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# Enhanced Pricing Strategy for Slotted ALOHA with ZigZag Decoding: A Stochastic Game Approach

Ahmed Boujnoui<sup>1</sup>, Abdellah Zaaloul<sup>1,2</sup> and Abdelkrim Haqiq<sup>1,3</sup>

<sup>1</sup>Hassan First University of Settat, Faculty of Sciences and Techniques,  
Computer, Networks, Mobility and Modeling laboratory: IR2M, 26000 - Settat, Morocco,  
*a.boujnoui@uhp.ac.ma, abdelkrim.haqiq@uhp.ac.ma*

<sup>2</sup>Ibn Zohr University of Agadir, Faculty of Sciences,  
Engineering, Mathematics and Informatics Laboratory (IMI). Agadir. Morocco,  
*a.zaaloul@uiz.ac.ma*

<sup>3</sup>Machine Intelligence Research Labs (MIR Labs) Member,  
Washington, USA

**Abstract:** In this paper, we propose a novel pricing mechanism to enhance the performance of the Slotted ALOHA mechanism combined with ZigZag Decoding (SA-ZD). We model the system using a stochastic game approach where the game state is given as a Markov process. We assume a cooperative game framework where users seek to optimize the same utility function. In our previous pricing mechanism [1], we associated a cost  $C \in [0, 1]$  for every transmission and retransmission attempt. Thus, if the transmission succeeds, the user receives a reward equal to  $1 - C$ . Otherwise, in the case of collision, he pays a penalty equal to  $C$ . Following this approach, users prefer to not take the risk of paying the penalty cost, which means they choose to wait rather than transmitting, especially in heavy traffic conditions. Even though it seems optimal to not transmit in such conditions, our results show that this behavior yields a dramatic decrease in the system performance. Besides, it leads to an inherent tradeoff between the backlogged and newly arrived traffic. Toward this end, we propose in this paper a novel pricing strategy where we associate a cost not only to transmission attempts but also to the idle event (i.e. when no one is transmitting). Moreover, we address the trade-off problem by associating different costs  $C_b$  and  $C_s$ , respectively, to backlogged and newly arrived packets. Therefore, when a successful transmission is going through the channel, users pay a cost denoted by  $C_s$  or  $C_b$ . If a collision occurs, they pay a cost  $C_c$ , and when no one is transmitting, they pay the idling cost  $C_{idle}$ . Compared to the old pricing mechanism, our results show that the proposed approach achieves the best performance and maintains a fairness level between backlogged and newly arrived packets.

**Keywords:** Stochastic game, Pricing strategy, Markov game, Markov model, Performance evaluation.

## I. Introduction

Slotted ALOHA (SA) [2, 3] and its modified versions [4, 5] are one of the most efficient random access MAC mechanisms

implemented in wireless communication networks. They are usually used in satellite communications and cellular telephone systems. Due to the simplicity of their implementation and their wide range of applications, they are still used by many recent architectures like LoRaWAN networks [5], NOMA for the Next Generation Internet of things (IoT) [6, 7] and IoT applications for COVID-19 pandemic [8].

In Slotted ALOHA, the time is divided into units called slots, where the duration of each slot is the transmission time of one data packet. Transmissions and retransmissions start only at the beginning of a slot. When a new packet is received by a node during the current slot, it shall transmit it in the next slot. If two or more packets are sent simultaneously, they collide, and all packets involved in the collision are corrupted. As a result, the collided nodes are considered backlogged, and they should retransmit the packet after a random time. After each successful transmission, the transmitter receives the transmission's feedback (i.e. success or collision). When no feedback is received, the transmission is assumed to be failed. The main inconvenience of the Slotted ALOHA mechanism is its instability nature, and its considerable collision rate in heavy traffic conditions [9, 10]. Unlike CSMA [11], Slotted ALOHA does not perform any channel detection, which makes it energy efficient and highly sensitive to collisions. Therefore, it is primordial to manage collisions to increase the system performance.

ZigZag Decoding (ZD) is an efficient interference resolution approach used by a receiver (e.g. the Access Point (AP)) to decode packets that arrived simultaneously. It is originally designed to mitigate the hidden terminal problem [12]. An AP equipped with ZD exploits the random jitter resulting from the sporadic nature of the wireless medium and the differentiation of the distance from the receiver. As a result, packets that are sent simultaneously arrive at the receiver with some bit shift (i.e. interference-free bits) which is implemented by the de-

coder to recover the collided packets. The main feature of ZD is it does not require any change in the Media Access Control (MAC) layer, and unlike the (Request To Send/Clear To Send) RTS/CTS mechanism, it does not introduce any overhead. We have proposed an enhancement of the Slotted ALOHA using the benefits of ZD. The mechanism named SA-ZD shows to be very efficient in terms of all performance metrics compared to the standard Slotted ALOHA [13, 9]. In SA-ZD, we assume that simultaneous transmissions of two packets can be decoded with ZD. Therefore, collisions occur only in the case of three or more simultaneous transmissions.

Game theory was initially introduced for studying cooperation and selfishness in economics. A game model consists of a set of players, a sequence of strategies for each player, and a utility function. The interaction between players defines the amount of information revealed to the players. In the complete information games, the player is aware of the utility functions, payoffs, strategies, and all game rules. Whereas in the incomplete or partial information games, players do not possess full information about other players nor about the game environment. Recently, game theory was used in network modeling, and performance evaluation of random access mechanisms [10, 14]. Since the channel access represents an interaction between users, we can model the Slotted ALOHA as a game either in a cooperative or a non-cooperative framework. In the Slotted ALOHA game, we consider the users as players and the transmission probability as the strategy, whereas the amount of information is defined by the design specifications of the mechanism. The utility function is either the throughput or the delay, or any other performance metrics of interest. In this work, we are interested in a specific class of games called stochastic games or Markov games which was initially introduced in [15]. A stochastic game is a game with probabilistic transitions played by a set of  $N$  players where the strategy is either a deterministic strategy or a mixed strategy. The main feature of stochastic games is that the history at each decision point is related to some state. In our study case of SA-ZD, the state represents the number of backlogged users which is following a Markov process, whereas the strategies are given as the retransmission probabilities. The rewards at every stage depend on the player's action and also on the current state.

Interest has been given in recent years to the cooperation in MAC mechanisms, which refer to the case where all users within a wireless system cooperate to optimize the same utility function. In this paper, we study the team problem of SA-ZD, in which users intend to maximize the system throughput or equivalently minimize the access delay of transmitted packets. Although this approach provides maximal throughput, it also yields a huge delay of backlogged packets. Therefore, to achieve the maximum throughput and maintain a bounded delay, we propose a novel approach allowing us to control the users' behavior (i.e. transmission probability) by introducing several costs.

