How do ALOHA and Listen Before Talk Coexist in LoRaWAN?

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***Abstract*—In this work we address the analysis of a LoRaWAN network where some devices access the channel according to the standard-compliant ALOHA protocol, while other devices transmit according to a Liste Before Talk paradigm based on the CSMA/CA mechanism. To analyze this scenario, we propose a mathematical model to obtain obtaining the Data Extraction Rate both for CSMA/CA and ALOHA devices, as well as the average delay experienced by messages transmitted by CSMA/CA devices. Simulation results show the accuracy of our model, as well as the benefits of letting CSMA/CA devices into the network, even when not all the devices implement this mechanism and must coexist with ALOHA devices.**

I. Introduction

The Internet of Things (IoT) vision is based on the idea of bringing (Internet) connectivity to unmanned devices immersed in the environment which can then enable a vast range of vertical applications including smart cities, environmental monitoring, e-health and surveillance. Most of these application scenarios are characterized by highly dense networks of field devices which intermittently generate small amount of data; such new traffic/network paradigm is often referred to as Machine-Type Communications opposed to the classical human-to-human services offered by mobile cellular networks [1].

New communication standards and solutions are being rolled out to cope with such new traffic paradigm. Mobile cellular operators are working to evolve “legacy” mobile cellular standards towards MTC-compliant solutions including LTE-M, EC-GSM, NB-IoT and 5G; at the same time, IoT-specialized network operators are gaining momentum by selling IoT connectivity through long-range, low-power wireless technologies like SigFox, LoraWAN [2], Weightless and Ingenu. Such low-power wireless technologies share the same proposition value of low energy consumption and Total Cost of Ownership (TCO), global reach and plug-and-play connectivity.

We focus here on LoRaWAN, which is characterized by an association-less star-of-stars topology in which end devices use single-hop spread spectrum wireless transmission to reach one or multiple gateways that relay messages towards a central network server in the backend. The performance of LoRaWAN networks in terms of coverage, end-to-end latency and Data Extraction Rate (DER) depend jointly on the network layout (number/position of the gateways), the configuration of the physical layer parameters (spreading factor, protection coding rate, channel bandwidth, emitted power) and the efficiency of the Medium Access Control (MAC) scheme.

Broadly speaking, the related work on the performance evaluation of LoRaWAN networks is either based on coverage assessment through experimental tests with commercial LoRa transceivers [3] - [6] or based on system level simulation [7] - [10]. At the moment of writing, there are few works proposing theoretical models to capture LoraWAN performances. Delobel *et al.* propose in [11] a Markovian analysis to assess the performance of Class B devices, whereas Georgious *et al.* propose in [12] a theoretical framework based on stochastic geometry to derive the uplink outage probability in LoRaWAN. Along the same lines, Zucchetto *et al.* analyze in [13] the performance of random access solutions long-range technologies.

The MAC scheme adopted by LoRaWAN is based on simple ALOHA which is proved to be a major performance bottleneck as the network size grows. Stimulated by this fact, we provide two main novel contributions with respect to the reference literature: (i) we propose a comprehensive theoretical framework based on Markovian analysis to assess the performance of Class A devices; (ii) we explore the possibility of using Listen Before Talk (LBT) approaches together with ALOHA at the MAC layer of LoRaWAN networks. In detail, we consider network scenarios heterogeneous from the MAC point of view with end devices running the standard ALOHA-based access scheme and other end devices operating according to LBT approaches. The proposed framework is used to derive the DER and the transmission delay in such mixed environment and is validated against simulation.

The manuscript is organized as follows: Section

II gives a brief overview of LoRaWAN; Section III describes the proposed modeling, whereas Section IV reports and comments on the performance evaluation campaign. Concluding remarks are given in Section V.

II. LoRaWAN Overview

LoRaWAN operates in the unlicensed radio spectrum in the Sub-GHz Industrial, Scientific and Medical (ISM) bands with region-specific carrier frequencies and PHY parameter configurations. The LoRaWAN physical layer is based on Long Range (LoRa^{TM}), a proprietary Chirp Spread Spectrum (CSS) modulation technique developed by Semtech, robust to multipath fading, Doppler shift and narrowband interference. Range and energy consumption of end devices depend on four parameters at the physical layer: (i) the channel bandwidth (BW), that defines the amplitude in the frequency domain of the used channel; (ii) the Spreading Factor (SF), that tells "how much" the reference signal is spread in time (the higher the SF, the longer the transmission range but also the lower the transmission rate); (iii) the Coding Rate (CR), that defines the redundancy of Forward Error Correction (FEC) optionally added to the LoRa messages; (iv) the transmission power (P_{tx}).

