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Modeling the coexistence of LECIM ALOHA PCA and CSMA/CA in unslotted IEEE 802.15.4 networks

Jorge Ortín, José Ramón Gállego, María Canales

***Abstract*—Wireless sensor networks are pivotal in critical infrastructure monitoring due to their cost-effectiveness and real-time data processing capabilities. The IEEE 802.15.4 standard, especially the Low Energy Critical Infrastructure Monitoring (LECIM) portions, plays a crucial role in enhancing monitoring efficiency of critical infrastructure. LECIM introduces Priority Channel Access (PCA) for traffic prioritization, particularly beneficial for critical information transmission. This paper investigates the coexistence of CSMA/CA-based nodes transmitting non-priority data and LECIM ALOHA PCA nodes handling critical information in unslotted IEEE 802.15.4 networks. We propose a novel theoretical framework to evaluate the performance of a heterogeneous LECIM network, where some nodes use the CSMA/CA channel access method while others use LECIM ALOHA PCA. The performance is measured in terms of reliability, delay and power consumption. Validation of the theoretical framework is conducted using a system-level simulator.**

***Index Terms*—wireless sensor networks, unslotted IEEE 802.15.4, Low Energy Critical Infrastructure Monitoring (LECIM), carrier sense multiple access with collision avoidance (CSMA/CA), ALOHA, priority channel access (PCA).**

I. INTRODUCTION

WIRELESS sensor networks (WSNs) play a vital role in the field of critical infrastructure monitoring by offering a cost-effective and flexible solution for real-time data acquisition and processing [1]. These networks, composed of spatially distributed autonomous sensors that communicate wirelessly, collect and process data about physical or environmental conditions, such as temperature, sound, vibration, pressure, or pollutants. The wireless nature of these networks allows for easy installation, scalability, and access to remote or hazardous locations. The application of WSNs in critical infrastructure monitoring, such as power grids, water supply systems, and transportation networks, has significantly enhanced operational efficiency and safety. By providing real-time, accurate, and comprehensive data, these networks enable early detection of anomalies, predictive maintenance, and efficient resource management. In the context of WSNs, the IEEE 802.15.4 standard [2], particularly the portions dedicated to Low Energy Critical Infrastructure Monitoring (LECIM), has emerged as a key enabler for energy-efficient and reliable monitoring of critical infrastructure [3]. Proposed use cases of LECIM networks include oil and gas pipeline monitoring, water leak detection, soil monitoring, inventory control with event-driven queries, and building monitoring with both time and event-driven data queries [4].

The IEEE 802.15.4 standard defines the operation of low-rate wireless networks in resource-constrained environments. The standard offers two primary modes of operation: the beacon-enabled mode and the non-beacon-enabled mode. In the beacon-enabled mode, a coordinator periodically transmits beacons, enabling devices to synchronize and schedule their transmissions. This mode is advantageous for applications requiring low latency and synchronized communication. Conversely, the non-beacon-enabled mode allows devices to transmit data without synchronization to a central coordinator, providing flexibility and reduced energy consumption in scenarios where strict timing constraints are not critical. In the beacon-enabled mode, both contention-based and contention-free access mechanisms are permitted, whereas in the non-beacon-enabled mode, only contention-based access methods are considered. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is the primary contention-based channel access mechanism in both beacon-enabled (slotted) and non-beacon-enabled (non-slotted) modes.

In addition, other modes of operation have been added to the IEEE 802.15.4 standard, such as Time-Slotted Channel Hopping (TSCH), which introduces deterministic scheduling and channel hopping mechanisms to enhance network reliability and efficiency, or the Deterministic and Synchronous Multi-channel Extension (DSME), which supports multi-channel operation in contention-free periods. Both TSCH and DSME modes target time-critical applications requiring high reliability and deterministic low latency, such as industrial automation or health care monitoring. They both require sophisticated slot scheduling mechanisms and are not primarily focused on energy efficiency [5].

On the other hand, the IEEE 802.15.4 standard defines specific physical (PHY) and Medium Access Control (MAC) layer features for LECIM networks, designed to support the requirements of critical infrastructure monitoring applications. These functional enhancements provide low-cost, low-data-rate, energy-efficient wireless access for battery-operated devices. One of these enhancements is the inclusion of Priority

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This research was supported by Grant PID2022-136476OB-I00 funded by MICIU/AEI/10.13039/501100011033/FEDER EU, ERDF/EU, and Gobierno de Aragón (reference group T31_20R). *(Corresponding author: José Ramón Gállego.)*

J. Ortín is with the Centro Universitario de la Defensa, 50090 Zaragoza, Spain and also with the Aragón Institute of Engineering Research, Universidad de Zaragoza, 50018 Zaragoza, Spain

J. R. Gállego and M. Canales are with the Aragón Institute of Engineering Research, Universidad de Zaragoza, 50018 Zaragoza, Spain (e-mail: jrgalleg@unizar.es).

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Channel Access (PCA) mechanisms to allow certain types of traffic to have priority access to the medium. Thus, LECIM networks allow the transmission of two types of data: priority (or critical) data using either CSMA/CA with PCA or LECIM ALOHA PCA channel access methods; and normal (or non-priority) data using either CSMA/CA or ALOHA channel access methods [6]. This diversity of channel access mechanisms underscores the importance of studying and analyzing their coexistence to understand the performance implications in each scenario. In the context of critical infrastructure monitoring, a common scenario involves the coexistence of nodes that prioritize channel access with PCA and nodes that access without priority.

The motivation for this work lies in analyzing the coexistence between both types of nodes. Specifically, we focus on a LECIM network with a star topology operating in a non-beacon-enabled mode, as this mode has lower energy consumption. We assume that nodes monitoring critical information access the channel using LECIM ALOHA PCA due to its lower energy consumption and delay, while nodes monitoring non-priority information access the channel via CSMA/CA. To the best of our knowledge, our work is the first to investigate the coexistence and performance of LECIM ALOHA PCA and CSMA/CA access methods in unslotted IEEE 802.15.4 networks. The main contributions of this work can be summarized as follows:

- We evaluate the performance of a heterogeneous LECIM network where nodes using the CSMA/CA channel access method and nodes using the LECIM ALOHA PCA channel access method coexist.
- We analyze and compare the performance and both types of channel access methods in terms of reliability, delay and power consumption.
- We propose a comprehensive theoretical framework to derive the performance of both types of channel access methods and validate it against a system-level, discrete-event simulator.

In summary, this work uniquely addresses the coexistence of LECIM ALOHA PCA and CSMA/CA access methods in unslotted IEEE 802.15.4 networks, a topic unexplored in previous research. Our contribution lies not only in evaluating the performance of heterogeneous networks under these conditions, but also in providing a comprehensive theoretical framework capable of accurately modeling and predicting their behavior, offering new insights into the operation of heterogeneous LECIM networks.

The remaining of the paper is organized as follows: Section II presents the related work. Section III includes the system model, describing the involved channel access methods and deriving the analytical model of their behaviour when they coexist. Section IV presents the obtained results, and finally, Section V summarizes the main conclusions.

II. RELATED WORK

The IEEE 802.15.4 standard has been the subject of numerous studies due to its wide application in WSNs and Internet of Things (IoT). A significant portion of this research has focused on the development of analytical models to evaluate the performance of its MAC protocol, both in slotted as in non-slotted CSMA/CA modes.

Regarding slotted CSMA/CA mode, authors in [7] focus on quantifying the behavior of key networking metrics of IEEE 802.15.4 beacon-enabled nodes. They correct and extend previous analyses based on Markovian modeling, such as the probability that a node senses the channel busy is not constant for all the stages of the backoff procedure or the probability of obtaining transmission access to the channel depends on the number of nodes that is simultaneously sensing it. [8] presents a generalized analysis of the slotted IEEE 802.15.4 MAC protocol in terms of reliability, delay, and energy consumption through a Markov chain, taking into account retry limits, acknowledgements, and unsaturated traffic. In [9], the superframe structure of IEEE 802.15.4 is analyzed through a four-dimensional Markov chain. The effects of the inactive portion of a superframe on average delay, and average power consumption are evaluated. [10] proposes two semi-Markov chains and one macro-Markov chain to predict throughput, packet delay and energy consumption of heterogeneous, unsaturated, unacknowledged IEEE 802.15.4 beacon-enabled networks. In [11], a modified IEEE 802.15.4 MAC protocol is proposed that dynamically adjusts the Contention Access Period (CAP) and utilizes the Guaranteed Time Slot (GTS) as per the application requirement. A five dimensional Markov chain model is proposed for unsaturated data traffic conditions with variable CAP and analysis is performed for both saturation and non-saturation mode.

As for the non-slotted CSMA/CA mode concerns, different analysis have been also conducted. For instance, a Markov chain model for unslotted, acknowledged 802.15.4 CSMA/CA is proposed in [12] for unsaturated nodes considering a deterministic idle time after every transmission. [13] analyzes the performance of a modified MAC mechanism assuming homogeneous and Poisson traffic. A different approach is followed in [14], where the modeling of unslotted CSMA/CA is carried out using Event Chains Computation instead of Markov chains, showing that this approach better models the case where nodes start reporting data simultaneously when an event is detected. In [15], a discrete Markov chain based model to analyze energy consumption for unsatured traffic under unslotted CSMA/CA access is proposed. [16] focuses on modeling heterogeneous traffic for acknowledged unslotted 802.15.4 networks. Based on this work, in [17] a Markovian model to evaluate the performance of heterogeneous unslotted 802.15.4 networks with classes of nodes with different packet generation rate is proposed. It captures an accurate calculation of the channel busy probability during the Clear Channel Assessment (CCA) process. In [18], a two-dimensional Markov chain based model is proposed to analyse the performance of MAC-layer. Collision probability is derived from the model and is combined with the PHY layer frame error rate (FER) to obtain cross-layer FER, which is used to propose a cross-layer energy model. Authors in [19] introduce a modified analysis model based on three-dimensional Markov chain for unslotted CSMA/CA access which focuses on the calculation of delay and reliability by using retransmissions and PHY layer packet

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loss. A trade-off analysis between average delay and reliablity using the maximum number of retransmissions is introduced. [20] presents a analytical Markov model for the IEEE 802.15.4 protocol in non-beacon enabled mode for periodic traffic in time critical sensor network applications considering reneging packets which exceed their time to live. The proposed model is applied to the both acknowledged and non-acknowledged modes under heterogeneous traffic.

Some recent works are specifically focused on the LECIM mode and the PCA access [21], [22], [6], [23]. The work in [21] evaluates through simulation a LECIM network that employs a Slotted Aloha with PCA channel access scheme in conjunction with non-saturated traffic conditions. In [22], authors propose a Markov-chain-based analytical model for analyzing the performance of both unslotted and slotted CSMA/CA with and without PCA for different traffic classes. Authors in [6] and [23] extend the model proposed in [22] in beacon-enabled and non-beacon-enabled modes respectively under saturated traffic conditions assuming fading channel environment which causes transmission errors in addition to the collisions considered in [22]. However, neither of these studies accounts for retransmissions in the PCA access.

III. System model

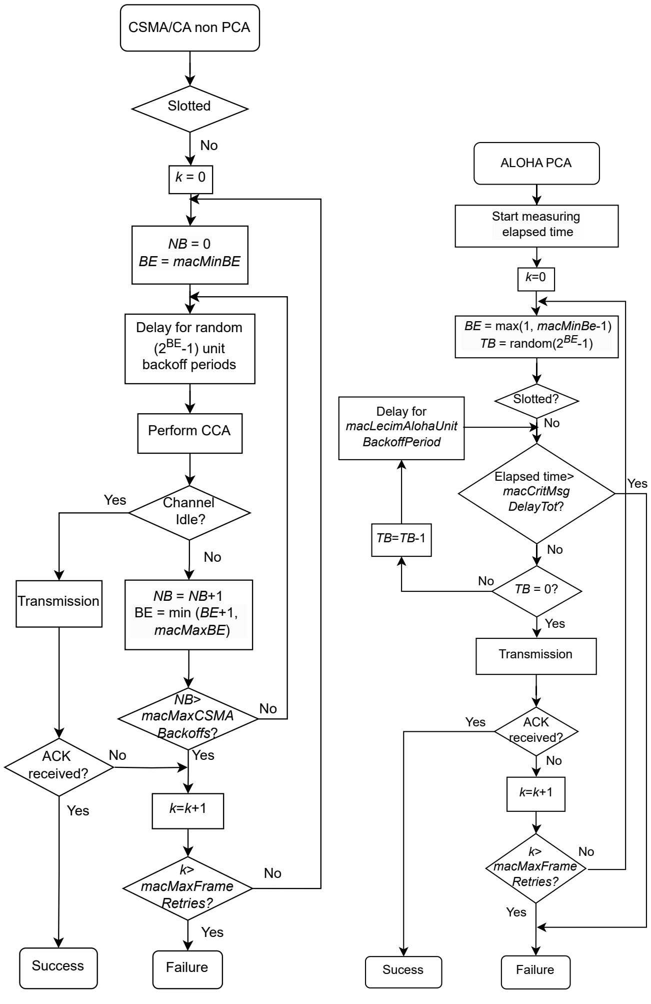
In this paper, we investigate a LECIM network operating in non-beacon-enabled mode, where a set of nodes transmits monitoring data to an IEEE 802.15.4 coordinator via direct links. These nodes fall into two categories: nodes monitoring non-priority information, which utilize the unslotted CSMA/CA channel access method; and nodes generating priority data, which employ the unslotted LECIM ALOHA PCA method.

Specifically, we examine a network comprising N_A nodes transmitting priority information and using the LECIM ALOHA PCA channel access method (in the following, ALOHA nodes) and N_C nodes transmitting non-priority information and using the CSMA/CA channel access method (in the following, CSMA/CA nodes). Both ALOHA and CSMA/CA nodes generate packets following a Poisson process of rates λ_A and λ_C respectively. The airtime of these packets is fixed at T_{pkt}. This models a critical infrastructure monitoring scenario, where traffic can be randomly and independently generated by the nodes depending on events occurring in the monitored area. The performance metrics that we aim to obtain with the proposed model are the probability of a successful transmission, the average delay and the average power consumption for both ALOHA and CSMA/CA nodes. Tables I and II summarize the notation used in this section.

