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FT-CSMA: A Fine-Tuned CSMA Protocol for LoRa-Based Networks

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***Abstract*—Advances in low-power networking have shown remarkable evolution for the Internet of Things. LoRa technology promises low power consumption and long-range connectivity while maintaining sufficient throughput. However, in environments with a higher density of nodes, there is a high potential for packet collisions, compromising the reliability of the technology. This is a direct consequence of using an Aloha-based protocol to access the channel. This article proposes a Carrier Sense Multiple Access (CSMA) protocol called FT-CSMA, a new collision avoidance technique based on a hybrid of CSMA in IEEE 802.15.4 and CSMA in IEEE 802.11. The design of this protocol aims to provide an acceptable trade-off between the performance parameters of LoRa-based networks. Energy consumption, packet delivery ratio, and delay are interdependent; improving one will affect the others. FT-CSMA outperforms other methods in terms of Quality of Service and energy efficiency, with a 2% reduction in energy consumption and a 5% increase in packet delivery ratio.**

***Keywords*—LoRa, LoRaWAN, Carrier Sense Multiple Access (CSMA), Channel Activity Detection (CAD), wireless network, collision**

I. INTRODUCTION

Wireless networks have become ubiquitous in diverse applications, yet their limited frequency range necessitates using a single transmission medium or channel. Consequently, multiple nodes share this same channel, which can result in collisions and potential data loss. As a result, data loss remains a significant concern within wireless networks. To avoid this problem, network communications use the Carrier Sense Multiple Access (CSMA) method to detect channel occupancy by measuring the carrier's Received Signal Strength Indication (RSSI). In LoRa-based networks, the CSMA protocol is a commonly used medium access control mechanism. However, it has been noted that this protocol may not be very efficient, this is because the receiver can detect signals even when they are below its noise level. Therefore, it is evident that the limitations of the CSMA protocol in these situations are quite significant. Furthermore, due to the orthogonality of LoRa signals with distinct Spreading Factors (SF), i.e., transmissions employing several SFs in the same channel, LoRa technology uses the Chirp Spread Spectrum (CSS) modulation approach. Wireless communication employs the Channel Activity Detection (CAD) strategy to avoid collisions.

The contribution of this paper is to propose an optimized technique for minimizing collision occurrences in Lora networks. This technique has been optimized and integrated as a new module and component in the NS3 simulator. This technique, called FT-CSMA, is based on the CSMA mechanism used in WiFi IEEE 802.11 and WSN IEEE 802.15.4.

Recent studies have delved into various strategies to reduce collisions in LoRa networks, which have emerged as a promising technology for Internet of Things (IoT) applications. In this context, this study proposes a technique called FT-CSMA that aims to enhance the reliability of LoRa networks. The proposed method optimizes carrier detection time, which is a critical factor that determines the network’s ability to transmit data successfully. By reducing collisions and improving the network's reliability, FT-CSMA can help address the challenges associated with IoT applications that require low-power, long-range communication.

Moreover, the proposed technique is compatible with the existing LoRaWAN protocol, which can facilitate its adoption by network operators and device manufacturers. Based on the data given in Table III, our protocol offers faster sensing time compared to other algorithms, synthesized in Table II, such $CSMA_{new}^{LoRa}$, LoHEC , and the three LMACs. Our technique requires no synchronization messages to stabilize LoRa networks. This sets it apart from the strategy $RTS_{messages}$ and FCA-LoRa given in Table II, which generate more control messages, leading to network overload. Additionally, our methodology has a minimal impact on latency. It is important to note that improving one network performance factor may affect

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others, such as energy consumption, packet delivery ratio, and delay. However, the delay was significantly affected by all other proposals made as part of this study, which is different in this research. FT-CSMA tests achieved a 5% increase in packet delivery ratio through incremental enhancements and adjustments and a 2% reduction in energy consumption compared to the original LoRa methodology. FT-CSMA has the potential to significantly improve the performance of LoRa wireless communication systems while maintaining optimal energy efficiency.

These findings leave no doubt about the game-changing potential of FT-CSMA, which is set to disrupt the industry and establish itself as the go-to solution for reliable and sustainable wireless communication.

The rest of the paper is organized as follows: describing the principles of LoRa and LoRaWAN and previous state-of-the-art CSMA protocols in Section II. Section III proposes a study and design of the proposed Fine Tuned CSMA (FT-CSMA) solution and presents the mechanisms for improving the Quality of Service (QOS) and increasing the energy efficiency of the LoRaWAN network. Section IV presents the results of the simulated scenarios and their explanations. Finally, in Section V, we conclude our project with remarks highlighting future work.

II. LITERATURE REVIEW

A. *Wireless Technology in IoT*

Wireless technology, particularly in the IoT, includes sensors, routers, applications, and other systems. Each option presents trade-offs between energy consumption, bandwidth, and range. A brief description of some technologies is in order.

WIFI enables high-speed data transfer but has essential limitations regarding scalability, range, and energy consumption. The energy consumption makes WIFI a weak solution for large networks with battery-powered sensors.

Cellular networks are reliable broadband communications used by almost all applications. It offers very high bandwidth. Nevertheless, they generally work in licensed bands.

Bluetooth is a wireless Personal Area Network (WPAN) for short-range communication with optimized power consumption. Bluetooth Low Energy (BLE) supports small-scale IoT applications with short-range communications.

Radio Frequency Identification (RFID) systems consist of tags (microchips) and an antenna, which communicate over distances varying from a few centimeters to several tens of meters. Some prototypes can exchange data at 10 Mbps.

Low-Power Wide Area Networks (LPWAN) provide long-range communications using small and inexpensive batteries. However, LPWANs can only send small data blocks at low data rates. This technology is also suitable when no time sensitivity or high bandwidth is required. Unfortunately, this technology lacks standardization to guarantee network security, interoperability, and reliability. Fortunately, lorawan's innovation addresses the majority of these shortcomings.

B. *LoRa and LoRaWAN*

LoRa is a modulation technology for Low Power Wide Area Network (LPWAN) networks using Industrial, Scientific, and Medical (ISM) bands. Initially, an improved version of CSS technology was widely used in radar. It offers long-range data links of up to ten kilometers. Its low operating power and high transmission capacity also characterize it. The LoRa signal is highly resistant to indoor and outdoor interference. It is also robust against multipath and fading, favorable for urban and suburban environments. This technology is widely adopted in the IoT world for its ease of deployment, especially by LoRaWAN. When LoRa is purely a physical layer implementation, LoRaWAN is a LoRa-based complementary network protocol. Its design satisfies IoT requirements. It provides bi-directional communication and end-to-end security with AES-128 encryption, mobility, and location-based services. Fig. 1 shows the relationship between the LoRa Physical Layer and the LoRaWAN MAC Layer in the OSI Stack [1].

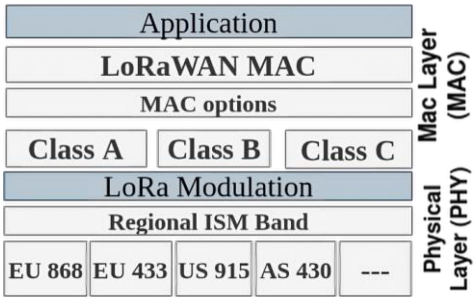

Fig. 1. The LoRaWAN network stack [1].

C. *LoRaWAN Architecture*

Many IoT technologies use a mesh network architecture. This system of networks can increase communication range and network cell size. However, nodes in a mesh network have the additional task of sending messages to other nodes that may be unrelated to them. This has a significant impact on the battery life of the device and generates collisions. LoRaWAN uses a star topology where messages are only sent to a central node called a gateway. This increases battery life when long-range connectivity is used. The LoRaWAN network is made up of several components:

- **LoRa nodes / End devices (ED)**: These are the sensors or applications with a LoRa transmitter/receiver. These nodes are placed remotely and can be static or mobile.
- **LoRa gateways (GW)**: All data transmitted by the nodes can be intercepted by any gateways within range, and each gateway that receives a signal forwards it to a network server. In general, gateways and network servers are connected via an ordinary link (Ethernet, cellular, Wi-Fi, or satellite).