The existing tradeoff between newly arrived packets and backlogged packets has also been noticed in the standard Slotted ALOHA mechanism. And it is resulting from the design specifications of the Slotted ALOHA mechanism, which specify that newly arrived packets are transmitted immediately in the next slot after their arrival. Therefore, when the arrival

probability tends to 1, the cooperative model defers the backlogged packets to allow newly arrived to be transmitted.

The remainder of this paper is organized as follows. In Sect. II, we present a detailed review of the related works. Section III outlines the principle of the Slotted ALOHA mechanism combined with ZigZag Decoding. In Sect. IV we develop the mathematical model of the proposed mechanism. Section V and VI present respectively the performance of the system and the performance of the backlogged packets. In Sect. VII, we optimize the system as a team problem with the old pricing strategy, and Sect. VIII present the proposed pricing mechanism. Section IX discusses the numerical results and provides a comparative study with the previous pricing strategy. Finally, conclusions are summarized in Sect. X.

## II. Related Work

The Slotted ALOHA mechanism was widely investigated and improved over the past few years. In [16], The authors developed a new enhancement to Slotted ALOHA using the ZigZag Decoding approach. The proposed mechanism named SA-ZD is very effective in terms of delay and throughput compared to the standard Slotted ALOHA. Through numerical analysis, they showed that the SA-ZD operates as the standard Slotted ALOHA in the case of no collision. However, when packets are sent simultaneously by two stations, it behaves as if the collided packets are sent in separate slots. Besides, they claimed that the proposed mechanism does not introduce any overhead and does not require any MAC layer modification.

The authors in [17] proposed a novel approach based on the policy trees to improve the Slotted ALOHA mechanism. The proposed approach makes a balance between the ALOHA-Q and DRL-based approaches. They introduced two ALOHA variants. The first one, named ALOHA-QT uses the Quantitative Tree (QT) algorithm which varies the transmission rate of the user and adapts to the number of active nodes. Whereas, ALOHA-QTF variant achieves fairness in short periods.

In [18], the authors provide an analytical model of the pure and Slotted ALOHA with Multiple Packet Reception (MPR). They found that time slotting has positive and negative consequences. On one hand, it prevents the ongoing transmission from colliding with another potential transmission. And on the other hand, it does not allow the larger packet size to transmit smaller ones.

The authors in [19] proposed to enhance the Slotted ALOHA using the Capture Effect (CE) mechanism. With the CE, the receiver can decode the packet sent at high power among simultaneous transmissions as long as the tagged packet is the only one sent with the highest power. The authors also proposed to combine both ZD and CE mechanisms to further enhance the Slotted ALOHA mechanism [20]. The extended mechanism showed very efficient in terms of all performance metrics. The authors showed that it outperforms the standard Slotted ALOHA [10] as well as the enhanced versions, i.e. with ZD [16], and with CE [19].

Another enhancement mechanism to the Slotted ALOHA is the Successive Interference Cancellation (SIC) which is a collision resolution approach based on the received signal-to-noise ratio (SNR). SIC refers to the ability of the receiver to

decode packets that are transmitted with an SNR higher than a given threshold. In [21], it was assumed that users select a transmission power level based on a given distribution. In [22], the receiver adopts a set of power levels and each user adapts the transmission power based on the channel state. In [23], the authors analyzed the maximum sum rates of Slotted ALOHA with ordered SIC and unordered SIC. They also studied the effect of MPR on system performance.

The authors in [24] presented a model analysis of an extension of the Slotted ALOHA named threshold-ALOHA. In this mechanism, the users implement the Slotted ALOHA mechanism only when their age reaches a certain threshold. Otherwise, they have to stay silent in order not to disturb the users who have larger ages. Thus, if the age is below a certain threshold, the user should stay silent, and if not, it will transmit with a fixed probability using the Slotted ALOHA mechanism.

The authors in [14] introduced a non-cooperative game investigation of the Slotted ALOHA mechanism in satellite network communications. They showed that in the case of a huge number of active stations, the Slotted ALOHA with a game is more efficient in terms of energy compared to the same mechanism without the game. In [10], they proposed a new pricing mechanism for the standard Slotted ALOHA using a cooperative and non-cooperative game framework. For every transmission and retransmission, they associated a cost denoted by  $c$ . Although the idea seems interesting, it yields the same tradeoff addressed in this paper for the improved version SA-ZD. A similar strategy was adopted in [25], where they investigated the Binary Exponential Backoff Algorithm with Multi-Power Diversity (MPL-BEB). The proposed game model shows that the MPL-BEB improved with the proposed pricing strategy outperforms the standard MPL-BEB and BEB.

In our previous work, we studied the SA-ZD mechanism under the cooperative and non-cooperative game framework [13, 9]. In the cooperative version of SA-ZD, we showed that it outperforms the SA in terms of all performance metrics. Furthermore, using different objective functions of the team problem, we showed that different configurations could be achieved depending on the system requirements. Moreover, we emphasized the existing tradeoff problem between the throughput and backlogged delay. Then, we proposed to introduce a transmission cost to the cooperative version of SA-ZD [1] in order to provide a more realistic scenario where users are battery power devices. However, the proposed pricing strategy shows that the user prefers to hold on the transmission in the case of high transmission cost which dramatically degrades the performance of the system. To address this issue, we propose in this paper an enhanced pricing mechanism taking into account the tradeoff problem between the throughput and the delay.

In the non-cooperative game framework of the SA-ZD, we analyzed the system as a game where every user attempts to optimize his own utility function. Either by maximizing his individual throughput or by minimizing the access delay of his packets. Our results showed that the contention between non-cooperative users results in a dramatic decrease in the overall system performance. To solve this problem, we proposed to

control the transmission cost in order to achieve the same performance as the cooperative game model.