The MAC level defines three classes of end devices: Class A devices transmit in the uplink using by standard a simple random ALOHA-based access protocol and can receive traffic in the downlink only after an uplink transmission. Class B devices can wake up periodically to receive scheduled downlink data traffic. Class C devices listen continuously and are typically mains-powered. Class A devices are, at the moment of writing, the ones with the highest diffusion in the market. To limit interference in the ISM band, Class A devices are mandated in Europe to operate with a duty cycle below 1% if running ALOHA access protocol, or, alternatively, adopting a Listen Before Talk approach with no limitations on the duty cycle.

III. Problem Statement and Formulation

We consider a single-gateway LoRaWAN servicing a set of end devices generating messages according to a Poisson process with rate λ. Each end device uses a specific SF in transmission out of the available six ($M = 6$). Two or more uplink transmission can collide only if performed with the same SF. The set of end devices includes devices running plain ALOHA access scheme and devices accessing the channel via a Listen Before Talk approach based on an unslotted CSMA/CA scheme similar to the one used in the IEEE 802.15.4.

According to this protocol, a device backs off transmission for a random number of backoff slots in the range $[0, 2^{BE}-1]$, being BE the backoff exponent that is initialized to m_{min}. When the backoff expires, the device senses the availability of the channel through energy detection or other Clear Channel Assessment (CCA) techniques. If channel is perceived as busy, the BE is increased by 1 up to a maximum value (m_{max}) and the device backs off again for a period randomly generated with the new value of BE. This process is repeated until the number of failed CCAs exceeds the parameter m. In that case, the message is discarded. If channel is clear, the device transmits the message.

We now propose a model to obtain the mean delay incurred by CSMA/CA devices and the DER of ALOHA and CSMA/CA devices sharing the same medium [1].

Let L_i be the airtime in ms of a message transmitted with SF i (we assume fixed message size for all the end devices), and $N_{C,i}$ and $N_{A,i}$ the number of CSMA/CA and ALOHA end devices using SF i, respectively. We also denote with t_b, t_{CCA} and t_{TA} the duration of a backoff slot, of a CCA, and the turnaround time from the listening mode to the transmitting mode. For simplicity, we assume that $t_{CCA} \approx t_{TA} \approx t_b/2$. We also assume that CCA is based on pure energy detection which means that the channel is perceived as busy if one message is being transmitted at CCA time, regardless the used SF.

We rely on the Markov chain shown in Fig. 1 to model the backoff, sensing and transmitting states of the CSMA/CA devices. A state is the tuple (i, j), with i the backoff stage and j the backoff counter ranging from 0 to $W_i = 2^{BE_i} - 1$, with BE_i the backoff exponent corresponding to the backoff stage i. In the states with $j = 0$, CCA is performed. The probability that a station finds the channel busy when it performs a CCA is α. Note that if the number of end devices is high (as typically happens on LoRaWAN), we can safely assume that this probability is the same for all the CSMA/CA devices irrespective of their SF.

The states $(-1, j)$ represent the transmission of a message, with $0 \leq j < L'_l$, and L'_l the duration in slots of a message transmitted using SF l including overhead and payload. The traffic generation of the devices is modeled with a message generation probability in idle state q_l. We also include in the model the probabilities of having a message ready to be transmitted after a channel access failure $q_{cf,l}$ and after a transmission attempt $q_{ta,l}$. The expressions of these probabilities are derived afterward.

The probability τ_l that a device attempts a CCA in a randomly chosen time slot can be derived as in [14]:

$$\tau_l = \left(\frac{1 - \alpha^{m+1}}{1 - \alpha} \right) p(0, 0), \qquad (1)$$

where $p(0, 0)$ is the steady state probability of the state $(0, 0)$. The expression for $p(0, 0)$ is given in Eq. (2). In that expression, $\hat{m} = m_{max} - m_{min}$.

[1] for ALOHA devices the delay is always the transmission time

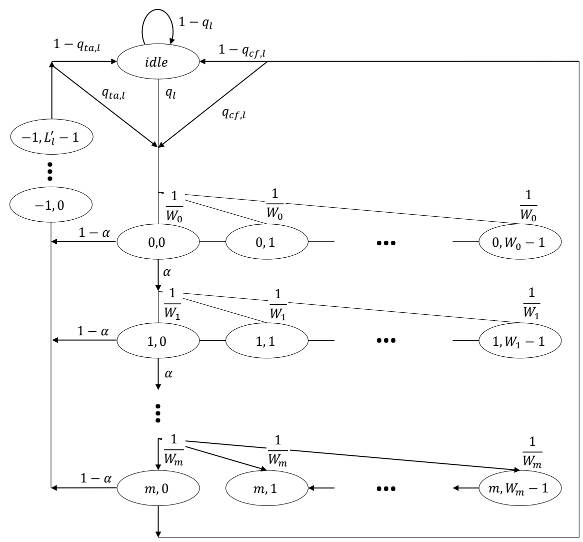


Fig. 1: Markov chain model of the unslotted CSMA/CA devices.