- **Network servers (NS)**: All the intelligence of the LoRaWAN system is implemented in the server. It filters duplicate packets arriving from different gateways, performs security checks, and sends acknowledgments (ACKs) to the gateways. Finally, it distributes the data packets to the relevant application servers, if any.
- **Application servers (AS)**: This is the ultimate data collection system. These applications process and transform the information to be exploited as needed.

The following Fig. 2 describes the LoRaWAN architecture [2].

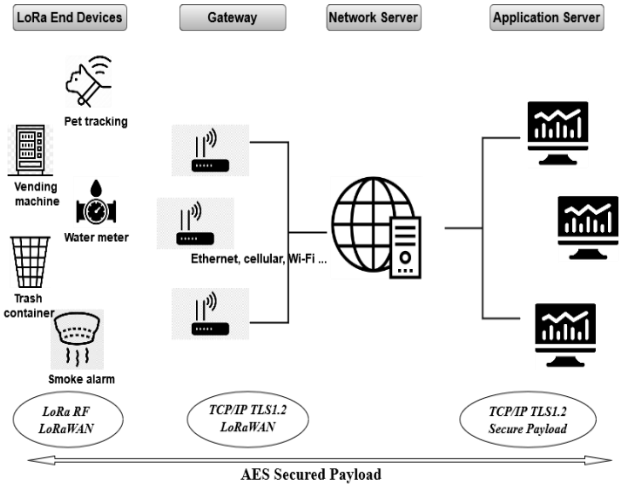

Fig. 2. LoRaWAN architecture.

D. Collision Management

It's worth noting that collisions can arise from various signals, not just LoRa. However, this research delves explicitly into collisions caused by LoRa signals, a topic that has yet to receive much attention. In this section, we'll introduce the main LoRa mechanisms and features that ensure stable and dependable transmission.

To avoid collisions, the LoRa modulation technique utilizes CSS by splitting the channel in different ways called "Spreading Factors" (SF). These SFs are orthogonal, which means multiple signals using different SFs can be sent simultaneously without any interference. However, if two packets with the same SF arrive on the same channel simultaneously, they may collide. This collision can be prevented if one packet is at least six decibels (dB) stronger than the other [3].

ADR also indirectly helps to avoid collisions. To ensure reliable node access to the network with low energy consumption. It controls the nodes to operate with a better distribution of SF. This reduces collisions considerably.

The Industrial Scientific Medical (ISM) bands are limited, and many communities use them. Therefore, so as not to abuse their use, the European Telecommunications Standards Institute (ETSI) recommends the duty cycle to alleviate the capacity of networks. For example, the regulations of the 868 MHz ISM band recommend and limit the duty cycle to 0.1% or 1%, depending on the selected sub-band. It consists of not using the same sub-band for a limited time [4].

$$T_{off} = \frac{ToA}{Dutycycle} - ToA \qquad (1)$$

If a LoRa frame takes a Time on Air (ToA), then the The device must not communicate during a Time of Toff. These constraints offer adequate sharing of resources and minimize intra- and inter-network collisions.

The above features, mechanisms, and requirements do not entirely prevent collisions. In addition, the use of the Channel Activity Detection (CAD) mechanism, recently integrated into the LoRa modules, can help avoid collisions. This mechanism will be detailed afterward.

E. Carrier-Sense (CS) Principle

The reason why LoRa does not use the existing carrier sense (CS) mechanism is not apparent. This section highlights the difference between previous CS mechanisms, namely ALOHA and CSMA, and the LoRa CAD mechanism. Especially the properties of LoRa signals that influence the choice of this mechanism. Besides these reasons, a brief explanation is required of these CS mechanisms because almost all the works cited in the state of the art derive from them:

1) Aloha

It was the first Protocol to communicate over wireless media. Its principle is simple: as soon as a packet arrives, the node transmits it. It is pure Aloha (P-ALOHA). The presence of overlapping packets in this protocol is a significant cause of collisions in important networks. By addressing this issue, this protocol can confidently prevent collisions and ensure the smooth functioning of the network. Another derived Aloha, called Slotted Aloha S-ALOHA, improves the first one:

- It uses frames of the same size;
- The time is divided into equal synchronized slots;
- Each frame is transmitted at the beginning of each slot as soon as it arrives;
- If a collision occurs, the Device attempts to transmit the frame at the next slot until success.

The synchronization of time slots necessarily requires a control system. In LoRaWAN, the Network server, through a gateway, plays the controller role. All this is possible if the nodes are of class B or C, which can receive commands from the gateway periodically. However, for class A, it is not possible. Because the LoRa node opens only two short periods after transmitting a message. i.e., the node is not visible to the gateway until it sends.

Despite their simplicity, synchronization and retransmissions generate more traffic and, therefore, more collisions. In addition, it is necessary to acknowledge them. As a result, gateways create more traffic and, therefore, more collisions.

2) CSMA in IEEE 802.11

IEEE describes two CSMA processes: the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). This study discusses only the basic DCF, where acknowledgment is not mandatory. Two concepts are the basis of the DCF operation: The back-off Exponent and the DCF Inter-Frame Space (DIFS) time.

a) DIFS

It is a fixed part starting the waiting time before each transmission attempt, which is equal to *50 μs*;

b) BACK-off scheme

Consists in choosing a random number between *[0, CW-1]* where *CW = 2 × k*, and k is the number of attempts. A calculus of the back-off time from this number is as follows:

$$BackoffTime = rand(0, CW - 1) \times SlotTime$$

where $SlotTime = 20\ \mu s$. After each transmission failure, the CW window doubles until it reaches its maximum. A reset of the CW follows each successful transmission. Alternatively, when the number of attempts reaches its maximum. This method uses the Back-off two times when a medium is busy or when a device does not receive an acknowledgment;

c) Distributed Coordination Function (DCF) operation

There are two modes in DCF. The basic one and the one using RTS/CTS. In the primary mode:

- The node that wants to transmit checks if another node is transmitting on the channel;
- If the channel is idle for a DCF Inter-Frame Space (DIFS) Time, it transmits;
- Otherwise, it waits for the end of transmission, followed by a DIFS, and then generates a Back-off time. This time is decremented as long as the channel is idle during each DIFS; if, in the meantime, the channel becomes busy, then the counter freezes and continues to decrement when the channel becomes idle again during a DIFS. The transmission will be done only if the counter reaches 0;
- If a collision occurs, then the CW window doubles.

3) CSMA in IEEE 802.15.4

If the device is ready to transmit, it immediately starts Back-off, randomly selecting several back-off periods in the interval $[0, 2^{BE} - 1]$. The duration of each back-off period is *0.32 ms*. Once the Back-off time has expired, it detects the carrier. If the channel is idle, the device transmits its frame. If the channel is busy, the back-off exponent BE increases by 1, and a new number is selected in the new range $[0, 2^{BE} - 1]$.The device restarts the Back-off, followed by carrier detection until the maximum number of attempts is reached.

4) RSSI and SNR

To show that the CSMA mechanism, based on the signal power, is infeasible. Table I [5] contains the Signal over Noise (SNR) of each SF that a LoRa module can tolerate to receive the signals correctly.

These values show the possibility of demodulating the LoRa signal up to 100 times below the noise floor for SF12 (*–20dBm*). In other words, detecting a high-powered signal does not necessarily mean the channel is busy.

The negative SNR means that the signal strength is less than the noise strength, and the demodulator can still decode it. However, if the negative value is less than the minimum SNR of −20 dBm at SF12, it does not guarantee that the receiver will be able to demodulate the signal.