Below, we provide a brief overview of both channel access methods in accordance with the standard 802.15.4 definition.

A. Channel Access Methods for LECIM Networks in Non-Beacon-Enabled Mode

Firstly, we describe the unslotted CSMA/CA channel access method, which is illustrated in Figure 1a. When a node intends to transmit a packet, it initiates a backoff process for a random number of slots within the range $\left[0, 2^{BE}-1\right]$, where BE represents the backoff exponent initialized to *macMinBe*. The slot duration, denoted as *aUnitBackoffPeriod*, comprises the time required for a CCA, *phyCcaDuration*, along with the transition time from the listening to the transmission mode, *aTurnaroundTime*. Subsequently, the node performs a CCA to ascertain channel availability. If the channel is busy, the node increments BE by 1 until it reaches *macMaxBe*, and retries the backoff procedure with the updated BE value. This process continues until the number of failed CCAs exceeds *macMaxCsmaBackoffs*, at which point the packet is discarded due to a channel access failure. Conversely, if the channel is clear, the node transmits the packet and awaits its acknowledgment (ACK). The transmission is successful when the node receives the ACK. If the ACK is not received, indicating a collision or other errors, the MAC layer resets BE to *macMinBe* and retries the CSMA/CA mechanism to retransmit the packet. The parameter *macMaxFrameRetries* dictates the maximum number of retransmission attempts, and if this threshold is surpassed, the packet is discarded due to reaching the retry limit.



(a) CSMA/CA (b) ALOHA PCA

Fig. 1. Flow-charts for (a) unslotted CSMA/CA and (b) ALOHA PCA channel access methods.

For the LECIM ALOHA PCA channel access method, which is illustrated in Figure 1b, the backoff exponent BE

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TABLE I
Notation: System level, PHY and MAC layer parameters and model events

Parameter	Definition
	System level, PHY and MAC layer parameters
BE	Backoff exponent of the backoff proccess
D_{max}	(*macCritMsgDelayTol*) Maximum delay for critical packets
λ_A	Traffic generation rate of the LECIM ALOHA PCA nodes
λ_C	Traffic generation rate of the CSMA/CA nodes
m	(*macMaxCsmaBackoffs*) Maximum number of failed CCAs
m_{max}	(*macMaxBe*) Maximum value of BE
m_{min}	(*macMinBe*) Minimum and initial value of BE
n	(*macMaxFrameRetries*) Maximum number of retransmission attempts
N_A	Number of LECIM ALOHA PCA nodes in the network
N_C	Number of CSMA/CA nodes in the network
P_{backoff}	Power consumption in backoff state
P_{cca}	Power consumption in channel sensing state
P_{idle}	Power consumption in idle state
P_{rx}	Power consumption in receiving state
P_{tx}	Power consumption in transmitting state
T_{ack}	ACK airtime
T_{aifs}	ACK Inter-Frame Spacing
T_{cca}	(*phyCcaDuration*) Time required to perform a CCA
T_{ifs}	Inter-Frame Spacing
T_{pkt}	Data packet airtime
$T_{\text{s},A}$	(*macLecimAlohaUnitBackffPeriod*) Slot duration for the LECIM ALOHA PCA channel access method
$T_{\text{s},C}$	(*aUnitBackoffPeriod*) Slot duration for the CSMA/CA channel access method
T_{ta}	(*aTurnaroundTime*) Transition time from the listening to the transmission mode
	Model events
$\mathcal{A}_{\text{at init}}$	Collision of an ALOHA transmission at its inception
$\mathcal{A}_{\text{after init}}$	Collision of an ALOHA transmission after its inception
$\mathcal{B}_A$	Busy channel due to an ALOHA transmission (packet or ACK)
$\mathcal{B}_C$	Busy channel due to a CSMA/CA transmission (packet or ACK)
$\mathcal{B}_{A,\text{pkt}}$	Busy channel due to an ALOHA packet transmission
$\mathcal{B}_{A,\text{ack}}$	Busy channel due to an ALOHA ACK transmission
$\mathcal{B}_{C,\text{pkt}}$	Busy channel due to a CSMA/CA packet transmission
$\mathcal{B}_{C,\text{ack}}$	Busy channel due to a CSMA/CA ACK transmission
$\mathcal{C}_A$	Collision between a CSMA/CA transmission (packet or ACK) and an ALOHA transmission (packet or ACK)
$\mathcal{C}_C$	Collision between a CSMA/CA transmission (packet or ACK) and another CSMA/CA transmission (packet or ACK)
$\mathcal{D}_i$	CSMA/CA node detects the channel idle at the $(i+1)$-th CCA attempt
$\mathcal{F}_j$	CSMA/CA packet discarded due to channel access failure after j previous collisions
$\mathcal{R}_i$	An ALOHA packet is transmitted i times
$\mathcal{S}_j$	Successful CSMA/CA transmission after j previous collisions
$\mathcal{T}_{A,\text{pkt}}$	There is an ongoing ALOHA packet transmission on the channel when an ALOHA node starts transmitting a packet
$\mathcal{T}_{A,\text{ack}}$	There is an ongoing ALOHA ACK transmission on the channel when an ALOHA node starts transmitting a packet
$\mathcal{T}_{C,\text{pkt}}$	There is an ongoing CSMA/CA packet transmission on the channel when an ALOHA node starts transmitting a packet
$\mathcal{T}_{C,\text{ack}}$	There is an ongoing CSMA/CA ACK transmission on the channel when an ALOHA node starts transmitting a packet

is initialized to the maximum of (*macMinBe*-1) or 1 before the initial transmission attempt and remains constant for subsequent retransmissions. Similar to unslotted CSMA/CA, the node undergoes a backoff process for a random number of slots within the range $[0, 2^{BE}-1]$. Upon expiration of this time interval and if the time since the packet generation does not exceed the parameter *macCritMsgDelayTol*, the packet is transmitted directly without conducting any CCA. Another difference compared to CSMA/CA is the slot duration, which is *macLecimAlohaUnitBackoffPeriod* instead of *aUnitBackoffPeriod*, where *macLecimAlohaUnitBackoffPeriod* is set to accommodate the transmission of a maximum-sized MAC Protocol Data Unit (MPDU) along with the associated Inter-Frame Spacing (IFS) and ACK.

For ease of reference throughout this paper, we represent the IEEE 802.15.4 MAC parameters mentioned in this section us-

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TABLE II
NOTATION: MODEL VARIABLES, PROBABILITIES AND PERFORMANCE METRICS

Parameter	Definition
Model variables, probabilities and performance metrics	
α	Probability that a CSMA/CA node encounters a busy channel during its CCA
B_j	Time elapsed from the start of the j-th backoff process until the end of the j-th attempt to transmit an ALOHA packet
D_A	Cumulative time an ALOHA packet spends in the backoff process and in failed transmissions
$\mathrm{E}\left[n_A\right]$	Average number of transmissions for a packet from an ALOHA node
$\mathrm{E}\left[n_{\text{suc},A}\right]$	Average number of transmissions of a successfully transmitted ALOHA packet
L	Duration measured in slots of a successful CSMA/CA transmission
L_{pkt}	Duration measured in slots of a packet
ω	Probability that there is an ongoing transmission on the channel when an ALOHA node starts transmitting a packet
P_A	Power consumption of an ALOHA node
P_C	Power consumption of a CSMA/CA node
$P_{\text{cf},C}$	Probability of a CSMA/CA packet being discarded due to a channel access failure
$P_{\text{col},A}$	Collision probability for a transmission from an ALOHA node
$P_{\text{col},C}$	Collision probability for a transmission from a CSMA/CA node
$P_{\text{ed},A}$	Probability of an ALOHA packet being discarded due to exceeding the maximum allowed delay D_{max}
$P_{\text{rl},A}$	Probability of an ALOHA packet being discarded due to reaching the retry limit
$P_{\text{rl},C}$	Probability of a CSMA/CA packet being discarded due to reaching the retry limit
$P_{\text{suc},A}$	Probability of a successfully transmitted ALOHA packet
$P_{\text{suc},C}$	Probability of a successfully transmitted CSMA/CA packet
q	Packet generation probability in the idle state for CSMA/CA nodes
q_{cf}	Probability of having a packet ready to transmit after a channel access failure for CSMA/CA nodes
q_{rl}	Probability of having a packet ready to transmit after retry limit for CSMA/CA nodes
q_{suc}	Probability of having a packet ready to transmit after a successful transmission for CSMA/CA nodes
T_b	Time spent in backoff or sensing states during the CSMA/CA procedure, given no channel access failure has occurred
$T_b^{(i)}$	Time spent in backoff or sensing states during the CSMA/CA procedure under event $\mathcal{D}_i$
$T_{\text{backoff},A}$	Time an ALOHA node spends in backoff between two consecutive packets
$T_{\text{cf},C}$	Delay of a CSMA/CA packet discarded due to a channel access failure
$T_{\text{cf},C}^{(j)}$	Delay experienced by a CSMA/CA packet when event $\mathcal{F}_j$ occurs
$T_{\text{inter},A}$	Time between ALOHA packets
$T_{\text{rl},A}$	Delay of an ALOHA packet discarded due to a retry limit
$T_{\text{rl},C}$	Delay of a CSMA/CA packet discarded due to a retry limit
$T_{\text{rx},A}$	Time an ALOHA node spends receiving between two consecutive packets
$T_{\text{suc},A}$	Delay of a successfully transmitted ALOHA packet
$T_{\text{suc},C}$	Delay of a successfully transmitted CSMA/CA packet
$T_{\text{suc},C}^{(j)}$	Delay of a successfully transmitted CSMA/CA packet when event S_j occurs
$T_{\text{tx},A}$	Time an ALOHA node spends transmitting between two consecutive packets
τ	Probability that a CSMA/CA node performs a CCA in a randomly selected time slot
W_i	Maximum value of the backoff counter at backoff stage i

ing the following notations: $m_{\text{min}} =$ *macMinBE*, $m_{\text{max}} =$ *macMaxBE*, $m =$*macMaxCSMABackoffs*, $n =$ *macMaxFrameRetries*, $T_{\text{cca}} =$ *phyCcaDuration*, $T_{\text{ta}} =$ *aTurnaroundTime*, $T_{\text{s},C} =$ *aUnitBackoffPeriod*, $T_{\text{s},A} =$ *macLecimAlohaUnitBackoffPeriod* and $D_{\text{max}} =$ *macCritMsgDelayTol*.

B. Outline of the system model

To obtain the probability of a successful transmission, the average delay and the average power consumption for ALOHA and CSMA/CA nodes, we first need to solve a system of five nonlinear equations with five variables that allow us to determine the operating point of the system. The variables of this system of equations are as follows: i) the probability τ that a CSMA/CA node performs a CCA in a randomly selected time slot, ii) the probability α that a CSMA/CA node encounters a busy channel during its CCA, iii) the collision probability for a transmission from a CSMA/CA node $P_{\text{col},C}$, iv) the probability ω that there is an ongoing transmission on the channel when an ALOHA node starts transmitting a packet, and v) the average number of transmissions for a packet from an ALOHA node $\mathrm{E}\left[n_A\right]$ (which in turn depends on the collision probability for a transmission from an ALOHA node). Once these variables are obtained, the system's performance metrics are derived from them. In each of the following subsections, an equation of the system of equations is derived. To do this, we calculate the value of each variable in the system based on the others.

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The final subsections correspond to the calculation of the performance metrics based on the system variables.

In the following, we will use the terms CSMA/CA packet and ALOHA packet to refer to the transmission of a packet from a CSMA/CA or ALOHA node to the coordinator, respectively. Similarly, we will use the terms CSMA/CA ACK and ALOHA ACK to refer to the transmission of an ACK from the coordinator to a CSMA/CA or ALOHA node, respectively.

C. Markov chain for CSMA/CA nodes and derivation of τ

To model the backoff, sensing and transmitting states of CSMA/CA nodes, we employ the Markov chain illustrated in Figure 2. This approach, extensively utilized in existing literature [8], [10], [12], [13], [15]–[17], [19], [22], [24], is presented here with the minimal set of equations necessary to depict the inner state behavior of CSMA/CA nodes, without a complete derivation. Each state in this chain is represented by a tuple (i, j, k), where i denotes the backoff stage, j the backoff counter and k the retransmission counter. The values of i and k are constrained by parameters m and n, respectively. Similarly, j ranges from 0 to $W_i = 2^{BE_i} - 1$, where BE_i corresponds to the backoff exponent for stage i. In states where $j = 0$ the node conducts a CCA.

States $(-1, j, k)$ represent a successful transmission, where $0 \leq j < L$, and L denotes the duration measured in slots of a successful transmission. This value is determined by $L = (T_{\text{pkt}} + T_{\text{aifs}} + T_{\text{ack}} + T_{\text{ifs}})/T_{\text{s},C}$, where T_{aifs} is the ACK Inter-Frame Spacing (AIFS), T_{ack} is the ACK airtime, and T_{ifs} denotes the Inter-Frame Spacing. Likewise, states $(-2, j, k)$ correspond to a collided transmission. We assume both events have equal duration, as typically the ACK timeout is set to $T_{\text{aifs}} + T_{\text{ack}} + T_{\text{ifs}}$. Notably, the interpretation of counter j depends on the value of i; it serves as either the backoff counter (for $i \geq 0$), or a counter traversing the slots of a successful/collided transmission (when $i = -1, -2$).

The traffic generation for CSMA/CA nodes is modeled with a packet generation probability in the idle state, denoted as q. Additionally, we incorporate probabilities for having a packet ready to transmit after a successful transmission q_{suc}, after a channel access failure q_{cf} and after a retry limit q_{rl}. These probabilities are derived in Subsection III-H.

