Performance of LoRaWAN CSMA in Dense LoRa Networks

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***Abstract*—LoRaWAN networks essentially overcome the low efficiency of ALOHA-based channel access method by relying on the frequency/Spreading Factor (SF) diversity and on the Adaptive Data Rate control mechanism. The Carrier Sense Multiple Access (CSMA) approaches were not considered by the LoRa Alliance until very recently when a LoRaWAN Technical Recommendation for enabling a CSMA protocol on LoRa networks was released, based on the Channel Activity Detection (CAD) mechanism. In this article, we study the performance and the scalability of the newly proposed LoRaWAN CSMA protocol with extensive simulations, in a very dense urban scenario and varying network topologies, radio and traffic conditions. We show that in such scenario the LoRaWAN CSMA has limited performance compared with a state-of-art multi-channel CSMA. We then propose gradual improvements of the LoRaWAN CSMA and thoroughly analyze their benefits.**

***Index Terms*—LoRaWAN, CSMA protocols, channel access**

I. Introduction

LoRa is an LPWAN technology (Low-Power Wide-Area Network) developed by Semtech that targets the Internet-of-Things (IoT) application domain. Proposed for transmission in the unlicensed spectrum, LoRa physical modulation uses a Chirp Spread Spectrum (CSS) method where the data rate depends on the channel bandwidth (BW) and a Spreading Factor (SF) which basically defines how long is a symbol. Longer symbol durations provides more robustness. LoRa proposes SF values from 7 to 12 and the symbol rate is defined as $BW/2^{SF}$. Each increase in SF doubles the symbol duration and improves signal sensitivity by about 2–3 dB.

From the very beginning, a LoRa/LoRaWAN network is basically a simple ALOHA network that relies on frequency & SF diversity to overcome the low efficiency of an ALOHA-based channel access method with very long packet transmission time (e.g. several seconds). On top of the LoRa physical layer, the LoRaWAN specification [1] defines the packet format and the network management mechanisms, e.g. the Adaptive Data Rate (ADR) mechanism that improves the SF assignments to the devices, depending on their distance (thus signal quality) to the gateway, thus the network capacity.

Starting in 2018, the research community has investigated the benefits of a Carrier Sense Multiple Access (CSMA) approach to reduce the number of collisions, as LoRa networks become more dense due to the huge interest in the deployment of LoRa IoT devices in multiple application domains [2], [3]. Therefore, the research community has been very active in proposing and evaluating a large number of CSMA variants [4]–[10] where various packet collision mitigation techniques are combined in the search for more efficient approaches. In general, CSMA-based channel access for LPWAN is more challenging than in other wireless technologies for many reasons. For instance, one main difficulty is to determine whether the channel is clear or occupied: with a high RX sensitivity, LPWAN devices can receive a packet below the noise floor. Besides, as the range increases, the hidden terminal problem gets worse [11]. However, as coordinated approaches, such as TDMA-based approaches, incur high synchronization overheads that are often incompatible with duty-cycle regulations for the unlicensed spectrum, CSMA-based protocols are still a promising approach to improve the performance of LoRa networks when they operate on the sub-GHz ISM bands.

The LoRa Alliance – the specification body behind LoRaWAN networks – did not consider CSMA approaches until very recently, relying instead, as indicated previously, on frequency & SF diversity and on the ADR mechanism. However, in dense urban environments, the efficiency of ADR can drop sharply as a vast majority of devices would need the highest SF values, leading to almost no SF diversity. In [7], the authors proposed the LMAC protocol that has later been adapted for a release of a LoRaWAN Technical Recommendation to enable a CSMA approach on LoRa networks [12]. Both approaches rely on an efficient Clear Channel Assessment (CCA) mechanism that Semtech provided and improved: the Channel Activity Detection (CAD) [10], [13], [14].

This article therefore studies with extensive simulations the performance and the scalability of the newly proposed CSMA protocol for LoRaWAN in various network topologies and traffic conditions. Noting this protocol LoRaWAN_CSMA, we first compare LoRaWAN_CSMA with a simple & basic CSMA-like protocol that implements a multi-channel CCA phase (trying on multiple frequency channels as proposed in [4]). In a second step, after analyzing the performance and identifying pros & cons of LoRaWAN_CSMA, we propose and evaluate several improvements to better address very dense scenarios. The rest of the paper is organized as follows: Section II quickly presents the LoRa radio technology, a basic CSMA approach for LoRa and the proposed LoRaWAN_CSMA protocol. Section III presents the simulation model and setup. Section IV presents the first performance comparison study with ALOHA, basic CSMA and LoRaWAN_CSMA. We analyze results and identify pros & cons of the newly proposed LoRaWAN_CSMA. In Section V we propose and evaluate several improvements to better address very dense scenarios. Related works are presented in Section VI. Section VII concludes.

II. LoRa and CSMA on LoRa

LoRa conveys information by linearly sweeping a given frequency band [15]. A symbol, carried on a chirp, is then identified with the sweep's starting frequency. Logical channels are formed around a set of carrier frequencies (named physical channels) by choosing the bandwidth (BW) and the sweep's speed (spreading factor, SF). Different coding rates (CR) allow for a trade-off of the amount of data carried on a symbol with the reliability of the transmission.

A frame transmission is constituted of a preamble comprising a sequence of specific symbols, designed to phase the receiver with the transmission, followed by a header carrying control information in a reliable CR, the payload and a validation field.

A. Basic CSMA on LoRa

The CSMA approach has been implemented for long on radio technologies, in particular in Wi-Fi, and for some mesh sensor networks such as IEEE 802.15.4. For LoRa, its development has been criticized in early research articles because LoRa generally operates below the noise floor, and first studies considered performing CCA by comparing the received signal strength indicator (RSSI) of received frames with a threshold; this approach has very limited performance in terms of detection of the signal, identification of the involved logical channel, and energy consumption.

To address these issues, Semtech introduced the Channel Activity Detection (CAD) mechanism [14], originally meant to detect preamble symbols on a specific logical channel by correlating signal samples with expected chirps. In recent LoRa modules, CAD has been improved and is now able to correctly detect frame header as well as payload symbols [7]. CAD suffers from the same uncertainty as the reception process regarding non orthogonal logical channels [16] but runs faster and is claimed to be much more energy efficient [17].