TABLE I. RECEIVED SIGNAL STRENGTH INDICATOR / SIGNAL-TO-NOISE RATIO [5]

SF	SF (chips/symbol)	SNR (Lora Demodulator)
7	128	−7.5dB
8	256	−10dB
9	512	−12.5dB
10	1024	−15dB
11	2048	−17.5dB
12	4096	−20dB

Another particularity of LoRa is the ability to decode partially superposed frames. The study done in [6] shows that the LoRa receiver can decode a frame, partially overlapped with another one, as long as at least six symbols remain non-overlapped;

5) LoRa CAD mechanism

The entire range of LoRa SX126X and SX127X radio components implements CAD. It is a simple Listen Before Talk (LBT). The principle is to detect the occupancy of the channel by the presence of a preamble of a transiting signal on the same channel having the same SF (in the case where the likelihood of a collision is maximum). This takes minimal time and reduces energy consumption [7].

In the range SX128X of LoRa and above, these modules can also detect the data payload by extending the time. The flow chart below, Fig. 3 explains the CAD operation [8].

If enabling CAD, packet transmission is only possible after a CAD operation. If a device detects a preamble, it skips until the next time by waiting a random time (Back-Off) and tries again using the same procedure.

F. Related Work

Several authors have tried to improve the CAD concept by the CSMA mechanism or channel/SF hopping approach.

T. H. To and A. Duda [4] created a module in NS3 with a custom CSMA. Even if the CAD and how its Clear Channel Assessment (CCA) works are not referred to, it offers two CSMA techniques, CSMA and CSMA-X, close to the CSMA in IEEE 802.15.4 that is used in WSN. Only the CCA time is fixed, and the back-off time is randomly chosen.

C. Pham gives a brief comparison, in [9], between the basic CSMA in IEEE 802.11 designed for wifi and the one in IEEE 802.15.4 intended for WSN. Due to the nature of WSN, where there is no coordinator, it adapts the first one for LoRaWAN networks, $CSMA_{802.11}^{LoRa}$. Its principle is to define the times used in CSMA regarding the time of a LoRa symbol. As the latter is a function of the SF and the BW then DIFS, SIFS, and the back-off will depend on it. DIFS = 9 CAD, SIFS = 3 CAD, CW from 18 CAD, and double up to 144 CAD. It claims that this adaptation of CSMA for LoRa is not reliable. The author proposes another one called, $CSMA_{new}^{LoRa}$, where the DIFS is based on the maximum ToA. This means a 255-byte packet sent with SF12 is equivalent to 9150 ms. During this time, DIF S(ToAmax), 9 CAD operations are performed with a duration of 1000 ms. With this configuration, One CAD will be performed every 1143ms in the case of SF12. The Back-Off of this version is constant and takes ToAmax. Despite the effort put into his work, the author only compares the energy consumption between his two proposals, except for the explanation that the reliability and energy efficiency of $CSMA_{new}^{LoRa}$ against $CSMA_{802.11}^{LoRa}$. In addition, the results in terms of quality of service are not reported.

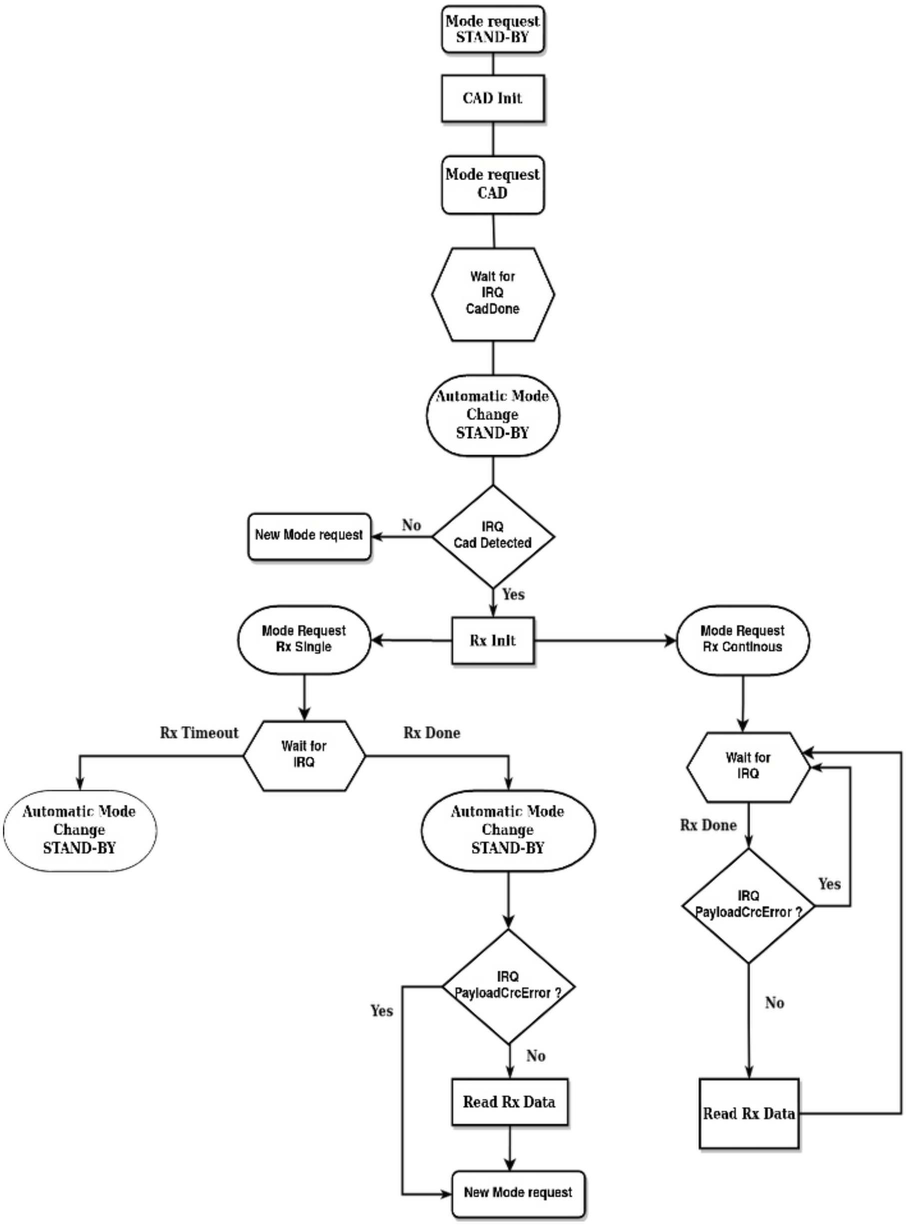

Fig. 3. LoRa CAD flow [8].

J. Liando *et al.* [10] proposed CSMA-CAD. The authors claim that two symbols are sufficient for the duration of a CAD. His state diagram shows that if, after one CAD, the channel is busy, then it takes another SF randomly. It achieves a 20% improvement in PDR at the expense of an energy loss of around 1.70mJ. It also testifies that an ideal CSMA can increase throughput by up to 56X compared with its CSMA-CAD.

L. Beltramelli *et al.* [11] studied the performance of three-channel access methods. Pure Aloha, Slotted Aloha, and Non-Persistent CSMA by proposing a probabilistic analytical model for the distribution of nodes around a gateway and their possible interferences. With the support of simulations done in MatLab, they confirm that:

- These methods, respectively, improve the throughput in the case of a large enough number of nodes;
- S-ALOHA is more reliable than P-ALOHA at the expense of energy in the case of a small number of nodes;

- CSMA is the most reliable and energy-efficient only if the nodes are close to the gateway and have a small SF.