From this model, we can calculate the probability τ that a CSMA/CA node conducts CCA in a randomly selected time slot. According to [16], this probability is expressed as:

$$\tau = \left(\frac{1 - \alpha^{m+1}}{1 - \alpha}\right)\left(\frac{1 - y^{n+1}}{1 - y}\right) p(0, 0, 0) \tag{1}$$

where $p(0, 0, 0)$ denotes the steady-state probability of state $(0, 0, 0)$ and $y = P_{\text{col},C}\left(1 - \alpha^{m+1}\right)$. The expression for $p(0, 0, 0)$ is provided in (2), where $W_0 = 2^{m_{\text{min}}} - 1$ is the maximum possible value of the backoff counter at stage $i = 0$.

The probability τ, as defined in the preceding equations, depends on two key probabilities: α, representing the probability that a CSMA/CA node encounters a busy channel during CCA, and $P_{\text{col},C}$, denoting the collision probability for a transmission from a CSMA/CA node. We proceed to derive both of these probabilities.

D. Derivation of the probability α that a CSMA/CA node encounters a busy channel during its CCA

To compute α, we first decompose it as the sum of the probabilities of the different transmitting events that can cause the channel to be busy when a CSMA/CA node performs its CCA, obtaining the following result:

Lemma 1. *Let $\mathcal{B}_{A,pkt}$, $\mathcal{B}_{A,ack}$, $\mathcal{B}_{C,pkt}$ and $\mathcal{B}_{C,ack}$ represent the events of the channel being busy when a CSMA/CA node performs its CCA due to the transmission of an ALOHA packet, of an ALOHA ACK, of a CSMA/CA packet and of a CSMA/CA ACK respectively, then the probability α can be expressed as*

$$\begin{aligned} \alpha = {} & P\left(\mathcal{B}_{A,pkt}\right) + P\left(\mathcal{B}^C_{A,pkt} \cap \mathcal{B}_{A,ack}\right) \\ & + P\left(\mathcal{B}^C_{A,pkt} | \mathcal{B}_{C,pkt}\right) P\left(\mathcal{B}_{C,pkt}\right) \\ & + P\left(\mathcal{B}^C_{A,pkt} | \mathcal{B}_{C,ack}\right) P\left(\mathcal{B}_{C,ack}\right) \end{aligned} \tag{3}$$

Proof: See Appendix A.

Note that in Lemma 1, $P(\mathcal{B}_{A,\text{pkt}})$ represents the probability that at least one ALOHA packet is being transmitted when a CSMA/CA node performs its CCA. This could include other transmissions besides the ALOHA packet(s), such as ALOHA ACKs or CSMA/CA packets or ACKs. $P(\mathcal{B}^C_{A,\text{pkt}} \cap \mathcal{B}_{A,\text{ack}})$ denotes the probability that an ALOHA ACK is being transmitted and that no ALOHA packets are being transmitted at the moment of the CCA. $P(\mathcal{B}^C_{A,\text{pkt}} | \mathcal{B}_{C,\text{pkt}})$ indicates the probability that no ALOHA packets are being transmitted, given that a CSMA/CA packet is being transmitted, when the CCA is performed. $P(\mathcal{B}_{C,\text{pkt}})$ corresponds to the probability that the channel is busy due to the transmission of at least one CSMA/CA packet. $P(\mathcal{B}^C_{A,\text{pkt}} | \mathcal{B}_{C,\text{ack}})$ represents the probability that no ALOHA packets are being transmitted, given that a CSMA/CA ACK is being transmitted, when the CCA is performed. Finally, $P(\mathcal{B}_{C,\text{ack}})$ denotes the probability that the channel is busy due to the transmission of a CSMA/CA ACK.

The next step is to obtain the expression for each of the probabilities that appear in (3). For the case of $P(\mathcal{B}^C_{A,\text{pkt}} \cap \mathcal{B}_{A,\text{ack}})$, $P(\mathcal{B}^C_{A,\text{pkt}} | \mathcal{B}_{C,\text{pkt}})$ and $P(\mathcal{B}^C_{A,\text{pkt}} | \mathcal{B}_{C,\text{ack}})$ we have the following Lemmas.

Lemma 2. *Let $\mathrm{E}\left[n_A\right]$ be the average number of transmissions for an ALOHA packet*[1] *and ω be the probability that there is an ongoing transmission on the channel when an ALOHA node starts transmitting a packet, then the probability $P(\mathcal{B}^C_{A,pkt} \cap \mathcal{B}_{A,ack})$ can be expressed as*

$$\begin{aligned} P(\mathcal{B}^C_{A,pkt} \cap \mathcal{B}_{A,ack}) = {} & \lambda_A N_A \mathrm{E}\left[n_A\right] \left(T_{ack} + T_{aifs}\right) \\ & \times e^{-\lambda_A N_A \mathrm{E}[n_A](T_{ack} + T_{aifs})} \\ & \times (1 - \omega) \\ & \times e^{-\lambda_A (N_A - 1)\mathrm{E}[n_A](T_{pkt} + T_{cca})} \end{aligned} \tag{4}$$

Proof: See Appendix B.

Lemma 3. *Let assume that a CSMA/CA node performs its CCA. The probability that there are no ALOHA packet transmissions on the channel at that moment, given that a*

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[1] This value can exceed 1 due to retransmissions.

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This article has been accepted for publication in IEEE Internet of Things Journal. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2025.3539786

$$p(0,0,0)=\begin{cases}\Big[\frac{1}{2}\left(\frac{1-(2\alpha)^{m+1}}{1-2\alpha}W_0+\frac{1-\alpha^{m+1}}{1-\alpha}\right)\frac{1-y^{n+1}}{1-y}+L\left(1-\alpha^{m+1}\right)\frac{1-y^{n+1}}{1-y} \\ +\frac{1-q_{\mathrm{cf}}}{q}\frac{\alpha^{m+1}(1-y^{n+1})}{1-y}+\frac{1-q_{\mathrm{rl}}}{q}y^{n+1}+\frac{1-q_{\mathrm{suc}}}{q}(1-P_{\mathrm{col},C})\frac{(1-\alpha^{m+1})(1-y^{n+1})}{1-y}\Big]^{-1}, \text{ if } m<\hat{m}=m_{\max}-m_{\min} \\ \Big[\frac{1}{2}\left(\frac{1-(2\alpha)^{\hat{m}+1}}{1-2\alpha}W_0+\frac{1-\alpha^{\hat{m}+1}}{1-\alpha}+\left(2^{m_{\max}+1}+1\right)\alpha^{\hat{m}+1}\frac{1-\alpha^{m-\hat{m}}}{1-\alpha}\right)\frac{1-y^{n+1}}{1-y}+L\left(1-\alpha^{m+1}\right) \\ \times\frac{1-y^{n+1}}{1-y}+\frac{1-q_{\mathrm{cf}}}{q}\frac{\alpha^{m+1}(1-y^{n+1})}{1-y}+\frac{1-q_{\mathrm{rl}}}{q}y^{n+1}+\frac{1-q_{\mathrm{suc}}}{q}(1-P_{\mathrm{col},C})\frac{(1-\alpha^{m+1})(1-y^{n+1})}{1-y}\Big]^{-1}, \text{ otherwise}\end{cases} \tag{2}$$

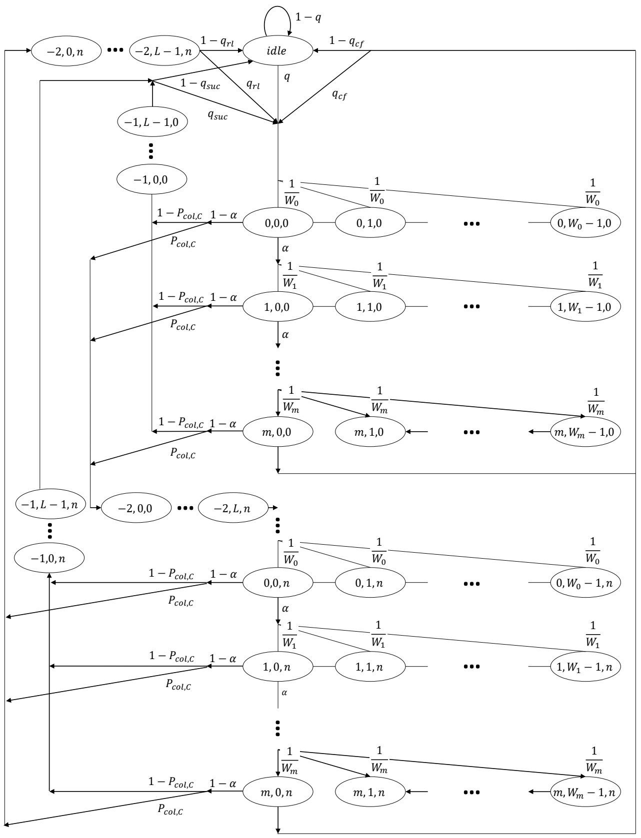

Fig. 2. Markov chain model of CSMA/CA algorithm for transmitting nodes in unslotted IEEE 802.15.4 MAC.

CSMA/CA packet is being transmitted, $P(\mathcal{B}_{A,pkt}^{C}|\mathcal{B}_{C,pkt})$, can be expressed as

$$P\left(\mathcal{B}_{A,pkt}^{C}|\mathcal{B}_{C,pkt}\right)=\frac{T_{ta}}{T_{pkt}+T_{cca}}e^{-\lambda_A N_A \mathrm{E}[n_A](T_{cca}+T_{pkt})} + \frac{e^{-\lambda_A N_A \mathrm{E}[n_A]T_{ta}}-e^{-\lambda_A N_A \mathrm{E}[n_A](T_{pkt}+T_{cca})}}{\lambda N_A \mathrm{E}\left[n_A\right]\left(T_{pkt}+T_{cca}\right)} \tag{5}$$

Proof: See Appendix C.

Lemma 4. *Let assume that a CSMA/CA node performs its CCA. The probability that there are no ALOHA packet transmissions on the channel at that moment, given that a CSMA/CA ACK is being transmitted, $P(\mathcal{B}_{A,pkt}^{C}|\mathcal{B}_{C,ack})$, can be expressed as*

$$P\left(\mathcal{B}_{A,pkt}^{C}|\mathcal{B}_{C,ack}\right)= \frac{e^{-\lambda_A N_A \mathrm{E}[n_A]T_{aifs}}-e^{-\lambda_A N_A \mathrm{E}[n_A](T_{ack}+T_{cca}+T_{aifs})}}{\lambda N_A \mathrm{E}\left[n_A\right]\left(T_{ack}+T_{cca}\right)} \tag{6}$$

Proof: See Appendix D.

Finally, using the previous lemmas, the following expression for α can be obtained.

Theorem 5. *Let assume that a CSMA/CA node performs its CCA. Then, the probability that this CSMA/CA node finds the channel busy is given by* (7).

Proof: See Appendix E.

As can be seen, the probability α is dependent on the probabilities τ and ω, as well as $\mathrm{E}\left[n_A\right]$.

E. Derivation of the collision probability for a CSMA/CA transmission $P_{col,C}$

To compute the collision probability for a CSMA/CA transmission, we assume that a collision occurs if either the packet or its corresponding ACK collides, obtaining the following result:

Theorem 6. *The collision probability for a CSMA/CA transmission $P_{col,C}$ can be expressed as:*

$$P_{col,C}=1-(1-\tau)^{N_C-1}e^{-\lambda_A N_A \mathrm{E}[n_A](T_{pkt}+T_{ta}+T_{ack}+T_{aifs})} \tag{8}$$

Proof: See Appendix F.

In this case, the probability $P_{\mathrm{col},C}$ is dependent on the probability τ, as well as $\mathrm{E}\left[n_A\right]$.

F. Derivation of the probability that there is an ongoing transmission on the channel when an ALOHA node starts transmitting a packet ω

The computation of ω is similar to the computation of α, but with some key distinctions. Here, we are concerned with the probability that there is an ongoing transmission when an ALOHA node begins transmitting a packet, whereas α represents the probability that there is an ongoing transmission when the CSMA/CA node performs its CCA. This leads to two main differences: Firstly, in ω, we calculate the probability that there is a transmission on the channel at a random time instant, whereas in α, we compute the probability that there is a transmission on the channel within a random time interval of duration T_{cca}. Secondly, in ω, the node that accesses the channel is an ALOHA node instead of a CSMA/CA node, thus the potential number of transmitting CSMA/CA and ALOHA nodes also differs. Once these two considerations are taken into account, the computation of ω follows the same approach as for α, obtaining the following result:

Theorem 7. *Let assume that an ALOHA node starts transmitting a packet, then the probability that there is an ongoing transmission on the channel ω is given by* (9).