Many approaches have since then proposed implementation of CSMA based on CAD [4]–[10]. In order to trade-off the reliability of CCA with its energy and time consumption, a sequence of a certain amount **n** of CADs, each one sampling during a certain amount of chirps durations, may be performed on a single physical channel [7]. But these CAD sequences could also be repeated over a given number **x** of different physical channels, hopping randomly among them, until one is found clear [4] or all are found busy. We denote this type of CCA as xCADs and argue that it is particularly suitable for LoRa networks because of its inherent frequency diversity.

In addition, in the CSMA family, the simplest protocols let devices directly transmit when the CCA states the logical channel is clear, wait otherwise a certain time before retrying (**r** retries). This behavior is denoted as backoff when busy (BO_B). Inheriting from the original CSMA [18] the BO_B is often binary exponential, i.e. its duration is randomly chosen below a maximum threshold that is doubled at each retry.

Therefore, the basic CSMA on LoRa, and denoted Basic_LoRa_CSMA in this article, would actually refer to CSMA with BO_B + xCADs.

B. CSMA for LoRaWAN by LoRa Alliance

However, under the presence of several competitors, BO_B has reduced performance because two simultaneous CCAs on a clear channel lead to a collision. Therefore, most of implemented CSMA protocols on wireless networks actually discriminate potential competitors for a clear channel with a random waiting BO when clear, referred to as BO_C.

In the CSMA protocol proposed by the LoRa Alliance for LoRa networks [12], [7] and noted in this article LoRaWAN_CSMA, the protocol adopts a BO_C approach and additionally makes it active and residual, very similar to the CSMA approach implemented in WiFi networks: the waiting device actively performs a sequence of CAD while waiting; if the channel gets busy due to the transmission of another competitor, only the residual time shall be waited at the following retry on a clear channel.

When the logical channel is seen busy, LoRaWAN_CSMA leverages another mechanism since the random discrimination of competitors is provided by the residual BO when the channel is clear: the devices simply switch to another physical channel – a mechanism we denote by CH for Channel Hopping – and retry a CCA. In order to reduce the overhead in case of densely occupied channels, the authors set the maximum number of retries to r=6 and the number of channels evaluated per try to x=1 [12]. When no more retries are possible, the device simply transmits as in ALOHA.

Therefore, LoRaWAN_CSMA would actually refer to CSMA with BO_C (active+residual) + 1-CADs + CH.

III. Simulation setup

We developed the LoRa-CSMA-Sim simulator [19] based on the original LoraSim (2016) [20] framework. LoRa-CSMA-Sim adds CAD & collision management, an improved energy consumption model, a more realistic Capture Effect model, multi-channel support, RX mode for devices and asymmetric path-loss for device-to-device (ED-ED) communications. The MAC protocols must be compatible with the LoRaWAN stack that follows duty-cycle constraints. More than 40 metrics are collected at each run. Therefore, the simulator enables a thorough comparison of CSMA approaches for LoRa networks.

A. Protocols and variants

The simulation runs are structured by a set of protocols under comparison, variants of these protocols with varying protocol parameters, and by ranges of traffic, scale, and

TABLE I: Protocols and parameters for variants

Protocol name	BO type and durations	Termination	Marker	Color
ALOHA	N/A	transmit	●	blue
Basic_LoRa_CSMA	BO_B: d_{min}=[5-45]B, e_{init}=[2-4], e_{max}=[7-10]	u_{min}=[0-45] sym, u_{max}=[22-120] sym	▽	yellow
LoRaWAN_CSMA	BO_C active residual s=[0-12] CADs, i=[0-8] sym	transmit, ALOHA-like	△	red
LoRaWAN_CSMA_1	BO_C active residual s=[0-8] CADs, i=0 sym	transmit, ALOHA-like	◁	green
LoRaWAN_CSMA_2	BO_C passive p_{min}=0, p_{max}=[0-8] sym + n CADs	u_{min}=[0-45] sym, u_{max}=[22-120] sym	▷	purple
LoRaWAN_CSMA_3	BO_C passive p_{max}=0 sym + n CADs, l_{min}=12 sym, l_{max}=[12-24] sym, NAV/CH threshold [2.5-4.5] s	NAV	□	maroon

radio propagation parameters. In the simulations we present in this article, we compare 64 variants of 5 protocols (Basic_LoRa_CSMA, LoRaWAN_CSMA and 3 improvements) with the default ALOHA. The variants of the protocols are synthesized in Table I. For all CSMA protocols, parameters for xCADs are (x=8, n=[1-4], r=6), except for LoRaWAN_CSMA where (x=1, n=[1-4], r=6). For all protocols, when changing to a new channel, each device follows a random sequence that is repeated over time. Additional restrictions imposed by regulations can be added in the model to be applied to all protocols. The “BO type and durations” column specifies the implementation of the BO for each variant. A BO_B has a minimal duration d_{min}, indicated as time-on-air of a frame of given length expressed in bytes (B), and initial and maximum exponent e for its random portion. A BO_C can be active residual, using a sequence of **s** CADs separated by an interval **i**, or passive, with duration between p_{min} and p_{max} expressed in symbol (sym) number. For LoRaWAN_CSMA_3, devices use RX mode with duration between l_{min} and l_{max}, enabling the computation of a NAV waiting period (see Section V-C for detailed explanations). The “Termination” column describes the mechanism in use after all r retries: a final passive BO can be applied, with duration between u_{min} and u_{max} symbols.

The variations over 4 values of 12 parameters are synthesized in Table II. For each variation value the simulation runs on 4 similar topologies. In total, there are 61632 runs, representing 6.29E9 frame generations.

