Analysis of a Persistent Multi-Channel Slotted ALOHA Protocol Without Acknowledgment

Andrea Zanella*, Andrea Baiocchi† and Alexey Rolich†
*Dept. of Information Engineering, University of Padova, Italy
†Dept. of Information Engineering, Electronics and Telecommunications (DIET), University of Rome Sapienza, Italy
andrea.zanella@unipd.it (orcid.org/0000-0003-3671-5190)
andrea.baiocchi@uniroma1.it, alexey.rolich@uniroma1.it

***Abstract*—In this paper, we focus on a persistent medium access mechanism for a wireless multichannel scenario without a return channel. It is a version of the legacy slotted ALOHA protocol in which each active user chooses a sub-channel (SC) to transmit its messages and, in each slot, it either keeps transmitting in the same SC (with persistence probability p) or chooses another SC among those left idle in the previous slot. This decision, however, is taken without any explicit information about the success or failure of the previous transmission, but only using high-level busy/idle information provided by, e.g., carrier-sensing mechanisms. This scenario is of interest when direct feedback is impractical, e.g., with broadcast traffic or unconfirmed data like status report update messages in massive Internet of Things (IoT). Despite the simplicity of the protocol, its performance analysis may become cumbersome because of the combinatorial nature of the multi-access problem. We overcome this difficulty by applying the mean-field approach to estimate some key performance indicators, such as throughput and Age of Information (AoI). The resulting model, though approximate, turns out to be accurate and scalable, as proved by comparing the mathematical results with the outcome of computer simulations when changing the key system parameters (channel load, persistence probability).**

***Index Terms*—ALOHA protocol, Random multiple access, persistence, Age of Information, Markov Chain models**

I. Introduction

In this paper, we address the medium access problem in multi-channel wireless systems, such as those using a time-frequency partition to define resource blocks (as in LTE and 5G cellular multiple access). We assume that time is divided into slots of equal duration, and that each time slot provides a number of sub-channels (SCs). Each SC can carry one packet transmission per slot. Multiple transmissions on the same SC generate destructive interference, which prevent the correct reception of the overlapping packets. As customary in the ALOHA literature, we refer to such an event as *packet collision*.

A distinctive aspect of our scenario, compared to others in the literature, is the lack of direct and complete feedback (acknowledgment) to the transmitters about the success or failure of their transmission attempts. The only information available to the transmitter is the idle/busy state of each SCs in the previous slot. This model applies to scenarios where the downlink channel is absent or highly constrained (as in LoRa or satellite links), making direct per-node feedback infeasible. One example is a large sensor network, where nodes transmit update messages (possibly to different destinations) without requiring feedback from the receiver(s) to conserve energy and to minimize congestion on a narrow-band downlink channel. Another example is a network with many nodes broadcasting short messages to all neighbors, where per-node feedback from every receiver would be impractical.

In these examples, transmitters have no access to explicit feedback regarding the success or failure of their transmissions. However, information about the busy or idle state of each SC can be determined using carrier-sense mechanisms, or provided to all transmitters by a monitoring node through a very narrow control channel where (e.g., the gateway in a data collection scenario, such as LoRaWAN [1]).

To manage channel access from multiple nodes in such a scenario we consider a variant of the legacy Multichannel Slotted ALOHA (MSA), which we have named *Blind Slotted ALOHA (BSA)*. In this protocol, each node with pending packets chooses a SC to transmit its message in a slot. In subsequent slots, each node continues to transmit in the same SC with a given probability, a mechanism we refer to as *probabilistic persistence*. Conversely, with the complementary probability, the node randomly selects another SC from those that were idle in the previous slot. This mechanism is similar to that proposed, e.g., in the case of 5G-NR V2X sidelink Mode 2 multiple access [2], [3].