Kouvelas *et al.* [12] model their p-CARMA with Markov chains. Every event is launched by probability, even the CAD operation. The operation's duration depends on several symbols, as Table III shows. While the back-off time, also executed with a probability, is randomly chosen between 0 and the ToA of its packet load. During back-off, the device does not detect the channel but goes into sleep mode. In this model, three probability values must be defined. The probability of generating and transmitting a frame, finding the channel busy or idle, and a probability that depends on the number of nodes. Depending on the values of these probabilities, three versions of p-CARMA are compared with the ALOHA standard. It shows a performance of 20% in PDR and a gain of around 0.48J in energy.

Pham and M. Ehsan [13] proposed approach that is totally different from the others. It introduces additional messages called RTS, carrying only the size of the future packet to be sent. The node wishing to transmit makes a back-off, sends an RTS, and finally listens to the other RTSs. If the channel is idle, it transmits; otherwise, it repeats the previous steps. He claims this approach reduces collisions from the outset and provides no guarantee for PDR, despite results showing a reduced battery life from 1265 to 1031 days.

Triantafyllou *et al.* [14] have presented their new and improved methods of accessing the FCA-LoRa medium. Its principle is to schedule and synchronize the nodes' transmissions through the gateway by broadcasting beacon frames. With simulations made in OMNeT++, he claims that his method can improve the throughput by up to 50% in the case of a gateway and many nodes up to 600 and that with several gateways and 500 nodes, it reaches 49% more throughput. In the paper, the nodes can only transmit after receiving a beacon frame. However, this mechanism is only feasible with LoRa classes B or C. In these classes, the node periodically opens a short reception window (class B) or continuously (class C). In this way, the nodes can be located and possibly receive frames. In all cases, its graphs show improvements in energy efficiency and QoS. Shao and Muta [15] claimed the network is heterogeneous Due to the multiplicity of SFs. The paper proposes a CSMA-like protocol called LoHEC based on CAD. It aims to improve energy fairness between nodes. In LoHEC, the end devices perform several CAD operations N_{SF} spaced by CAD intervals to access the channel. This protocol mainly aims to determine CAD intervals based on energy consumption under different SF. The results show that LoHEC can improve energy fairness by 0.6 to 0.8 times compared to other solutions. However, the multiplicity of SFs in LoRa is never considered heterogeneous. On the contrary, their orthogonality and diversity are the key elements of this technology that improve communication capacity. Moreover, in the literature, the times used by the CAD operation are calculated in terms of the time of a symbol, which depends on the SF and the BW.

Alonso *et al.* [16] introduced the Longest First Slotted CSMA (LFS-CSMA). By combining S-ALOHA and CSMA, they define the time of the longest frame as the time slot. The main feature is the delay in transmitting the frames, so they finish just at the end of the time slot. In this configuration, the longest frames will be sent first. The other competing frames, which are less long, will listen to the channel with the CAD mechanism before transmitting. They give probabilistic analytical models for P-ALOHA, S-ALOHA, and their LFS-CSMA to prove their proposals. The comparison between the latter in terms of performance shows an improvement in their proposal. Nevertheless, the studies done by operating with a single SF are restrictive and demonstrate the performance of only one part of a network. It remains to be seen what the results and overall performance of a network operating with all possible LoRa SFs would be.

Gamage *et al.* [17] adopted the basic CSMA DFS for his LMAC-1. He sets the DIFS to *12 CAD* operations and a random back-off (BO) between 4 and 64 times the duration of a successful CAD. With the same parameters, he proposes a second LMAC-2. It only switches to another channel/SF in the latter when DIFS or BO fails. This switchover is based on information gathered by the nodes during previous CAD operations. Both proposals are ideally suited for LoRa Class A. For class B, he proposes LMAC-3, an improved version of LMAC-2. The information collected by the nodes is replaced by beacon messages from the gateways. These contain statistics on the channel/SF. Real-life tests show a good improvement in QoS and energy for class A. For class B, delivery stabilizes at 90%, with the lowest energy consumption of all methods.

Yu *et al.* [18] proposed a study of the CAD operation itself, which is worth mentioning here. They found that a CAD can detect the channel occupancy of another signal with different SF and BW in the narrow bands, leading to false positives. False positives occur when these signals have the same slope in the time-frequency domain, coinciding with a doubling of the BW and an increase in the SF by two values. They argue that the CAD is based on cross-correlation for carrier detection. They propose LoRadar, a cross-channel scanning method that distinguishes the effective channel based on the distribution of results collected during many successive ($7 \times CAD$). The duration of the CAD itself is reduced to one symbol and preceded by RSSI measurements to lend credibility to the distribution. This LoRadio (Scan) mechanism achieves accuracy with a detection time reduction of 90% compared to the CAD mechanism.

III. MATERIALS AND METHODS

Table II distinguishes the parameters used in the previous CSMA proposals cited above. Despite all these results, collisions persist, and the need for a new approach continues.

Based on the documentation provided in the previous section and according to the parameter table II, the list above summarizes the main constraints that a new CSMA protocol has to overcome:

(1) The time required for a CAD operation does not guarantee the absence of a signal in transit;
(2) CAD operations can lead to false positives;
(3) Increasing the number of CAD operations also increases energy consumption;
(4) A random mechanism is needed to separate the times between concurrent nodes;
(5) Channel detection periodically during the back-off time only increases energy consumption.

A. Design and Implementation in NS3

Based on discrete events, we chose the NS3 network simulator to design and test our project open-source software, licensed under the GNU GPLv2, designed for teaching and research. Several implementations of LoRaWAN modules exist in NS3. The LoRaWAN module from David Magrin signetlabdei/LoRaWAN chosen for testing does not implement CAD. ALOHA is the basic protocol used. Our contribution is to add the CAD operation to this module to test the performance of the LoRaWAN network with CAD carrier sense in terms of quality of service and scalability. These tests led us to propose the so-called FT-CSMA.1, a simple CSMA collision avoidance mechanism. Finally, the implementation of the CSMA proposed in [17] allowed us to propose the final FT-CSMA, an amalgamation between the CSMA of WIFI in 802.11 and WSN in 802.15.4. In addition, with these modifications, all the suggestions proposed and cited in recent works can be tested and improved. In particular, the addition of other high-performance CSMA mechanisms. The following details the FT-CSMA proposal's temporal sequence:

1) CAD/FT-CSMA operation time

According to the Semtech documentation quoted in “CAD Mechanism” section, the CAD time should be:

$$T_{CAD} = T_{symb} + \frac{32}{BW} \tag{2}$$

where: $T_{symb} = \frac{2^{SF}}{BW}$

Another technical document [19] describes the ideal detection time as 1, 2, 4, 8, or 16 symbols. Almost half of this time defines the Rx reception mode. However, in the Datasheet [8], the time of the CAD operation depends on the SF. Table III clearly demonstrates that in order to ensure accurate preamble detection and prevent false results, it is imperative to subtract several symbols. This study adopts this configuration in both implementation and testing. This is an adequate time for this type of operation. The abuse of using several CADs to ensure carrier detection is energy-consuming.

In [13], non-detection of the carrier, even if it exists, does not mean a false detection. Only sometimes, this solution misses avoiding a collision. What is important is that if the detection is positive, then it is sure there is a signal in the air. This choice meets criterion number 1. False-positive results for the second criterion are avoided using one of the three basic frequencies of the exclusive 125kHz bandwidth specified by regulation [20] 868.10 MHz, 868.30 MHz, 868.50 MHZ.

2) CAD/FT-CSMA waiting time (Back-off)

After the CAD operation, the channel can be busy or idle. When busy, the device waits to restart the CAD until the channel becomes idle to transmit. As all messages sent, this time must follow the duty cycle regulation, which is 1% in our case. However, nothing in the documentation specifies the value of this waiting time.