B. Baseline Scenario

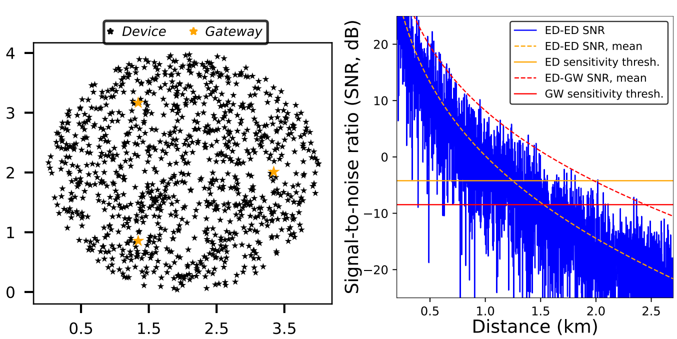

Fig. 1: Topology and propagation conditions in BS.

The Baseline Scenario (BS) adopts a circular topology where devices are uniformly spread and 3 gateways (GWs) are equi-positioned on a triangle at 2/3 of the topology’s radius (see Fig. 1 left). GWs collect the uplink traffic from the devices and a frame is successfully collected when at least one of the GWs has fully received it.

Frame receptions are possible on both devices and GWs as long as the signal-to-noise ratio (SNR) is above a threshold, related to their sensitivities (Fig. 1 right). Path loss is driven by a log-distance model such as in [9], but with different exponents (PLE) for ED-to-ED links and ED-to-GW links.

In our code a GW can be receiving multiple frames overlapping in time as long as they belong to different (orthogonal) logical channels. Devices can only receive on a single logical channel at a time, after prior configuration of their radio chipset. For overlapping frames on the same logical channel, the reception of at most one of all them is conditioned to the margin between its signal strength and the interference, the noise level, and to whether the receiver has phased with one of the preamble’s symbols or not. These conditions are referred to as the conditions of Capture Effect (CE).

CADs are modeled at each distance such that their success is as probable as the frame reception rate in the same conditions. The CAD’s reliability is studied by varying the PLE of the equivalent link budget, thus the success rate (Table II).

Our scenario focuses on uplink transmissions using BW125 and SF12, on 8 physical channels in the 868 MHz band. Despite the ADR mechanism to optimize SF assignment, SF12 will most likely be the configuration for a large majority of devices in dense urban deployment scenarios. Without losing generality, with SF12, the longer time-on-air emphasizes the impact of overlaps (more collisions) and allows us to better discriminate the mitigation techniques.

TABLE II: Parameters for BS and variations **(X-axes)**

Parameter	Distrib	Value in BS	Range of variation
inter pkt	exp	200 s	[100,**200**,400,800]
scale	uniform	radius 2000 m	[1500,**2000**,2500,3000]
max. r	const	6	[3,**6**,12,24]
payload	normal	45 B	[15,**45**,80,130]
fading (dB)	exp (dB)	0 dB	[-4,-2,**0**,1]
device PLE	normal	3.8	[3.6,**3.8**,4.2,5]
gateway PLE	const	3.4	[3,3.2,**3.4**,3.8]
% interfering dev.	uniform	0%	[**0**,20,40,60]
obstruct (dB)	log-dist	8×0.4 dB/km	[2,4,**8**,16]
CE lock	uniform	0.5	[0.1,0.3,**0.5**,0.8]
CAD reliability	log-dist	PLE+0	[-0.4,**0**,0.4,0.8]
#devices	const	1000	[500,**1000**,1500,2000]

7 metrics are computed for each device / run and averaged **(Y-axes)**: (1) the Payload Delivery Ratio (PDR) is the ratio of successfully received payload bytes at at least one GW over

the total generated; (2) the consumed energy per successfully transmitted payload byte (E/S); (3) the total energy (TE) consumed by each device; (4) the mean success latency (MSL) for each frame; (5) the number of collided frames (#CO) for each device; (6) the number of channel hops (#CH) and (7) the consumed energy when doing CAD (ECAD)(J).

For each protocol we refer to the variant obtaining the highest average PDR in the baseline scenario as the **best performing variant**. Similarly, **the most efficient variant** corresponds to the variant obtaining the lowest average E/S in the baseline scenario.

Also, in all figures, we use the same legend in terms of colors, markers and line styles for each protocol. Best performing variants are displayed with empty violin plots and dashed lines (uniting mean values). Most efficient variants are displayed with plain violins and lines. Markers and colors are listed in Table I (e.g. ALOHA uses • markers and blue lines).

IV. ALOHA vs Basic LoRa CSMA vs LoRaWAN_CSMA

In this first performance study we compare ALOHA (blue), Basic_LoRa_CSMA (yellow) and LoRaWAN_CSMA (red).

A. Comparison in Baseline Scenario

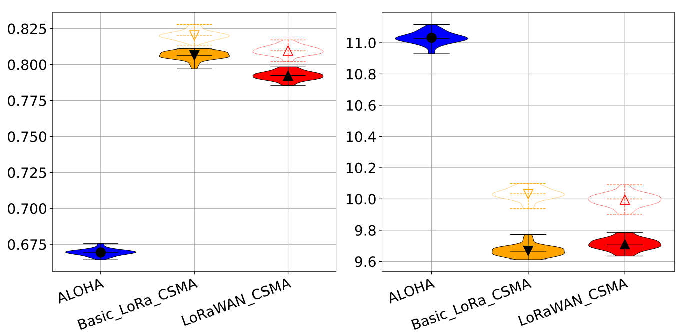

Fig. 2: Protocols in Baseline Scenario (BS) (X-axis) – PDR (left) and E/S (right) (Y-axes). ALOHA reaches a mean PDR of 67%, with an efficiency of above 11 mJ per successfully transmitted payload byte.

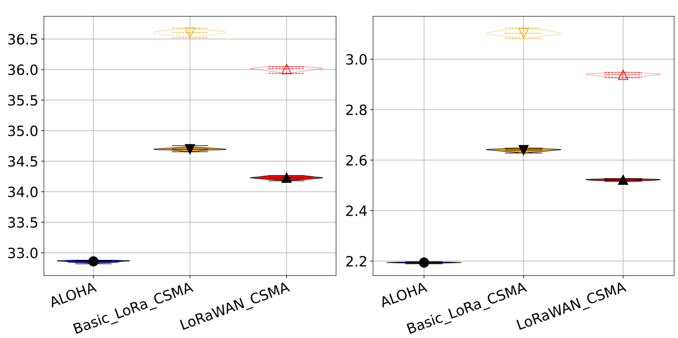

Fig. 3: BS – TE (left) and MSL (right). Devices running the best performing variant of Basic_LoRa_CSMA consume in average 36.6 J for every 100 transmission attempts. A successful transmission takes in average 3.1 s for the best performing variant and 2.6 s for its most efficient variant.