### III. Overview of Slotted ALOHA Combined with ZigZag Decoding

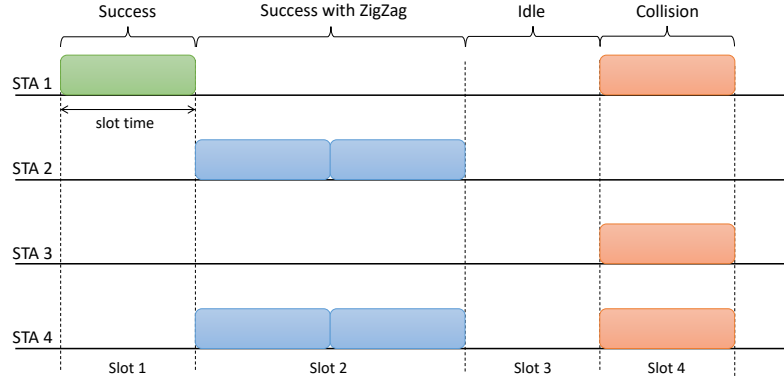
The Slotted ALOHA is a random access mechanism designed to allow transmission from competed users. Each transmission starts only at the beginning of the time interval called "slot". A Slotted ALOHA network consists of an AP and a set of connected devices which are in the coverage range of each other. The performance analysis of the Slotted ALOHA shows that it outperforms its unslotted version in terms of all performance parameters. However, it is still open to enhancements. The ZigZag Decoding [12] is one of the proposed approaches to improving the ALOHA performance. In ZD, the AP is able to decode packets sent by two simultaneous transmissions. The idea behind the ZD mechanism is straightforward: When a collision of two packets is detected over the channel, the AP triggers the ZD mechanism in order to decode the collided packets and recover the data from the collision. Since ZD uses a set of two collision events, the second slot is also dedicated to the same packets to collide again. Thus, we consider that the two packets are successfully received in two successive slots as illustrated in Fig. 1. The main feature of ZD is that it does not require any MAC layer modifications and when no collision is detected, it behaves as a standard random mechanism. ZD implements the random jitter differentiation between transmitted packets. When two users transmit their packets in the same slot, they will not perfectly collide at the receiver side. In fact, they will reach the destination with some free-interference bits which is called jitter. Thus, the receiver can trigger the ZigZag decoder in order to decode the two packets.

In our network model, a station receives an Acknowledgment (ACK) about the transmission state using one of the following feedbacks:

- 0: Idle, when no one is transmitting over the channel,
- 1: Success, in the case of a single successful transmission,
- ZigZag, in the case of simultaneous transmission of two packets,
- C: Collision, otherwise, when more than two packets are transmitted simultaneously.

### IV. Stochastic Game Formulation

We consider a wireless network consisting of an AP and a set of  $M$  buffer-less devices operating the SA-ZD mechanism. Thus, no packets are generated until the current one is successfully transmitted. As we are modeling the Slotted ALOHA, the time is divided into equal periods (i.e. "slots"). We assume that a slot is the required time to transmit a single packet. We assume that the arrival traffic at each station follows a Bernoulli process with a parameter  $p_a$ , where all arrivals are independents. For simplicity purposes, we consider the arrival



**Figure. 1:** The principle of Slotted ALOHA combined with ZigZag Decoding, slot time equals two slots in the case of ZigZag and equals to one slot otherwise. We emphasize that packets transmitted with ZD are received twice by the AP.

Notation	Description
$M$	Total number of active nodes
$N$	Number of backlogged nodes
$p_a$	Transmission probability of newly arrived packets
$q_r$	Retransmission probability of backlogged packets
$P$	Transition matrix
$\pi(p_a, q_r)$	Steady-state probability
$T$	Generic slot time. It is equal to two slot in the case of ZigZag, and one slot otherwise

Table 1: Notation and terminology

rate is the same for all users. Table 1, shows some notations used in the paper.

Let  $Q_a(i, N)$  be the probability that  $i$  unbacklogged nodes transmit a packet in a given time slot. we have:

$$Q_a(i, N) = \binom{M-N}{i} (1-p_a)^{(M-N-i)} p_a^i, \quad (1)$$

and let  $Q_r(i, N)$  be the probability that  $i$  backlogged nodes retransmit their packet in a given time slot.

$$Q_r(i, N) = \binom{N}{i} (1-q_r)^{(N-i)} q_r^i. \quad (2)$$

We consider the stochastic process  $N$  as the number of backlogged packets in the system. Our model is given as a Markov process for every  $q_r$  in the range  $]0, 1]$ . The Markov property holds since the future and the past states are conditionally independent given the present state. Therefore, our stochastic process  $N$  is a Markov chain with a finite state space  $E = \{0, 1, \dots, M\}$ . The transition diagram of the proposed Markov chain is given in Fig. 2, and transition probabilities are expressed as follows:

$$P_{(N, N+i)} = \begin{cases} Q_a(i, N), & 3 \leq i \leq M-N, \\ Q_a(1, N) (1 - Q_r(0, N) - Q_r(1, N)), & i = 1, \quad 2 \leq N \leq M-1, \\ Q_a(2, N) (1 - Q_r(0, N)), & i = 2, \quad 1 \leq N \leq M-2, \\ Q_a(0, N) [1 - Q_r(1, N) - Q_r(2, N)] \\ + Q_a(1, N) Q_r(0, N) + Q_a(2, N) Q_r(0, N), & i = 0, \\ Q_a(0, N) Q_r(1, N) + Q_a(1, N) Q_r(1, N) & i = -1, \quad 1 \leq N \leq M, \\ Q_a(0, N) Q_r(2, N), & i = -2, \quad 2 \leq N \leq M, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

**Lemma 1.** For every retransmission probability  $q_r$  in the range  $]0, 1]$ , the proposed Markov chain is ergodic and admits a unique stationary distribution.

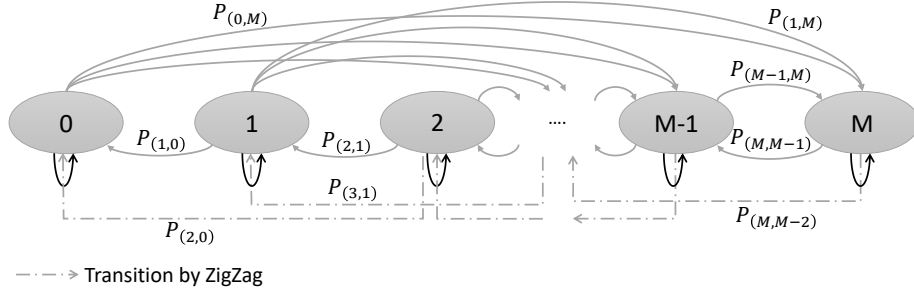
*Proof.* We assume that  $q_r = 0$  and  $p_a > 0$ . If we start from any given state  $i$  where  $i = 0, \dots, M-3$ , the Markov chain will end up on one of the following absorbing states:  $M-2$ ,  $M-1$  and  $M$  with non-null probability. Thus, a unique stationary distribution exists if and only if  $q_r$  is within the range  $]0, 1]$ . Therefore, we shall exclude the case of  $q_r = 0$  in order to maintain the ergodicity of the Markov chain and then the uniqueness of the stationary distribution. It is trivial to show that the Markov chain is ergodic since all states are aperiodic and positive recurrent for every  $q_r \in ]0, 1]$ .  $\square$

**Remark 2.** We emphasize that when  $q_r = 0$  and when the Markov chain ends up on the absorbing state  $M-1$ , the system throughput will equal the arrival probability  $p_a$  because the new arrived packets of the remaining unbacklogged node will be transmitted in free-collision mode. However, if we reach the absorbing state  $M$ , the system throughput will equal 0. Hereafter, we denote  $\pi_i(p_a, q_r)$  where  $i \in \{0, 1, \dots, M\}$ , as the steady distribution of the Markov chain.

