

# Performance Evaluation of Framed Slotted ALOHA with Reservation Packets for M2M Networks

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**Abstract**—In the near future, it is expected that a large number of machine-to-machine (M2M) communication devices will provide with ubiquitous information and services. Random access protocols like ALOHA and CSMA have been considered for M2M networks for their simplicity of operation. This paper evaluates the performance of a Frame Slotted-ALOHA protocol that deploys reservation and data packets (FSA-RDP), in a scenario where a controller node collect data packets transmitted by a finite number of M2M devices. In FSA-RDP, frames of variable length are divided in two parts, the reservation and data subframes. During the reservation subframe, active devices send short reservation packets to the controller. The controller assigns reserved slots in the data subframe to those devices that succeeded with the reservation. Two queue disciplines are considered, the First In First Out - Blocking (FIFO-BL) and the Last In First Out - Push-Out (LIFO-PO). We develop a discrete-time Markov chain to derive the protocol efficiency. For the FSA-RDP protocol, we also derive the cumulative distribution function of the delay for data packets that are successfully transmitted, when deploying both queue disciplines. Numerical results show that the protocol efficiency of FSA-RDP is between one and two orders of magnitude larger than the efficiency of the conventional Frame Slotted ALOHA. In addition, we show that the difference between the packet delay for FIFO-BL and LIFO-PO is only significant in scenarios with high load and high collision rate.

## I. INTRODUCTION

A fundamental part of the Internet of Things (IoT) is the concept of machine-to-machine (M2M) communications, that allows the autonomous exchange of data between a large population of devices [1]. The rapid increase in the number of M2M devices deployed brings serious design challenges. One of these challenges is the efficiency of the Medium Access Control (MAC). The operation simplicity of random access protocols, such as ALOHA or Carrier Sense Multiple Access (CSMA), makes them a good choice for M2M communications.

Since the seminal work of the ALOHA protocol [2], and its slotted version S-ALOHA [3], many different extensions to the original protocol have been proposed. It is worth mentioning the Frame Slotted-ALOHA (FSA), studied in detail in [4], [5]. Due to its simplicity of implementation, Frame Slotted-ALOHA (FSA) has been proposed as the access protocol in several systems such as Radio Frequency IDentification (RFID) [6] and M2M communications [7].

A common operation feature in many of these proposals is that FSA is used to transmit only data packets. However, when a collision occurs the entire data slot is lost. A more efficient

approach is to deploy short reservation packets (RVP) during the contention part, and allocate reserved data slots for those devices that succeeded with the reservation. In this way, when RVP collide, only reservation mini-slots are lost, instead of the more valuable data slots. We call this protocol FSA with reservation and data packets (FSA-RDP).

FSA-RDP is different to other ALOHA reservation protocols like Reservation-FSA (RFSA) [8]. RFSA was proposed for scenarios where nodes have to transmit long messages, that are divided into shorter packets. The contention is solved using packet (data) slots. Once a device successfully sends the first packet of the message, the controller reserves a data slot in subsequent frames for the transmission of the rest of the packets that compose the message. Therefore, FSA-RDP could also be used to improve the performance of RFSA.

The FSA-RDP protocol has been studied in [9] by simulation. However, the main contribution of this paper is the analytical performance analysis of the FSA-RDP protocol. We develop a discrete-time Markov chain (DTMC) to determine the packet delay distribution. We consider two queue disciplines for the M2M devices, the First In First Out - Blocking (FIFO-BL) and the Last In First Out - Push-Out (LIFO-PO) [10]. When a data packet arrives to a M2M device with a full buffer, it is lost when deploying FIFO-BL. However, when LIFO-PO is deployed, the arrival of a new data packet pushes-out the data packet stored at the head of the full buffer.

The paper is organized as follows. After the introduction, Section II describes the system under study and introduces the DTMC that defines the evolution of the number of active devices with time. In Section III the probability generating functions of the delay distribution for successfully transmitted packets are derived, both for the FIFO-BL and LIFO-PO queue disciplines. In Section IV two performance parameters are evaluated in a reference scenario, the protocol efficiency and the cumulative distribution function of the packet delay. The conclusions of the study are described in Section V.