TABLE II. RECENT CSMA PROPOSAL PARAMETERS

Ref.	**Year**	**CSMA**	**Carrier Sense Duration**	**Back-OFF/CW**	**Environment**	**Results**
To and Duda [4]	2018	CSMA CSMA-X	CCA CCG = 10ms	$T_{sf} = rand(0,2k-1)$ $T_{offset} = 1s$	Testbed + NS3	Lower collision and energy consumption
C. Pham [9]	2018	$CSMA_{802.11}^{LoRa}$ $CSMA_{new}^{LoRa}$	9×CAD sequential 9×CAD during ToAmax	18-144 × CAD Exponent ToAmax Fixe	Framework	Energy efficiency, collision avoidance
J. Liando *et al.* [10]	2019	CSMA-CAD	1CAD = 2 Symbols	$Sf = rand(7,12)$	Simulation	+ 20% PDR 56 x throughput
L. Beltramelli *et al.* [11]	2020	NP-CSMA	1CAD = 2 Symbols		Analytic + Monte Carlo	Improve throughput with small SF
N. Kouvelas *et al.* [12]	2020	P-CARMA	$P \times CAD, 0 \leq p \leq 1$	$T_{sf} = rand(0, ToA)$	Framework + NS3	+ 20% PDR - 0.48J energy
C. Pham and M. Ehsan [13]	2021	RTS messages	$7 \times T_{preamble} + ToA_{RTS}$	$7 \times T_{preamble}$	Framework	Reduce collision, Battery life 234days
A. Triantafyllou *et al.* [14]	2021	FCA-LORA	GW Synchronisation By beacons broadcasting		OMNeT++	+ 49–50% throughput
C. Shao and O. Muta [15]	2022	LOHEC	$N_{SF} = \frac{N \times E_{min}}{E_{sf}}$ CAD	$T_{SF} = \frac{T_{min} \times E_{SF}}{E_{min}}$ $T_{offset} = rand(0, T_{SF})$	Framework	Improve energy by 0.6 – 0.8 times
S. H. Alonso *et al.* [16]	2022	LFS-CSMA	$slot = ToA_{max} + T_g$ *Frames aligned at end slots*	Next slot	Analytic	Improve QoS, energy
A. Gamage *et al.* [17]	2022	LMAC-1 LMAC-2 LMAC-L	12×CAD	4..64 × CAD Auto select channel Channel selected by ACK	Framework	+ 90% PDR in Class B with the lowest energy consumption
Proposed	2023	FT-CSMA	1CAD	$ToA_{max} + rand(1,3) \times CAD$	NS3	+ 5% PDR –2% energy

TABLE III. CAD DURATION IN TERMS OF SPREADING FACTOR.

SF	Number of Symbols
7	1.92
8	1.78
9	1.75
10	1.77
11	1.80
12	1.85

To avoid overlapping frames. We choose T_{bK} as the back-off time, with the highest ToA value corresponding to the highest SF value SF12. To satisfy the fourth and fifth criteria, it is best to add an additional Time $(B \times T_{CAD})$ to the Back-off. Where B is a random number from 1 to 3

$B = rand(1,3)$. And T_{CAD} is the time of the CAD operation itself. Finally, back-off time is

$$T_{BackOff} = T_{bk} + (B \times T_{CAD}) \quad (3)$$

All of these times ensure the end of transmissions of frames operating with large SF and therefore long ToA. Above all, to avoid any possible synchronization between nodes that are competing on the channel. The back-off time (T_{bK}) is calculated according to the payload used in the simulations and not LoRa’s maximum payload of 255 bytes.

The LoRa modem has two types of packet format: explicit and implicit. The explicit packet includes a short header, a code rate and an optional CRC. Fig. 4 shows the packet format [19].

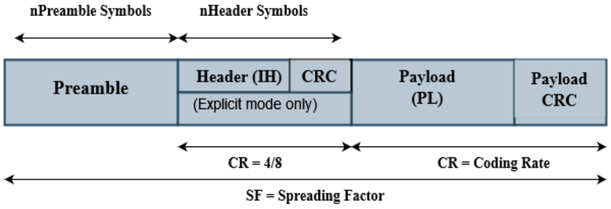

Fig. 4. LoRa packet format [19].

Equations (4 - 7) from the data sheet [19] are used to calculate Tbk, which is defined as the highest ToA.

$$ToA = T_{preamble} + T_{payload} \quad (4)$$

$$T_{preamble} = \left(n_{preamble} + 4.25\right) \times T_{symbol} \quad (5)$$

$$T_{payload} = n_{payload} \times T_{symbol} \quad (6)$$

$$N_{payload} = 8 + \left\lceil \frac{8PL-4SF+8+CRC+H}{4(SF-2)} \right\rceil \times (CR+4) \quad (7)$$

where:

- $8 \leq n_{preamble} \leq 255$;
- *PL* the simulation payload size 12 / 24 bytes;
- *SF* the spreading factor, $7 \leq SF \leq 12$;
- *H* the number of header symbols;
- *CRC* the Cyclic redundancy check in bits;
- *CR* the coding rate.

Note that the device does not periodically detect the channel during the back-off time but only at the end. This is the principle used in WSN networks. Testing will be done first on T_{BK}, a fixed Time; second, on a specified waiting time defined in terms of the number of symbols; and third, on a random time. In all cases, the device transmits directly after detecting a free channel with CAD or waits for another Back-off time, whether random or fixed.

3) CAD/FT-CSMA energy consumption

During the whole CAD operation, the node must take on two modes. The CAD mode detects the preamble, followed by the Rx reception mode (Rx) to detect the data symbols.

The latter takes a very short time to reduce the power consumption. The device is considered to be in standby or sleep mode during the back-off time. The table on [8] page 45 gives a power consumption of *6 mA* in CAD mode and *11.5 mA*in Rx mode. These measures are correct when a LoRa device operates in 125 kHz bandwidth. Nevertheless, in the SX1261/2 series, in the CAD mode, the devices detect the LoRa preamble or data, while the previous series could only detect LoRa preambles. To generalize the implementation and cover all ranges of LoRa devices, nodes are set to CAD mode for half of the CAD operation time and the other half in RX mode. Therefore, the power consumption when operating at 125 kHz is:

TABLE IV. LORA CAD CONSUMPTION.

Module	Rx (mA)	CAD (mA)	STANDBY (mA)
SX1272	10.8	5.6	1.5
SX1276/7/8/9	11.5	6	1.5

$$E = E_{RX} + E_{CAD} \quad (8)$$

$$E = T_{CAD} \times P_{CAD} + T_{RX} \times P_{RX} \quad (9)$$

With the assumption that the times of both modes are equal $T_{CAD} = T_{Rx} = T$, then:

$$E = T \times (P_{CAD} + P_{RX}) \quad (10)$$

Finally, $E = T \times (6 + 11.5)$, Then $P_{total} = 17.5mA$. For FT-CSMA, the additional Back-off time is in standby or sleep mode. The device is set to standby mode despite consuming more power than sleep mode. This is because, firstly, the duration is low; secondly, the device can perform CAD-back-off operations several times; and thirdly, for generalization reasons.

When the device tries to transmit, there are two possible situations: the device may never run the Back-off, and then consumption is:

$START_P = P_{total} = 17.5mA$.

Or it runs one or three back-offs, so consumption is:

$MinP = P_{total} + 1 \times P_{standby} = 17.5 + 1 \times 1.5 = 19mA$.

$MaxP = P_{total} + 3 \times P_{standby} = 17.5 + 3 \times 1.5 = 22mA$.

The average consumption is, therefore,*20.5mA*. The device repeats this step without exceeding the Duty Cycle, so it aborts the transmission, or the channel will be idle with a successful transmission.

B. *Implemented Algorithm*

The CAD algorithm in the flowchart cited in the previous section needs to mention the duration of each step. It is very technical, and its implementation concerns the LoRa module framework. The FT-CSMA algorithm below contains a simplified CAD version tagged with the necessary time for each stage. Note that the Semtech data sheets do not indicate the duration of the Back-off. It is better to wait for a random time without specifying exact values.