We compute the steady-state of our Markov process using the following system:

$$\begin{cases} \pi(p_a, q_r) = \pi(p_a, q_r) P(p_a, q_r), \\ \pi_N(p_a, q_r) \geq 0, \\ \sum_{N=0}^M \pi_N(p_a, q_r) = 1. \end{cases} \quad N = 0, \dots, M, \quad (4)$$

A simple iterative method can be followed in order to compute the steady-state distribution from the system (4).



**Figure. 2:** Markov transition diagram of the proposed team problem, where the state represents the number of backlogged packets in the system.

## V. Performance Metrics of the System

### A. Normalized throughput

We define the throughput as the average number of the successfully transmitted packets by the users in a given slot time  $T$ .

$$Th(p_a, q_r) = \frac{1}{T} \sum_{N=1}^M [P_{succ}^N \pi_N(p_a, q_r) + (Q_a(1, 0) + 2Q_a(2, 0)) \pi_0(p_a, q_r)] \quad (5)$$

$$= \frac{p_a}{T} \sum_{N=0}^M (M - N) \pi_N(p_a, q_r), \quad (6)$$

where

$$P_{succ}^N = Q_a(0, N)Q_r(1, N) + Q_a(1, N)Q_r(0, N) + 2Q_a(0, N)Q_r(2, N) + 2Q_a(2, N)Q_r(0, N) + 2Q_a(1, N)Q_r(1, N), \quad (7)$$

and

$$T = 1 + P_{ZigZag}. \quad (8)$$

$P_{ZigZag}$  is the ZigZag probability, and it is defined by:

$$P_{ZigZag} = \sum_{N=0}^M [Q_a(0, N)Q_r(2, N) + Q_a(2, N)Q_r(0, N) + Q_a(1, N)Q_r(1, N)] \pi_N(p_a, q_r). \quad (9)$$

### B. Access delay

We define the delay as the average time required by a station to transmit a data packet from the source to the destination. We can derive its expression using Little's result. Thus, we have:

$$D(p_a, q_r) = 1 + \frac{S_B(p_a, q_r)}{Th(p_a, q_r)}, \quad (10)$$

where  $S_B(p_a, q_r) = \sum_{N=0}^M N \pi_N(p_a, q_r)$  is the average number of backlogged packets.

## VI. Performance of Backlogged Packets

### A. Backlogged throughput

The throughput of backlogged packets is defined as the number of backlogged packets that have been transmitted over the channel. The ability to transmit the awaiting packets is very interesting in real-time services. Let  $Th_{succ}(p_a, q_r)$  be the average throughput of newly arrived packets that has been transmitted. The average throughput for backlogged packets is given by:

$$TH_B(p_a, q_r) = Th(p_a, q_r) - Th_{succ}(p_a, q_r), \quad (11)$$

where

$$Th_{succ}(p_a, q_r) = \frac{1}{T} \sum_{N=0}^{M-1} [Q_a(1, N)Q_r(0, N) + Q_a(1, N)Q_r(1, N) + 2Q_a(2, N)Q_r(0, N)] \pi_N(p_a, q_r). \quad (12)$$

### B. Backlogged delay

The access delay is defined as the time elapsed from the moment of the transmission until the reception of the packet, and it is given by:

$$D_B(p_a, q_r) = \frac{Th_B(p_a, q_r) + S_B(p_a, q_r)}{Th_B(p_a, q_r)} \quad (13)$$

$$= 1 + \frac{S_B(p_a, q_r)}{Th_B(p_a, q_r)}. \quad (14)$$

### C. Backlog level

We define the backlog level as the ratio of backlogged nodes among the total number  $M$ , and it is given by:

$$Backlog(p_a, q_r) = \left( \frac{S_B(p_a, q_r)}{M} \times 100 \right) \%. \quad (15)$$

We emphasize that the backlog level in the system is very important in ensuring fairness between newly arrived and backlogged packets.

## VII. Optimization Analysis of the Cooperative Model

In a cooperative game scenario, all the active nodes seek to optimize the same utility function. Thus, we can express the

team problem as follows:

$$\begin{aligned} & \max_{q_r \in [\epsilon, 1]} \text{Utility}(p_a, q_r) \\ & \text{subject to} \begin{cases} \pi(p_a, q_r) = \pi(p_a, q_r) \cdot P(p_a, q_r), \\ \pi_N(p_a, q_r) \geq 0, N = 0, \dots, M, \\ \sum_{N=0}^M \pi_N(p_a, q_r) = 1. \end{cases} \end{aligned} \quad (16)$$

As introduced in our previous work [1], each transmission and retransmission is associated with a cost, which is denoted by  $C$ . We consider that the cost is normalized within the range  $[0, 1]$  where 1 represent the maximum cost and 0 represents a free cost. Now, we can express the utility function of the team as:

$$\text{Utility}(p_a, q_r) = (1 - c)Th(p_a, q_r) - cq_r \sum_{N=1}^M N \pi_N(p_a, q_r). \quad (17)$$

**Remark 3.** Equation (17) arises from the fact that the node earns  $(1 - c) \geq 0$  for every successful transmission, where 1 represents the packet successfully transmitted and  $-c$  is the cost of its transmission. Whereas in the case of collision (i.e. the second part of the equation), only the transmission cost is paid.

**Lemma 4.** For all  $q_r \in [\epsilon, 1]$  where  $\epsilon > 0$ , the problem (16) has a unique solution.

*Proof.* According to Lemma 1 the stationary distribution  $\pi(p_a, q_r)$  exists and is unique. Moreover,  $\pi(p_a, q_r)$  are continuous over  $0 < q_r \leq 1$  which is not a close interval, therefore a solution of the problem (16) may not exist. However, as we restrict to the closed interval  $[\epsilon, 1]$  where  $\epsilon > 0$ , an optimal solution indeed exists. Therefore, for any  $\gamma > 0$ , there exists some  $q_r^* > 0$  which is  $\gamma$ -optimal. ( $q_r^* > 0$  is said to be  $\gamma$ -optimal if it satisfies  $\text{utility}(p_a, q_r^*) \geq \text{utility}(p_a, q_r^*) - \gamma$  for all  $q_r \in [\epsilon, 1]$ .)  $\square$

## VIII. Enhanced Pricing Mechanism

In this section, we provide an enhancement of the pricing mechanism proposed in section VII. We associate a cost to each event respectively as follows:

- $C_s$ : Price for a new arrived packet crowned with success.
- $C_b$ : Price for successful transmission of backlogged packet.
- $C_{idle}$ : Price for idling.
- $C_c$ : Price for collision.

where all the prices are normalized in the range  $[0, 1]$ .