## II. SYSTEM MODEL

### A. Protocol Operation

We consider a wireless network composed by a controller (gateway) and a finite number of  $M$  devices forming a star topology. Each device, operates independently and generates data packets (DAP) of constant length as a consequence of its activity. In FSA-RDP time is slotted, and the frames are of

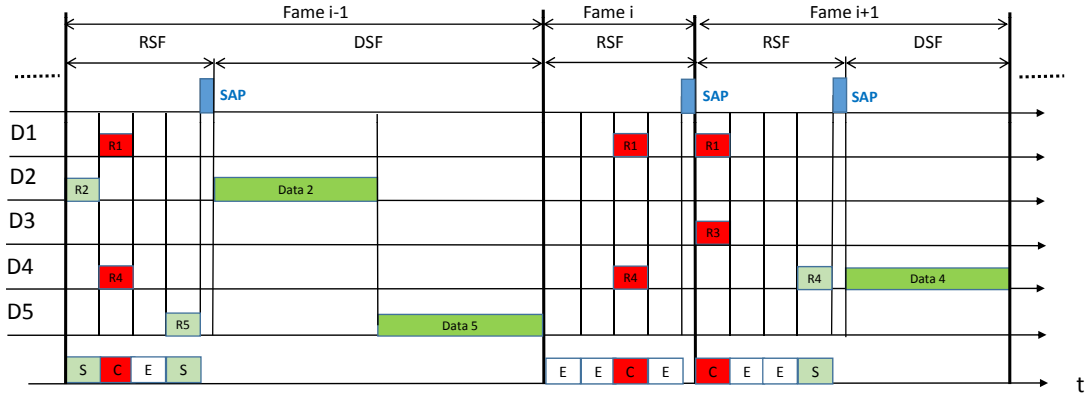


Fig. 1: Example of the operation of the FSA-RDP protocol.

variable length. Each frame is composed by two subframes, the reservation sub-frame (RSF) and the data transmission sub-frame (DSF). In the RSF, active devices (with packets in their queues) contend for the transmission of RVP to the controller. At the end of the RSF, the controller broadcasts a slot allocation packet (SAP) that contains the data slots allocated to those devices that succeeded with the reservation. Following the SAP, the successful device initiates the transmission of DAP in the reserved data slots, i.e., in a contention free manner.

Figure 1 describes an example of the operation of FSA-RDP, where  $M = 5$ . At frame  $i-1$  four M2M devices contend for access sending their respective RVP during the RSF. Two devices succeed, while other two collide. At the end of the RSF, the controller broadcasts the SAP to allocate data slots to the successful devices. Then, devices 2 and 5 send their DAP during the DSF. At frame  $i$ , devices 1 and 4 collide again. Then, the controller broadcasts the SAP informing that the DSF is omitted in this frame.

### B. Network Model

Let  $V$  be the number of reservation mini-slots in the RSF. It can be shown that the best performance is obtained when  $V$  coincides with the number of contenders in each frame. We consider a fixed value for  $V$ , but we introduce an access permission probability  $r$ . At each frame, active devices send a RVP with probability  $r$ . For model tractability, we assume a fixed value for  $r$ . However,  $r$  can be adjusted by the controller according to the observed outcomes of the previous RSF. The adaptive algorithm is left for further study.

Let  $i$  be the number of active devices at the beginning of a frame. Then, the probability that  $j$  of them,  $j \leq i \leq M$ , transmit a RVP follows a binomial distribution, and denote it as  $B_j^i(r)$ . Note that a device chooses any of the  $V$  mini-slots to transmit the RVP with equal probability ( $1/V$ ).

Let  $S(j, k, V)$  denote the probability that  $k$  among  $j$  contending devices succeed with the reservation. It can be

obtained recursively as,

$$S(m, k, V) = \begin{cases} \sum_{j=0, \neq 1}^m B_j^m(1/V) S(m-j, k, V-1) & k = 0. \\ B_1^m(1/V) S(m-j, k-1, V-1) \\ + \sum_{j=0, \neq 1}^{m-k} B_j^m(1/V) S(m-j, k, V-1) & k = 1, \dots, V. \end{cases} \quad (1)$$

Also, let  $D_k^i(r, V)$  denote the probability that  $k$  devices succeed in a frame with  $i$  active devices,  $0 \leq k \leq j \leq i$ ,

$$D_k^i(r, V) = \sum_{j=k}^i B_j^i(r) S(j, k, V) = \sum_{j=k}^i B_j^i(r) S_k^j(V). \quad (2)$$

We assume that devices have a buffer with capacity for a single packet, that is managed according to the corresponding queue discipline (FIFO-BL, LIFO-PO). Packet arrivals to the buffer follow a Poisson process with rate  $\lambda$  packets per mini-slot.