After explaining the choice of parameters for our new FT-CSMA method: the CAD waiting time, the back-off time after a busy channel, and the energy consumed in each stage, it's convenient to conclude the work with the following algorithm: it starts with an initial CAD operation before entering the while loop to avoid unnecessary back-off. The (n) here, in the comment, is the number of symbols the CAD operation should take according to Table III configuration. Note that another component ensures the algorithm termination, which calculates the transmission time T*tr* and compares it with the duty-cycle DC, also implemented at the MAC level of this module.

Algorithm 1. FT-CSMA algorithm with Simplified CAD

```
Require: Packet to send
Require: In STANDBY or SLEEP mode
Ttr ← 0
run CAD                                  ▷ TCAD = n ∗ Tsymb
Ttr ← Ttr + TCAD
while Channel busy and Ttr ≤ DC do
    BackOff                       ▷TBackOff = rand (1, 3) ∗ TCAD
    run CAD                              ▷ TCAD = n ∗ Tsymb
    Ttr ← Ttr + TCAD + TBackOff
end while
if the Channel is idle, then
    Transmit
    turn to STANDBY
    End
end if
```

IV. RESULT AND DISCUSSION

We used simulator NS3 version 3.37. It offers a wide range of propagation models. All simulated scenarios use Log Distance Path Loss with a Path-Loss Exponent (PLE) of 3.7, corresponding to urban areas. It also uses several mobility models. However, with the activation of ADR, the standard suggests static devices. Therefore, constant mobility is our choice.

A. *Device Locations and SF Distribution*

The node's distributions are uniformly within a disc of radius 6400m. Since the goal of CAD is to improve packet delivery by avoiding collisions, the simulation should run on many nodes. Furthermore, taking the simulation results after sending at least 20 periods is preferable. This precaution ensures that the CAD mechanism is operational even after the nodes have converged to the SF, Data Rate (DR), and stability frequency. The nodes automatically achieve this convergence either with the Adaptive Data Rate ADR mechanism or the LoRa *LowDataRateOptimize* mechanism.

Fig. 5 shows the position of the nodes and their SFs at the start of the simulation; two black spots mark the two gateways. Fig. 6 shows the same nodes with new SFs after 20 simulation periods. The nodes closest to the gateway take the SF7 value, marked with red dots, while those furthest away take the SF12 value, marked with a blue(x) sign.

In other words, to ensure reception, messages must arrive with an RSSI higher than the gateway's sensitivity and with an acceptable Signal over Noise Ratio (SNR) as shown in Table I.

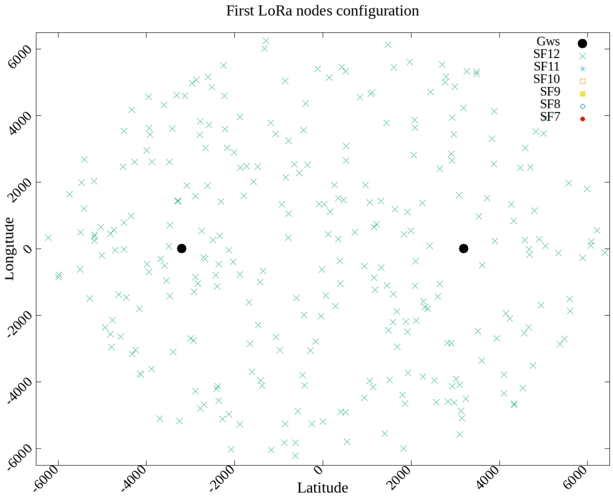

Fig. 5. Initial state.

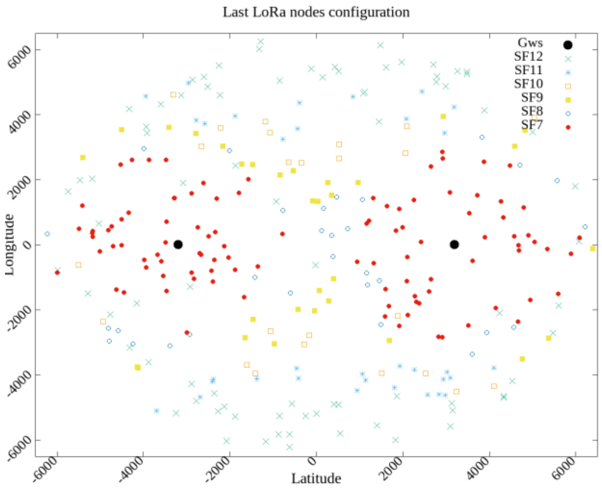

Fig. 6. Convergence state.

In energy terms, power consumption increases with distance since the ToA transmission time doubles as the SF increases, forcing distant nodes to operate with high transmission power (Tr), therefore, more energy, to ensure link stability, as shown in Fig. 7.

Negotiating between the devices and the network server automatically ensures this optimization [21]. As long as ADR is active, the network server uses the data collected from the gateways to determine the optimum configuration for the nodes. This configuration affects the SF, power, or

DR, which must ensure the correct reception of messages with reduced energy consumption.

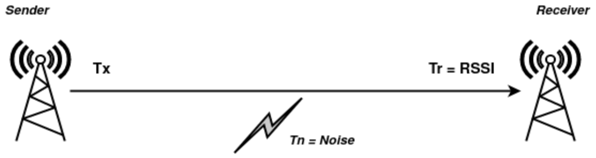

Fig. 7. Requirements for receiving a message.

B. *Simulation Scenarios*

Another MAC protocol is implemented. S-ALOHA in NS3's LoRaWAN module for validation and comparison. For a given application, the LoRa nodes deployed are generally equipped with the same sensors, i.e., they send messages of the same size. In this context, S-ALOHA is a suitable candidate and easy to implement. For simplicity's sake, the slot synchronization module is omitted. S-ALOHA time slots are also the maximum ToA as the previous CAD back-off time $T_{slot} = T_{bk}$.

To explore LoRa's scalability, from one hundred to a thousand nodes are uniformly distributed randomly (with constant density) within a disc of radius *6400m*. Table V below summarizes the main parameters used in the simulated scenarios. Nodes generally have a sensor that collects data in the order of a few bytes. Therefore, 24-byte or 12-byte packets are perfectly suitable for testing.

Using this basic implementation, also one of the proposals cited above in state of the art is implemented, like LMAC in [17]. A discussion on this work is at the end of this section.

TABLE V. SIMULATION PARAMETERS.

Parameter	Value
Radio propagation model	Log distance (PLE=3.7)
Environment	Line of the site (Free space)
Mobility	Constant (Uniform in a disc)
Radius (Area)	6400 m (disc surface)
Transmission range	3200 m - 9600 m
Bandwidth (BW)	125 kHz
Type of Traffic	CBR
SF	7-12
Packet Size	12 - 24 Bytes
Simulation Time	180s x 20 periods
Gateways	1-5
Nodes	100-1000
Back-off Time	[1.15507s, 1. 48275s, Tbk]+ rand(1,3) x T*cad*
Tbk	Max (ToA) with simulated packet payload
Rand	Uniform Random Variable with timestamp seed
ADR	Enabled
CAD	Enabled

C. *Impact on QoS*

Packet Delivery Ratio (PDR) and Delay are the leading measures of Quality of Service (QoS). Gateway loads with a large number of nodes increase collisions. This is when PDR starts to fall, and CAD shows its effect. We cannot display all simulation results here, from 1 to 5 gateways. Only the 1-gateway and the 4-gateway scenario are chosen as samples. Numerical results are given as a comparison and improvement of FT-CSMA over Aloha.

1) PDR

In Fig. 8, one gateway, when the number exceeds approximately 390 Nodes, CAD improves the PDR by more than 5%, followed by S-ALOHA by 4%. In Fig. 9, four gateways, improvement begins at roughly 600 EDs.