The utility function of the new proposed game is given by:

$$\text{Utility}(p_a, q_r) = C_s P_{succN} + C_b P_{succB} + C_{idle} P_{idle} + C_c P_c. \quad (18)$$

Scheme	1	2	3
$C_s$	0.1	0.3	0.1
$C_b$	0.1	0.1	0.1
$C_{idle}$	0.5	0.5	0.3
$C_c$	0.5	0.5	0.8

Table 2: Parameters used in the numerical results of different schemes

$P_{succN}$  is the probability that a newly arrived packet will be transmitted successfully at the first attempt, and it is given by:

$$P_{succN} = \sum_{N=0}^M [Q_a(1, N)Q_r(0, N) + Q_a(2, N)Q_r(0, N) + Q_a(1, N)Q_r(1, N)] \pi_N(p_a, q_r). \quad (19)$$

$P_{succB}$  is the probability that a backlogged packet will be successfully transmitted in a given slot. It is given by:

$$P_{succB} = \sum_{N=0}^M [Q_a(0, N)Q_r(1, N) + Q_a(0, N)Q_r(2, N) + Q_a(1, N)Q_r(1, N)] \pi_N(p_a, q_r). \quad (20)$$

$P_{idle}$  is the idle probability and it is defined as the probability that no one is transmitting or retransmitting over the channel. It is given by:

$$P_{idle} = \sum_{N=0}^M Q_a(0, N)Q_r(0, N) \pi_N(p_a, q_r). \quad (21)$$

Finally,  $P_c$  is the collision probability and it is given by:

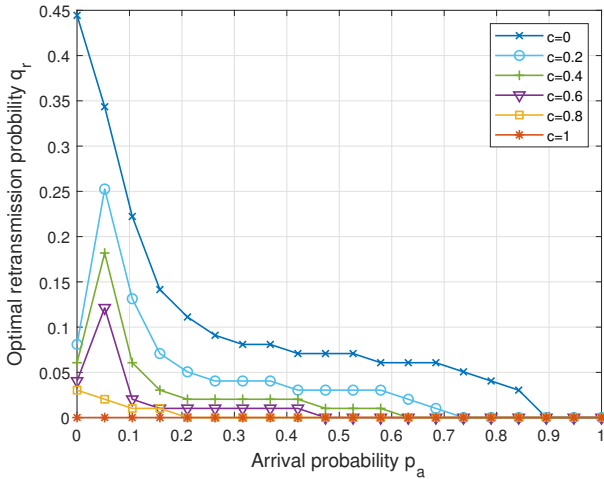
$$P_c = 1 - P_{succN} - P_{succB} - P_{idle}. \quad (22)$$

The optimal policy to save energy and to avoid collisions is to not transmit at all. However, this is not the optimal policy that we are interested in since we aim to maximize the throughput and minimize the delay. In the following results, we plot the performance metrics of different cost configurations.

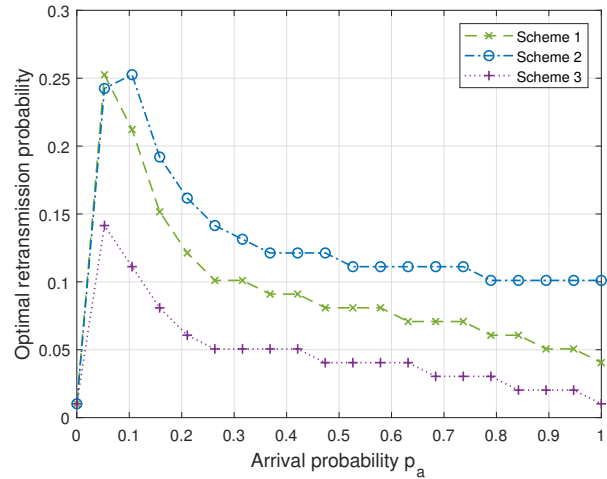
## IX. Numerical Results and Discussions

In this section, we evaluate the performance of the two pricing strategies under different load conditions. We set the number of nodes to 10, and we vary the arrival probability  $p_a$  from 0 to 1. We set  $\epsilon = 10^{-4}$ .

In the first approach, we consider a fixed cost in the set  $C = \{0, 0.2, 0.4, 0.6, 0.8, 1\}$  for every transmission and retransmission attempt, and we compare the performance metrics obtained for all arrival probabilities. In the second approach, we adopt a different pricing strategy in order to improve the system performance. Therefore, we associate to every newly arrived packet which is crowned with success a cost denoted by  $C_s$ ; for a successful transmission of a backlogged packet, we associate a cost  $C_b$ . In the case of no transmission, we associate a cost  $C_{idle}$ , and finally, we associate a cost

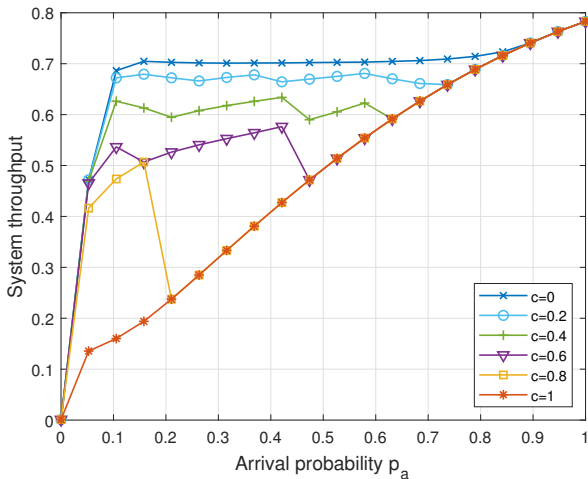


(a) Old pricing mechanism [1]

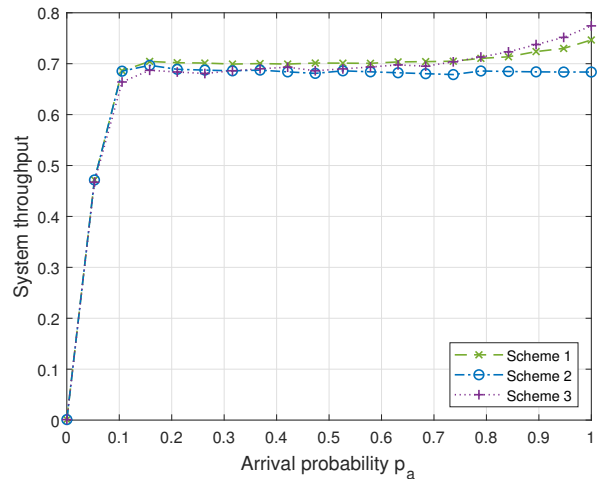


(b) Improved pricing mechanism

**Figure 3:** Optimal retransmission probability as a function of arrival probability for both pricing mechanisms



(a) Old pricing mechanism [1]



(b) Improved pricing mechanism

**Figure 4:** Normalized throughput of the system, which includes the backlogged and newly transmitted packets

$C_c$  for the collision. The numerical results are obtained using Matlab, and the parameters used for the second approach are listed in Table 2.