The evolution of the number of active devices observed at the beginning of each RSF can be modeled as a DTMC. Let  $\{P_{i,j}\}$  denote the transition probabilities of the DTMC, i.e., the probability of  $j$  active devices in the next frame, conditioned on  $i$  active ones in the current frame. They are given by,

$$P_{ij} = \sum_{k=\max(0, i-j)}^{\min(i, V)} D_k^i(r, V) A_{j-i+k}^{M-i+k}(a_k) \quad (3)$$

where  $A_u^s(a_k)$  is the probability that  $u$  devices become active out of  $s$  inactive in a frame with  $k$  successful reservations, that follows a binomial distribution. For Poisson arrivals, it follows a binomial distribution, where  $a_k = 1 - e^{-\lambda t_k}$ , and  $t_k = V + kW$ ,  $0 \leq k \leq V$ . Then,  $a_k$  is the probability that a data packet arrives to a device during the frame,  $t_k$  is the duration of the frame in mini-slots,  $W$  is the duration of a data slot in mini-slots, and  $k$  is number of successful reservations in the frame. Note that with FIFO-BL packet arrivals along

a frame are transferred to the (transmission) buffer as soon as the current data packet in the buffer (if any) leaves the device, or the end of the frame occurs. In the later case, the new packet is dropped. However, with LIFO-PO a new packet, upon arrival, pushes-out the packet in the buffer (if any). The transmission of a SAP by the controller requires a single mini-slot. For simplicity, this constant delay term has been omitted. For convenience, we define  $\delta = e^{-\lambda}$ . Then,  $a_k = 1 - \delta^{(V+kW)}$ . Finally, note that the definition of  $t_k$  allows the model to determine the delay of data packet at the granularity of a mini-slot.

Let  $\pi_i$  denote the stationary probability of finding  $i$  active devices in a frame. The stationary probabilities  $\boldsymbol{\pi} = [\pi_0, \pi_1, \dots, \pi_M]$  are obtained by solving the system of linear equations  $\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P}$  with the normalization condition of  $\boldsymbol{\pi}\mathbf{e} = 1$ , where  $\mathbf{e}$  is a column vector of 1s. Let  $f_k$  be the fraction of frames which duration is equal to  $t_k = V + kW$ . It is given by  $f_k = \sum_{n=k}^M \pi_n D_k^n$ . Then, the carried data packet rate per mini-slot can be evaluated as,

$$\gamma = \sum_{k=0}^V k f_k / \sum_{k=0}^V t_k f_k. \quad (4)$$

### III. DATA PACKET DELAY DISTRIBUTION

We derive the delay distribution of successfully transmitted data packet under the FIFO-BL and LIFO-PO disciplines. Those distributions follow a Phase-type (PH) distribution, represented as  $(\boldsymbol{\alpha}, \mathbf{T}, \mathbf{T}^0)$ , [11], [12], where  $\boldsymbol{\alpha}$  defines the probabilities that the absorbing process is initiated at each of its transient states,  $\mathbf{T}$  defines the transition probabilities between transient states, and  $\mathbf{T}^0 = \mathbf{e} - \mathbf{T}\mathbf{e}$  is a column vector that defines the transition probabilities from transient states to the absorbing state. For the FIFO-BL and LIFO-PO disciplines we denote them as  $(\boldsymbol{\alpha}_F, \mathbf{T}_F, \mathbf{T}_F^0)$ , and  $(\boldsymbol{\alpha}_L, \mathbf{T}_L, \mathbf{T}_L^0)$ . We derive them below.