A channel can be found busy upon CCA because occupied by ALOHA and/or CSMA/CA transmissions. The corresponding probability, α, can be written as

$$\alpha = P(\mathcal{B}_{\mathcal{A}} \cup \mathcal{B}_{\mathcal{C}}) = P(\mathcal{B}_{\mathcal{A}}) + P(\mathcal{B}_{\mathcal{A}}^C \cap \mathcal{B}_{\mathcal{C}}), \qquad (3)$$

where $\mathcal{B}_{\mathcal{A}}$ indicates the event that channel is found busy because of an ALOHA transmission and $\mathcal{B}_{\mathcal{C}}$ indicates the event that the channel is busy because of a CSMA/CA transmission.

The term $P(\mathcal{B}_{\mathcal{A}})$ is

$$P(\mathcal{B}_{\mathcal{A}}) = 1 - \prod_{l=1}^{M} e^{-\lambda N_{A,l}(L_l + t_{CCA})}, \qquad (4)$$

i.e., the probability that any ALOHA station starts its transmission in the $L_l + t_{CCA}$ seconds before the beginning of the CCA.

On the other hand, the term $P(\mathcal{B}_{\mathcal{A}}^C \cap \mathcal{B}_{\mathcal{C}})$ can be expressed as

$$\begin{aligned} P(\mathcal{B}_{\mathcal{A}}^C \cap \mathcal{B}_{\mathcal{C}}) &= P\left(\mathcal{B}_{\mathcal{A}}^C \bigcap \left(\bigcup_{l=1}^{M} \mathcal{B}_{\mathcal{C},l}\right)\right) \\ &= \sum_{l=1}^{M} P\left(\mathcal{B}_{\mathcal{A}}^C \bigcap \mathcal{B}_{\mathcal{C},l} \bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C\right) \\ &= \sum_{l=1}^{M}\left[P\left(\mathcal{B}_{\mathcal{A}}^C \middle| \mathcal{B}_{\mathcal{C},l} \bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C\right) P\left(\mathcal{B}_{\mathcal{C},l} \bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C\right)\right]. \end{aligned} \qquad (5)$$

with $\mathcal{B}_{\mathcal{C},l}$ the event that the CCA fails because there is transmitting a CSMA/CA device with SF l. Additionally, $\bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C = \Omega$ when $j = 1$. On the other hand, the event that the channel is not found busy because of the transmission of an ALOHA station ($\mathcal{B}_{\mathcal{A}}^C$) given that there is a collision with a CSMA/CA device using SF l ($\mathcal{B}_{\mathcal{C},l}$) does not depend on the fact that there has not been a collision with other CSMA devices using other SFs ($\bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C$). Therefore, we can rewrite the previous expression as

$$\begin{aligned} P\left(\mathcal{B}_{\mathcal{A}}^C \cap \mathcal{B}_{\mathcal{C}}\right) &= P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},1}\right) P\left(\mathcal{B}_{\mathcal{C},1}\right) \\ &+ \sum_{l=2}^{M}\left[P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},l}\right) P\left(\mathcal{B}_{\mathcal{C},l} \bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C\right)\right]. \end{aligned} \qquad (6)$$

Leveraging the commutativity of set union, we can assume that $j = 1$ corresponds to the SF for which the messages last longer and that the different SF are ordered in descending order of its duration (i.e $L_i < L_j$ for $j < i$). With this, we can operate on the previous equation to obtain

$$\begin{aligned} P\left(\mathcal{B}_{\mathcal{A}}^C \cap \mathcal{B}_{\mathcal{C}}\right) &= P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},1}\right) P\left(\mathcal{B}_{\mathcal{C},1}\right) \\ &+ \sum_{l=2}^{M}\left[P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},l}\right) P\left(\bigcap_{m=1}^{l-1} \mathcal{B}_{\mathcal{C},m}^C \middle| \mathcal{B}_{\mathcal{C},l}\right) P\left(\mathcal{B}_{\mathcal{C},l}\right)\right] \\ &= P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},1}\right) P\left(\mathcal{B}_{\mathcal{C},1}\right) \\ &+ \sum_{l=2}^{M}\left[P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},l}\right) P(\mathcal{B}_{\mathcal{C},l}) \prod_{m=1}^{l-1} P\left(\mathcal{B}_{\mathcal{C},m}^C | \mathcal{B}_{\mathcal{C},l}\right)\right], \end{aligned} \qquad (7)$$

The term $P\left(\mathcal{B}_{\mathcal{C},l}\right)$ is related with the probability that at least one device using SF l has accessed the channel and found it free multiplied with the duration of the message it transmits (as this term corresponds to the classical probability to sense busy in a CSMA/CA network without ALOHA users, the interested reader can to obtain a full derivation of it in [15]). Therefore,

$$P\left(\mathcal{B}_{\mathcal{C},l}\right) = (1 - (1 - \tau_l)^{N_{C,l}})(1 - \alpha) L'_j. \qquad (8)$$