We therefore consider a random multi-channel access scheme characterized by three key features: (i) channel sensing, used to determine which SCs were idle in the previous time period (which are possible candidates for subsequent transmissions); (ii) persistence probability, which defines the likelihood that a previously selected SC will be retained for additional slots; (iii) the lack of direct feedback on the outcome of data transmission, which makes the transmitter's choice *blind* to the actual status of the selected SC. The three model assumptions establish a coherent framework that is well-suited for IoT environments, particularly those involving broadcast traffic or massive update transmissions. The integration of these three features results in an intriguing multiple access scheme that maintains the simplicity of Slotted ALOHA, while further reducing the complexity of the node's architecture due to the *blindness* assumption.

Properly tuning the relevant parameters, such as the persistence probability and the number of SCs relative to the number of backlogged users, becomes a critical task. This is especially true when considering performance metrics like the Age of Information (AoI).

To understand the impact of persistence on performance, we compare BSA to a basic version of MSA, which lacks sensing and persistence and does not provide feedback on transmission outcomes, maintaining consistency with our model. This comparison aims to highlight the contributions of sensing and persistence to the success probability and AoI metrics in the blind environment of our study, where feedback on transmission outcomes is absent.

The main original contributions of this paper are:

- We propose an approximate, yet effective, analytical model of the BSA protocol, enabling the straightforward determination of key performance indicators.
- We demonstrate that the solution to the analytical model hinges on a fixed point equation.[1] The model's complexity scales efficiently with the system's size (number of SC, number of users), making it a valuable tool for evaluating performance under various scenarios.
- We analyze the primary performance metrics, namely throughput, Peak Age of Information (PAoI) and average AoI, when varying traffic load and persistence probability, gaining insights on the impact of such parameters on system performance.

The rest of the paper is organized as follows. Section II provides an overview of slotted ALOHA protocols and related PAoI and AoI metric studies. Section III outlines our proposed analytical model. Section IV analyses key performance metrics. Section V validates the model through simulations and discusses the results. Section VI concludes the paper.

II. Related work

As mentioned, the ALOHA protocol has been widely and deeply studied, and the related literature is huge. Nonetheless, to the best of our knowledge, no previous study addressed the case with only idle/busy channel feedback, addressed in this work. We hence consider only a few papers, particularly relevant to our study for their focus on the AoI performance in ALOHA systems.

The paper [4] investigates threshold-ALOHA, a modified slotted ALOHA where terminals wait for AoI to cross a threshold before transmitting with a set probability. The study explores time-average AoI and its scaling with network size, revealing reduced AoI through optimized parameters and showcasing substantial improvement over slotted ALOHA, with potential for broader applications. In [5], Atabay *et al.* analyze AoI in a random access channel for shared updates. They introduce a threshold-based "LAZY" Slotted ALOHA variant, deriving time-average AoI. LAZY policy surpasses the legacy slotted ALOHA, approaching round-robin performance. The study focuses on a 2-source network, presenting novel AoI derivation and closed-form expressions under LAZY. Another version of slotted ALOHA, called MiSTA, is presented in [6]. By implementing threshold-based transmissions, MiSTA achieves a 32% reduction in network-wide AoI and a 45% throughput increase compared to the threshold ALOHA policy, with potential for further exploration in scenarios with adaptive data rates.

In [7] Wang *et al.* conducted a thorough analysis of AoI within Frame Slotted ALOHA (FSA), a crucial protocol in ultra-low-power IoT. Despite AoI's significance, its integration with FSA was underexplored. The study systematically examined four FSA variations, employing Markov chain models to derive AoI expressions and analyze delay and inter-delivery time statistics. Key outcomes encompassed AoI lower bounds, exact expressions for FSA protocols, and optimal frame lengths. The authors investigated parameters' impact on AoI and showcased retransmission benefits for low arrival rates. The paper [8] introduces a FSA-based protocol for random access networks, assessing its impact on timeliness using the AoI metric. Analyzing Poisson bipolar and cellular networks, the study derives expressions for mean and variance of AoI, revealing how FSA reduces the mean AoI and stabilizes age performance in dense networks.