#### A. Initial states for FIFO-BL and LIFO-PO disciplines

We select an arbitrary device and refer to it as the tagged device. At the beginning of an arbitrary frame  $n$ ,  $k$  devices are active, and the tagged device might be active or inactive. Assume a new data packet arrives to the tagged device along frame  $n$ , we refer to it as the tagged packet. Then, the tagged device will contend for access in the following frame  $n+1$ . We consider three possible cases:

1) *Case A*: At the beginning of frame  $n$  the tagged device is not active, i.e., it is not among the  $k$  active ones. This occurs with probability  $(M-k)/M$ . The probability (fraction of frames) of finding  $j$  active devices other than the tagged one in frame  $n+1$ ,  $0 \leq j \leq M' = M-1$ , when frame  $n$  is of duration  $t_m$ , is given by

$$P_A(M, m, j) = \sum_{k=m}^M \pi_k \frac{M-k}{M} D_m^k(r, V) A_{j-k+m}^{M'-k+m}(a_m) \quad (5)$$

When the duration of frame  $n$  is  $t_m$ , consider the random variable mini-slot number in this frame where the tagged

packet arrives. Then, the probability generating functions (pgf) of this arrival distribution for the FIFO-BL or LIFO-PO disciplines is given by

$$F_m(z) = \sum_{n=0}^{V+mW-1} (1-\delta) \delta^{V+mW-1-n} z^n \quad (6)$$

$$L_m(z) = \sum_{n=0}^{V+mW-1} (1-\delta) \delta^n z^n \quad (7)$$

Consider now the random variable mini-slot number in a frame of arbitrary duration where the tagged packet arrives, conditioned on the fact that the arrival happens and the tagged device contends with other  $j$  active devices in the next frame. Then, its pgf is given by

$$P_{A,X}(M, j, z) = (1/G_a) \sum_{m=0}^V X_m(z) P_A(M, m, j) \quad (8)$$

where  $G_a = \sum_{n=0}^V a_n f_n$ , and  $X_m(z) = F_m(z), L_m(z)$ , for FIFO-BL or LIFO-PO disciplines, respectively. Note that  $a_m/G_a$  is the probability that the tagged packet arrives in a frame of duration  $t_m$ , conditioned on the fact that the arrival happens. In (8), the term  $X_m(z)$  accounts for the probabilities of the packet arriving at any mini-slot of the frame. It can be shown that  $a_m = F_m(1) = L_m(1)$ .

2) *Case B*: At the beginning of the frame  $n$  the tagged device is active, i.e. it is one of the  $k$  active devices. This situation occurs with probability  $k/M$ . Assuming that  $m$  out of  $k$  devices succeed with the reservation, the tagged device succeeds with probability  $m/k$ . Then, the tagged packet arrives to the buffer as soon as the current packet in the buffer is transferred. The probability that the tagged device will compete in the next frame, frame  $n+1$  with other  $j$  active devices,  $0 \leq j \leq M' = M-1$  is given by,

$$P_B(M, m, j) = \sum_{k=m}^M \pi_k \frac{m}{M} D_m^k(r, V) A_{j-k+m}^{M'-k+m}(a_m). \quad (9)$$

As in (8), weighting the expression (9) we get,

$$P_{B,X}(M, j, z) = (1/G_a) \sum_{m=0}^V X_m(z) P_B(M, m, j) \quad (10)$$

3) *Case C*: This case complements the *Case B*, where we assumed that the tagged device was active. Here we assume that the tagged device does not succeed with the reservation. This occurs with probability  $(k-m)/k$ . Then, the tagged data packet that arrives along frame  $n$  will be lost with FIFO-BL discipline (as buffer is full), but admitted with LIFO-PO discipline (as it pushes-out the packet at the buffer). In the later case, the probability that the tagged packet contends with other  $j$  active devices, in the next frame  $n+1$ ,  $0 \leq j \leq M' = M-1$  is given by,

$$P_C(M, m, j) = \sum_{k=m}^M \pi_k \frac{k-m}{M} D_m^k(r, V) A_{j-k+m+1}^{M-k+m}(a_m). \quad (11)$$

Also, as in (8) and (10), weighting the expression (11) we get,

$$P_{C,L}(M, j, z) = (1/G_a) \sum_{m=0}^V X_L(z) P_C(M, m, j) \quad (12)$$

Finally, the initial probability vectors for the PH distributions follows from (8), (10) and (12). For FIFLO-BL we have,  $\alpha_F(z) = [\alpha_{F,0}(z), \dots, \alpha_{F,M'}(z)]$ , and for LIFO-PO discipline,  $\alpha_L(z) = [\alpha_{L,0}(z), \dots, \alpha_{L,M'}(z)]$ , where

$$\begin{aligned} \alpha_{F,j}(z) &= P_{A,F}(M, j, z) + P_{B,F}(M, j, z), \\ \alpha_{L,j}(z) &= P_{A,L}(M, j, z) + P_{B,L}(M, j, z) + P_{C,L}(M, j, z). \end{aligned}$$

Note that  $\alpha_F(1)$  is a sub-stochastic vector,  $\alpha_F(1)\mathbf{e} < 1$ , while  $\alpha_L(1)$  is a stochastic vector,  $\alpha_L(1)\mathbf{e} = 1$ .