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$$\begin{aligned}\alpha = 1 &- e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{cca}})} + (1-\omega)\,\lambda_A N_A \mathrm{E}\left[n_A\right](T_{\text{ack}}+T_{\text{aifs}}) e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{ack}}+T_{\text{aifs}})} e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{cca}})} \\ &+ \left(\frac{T_{\text{ta}}}{T_{\text{pkt}}+T_{\text{cca}}} e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}+T_{\text{pkt}})} + \frac{e^{-\lambda_A N_A \mathrm{E}[n_A] T_{\text{ta}}} - e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{cca}})}}{\lambda_A N_A \mathrm{E}\left[n_A\right](T_{\text{pkt}}+T_{\text{cca}})}\right)\left(1-(1-\tau)^{N_C-1}\right)(1-\alpha)\frac{T_{\text{pkt}}}{T_{\text{s},C}} \\ &+ \frac{e^{-\lambda_A N_A \mathrm{E}[n_A] T_{\text{aifs}}} - e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{ack}}+T_{\text{cca}}+T_{\text{aifs}})}}{\lambda_A N_A \mathrm{E}\left[n_A\right](T_{\text{ack}}+T_{\text{cca}})}\left(N_C-1\right)\tau\left(1-\tau\right)^{N_C-2}(1-\alpha)\frac{T_{\text{ack}}}{T_{\text{s},C}} e^{-\lambda_A N_A \mathrm{E}[n_A]\left(T_{\text{pkt}}+T_{\text{ta}}\right)}\end{aligned} \tag{7}$$

$$\begin{aligned}\omega = 1 &- e^{-\lambda_A (N_A-1)\mathrm{E}[n_A] T_{\text{pkt}}} + (1-\omega)\,\lambda_A\left(N_A-1\right)\mathrm{E}\left[n_A\right](T_{\text{ack}}+T_{\text{aifs}}) e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{\text{ack}}+T_{\text{aifs}})} e^{-\lambda_A (N_A-2)\mathrm{E}[n_A] T_{\text{pkt}}} \\ &+ \left(\frac{T_{\text{ta}}}{T_{\text{pkt}}} e^{-\lambda_A (N_A-1)\mathrm{E}[n_A] T_{\text{pkt}}} + \frac{e^{-\lambda_A (N_A-1)\mathrm{E}[n_A] T_{\text{ta}}} - e^{-\lambda_A (N_A-1)\mathrm{E}[n_A] T_{\text{pkt}}}}{\lambda_A\left(N_A-1\right)\mathrm{E}\left[n_A\right] T_{\text{pkt}}}\right)\left(1-(1-\tau)^{N_C}\right)(1-\alpha)\frac{T_{\text{pkt}}}{T_{\text{s},C}} \\ &+ \frac{e^{-\lambda_A (N_A-1)\mathrm{E}[n_A] T_{\text{aifs}}} - e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{\text{ack}}+T_{\text{aifs}})}}{\lambda_A\left(N_A-1\right)\mathrm{E}\left[n_A\right] T_{\text{ack}}} N_C\tau\left(1-\tau\right)^{N_C-1}(1-\alpha)\frac{T_{\text{ack}}}{T_{\text{s},C}} e^{-\lambda_A (N_A-1)\mathrm{E}[n_A]\left(T_{\text{pkt}}+T_{\text{ta}}\right)}\end{aligned} \tag{9}$$

Proof: See Appendix G.

As can be seen, the probability ω is dependent on the probabilities τ and ω, as well as $\mathrm{E}\left[n_A\right]$. Comparing (7) and (9), it is worth noting that if $N_A \gg 1$, $N_C \gg 1$, and $T_{\text{cca}} \ll T_{\text{pkt}}$,then $\alpha \approx \omega$. Consequently, we do not need to compute ω explicitly in that case.

G. Derivation of the collision probability for an ALOHA transmission $P_{col,A}$ and of the average number of transmissions $\mathrm{E}\left[n_A\right]$ for an ALOHA packet

As in the case of CSMA/CA transmissions, to compute the collision probability for ALOHA transmissions, we assume that a collision occurs if either the packet or its corresponding ACK collides, obtaining the following result:

Theorem 8. *The collision probability for an ALOHA transmission is given by:*

$$P_{col,A} = 1 - (1-\omega)\, e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{pkt}+T_{aifs}+T_{ack})} \tag{10}$$

and the average number of transmissions for an ALOHA packet is:

$$\mathrm{E}\left[n_A\right] = \frac{1-P_{col,A}^{n+1}}{1-P_{col,A}} \tag{11}$$

Proof: See Appendix H.

Equations (1), (7), (8), (9) and (11) constitute a system of coupled nonlinear equations with variables τ, α, ω and $\mathrm{E}\left[n_A\right]$ which can be numerically solved to determine the network's operational point. Subsequently, various performance metrics can be derived from these equations.

H. Derivation of the performance metrics for CSMA/CA nodes

To begin, we derive the probability of a packet being discarded for a CSMA/CA node, considering two cases: discard due to reaching the retry limit ($P_{\text{rl},C}$) and discard due to channel access failure ($P_{\text{cf},C}$). From the Markov chain illustrated in Figure 2, these probabilities are given by:

$$P_{\text{cf},C} = \frac{\alpha^{m+1}\left(1-\left(P_{\text{col},C}\left(1-\alpha^{m+1}\right)\right)^{n+1}\right)}{1-P_{\text{col},C}\left(1-\alpha^{m+1}\right)} \tag{12}$$

and

$$P_{\text{rl},C} = \left(P_{\text{col},C}\left(1-\alpha^{m+1}\right)\right)^{n+1} \tag{13}$$

With these, the probability of a successfully transmitted CSMA/CA packet is given by $P_{\text{suc},C} = 1 - P_{\text{cf},C} - P_{\text{rl},C}$.

Next, we present expressions for the average delay experienced by a CSMA/CA packet in different scenarios, whether it is successfully transmitted or discarded due to a channel access failure or reaching the retry limit[2]. We denote $T_{\text{suc},C}$ as the delay of a successfully transmitted packet, $\mathcal{S}_j$ as the event of a successful transmission after j previous collisions, and $T_{\text{suc},C}^{(j)}$ as the delay experienced under $\mathcal{S}_j$. Following the approach in [16], we have:

$$\mathrm{E}\left[T_{\text{suc},C}\right] = \sum_{j=0}^{n} P(\mathcal{S}_j)\mathrm{E}\left[T_{\text{suc},C}^{(j)}\right] \tag{14}$$

where $P(\mathcal{S}_j)$ is given by

$$P(\mathcal{S}_j) = \frac{\left(1-P_{\text{col},C}\left(1-\alpha^{m+1}\right)\right)P_{\text{col},C}^{j}\left(1-\alpha^{m+1}\right)^{j}}{1-\left(P_{\text{col},C}\left(1-\alpha^{m+1}\right)\right)^{n+1}} \tag{15}$$

and

$$\mathrm{E}\left[T_{\text{suc},C}^{(j)}\right] = (j+1)\left(L\cdot T_{\text{s},C} + \mathrm{E}\left[T_b\right]\right) \tag{16}$$

where T_b is the time spent in backoff or sensing states during the CSMA/CA procedure, given no channel access failure has occurred. The expected value of T_b is given by:

$$\mathrm{E}\left[T_b\right] = \sum_{i=0}^{m} P(\mathcal{D}_i)\mathrm{E}\left[T_b^{(i)}\right] \tag{17}$$

where $P(\mathcal{D}_i)$ is the probability of finding the channel idle at the $(i+1)$-th attempt, and $T_b^{(i)}$ is the time spent in backoff or sensing states under event $\mathcal{D}_i$. The probability $P(\mathcal{D}_i)$ can be calculated as:

$$P(\mathcal{D}_i) = \frac{\alpha^i}{\sum_{k=0}^{m}\alpha^k} = \alpha^i\frac{1-\alpha}{1-\alpha^{m+1}} \tag{18}$$

---

[2] We consider only the time from the instant the packet enters the backoff process for the first time until an ACK is received or until it is discarded (i.e., we do not include queuing time in this analysis).

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This article has been accepted for publication in IEEE Internet of Things Journal. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2025.3539786

and $\mathrm{E}[T_b^{(i)}]$ is given by:

$$\mathrm{E}\left[T_b^{(i)}\right] = (i+1)T_{\mathrm{cca}} + \sum_{k=0}^{i} T_{\mathrm{s},C}\frac{W_k-1}{2} \tag{19}$$

To determine the delay experienced by a packet discarded due to a channel access failure, denoted as $T_{\mathrm{cf},C}$, we can derive it using the same approach employed in computing $T_{\mathrm{suc},C}$:

$$\mathrm{E}\left[T_{\mathrm{cf},C}\right] = \sum_{j=0}^{n} P(\mathcal{F}_j)\mathrm{E}\left[T_{\mathrm{cf},C}^{(j)}\right] \tag{20}$$

Here, $\mathcal{F}_j$ represents the event of a packet being discarded due to a channel access failure after j previous collisions, and $T_{\mathrm{cf},C}^{(j)}$ denotes the delay experienced by a packet when event $\mathcal{F}_j$ occurs. It can be straightforwardly deduced that $P(\mathcal{F}_j) = P(\mathcal{C}_j)$, and

$$\begin{aligned}\mathrm{E}\left[T_{\mathrm{cf},C}^{(j)}\right] &= j\left(L\cdot T_{\mathrm{s},C} + \mathrm{E}\left[T_b\right]\right) + (m+1)\,T_{\mathrm{cca}} \\ &+ \sum_{k=0}^{m} T_{\mathrm{s},C}\frac{W_k-1}{2}\end{aligned} \tag{21}$$

The delay experienced by a packet discarded due to a retry limit, denoted as $T_{\mathrm{rl},C}$, is given by:

$$\mathrm{E}\left[T_{\mathrm{rl},C}\right] = (n+1)\left(L\cdot T_{\mathrm{s},C} + \mathrm{E}\left[T_b\right]\right) \tag{22}$$

Lastly, the probabilities of having a packet ready for transmission in idle state, after a successful transmission, after a channel access failure, and after a retry limit are represented by $q = 1 - e^{-\lambda_C T_{\mathrm{s},C}}$, $q_{\mathrm{suc}} = \lambda_C \mathrm{E}\left[T_{\mathrm{suc},C}\right]$, $q_{\mathrm{cf}} = \lambda_C \mathrm{E}\left[T_{\mathrm{cf},C}\right]$, and $q_{\mathrm{rl}} = \lambda_C \mathrm{E}\left[T_{\mathrm{rl},C}\right]$. A detailed derivation of these probabilities can be found in [16]. It's worth noting that when a station is saturated, $q_{\mathrm{suc}} = q_{\mathrm{rl}} = q_{\mathrm{cf}} = 1$, resulting in the removal of the idle state from the Markov chain depicted in Figure 2.

The power consumption of CSMA/CA nodes can be calculated from the state probabilities of the Markov chain shown in Figure 2 as follows:

$$\begin{aligned}P_C =& P_{\mathrm{idle}}\cdot p\left(idle\right) + \sum_{i=0}^{m}\sum_{j=1}^{W_i}\sum_{k=0}^{n} P_{\mathrm{backoff}}\cdot p\left(i,j,k\right) \\ &+ \sum_{i=0}^{m}\sum_{k=0}^{n} P_{\mathrm{cca}} p\left(i,0,k\right) \\ &+ \sum_{j=0}^{L_{\mathrm{pkt}}-1}\sum_{k=0}^{n} P_{\mathrm{tx}}\left(p\left(-1,j,k\right) + p\left(-2,j,k\right)\right) \\ &+ \sum_{j=L_{\mathrm{pkt}}}^{L-1}\sum_{k=0}^{n} P_{\mathrm{rx}}\left(p\left(-1,j,k\right) + p\left(-2,j,k\right)\right)\end{aligned} \tag{23}$$

where P_{idle}, P_{backoff}, P_{cca}, P_{tx} and P_{rx} represent the power consumption in idle, backoff, channel sensing, transmitting and receiving states, respectively. We assume that the radio is set to the receiving state during $T_{\mathrm{aifs}} + T_{\mathrm{ack}} + T_{\mathrm{ifs}}$ seconds after a packet transmission, regardless of whether the ACK is received or not. $L_{\mathrm{pkt}} = T_{\mathrm{pkt}}/T_{\mathrm{s},C}$ corresponds to the duration of a packet in time slots. All the probabilities in (23) can be derived from the transition probabilities of the Markov chain depicted in Figure 2 and the probability of state $(0,0,0)$ given in (2).

I. Derivation of the performance metrics for ALOHA nodes

We derive the probability of a packet being discarded for an ALOHA node, considering two cases: discard due to reaching the retry limit, $P_{\mathrm{rl},A}$, and discard due to delay exceeded, $P_{\mathrm{ed},A}$. The expression for $P_{\mathrm{rl},A}$ is:

$$P_{\mathrm{rl},A} = \left(P_{\mathrm{col},A}\right)^{n+1} \tag{24}$$

On the other hand, $P_{\mathrm{ed},A}$ represents the probability that the cumulative time D_A an ALOHA packet spends in the backoff process and in failed transmissions exceeds D_{max}. Hence:

$$\begin{aligned}P_{\mathrm{ed},A} &= P\left(D_A > D_{\mathrm{max}}\right) \\ &= \sum_{i=1}^{n+1} P\left(D_A > D_{\mathrm{max}}|\mathcal{R}_i\right) P\left(\mathcal{R}_i\right)\end{aligned} \tag{25}$$

Here, $\mathcal{R}_i$ represents the event that the packet has been transmitted i times, and its probability is computed using (56). The expression for $P(D_A > D_{\mathrm{max}}|\mathcal{R}_i)$ is as follows:

$$P\left(D_A > D_{\mathrm{max}}|\mathcal{R}_i\right) = P\left(\sum_{j=1}^{i} B_j > D_{\mathrm{max}} + T_{\mathrm{s},A}\right) \tag{26}$$

with $\{B_j\}$ representing a set of independent and identically distributed discrete uniform random variables with support $\{T_{\mathrm{s},A}, 2\cdot T_{\mathrm{s},A}, ...2^{m_{\mathrm{min}}-1}\cdot T_{\mathrm{s},A}\}$. These variables model the time elapsed from the start of the j-th backoff process until the end of the j-th attempt to transmit an ALOHA packet. It is noteworthy that we add the term $T_{\mathrm{s},A}$ to D_{max} since the transmission time of the packet (and the reception time of its corresponding ACK) must not be included for the last transmission attempt, as the decision on whether the packet must be discarded for exceeding D_{max} is made before it is transmitted.

The computation of this probability becomes straightforward as the probability mass function (PMF) of the sum of multiple discrete random variables is the convolution of the PMF of each individual variable. Furthermore, it is important to note that $P_{\mathrm{ed},A} = 0$ whenever $2^{m_{\mathrm{min}}-1}(n+1)T_{\mathrm{s},A} - T_{\mathrm{s},A} < D_{\mathrm{max}}$, since $2^{m_{\mathrm{min}}-1}(n+1)T_{\mathrm{s},A}$ is the upper time limit for transmitting an ALOHA packet.

With these, the probability of a successfully transmitted ALOHA packet is given by $P_{\mathrm{suc},A} = 1 - P_{\mathrm{rl},A} - P_{\mathrm{ed},A}$.