Munari [9] addresses the significance of the AoI metric in IoT systems, emphasizing its role in capturing device status freshness. It introduces the Irregular Repetition Slotted ALOHA (IRSA) protocol and employs a Markovian analysis to track AoI evolution, establishing ergodicity and deriving a closed-form stationary distribution. This enables precise calculation of average AoI and age violation probability. Comparative analysis with simpler protocols highlights IRSA's potential in enhancing information freshness, offering valuable design insights. In [10], Huang *et al.* introduced a novel graph-based spatially coupled irregular repetition slotted ALOHA (G-SC-IRSA) protocol, utilizing pseudo-random access patterns, coupled frames, and sliding window decoding. The study provides approximate expressions for normalized average AoI, formulates an average AoI minimization problem under G-SC-IRSA, and employs density evolution to evaluate system load thresholds. The proposed protocol showcases enhanced Packet Loss Rate and average AoI performance compared to benchmark schemes.

In [11] Badia *et al.* expanded AoI analysis to slotted ALOHA with capture effect, using game theory to assess how selfish nodes could minimize their individual AoI considering transmission costs. Through analytical derivations and existing AoI formulations, they identified the impact of parameters like cost coefficient and capture threshold on achieving equilibrium. The study suggests that in scenarios with limited terminals and a strong capture effect, the Nash equilibrium can lead to near-optimal performance, revealing insights into selfish nodes' behavior in slotted ALOHA and their potential for effective AoI reduction.

Asvadi *et al.* [12] investigate PAoI in a discrete-time slotted ALOHA network with M buffer-less nodes, considering collisions and preemptive queueing. They propose a trellis-based model to analyze packet system time and derive exact average PAoI for symmetric and asymmetric slotted ALOHA networks, confirmed through simulations. In [13]

[1]The existence and uniqueness of the fixed point solution can be proved mathematically, but we omit the proof being rather long and not very insightful.

Fiems and Vinel present a precise mean value analysis of the AoI in slotted ALOHA, providing exact results for mean AoI at random slot boundaries and PAoI. In [14], Wu *et al.* investigate enhancing PAoI in IoT services through improved slotted Aloha networks. They analyze PAoI using first-come-first-served service and Bernoulli packet arrivals, optimizing it individually or jointly by adjusting channel access probability and packet arrival rate. The study yields optimal settings, minimum PAoI, and age-throughput trade-off insights, highlighting the benefits of joint optimization in scaling PAoI with network size for better age performance and reduced throughput loss.

Lai *et al.* [15] investigate the potential improvement of AoI performance in MSA networks. In MSA-Collided users sending First (MSA-CF), collided users transmit packets in subsequent time slots after a collision. Simulations demonstrate that MSA-CF achieves a lower average AoI compared to MSA.

The articles discussed in this section offer valuable insights into the performance evaluation of various ALOHA protocols, particularly in terms of PAoI, AoI, and throughput metrics. However, none of these studies delve into the analysis of PAoI, AoI, and throughput for multichannel blind slotted ALOHA.

III. System model

We consider N users that share a multi-channel communication system. Channel access is organized in time-slots of size T, referred to as *frames* in the following. In each frame, R orthogonal transmission resources are available, named SCs. A SC is sized to accommodate the transmission of a single message (packet).

Each user generates a new message at the beginning of each frame and chooses a SC for transmission. At the end of the frame, users are assumed to be informed about the idle/busy state of SCs belonging to that frame, e.g., by means of channel sensing or through a broadcast notification from a channel-monitoring station (only able to detect energy on each SC, but without decoding capabilities). Then, each user independently and randomly decides, with persistence probability p, to perform the next transmission on their current SC. Conversely, with probability $q = 1 - p$, they select a new SC, uniformly chosen at random from those reported as idle in the last frame.