#### B. Matrix $\mathbf{T}_F | \mathbf{T}_F^0$ for FIFO-BL discipline

Let  $T_{F,k;i,j}$  be the probability that the tagged device contends with other  $i$  active devices in a frame,  $k$  devices succeed with the reservation, but the tagged device does not succeed, and contends in the next frame with  $j$  other active devices. Then,

$$\begin{aligned} T_{F,k;i,j} &= (1 - \frac{C_{k-1}^i}{C_k^{i+1}}) D_k^{i+1}(r, V) A_{k-i+j}^{M-i-1+k}(a_k) \\ &= (1 - \frac{k}{i+1}) D_k^{i+1}(r, V) A_{k-i+j}^{M-i-1+k}(a_k) \end{aligned} \quad (13)$$

where  $C_j^i = \binom{i}{j}$ , In matrix notation and in terms of the pgf we have,

$$\mathbf{T}_F(z) = \sum_{k=0}^V \mathbf{T}_{F,k} z^{(V+kW)}. \quad (14)$$

Let  $T_{F,k;i}^0$  be the probability that the tagged device contends with other  $i$  active devices in a frame,  $k$  devices succeed with the reservation, and the tagged device is one of them. It is given by,

$$T_{F,k;i}^0 = \frac{C_{k-1}^i}{C_k^{i+1}} D_k^{i+1}(r, V) = \frac{k}{i+1} D_k^{i+1}(r, V). \quad (15)$$

Then, let  $\mathbf{T}_{F,k}^0$  denote the column vector with elements given by (15). Again, in matrix notation and in terms of the generating functions, we have the following column vectors,

$$\mathbf{T}_F^0(z) = \sum_{k=0}^V \mathbf{T}_{F,k}^0 z^{(V+kW)}. \quad (16)$$

#### C. Matrix $\mathbf{T}_L | \mathbf{T}_L^0$ for LIFO-PO discipline

Let  $T_{L,k;i,j}$  be defined as (13) but with the additional condition that no packets will arrive to the tagged device during a frame of duration  $t_k$ . Then,

$$T_{L,k;i,j} = (1 - a_k) T_{F,k;i,j}. \quad (17)$$

Then, let  $\mathbf{T}_{L,k}$  denote a matrix with elements given by (17). In matrix notation and in terms of the generating functions, we have,

$$\mathbf{T}_L(z) = \sum_{k=0}^V \mathbf{T}_{L,k} z^{(V+kW)} = \sum_{k=0}^V (1 - a_k) \mathbf{T}_{F,k} z^{(V+kW)}. \quad (18)$$

The tagged packet is pushed-out in a frame of duration  $t_k$  with probability  $a_k \sum_{j=0}^{M'} T_{F,k;i,j} = a_k T_{F,k;i}$ , which is the complementary to expression (17). Then,

$$T_{L,k;i}^0 = T_{F,k;i}^0 + a_k T_{F,k;i}, \quad (19)$$

as the absorption occurs when the tagged packet is transmitted or when it is pushed-out. However, we are only interested in finding the delay for packets that are finally transmitted. The, the pgf of the absorption vector is given by,

$$\mathbf{T}_L^0(z) = \mathbf{T}_F^0(z). \quad (20)$$

#### D. Data Packet Delay Distributions

The pgf of the delay distribution of transmitted packets for FIFO-BL and LIFO-PO are given by,

$$R_F(z) = \alpha_F(z) [\mathbf{I} + \mathbf{T}_F(z) + \mathbf{T}_F^2(z) + \dots] \mathbf{T}_F^0(z) \quad (21)$$

$$= \alpha_F(z) [\mathbf{I} - \mathbf{T}_F(z)]^{-1} \mathbf{T}_F^0(z),$$

$$R_L(z) = \alpha_L(z) [\mathbf{I} + \mathbf{T}_L(z) + \mathbf{T}_L^2(z) + \dots] \mathbf{T}_L^0(z) \quad (22)$$

$$= \alpha_L(z) [\mathbf{I} - \mathbf{T}_L(z)]^{-1} \mathbf{T}_L^0(z).$$

where  $\mathbf{T}_L^0(z) = \mathbf{T}_F^0(z)$  for served packets. Note that  $R_F(1) < 1$  and  $R_L(1) < 1$ , as neither rejected nor pushed-out packets are accounted for.