In the baseline scenario, ALOHA is outperformed in terms of PDR and energy efficiency (Fig. 2). Note that for each frame transmission attempt, the two CSMA approaches consume 4.0% to 10.2% of the energy performing CADs. LoRaWAN_CSMA has lower PDR than Basic_LoRa_CSMA, for both best performing (-1.05%) and most efficient (-1.41%) variants: while limiting the number of channel hopping can reduce the overhead, it impairs the PDR by forcing a transmission when the channel is busy. The energy efficiency is similar for the best performing variants of CSMA, but slightly impaired for LoRaWAN_CSMA's most efficient variant (+0.42% compared to Basic_LoRa_CSMA). This latter consumes less energy in average (0.47 J, -1.34%), and has reduced latency (117 ms, -4.44%), Fig. 3, because fewer CADs are performed.

B. Variation of the number of devices

For all protocols, the collision rate increases linearly with the number of simulated devices. Similarly, the efficiency gets degraded (Fig. 4). In contrast, the number of channel hopping (#CH) and the consumed energy in CAD drastically diverge for Basic_LoRa_CSMA, but not for LoRaWAN_CSMA (Fig. 5): the increased number of competitors makes LoRaWAN_CSMA behave per default as ALOHA in more cases, limiting its increase in energy consumption.

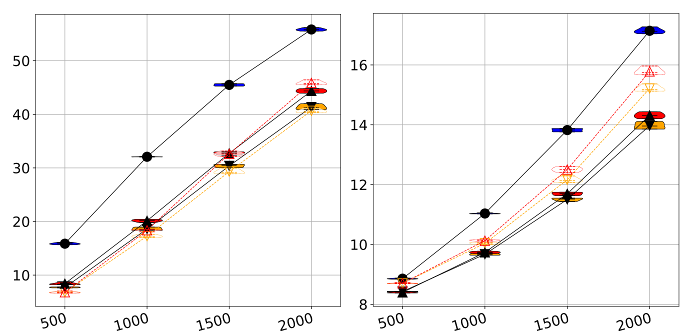

Fig. 4: Varying #devices (X-axis) – #CO (left) and E/S (right) (Y-axes). With 500 devices, the CSMA approaches reduce the collision rate to 8% (16% for ALOHA), but with 2000 devices, it is increased above 40% (55% for ALOHA).

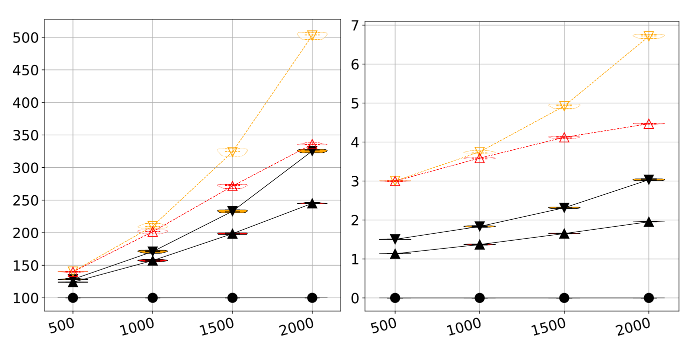

Fig. 5: Varying #devices – #CH (left) and ECAD (right). With 1500 devices, the most efficient variant of LoRaWAN_CSMA tries 2 channels per frame and consumes 1.7 J in CAD.

C. Variation of scale

When the distances to the center of the topology increase, see Fig. 6 and Fig. 7, the two main CSMA protocols are similarly impacted and the slopes are higher than for ALOHA. The differences between the approaches decrease when the distances increase, because CS becomes less effective.

At shorter distances (radius 1500 m), Basic_LoRa_CSMA is a bit more efficient than LoRaWAN_CSMA because it has a better success rate. LoRaWAN_CSMA devices consume less than in Basic_LoRa_CSMA because they perform fewer CADs (the xCADs mechanism detects more traffic in closer neighborhoods).

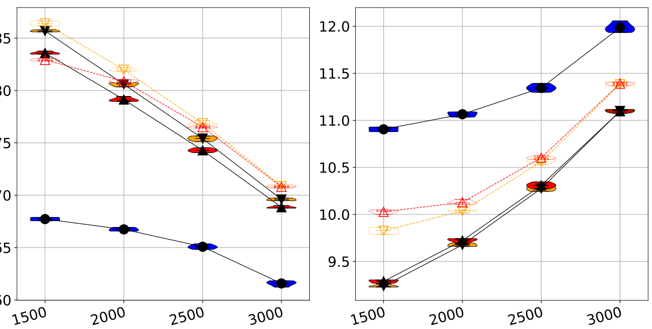

Fig. 6: Varying scale (radius of the topology (m), X-axis) – PDR (left) and E/S (right) (Y-axes).

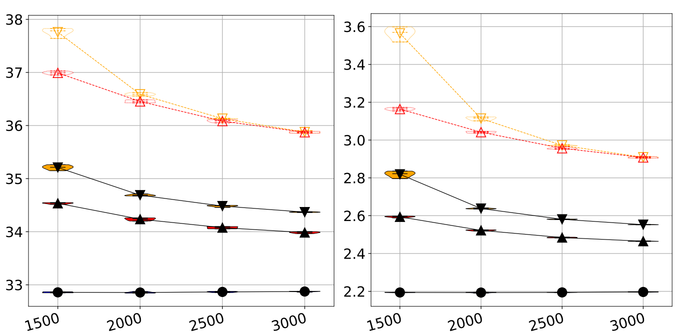

Fig. 7: Varying scale – TE (left) and MSL (right).