Now we calculate the average delay experienced by an ALOHA packet, whether it is successfully transmitted or discarded due to reaching the retry limit. Denoting $T_{\mathrm{rl},A}$ as the delay of an ALOHA packet discarded due to a retry limit, it can be expressed as:

$$\mathrm{E}\left[T_{\mathrm{rl},A}\right] = (n+1)\,T_{\mathrm{s},A}\frac{2^{m_{\mathrm{min}}-1}+1}{2} \tag{27}$$

This delay is the maximum allowed number of transmissions, $n+1$, multiplied by the mean of the discrete uniform random variable B_j, which models the delay introduced by one backoff and one transmission attempt of an ALOHA packet.

On the other hand, the average delay experienced by an ALOHA packet successfully transmitted is given by:

$$\mathrm{E}\left[T_{\mathrm{suc},A}\right] = \mathrm{E}\left[n_{\mathrm{suc},A}\right] T_{\mathrm{s},A}\frac{2^{m_{\mathrm{min}}-1}+1}{2} \tag{28}$$

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This article has been accepted for publication in IEEE Internet of Things Journal. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2025.3539786

Here, $\mathrm{E}\left[n_{\text{suc},A}\right]$ represents the average number of transmissions of a successfully transmitted ALOHA packet. This can be computed as:

$$\begin{aligned}\mathrm{E}\left[n_{\text{suc},A}\right] &= \sum_{i=1}^{n+1} i \frac{\left(1-P_{\text{col},A}\right) P_{\text{col},A}^{i-1}}{\sum_{j=1}^{n+1}\left(1-P_{\text{col},A}\right) P_{\text{col},A}^{j-1}} \\ &= \sum_{i=1}^{n+1} i \frac{\left(1-P_{\text{col},A}\right) P_{\text{col},A}^{i-1}}{1-P_{\text{col},A}^{n+1}} \\ &= \frac{1-(n+2) P_{\text{col},A}^{n+1}+(n+1) P_{\text{col},A}^{n+2}}{\left(1-P_{\text{col},A}\right)\left(1-P_{\text{col},A}^{n+1}\right)}\end{aligned} \tag{29}$$

The power consumption of ALOHA nodes corresponds to the average of the power levels in the transmission, reception, backoff and idle states, weighted by the percentage of time spent in each of these four states:

$$\begin{aligned}P_A = &P_{\text{tx}} \frac{\mathrm{E}\left[T_{\text{tx},A}\right]}{\mathrm{E}\left[T_{\text{inter},A}\right]} + P_{\text{rx}} \frac{\mathrm{E}\left[T_{\text{rx},A}\right]}{\mathrm{E}\left[T_{\text{inter},A}\right]} + P_{\text{backoff}} \frac{\mathrm{E}\left[T_{\text{backoff},A}\right]}{\mathrm{E}\left[T_{\text{inter},A}\right]} \\ &+ P_{\text{idle}} \frac{\mathrm{E}\left[T_{\text{inter},A}\right]-\mathrm{E}\left[T_{\text{tx},A}\right]-\mathrm{E}\left[T_{\text{rx},A}\right]-\mathrm{E}\left[T_{\text{backoff},A}\right]}{\mathrm{E}\left[T_{\text{inter},A}\right]}\end{aligned} \tag{30}$$

with $\mathrm{E}\left[T_{\text{tx},A}\right]$, $\mathrm{E}\left[T_{\text{rx},A}\right]$ and $\mathrm{E}\left[T_{\text{backoff},A}\right]$ representing the average time an ALOHA node spends transmitting, receiving, and in backoff between two consecutive packets, and $\mathrm{E}\left[T_{\text{inter},A}\right]$ representing the average time between packets. Eq. (30) can be easily computed by considering that $\mathrm{E}[T_{\text{inter},A}] = 1/\lambda_A$, $\mathrm{E}[T_{\text{tx},A}] = \mathrm{E}[n_A] \cdot T_{\text{pkt}}$, $\mathrm{E}[T_{\text{rx},A}] = \mathrm{E}[n_A](T_{\text{aifs}} + T_{\text{ack}} + T_{\text{ifs}})$, and $\mathrm{E}[T_{\text{backoff},A}] = \mathrm{E}[n_A] \cdot T_{\text{s},A} \cdot 2^{m_{\min}-1}/2$.

IV. RESULTS AND MODEL VALIDATION

To evaluate the proposed model, we have explored various network scenarios, altering the configuration by adjusting the number of nodes engaged in monitoring non-priority information using the CSMA/CA channel access method, alongside the number of nodes generating priority data and utilizing the LECIM ALOHA PCA method. Additionally, we analyze the impact of retransmissions within LECIM ALOHA PCA transmissions and the duration of the backoff procedure. The results derived from the model are cross-validated against an ad-hoc system-level, C++ discrete-event simulator emulating the IEEE 802.15.4 PHY/MAC layers. Specifically, the simulator comprises a set of ALOHA and CSMA/CA nodes, along with a central coordinator. Each node generates packets with an exponential interarrival time. Once a packet is generated, the flowcharts in Figure 1 are executed to emulate the corresponding MAC layer behavior of the two access methods. All simulated outcomes represent the averages obtained from 10^6 generated packets. Although we used an exponential interarrival time for the model and the results presented in this section, we found that the results are very similar when the packet interarrival time is a constant value. The PHY and MAC parameters employed in the simulations are shown in Table III and satisfy the LECIM Direct Sequence Spread Spectrum (DSSS) PHY layer requirements specified in the IEEE 802.15.4-2020 standard.

TABLE III
PHY AND MAC LAYER RELATED PARAMETERS

Parameter	Value
$m_{\min}$ (*macMinBe*)	3
$m_{\max}$ (*macMaxBe*)	5
m (*macMaxCsmaBackoffs*)	4
n (*macMaxFrameRetries*)	3
$T_{\text{s},C}$ (*aUnitBackoffPeriod*)	2 ms
T_{cca} (*phyCcaDuration*)	1 ms
T_{ta} (*aTurnaroundTime*)	1 ms
$T_{\text{s},A}$ (*macLecimAlohaUnitBackffPeriod*)	7.12 ms
$D_{\max}$ (*macCritMsgDelayTol*)	15000 ms
T_{pkt} (data packet airtime)	4.288 ms
T_{ack} (ACK airtime)	0.832 ms
T_{ifs} (Inter-Frame Spacing)	1 ms
T_{aifs} (ACK Inter-Frame Spacing)	1 ms
λ_A (ALOHA PCA traffic rate)	0.1 pkts/s
λ_C (CSMA/CA traffic rate)	0.1 pkts/s
P_{idle} (power consumption in idle state)	144 nW
P_{backoff} (power consumption in backoff state)	712 μW
P_{cca} (power consumption in channel sensing state)	35.28 mW
P_{tx} (power consumption in transmitting state)	31.32 mW
P_{rx} (power consumption in receiving state)	35.28 mW

The values for $m_{\min}$, $m_{\max}$, m, n, and $D_{\max}$ corresponds to the defaults outlined in the standard. Both T_{ta} and T_{aifs} are fixed at 1 ms for the LECIM DSSS PHY layer. We configure T_{cca} to 1 ms to ensure busy channel detection during the AIFS. Consequently, $T_{\text{s},C}$ is defined as T_{ta} + T_{cca}. Additionally, T_{ifs} is set to 1 ms, as the standard requires that $T_{\text{ifs}} \geq T_{\text{aifs}}$. The airtimes T_{pkt} and T_{ack} are also compliant with the LECIM DSSS PHY standard. To derive them, we consider a data PHY Service Data Unit (PSDU) size of 32 bytes, a 2-byte Preamble, and a 1-byte Start-of-Frame Delimiter (SFD). This results in a PHY Protocol Data Unit (PPDU) size of 35 bytes. We set the data rate to 62500 kbps, corresponding to a Spreading Factor of 16, a modulation rate of 1000 ksymbols/second, and Offset Quadrature Phase Shift Keying (O-QPSK) modulation. Similarly, the ACK size is configured to 8 bytes: 5 bytes for the PSDU, plus the same Preamble and SFD used for the data frames. Consequently, $T_{\text{pkt}} = 4.288$ ms and $T_{\text{pkt}} = 0.832$ ms. Finally, the standard stipulates that $T_{\text{s},A}$ should accommodate the transmission of a maximum-sized MPDU with the associated IFS and ACK, resulting in $T_{\text{s},A} = T_{\text{pkt}} + T_{\text{aifs}} + T_{\text{ack}} + T_{\text{ifs}} = 7.12$ ms. The power consumption values P_{idle}, P_{backoff}, P_{cca}, P_{tx} and P_{rx} are obtained from a commercial radio implementing the 802.15.4 standard, the Chipcon CC2420 [25]. All results are derived by varying the total number of nodes from 100 to 1000, employing various combinations of CSMA/CA (N_C) and ALOHA nodes (N_A). Specifically, we analyze the following configurations: $N_C = 90\%$ and $N_A = 10\%$; $N_C = 50\%$ and $N_A = 50\%$; and $N_C = 10\%$ and $N_A = 90\%$.

First, we follow the results presented in [22], [6], and [23] and assume that priority packets are not retransmitted when a collision occurs. Consequently, we assume that non-priority traffic from CSMA/CA nodes can be retransmitted up to n times, while priority traffic from ALOHA nodes is not retransmitted at all (i.e. $n = 3$ for CSMA/CA nodes and $n = 0$ for ALOHA nodes).

Figure 3 shows the packet reliability as a function of the total number of nodes in the network for different combi-

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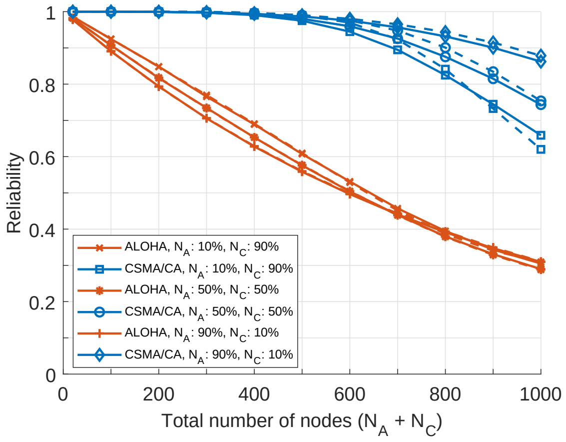

Fig. 3. Packet reliability for different ratios of N_C and N_A. Standard backoff ($m_{\text{min}} = 3$, $m_{\text{max}} = 5$) and no retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

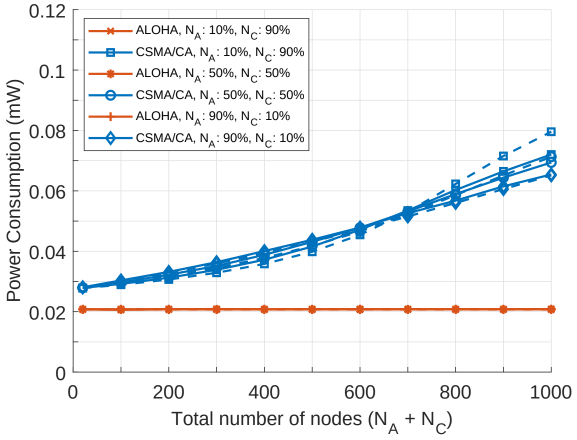

Fig. 5. Power consumption for different ratios of N_C and N_A. Standard backoff ($m_{\text{min}} = 3$, $m_{\text{max}} = 5$) and no retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

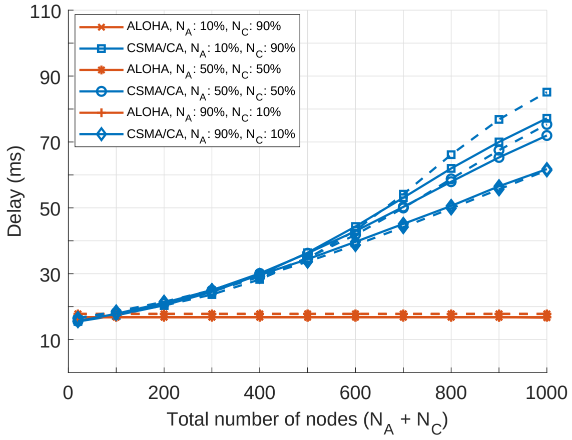

Fig. 4. Average delay for a successfully transmitted packet for different ratios of N_C and N_A. Standard backoff ($m_{\text{min}} = 3$, $m_{\text{max}} = 5$) and no retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

nations of N_C and N_A. In this and the following figures, we use solid lines to represent the results from the discrete event simulator and dotted lines for the results from our analytical model. Blue lines indicate results for CSMA/CA nodes, while red lines correspond to results for ALOHA nodes. As expected, the performance of CMSA/CA nodes is significantly better than that of ALOHA nodes as the CSMA/CA channel access method prevents collisions when there is an ongoing transmission on the channel. However, the graphs display a behavior that is not intuitive at first glance. When comparing the reliability for a fixed number of nodes, we observe that increasing the percentage of ALOHA nodes improves the reliability for CSMA/CA nodes while remaining practically unchanged for ALOHA nodes. This behavior is primarily due to the fact that packets generated by ALOHA nodes are not retransmitted. Consequently, the negative impact on the collision probability caused by using the ALOHA PCA method instead of CSMA/CA is mitigated by the reduction in the overall network traffic due to the absence of retransmissions.

Figure 4 illustrates the average delay for a successfully transmitted packet as a function of the total number of nodes. As observed, the average delay for ALOHA nodes is lower than that of CSMA/CA nodes and remains independent of the number of nodes. This is due to the absence of retransmissions, resulting in the average delay being comprised solely of one average backoff time plus one transmission time. In contrast, for CSMA/CA nodes, the delay increases with the number of nodes due to more frequent retransmissions (arising from increased collisions) and more backoffs (as the probability of sensing the channel busy α during a CCA rises).

