. 1.

The transition probability matrix M (column stochastic) for a deadline of $D = 3$ is:

$$M = \begin{bmatrix} 1-\lambda & \mu(1-\lambda) & \mu(1-\lambda)^2 & \mu(1-\lambda)^3 \\ \lambda & \mu\lambda & \mu\lambda(1-\lambda) & \mu\lambda(1-\lambda)^2 \\ 0 & 1-\mu & \mu\lambda & \mu\lambda(1-\lambda) \\ 0 & 0 & 1-\mu & \mu\lambda \end{bmatrix}.$$

B. Number of retransmissions $n < D - 1$

In this case, a packet can be dropped for two reasons: either the number of retransmissions reached the maximum allowed number or the packet expired. The motivation behind limiting the number of retransmissions is to reduce the amount of packets waiting at the queue in order to reduce

Fig. 2. Markov Chain for $D = 3$ when the number of retransmissions is $n = 1$.

the amount of packets that will expire, and hence increase the throughput of the system. For a given deadline D , the Markov chain has $D(n+1)+1-\frac{n(n+1)}{2}$ states and, as before, two additional *virtual* states, which help in the visualization of the successful transmissions. For example, when one retransmission is allowed ($n = 1$), we have $2D$ states (for a deadline of 3, as depicted in Fig. 2, there are 6 states).

Remark 1. The throughput, T , of the system is derived by considering the probability of being at the virtual state S . This is found by finding the states from which a successful transmission can occur. More specifically, the throughput is given by

$$T = \sum_{s \in S} \pi(s)\mu, \quad (3)$$

where $\pi(s)$ is the steady-state of state s in the Markov chain, s is a state of the Markov chain belonging in the set of states S from which a successful transmission can take place. In the case of the Markov chain in Fig. 2, states 1, 2, 0, 2, 1, 3, 0 and 3, 1 belong to set S .

The drop rate (or drop probability), DR , is correspondingly found by considering the states from which a packet might get drop due to the deadlines or lack of retransmissions. More specifically, the drop rate is given by

$$DR = \sum_{i \in \{0, \dots, n\}} \pi(D, i)(1-\mu) + \sum_{f \in \mathcal{F}} \pi(f)(q-\mu), \quad (4)$$

where f is a state of the Markov chain belonging in the set of states $\mathcal{F}$ from which the last unsuccessful transmission of a packet can take place. The states of steady-state $\pi(D, i)$ in the case of the Markov chain in Fig. 2, are 3, 0 and 3, 1. State 2, 1 belongs to set $\mathcal{F}$.

Remark 2. The construction of these Markov chains with the virtual states provides a systematic way of studying the evolution of such complicated systems in which packets may have a limited number of retransmissions.

Fig. 3. Drop probability for various q values for the first Markov chain for which $n = D - 1 = 2$.

Fig. 4. Average throughput for various q values for the first Markov chain for which $n = D - 1 = 2$.

Fig. 5. Drop probability for various q values for the second Markov chain for which $D = 3$ and $n = 1$.

Fig. 6. Average throughput for various q values for the second Markov chain for which $D = 3$ and $n = 1$.

V. SIMULATION AND NUMERICAL RESULTS

In this section, simulation and numerical results are presented for a topology where buffer-aided nodes have buffer size¹ $L = 3$ and the packet deadline is $D = 3$. More specifically, we evaluate the performance of a non-backlogged device in terms of drop rate and average throughput measured in bps/Hz for various values of transmit probability q and number of retransmissions n . It is noted that the number of users in the network is $N = 2$, with one user being non-backlogged and the other one backlogged, *i.e.*, it always has a packet to transmit. Regarding the non-backlogged user, the packet arrival probability is $\lambda = 0.5$.

A. Number of retransmissions $n = D - 1$

The first scenario examines the impact of varying q , while the number of retransmissions is $n = D - 1 = 2$. Fig. 3 depicts the drop rate for varying values of transmit probability q , equal for both users. It can be observed that the drop rate for the non-backlogged user is minimized when $q = 0.5$. For lower q values, the drop rate increases, as the device does not access the wireless channel that is vacant several instances. In such cases, packets remain for more

¹Our analysis does not consider the effect of buffer size, because we assume that the buffer size is at least as big as the deadline of the packets and if the buffer size exceeds the deadline, the packets at the back of the buffer will be never transmitted.

time-slots in the buffer and are dropped due to expiration. Then, for higher q , collisions might occur and the drop rate increases.

Then, Fig. 4 depicts the average throughput performance for various q values. Here, throughput is maximized when $q = 0.5$. As already observed for the drop rate performance, when this q value is adopted, the non-backlogged user improves its throughput, as more packets are successfully transmitted to the destination. More specifically, a $q = 0.5$ optimizes the trade-off between channel access and collisions with the backlogged user.

B. Number of retransmissions $n < D - 1$

For the second scenario, the maximum number of retransmissions is $n = 1$. So, Fig. 5 depicts the drop rate for various q values. Again, a similar trend with the first scenario can be seen. For the non-backlogged user the minimum drop rate is observed when $q = 0.5$. Regarding the impact of n on the drop rate, a slight increase is observed for higher q values, since n is equal to one and packets are more frequently dropped, after a collision.

Finally, Fig. 6 depicts the average throughput performance for varying q . The throughput performance follows closely that of the first scenario. Thus, for $q = 0.5$ maximum throughput is obtained for the non-backlogged user, while for higher q values, the average throughput performance

Fig. 7. Drop probability for various q values for $D = 5$ and $n = 0, 1, 4$.

is marginally degraded. In conclusion, when considering both cases of n , it is observed that the performance of the non-backlogged user is almost identical and the number of retransmissions does not significantly affect the drop rate and the average throughput for a small deadline values and low number of users.

C. Comparisons

In this case, we compare the performance of the system when all the packets have deadline $D = 5$, and additionally, (i) there are no retransmissions ($n = 0$), (ii) there are some retransmissions (in this case $n = 1$), and (iii) there are as many retransmissions as needed ($n = D - 1 = 4$). We observe in both Fig. 7 and Fig. 8 that the performance is improved, when there are more retransmissions. This is expected in this case in which there are no packets with the same or lower deadlines further back in the queue due to the fact that the inflow of packet is low and the deadline is assumed to be the same for all packets.

VI. SUMMARY AND FUTURE DIRECTIONS

In this paper, we considered a network of buffer-aided wireless devices having to transmit deadline-constrained data packets on a slotted-ALOHA random-access channel. We studied how deadline-constrained transmission with retransmissions performs, since the transmission of packets in a queue might get delayed due to retransmissions, and as a result they might get dropped before reaching the head of the queue. The aim of this work is to reveal the trade-off between the packet deadline and the number of retransmissions as a function of the arrival rate. We analyzed the system using Markov chains and numerical and simulation results are included to highlight the effect of varying the transmit probability and the number of retransmissions on the drop probability and the average throughput.

Part of ongoing research is to study the performance of multi-packet reception (MPR) using Direct Sequence Code Division Multiple Access (DS-CDMA), which can be incorporated in order to help improve the performance of the wireless MAC protocol. Such a scheme will allow for multiple simultaneous transmissions that would otherwise lead to a collision.

Fig. 8. Average throughput for various q values for $D = 5$ and $n = 0, 1, 4$.

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