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Leveraging fairness in LoRaWAN: A novel scheduling scheme for collision avoidance☆

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ABSTRACT

The employment of Low-Power Wide Area Networks (LPWANs) has proven quite beneficial to the advancement of the Internet of Things (IoT) paradigm. The utilization of low power but long range communication links of the LoRaWAN technology promises low energy consumption, while ensuring sufficient throughput. However, due to LoRa's original scheduling process there is a high chance of packet collisions, compromising the technology's reliability. In this paper, we propose a new Medium Access Control (MAC) protocol, entitled the FCA-LoRa leveraging fairness and improving collision avoidance in LoRa wide-area networks. The novel scheduling process that is introduced is based on the broadcasting of beacon frames by the network's gateway in order to synchronize communication with end devices. Our results demonstrate the benefits of FCA-LoRa over an enhanced version of the legacy LoRaWAN employing the ALOHA protocol and an advanced adaptive rate mechanism, in terms of throughput and collision avoidance. Indicatively, in a single gateway scenario with 600 nodes, FCA-LoRa can increase throughput by nearly 50% while in a multiple gateway scenario, throughput reaches an increase of 49% for 500 nodes.

1. Introduction

Today, the Internet of Things (IoT) technology grows into a need for modern society, integrating a variety of communication technologies through wireless battery driven sensor nodes and networks. The selection of appropriate communication technologies helps to manage and to maintain the quality of service in the IoT platform based on limited resources. A qualified networking technology should be scaleable enough, reliable in terms of throughput with minimum delays and last but not least, promote energy conservation and data privacy [1]. In order to satisfy these requirements, another range of protocols and technologies have emerged, known as Low-Power Wide Area Networks (LPWAN). A LPWAN can provide radio coverage over a very large area at a low bit rate. These specific characteristics distinguish a LPWAN from a wireless WAN, that is intended to connect users or businesses, and carry more data, using more power. Low power networking technologies have already become very popular, especially in smart city applications on environmental parameters monitoring, road traffic management, precision agriculture, smart parking, and home automation [2,3].

Our study is focused on the LoRaWAN technology. LoRa stands for Long Range and has been adopted by the European countries and the USA, operating on the 868/915-MHz ISM bands, available worldwide. This technology has the ability to transmit at data rate of up to 50 Kbps using an advertised radio range of up to 15–30 km in rural areas, while providing battery life of about 10 years [4]. However, based on recent studies, LoRa has been shown to face several challenges, due to its regulatory constraint on duty-cycle, which disables a device from sending data packets at will [2]. The utilization of low power but long range communication links of the LoRaWAN technology promises low

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energy consumption, while resulting in sufficient throughput. Nevertheless, due to LoRa's original scheduling process, there is a high chance of packet collisions, compromising the technology's reliability [5]. The employment of high spreading factors in LoRa's physical layer and random access in shared channels leads to an increase in packet transmission time and consequently to a higher chance of collision [6].

The contribution of our work lies in the improvement of LoRaWAN technology by defining an efficient scheduling method that can address the aforementioned challenges. We aim to demonstrate a fair Medium Access Control (MAC) scheme that can effectively handle uplink and downlink transmissions in a LoRaWAN network, promoting reliability and high channel utilization. In particular, the following contributions are provided:

- The design and development of a novel LoRa MAC mechanism, named FCA-LoRa, that enables a fair, scalable and reliable scheduling procedure in low power wide-area networks.
- FCA-LoRA targets multiple channel access scheduling in a way that promotes fairness, while also preserving energy consumption in average levels.
- Novel beacon frames are periodically broadcasted by the network's LoRa gateways in order to synchronize communication with LoRa end devices.
- The Carrier-sense multiple access with collision avoidance (CSMA/CA) algorithm is utilized during up-link communications to leverage throughput.
- Nodes are instructed to transmit randomly, according to the scheduling information acquired by the beacons, utilizing different spreading factor values in the available channels in order to increase the reliability of the network.
- The proposed scheduling process is evaluated in a single gateway scenario and in a multiple gateway scenario, including a variety of nodes from 100 to 600 in steps of 100 nodes.
- Simulation results demonstrate that down-link transmissions are safeguarded, collisions are significantly decreased, high channel utilization is achieved, and throughput increases.
- FCA-LoRa manages to increase throughput by nearly 50% while in a multiple gateway scenario, throughput reaches an increase of 49% for 500 nodes.

The remainder of this paper is organized as follows. Section 2 provides an overview of the LoRaWAN technology, while Section 3 is dedicated to related work. Section 4 describes the FCA-LoRa scheme. Section 5 emphasizes on how fairness is achieved via the FCA-LoRa mechanism, while Section 6 focuses on implementation details regarding the proposed scheduling method. Section 7 demonstrates the appointed simulation scenarios and experimental results towards evaluating the FCA-LoRa scheme. Finally, Section 8 concludes the study.

2. Background

2.1. LoRaWAN architecture

LoRaWAN is an open standard specification for LPWANs defining the operational structure of the system and network implementation protocols for resource constrained devices. A basic LoRaWAN scenario may involve multiple sensor nodes or end nodes guided to transmit data packets to an according gateway. Each node typically includes various sensors, a LoRa transponder for signal transmissions and optionally a micro-controller. Gateways can cover hundreds of square km in range and are responsible for forwarding incoming transmissions to a specific network server by utilizing a back-haul network such as 4G or Ethernet. An application server is also involved, communicating with the network server via TCP/IP connection. In order to safeguard data privacy in radio transmissions, the LoRaWAN protocol adopts the technique of symmetric cryptography by utilizing session keys extracted from the device's root keys [7].

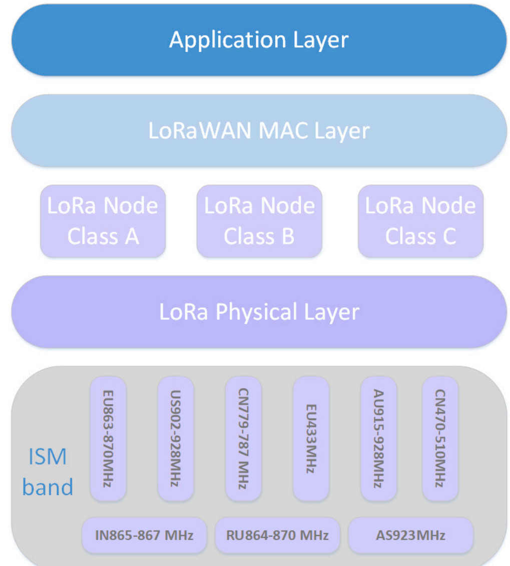

Fig. 1. LoRaWAN protocol stack.

LoRa has proven to be quite useful in numerous IoT applications. However, the low data rate restricts LoRa's employment in applications which produce low amounts of data traffic. Depending on the application scenario, LoRaWAN nodes can be of three different types utilizing bi-directional traffic [7]: *(a) class A nodes*, that randomly transmit data packets to the gateway and then wait for a short period to receive their pending messages from the gateway, *(b) class B nodes*, which send messages on demand, but also schedule specific receive windows for the gateway to answer, and *(c) class C nodes*, which are always listening to the channel, keeping almost continuous receive windows so as to check for messages from the gateway. In LoRaWAN, device-to-device communications are not enabled. Packets are only allowed to be transmitted from an end-device to the gateway and further on to the network server, or backwards.

2.2. The LoRa physical layer

The physical layer of LoRa consists of a specific type of spread spectrum modulation technique, which uses frequency chirps with a linear variation of frequency over time in order to encode information. LoRa modulation is characterized by the utilized *Bandwidth (BW), Spreading Factor (SF) and Code Rate (CR)* parameters. This technology requires encoding each symbol with 2^{SF} chirps, where SF takes a value between 7 to 12. SFs can greatly impact the communication range. Since, the chirp rate defines the bandwidth (one chirp per second per Hertz of bandwidth) utilizing a higher value of SF will lead to a longer time for each symbol transmission and yield a longer communication range. The duration of a LoRa symbol is calculated as follows:

$$T_{sym} = \frac{2^{SF}}{Bandwidth} \tag{1}$$

Furthermore, LoRa modulation involves the addition of error correction bits in every data transmission, known as *forward error correction (FEC)*. Regarding the definition of the *CR* parameter, it indicates the percentage of bits being transmitted that actually carry information. An increase in the CR value impacts the duration of the transmission, leading to a decrease in battery life.