This first set of comparisons shows the limitation of the channel hopping mechanism as proposed by LoRaWAN_CSMA where having x=1 definitely impairs its performance in the considered dense scenario.

V. Improvements to LoRaWAN_CSMA

In the light of the results, we can amend the original LoRaWAN_CSMA proposition with the objective of better performance than Basic_LoRa_CSMA in terms of PDR and/or efficiency.

A. LoRaWAN_CSMA_1: testing more channels

By allowing the transmitter to perform CADs on up to x=8 channels before decrementing the allowed number of retries, LoRaWAN_CSMA_1 (green) adds the logic of [4] into LoRaWAN_CSMA.

1) Variation of payload size: The PDR linearly decreases for all protocols when the mean payload size increases (Fig. 8). LoRaWAN_CSMA_1 is more scalable, both for best performing and most efficient variants. The efficiency is highly impacted for very short payload sizes, for all protocols, because the overhead is too high. The best performing variant of LoRaWAN_CSMA_1 is less efficient than LoRaWAN_CSMA for short frames, but this tendency is inverted for larger payloads. For 130 B we can see that LoRaWAN_CSMA consumes more than 12 mJ/B while LoRaWAN_CSMA_1 only consumes 11.4 mJ/B while providing a better PDR.

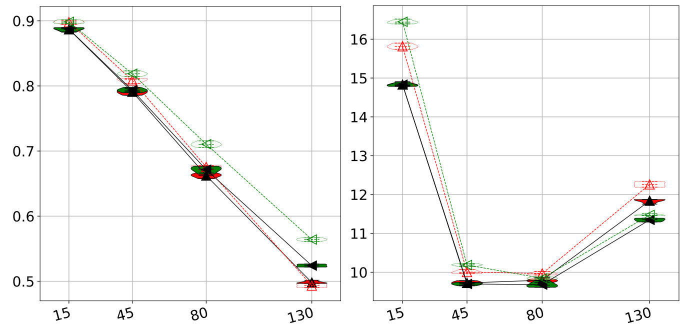

Fig. 8: Varying payload size (in byte, X-axis) – PDR (left) and E/S (right) (Y-axes). LoRaWAN_CSMA_1 (green) compared with LoRaWAN_CSMA (red). Best variant pairs.

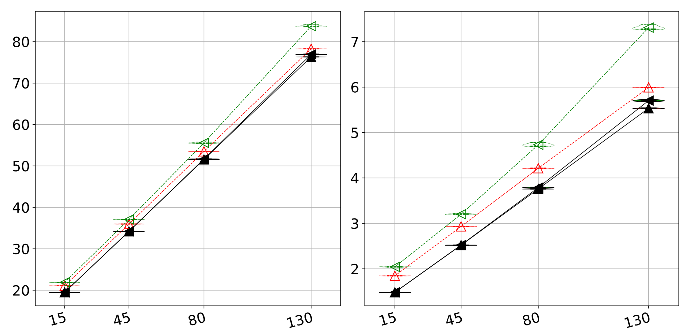

Fig. 9: Varying payload size – TE (left) and MSL (right).

Fig. 9 confirms our analysis: the gain in PDR with LoRaWAN_CSMA_1 is obtained using more CADs on more channels, thus consuming more energy and time.

2) Variation of scale: Fig. 10 shows that for all scale scenarios, LoRaWAN_CSMA_1 reduces the number of collisions compared to LoRaWAN_CSMA while maintaining the energy efficiency. At shorter scale (radius of 1500 m) the difference between protocols is higher because more activity is detected when doing CADs. We can also see the benefit of xCADs over 1-CAD and Fig. 11 shows that in the best performing variants the transmitters perform 30% more channel hopping.

Smaller scales are more beneficial to the most efficient variants of both protocols than for their best performing ones. In particular, LoRaWAN_CSMA's best performing variant in the baseline scenario (radius of 2 km) has more collisions than its most efficient counterpart with a radius of 1.5 km, as shown in Fig. 10 left. This is because the maximum number of retries is reached more often and because of the choice of ultimately transmit while the channel is busy.

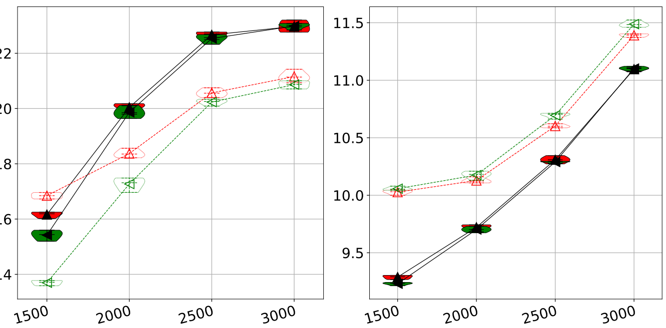

Fig. 10: Varying scale (X-axis) – #CO (left) and E/S (right).

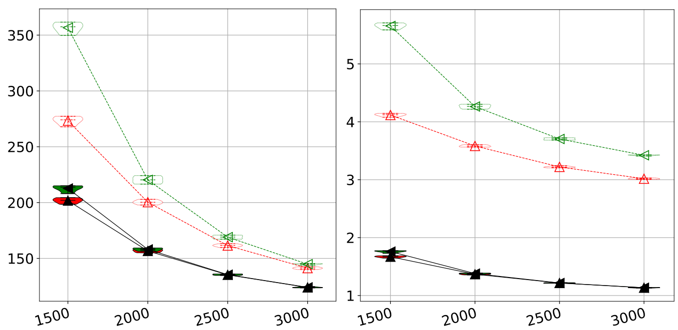

Fig. 11: Varying scale – #CH (left) and ECAD (right).

B. LoRaWAN_CSMA_2: passive BO and softer termination

This second improvement targets both PDR and energy efficiency. We first replace the BO_C active residual with a passive version: when a device senses a channel clear, it waits a random duration (in sleep state, thus with a lower energy consumption than for an active BO) before transmitting. On a given channel, the competitor with the shortest passive BO wins. The remaining competitors must avoid a collision, therefore LoRaWAN_CSMA_2 performs an additional n CADs check after the BO to make sure that the channel is still clear.