Likewise, $P\left(\mathcal{B}_{\mathcal{C},m}^C | \mathcal{B}_{\mathcal{C},l}\right)$ is the probability that no device using SF m performs a CCA at the same time as a device using SF l, which is

$$P\left(\mathcal{B}_{\mathcal{C},m}^C | \mathcal{B}_{\mathcal{C},l}\right) = (1 - \tau_l)^{N_{C,l}}. \qquad (9)$$

The probability of not finding the channel busy because of the transmission of an ALOHA station conditioned on the fact the it has been found busy because of a CSMA/CA transmission using SF l, $P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},l}\right)$, is

$$P\left(\mathcal{B}_{\mathcal{A}}^C | \mathcal{B}_{\mathcal{C},l}\right) = \prod_{m=1}^{M} P\left(\mathcal{B}_{\mathcal{A},m}^C | \mathcal{B}_{\mathcal{C},l}\right). \qquad (10)$$

The conditional probability $P(\mathcal{B}_{\mathcal{A},m}^C | \mathcal{B}_{\mathcal{C},l})$ corresponds to the probability that no ALOHA transmission using SF m starts in the period from the beginning of the CSMA/CA transmission using SF l that has occupied the channel to the end of the CCA period. Since the beginning of that CSMA/CA transmission is uniformly distributed in the $[-L_l, t_{CCA}]$ period (assuming that the CSMA/CA station that finds the channel busy starts its

$$p_l(0,0)=\begin{cases}\left[\frac{1}{2}\left(\frac{1-(2\alpha)^{m+1}}{1-2\alpha}W_0+\frac{1-\alpha^{m+1}}{1-\alpha}\right)+L'_l\left(1-\alpha^{m+1}\right)+\frac{1-q_{cf,l}}{q_l}\alpha^{m+1}+\frac{1-q_{ta,l}}{q_l}\left(1-\alpha^{m+1}\right)\right]^{-1}, \text{ if } m<\hat{m} \\ \left[\frac{1}{2}\left(\frac{1-(2\alpha)^{\hat{m}+1}}{1-2\alpha}W_0+\frac{1-\alpha^{\hat{m}+1}}{1-\alpha}+\left(2^{m_b+1}+1\right)\alpha^{\hat{m}+1}\frac{1-\alpha^{m-\hat{m}}}{1-\alpha}\right)+L'_l\left(1-\alpha^{m+1}\right)+\frac{1-q_{cf,l}}{q_l}\alpha^{m+1}\right. \\ \left.+\frac{1-q_{ta,l}}{q_l}\left(1-\alpha^{m+1}\right)\right]^{-1}, \text{ otherwise}\end{cases} \tag{2}$$

CCA at time instant 0). Additionally, $P(\mathcal{B}^C_{\mathcal{A},m}|\mathcal{B}_{\mathcal{C},l})$ depends on the relationship between L_m and L_l. If $L_m > L_l$, we have

$$\begin{aligned} P(\mathcal{B}^C_{\mathcal{A},m}|\mathcal{B}_{\mathcal{C},l}) &= \int_{-L_l}^{t_{CCA}} \frac{e^{-\lambda N_{A,m}(t_{CCA}-t+t_{TA})}}{L_l+t_{CCA}}dt \\ &= \frac{e^{\lambda N_{A,m}t_{TA}}(1-e^{-\lambda N_{A,m}(L_l+t_{CCA})})}{\lambda N_{A,m}(L_l+t_{CCA})}. \end{aligned} \tag{11}$$

The integrand of the previous equation indicates that if the CSMA/CA transmission with SF l that has occupied the channel has begun at a time instant $t\in[-L_l,t_{CCA}]$, the event $\mathcal{B}^C_{\mathcal{A},m}|\mathcal{B}_{\mathcal{C},l}$ implies that there has not been any ALOHA transmission with SF m in the time period $[t-t_{TA},t_{CCA}]$. Likewise, if $L_m \le L_l$

$$\begin{aligned} P(\mathcal{B}^C_{\mathcal{A},m}|\mathcal{B}_{\mathcal{C},l}) &= \int_{-L_l}^{-L_m+t_{TA}} \frac{e^{-\lambda N_{A,m}(L_m+t_{CCA})}}{L_l+t_{CCA}}dt \\ &\quad+\int_{-L_m+t_{TA}}^{t_{TA}} \frac{e^{-\lambda N_{A,m}(t_{CCA}-t+t_{TA})}}{L_l+t_{CCA}}dt \\ &= \frac{(L_l-L_m+t_{TA})e^{-\lambda N_{A,m}(L_m+t_{CCA})}}{L_l+t_{CCA}} \\ &\quad+\frac{e^{-\lambda N_{A,m}t_{TA}}-e^{-\lambda N_{A,m}(L_m+t_{CCA})}}{\lambda N_{A,m}(L_l+t_{CCA})}. \end{aligned} \tag{12}$$