## IV. NUMERICAL RESULTS

Two performance parameters are studied, the protocol efficiency and the cumulative distribution function of the packet delay time for packets that are successfully transmitted to the controller. The packet delay is the time elapsed since the packet arrival to departure (when is transmitted).

We measure the protocol efficiency in terms of the data packet loss probability,  $P_L$ . According to (4), it is given by,

$$P_L = 1 - \frac{\gamma}{M\lambda}. \quad (23)$$

Note that for both queue disciplines, the fraction of new packets that are lost is the same.

We define a reference scenario where  $M = 8$  and  $W = 10$ . Also, we define the total traffic load as  $\rho_T = M\rho_i$ , where  $\rho_i = \lambda W$ , is the load of device  $i$ . Three traffic loads are considered: i) low,  $\rho_T = 0.3$ ; ii) medium,  $\rho_T = 0.5$ ; and iii) high,  $\rho_T = 0.8$ .

#### A. Efficiency of the FSA-RDP protocol

We compare three protocols: i) FSA; ii) FSA-RDP; and iii) ideal FSA-RDP (FSA-RDP-I). In FSA the contention occurs in data slots, while in FSA-RDP occurs in reservation mini-slots. In FSA-RDP-I there is no contention. It is assumed that the controller knows the state of the devices at the beginning of a

frame, and it sends the SAP without the need for contention. In order to perform a fair comparison, the frame structure for FSA-RDP-I is the same as the one defined for FSA-RDP in Fig. 1. That is, it is composed also by the RSF and DSF, and the maximum number of packets that can be transferred during the DSF is  $V$ . Note that the performance of FSA-RDP is upper bounded by the performance of FSA-RDP-I.

The model for FSA-RDP-I is the same as the one developed for FSA-RDP, except that the permission probability is set to  $r = 1$ , and  $D_k^i(1, V)$  is now defined as,

$$D_k^i(1, V) = \begin{cases} 1 & i \leq V, k = i, \\ 1 & V < i, k = V, \\ 0 & \text{elsewhere} \end{cases} \quad (24)$$

Table I shows the minimum  $P_L$  for different values of  $V$  and for the three loads considered. Note that the minimum  $P_L$  is achieved at the corresponding optimal permission probability ( $r_{opt}$ ), that is obtained by exhaustive search.

For a fixed load and a given protocol  $X = \{\text{FSA}, \text{FSA-RDP}\}$ , we define  $P_{L,X}^*$  as the minimum  $P_L$  obtained from Table I for different values of  $V$ , and denote by  $V^*$  the value of  $V$  at which  $P_{L,X}^*$  is achieved. For  $V < V^*$ ,  $P_{L,X} > P_{L,X}^*$ , as more collisions are expected due to the small number of data slots (FSA) or reservation slots (FSA-RDP). Then, packets stay longer in the buffer, which increases the probability that new packets are rejected (FIFO-BL) or new packets push-out the packet in the buffer (LIFO-PO). Also, for  $V > V^*$ ,  $P_{L,X} > P_{L,X}^*$ , the carried data packet rate does not grow substantially but frame durations are longer (more data slots or reservation slots). Then, more data packets can arrive to the same device during a frame, which increases the losses.

For a given load, we define the relative increase of  $P_{L,X}^*$  as  $(P_{L,X}^* - P_{L,I}) / P_{L,I}$ , where  $I$  refers to FSA-RDP-I. Note that  $P_{L,I}$  corresponds to the packet loss probability achieved by FSA-RDP-I at the same load and protocol configuration (value of  $V$ ) at which  $P_{L,X}^*$  is found. For FSA, the relative packet loss probability increases are  $\{9.99, 8.14, 4.08\}$ , for low, medium and high loads, respectively. However, for FSA-RDP, the relative packet loss probability increases are  $\{0.20, 0.27, 0.39\}$ , respectively. That is, the efficiency increase obtained by FSA-RDP respect to FSA is between one and two orders of magnitude, depending on the load. As observed, the difference between the efficiency of FSA-RDP and FSA-RDP-I increases as load increases. This effect was expected, as the contention increases with the load. Nevertheless, the performance of FSA-RDP is quite close to the performance of FSA-RDP-I.