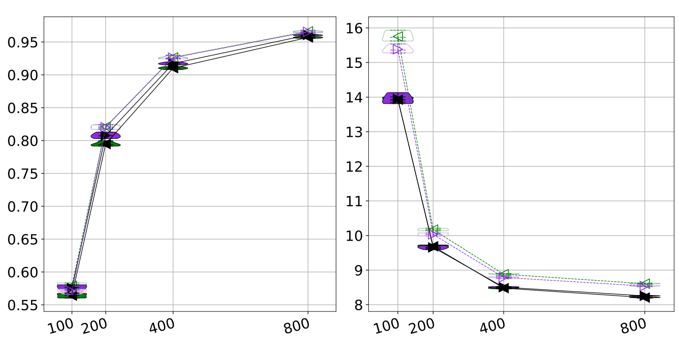

Fig. 12: Varying inter packet time (X-axis) – PDR (left) and E/S (right) (Y-axes). LoRaWAN_CSMA_2 (purple) versus (_1). For an inter packet time of 400 s, LoRaWAN_CSMA_2 achieves a PDR of 93%, for an efficiency of 8.8 mJ/B.

Second, we spread in time the transmissions of last resort: when the maximum number of retries has been reached for a frame, it is either transmitted after an ultimate passive random BO (with duration u in Table I), or discarded. This addition improves the PDR thanks to a less aggressive termination.

1) Variation of inter packet time: The inter packet time follows an exponential distribution and the mean is set to 200s for the baseline scenario.

In Fig. 12, doubling the traffic load impacts all PDRs by 20%. However, the efficient variant of LoRaWAN_CSMA_2 maintains a better PDR than LoRaWAN_CSMA_1 for similar efficiency, and its best performing variant has similar PDR for an improved energy efficiency.

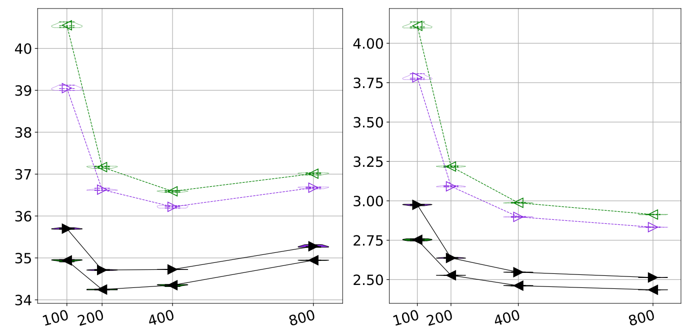

Fig. 13: Varying inter packet time – TE (left) and MSL (right).

Fig. 13 shows that LoRaWAN_CSMA_2 succeeds in reducing energy consumption and delays. The TE has an inflection for 200s-400s inter packet time: above 400s, it increases slower, due to a larger sleep time between frame arrivals, than below 200s, where the presence of more competitors dramatically increases the energy consumption.

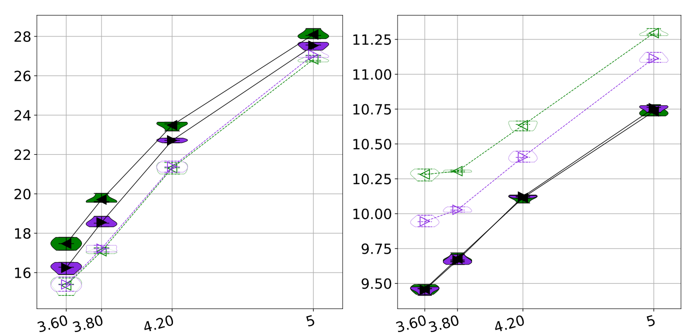

Fig. 14: Varying PLE – #CO (left) and E/S (right). In BS, with PLEs normally distributed around 3.8, only 18.5% of the frames collide for the most efficient variant of LoRaWAN_CSMA_2, w.r.t. LoRaWAN_CSMA_1's 20%, with better efficiency (-0.3 mJ/B for their best performing ones).

2) Variation of Path Loss Exponent (PLE): In our simulation model, the PLE for ED-ED links impacts the CAD's reliability. Thus, PLE variations impact both approaches (Fig. 14). When the link quality degrades, so does the PDR but also the differences between protocols because CS is less effective (Fig. 15). While doing fewer CADs thanks to a passive BO_C, LoRaWAN_CSMA_2 improves the performance of the most efficient variant, and the efficiency of its best performing one.

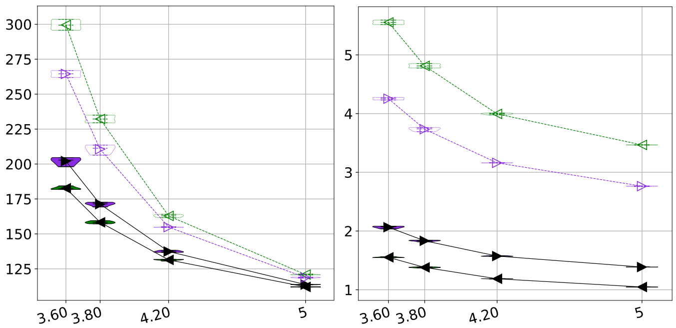

Fig. 15: Varying PLE – #CH (left) and ECAD (right).

C. *LoRaWAN_CSMA_3: Neighbor listening*

The last improvement is inspired from [9] where a device in the proposed CANL protocol uses reception mode (RX) to receive a very short control packet (as in the Request-To-Send (RTS) mechanism, or simply the packet header) indicating the payload size (thus the transmission duration) of an up-coming data packet. Upon reception, the device can passively wait until the transmission finishes before trying again to get the channel. We denote this passive waiting of fixed duration a NAV (from the Network Allocation Vector of WiFi DCF [21]).