At this stage of the work, we consider a simple collision channel model, neglecting channel errors and capture effects: a transmission is successful if and only if the user selects a SC that is not selected by any other user.[2]

In the following we assume $0 \le p < 1$. Moreover, we assume the number R of SCs is larger than the number of users, $R > N$, so that there are always idle SCs.[3]

We define $C_i(k)$ as the set of all SCs selected by exactly i users at frame k, so that: $C_0(k)$ is the set of idle SCs during frame k; $C_1(k)$ is the set of SCs with just one user (successful transmissions); and $\{C_h(k)\}$ with $h > 1$ are the sets of SCs with multiple (namely, h) transmitting (and colliding) users.

Let $r_i(k) = |C_i(k)|$ be the number of SCs in the set $C_i(k)$. We can hence define a vector $\mathbf{s}(k) = [r_0(k), r_1(k), \ldots, r_N(k)]$ that makes it possible to describe the state of the system and track its evolution in time. The vector $\mathbf{s}(k)$ is the state of a multi-dimensional, irreducible, finite-state Markov chain. In principle, we can determine the state-transition matrix and the asymptotic distribution of $\mathbf{s}(k)$, however this becomes computationally demanding, even for moderate values of R and N, due to the combinatorial growth of the state space size.[4]

Instead, we develop an approximate analysis based on the mean-field approach. We focus on the *average* behavior of the system as a whole, and look for an equilibrium point, i.e., a *self-consistent* state, where the mean of the system remains constant over time [16]. In practice, we set

$$\mathrm{E}[\mathbf{s}(k+1)|\mathbf{s}(k) = \mathbf{s}] = \mathbf{s} \tag{1}$$

and solve for $\mathbf{s}$. Assuming the system admits one single solution $\mathbf{s} = [r_0, r_1, \ldots, r_N]$, then the value r_i approximates the stationary value of $\mathrm{E}[r_i(k)]$.

An easy way to find the equilibrium point is to balance the *transitions* of SCs between different sets $\{C_i\}$.[5] Based on the p-persistent mechanism, at each frame, users keep transmitting on the previously selected SCs with probability p, while with probability $1 - p$ they will pick at random another SCs among those in set C_0. Therefore, at each frame we have random transitions of users between SCs and, in turn, of SCs between sets. On average, the number of SCs leaving a certain set C_i in one frame is given by

$$O_i = r_i(1 - p^i)\,, \tag{2}$$

since for each SC in set C_i, the probability that at least one of the i users will pick another SC is $1 - p^i$. At equilibrium, O_i must be balanced by as many SCs entering set C_i from other sets. These transitions are only possible from the following sets:

- C_j, with $j > i$, when exactly $j - i$ users belonging to the same SC in set C_j decide to switch SC (picking at random one SC from those in C_0). The mean number of SCs that transit from C_j to C_i is hence:
$$I_{j\to i} = r_j \left(\begin{array}{c} j \\ j-i \end{array} \right) p^i q^{j-i}\,. \tag{3}$$
- C_0, in case exactly i users from other SCs decide to switch and pick the same idle SC, which hence exits set

[2] Considering a more realistic model, though possible in our framework, would come at the cost of more cumbersome notation and derivation, which is not compatible with the space constraints of a conference paper.

[3] With $p = 1$ the system becomes non-ergodic and its performance only depends on the initial allocation of the users to the SCs. With $R \le N$ there is a non-zero probability that all SCs in a frame get occupied, thus preventing any further variation of the system state. Both these cases are of little interest for our study, being trivial to analyze.

[4] Taking into account that $N < R$ implies $s_0(k) > 0$, $\forall k$, the number of states of the Markov chain is $\binom{R+N-1}{N}$.

[5] We drop the time notation (k) because we refer to the equilibrium condition, which is time invariant by definition.