An interesting observation is that, for a fixed  $V$ , to achieve the minimum  $P_L$  in FSA, the optimal permission probability has to be appropriately set (values lower than 1), particularly as load increases. However, for FSA-RDP, the optimal permission probability is constant to 1 for large range of loads an values of  $V$ .

TABLE I: Minimum Packet Loss Probability ( $P_L$ )

$M = 8$	MAC	$\rho_T = 0.3$	$\rho_T = 0.5$	$\rho_T = 0.8$
$V = 1$	FSA-RDP-I	0.010865	0.033768	0.107811
	FSA-RDP	0.015116	0.048350	0.153930
	$r_{opt}$	0.64	0.52	0.39
	FSA	0.134299	0.309733	0.522729
	$r_{opt}$	0.38	0.29	0.21
$V = 2$	FSA-RDP-I	0.011489	0.032235	0.102044
	FSA-RDP	0.013056	0.041071	0.146593
	$r_{opt}$	1	1	0.79
	FSA	0.124342	0.303574	0.521052
	$r_{opt}$	0.76	0.56	0.41
$V = 3$	FSA-RDP-I	0.013714	0.035400	0.104036
	FSA-RDP	0.015359	0.043837	0.141340
	$r_{opt}$	1	1	1
	FSA	0.119443	0.298006	0.519617
	$r_{opt}$	1	0.82	0.61
$V = 4$	FSA-RDP-I	0.016210	0.040062	0.110301
	FSA-RDP	0.017914	0.048607	0.146524
	$r_{opt}$	1	1	1
	FSA	0.134510	0.294533	0.518398
	$r_{opt}$	1	1	0.79
$V = 5$	FSA-RDP-I	0.018733	0.045084	0.118643
	FSA-RDP	0.020522	0.053741	0.154249
	$r_{opt}$	1	1	1
	FSA	0.153389	0.307008	0.517328
	$r_{opt}$	1	1	0.97
$V = 6$	FSA-RDP-I	0.021246	0.050130	0.127738
	FSA-RDP	0.023141	0.058965	0.162608
	$r_{opt}$	1	1	1
	FSA	0.172423	0.325533	0.519808
	$r_{opt}$	1	1	1

## B. Packet Delay Distributions

Figure 2 represents the cumulative distribution function (CDF) of the packet delay for high and medium loads, when FSA-RDP is deployed. That is, for a given number of mini-slots, say  $s$ , the figures represent the fraction of packets which packet delay is shorter than  $s$ . Recall that the duration of a frame is  $V + kW$  mini-slots, where  $k$  is the number of data packets transferred.

In Fig. 2a, three representative protocol configurations are selected to show the CDF for high load. These are: i)  $(V, r_{opt}) = (1, 0.39)$ ; ii)  $(V, r_{opt}) = (3, 1)$ ; and, iii)  $(V, r_{opt}) = (5, 1)$ . Note that for high load,  $P_{L,\text{FSA-RDP}}^*$  is achieved at configuration  $(V, r_{opt}) = (3, 1)$ . As observed, the difference between the CDF obtained for the FIFO-BL and LIFO-PO queue disciplines are small. The difference is more important for the configuration  $(V, r_{opt}) = (1, 0.39)$ , due to the small number of reservation mini-slots ( $V = 1$ ), which leads to the occurrence of more collisions during the RSF. When more collisions occur during the RSF, packets remain longer in the queue when FIFO-BL is deployed. However, when LIFO-PO is deployed, as collisions increase, the probability that packets are pushed-out of the queue increases. In other words, the replacement rate of old data packets in the queue by new ones increase with collisions. This fact explains why the data packet delay for LIFO-PO is slightly smaller than