CANL was originally motivated by the unstable reliability of CAD. But in scenarios where the CAD is as reliable as the reception, which is commonly admitted on single channels [7], [13], [22], CANL is too energy expensive. We propose here to trigger RX mode only when the channel goes from clear to busy (i.e. a CAD yields true). In this way, the listening device has a higher probability to correctly receive the short control packet. However, with this mechanism, long packets will hold neighbors in very long NAV periods, increasing latency. In case of a too long NAV duration, i.e. above a chosen threshold, we propose to let the sender switch to another channel using the CH mechanism. In short, LoRaWAN_CSMA_3 adds a CAD-triggered header listener and a NAV/CH threshold.

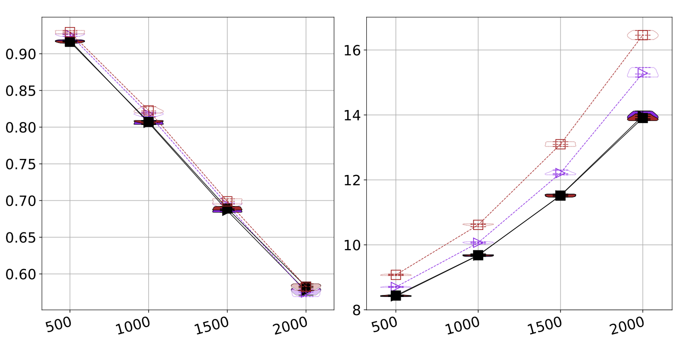

Fig. 16: Varying #devices – PDR (left) and E/S (right).

1) Variation of number of devices: All the variants drop in performance as the number of devices increases (Fig. 16). LoRaWAN_CSMA_3's most efficient variant has similar results as LoRaWAN_CSMA_2's, whereas its best performing variant improves the PDR (from 81.92% to 82.37% in BS) at the expense of a little degradation in efficiency (+0.57 mJ/B in BS, with limited increase over the variation).

2) Variation of the proportion of interfering devices: LoRaWAN_CSMA_2 and LoRaWAN_CSMA_3 are similarly impacted by the increase of unpredictable interferers. However, LoRaWAN_CSMA_3 is more resilient whatever the proportion is, validating its ability to handle neighboring traffic (Fig. 17). Interestingly, both #CH and ECAD decrease with more interferers (Fig. 18). This reflects the impact of external frames that are transmitted after the beginning of the legitimate ones. The 2 CSMA protocols cannot predict the ALOHA traffic, thus perform faster and use less energy.

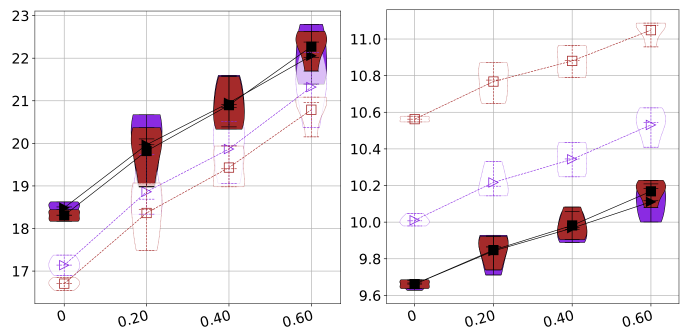

Fig. 17: Varying % of interfering devices – #CO (left) and E/S (right). With 40% of interferers using ALOHA, the collision rate is maintained below 20% for both LoRaWAN_CSMA_2 and LoRaWAN_CSMA_3, with their best performing variants.

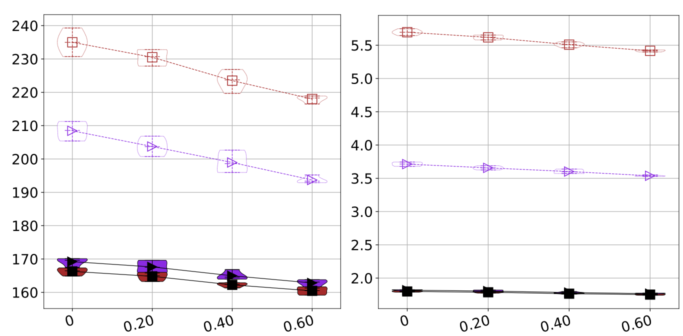

Fig. 18: Varying % of interfering devices – #CH (left) and ECAD (right). LoRaWAN_CSMA_3 (maroon) vs _2 (purple).

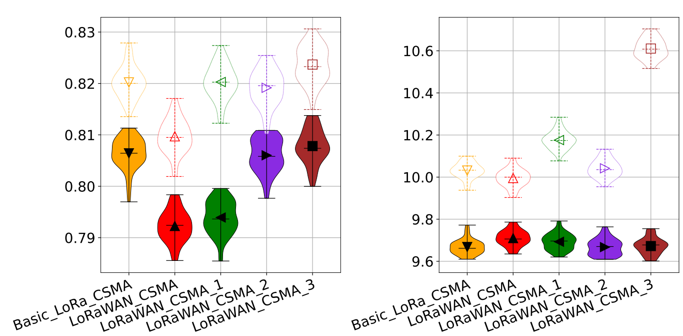

Fig. 19: Baseline Scenario – PDR (left) and E/S (right).

D. Synthesis/Discussion

In the baseline scenario LoRaWAN_CSMA_3 outperforms both LoRaWAN_CSMA and Basic_LoRa_CSMA in term of PDR: its best performing variant obtains a PDR of 82.37% when LoRaWAN_CSMA only reaches 80.97% (Fig. 19). Its most efficient variant also outperforms all the efficient variants with similar efficiency (in contrast with the best performing variant which degrades the efficiency by 5%).

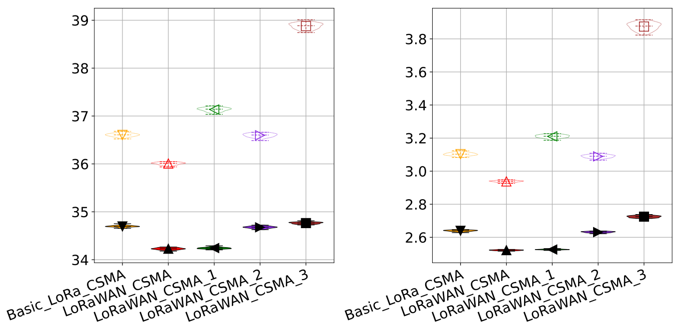

Fig. 20: Baseline Scenario – TE (left) and MSL (right).