Figure 3 shows the optimal retransmission probability as a function of the arrival probability for different pricing mechanisms. In the old approach, we notice that the optimal retransmission probability is considerably lower compared to the enhanced pricing strategy. The reason behind this behavior is straightforward: In the old approach, users do not charge any cost when they do not transmit. Therefore, they prefer to hold on the transmission rather than attempting to transmit. On the other hand, in the old approach, the optimal retransmission probability goes to 0 in heavy load conditions (i.e. when  $p_a \rightarrow 0$ ) regardless of the price used. In fact, this is not efficient because when the retransmission probability  $q_r^* = 0$  the backlogged packets will not be transmitted which yields a huge delay. On the contrary, our enhanced pricing strat-

egy keeps the optimal retransmission probability above 0 for the three different pricing schemes. We can see however that scheme 2 provides the highest retransmission probability followed by the scheme 1 and 3 respectively.

In Fig. 4, we show the overall system throughput as a function of arrival rate. The throughput is given in equation (6) and it includes the newly arrived packets that are transmitted successfully at the first attempt and also the backlogged packets that are successfully transmitted after a previous collision. We emphasize that the throughput, as well as the other performance metrics, are derived from the optimal retransmission probability depicted in Fig. 3. In the old pricing strategy, the throughput decreases as the price increases, which is expected since the corresponding retransmission probability shown in Fig. 3a decreases dramatically as the price increase. This can be explained by the fact that users do not take the risk of transmitting a packet when the price is high. Instead, they prefer to

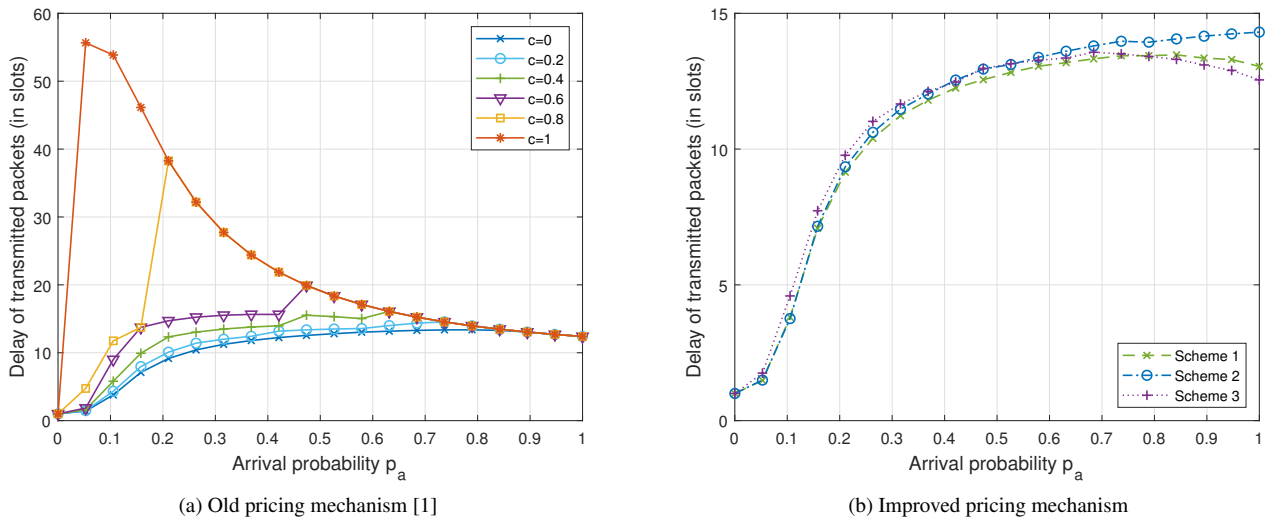


Figure 5: Delay of transmitted packets, which is given in terms of slots

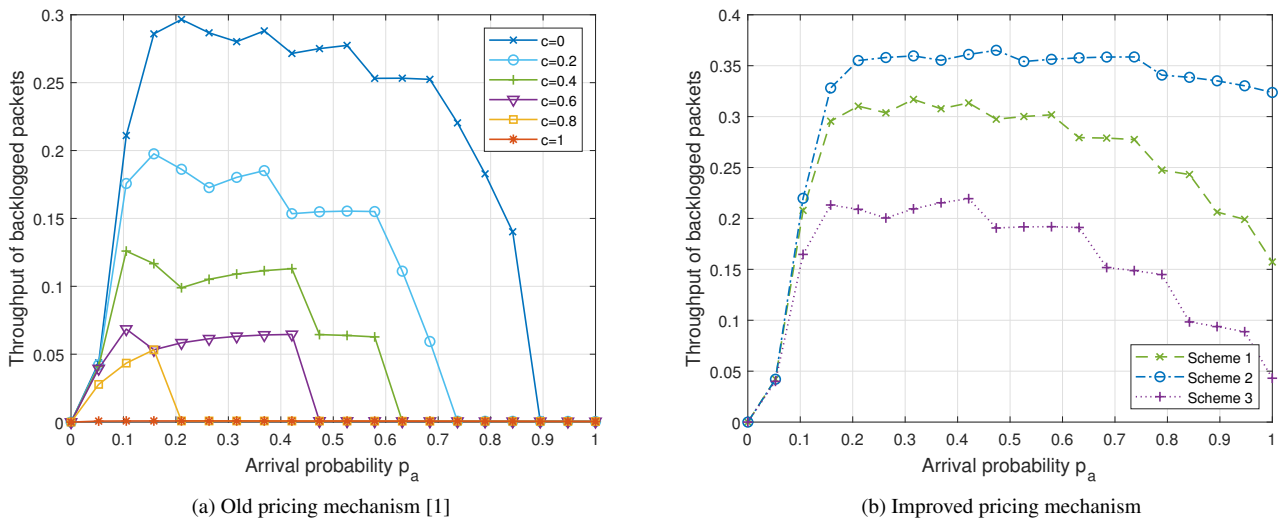


Figure 6: Throughput of backlogged packets

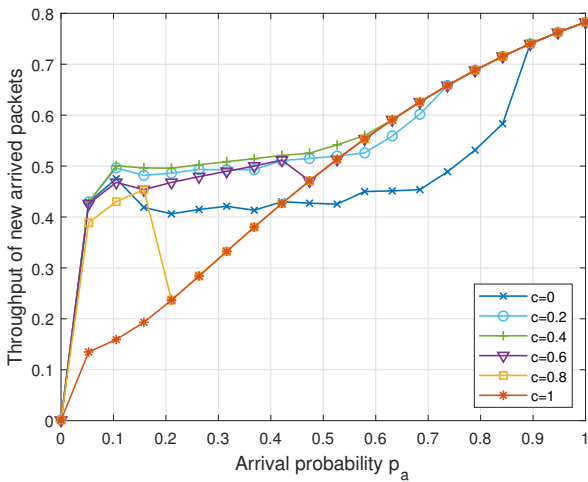
not transmit, which negatively affects the system throughput. However, in the second approach, the system throughput stays at a high value for the tree schemes with a slight difference in heavy load conditions.