C_0 and enters C_i. The mean number of SCs that transit from C_0 to C_i is hence:

$$I_{0\to i} = r_0 \begin{pmatrix} N \\ i \end{pmatrix} (q/r_0)^i (1-q/r_0)^{N-i} . \quad (4)$$

Balancing the inbound and outbound flows of set C_i we get

$$O_i = \sum_{j=i+1}^{N} I_{j\to i} + I_{0\to i} \quad (5)$$

$$r_i(1-p^i) = \sum_{j=i+1}^{N} r_j \begin{pmatrix} j \\ j-i \end{pmatrix} q^{j-i} p^i + r_0 \binom{N}{i} \left(\frac{q}{r_0}\right)^i \left(1-\frac{q}{r_0}\right)^{N-i} . \quad (6)$$

This expression holds for $i = 0$ to $i = N-1$. We finally require that the sum of the mean number of SCs in each set equals R, i.e.,

$$R = r_0 + r_1 + \ldots + r_N . \quad (7)$$

The system of equations to compute the r_i for $i \geq 1$ can be written as follows

$$r_i = r_0 \binom{N}{i} \left(\frac{q}{r_0}\right)^i \left(1-\frac{q}{r_0}\right)^{N-i} + \sum_{j=i}^{N} r_j P_{ji} ; \quad (8)$$

where

$$P_{ji} = \begin{cases} \binom{j}{j-i} q^{j-i} p^i, & i = 1, .., j ; \\ 0, & \text{otherwise.} \end{cases} \quad (9)$$

We can then define the $N \times N$ lower triangular matrix $\mathbf{P}$ with entries $\{P_{ji}\}$. The matrix $\mathbf{P}$ is sub-stochastic, since the sum of elements on the j-th row is:

$$\sum_{i=1}^{j} P_{ji} = 1 - q^j . \quad (10)$$

Let us define the $1 \times N$ vector $\mathbf{r} = [r_1, \ldots, r_N]$, and the $1 \times N$ vector $\mathbf{w}$ with entries

$$w_i = \binom{N}{i} (q/r_0)^i (1-q/r_0)^{N-i}, \qquad i = 1, \ldots, N . \quad (11)$$

Then, we can re-write the linear system in (8) more compactly as follows:

$$\mathbf{r} = r_0 \mathbf{w} + \mathbf{r}\mathbf{P} \qquad \Rightarrow \qquad \mathbf{r} = r_0 \mathbf{w}(\mathbf{I}-\mathbf{P})^{-1} \quad (12)$$

where $\mathbf{I}$ is the identity matrix of same size as $\mathbf{P}$.

Note that, since $\mathbf{P}$ is sub-stochastic, the inverse of $\mathbf{I}-\mathbf{P}$ exists and the matrix $(\mathbf{I}-\mathbf{P})^{-1}$ is non-negative (all entries are ≥ 0). We have the congruence equation $R = r_0 + r_1 + \cdots + r_N = r_0 + \mathbf{r}\mathbf{1}$, where $\mathbf{1}$ is a column vector of ones. Substituting the expression of $\mathbf{r}$ from (12), we get

$$R = r_0 + r_0 \mathbf{w}(\mathbf{I}-\mathbf{P})^{-1}\mathbf{1} \;\Rightarrow\; r_0 = \frac{R}{1 + \mathbf{w}(\mathbf{I}-\mathbf{P})^{-1}\mathbf{1}} . \quad (13)$$

Since $\mathbf{w}$ and $\mathbf{P}$ are themselves functions of r_0, this equation provides a fixed point iteration, which makes it possible to find r_0 numerically.

The existence and uniqueness of the fixed point solution can be formally proved, following these steps (we omit the details for space reasons): Let $x = f(x)$, $x \in [1, R]$ be the fixed point equation. Existence of at least one fixed point is proved by recalling Brouwer's theorem, since $f(x)$ is a continuous map of $[1, R]$ onto itself. As for uniqueness, first it is proved that the function $f(x)$ is monotonously strictly increasing in $[1, R]$. Then it is proved that $f(1) > 1$ and $f(R) < R$. Finally, it is proved that the slope of $f(x)$ at any given fixed point must be strictly less than 1.