The LoRaWAN protocol stack is presented in Fig. 1. LoRaWAN is scheduled to function on different ISM bands, depending on the network deployment areas, as presented in [8]. There are various combinations of frequency channels and data rates for establishing communication between LoRa end-devices and gateways [7]. The minimum LoRa data rate is 0.3 kbps and can reach up to 50 kbps. The data rate selection depends on the messages' duration and the required communication range. In addition, towards maximizing the end devices' battery life and overall network capacity, LoRa utilizes an Adaptive Data Rate (ADR) scheme for each end-device individually [9]. For Europe, the 863–870 MHz ISM band is used, involving a bandwidth of 125 KHz, a data rate of 250 bps, three frequency channels around 868.10 MHz, 868.30 MHz and 868.50 MHz, and a less than one percent duty cycle specification.

Regarding the *duty-cycle* definition, it is referred to as the required amount of time that an end-device needs to wait before the next data transmission [2]. Towards reducing collisions as well as increasing channel utilization by different transmitters, LoRa requires a limit to be set for every end-device regarding the maximum duty-cycle. Based on this assumption, the duty-cycle limit guides the LoRa end-device to use another channel for the next data transmission, until a specific period of silence has passed. This wait timer is something that applies to all LoRaWAN transmitters, including the gateways.

2.3. The LoRa MAC layer

LoRa's MAC layer defines the process of end-devices accessing the wireless medium in order to communicate with LoRa gateways. LoRaWAN utilizes an ALOHA-based MAC protocol [10], able to reduce the complexity of end-devices. Its basic operation lies upon the ability of end-devices to transmit information to the LoRa gateway whenever they are ready. Each LoRa gateway listens to a specific sub-band and is responsible of forwarding the packets received from end-devices to the network server. For an up-link transmission to occur, a LoRa end-device must select an available frequency channel, the bandwidth and an SF value for the according data rate. Up-link messages can be either confirmed or unconfirmed. A confirmed message triggers the gateway to provide an acknowledgement. The acknowledgements sent by the gateway may not be necessary, however, they promote a proper working connection between the end-node and the rest of the network, especially due to the operational circumstances of the ALOHA protocol. Based on confirmation receptions, the MAC layer can better manage the selection of SFs and bandwidth towards increasing throughput. If an acknowledgement is requested, after each up link transmission, the gateway has to choose between two down link slots at fixed time instances, so as to provide an answer to the corresponding end-device. The first slot opens after the transmission, lasting for at least one second, while the second slot lasts exactly one second after the first one. According to the agreement made between the end-device and the gateway, different communication parameters regarding this slot can be selected. Regardless, the total air transmission time of a LoRa packet, Time on Air (ToA) is calculated as follows:

$$ToA = T_{packet} = T_{preamble} + T_{payload} \tag{2}$$

where $T_{preamble}$ is the preamble duration in seconds and $T_{payload}$ is the payload duration in seconds. ToA is equal to the total packet duration. The preamble is the first element of the LoRa packet format utilized by receivers in order to identify incoming packets [4].

$$T_{preamble} = (n_{preamble} + 4.25) * T_{sym} \tag{3}$$

where $n_{preamble}$ is the size of the preamble payload, the number of symbols to be transmitted via the physical layer.

Regarding the payload transmission time the following equations can be utilized for calculating the assigned LoRa symbols.

$$T_{payload} = n_{payload} * T_{sym} \tag{4}$$

$$n_{payload} = 8 + max((\frac{8 \times payload - 4 \times SF + 8 + CRC + H}{4 \times (SF - DE)}) \times (\frac{4}{CR}), 0) \tag{5}$$

where payload refers to the size of the PHY payload in bytes (1 to 255), SF defines the spreading factor and CRC refers to the addition or not of a 16-bit section utilized at the end of the payload. The utilization an implicit header is denoted by H. If the PHY header is enabled H takes the value 0 and if no header is present, H takes the value 1. Moreover, if the low data rate optimization mechanism is enabled, by employing a symbol time larger than 16 ms, DE takes the value 2 or else stays at 0. Lastly, CR refers to the coding rate provided by the following equation:

$$CR = \frac{4}{4+n}, n \in 1, 2, 3, 4 \tag{6}$$

Furthermore, due to the ALOHA protocol scheme, it is quite possible for two end-devices to attempt to communicate with the same gateway, at the same time. In such a case, if both end-devices use the same channel and also modulate their data with the same SF, interference will be caused, leading to packet collision. The employment of Slotted-ALOHA scheme could help eliminate partial collisions, since it utilizes time-slots for data transmission. Each node is allowed to send a packet only at the beginning of a time-slot. However, access in the medium remains uncontrolled. The occurrence of a collision depends on the decision of more than one end-devices to transmit a packet simultaneously [11]. The lack of coordination and the absence of scheduling in packet transmissions are the main reasons that a real-time poor performance is caused for both pure and slotted ALOHA.

3. Related work

LoRaWAN is a trending technology attracting the attention of many researchers. Significant contributions have been made upon investigating the performance and characteristics of the LoRaWAN MAC protocol. Several studies have been focused on modelling, testing and improving the network capacity and scalability of LoRaWAN [12]. In [13–15] and [16] the uplink traffic of LoRaWAN was studied, highlighting that the most critical drawbacks are low reliability, substantial delays and potentially poor performance in terms of downlink traffic. Due to the ALOHA-based network, packet delivery ratio, including receiving acknowledgements, decreases when the number of devices is increased. In addition, based on the results in [17] and [18] it is shown that specific SF values cannot alter this negative impact on network performance. Furthermore, the analysis conducted in [19] presented that the reliability of LoRaWAN network can be increased if nodes select their preferred spreading factors. However, the approach proposed does not seem to favour the energy consumption. Quite recently, Centenaro et al. proposed a novel operation model called time-power multiplexing, towards improving the capacity of LoRa-based networks by decoupling uplink and downlink traffic [20]. An effort to improve reliability and scalability of LoRaWANs has also been done in [21] through lightweight scheduling. This study proposes a coarse-grained scheduling for gateways by dynamically specifying the according spreading factors and transmission power for each channel. However this scheme does not seem to balance efficiently the energy consumption factor.

A quite informative energy efficiency analysis of LoRa-based MAC protocol has been conducted in [24] and [23]. In [24] the analysis was made with respect to network scale, transmission delay, and payload size by promoting the use of synchronous protocols instead of contention-based protocols regarding battery lifetime. On the other hand, the authors in [23] presented analytical models that characterize device current consumption, device lifetime and energy cost of data delivery in LoRaWAN. Considering energy consumption, the study in [25] proposed the use of CSMA (Carrier Sense Multiple Access) in order to lower the collision ratio, while maintaining an energy efficient network. Based on an important observation regarding collision rate avoidance, the authors in [26] proposed the design of a contention-aware adaptive data rate. Another way to minimize collisions was proposed in [22], where a dual-channel medium access control (MAC) is presented to maintain quality of service, while dealing with the priority of different

Table 1
Related work contributions regarding LoRaWAN.

Contribution	Scalability	Node fairness	Throughput	Channel fairness	Energy consumption	Collisions
Georgiou et al [13]	✓	x	x	x	x	x
Mikhaylov et al [16]	✓	x	x	x	x	x
Haxhibeqiri et al [14]	✓	x	x	x	x	x
Van den Abeele et al [15]	✓	x	x	x	x	x
Kim et al [22]	✓	x	✓	x	x	✓
Mikhaylov et al [18]	✓	x	x	x	x	x
Reynders et al [19]	x	✓	x	x	x	✓
Casals et al [23]	x	x	✓	x	✓	✓
Islam et al [2]	x	x	✓	x	x	x
Centenaro et al [20]	✓	x	✓	x	x	✓
Reynders et al [21]	✓	✓	x	✓	✓	✓
Hassan et al [24]	✓	x	x	x	✓	x
To et al [25]	✓	x	✓	x	✓	✓
Kim et al [26]	✓	x	✓	x	x	✓
Piyare et al [27]	✓	x	✓	x	✓	x
This work	✓	✓	✓	✓	✓	✓

data types. Moreover, an analytical model of the LoRaWAN uplink (UL) that characterizes the performance superficially in terms of latency and collision rate, was proposed in [28]. This study takes into account the restrictions placed in scheduling due to the aggregated duty cycling. Based on this fact the authors in [2] presented a duty-cycle-aware real-time scheduling scheme for LPWANs. However, due to the extreme duty cycling of LoRa end-nodes the latency arises for reducing the overall energy consumption. To overcome this disadvantage, a recent study [27] proposed an energy-efficient On-demand TDMA communication scheme improving both the device lifetime and the data latency of standard LoRa networks.