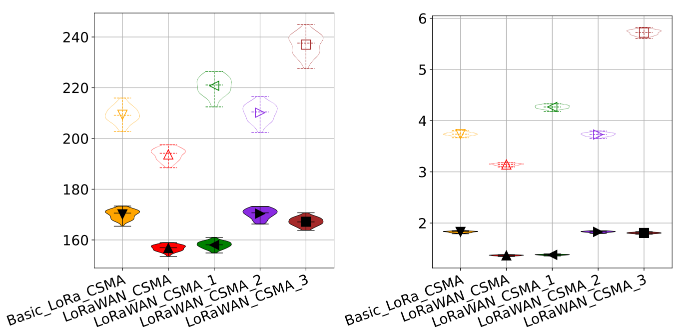

Fig. 21: Baseline Scenario - #CH (left) and ECAD (right).

The latency for a successful transmission is increased for the best performing LoRaWAN_CSMA_3 variant: about 3.9 s instead of less than 3 s for the efficient variants of the other approaches (Fig. 20). However, this difference can be neglected when compared to the inter packet time. LoRaWAN_CSMA_3 has also a limited increase for the number of channel hopping and CADs as shown in Fig. 21.

For all these reasons, LoRaWAN_CSMA_3 seems best suited for the considered baseline scenario. However, when moving from the baseline scenario, the extensive simulation results[1] suggest the following deployment possibilities:

1) LoRaWAN_CSMA_3 for denser traffic, larger scales, to achieve higher performance with longer frames especially in presence of many interferers or conditions where CAD reliability is degraded;
2) ALOHA for efficiency in very light traffic conditions;
3) LoRaWAN_CSMA_1 for efficiency with shorter frames, higher building obstruction or conditions where CAD reliability is degraded;
4) LoRaWAN_CSMA for performance with shorter frames or for higher efficiency in presence of many interferers;
5) LoRaWAN_CSMA_2 for efficiency with longer frames or in areas with low obstruction from building;
6) Basic_LoRa_CSMA for higher performance under ideal CAD reliability.

[1]All the simulation data supporting these recommendations are available with the source code.

VI. Related Work

The issue of collisions in LoRa and LoRaWAN networks has been a focal point for many researchers. Proposals for collision avoidance, mitigation, and recovery are still being studied [15], [17]. Simulation tools have played a central role in evaluating LoRa(WAN). The earliest open-source development used Python Simpy [20], has inspired many subsequent studies [23]–[25]. A few of them included a CSMA mechanism for LoRa [3], but did not provide such an easily accessible and flexible source code as we do.

A. Listen Before Talk, Carrier Sense, and CSMA mechanisms

Carrier sensing and LBT-based MAC protocols have been explored to improve channel utilization in LoRa networks [26]–[28]. Farooq et al. [4] compared different CSMA variants for LoRa and highlighted the benefits of multi-channel CCA in high-density deployments.

Duda et al. [3] presented one of the first NS-3 modules to evaluate CSMA-based improvements for LoRa. Their results showed reduced collision rates and improved energy efficiency, prior to the existence of the CAD.

Channel Activity Detection (CAD) has emerged as a critical mechanism for enabling intelligent medium access in LoRa networks. CAD has been largely studied and used up to now [5]–[8], [17], [29]. Zheng et al. [22] recently updated LoRadar, a cross-channel scanning technique that improves wide band activity detection smartly using multiple CADs.

Experimental campaigns validated PDR gains with CSMA schemes on real LoRa testbeds [2], or in the field [17] using and evaluating CADs. Gamage et al. [7] implemented LMAC(1, 2 and 3), 3 CSMA-based protocols for LoRa relying on CAD. Kouvelas et al. [6] introduced np-CECADA, a non-persistent CSMA with dynamical adaptation. Both LMAC_3 and np-CECADA rely on downlink feedback from the GW. Kaburaki et al. [30] extended the CS to the downlink to tackle the hidden terminal problem. In contrast, we only rely on the individual information of each device (CAD or RX).

B. Other Collision Avoidance and Mitigation Techniques

In addition to avoiding collisions through contention mechanisms, recent approaches have increasingly aimed at reducing the impact of collisions through interference cancellation and decoding simultaneous frames in the GW [16]. Xia et al. [15] proposed Pcube, Wang et al. [31] introduced OCT (Online Concurrent Transmissions). These approaches exploit the physical-layer aspects of LoRa, with inherent limitations (e.g. in case of multiple overlaps, or with strong CE [16]) thus are complementary to the MAC-level CSMA techniques.

Several studies focus on resource allocation strategies [32]–[34]. Chinchilla et al. [35] proposed CARA, a channel-SF-time block allocation strategy for dense LoRaWAN environments. But resource allocation generally requires downlink control flows and accurate synchronization, which are hard points to tackle in large-scale LoRa networks [8].

More recent work explores machine and deep learning techniques for collision prediction [36] and dense LoRa resource management [37]. Elkarim et al. [38] provided a survey on applying ML to LoRa networks, not including adaptive BO algorithms or CAD-based CSMA. Our study fully details the parameters of new CSMA protocols and could use future optimizations based on ML.

VII. Conclusion

In this article, we extensively evaluated by simulations the performance of LoRaWAN_CSMA, the newly proposed CSMA protocol by LoRa Alliance for LoRaWAN networks. We showed that LoRaWAN_CSMA is not optimal for urban dense deployment scenarios where both traffic density and long time-on-air are challenging issues. After analyzing the performance and identifying pros & cons of LoRaWAN_CSMA, we proposed and evaluated several improvements to better address dense scenarios. We showed that a randomized multi-channel LBT using CADs improves both efficiency and performance of a CSMA approach for LoRa networks. We also further showed that careful and wise use of RX mode for neighbor header listening allowing adjusted NAV greatly reduces collisions and improves the packet delivery rate. Our analysis also led to some recommendations on the combination of mitigation mechanisms according to payload size, traffic density and application's objectives – reliability or latency or energy.

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