IV. Performance analysis

From $\{r_j\}$, $j = 1, \ldots, N$, we can estimate some key performance metrics, like throughput and AoI, as explained in the following.

A. Throughput

The average throughput S of the system is defined as the mean number of successful transmissions per resource block, and can be estimated as

$$S = r_1 / R , \quad (14)$$

where r_1 approximates the average number of SCs carrying single (and, hence, successful) transmissions.

B. Age of information

The AoI of a node is the time elapsed since the *generation* epoch of the last successfully delivered message from the same node. In the considered system, a new packet is generated at each slot, so that the AoI of a user corresponds to the time elapsed since the last non-collided packet transmission of that user. In this case, the PAoI is the maximum AoI reached by a user just before a successful transmission, i.e., the number of slots between two consecutive successfully delivered messages.

The AoI thus depends on whether a message transmission is successful or collided. We say a user is in state $\mathcal{S}$ (Successful) when it belongs to C_1, i.e., it selects a SC not chosen by any other user. Conversely, we say a user is in state $\mathcal{C}$ (Collision) when it belongs to any C_i where SCs are occupied by $i > 1$ nodes. In state $\mathcal{S}$, each slot carries a new packet that is successfully delivered to the destination, while in state $\mathcal{C}$ the transmission collides with some other node and the message is not delivered. The AoI is hence the number of slots elapsed since the last slot the node was in state S. For example, if a user remains for k steps in state $\mathcal{C}$ before returning to state $\mathcal{S}$, its PAoI will be $k+1$.

To determine the AoI metrics, we need first to compute the transition probabilities between states $\mathcal{S}$ and $\mathcal{C}$. Let $P_{x,y}$ denote the steady-state transition probability from state x to state y in one step, with $x, y \in \{\mathcal{S}, \mathcal{C}\}$. A user in state S remains in that state when either it does not change SC or it does changes SC and chooses an idle SC that is not selected by any other nodes. The probability of these events can be expressed as

$$P_{\mathcal{S}\mathcal{S}} = p + q(1-q/r_0)^{N-1} . \quad (15)$$

The expression of the transition probability from $\mathcal{C}$ to $\mathcal{C}$ is more involved. Let $P(k)$ denote the stationary probability that a user belongs to C_k (i.e., its last transmission occurred in a SC of C_k). We can approximate $P(k)$ using the estimated cardinality of the sets at equilibrium, obtaining:

$$P(k) = \frac{kr(k)}{\sum_{j=1}^{N} jr(j)} .$$

Given that a user is in a collided SC, the probability that it is in one with $k-1$ other users is hence $P(k)/(1-P(1))$. Then, we can write P_{CC} as follows

$$P_{CC} = (1-p)(1-(1-(1-p)/r_0)^{N-1}) + \sum_{k=2}^{N} \frac{P(k)}{1-P(1)} p(1-(1-p)^{k-1}) . \tag{16}$$

The first part accounts for the event in which the tagged user decides to switch SC and jumps into an idle SC that, however, is selected by some other user. The second term, instead, accounts for the probability that the tagged user belongs to a collided set with k users and that it remains in the same SC with at least one of the other $k-1$ users.