Up until now, there have been several attempts towards addressing vulnerabilities in LoRaWAN technology. As presented in Table 1, FCA-LoRA is the first scheme to our knowledge that targets multiple channel access scheduling in a way that promotes fairness, while also preserving energy consumption in average levels. Collisions are significantly increased and remain stable, regardless the scalability of the network.

4. FCA-LoRa framework

In FCA-LoRa the definition of synchronous up-link and down-link channels is required for the whole available bandwidth. We assume that there are nine available channels (868.10 MHz, 868.30 MHz, 868.50 MHz, 867.10 MHz, 867.30 MHz, 867.50 MHz, 867.70 MHz, 867.90 MHz and 868.80 MHz), all arranged in units of superframes, which have a specific structure and duration.

4.1. LoRa gateways scheduling

In FCA-LoRa, scheduling is coordinated by gateways. Each gateway transmits beacon frames in a distributed manner, changing transmission channels within a specific time period called *Gateway Cycle (GWDC)*. In each GWDC, gateways will have broadcasted their beacons in all available channels, synchronizing the LoRa nodes and making it possible for every node located in the appropriate distance to receive them regardless the channel they listen to. Nodes harness beacons' scheduling information in order to successfully transmit their data to a gateway by utilizing the same channel through which the latest beacon was received.

Furthermore, each LoRa gateway utilizes a different SF value for beacon transmission in order to increase reception probability and favour channel utilization in the process. In FCA-LoRa, gateways manage the LoRa nodes joining process just as in the legacy LoRaWAN. Once a LoRa node receives its first beacon from a gateway, a join request message is transmitted. Then the gateway sends its response, as well as the next beacon to the according channel. According to the FCA-LoRa scheduling scheme, all channels are specifically scheduled and structured in order to maintain fairness between transmissions and

Table 2
FCA-LoRa PHY specification parameters.

Parameter	Value
Superframe duration	128 s
Beacon Period	128 s
Beacon Reserved	2.12 s
Beacon Guard	3 s
Number of timeslots	4096
Timeslot duration	0.03 s

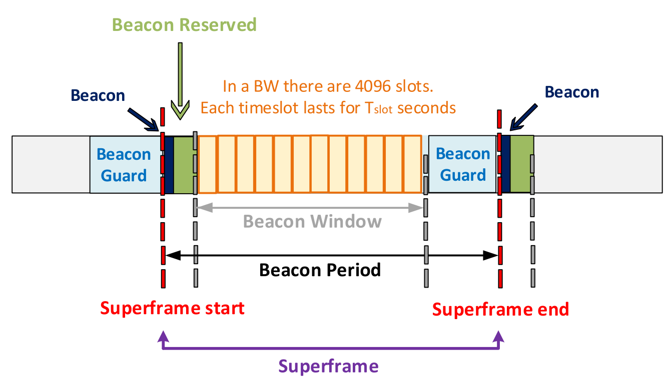

Fig. 2. Structure of Superframes in the FCA-LoRa scheme.

also allow flexibility in choosing SF values. By utilizing different values of SFs the network reliability is highly enhanced, since data frames can simultaneously arrive at their destination and be accepted. However, a balance should be kept between reliability and energy consumption, since the employment of higher SF values will consume larger amounts of energy by enabling longer transmissions [29].

4.2. Superframes and beacons

Each superframe lasts for T_{super} seconds and it is initiated by a beacon frame. Beacon frames are transmitted by gateways. In a superframe, beacon frames are followed by a Beacon Period (BP), defined as the interval between the start of two successive beacons.

Each BP is further divided into a Beacon Reserved (BR) time interval, which lasts T_{BR} seconds, a Beacon Guard (BG) time interval, which lasts T_{BG} seconds and a Beacon Window (BW) time including time slots during which nodes can transmit their packets lasting T_{BW} seconds. Each time slot lasts T_{slot} seconds. Table 2 presents the specific values assigned to these parameters in the FCA-Lora scheme. Each beacon transmission is aligned with the beginning of the BR time interval, as presented in Fig. 2. Then, follows the BW time interval including time

MAC	Fields	Packet Type	Gateway ID	Superframe ID	GWDC ID	Length	BW End Time	SF Selected	List of Channels	Length of Channels
	Length	4 bits	16 bits	8 bits	8 bits	8 bits	32 bits	6 bits	variable	6 bits

Fig. 3. Structure of Beacons in the FCA-LoRa scheme.

slots for data transmissions from the end of the BR time interval to the beginning of the next BG interval. Based on these assumptions the following equations can be formed:

$$T_{super} = T_{beacon} + T_{BR} + T_{BW} + T_{BG} \quad (7)$$

where T_{super} is the amount of time that a superframe occupies in a channel frequency.

$$T_{BW} = N_{slots} \times T_{slot} \quad (8)$$

where the duration of a BW period is defined by the number of timeslots defined in a superframe and the duration of each one of them in seconds.

$$T_{DeviceInSlotN1} = T_{BR} + N_1 \times 0.03 \quad (9)$$

Eq. (9) defines the amount of time that a LoRa node using timeslot N_1 requires in order to turn on each receiver, after the start of the beacon broadcasted in the current superframe.

$$T_{lastTimeSlot} = T_{BR} + N_{4095} \times 0.03 = 124.970 \text{ s} \quad (10)$$

In more detail, Eq. (10) defines the time that the latest time slot starts after the start of the beacon.

In FCA-LoRa, each BG time interval depends on the transmission time of the longest allowed packet frame in LoRaWAN, in order to insure the completion of all down-link transmissions initiated during a time slot and avoid collision with the beacon transmission.

Beacon frames include information regarding the utilization of up-link/down-link slots in each corresponding superframe. Beacons contain information regarding packet type identification and communication parameters, as presented in Fig. 3. In the first 4-bit field, *Packet Type*, the type of the respective packet is provided. Then, follows the 16-bit *Gateway ID* field and the 8-bit *Superframe ID* field, giving nodes information about the timing in the LoRa network. Next, the 8-bit *GWDC ID* field contains information regarding the utilization of the current channel for beacon transmissions. The length of the current beacon is specified in field *Length* that takes 8 bits. The following 32-bit field, *BW End Time* informs the end-device regarding the timing in the according BP. A 6-bit field *SF selected* specifies the value of SF chosen by the gateway for this transmission. The remaining two fields, a variable *List of Channels* and a 6-bit *Length of Channel* list the available frequency channels for the current LoRaWAN.

All this information helps end-devices to more efficiently schedule their transmissions to the gateway by utilizing the appropriate frequency channel so as to avoid packet collisions.

4.3. LoRa nodes scheduling

LoRa end-devices listen to the latest beacon broadcasted by each gateway in order to synchronize their clocks. Beacon frames enable LoRa nodes to choose between different SF values for each transmission leading to an increased probability of successful reception in the destination gateway receiver. In addition, FCA-LoRa promotes a duty-cycle aware scheduling method, where LoRa nodes take into consideration the according duty cycle restrictions so as to utilize each channel in its fullest potential. In Europe, the duty cycle is set to 1% for EU863–870 MHz ISM Band. Based on these assumptions, the total number of transmissions allowed by a LoRa end device in one day (86.400 s) are given by the following equation:

$$n_{trans} \times (T_{minIn} + ToA) = 86.400 \quad (11)$$

$$T_{minIn} = ToA \times (\frac{1}{DC} - 1) = \frac{ToA}{DC} - ToA \quad (12)$$

$$DutyCycle = (n_{trans} \times ToA)/86.400 \quad (13)$$

where T_{minIn} is the amount of time that a LoRa node device must wait before transmitting another packet again in a specific channel frequency. This value is directly affected by the duty cycle restriction as presented in Eqs. (11) and (12).