In this case, if the CSMA/CA transmission that has occupied the channel has begun at a time instant $t\in[-L_l,-L_m+t_{TA}]$, the event $\mathcal{B}^C_{\mathcal{A},m}|\mathcal{B}_{\mathcal{C},l}$ implies that there has not been any ALOHA transmission with SF m in the time period $[-L_m,t_{CCA}]$. Similarly, if the CSMA/CA transmission has begun at time instant $t\in[-L_m+t_{TA},t_{TA}]$, then there cannot have been any ALOHA transmission in the time period $[t-t_{TA},t_{CCA}]$. Note that $P(\mathcal{B}^C_{\mathcal{A},m}|\mathcal{B}_{\mathcal{C},l})=1$ in eqs. (11) and (12) if $N_{A,m}$ is zero.

Eqs. (1) (one for each SF) and (3) form a system of $M+1$ coupled nonlinear equations with variables τ_l and α that can be solved numerically to obtain the point of operation of the network. From these variables different performance metrics can be obtained. First, the probability that a message transmitted by an CSMA/CA device using SF l collides is

$$\begin{aligned} P_{c,l,C} &= P\left(\mathcal{C}_{l,\mathcal{A}}\right)+P\left(\mathcal{C}_{i,\mathcal{C}}\right)-P\left(\mathcal{C}_{l,\mathcal{A}}\cap\mathcal{C}_{l,\mathcal{C}}\right) \\ &= P\left(\mathcal{C}_{l,\mathcal{A}}\right)+P\left(\mathcal{C}_{l,\mathcal{C}}\right)-P\left(\mathcal{C}_{l,\mathcal{C}}\right)P\left(\mathcal{C}_{l,\mathcal{A}}\right). \end{aligned} \tag{13}$$

In this expression, $\mathcal{C}_{l,\mathcal{A}}$ (or $\mathcal{C}_{l,\mathcal{C}}$) corresponds to the event that the CSMA/CA station using SF l collides with an ALOHA (or CSMA/CA) station using its same SF. Note that the last step in Eq. (13) can be done as the probability of colliding with a CSMA/CA device is independent of the probability of colliding with an ALOHA device. The term $P\left(\mathcal{C}_{l,\mathcal{A}}\right)$ is

$$P\left(\mathcal{C}_{l,\mathcal{A}}\right)=1-e^{\lambda N_{A,l}(L_l+t_{TA})}, \tag{14}$$

which corresponds to the probability that there is at least one transmission of an ALOHA device using SF l during the transmission of the CSMA/CA device. Similarly, $P\left(\mathcal{C}_{i,\mathcal{C}}\right)$ is the probability that any other CSMA/CA device performs the CCA at the same time as the CSMA/CA station,

$$P\left(\mathcal{C}_{i,\mathcal{C}}\right)=1-\left(1-\tau_i\right)^{N_{C,i}-1}. \tag{15}$$

With this, the DER of a CSMA/CA device using SF l corresponds to the probability of a successful transmission

$$DER_{l,C}=\left(1-P_{c,l,C}\right)\left(1-\alpha^{m+1}\right), \tag{16}$$

i.e., the probability that the CSMA/CA finds the channel free in any of the CCA attempts times the probability that the message does not collide given that it is transmitted.

We derive now the expressions for the average delay experienced by a CSMA/CA message. We distinguish between two different cases: (i) when the channel has been found idle in any of the $m+1$ allowed CCAs and the message has been able to be transmitted and (ii) when the message is discarded because of a channel access failure (i.e., the channel has been found busy in the $m+1$ CCAs). To compute these metrics, we consider only the interval from the time the message is ready to be transmitted (i.e., we do not include any queuing time).

In the first case, the average delay is

$$\mathrm{E}\left[T_{ta,l}\right]=L_l+\mathrm{E}\left[T_b\right], \tag{17}$$

being T_b the random time that a device spends in back-off or sensing states during the CSMA/CA mechanism. The expected value of T_b is

$$\mathrm{E}\left[T_b\right]=\sum_{i=0}^{m}P(\mathcal{D}_i)\mathrm{E}\left[T_{b,i}\right], \tag{18}$$

where $P(\mathcal{D}_i)$ is the probability of finding the channel idle at the $i+1$th attempt, given that the channel has been found busy in the preceding i attempts and the message has not been discarded due to a channel access failure; and $\mathrm{E}\left[T_{b,i}\right]$ is the expected time a device spends in backoff or sensing states given the event $\mathcal{D}_i$. $P(\mathcal{D}_i)$ can be calculated as