Figure 5 shows the average power consumption per node as a function of the total number of nodes. As can be seen, ALOHA nodes consume less power than CSMA/CA nodes, with a strong correlation to the delay results shown in Figure 4. Similar to the delay, the average power consumption of ALOHA nodes remains constant and independent of the number of nodes, as each packet is only transmitted once, involving a single backoff, a single transmission and a single reception of the ACK. In contrast, the power consumption for CSMA/CA nodes increases with the number of nodes due to more retransmissions and backoffs, which extend the time a CSMA/CA node spends in more power-demanding states.

Comparing the model and the simulation results in terms of packet reliability, average delay and power consumption, we find a close alignment between the model and the simulations for ALOHA nodes, while the model provides a strong approximation for CSMA/CA nodes. The slight differences observed in CSMA/CA nodes can be attributed to the assumption made in the Markov chain model of the CSMA/CA nodes that α—the probability of a CSMA/CA node detecting a busy channel during CCA—is independent of the node's backoff stage (i.e., of the number of previous CCAs that have found the channel busy for transmitting a given packet) or the retransmission counter. This assumption may impact the

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model's accuracy as discussed in [17] [3].

Next, in Figures 6, 7 and 8, we analyze the impact of retransmissions on the ALOHA PCA method (up to 3 retransmissions, similar to CSMA/CA nodes), focusing on packet reliability, average packet delay and power consumption. The inclusion of retransmissions significantly increases the reliability of ALOHA nodes, narrowing the reliability gap with CSMA/CA nodes. In fact, in certain cases, such as high traffic rates where N_A is 10% and N_C is 90%, the performance of ALOHA nodes can even surpass that of CSMA/CA nodes. This is because the channel becomes so congested that channel access failures for CSMA/CA nodes skyrocket. As expected, increasing the percentage of ALOHA nodes leads to a degradation in reliability for both CSMA/CA and ALOHA nodes due to the increased number of collisions. Finally, when comparing the packet reliability with and without retransmissions for the ALOHA PCA method (Figures 3 and 6), we observe that the reliability of ALOHA nodes improve, as there are more attempts to transmit a packet when it collides. In contrast, the reliability of CSMA/CA nodes decreases due to a higher incidence of collisions and channel access failures.

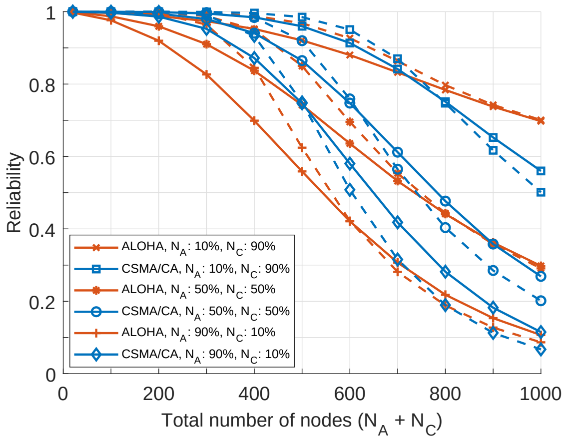

Fig. 6. Packet reliability for different ratios of N_C and N_A. Standard backoff ($m_{\text{min}} = 3$, $m_{\text{max}} = 5$) and up to $n = 3$ retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

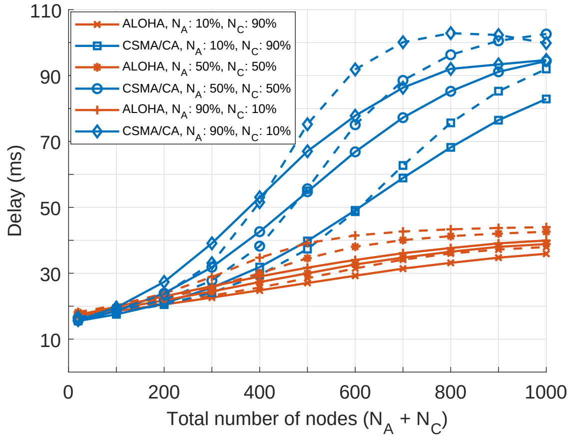

Fig. 7. Average delay for a successfully transmitted packet for different ratios of N_C and N_A. Standard backoff ($m_{\text{min}} = 3$, $m_{\text{max}} = 5$) and up to $n = 3$ retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

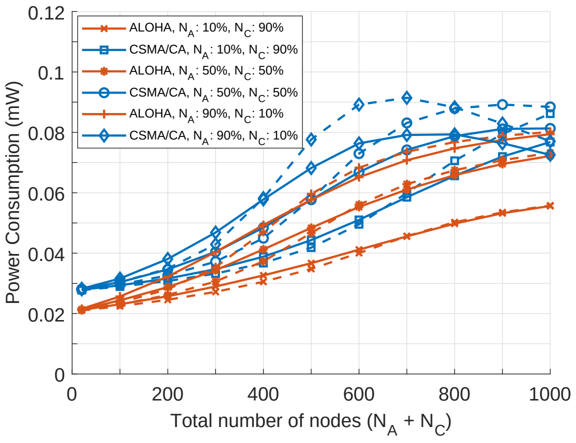

Fig. 8. Power consumption for different ratios of N_C and N_A. Standard backoff ($m_{\text{min}} = 3$, $m_{\text{max}} = 5$) and up to $n = 3$ retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

On the other hand, as expected, the possibility of retransmitting ALOHA packets increases the average delay for a successfully transmitted packet for both ALOHA and CSMA/CA nodes compared to the scenario where there are no retransmissions for ALOHA nodes. In this case, the delay increases as the total number of nodes grows, since the probability of collision, and therefore packet retransmission, increases with the number of nodes. However, if we compare the delay experienced by ALOHA packets with that of CSMA/CA packets, it is significantly lower across all combinations of N_C and N_A. A similar effect is observed in the power consumption: as the number of retransmissions increases, the average power consumption for both CSMA/CA and ALOHA nodes also rises. This is due to the increased percentage of time the nodes spend in transmitting and receiving states, which are the most power-consuming states.

Regarding the model's accuracy, it can be observed that it still provides a good approximation, although the discrepancy between simulation and model is more pronounced than in the scenario without retransmissions for ALOHA nodes. Similarly to the previous scenario, this discrepancy mainly arises from the inaccurate assumption that α —the probability that a CSMA/CA node encounters a busy channel when performing the CCA— and ω —the probability that there is an ongoing transmission when an ALOHA node starts transmitting a packet— remain constant and do not depend on whether the packet is being retransmitted or the backoff stage, especially when the backoff parameters m_{min} and m_{max} are low.

To validate this reasoning and decorrelate consecutive CCAs or retransmission attempts over time, we conducted a simi-

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[3] For example, consider a network with very low traffic and a CSMA/CA node performing a CCA for the first time. In this scenario, the probability of detecting a busy channel is very low and is the probability that another node has initiated a transmission within the previous T_{pkt} seconds. If the channel is busy, then the probability of finding it busy again during the second CCA will also depend on whether the transmission that occupied the channel during the first CCA has concluded by the time of the second CCA.

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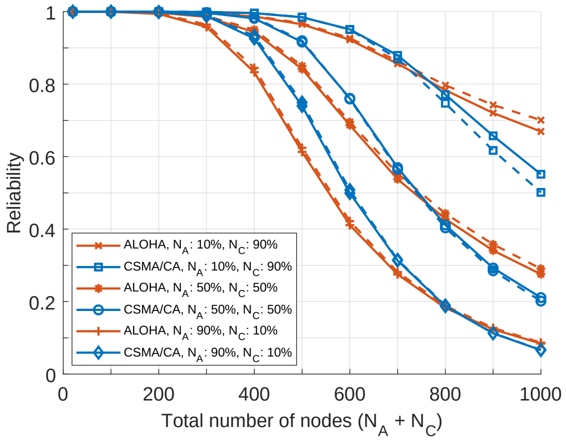

Fig. 9. Packet reliability for different ratios of N_C and N_A. Long backoff ($m_{\min} = m_{\max} = 8$) and up to $n = 3$ retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

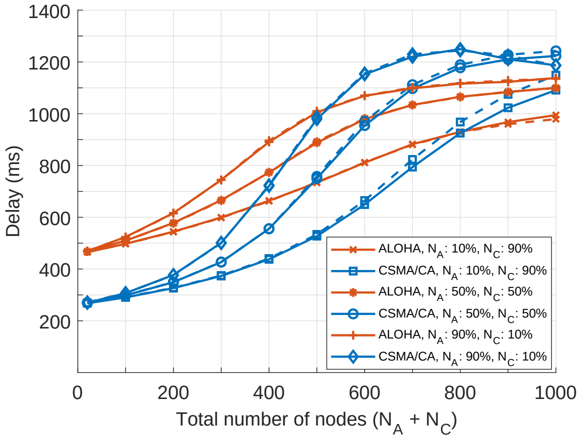

Fig. 10. Average delay for a successfully transmitted packet for different ratios of N_C and N_A. Long backoff ($m_{\min} = m_{\max} = 8$) and up to $n = 3$ retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

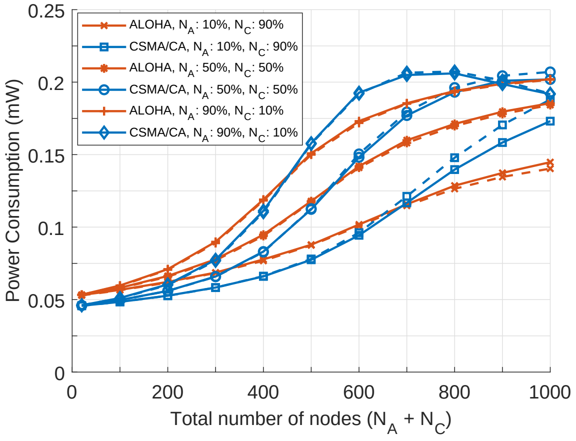

Fig. 11. Power consumption for different ratios of N_C and N_A. Long backoff ($m_{\min} = m_{\max} = 8$) and up to $n = 3$ retransmissions for ALOHA nodes. Solid lines for simulator and dotted lines for analytical model.

lar evaluation with increased backoff times. Specifically, in Figures 9, 10 and 11, we present the same results as in Figures 6, 7 and 8, but with the parameters controlling the backoff times set to the maximum values allowed by the standard ($m_{\min} = m_{\max} = 8$). As depicted, in this scenario, the model's accuracy improves significantly for both ALOHA and CSMA/CA nodes, resulting in outcomes very closely aligned with the simulations. Comparing these results with the previous scenario, we observe a notable increase in the average delay for both ALOHA and CSMA/CA nodes, which is expected given the higher values of the backoff parameters now. The same effect is observed in power consumption, as the power associated with the backoff states increases significantly. Similar to the delay, when the number of nodes is low, the power consumed by ALOHA nodes can be even higher than that consumed by CSMA/CA nodes. This is because the duration of a backoff slot for an ALOHA node is much longer than that of a CSMA/CA node, resulting in more time spent in backoff for ALOHA nodes. In terms of reliability, CSMA/CA nodes maintain a similar performance, whereas ALOHA nodes show a significant improvement in reliability under low network loads. This improvement stems from the fact that with lower backoff exponents, the probability of a collision between retransmitting ALOHA nodes after an initial collision is higher, leading to decreased reliability. Conversely, higher backoff exponents reduce the probability of simultaneous retransmissions, lowering collision rates and consequently enhancing reliability.

In summary, the results presented in this chapter show that the performance of the proposed model closely aligns with the outcomes from the discrete-event simulator, with a few discrepancies attributed to the assumptions made regarding the CSMA/CA backoff process. The improved accuracy of the model when backoff times are increased—helping to decorrelate consecutive CCAs and retransmission attempts—confirms that these discrepancies are due to those assumptions.

When no retransmissions are allowed, it is worth mentioning the improvement in reliability for CSMA/CA nodes as the percentage of ALOHA nodes increases, primarily due to the reduction in overall network traffic and the significantly lower average delay and power consumption for ALOHA nodes.

Additionally, the analysis of retransmissions within the ALOHA PCA method reveals that including retransmissions significantly enhances packet reliability. In some cases, this leads to ALOHA nodes outperforming CSMA/CA nodes, particularly in high-traffic scenarios, where channel access failures for CSMA/CA nodes increase substantially. However, this improvement in reliability for ALOHA nodes comes at the cost of increased average delay and power consumption, although these values remain lower than those for CSMA/CA nodes. It is also worth noting that in this case increasing the percentage of ALOHA nodes leads to a degradation in reliability for both CSMA/CA and ALOHA nodes due to the increased number of collisions.

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V. CONCLUSIONS

This study investigates the coexistence of nodes using the CSMA/CA channel access method and nodes using the LECIM ALOHA PCA method within unslotted IEEE 802.15.4 networks, with a specific focus on the impact on the network reliability, delay and power consumption in critical infrastructure monitoring scenarios.

The results indicate that nodes using the LECIM ALOHA PCA method, operating without retransmissions, exhibit lower average delays and power consumption compared to nodes using the CSMA/CA channel access method. This makes them particularly appealing for applications prioritizing low-latency data transmission. Additionally, introducing retransmissions for nodes using the LECIM ALOHA PCA method significantly enhances their reliability, bringing their performance closer to that of nodes using CSMA/CA, particularly in high network congestion scenarios. Although this improvement leads to an increase in average delay and power consumption, it remains lower than that observed for nodes using CSMA/CA.

The theoretical framework developed and validated in this study provices a robust approximation of network performance in terms of reliability, delay and power consumption. Despite minor discrepancies, the model offers valuable insights into the performance differences between these channel access methods. Overall, these findings contribute to a deeper understanding of the coexistence of the LECIM ALOHA PCA and the CSMA/CA channel access methods, and can inform the design and implementation of WSNs in critical infrastructure monitoring applications.

APPENDIX A
PROOF OF LEMMA 1

The probability α can be expressed as:

$$\alpha = P\left(\mathcal{B}_A \cup \mathcal{B}_C\right) = P\left(\mathcal{B}_A\right) + P\left(\mathcal{B}_A^C \cap \mathcal{B}_C\right) \tag{31}$$

Here, $\mathcal{B}_A$ represents the event of the channel being busy due to an ALOHA transmission (either a packet or an ACK), while $\mathcal{B}_C$ represents the event of the channel being busy due to a CSMA/CA transmission (either a packet or an ACK).