Moreover, in order to deal with weakness in the ALOHA protocol regarding channel access, the CSMA-CA model is adopted. The CSMA-CA employs the *Listen Before Talk* technique in order to test the channel for occurring transmissions. Nevertheless, FCA-LoRa employs a alternative version of the CSMA-CA algorithm, where LoRa nodes define a random time offset during which the according channel is checked before the transmission of a packet. If during this period, no channel activity is detected, the LoRa node is free to attempt a transmission. The employment of such a listening technique might increase the consumed energy, however it more likely to improve collision avoidance and consequently reduce the overall energy consumption [30].

The adoption of CSMA-CA model increases the chances of a successful transmission in the corresponding BP of a superframe, since many nodes may attempt to transmit in the same time period. Based on the proposed method, every time a data transmission of an end-device is scheduled, an estimation is provided regarding the possibility of successfully reaching the gateway. If the transmission is estimated to be placed outside the BW of the specific superframe, it is cancelled. In such a case, the end-device waits for the next beacon to transmit again. During a BW, multiple transmissions may occur by different end-devices. End-devices have the ability to transmit more than once in the same BW. Due to the proposed scheduling method, no acknowledgements are required and the gateway almost always successfully receives the transmitted packets, leading to a minimum number of collisions at the receiver [31].

5. Fairness in FCA-LoRA

Scheduling is a critical challenge in wireless network applications. Fairness and acceptable throughput are the two most basic parameters of scheduling towards achieving high quality of service and efficiency in network performance [32]. Nevertheless, a variety of existing techniques focus on leveraging only one of the two parameters either time [33]. It is a difficult task to address efficiently both of these performance metrics, since they are contradicting parameters and require different ways to be handled with. Most existing solutions utilize a model of hard fairness by investigating fairness without considering its effect on throughput and efficiency.

Hard fairness [34,35] refers to the round-robin scheduling method. Due to its low complexity it has been used in numerous wireless networks up until know. It is considered to be a fair scheduling scheme due to the equal amount of time that is granted for each participating node in a specific order. However, hard fairness has some advantages regarding efficient time and channel utilization. Very low overall throughput may be caused due to some nodes inability to transmit in their appointed time period in the channel.

It is challenging to define a compromise between hard-fairness and maximum throughput. According to *maximum throughput scheduling*, weaker nodes in terms of priority or longer distance from the gateway, tend to be degraded and starve for traffic load. This may cause significant performance problems, since packets will be dropped due to the long waiting in the queues.

FCA-LoRa aims to achieve fairness and maximize the LoRaWAN throughput through a structured bandwidth allocation technique that leverages the network's scalability and minimizes collisions in the Lora

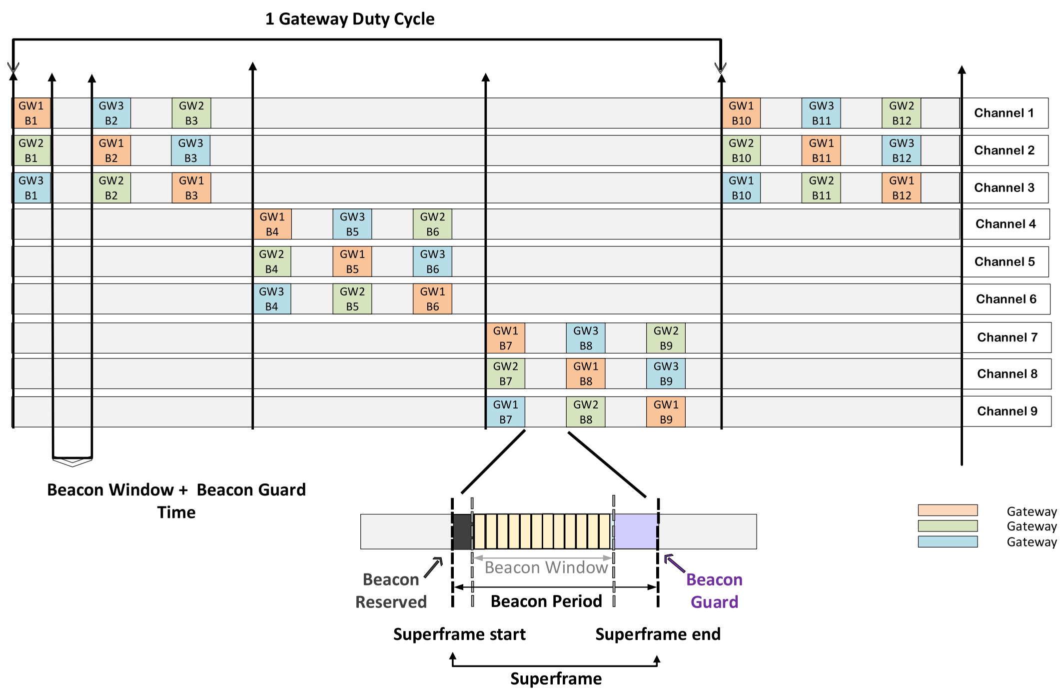

Fig. 4. Structure of channels in the FCA-LoRa scheme by utilizing only 3 gateways.

gateway receivers. The employment of time slots for packet transmissions, as well as superframes, leverages node fairness and provides a fair share of channel time [36] to each LoRa node, including waiting times. *Node fairness* is preserved when all participating nodes with packets to send, receive an equal share of the channel [37]. FCA-LoRa focuses on efficiently managing the involved network resources, without wasting any chances for transmission [29]. This novel scheduling method is set on providing LoRa nodes with appropriate time intervals, taking into consideration the duty cycle restrictions.

In addition, due to the enforced GWDCs channel fairness is also considered. *Channel fairness* is referred to as the appropriate amount of time that LoRaWAN packets occupy in each channel [38]. During GWDCs, LoRa gateways transmit each new beacon on the next channel in the available bandwidth, iterating over all available channels, as presented in Fig. 4.

$$1GWDC_{seconds} = n_{channels} \times T_{super} \quad (14)$$

Eq. (14) calculates the amount of time in seconds that a GWDC can last in the FCA-LoRa scheme, while Equation (15) denotes the minimum ammount of time that a LoRa gateway can re-transmit a beacon frame in the same channel frequency.

$$T_{minGWDCIn} = n_{channels} \times (T_{BR} + T_{BW} + T_{BG}) \quad (15)$$

This way, LoRa nodes will eventually receive a beacon frame, regardless the channel they are listening to, and will be able to send their data packets to according gateway after a random period of time. FCA-LoRa leverages a high channel utilization favouring multiple gateway scenarios.

6. FCA-LoRa implementation

The proposed FCA-LoRa scheme is developed in OMNeT++ [39] discrete event simulator by using the FLoRa (Framework for LoRa) simulation tool [40] and the INET framework, an open-source OMNeT++ model suite for wired, wireless and mobile networks. FLoRa is an open source tool implementing various modules of the LoRaWAN network, including the LoRa physical layer and the legacy LoRaWAN MAC protocol operations. Furthermore, FLoRa provides a module to characterize the energy consumption of LoRa end devices. In order to implement FCA-LoRa, the physical, MAC and application layers in FLoRa were programmed from the beginning. In Fig. 5, a topology diagram is provided in order to identify the basic networking components of a LoRaWAN network employing the FCA-LoRa scheduling scheme.

Table 3
European regional parameters for LoRaWAN.