We plot in Fig. 5 the delay of transmitted packets as a function of the arrival probability. The delay is given in terms of slots and represents the time required for a packet to be transmitted from its source to the destination. When a high price is used in the old approach, the delay increase due to the considerably low transmission policy as we have seen in Fig. 3. However, the enhanced approach provides a lower delay compared to the old one, and this is for the three proposed schemes.

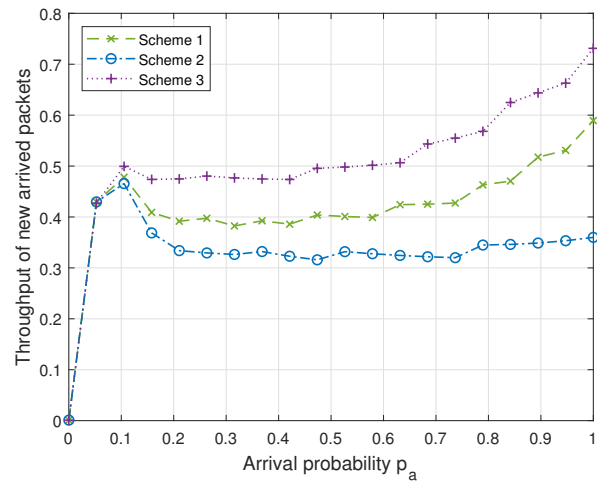
Figure 6 shows the throughput of backlogged packets as a function of the arrival probability. In the case of a low price, the backlogged throughput in the old approach increases then decreases for the arrival probability. When we increase the price, the backlogged throughput decreases dramatically, es-

pecially in the higher price case (i.e.  $C = 1$ ), where the backlogged throughput becomes 0 which means no backlogged packet is transmitted over the channel. However, in the improved approach, the backlogged throughput never drops to 0 which is very impressive. The three proposed schemes provide different backlogged throughput values. In particular, the second scheme ensures the highest value compared to the first and the third one.

In Fig. 7, we plot the throughput of packets that are arrived and successfully delivered in the first attempt. We notice that different costs provide different throughput values. In light traffic, increasing the cost results in a throughput drop. Whereas, in high traffic load, increasing the price improves the throughput but at the expense of the backlogged throughput. On the other hand, the results depicted in Fig. 7b show a reasonable throughput without sacrificing the backlogged packets. Unlike the results shown in Fig. 6, we notice that scheme 2

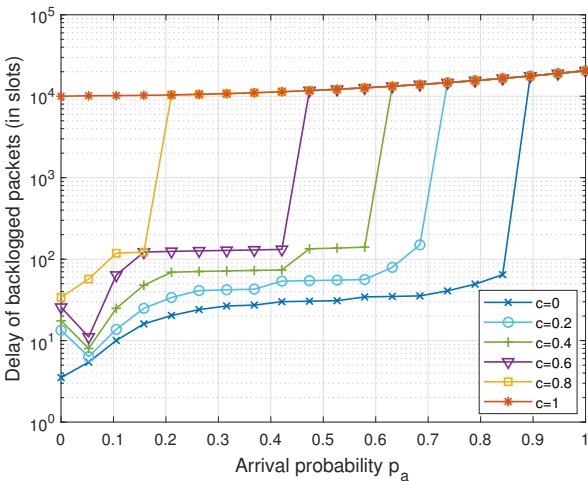


(a) Old pricing mechanism [1]

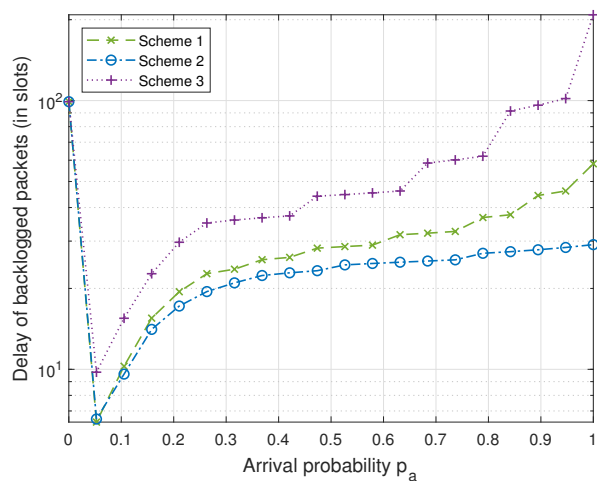


(b) Improved pricing mechanism

**Figure. 7:** Normalized throughput of newly arrived packets



(a) Old pricing mechanism [1]



(b) Improved pricing mechanism

**Figure. 8:** Delay of backlogged packets, which is given in terms of slots

provides the lowest throughput compared to the third scheme. In fact, scheme 2 prefers the backlogged packets and scheme 3 prefers newly arrived ones, whereas scheme 1 compromises between the two schemes.

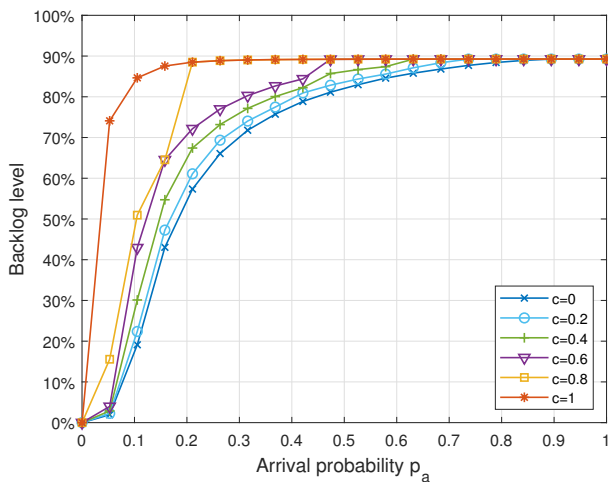
Figure 8 shows the delay of backlogged packets as a function of the arrival probability. In the old approach, increasing the price yields a huge delay ( $10^4$  slots). In heavy load conditions, the delay becomes huge even when no cost is included ( $C = 0$ ). However, as seen in Fig. 4, the corresponding throughput of  $C = 0$  is very good. This tradeoff between the throughput and backlogged delay is a very challenging task since we are interested in maximizing the throughput and meanwhile minimizing the backlogged delay which does not seem to be done using the old approach. However, Our approach is very efficient in addressing this tradeoff. Figure 8b, shows the delay of backlogged packets using the improved pricing mechanism. Compared to the old approach, it pro-

vides a backlogged delay of less than 100 slots for the three proposed schemes while maintaining a maximal throughput.