The term $P\left(\mathcal{B}_A\right)$ can be further decomposed as:

$$\begin{aligned} P\left(\mathcal{B}_A\right) &= P\left(\mathcal{B}_{A,\text{pkt}} \cup \mathcal{B}_{A,\text{ack}}\right) \\ &= P\left(\mathcal{B}_{A,\text{pkt}}\right) + P\left(\mathcal{B}_{A,\text{pkt}}^C \cap \mathcal{B}_{A,\text{ack}}\right) \end{aligned} \tag{32}$$

On the other hand, the joint probability $P(\mathcal{B}_A^C \cap \mathcal{B}_C)$ can be expressed as:

$$\begin{aligned} P\left(\mathcal{B}_A^C \cap \mathcal{B}_C\right) &= P\left(\mathcal{B}_A^C \cap \left(\mathcal{B}_{C,\text{pkt}} \cup \mathcal{B}_{C,\text{ack}}\right)\right) \\ &= P\left(\mathcal{B}_A^C | \mathcal{B}_{C,\text{pkt}}\right) P\left(\mathcal{B}_{C,\text{pkt}}\right) \\ &\quad + P\left(\mathcal{B}_A^C | \mathcal{B}_{C,\text{ack}}\right) P\left(\mathcal{B}_{C,\text{ack}}\right) \end{aligned} \tag{33}$$

The transition from the first equality to the second can be made since the events $B_{C,\text{pkt}}$ and $B_{C,\text{ack}}$ are mutually exclusive (i.e., it is impossible that the transmission of a CSMA/CA packet and of a CSMA/CA ACK happen simultaneously, as the CSMA/CA node transmitting the packet would have found the channel busy, refraining its transmission). Now we proceed to derive $P(\mathcal{B}_A^C|\mathcal{B}_{C,\text{pkt}})$, $P(\mathcal{B}_{C,\text{pkt}})$, $P(\mathcal{B}_A^C|\mathcal{B}_{C,\text{ack}})$ and $P(\mathcal{B}_{C,\text{ack}})$.

Regarding $P(\mathcal{B}_A^C|\mathcal{B}_{C,\text{pkt}})$ we can further operate as follows:

$$\begin{aligned} P\left(\mathcal{B}_A^C | \mathcal{B}_{C,\text{pkt}}\right) &= P\left(\left(\mathcal{B}_{A,\text{pkt}} \cup \mathcal{B}_{A,\text{ack}}\right)^C | \mathcal{B}_{C,\text{pkt}}\right) \\ &= P\left(\mathcal{B}_{A,\text{pkt}}^C \cap \mathcal{B}_{A,\text{ack}}^C | \mathcal{B}_{C,\text{pkt}}\right) \\ &= P\left(\mathcal{B}_{A,\text{ack}}^C | \mathcal{B}_{C,\text{pkt}}, \mathcal{B}_{A,\text{pkt}}^C\right) P\left(\mathcal{B}_{A,\text{pkt}}^C | \mathcal{B}_{C,\text{pkt}}\right) \\ &= P\left(\mathcal{B}_{A,\text{pkt}}^C | \mathcal{B}_{C,\text{pkt}}\right) \end{aligned} \tag{34}$$

For the last step, we have considered that the transmission of an ALOHA ACK cannot occur if a CSMA/CA packet is being transmitted at that moment. If a CSMA/CA packet is being transmitted: i) there cannot be a previous ALOHA transmission (neither packet nor ACK) since the CSMA/CA node would have detected the channel busy, refraining from transmitting, and ii) any ALOHA packet transmitted after the beginning of the transmission of the CSMA/CA packet would result in a collision, thus preventing the generation of the ALOHA ACK. Therefore, $P(\mathcal{B}_{A,\text{ack}}^C|\mathcal{B}_{C,\text{pkt}}, \mathcal{B}_{A,\text{pkt}}^C) = 1$. The same reasoning applies to demonstrate that:

$$P\left(\mathcal{B}_A^C | \mathcal{B}_{C,\text{ack}}\right) = P\left(\mathcal{B}_{A,\text{pkt}}^C | \mathcal{B}_{C,\text{ack}}\right) \tag{35}$$

Thus, by substituting (34) and (35) into (33), we obtain:

$$\begin{aligned} P\left(\mathcal{B}_A^C \cap \mathcal{B}_C\right) &= P\left(\mathcal{B}_{A,\text{pkt}}^C | \mathcal{B}_{C,\text{pkt}}\right) P\left(\mathcal{B}_{C,\text{pkt}}\right) \\ &\quad + P\left(\mathcal{B}_{A,\text{pkt}}^C | \mathcal{B}_{C,\text{ack}}\right) P\left(\mathcal{B}_{C,\text{ack}}\right) \end{aligned} \tag{36}$$

Finally, substituting (32) and (36) into (31) we obtain (3) and the lemma is demonstrated. □

APPENDIX B
PROOF OF LEMMA 2

Assuming that the CCA starts at time instant 0, the occurrence of the event $\mathcal{B}_{A,\text{pkt}}^C \cap \mathcal{B}_{A,\text{ack}}$ hinges upon three conditions:

- Only one ALOHA node starts a packet transmission within the time span $(-T_{\text{pkt}} - T_{\text{ack}} - T_{\text{aifs}}, -T_{\text{pkt}})$. This transmission is the one whose ACK will render the channel busy during the time span $(0, T_{\text{cca}})$. The probability of this to happen is $\lambda_A N_A \mathrm{E}\left[n_A\right]\left(T_{\text{ack}} + T_{\text{aifs}}\right) e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{ack}}+T_{\text{aifs}})}$.
- There are no other transmissions on the channel when the transmission of the ALOHA packet mentioned in the previous paragraph begins. Otherwise, it would collide and no ACK would be generated. The probability of this is $1 - \omega$.
- No other ALOHA node starts a packet transmission within the time span $(-T_{\text{pkt}}, T_{\text{cca}})$, given that just one ALOHA node has started a packet transmission within $(-T_{\text{pkt}} - T_{\text{ack}} - T_{\text{aifs}}, -T_{\text{pkt}})$. This condition ensures both the event $\mathcal{B}_{A,\text{pkt}}^C$ and that the ALOHA packet causing the ACK does not collide after the beginning of its transmission (as a collision would prevent the generation of the ACK). The probability of this is $e^{-\lambda_A (N_A - 1) \mathrm{E}[n_A](T_{\text{pkt}} + T_{\text{cca}})}$. Note that once the ALOHA transmission has started, the CSMA/CA mechanism prevents the CSMA/CA nodes to transmit and therefore they do not appear in this probability.

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If we multiply the probabilities of these three conditions, we obtain (4) and the lemma is demonstrated. □

APPENDIX C
PROOF OF LEMMA 3

Let assume that time instant 0 corresponds to the beginning of the CCA that senses the channel as busy. Then, the start of the CSMA/CA packet transmission generating the event $\mathcal{B}_{C,\text{pkt}}$ must fall within the time interval $(-T_{\text{pkt}}, T_{\text{cca}})$. Additionally, the beginning of that packet transmission is uniformly distributed in $(-T_{\text{pkt}}, T_{\text{cca}})$, as all the transmitting states in the Markov chain of Figure 2 have the same probability for a given value of k.

Let assume that the CSMA/CA packet transmission generating the event $\mathcal{B}_{C,\text{pkt}}$ begins at time instant $t \in (-T_{\text{pkt}}, T_{\text{cca}})$. Then, we know for sure that there are no other transmissions before time instant $t - T_{\text{ta}}$. Otherwise, the channel would have been detected as busy, and the CSMA/CA packet transmission causing the event $\mathcal{B}_{C,\text{pkt}}$ would not have occurred. Therefore, the probability that there are no ALOHA packet transmissions at the moment of the CCA, given that there is a CSMA/CA packet transmission started at time instant t, $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt started at }t})$, is the probability that no ALOHA node has started transmitting a packet from time instant $t - T_{\text{ta}}$ to time instant T_{cca}, with the exception described in the next paragraph. This probability is:

$$P\left(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt started at }t}\right) = e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}-(t-T_{\text{ta}}))} \quad (37)$$

Figure 12 shows graphically this reasoning. When $t \in (-T_{\text{pkt}}, -T_{\text{pkt}} + T_{\text{ta}})$, we must only ensure that no ALOHA node starts a packet transmission in the interval $(-T_{\text{pkt}}, T_{\text{cca}})$, since the condition in the previous paragraph would also include packet transmissions that are not related to the event $\mathcal{B}^C_{A,\text{pkt}}$. For instance, it $t = -T_{\text{pkt}}$, the ALOHA packet transmissions started in $(-T_{\text{pkt}} - T_{\text{ta}}, -T_{\text{pkt}})$ finish before time instant 0 (i.e. the beginning of the CCA). Then,

$$P\left(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt started at }t}\right) = e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}+T_{\text{pkt}})} \quad (38)$$

Therefore, to compute $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt}})$, we need to divide the time interval $(-T_{\text{pkt}}, T_{\text{cca}})$ into two parts and integrate the probabilities given above in each of them. In the first part, when $t \in (-T_{\text{pkt}} + T_{\text{ta}}, T_{\text{cca}})$, we use the probability that no ALOHA node starts a packet transmission from time instant $t - T_{\text{ta}}$ to T_{cca}. In the second part, when $t \in (-T_{\text{pkt}}, -T_{\text{pkt}} + T_{\text{ta}})$, we use the probability that no ALOHA node starts a packet transmission from time instant $-T_{\text{pkt}}$ to T_{cca} (as in this case, any ALOHA packet transmission started before time instant $-T_{\text{pkt}}$ would not occupy the channel at time instant 0). With this, we have:

$$\begin{aligned} P\left(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt}}\right) &= \int_{-T_{\text{pkt}}}^{T_{\text{cca}}} \frac{P\left(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt started at }t}\right)}{T_{\text{pkt}} + T_{\text{cca}}} dt \\ &\int_{-T_{\text{pkt}}}^{-T_{\text{pkt}}+T_{\text{ta}}} \frac{e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}+T_{\text{pkt}})}}{T_{\text{pkt}} + T_{\text{cca}}} dt \\ &+ \int_{-T_{\text{pkt}}+T_{\text{ta}}}^{T_{\text{cca}}} \frac{e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}-t+T_{\text{ta}})}}{T_{\text{pkt}} + T_{\text{cca}}} dt \end{aligned} \quad (39)$$

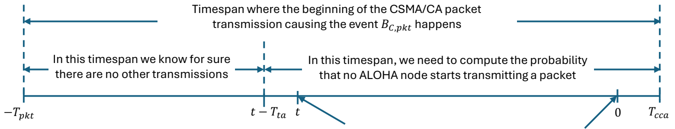

Fig. 12. Graphical description of the computation of $P\left(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt}}\right)$.

If we perform these integrals, we obtain the expression in (5) and the lemma is proven. □

APPENDIX D
PROOF OF LEMMA 4

Let assume that time instant 0 corresponds to the beginning of the CCA that senses the channel as busy. Then, the start of the CSMA/CA ACK transmission generating the event $\mathcal{B}_{C,\text{ack}}$ must fall within the time interval $(-T_{\text{ack}}, T_{\text{cca}})$ and it is uniformly distributed within this interval.

If the CSMA/CA ACK transmission begins at time instant $t \in (-T_{\text{ack}}, T_{\text{cca}})$, we can be certain that there are no other transmissions before time instant $t - T_{\text{aifs}}$. Otherwise, the CSMA/CA packet generating the ACK would have collided and the ACK transmission that causes the event $\mathcal{B}_{C,\text{ack}}$ would not have occurred.

Hence, to compute $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{ack}})$, we have to determine the probability that no ALOHA node starts a packet transmission from time instant $t - T_{\text{aifs}}$ to T_{cca}, which is $e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}-(t-T_{\text{aifs}}))}$, and integrate it over the time interval $(-T_{\text{ack}}, T_{\text{cca}})$:

$$P\left(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{ack}}\right) = \int_{-T_{\text{ack}}}^{T_{\text{cca}}} \frac{e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{cca}}-t+T_{\text{aifs}})}}{T_{\text{ack}} + T_{\text{cca}}} dt \quad (40)$$

If we perform this integral, we obtain the expression in (6) and the lemma is proven. □

APPENDIX E
PROOF OF THEOREM 5

To prove the theorem, we need to calculate all the probabilities that appear in Lemma 1 and substitute them into it. The terms $P(\mathcal{B}^C_{A,\text{pkt}} \cap \mathcal{B}_{A,\text{ack}})$, $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt}})$, and $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{ack}})$ have been determined in Lemmas 2, 3, and 4; the expressions for $P(\mathcal{B}_{A,\text{pkt}})$, $P(\mathcal{B}_{C,\text{pkt}})$ and $P(\mathcal{B}_{C,\text{ack}})$ still need to be obtained. Regarding $P\left(\mathcal{B}_{A,\text{pkt}}\right)$, it can be computed as follows:

$$P\left(\mathcal{B}_{A,\text{pkt}}\right) = 1 - e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{cca}})} \quad (41)$$

In essence, $P\left(\mathcal{B}_{A,\text{pkt}}\right)$ quantifies the probability that any ALOHA node starts a packet transmission within $T_{\text{pkt}} + T_{\text{cca}}$ seconds before the end of the CCA. We have multiplied the traffic generation rate of each ALOHA node λ_A by $\mathrm{E}\left[n_A\right]$ to account for the fact that each generated packet is transmitted on average $\mathrm{E}\left[n_A\right]$ times. We also assume that during the CCA period, there cannot be any ongoing transmission in order to detect the channel idle.