Parameter	Value
Bandwidth	125 kHz
Frequency	863–870 MHZ ISM Band
Spreading Factor	7 to 12
Duty Cycle	<1%
Bit Rate	0.3–5 kbps
Transmission power	2 dBm to 14 dBm

6.1. *FCA-LoRa physical layer specifications*

The FCA-LoRa scheduling scheme is implemented based on the European regional parameters as presented in Table 3. FCA-LoRa defines that in order for a signal to be successfully received, its reception power should be greater that the sensitivity of the receiver. The signal's reception power is affected by the transmitter's transmission power, as well as the losses caused by signal attenuation and shadowing. The path loss model with shadowing utilized in FCA-LoRa is for long distances [41]. Based on this model, path loss is calculated as follows:

$$PathLoss(dist) = \overline{PathLoss(dist_0)} + 10alog(\frac{dist}{dist_0}) + G \quad (16)$$

where dist is the distance between the transmitter and the receiver, $PathLoss(dist_0)$ is the mean path loss for $dist_0$, a is the path loss exponent, and G is a zero-mean Gaussian distributed random variable with standard deviation.

6.1.1. *PHY for LoRa nodes*

The LoRa node PHY layer manages the node's input and output flows in the according channels. Whenever a new packet is detected, the *LoRaRadio* handles the reception process by the following steps:

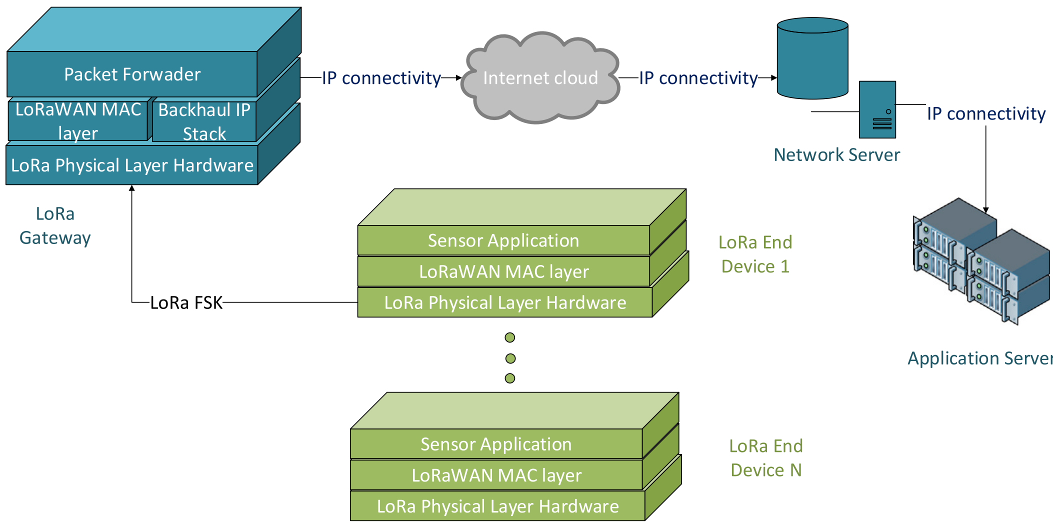

Fig. 5. Topology diagram of the FCA-LoRa scheme.

1. Check the radio transceiver's state.
2. Check if another reception is in progress.
3. Checking if the transmitter is indeed a potential receiver.
4. Detect any interference that may interrupt the reception process.
5. Approve or decline the received signal.
6. Initiate and terminate a reception timer if the packet is approved.
7. Check if the packet received is a beacon and store it to the according gateway list.
8. Decapsulate the packet if approved to be successfully received.
9. Forward the decision and the packet (if approved) to the *LoRaMAC* layer.
10. The transceiver state is updated.

The PHY layer also handles the packaging of planned transmissions. If a packet is forwarded to this layer by the *LoRaMAC* layer the following actions are executed:

1. Check the transmitter state. If a transmission is currently in progress the packet must wait and the *LoRaMAC* layer is notified.
2. If the transmission is possible, the packet is encapsulated into a RadioFrame.
3. Based on the communication parameters and range specified by the *LoRaMAC* layer, the time of the arrival to the defined destination is estimated.
4. A transmission timer is initiated and terminated accordingly.
5. The transceiver state is updated.

6.1.2. PHY for LoRa gateways

The LoRa gateway PHY layer manages the node's beacon transmissions and incoming packets from LoRa nodes in the according channels. Due to the fact that a Lora gateway has the ability to receive multiple packets simultaneously, a different PHY layer is required. The *LoRaGWRadio* is mainly based on the *LoRaRadio* implementation, the LoRa node PHY layer, including some additional modifications. Each gateway in constantly listening to the available channels. Whenever an incoming packet is detected, the *LoRaGWRadio* handles the reception process by the following steps:

1. Check the radio transceiver's state.
2. Checking if the transmitter is indeed a potential receiver.
3. Check if another reception is in progress in the same channel. If more than one packets arrive at the same time, a collision will occur at the gateway's receiver.
4. Approve or decline the received signal.
5. Initiate and terminate a reception timer if the packet is approved.
6. Calculating the signal to noise ratio value and store the received signal value to a list of receptions.
7. Decapsulate the packet if received successfully.
8. Forward the decision and the packet (if received successfully) to the *LoRaGWMAC* layer.
9. The transceiver state is updated.

Regarding the transmission of a downlink message, specifically a beacon frame, the following actions are executed in the LoRa gateway PHY:

1. Check the transmitter state. The transmitter should be activated. No transmissions other transmissions are programmed during this time.
2. The beacon packet is encapsulated into a RadioFrame.
3. Based on the communication parameters and range specified by the *LoRaGWMAC* layer, the beacon is broadcasted in the according channel.
4. A transmission timer is initiated and terminated accordingly.
5. The transceiver state is updated.

FCA-LoRa defines collisions on the gateway receiver based on the model proposed by Bor et al. in [12]. A collision occurs only when two packets with the same SF value, overlap in time in the same channel frequency. Based on Bor et al.'s model, if a collision occurs, only then stronger of the two colliding signals is decoded. However, the strongest signal power should more than 6 dBm higher than the second one's. In addition, at least 5 symbols should be able to be detected in the preamble.

6.2. FCA-LoRa MAC layer specifications

6.2.1. MAC for LoRa nodes

The LoRa node MAC layer manages the node's communication parameters and transmission timers. Whenever a beacon is forwarded to this layer by the *LoRaRadio* the Lora node stores the received beacon in a list and then notifies the node's application layer (*LoRaApp*).

The transmission of a new packet to a specific gateway is coordinated by the application layer as well. The LoRa node MAC layer simply receives the application packet with the selected communication parameters and then initiates a CSMA-CA procedure in order to transmit the data successfully. In order to implement the CSMA-CA process,

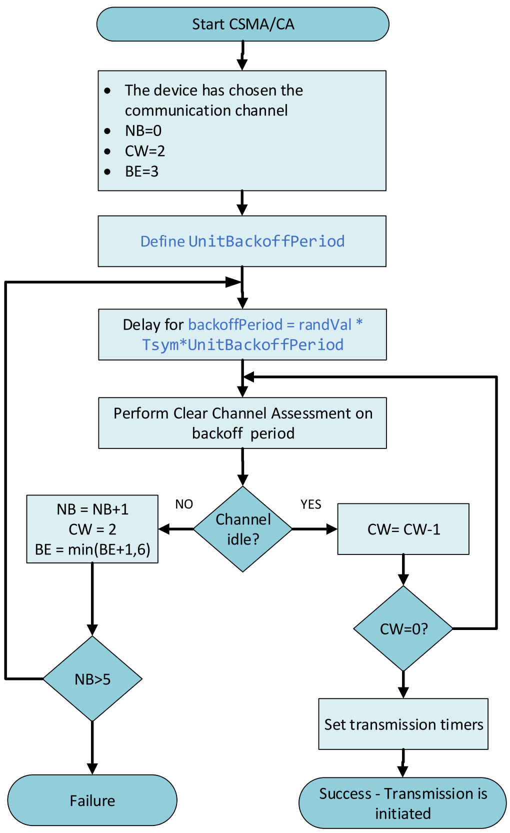

Fig. 6. CSMA/CA flowchart in the FCA-LoRa scheme.

three basic parameters are utilized. The first one is *NB* denoting the number of times the CSMA-CA algorithm is required to backoff while attempting the current transmission. The second one is *CW* referring to the contention window length that defines the number of backoff periods that need to be clear of channel activity before the transmission can commence. Last but not least, *BE*, the backoff exponent, which is related to how many backoff periods a device shall wait before attempting to assess a channel. A diagram of this process is presented in Fig. 6.