$$P(\mathcal{D}_i) = \frac{\alpha_l^i}{\sum_{k=0}^{m} \alpha_l^k}\alpha_l^i = \frac{1-\alpha_l}{1-\alpha_l^{m+1}}, \qquad (19)$$

while

$$\begin{aligned} \mathrm{E}\left[T_{b,i}\right] &= (i+1)t_{CCA} + \sum_{k=0}^{i} \mathrm{E}\left[B_k\right] t_b \\ &= (i+1)t_{CCA} + \sum_{k=0}^{i} t_b \frac{W_k-1}{2}, \end{aligned} \qquad (20)$$

with $B_k = \mathcal{U}(0, W_k)$ a discrete uniform random variable indicating the backoff outcome at backoff stage k.

Regarding the delay suffered by a message when it is discarded due to a channel access failure, $T_{cf,l}$, it is

$$\mathrm{E}\left[T_{cf,l}\right] = \sum_{k=0}^{m} t_b \frac{W_k-1}{2}, \qquad (21)$$

which is independent of the SF l used by the CSMA/CA device.

Finally, the probabilities of having a packet ready to be transmitted in idle state, after a transmission attempt and after a channel access failure are

$$q_l = 1 - e^{-\lambda_l t_b}, \qquad (22)$$

$$q_{suc,l} = \lambda \mathrm{E}\left[T_{suc,l}\right] \qquad (23)$$

and

$$q_{cf,l} = \lambda \mathrm{E}\left[T_{cf,l}\right]. \qquad (24)$$

A detailed explanation of their derivation is found in [14].

The DER for an ALOHA device using SF l is its probability of having a successful transmission

$$\begin{aligned} DER_{A,l} &= 1 - P(\mathcal{A}_{\mathcal{A},l} \cup \mathcal{A}_{\mathcal{C},l}) \\ &= 1 - P(\mathcal{A}_{\mathcal{A},l}) - P(\mathcal{A}_{\mathcal{A},l}^C | \mathcal{A}_{\mathcal{C},l}) P(\mathcal{A}_{\mathcal{C},l}), \end{aligned} \qquad (25)$$

where $\mathcal{A}_{\mathcal{A},l}$ indicates the event that the ALOHA device collides with another ALOHA device using its same SF and $\mathcal{A}_{\mathcal{C},l}$ indicates the event that the ALOHA device collides with a CSMA/CA device.

The term $P(\mathcal{A}_{\mathcal{A},l})$ is the probability that there is at least one transmission of another ALOHA device using the same SF in the timespan $2L_l$, which is

$$P(\mathcal{A}_{\mathcal{A},l}) = 1 - e^{-2\lambda(N_{A,l}-1)L_l}. \qquad (26)$$

Likewise $P(\mathcal{A}_{\mathcal{C},l})$ is the probability that at least one CSMA/CA device with the same SF has begun a transmission in the $L_l + t_{TA}$ seconds before the transmission attempt of the ALOHA device,

$$P(\mathcal{A}_{\mathcal{C},l}) = \left(1 - (1-\tau_l)^{N_{C,l}}\right)(1-\alpha)\left(L' + \frac{t_{TA}}{t_b}\right) \qquad (27)$$

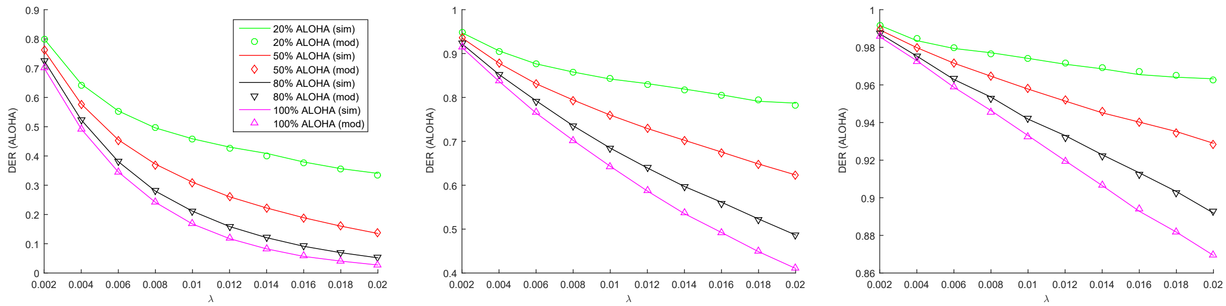
The conditional probability $P(\mathcal{A}_{\mathcal{A},l}^C | \mathcal{A}_{\mathcal{C},l})$ corresponds to the probability there is not another ALOHA transmission from the beginning of the CSMA/CA transmission that has caused the collision to the end of the collided ALOHA transmission. The beginning of the colliding CSMA/CA transmission is uniformly distributed in the time period $[-L_l, t_{TA}]$ (considering that the beginning of the collided ALOHA transmission occurs at time instant 0). Therefore, if the colliding CSMA/CA transmission has begun at a time instant $t \in [-L_l, -L_l + t_{TA}]$, the event $\mathcal{A}_{\mathcal{A},l}^C | \mathcal{A}_{\mathcal{C},l}$ implies that there has not been another ALOHA transmission in the time period $[-L_l, L_l]$. Similarly, if the colliding CSMA/CA transmission has begun at time instant $t \in [-L_l + t_{TA}, t_{TA}]$, then there cannot have been another ALOHA transmission in the time period $[t - t_{TA}, L_l]$. Therefore,