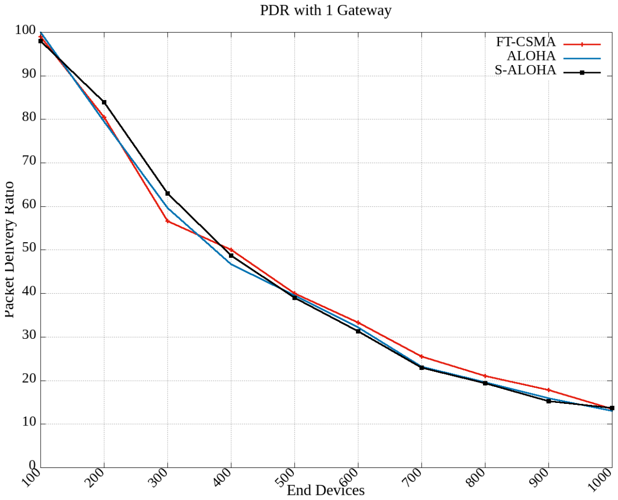

Fig. 8. PDR with 1 gateway.

Note that the PDR for one gateway drops very fast as the number of nodes increases. This is due to the limited capacity of a gateway in terms of the number of nodes. Even if the Gateway is multi-channel, i.e., it can receive simultaneously on 8 or 10 channels and 6 SF, it cannot support many devices.

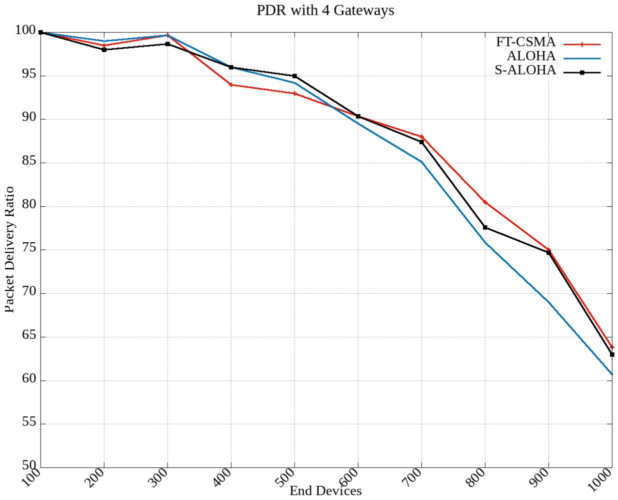

Fig. 9. PDR with 4 gateways.

The end-device distribution also has an impact on the PDR. As the number of nodes increases, more nodes will have the same distance from the gateway and, therefore, influenced by ADR, operate in the same SF. As a result, the probability of collisions increases.

We can already conclude that a large IoT network requires a preliminary study on the minimum number of gateways to cover the massive number of deployed nodes.

2) DELAY

Delays, however, start to deteriorate as the load increases because of waiting times and back-offs. The previous results show a relationship between this behavior and the PDR. In Fig. 10, one gateway, the increase in delay starts at 320 nodes to reach (1.19–0.66 = 0.53%) at 1000 nodes.

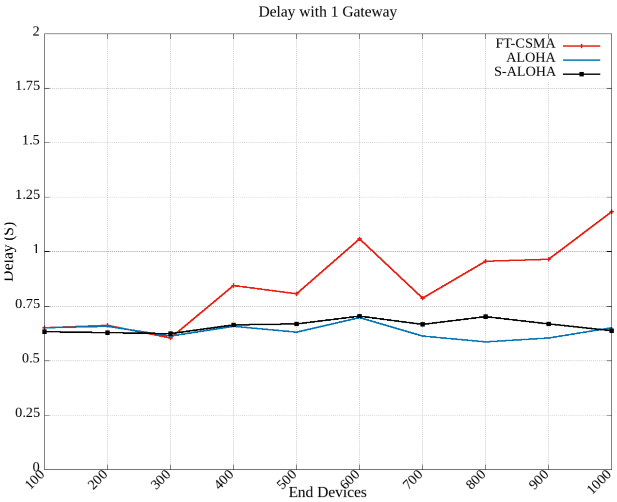

Fig. 10. Delay with 1 gateway.

In Fig. 11, four gateways, Like the PDR, the degradation begins at 580 nodes and reaches a loss of only (0.77–0.58 = 0.19%) at 1000 nodes.

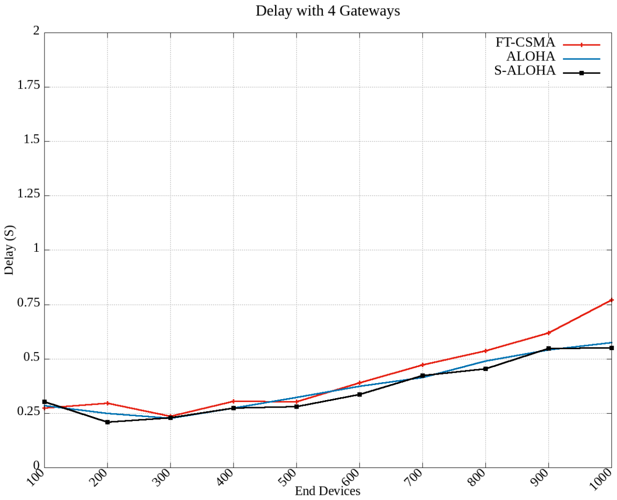

Fig. 11. Delay with 4 gateways.

If a planned network requires a specific margin for the PDR, we can estimate the maximum number of nodes allocated for each gateway deployed to stay within this margin.

Table VI shows an example of a study on the estimated distribution of nodes per gateway to achieve an acceptable PDR of 90%, with reservations about the environment and node positions. These results apply to the FT-CSMA scenario, while the ALOHA scenario is below.

TABLE VI. NODES DISTRIBUTION PER GATEWAY AT 90% OF PDR

Gateways	**Nodes (12Bytes)**	**Average**	**Nodes (24Bytes)**	**Average**
1	150	150	140	140
2	300	150	260	130
3	480	160	400	133
4	630	157	560	140
5	740	148	700	140
Average		153		137

The capacity of gateways in terms of devices is not our current research, but we can already observe the impact of collisions and packet size.

D. Impact on Energy

Based on the results obtained, it can be concluded that the energy consumption is consistent with the expected values. In Fig. 12, it is observed that with a single gateway, the energy consumption is improved by approximately 1.5% (1.85-0.35). However, for a sufficient number of nodes where collisions are minimal, it is evident that the energy consumption increases to 2% (2.9-0.9).

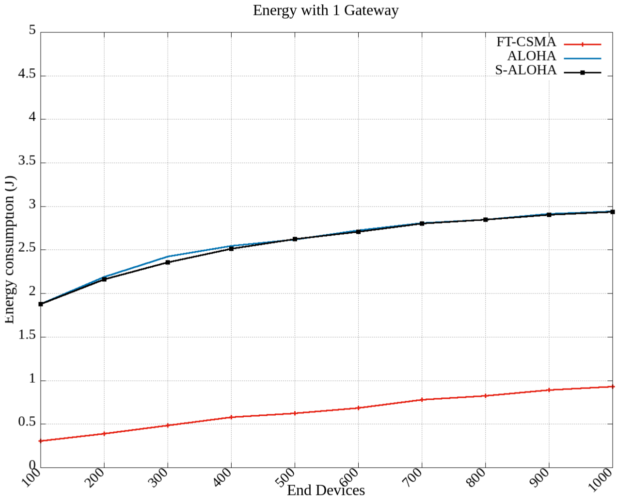

Fig. 12. Energy consumption with 1 gateway.

In Fig. 13, we observe similar results for four gateways where the improvement starts at (1.3–0.3 = 1%) and reaches (2.5–0.8 = 1.7%).