6.2.2. MAC for LoRa gateways

The *LoRaGWMAC* manages the gateway's communication parameters and forwards the LoRa nodes' incoming traffic to the Network Server (*NetworkServerApp*).

This layer is responsible for scheduling beacon transmissions in the according time and channel, as well as initiating beacon broadcasting simultaneously for all LoRa gateways in a simulation scenario based on the Network Server's instructions. Each gateway utilizes the same SF value for all beacon transmissions. Each beacon is filled with the according information as presented in Fig. 3. After each beacon transmission, another is scheduled in the next channel in a specific order and in a specific amount of time, as presented in Fig. 4. A timer is set for every beacon transmission as well.

Moreover, when a packet is successfully received by a gateway, the *LoRaGWMAC* reserves two timeslots for a potential downlink transmission in the form of an acknowledgement as required in the legacy LoRaWAN. However, in our scheme no acknowledgements are considered in its current state. The Lora node's message from the node, including some transmission parameters, is then forwarded to the *PacketForwader* in order to travel through the *InternetCloud* and then reach the Network Server (*NetworkServerApp*) for further processing.

6.3. FCA-LoRa application layer specifications

Application layers are implemented for the LoRa nodes and the LoRa Network Server that controls the whole network.

6.3.1. LoRa node application layer

The *LoRaApp* module is responsible for initiating packet transmissions to gateways and also handling the received beacon scheduling information. A new transmission is always scheduled in a random time period and the chosen destination is selected in a first in, first out (FIFO) manner from the beacon frame queue list [42].

Once the gateway is chosen, the LoRa node tunes to the beacon's channel and utilizes a random SF value to code the data. Once the SF value is selected, an evaluation procedure is initiated in order to determine if the node can transmit within the gateway's BW of the latest received beacon, while also taking into consideration the duty cycle restrictions. If the transmission cannot be performed, another SF is selected and the procedure is repeated. A maximum of five tries is permitted per transmission. If the selected parameters are not favourable after the five tries, the transmission is cancelled and the node waits for the next beacon in order to send again to the specific gateway. Another beacon is chosen then in order to send data to another gateway following the same procedure. This is demonstrated through specific steps in the following pseudo-code section .

Listing 1: Pseudo-code

```
//--Decide LoRa Node Transmission parameters--
// 1. Peak the earliest gateway beacon
 Beacon chosen_b = beaconReceivedQueue[0];
// 2. Specify the gateway that send it
 LoRaGW GW = beaconReceivedQueue[0].getLoRaGW();
// 3. Choose a random SF value from 7 to 12
 int loRaSF = rand() % 5 + 7 ;
// 4. Specify the channel frequency
 int loRaCF = units::values::Hz(chosen_b->getB_options()
      .getLoRaCF());
// 5. Specify time interval according to Duty Cycle
        if(loRaSF == 7) {
                TimeInterval = 7.729920;
        }
        if(loRaSF == 8) {
                TimeInterval = 13.837824;
        }
        if(loRaSF == 9) {
                TimeInterval = 24.431616;
        }
        if(loRaSF == 10) {
                TimeInterval = 48.863232;
        }
        if(loRaSF == 11) {
                TimeInterval = 97.726860;
        }
        if(loRaSF == 12) {
                TimeInterval = 169.50087;
        }
// 6. Check chosen parameters to proceed with transmission
 if((T_lastFrame+TimeInterval)>(simTime()+timeToNP))
 {
   while(counter<5){
        // Choose another SF value and recalculate
        counter=counter+1; }
 }
// 7. Check if the transmission fits in the current
     superframe
 if ((chosen_B->getBeacon_window().
      getBeacon_window_start_time()<(simTime()+timeToNP
      )) && ((simTime()+timeToNP)< (chosen_B->
      getBeacon_window().getBeacon_window_end_time())))
      {
```

```
            // 8. Setting the packet
            // 9. Add LoRa control info
            LoRaMacControlInfo cInfo = new
                LoRaMacControlInfo;
            cInfo->setDest(chosen_B->getB_options().
                getTransmitterAddress());
            cInfo->setSrc(mac_Ad.generateAutoAddress
                ());
            scheduleAt(simTime()+ timeToNP, packet);
            sentPackets++;
 }
 else { EV_INFO << "PacketdoesnotfitinBeacon'sWindow!
     Mustwaitforthenextbeacon"<<endl;}
}
```

6.3.2. Network server application layer

The *NetworkServerApp* module defines all initialization values for the network's gateways and forwards a lunch message to each one of them in order to initiate the broadcasting of beacons. All successfully received LoRa node packets are forwarded to the *NetworkServerApp* by the gateways as soon as they are received. However, FCA-LoRa does not consider any further process of the enclosed packet information regarding scheduling in its current state. In the FLoRa framework, an Adaptive Data Rate (ADR) mechanism is employed, which manages the transmission parameters for the communication links between LoRa nodes and the gateway in a dynamic way. The ADR mechanism is applied at LoRa end-nodes and at the network server asynchronously. Its basic contribution is the enhancement of the network's performance under variable channel conditions. Nevertheless, FCA-LoRa does not involve this kind of process. The *NetworkServerApp* module simply calculates network performance statistics based on the received information. Every gateway in the LoRa network communicates with the Network Server over Internet Protocol (IP). Existing INET modules such as Ethernet and WiFi links are utilized in order to simulate the physical layer between the gateways and the Network Server. The backhaul network is structured just as in the FLoRa framework.

6.4. Energy consumer module

In LoRaWAN, the evaluation of energy performance includes monitoring the end-devices' current consumption, the remaining battery lifetime, as well as the energy efficiency of data delivery [23]. It is also a fact that between the three different device classes, LoRaWAN Class A devices are considered the most efficient ones in the protocol in terms of energy. The major difference regarding the operation of the three classes lays on the procedure of packet reception [43]. Class A devices define the existence of only two short windows for reception, following the transmission of each packet. Once the time period of these two windows passes, Class A devices enable sleep mode towards conserving energy. According to [44], in order to study the energy performance of each end device in a LoRaWAN network, all changes of the different radio states of the device′s PHY layer should be monitored at the length of time.

In 2018, a detailed energy model for LoRa/LoRaWAN technologies was proposed [45]. The presented model takes into account the different transmission modes and LoRaWAN communication parameters in order to define the best one regarding battery life extension and energy consumption optimization. In wireless sensor networks, it is of considerable importance to take into account the energy consumed during the devices' sleep mode. This kind of energy can greatly affect the overall power consumption of the sensor. According to [45], the total energy consumed E_{Total} in each LoRaWAN DC is given by the following equation:

$$E_{Total} = E_{Sleep} + E_{Active} \tag{17}$$

where E_{Sleep} and E_{Active} are the total energy consumed during sleep mode and the total energy consumed by the device's microcontroller during the active mode, respectively. Furthermore, regarding each LoRaWAN end device the energy per useful bit can be defined as follows:

$$E_{bit} = \frac{E_{Total}}{8 * Payload_{bytes}} \tag{18}$$

In FCA-LoRa, three states of the LoRa radio module are defined. These are *transmit, receive and idle*. In idle mode the node is inactive, sleeping. At the end of every reception or transmission, the LoRa node switches in idle mode. In FCA-LoRa, energy consumption is measured by the employment of energy consumer modules in LoRa nodes, monitoring the variations performed in each particular radio state. Energy consumption during transmission is mainly based on the employed transmission power of each Lora node [46]. For each transmission power level, the current values utilized were obtained from [12]. In addition, the Semtech SX1272/73 datasheet of 2019 [47] was utilized, with a supply voltage of 3.3 V, in order to define the drawn current in the receive and idle modes.

7. Simulation experiments

7.1. Simulation set up

In this section, we present a single cell and a multiple cell simulation scenario in OMNeT++, so as to evaluate the performance of FCA-LoRa compared to an enhanced version of the legacy LoRaWAN as implemented in the FLoRa framework by Slabicki et al. [40].

The simulation scenarios included arbitrarily placed LoRa nodes and specifically placed LoRa gateways in the deployment area. Each LoRa gateway maintained an Ethernet connection with a single network server and the respective networking entities, i.e., routers, a packet forwarder, and the Internet cloud. In order to implement the Internet cloud component, the INET framework was adopted. The ideal backhaul network was modelled to have zero packet loss and a transmission delay of 10 ms, while being based on Gigabit Ethernet links.