$$\begin{aligned} P(\mathcal{A}_{\mathcal{A},l}^C | \mathcal{A}_{\mathcal{C},l}) &= \int_{-L_l}^{-L_l + t_{TA}} \frac{e^{-2\lambda(N_{A,l}-1)L_l}}{L_l + t_{TA}} dt \\ &\quad + \int_{-L_l + t_{TA}}^{t_{TA}} e^{-\lambda(N_{A,l}-1)(L_l - t + t_{TA})} dt \\ &= \frac{t_{TA} \cdot e^{-2\lambda(N_{A,l}-1)L_l}}{L_l + t_{TA}} \\ &\quad + \frac{e^{-\lambda(N_{A,l}-1)L_l} - e^{-2\lambda(N_{A,l}-1)L_l}}{\lambda(N_{A,l}-1)(L_l + t_{TA})}. \end{aligned} \qquad (28)$$

IV. Numerical Results

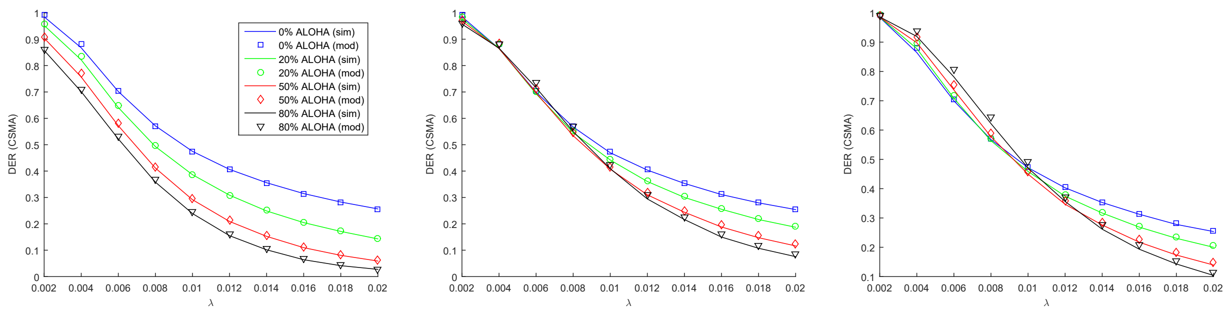
We consider a system with 300 end devices serviced by a single gateway and different configurations of ALOHA and CSMA/CA devices. To validate the proposed model, we built up a system-level discrete event simulator written in C++. The simulation results shown hereafter are obtained by averaging of ten simulation runs consisting each of 10^7 frame transmissions (we do not represent the 95%-confidence intervals as their relative size is well below 1%).

The LoRA parameters used in the simulations are listed in Table I. The MAC parameters used in this section are $m_{min} = m_{max} = 12$ and $m = 4$. We have also set the duration of a backoff slot to 1.4 ms, which corresponds to the time required to transmit the 8 bytes of the LoRaWAN physical layer preamble using the SF 7 with a bandwidth of 125 kHz. The election of high backoff exponents is due to the high duration of the messages transmitted using high SFs (for instance, the duration of a message transmitted with SF 12 is 1293 slots). If they were not that high, the probability of finding the channel busy in successive CCAs given that it was busy in the first CCA would be high since



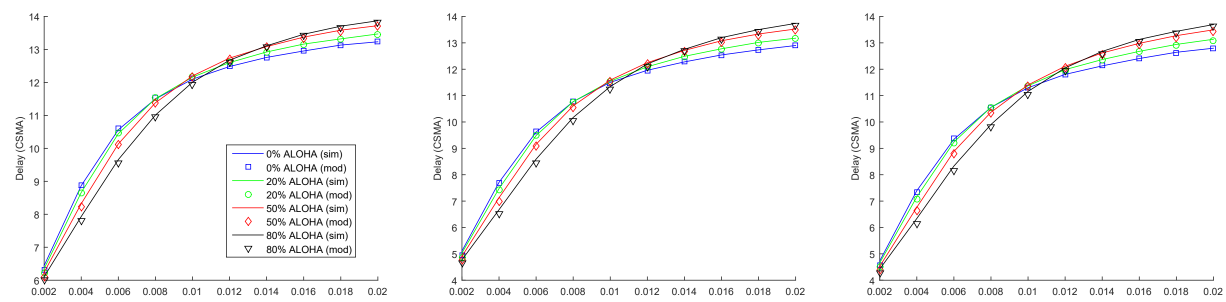
(a) $L = 1810.43$ ms (SF = 12) (b) $L = 452.61$ ms (SF = 10) (c) $L = 71.94$ ms (SF = 7)