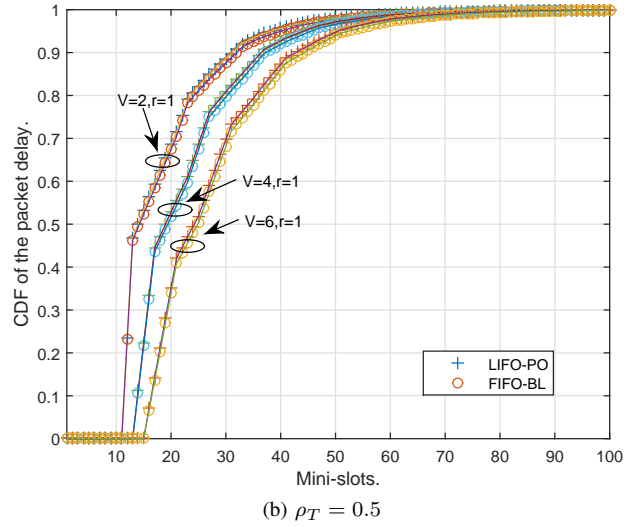
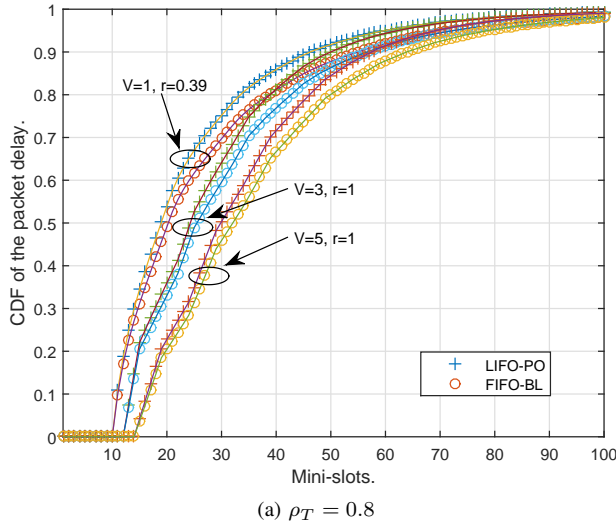


Fig. 2: Cumulative distribution functions of the packet delay.

for FIFO-BL.

In Fig. 2b, three representative protocol configurations are selected to show the CDF for medium load. These are: i)  $(V, r_{opt}) = (2, 1)$ ; ii)  $(V, r_{opt}) = (4, 1)$ ; and, iii)  $(V, r_{opt}) = (6, 1)$ . Note that for medium load,  $P_{L, \text{FSA-RDP}}^*$  is achieved at configuration  $(V, r_{opt}) = (2, 1)$ . Clearly, the difference between the CDF obtained for the FIFO-BL and LIFO-PO queue disciplines is negligible. This is due to the fact that a lower load is used when compared to the scenario of Fig. 2a, and, in addition, larger values of  $V$  are deployed. As a consequence, a lower collision rate is experienced by the system.

## V. CONCLUSION

In this paper we study a type of Frame Slotted ALOHA protocol that deploys reservation and data packets, and name it FSA-RDP. In FSA-RDP frames are divided in two subframes, the reservation and the data subframes. In the reservation subframes active terminals that have access permission contend for sending reservation packets to the controller. Those that succeed (their reservation packets do not collide) are assigned a dedicated slot to transfer a data packet during the data subframe.

We model the operation of the FSA-RDP protocol with a discrete-time Markov chain and determine the packet delay distribution and the protocol efficiency, for a scenario where M2M devices have a buffer to store a single packet. We define the protocol efficiency in terms of the data packet loss probability. We compare the efficiency of the FSA-RDP protocol and the conventional Frame Slotted ALOHA (FSA), with the efficiency and an idealistic version of the FSA-RDP protocol (FSA-RDP-I), which efficiency can be considered as an upper bound for the efficiency of the FSA-RDP protocol. Results show that the protocol efficiency of FSA-RDP is between one and two orders of magnitude larger than the

efficiency of the conventional FSA. In addition, the efficiency of FSA-RDP is close to one obtained for FSA-RDP-I.

We determine the cumulative distribution function of the packet delay for FSA-RDP, when both the FIFO-BL and LIFO-PO queue disciplines are deployed. We study different loads and configurations for the protocol. In the scenarios studied, results show that the packet delay for LIFO-PO is smaller than the one obtained for FIFO-BL. However, the difference between the delay obtained by both queue disciplines is only significant for high loads, and when the number of mini-slots in the reservation subframe is small. That is, when the collision rate is high.

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