In both scenarios, LoRa nodes were initially assigned a random SF value and a uniformly distributed transmission power level in order to cover all possible device configurations. The default SF for the LoRa Gateway was nine. The participating LoRa nodes formed a 20 byte packet after a random period of time following an exponential distribution with a mean of 1000 s. Each LoRa node was instructed to transmit a specific number of data packets to the gateway, without requesting acknowledgements. According to the FCA-LoRa model, node transmissions began only after the reception of a beacon by the gateway. The gateway must also acquire permission from the network server in order to initiate the beacon broadcasting.

Each scenario with a single gateway was evaluated based on a variety of nodes from 100 to 600 in steps of 100 nodes, while the multiple gateway scenarios were evaluated based on a variety of nodes from 100 to 500 in steps of 100 nodes. Each experiment lasted for 7 days, equally to 604.800 secs of simulated time.

Regarding the Slabicki's et. LoRaWAN model, an ADR mechanism is employed, which manages the transmission parameters for the communication links between LoRa nodes and the gateway in a dynamic way. The ADR mechanism is applied at LoRa end-nodes and at the network server asynchronously. Its basic contribution is the enhancement of the network′s performance under variable channel conditions.

7.2. Single gateway scenario

The schemes' evaluation in the single-gateway scenario was focused on the following performance metrics, as presented in Table 4: *(1) throughput, measured as the number of messages correctly received by the gateway divided by the total number of messages sent by the end nodes and (2) total number of collisions that occurred in the LoRa Gateway′s receiver regarding up-link transmissions.*

Table 4
Simulation scenarios evaluation metrics.

Parameters	Single GW scenario	Multiple GW scenario
Throughput (%)	✓	✓
Collisions (Integer)	✓	✓
Packet error rate (%)	x	✓
Mean power consumption (Watt)	x	✓
Channel utilization (%)	x	✓
Successful receptions during GWDCs (Integer)	x	✓

Table 5
Single gateway scenario parameters.

Parameter	Value
Number of GWs	1
Bandwidth	125 kHz
Frequencies	868.10/868.30/868.50 MHz
Spreading Factor	7 to 12
Initial GW SF value	9
Duty Cycle	<1%
Code Rate	4/8
Transmission power	2 dBm to 14 dBm
Time to first packet	exponential(100 s)
Max produced packets	1500
Packet size	20 bytes
Simulation time	7 days
Deployment area	480 × 480 m

Table 6
Multiple gateways scenario parameters.

Parameter	Value
Number of GWs	7
Bandwidth	125 kHz
Frequencies	868.10/868.30/868.50/ 867.10/867.30/867.50/ 867.70/867.90/868.80 MHz
Spreading Factor	7 to 12
Initial GW SF value	7 to 12
Duty Cycle	<1%
Code Rate	4/8
Transmission power	2 dBm to 14 dBm
Time to first packet	exponential(100 s)
Max produced packets	20 000
Packet size	20 bytes
Simulation time	7 days
Deployment area	5000 × 5000 m

In this scenario, both LoRa models utilize the European regional parameters for the LoRa physical layer in a deployment area of 480 m × 480 m. The transmission power range was from 2 dBm to 14 dBm, the chosen CR was 4/8, bandwidth was 125 kHz, SFs ranging from 7 to 12, and carrier frequency was set to 868 MHz for the legacy LoRaWAN implementation, while FCA-LoRa utilized channels 868.10 MHz, 868.30 MHz and 868.50 MHz. Both implementations followed a less than one percent duty cycle specification. LoRa end-nodes were randomly distributed over the deployment area, while a single gateway is placed at the centre. Table 5 summarizes the scenario's implementation parameters.

Fig. 7 verifies the superiority of the FCA-LoRa scheduling method by eliminating packet collisions in the LoRa gateway receiver in contrast to Slabicki's et al. scheduling method [40]. Additionally, Fig. 8 presents a significant increase in throughput based on the FCA-LoRa scheduling method despite the scaling up of number of end-devices and the duty cycle restrictions.

7.3. Multiple gateways scenario

The schemes' evaluation in the multi-gateway scenario was focused on the following performance metrics, as presented in Table 4: *(1) throughput, measured as the number of messages correctly received by the gateway divided by the total number of messages sent by the end nodes, (2) total number of collisions that occurred in the LoRa Gateway's receiver regarding up-link transmissions, (3) packet error rate (PER), measured as the number of packets that did not successfully reach a gateway, divided by the total number of messages sent by the end nodes, (4) mean power consumed in each end device during simulation, (5) channel utilization percentages, and (6) average successful receptions in GWDCs from all gateways in the network.* The selected performance metrics can verify the superiority of the proposed scheduling scheme, while also promoting scalability.

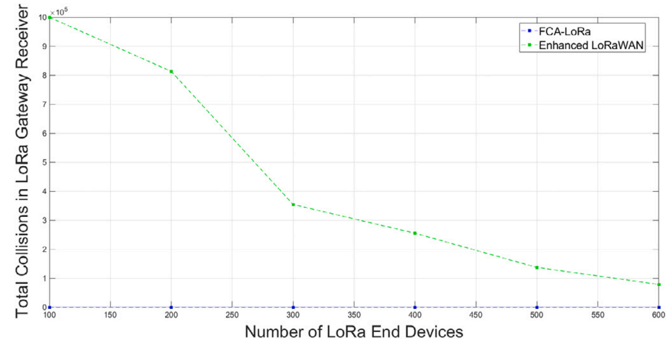

Fig. 7. Collision occurrences in a single cell LoRaWAN scenario.

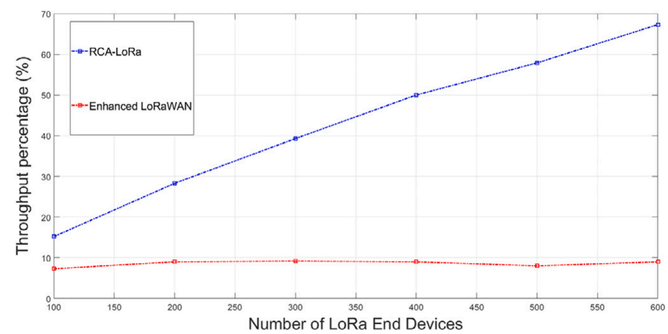

Fig. 8. Throughput evaluation in a single cell LoRaWAN scenario.

In this scenario, both LoRa models utilize the European regional parameters for the LoRa physical layer in a deployment area of 5000 m × 5000 m. The transmission power range was from 2 dBm to 14 dBm, the chosen CR was 4/8, bandwidth was 125 kHz, SFs ranging from 7 to 12, and carrier frequency was set to 868 MHz for the legacy LoRaWAN implementation, while FCA-LoRa utilized channels 868.10 MHz, 868.30 MHz, 868.50 MHz, 867.10 MHz, 867.30 MHz, 867.50 MHz, 867.70 MHz, 867.90 MHz and 868.80 MHz. Both implementations followed a less than one percent duty cycle specification. Moreover, LoRa end-nodes were randomly distributed over the deployment area, while seven LoRa gateways, located as presented in Fig. 9, maintain a maximum distance of 1000 m between them. Table 6 summarizes the scenario's implementation parameters.

More specifically, Fig. 10 validates FCA-LoRa capabilities regarding collision avoidance. It is obvious that despite the increasing number of nodes in the network, no collisions are observed in the receiver of any of the seven gateways. This is an anticipated fact considering the assumptions and principles of FCA-LoRa, as well as the variety of existing channels and the employment of the CSMA-CA algorithm on ToA transmissions.

Furthermore, regarding throughput a raise of 16% is recorded for 100 end devices by utilizing FCA-LoRa, as presented in Fig. 11. The throughput percentage continues to increase in accordance to the increasing number of the nodes in the network reaching a difference of 49% for 500 end devices.