Fig. 2: Success probability for ALOHA nodes with 50 nodes using each SF (300 users in total)



(a) $L = 1810.43$ ms (SF = 12) (b) $L = 452.61$ ms (SF = 10) (c) $L = 71.94$ ms (SF = 7)

Fig. 3: Success probability for CSMA/CA nodes with 50 nodes using each SF (300 users in total)



(a) $L = 1810.43$ ms (SF = 12) (b) $L = 452.61$ ms (SF = 10) (c) $L = 71.94$ ms (SF = 7)

Fig. 4: Average delay in seconds for CSMA/CA nodes with 50 nodes using each SF (300 users in total)

the transmitted message(s) causing the first failed CCA may not has ended in the next CCA.

TABLE I: LoRaWAN PHY Parameters

Application payload [byte]	20					
LoRaWAN header [byte]	13					
Coding rate	4/5					
Preamble [byte]	8					
Bandwidth [kHz]	125					
SF	7	8	9	10	11	12
Air Time [ms]	71.94	133.63	246.78	452.60	987.13	1810.43

Fig. 2 shows the DER of ALOHA devices for different SFs, message generation rates and percentages of ALOHA and CSMA/CA devices. These graphs (as well as in those on Figs. 3 and 4) were obtained under uniform SF assignment to end devices, that is, with 50 devices using each SF. Therefore, the 20% ALOHA line indicates that there are 10 ALOHA devices in each SF and 60 ALOHA devices in total. As can be seen, the inclusion of CSMA/CA devices in a LoRaWAN network impacts positively on the probability of having a successful transmission for ALOHA devices in all the cases, independently of the message generation rate and the specific SF used by the devices. The reason behind this behavior is evident: if there is an ALOHA transmission on the channel, CSMA/CA devices will detect it and will refrain from transmitting, thus decreasing the collision probability of ALOHA messages.

Similarly, Fig. 3 shows the DER of CSMA/CA devices for different SFs, message generation rates and percentages of ALOHA and CSMA/CA devices.

As clear from the figure, similarly to what observed for ALOHA devices, the probability of a successful transmission for CSMA/CA devices using high values of SF increases as the fraction of ALOHA devices decreases. On the contrary, for low values of SF, it is better to have a higher percentage of ALOHA devices when λ is also low. The reason behind this is the following: the prevailing source of error for CSMA/CA devices with low values of SF is a channel access failure, whose probability for low λ is higher when the number of CSMA/CA devices in the network is high. On the other hand, for high λ this probability is higher when the number of ALOHA devices is high. For low values of λ, CSMA/CA devices have higher successful probabilities than ALOHA devices, while for high values of λ ALOHA devices tend to obtain better results. This behavior is due to the fact that for high λ, the main error source for CSMA/CA devices is channel access failures. This kind of errors refrains CSMA/CA devices from transmitting, which lowers the collision probability for ALOHA devices. Finally, the probability of a successful transmission amongst the different SF is more similar for CSMA/CA devices than for ALOHA devices, which is due to the fact that the probability of finding the channel busy do not depend of the SF.

Fig. 3 shows the average delay suffered by a CSMA/CA message from the moment it initiates the backoff process until it is received (wrongly or not) or discarded due to a channel access failure. The depicted results correspond to

$$T_l = \alpha^{m+1}\mathrm{E}\left[T_{ta,l}\right] + \left(1 - \alpha^{m+1}\right)\mathrm{E}\left[T_{cf,l}\right]. \qquad (29)$$

In this case, the average delay is similar for all the SF, as this delay depends mainly on the term $\alpha^{m+1}\mathrm{E}\left[T_{ta,l}\right]$, which is the same for all the SF.

As a final remark, it is worth mentioning that our model fits closely the results obtained with simulations in all the cases, demonstrating its accurateness and utility to obtain performance results with a low computational cost.

V. Concluding Remarks

We have addressed the performance evaluation of LoRaWAN Class A end devices by introducing a theoretical framework for the modeling of Data Extraction Rate and average transmission delay in the uplink segment. The proposed model was used to evaluate the coexistence in the same network of two different MAC schemes: plain ALOHA and Listen Before Talk based on Carrier Sensing Multiple Access through energy detection. The numerical results of the model validated against simulation demonstrate the model is indeed successful in capturing the performance of LoRaWAN networks. To the best of our knowledge, ours is the first work assessing the performance of "mixed" MAC situations.

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