The reduction in energy consumption is due to the decrease in retransmissions. The low-consumption CADs, followed by a single transmission, replace these energy-costing retransmissions if the device finds the channel idle. i.e., in energy consumption, the sum of all CAD operations and a single transmission following them is less than the sum of retransmissions without enabling CAD.

According to the results of the analytical and theoretical models performed on S-ALOHA, the improvements are not entirely apparent. This is because:

- The difference in packet processing time depending on the SF, even if the packets have the same size;
- The simultaneous sending of packets at the start of the experiment;

- He lost packets by attenuating signals for nodes further away from Gateways.

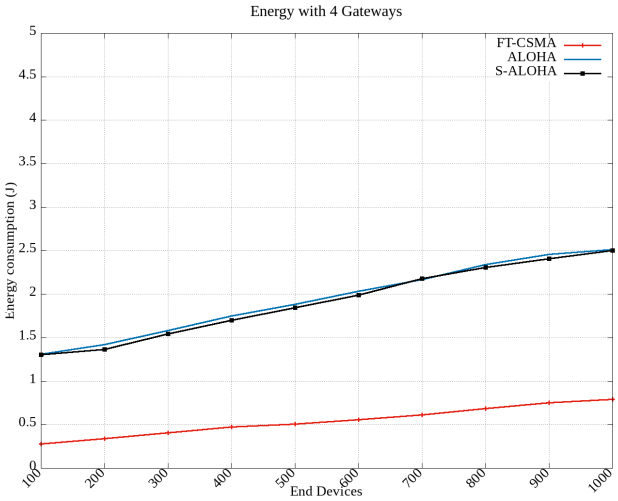

Fig. 13. Energy consumption with 4 gateways.

E. Comparison with Other Proposals

We have also implemented the LMAC-1 version of the previously cited article in [17]. Table VII illustrates the parameters used in the simulation.

TABLE VII. LMAC-1'S DIFS AND BACK-OFF DURATION IN TERMS OF CAD

Difs (CAD)	**Back-off (CAD)**
4	[4–32]
8	[4–32]
12	[8–64]

Fig. 14 and Fig. 15 show the difference between the LMAC-1 scenarios and FT-CSMA regarding quality of service. The results with 4 Gateways, 24 bytes of payloads, and a radius of 6400m are given. The other simulations look the same.

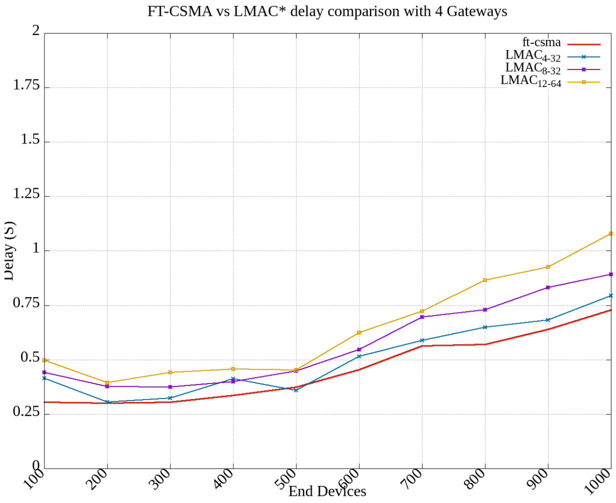

Fig. 14. Delay comparison between LMAC-* and FT-CSMA.

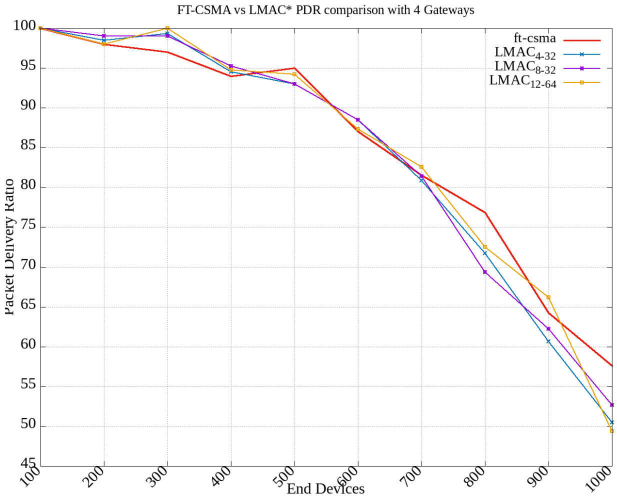

Fig. 15. PDR Comparison between LMAC-* and FT-CSMA.

Even though the QoS results seem very close for energy consumption, however, Fig. 16 shows the success of CAD on LMAC-1. Henceforth, the one with $DIFS = 4 \times CAD$ and a Back-off between [4–32] gives the best results. This proves that using CAD in CSMA methods relatively avoids collisions. However, overuse of the technique does have an impact on energy consumption. Therefore, the choice of the number of CADs used in DIFS or Back-Off is made with extreme prudence.

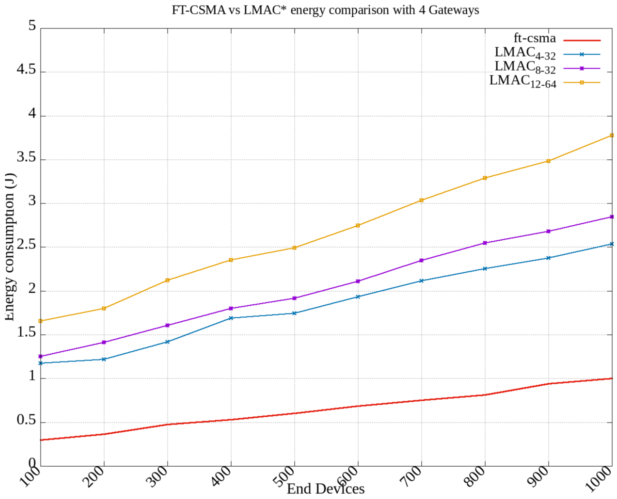

Fig. 16. Energy in LMAC-*and standard FT-CSMA.

Note that using CADs in the Back-off consumes additional energy. For this reason, we should adopt the Back-off used in CSMA *802.15.4* without channel detection here instead of CSMA *802.11*.

V. CONCLUSION

Wireless networks are prone to collisions that can negatively impact their efficiency, dependability, and scalability. Carrier Sense Multiple Access (CSMA) protocols have been developed through extensive scientific research to mitigate this issue. While signal strength-based CSMA approaches are commonly used, CSMA protocols that rely on channel activity detection

(CAD) are crucial for successfully deploying LoRa technology.

In this article, we present a new, modernized CSMA protocol called FT-CSMA. To ensure dependable and efficient CAD operation, selecting an appropriate CAD number, determining proper CAD durations, and incorporating a back-off delay is necessary. FT-CSMA is a well-optimized method, following the trustworthy and established techniques, such as those standardized and implemented for IEEE CSMA specifications. The NS3 simulator has been instrumental in demonstrating our remarkable improvements in Packet Delivery Ratio (PDR) of about 5% and significant improvements in energy efficiency up to 2%, without significantly compromising the delay. The findings of this research indicate that CAD operations are successful. LoRa-based networks and low-power wide area network (LPWAN) technologies can be leveraged for numerous applications in the Internet of Things (IoT) ecosystem.

By integrating Channel Activity Detection (CAD) into NS3's LoRaWAN module, this study provides valuable insights to the scientific community. Our objective is to thoroughly test the proposed CSMA solutions by conducting multiple CAD processes and evaluating their effectiveness before introducing a new, more optimized option.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Chaib Mostefa prepared, analyzed the data, and wrote the paper; Tahar Abbes Mounir conducted and analyzed the research, and proofread the English language; Allali Mohamed Abdelmadjid modified the paper's organization and outline; Abdelouahab Nouar validated the results. All authors had approved the final version.

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