1) Peak AoI: Let Y be the PAoI of a user, expressed in slots (i.e., normalized with respect to the slot duration T). If V_0 denotes the visit time in state $\mathcal{C}$, we have

$$Y = \begin{cases} 1 & \text{w.p. } P_{SS}, \\ 1+V_0 & \text{w.p. } P_{SC} = 1-P_{SS}. \end{cases} \tag{17}$$

The random variable V_0 is Geometric with ratio P_{CC}, hence

$$\mathrm{E}[V_0] = \frac{1}{1-P_{CC}} \tag{18}$$

Hence we have

$$\mathrm{E}[Y] = P_{SS} + P_{SC}\left(1+\frac{1}{1-P_{CC}}\right) = 1 + \frac{1-P_{SS}}{1-P_{CC}} . \tag{19}$$

2) Average AoI: The average AoI is the mean value of AoI as estimated by a random observer. By using the random look theory, we hence have:

$$\mathrm{E}[\mathrm{AoI}] = \frac{\mathrm{E}[Y^2]}{2\mathrm{E}[Y]} + 1/2 \tag{20}$$

where the $1/2$ term is due to discretization of time and

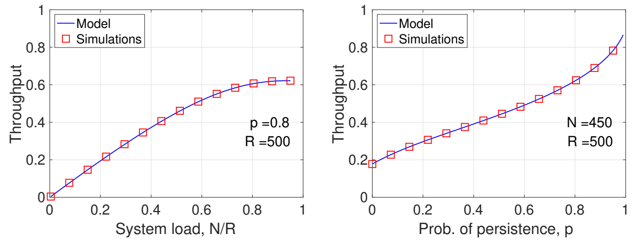
$$\mathrm{E}[Y^2] = 1 + (1-P_{SS})\frac{3-P_{CC}}{(1-P_{CC})^2} , \tag{21}$$

as can be derived from (17), using (18) and the statistical power of V_0 given by

$$\mathrm{E}[V_0^2] = \frac{1+P_{CC}}{(1-P_{CC})^2} . \tag{22}$$

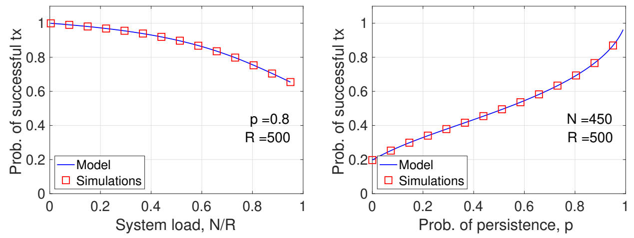
V. Numerical results

In this section we analyze the performance of multi-channel BSA obtained from the Proposed approximate model, detailed in Section III, and from a MATLAB-based Simulation model. The performance metrics under consideration encompass throughput, transmission success probability, PAoI, and average AoI. The simulation adopts the model described in Section III, with PAoI and AoI normalized to the slot's duration T.



(a) (b)

Figure 1. Throughput $S = r_1/R$ for $R = 500$: (a) as a function of system load $\rho = N/R$ for $p = 0.8$; (b) as a function of probability of persistence p for $\rho = 0.9$.



(a) (b)

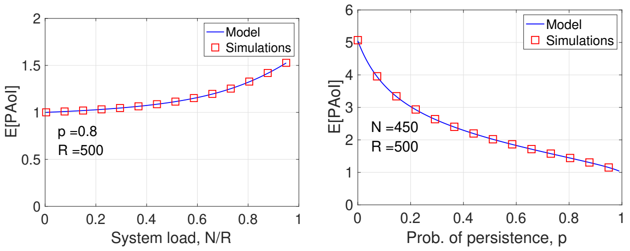
Figure 2. Probability of success $p_s = r_1/N$ for $R = 500$: (a) as a function of system load $\rho = N/R$ for $p = 0.8$; (b) as a function of probability of persistence p for $\rho = 0.9$.

For each performance metric, we provide a figure containing two plots, (a) on the left, and (b) on the right. Figures (a) show the performance metrics in relation to the channel load, which is expressed as load factor $\rho = N/R$. We typically fix $R = 500$ and increase the number N of users, keeping the persistence probability constant and equal to $p = 0.8$. Figures (b), instead, are obtained by fixing the load factor to $\rho = 0.9$ and varying the persistence probability p.

Figure 1 illustrates the system's throughput, Figure 2 the probability of successful message transmission (r_1/N), and Figures 3 and 4 the PAoI and AoI metrics, respectively.