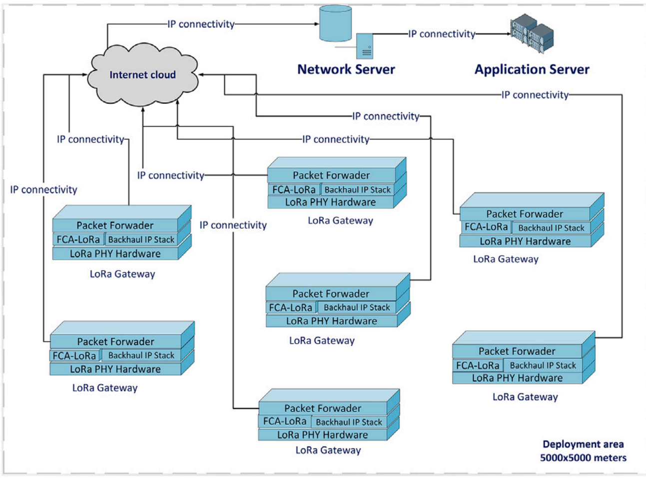

Fig. 9. Multiple gateway scenario topology diagram.

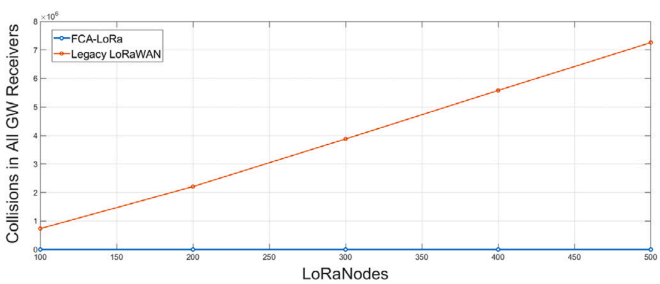

Fig. 10. Collision occurrences in a multi gateway LoRaWAN scenario.

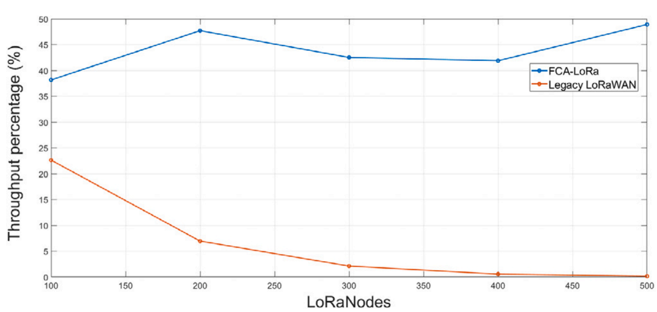

Fig. 11. Throughput evaluation in a multi gateway LoRaWAN scenario.

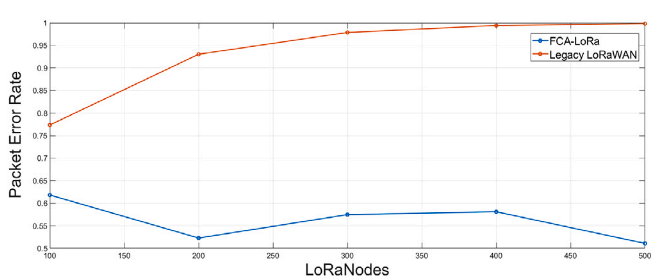

Fig. 12. Packet Error Ratio in a multi gateway LoRaWAN scenario.

Fig. 12 presents the superiority of FCA-LoRa scheme regarding the PER metric. It is obvious that FCA-LoRa promotes a decreasing value of the current metric, despite the increasing number of nodes in the network. A difference of almost 90% is detected in 500 end node scenario.

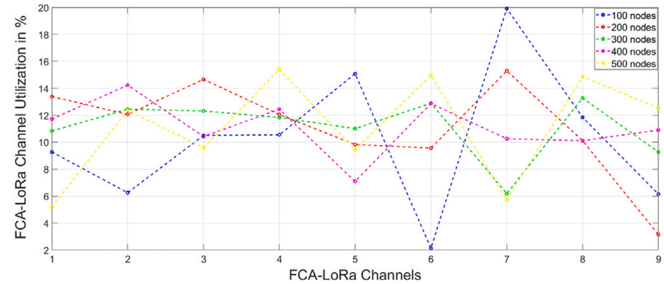

Fig. 13. Channel utilization in a multi gateway LoRaWAN scenario.

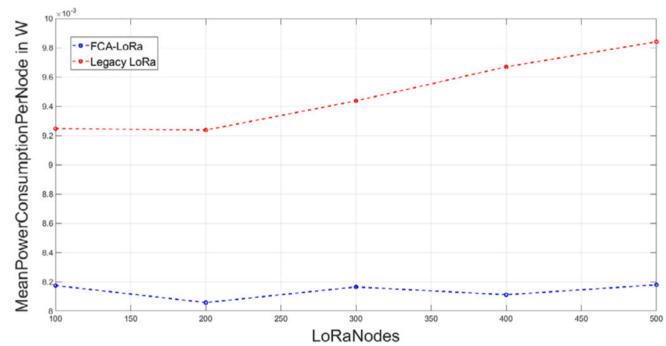

Fig. 14. Mean power consumption per LoRa node in W in a multi gateway LoRaWAN scenario.

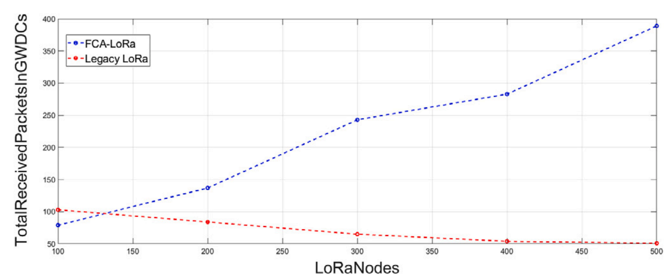

Fig. 15. Total received LoRa packets in GWDCs in a multi gateway LoRaWAN scenario.

FCA-LoRa focuses on efficiently managing the involved network resources, without wasting any chances for transmission. Due to the enforced GWDCs, FCA-LoRa leverages a high channel utilization favouring multiple gateway scenarios. This assumption can be verified in Fig. 13. It is shown that FCA-LoRa utilizes almost equally all available channels for listening and transmissions as well.

Moreover, due to the almost continuous listening in available frequency channels by LoRa end devices, FCA-LoRa could raise concerns regarding energy consumption. However, as presented in Fig. 14, the overall mean power consumption is detected to be less than the amounts consumed in the Legacy LoRaWAN scenario, throughout all simulation scenarios. This is possible considering the employment of the CSMA-CA model that improves collision avoidance, as well as the specific scheduling procedure in each LoRa node, avoiding any unnecessary re-transmissions and aggravating radio mode changes.

Last but not least, an estimation of the average amount of packets received during all GWDCs is presented in Fig. 15. It is obvious that a considerable increase occurs in successful packet transmission to all gateways in the network, while the number of end devices participating increases.

Despite the randomness in the communication parameters selection, as well as the distances and location of the LoRa end devices in all scenarios, FCA-LoRa has proven to perform better than the Legacy

LoRaWAN scheduling mechanism, despite the utilization of the ADR mechanism.

8. Conclusions

In this paper we presented, implemented, and evaluated FCA-LoRa, a novel MAC protocol towards improving reliability and collision avoidance in LoRa wide-area networks. This novel scheduling process is based on the broadcasting of beacon frames by the network's gateway in order to synchronize communication with end-devices and the ability to optimize channel utilization by employing different SFs. As shown by our simulations in OMNeT++, FCA-LoRa upgrades the performance of the traditional LoRaWAN scheduling method in terms of throughput and collision avoidance. Going forward, we will study energy consumption parameters and further optimize network performance of the FCA-LoRa scheme for multiple gateway scenarios.

CRediT authorship contribution statement

Anna Triantafyllou: Conceptualization, Methodology, Software, Validation, Writing - original draft, Formal analysis. **Panagiotis Sarigiannidis:** Supervision, Project administration, Writing - review & editing, Resources. **Thomas Lagkas:** Writing - review & editing, Formal analysis, Resources, Validation. **Ioannis D. Moscholios:** Writing - review & editing, Resources, Validation, Visualization. **Antonios Sarigiannidis:** Investigation, Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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