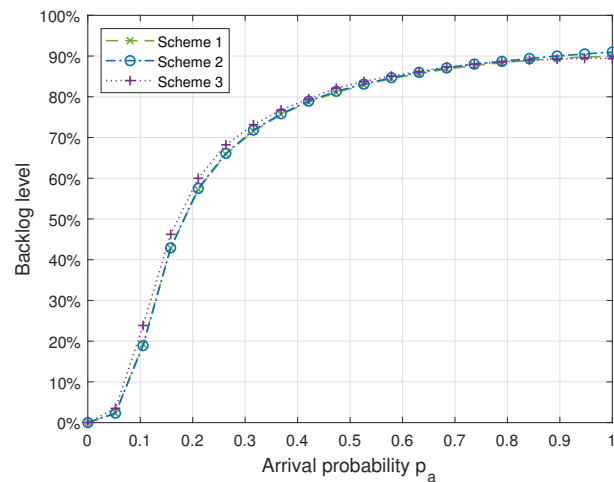
Finally, we plot in Fig. 9 the backlog level which is defined as the percentage of backlogged users among all contended users. It also refers to the number of packets that require re-transmission over all packets in the system. Figure 9a shows that, in the old approach, the backlog level of the system goes up very quickly to 90%. However, the three schemes of the enhanced approach achieve a 90% of the backlog level only in heavy load conditions which is expected since the collision rate increases due to the increasing number of transmission attempts.

### X. Conclusion

We have introduced in this paper a new pricing strategy in order to further improve the performance of the Slotted ALOHA



(a) Old pricing mechanism [1]



(b) Improved pricing mechanism

**Figure. 9:** Backlog level, which is defined as the ratio of backlogged nodes among the total number  $M$ .

mechanism combined with ZigZag Decoding. First, we developed a cooperative game model where all users optimize the same utility function. Then, using a Markov process model, we derived all the performance metrics of interest. Our model includes throughput and delay analysis of both backlogged and newly arrived packets.

In our previous work [1], we associated a cost to every transmission and retransmission attempt. Using this approach, we found that users prefer to not transmit, fearing potential collisions. This behavior leads to a huge increase in the backlogged delay and a dramatic decrease in the system performance. To address this problem, we proposed a new pricing strategy by imposing four different costs which we denoted by:  $C_s$ ,  $C_b$ ,  $C_{idle}$  and  $C_c$ . This approach allowed us to control the users' behavior and therefore improve the performance of the system. Then, we proposed three different schemes. Our main goal was twofold: (1) to improve the system performance in terms of throughput and delay; and (2) to address the existing tradeoff between backlogged and newly arrived packets. In our analysis, we also included a comparative analysis with our old pricing approach [1]. Our results show that the proposed approach is very efficient in terms of all performance metrics.

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## Author Biographies



**Ahmed Boujnoui** received his Bachelor's degree in Mathematics and Applications at the Faculty of Sciences, Ibn Zohr University, Agadir, Morocco in 2013. In 2016, he obtained his Master's degree in Mathematics and Applications from the University of Hassan First of Settat, Morocco. He is currently a Ph.D. student in Applied Mathematics at Computer, Networks, Mobility and Modeling laboratory, Faculty of Sciences and Techniques, Hassan First of Settat, Morocco. His research interests include game theory, Markov chains, stochastic processes, queuing theory, wireless networks, and mathematical modeling of the IEEE 802.11 networks.



**Dr. Abdellah Zaaloul** has a PhD (Doctorat d'Etat) in Applied Mathematics, option modeling and performance evaluation of computer communication networks, in the Department of Mathematics and Computer at Faculty of Sciences and Techniques (FSTS), Settat, Morocco. He received his M.Sc. degree in Mathematical and Applications engineering from the Hassan 1st University, Faculty of Sciences and Techniques (FSTS), Settat, Morocco, in 2011. And he has been working as a professor of mathematics in high school from 1992 until May 2018, in Settat, Morocco. And Since that date, he has been working as a Professor at the department of Mathematics Faculty of Legal, Economic and Social Sciences of Ait Melloul, Ibn Zohr University, Agadir, Morocco. Currently, he is a member of the e-NGN research group. Dr. Abdellah ZAALOU's interests lie in the areas

of modeling and performance evaluation of communication networks, mobile communications networks, cloud computing and security, queueing theory and game theory, stochastic control, networking games.



**Dr. Abdelkrim Haqiq** has a High Study Degree (Diplôme des Etudes Supérieures de troisième cycle) and a PhD (Doctorat d'Etat), both in the field of modeling and performance evaluation of computer communication networks, from Mohammed V University, Faculty of Sciences, Rabat, Morocco. Since September 1995 he has been working as a Professor at the department of Applied Mathematics and Computer at the Faculty of Sciences and Techniques, Settat, Morocco.

He is the Director of Computer, Networks, Mobility and Modeling laboratory: IR2M. He is an IEEE senior member and an IEEE Communications Society member. He is also a member of Machine Intelligence Research Labs (MIR Labs), Washington, USA and a member of the International Association of Engineers (IAENG). He was a co-director of a NATO Multi-Year project entitled "Cyber Security Analysis and Assurance using Cloud-Based Security Measurement system", having the code: SPS-984425. Prof. Abdelkrim HAQIQ's interests lie in the areas of modeling and performance evaluation of communication networks, mobile communications networks, cloud computing and security, emergent technologies, Markov Chains and queueing theory, Markov decision processes theory, and game theory. He is the author and co-author of more than 170 papers (international journals and conferences/workshops). He supervised 16 PhD thesis and co-supervised 3 others. Actually, he is supervising and co-supervising more than 8 PhD thesis. He is an associate editor of the International Journal of Computer International Systems and Industrial Management Applications (IJCISM), an editorial board member of the International Journal of Intelligent Engineering Informatics (IJIEI) and of the International Journal of Blockchains and Cryptocurrencies (IJBC), an international advisory board member of the International Journal of Smart Security Technologies (IJSST) and of the International Journal of Applied Research on Smart Surveillance Technologies and Society (IARSSTS). He is also an editorial review board of the International Journal of Fog Computing (IJFC) and of the International Journal of Digital Crime and Forensics (IJDCF). Prof. Abdelkrim HAQIQ was a chair and a technical program committee chair/member of many international conferences and scientific events. He was also a Guest Editor and Co-Editor of special issues of some journals, books and international conference proceedings.