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The term $P(\mathcal{B}_{C,\text{pkt}})$ corresponds to the probability that at least one CSMA/CA node has sensed the channel as idle in any of the previous $T_{\text{pkt}}/T_{\text{s},C}$ slots that lasts a packet transmission. Therefore,

$$P\left(\mathcal{B}_{C,\text{pkt}}\right) = \left(1-(1-\tau)^{N_C-1}\right)(1-\alpha)\frac{T_{\text{pkt}}}{T_{\text{s},C}} \tag{42}$$

Finally, $P\left(\mathcal{B}_{C,\text{ack}}\right)$ represents the scenario where exactly one out of the remaining N_C-1 CSMA/CA nodes has sensed the channel during any of the previous $T_{\text{ack}}/T_{\text{s},C}$ slots, found it idle, and no ALOHA node has collided with the CSMA/CA packet generating the ACK:

$$\begin{aligned} P\left(\mathcal{B}_{C,\text{ack}}\right) = {} & (N_C-1)\,\tau\,(1-\tau)^{N_C-2}(1-\alpha)\frac{T_{\text{ack}}}{T_{\text{s},C}} \\ & \times e^{-\lambda N_A \mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{ta}})} \end{aligned} \tag{43}$$

By substituting (4), (5), (6), (41), (42) and (43) into (3), we derive the expression in (7) for computing α.

□

APPENDIX F
PROOF OF THEOREM 6

The collision probability for a CSMA/CA transmission is given by:

$$P_{\text{col},C} = P\left(\mathcal{C}_C \cup \mathcal{C}_A\right) = 1 - P\left(\mathcal{C}_C^C\right)P\left(\mathcal{C}_A^C\right) \tag{44}$$

Here, $\mathcal{C}_C$ and $\mathcal{C}_A$ represent the event that the CSMA/CA transmission (packet or ACK) collides with another CSMA/CA or ALOHA transmission, respectively. Hence, $P(\mathcal{C}_C^C)$ and $P(\mathcal{C}_A^C)$ correspond to the probability that the CSMA/CA transmission does not collide with another CSMA/CA or ALOHA transmission, respectively. These probabilities are independent, as ALOHA packet transmissions commence irrespective of other ongoing transmissions.

The term $P(\mathcal{C}_A^C)$ represents the probability that no ALOHA node starts a packet transmission after the end of the CCA and until the end of the ACK:

$$P\left(\mathcal{C}_A^C\right) = e^{-\lambda_A N_A \mathrm{E}[n_A](T_{\text{ta}}+T_{\text{pkt}}+T_{\text{aifs}}+T_{\text{ack}})} \tag{45}$$

It is important to note that a collision between a CSMA/CA transmission (packet or ACK) and an ALOHA ACK is not feasible. This can be attributed to two reasons: first, let us assume that during the CCA, there is an ongoing ALOHA transmission. In such a scenario, the channel would be detected as busy, thus hindering the CSMA/CA nodes from transmitting. Second, if the CSMA/CA transmission has commenced, any subsequently transmitted ALOHA packet would inevitably result in a collision, thus preventing the generation of the ALOHA ACK.

Similarly, we have the following expression for $P(\mathcal{C}_C^C)$:

$$P\left(\mathcal{C}_C^C\right) = (1-\tau)^{N_C-1} \tag{46}$$

This expression represents the probability that no other CSMA/CA node performs the CCA at the same time slot as the CSMA/CA node initiating its transmission. Due to the CSMA/CA mechanism, collisions between CSMA/CA transmissions occur only when both commence simultaneously. To avoid collisions with ACKs, it is assumed that the duration of the CCA is longer than the AIFS.

By substituting (45) and (46) into (44), we obtain (8) and the theorem is proven.

□

APPENDIX G
PROOF OF THEOREM 7

Proceeding as in (31), (32) and (36), we can express ω as:

$$\begin{aligned} \omega = {} & P\left(\mathcal{T}_{A,\text{pkt}}\right) + P\left(\mathcal{T}_{A,\text{pkt}}^C \cap \mathcal{T}_{A,\text{ack}}\right) \\ & + P\left(\mathcal{T}_{A,\text{pkt}}^C | \mathcal{T}_{C,\text{pkt}}\right) P\left(\mathcal{T}_{C,\text{pkt}}\right) \\ & + P\left(\mathcal{T}_{A,\text{pkt}}^C | \mathcal{T}_{C,\text{ack}}\right) P\left(\mathcal{T}_{C,\text{ack}}\right) \end{aligned} \tag{47}$$

with $\mathcal{T}_{A,\text{pkt}}$ and $\mathcal{T}_{A,\text{ack}}$ representing the events that there is another ongoing ALOHA packet or ACK transmission on the channel when the ALOHA node starts transmitting a packet; and $\mathcal{T}_{C,\text{pkt}}$ and $\mathcal{T}_{C,\text{ack}}$ the events that there is an ongoing CSMA/CA packet or ACK on the channel when the ALOHA node starts transmitting a packet.

The term $P\left(\mathcal{T}_{A,\text{pkt}}\right)$ represents the probability that another ALOHA node initiates a packet transmission within T_{pkt} seconds before the beginning of the packet transmission from the ALOHA node:

$$P\left(\mathcal{T}_{A,\text{pkt}}\right) = 1 - e^{-\lambda_A (N_A-1)\mathrm{E}[n_A]T_{\text{pkt}}} \tag{48}$$

The expression for $P(\mathcal{T}_{A,\text{pkt}}^C \cap \mathcal{T}_{A,\text{ack}})$ is given by:

$$\begin{aligned} P\left(\mathcal{T}_{A,\text{pkt}}^C \cap \mathcal{T}_{A,\text{ack}}\right) = {} & \lambda_A\left(N_A-1\right)\mathrm{E}\left[n_A\right]\left(T_{\text{ack}}+T_{\text{aifs}}\right) \\ & \times e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{\text{ack}}+T_{\text{aifs}})} \\ & \times (1-\omega) \\ & \times e^{-\lambda_A \mathrm{E}[n_A](N_A-2)T_{\text{pkt}}} \end{aligned} \tag{49}$$

This equation mirrors conditions akin to those of $P(\mathcal{B}_{A,\text{pkt}}^C \cap \mathcal{B}_{A,\text{ack}})$, albeit with two differences: Firstly, N_A is replaced by N_A-1. This adjustment is necessary because, in this case, the ALOHA node for which we are computing $P(\mathcal{T}_{A,\text{pkt}}^C \cap \mathcal{T}_{A,\text{ack}})$ must not be considered in order to compute the probability of occupying the channel with an ACK. Secondly, we do not have the term T_{cca}, as in this case we are assessing the probability at a specific time instant rather than over a time interval of duration T_{cca}.

The term $P(\mathcal{T}_{C,\text{pkt}})$ corresponds to the probability that at least one CSMA/CA node has sensed the channel as idle in any of the previous $(T_{\text{pkt}}+T_{\text{ta}})/T_{\text{s},C}$ slots that lasts a packet transmission. Therefore,

$$P\left(\mathcal{T}_{C,\text{pkt}}\right) = \left(1-(1-\tau)^{N_C}\right)(1-\alpha)\left(\frac{T_{\text{pkt}}+T_{\text{ta}}}{T_{\text{s},C}}\right) \tag{50}$$

This equation resembles $P(\mathcal{B}_{C,\text{pkt}})$, albeit with the substitution of N_C-1 by N_C, as the number of CSMA/CA nodes to consider is one more than in that case. Additionally, we have incorporated the term T_{ta} into this probability to account for the event that the ALOHA node begins the packet transmission during the turnaround time of a CSMA/CA node.

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This article has been accepted for publication in IEEE Internet of Things Journal. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2025.3539786

The rationale for computing $P(\mathcal{T}^C_{A,\text{pkt}}|\mathcal{T}_{C,\text{pkt}})$ is analogous to computing $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{pkt}})$, with the exception of substituting N_A by $N_A - 1$ and setting $T_{\text{cca}} = 0$:

$$\begin{aligned} P\left(\mathcal{T}^C_{A,\text{pkt}}|\mathcal{T}_{C,\text{pkt}}\right) &= \frac{T_{\text{ta}}}{T_{\text{pkt}}} e^{-\lambda_A (N_A-1)\mathrm{E}[n_A]T_{\text{pkt}}} \\ &+ \frac{e^{-\lambda_A (N_A-1)\mathrm{E}[n_A]T_{\text{ta}}} - e^{-\lambda_A (N_A-1)\mathrm{E}[n_A]T_{\text{pkt}}}}{\lambda(N_A-1)\mathrm{E}\left[n_A\right]T_{\text{pkt}}} \end{aligned} \tag{51}$$

The probability that there is an ongoing CSMA/CA ACK transmission when an ALOHA begins transmitting a packet corresponds to the probability that exactly one out of the N_C CSMA/CA nodes has sensed the channel during any of the previous $T_{\text{ack}}/T_{\text{s},C}$ slots, found it idle, and no other ALOHA node has collided with the CSMA/CA packet that generates the ACK:

$$\begin{aligned} P\left(\mathcal{T}_{C,\text{ack}}\right) = N_C \tau \left(1-\tau\right)^{N_C-1} \left(1-\alpha\right) \frac{T_{\text{ack}}}{T_{\text{s},C}} \\ \times e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{ta}})} \end{aligned} \tag{52}$$

Once more, to compute $P(\mathcal{T}^C_{A,\text{pkt}}|\mathcal{T}_{C,\text{ack}})$, we utilize the same expression as for $P(\mathcal{B}^C_{A,\text{pkt}}|\mathcal{B}_{C,\text{ack}})$, with the modification of substituting N_A by $N_A - 1$ and setting $T_{\text{cca}} = 0$:

$$\begin{aligned} &P\left(\mathcal{T}^C_{A,\text{pkt}}|\mathcal{T}_{C,\text{ack}}\right) = \\ &\frac{e^{-\lambda_A \mathrm{E}[n_A](N_A-1)T_{\text{aifs}}} - e^{-\lambda_A \mathrm{E}[n_A](N_A-1)(L_{\text{ack}}+T_{\text{aifs}})}}{\lambda_A \mathrm{E}\left[n_A\right]\left(N_A-1\right)L_{\text{ack}}} \end{aligned} \tag{53}$$

By substituting (50), (51), (52), (53), (49) and (48) into (47), we derive the expression in (9) for computing ω and the theorem is proven.

□

APPENDIX H
PROOF OF THEOREM 8

The collision probability for an ALOHA transmission is given by:

$$\begin{aligned} P_{\text{col},A} &= P\left(\mathcal{A}_{\text{at init}} \cup \mathcal{A}_{\text{after init}}\right) \\ &= 1 - P\left(\mathcal{A}^C_{\text{at init}}\right) P\left(\mathcal{A}^C_{\text{after init}}|\mathcal{A}^C_{\text{at init}}\right) \end{aligned} \tag{54}$$

Here, $P(\mathcal{A}_{\text{at init}})$ denotes the collision probability for an ALOHA transmission at its inception, i.e. the probability that there is another transmission on the channel when the ALOHA node starts transmitting, which corresponds to ω. $P(\mathcal{A}^C_{\text{after init}}|\mathcal{A}^C_{\text{at init}})$ represents the probability that the ALOHA transmission, spanning the packet and the ACK, does not collide given that it has not collided at its inception. Due to the CSMA/CA method, which avoids any transmission from CSMA/CA nodes on the channel if it is busy, this probability corresponds to the probability that no other ALOHA node initiates a packet transmission during the duration of the packet and the ACK, i.e.,

$$P\left(\mathcal{A}^C_{\text{after init}}|\mathcal{A}^C_{\text{at init}}\right) = e^{-\lambda_A (N_A-1)\mathrm{E}[n_A](T_{\text{pkt}}+T_{\text{aifs}}+T_{\text{ack}})} \tag{55}$$

Considering that $P(\mathcal{A}^C_{\text{at init}}) = 1 - \omega$ and susbtituting (55) into (54), we obtain (10).

Utilizing the expression for $P_{\text{col},A}$, we can calculate the probability that the packet is transmitted i times, denoted as $P\left(\mathcal{R}_i\right)$, as follows:

$$P\left(\mathcal{R}_i\right) = \begin{cases} \left(1-P_{\text{col},A}\right) P^{i-1}_{\text{col},A} & \text{if } i < n+1 \\ P^{i-1}_{\text{col},A} & \text{if } i = n+1 \end{cases} \tag{56}$$

With this, the average number of transmissions of an ALOHA packet is given by:

$$\mathrm{E}\left[n_A\right] = \sum_{i=1}^{n+1} i P\left(\mathcal{R}_i\right) = \frac{1-P^{n+1}_{\text{col},A}}{1-P_{\text{col},A}} \tag{57}$$

□

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Jorge Ortín was born in Zaragoza, Spain, in 1981. He received the Engineer of Telecommunications MS and Ph.D. degrees from the Universidad de Zaragoza in 2005 and 2011 respectively.

In 2008, he joined the Aragón Institute of Engineering Research, Universidad de Zaragoza, where he has participated in different projects funded by public administrations and by major industrial and mobile companies. In 2012, he joined the Universidad Carlos III of Madrid, Madrid, Spain, as a Post-Doctoral Research Fellow. From 2013, he works at Centro Universitario de la Defensa Zaragoza. Research interests include wireless communications systems

José Ramón Gállego was born in Zaragoza, Spain, in 1978. He received the Engineer of Telecommunications MS and Ph.D. degrees from the Universidad de Zaragoza, Spain, in 2001 and 2007, respectively.

In 2002, he joined the Departamento de Ingenierá Electrónica y Comunicaciones, Universidad de Zaragoza, where he is currently an Associate Professor and a member of the Aragón Institute of Engineering Research. His current research interests include wireless communications and network virtualization.

María Canales was born in Zaragoza, Spain, in 1978. She received the Engineer of Telecommunications MS and Ph.D. degrees from the Universidad de Zaragoza, Spain, in 2001 and 2007, respectively.

In 2002, she joined the Departamento de Ingeniería Electrónica y Comunicaciones, Universidad de Zaragoza, where she is currently an Associate Professor and a member of the Aragón Institute of Engineering Research (I3A). Her current research interests include wireless communications and network virtualization.

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