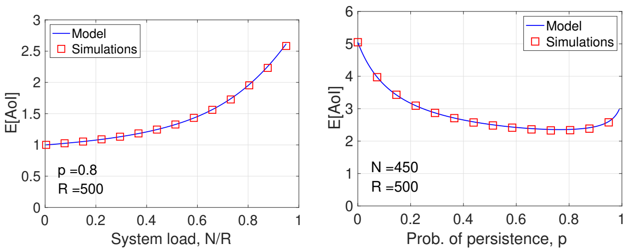
Upon analyzing the throughput and PAoI metrics, a consistent trend emerges: optimal performance (when $R > N$) is consistently achieved as p approaches 1. This phenomenon can be intuitively understood. As p approaches 1, the likelihood of multiple nodes simultaneously switching to an idle SC decreases significantly, thus minimizing the risk of collisions. Consequently, with sufficiently large p, the probability of simultaneous switching in a slot becomes negligible, and even more so the risk of collision. In such scenarios, it is highly likely that users switch to an idle SC singularly, thus succeeding in their transmissions. In the long term, the PAoI converges to 1 and the throughput to ρ, as for the outcomes presented in Figures 1b, 2b and 3b.

Notably, the AoI analysis unveils a non-monotonic correlation between AoI and persistence probability, pinpointing an optimal value around 0.77. This phenomenon can be clarified as follows: Lower persistence probabilities yield frequent SC switches that lead to collisions and larger variance in inter-message delivery times, thereby increasing the average AoI. Conversely, at elevated p values, nodes facing colli-



(a) (b)

Figure 3. Mean Peak Age of Information $\mathrm{E}[A_P]$ for $R = 500$: (a) as a function of system load $\rho = N/R$ for $p = 0.8$; (b) as a function of probability of persistence p for $\rho = 0.9$.



(a) (b)

Figure 4. Mean Age of Information $\mathrm{E}[A]$ for $R = 500$: (a) as a function of system load $\rho = N/R$ for $p = 0.8$; (b) as a function of probability of persistence p for $\rho = 0.9$.

sions essentially experience an "outage," remaining inactive for extended intervals akin to a disrupted communication channel, resembling an ON-OFF system with sporadic but long interruptions. Moreover, while long-term symmetry and fairness are achieved, within the short term (comparable to the sojourn times of the two-state Markov chain), most nodes transmit successfully, but a minority consistently encounter transmission failures over consecutive time slots.

Finally, we observe that the proposed model exhibits remarkable accuracy across all considered metrics.

VI. Conclusions

We have considered a random multiple access model loosely inspired by the current 5G NR V2X Mode 2 multiple access known as Semi-Persistent Scheduling, but potentially of interest in any situation where a common communication channel is shared by nodes that send update messages to one or multiple target receivers and single acknowledgments are not possible. We refer to this kind of multiple access as "blind", since the transmitting nodes cannot know the outcome of their transmission attempts. The other main specific features of the considered access procedure are: (i) nodes exploit the idle/busy status of communication resources as learned in previous time slots; (ii) once a communication resource is chosen by a node, the node persists using that resource with a given probability.

We define a simple approximate analytical model that turns out to be extremely accurate and exhibits negligible complexity for any reasonable choice of system parameters. The insight gained from the model shows that persistence is beneficial to throughput and probability of success, while an optimal level of persistence exists for the mean AoI metric.

Further work should address more general model settings, e.g., with unsaturated traffic sources, or when the idle/busy status of communication resources in previous time slots is not perfectly known because of hidden nodes. It is also worth investigating the interwining of multi-channel persistent multiple access with sophisticated multi-packet reception procedures, e.g., through packet coding and/or successive interference cancellation [17]–[19]. A further development line is to define a distributed algorithm that drives nodes to set their own persistence probability in an optimal way, i.e., so as to minimize AoI.

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