Radio Resource Optimization for Spectrum-Aware LoRa Secondary System

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***Abstract*—The implementation of the IoT (Internet of Things) concept unleashed the race for adequate wireless communications. The Low Power Wide Area Networks (LPWAN), where LoRaWAN is one of the most adopted, are flourishing to satisfy the requirements of IoT devices in regard to power efficiency and long-distance connections. In this context, network operators are competing for a new spectrum to satisfy the quick proliferation of LPWAN networks and some of them are even calling to put up the unlicensed band for sale in order to exploit the newly vacant spectrum. This scenario could put into jeopardy the LoRa technology, which operates within the unlicensed band unless a way is found that allows the coexistence of LoRa as a secondary network with other primary licensed technologies in the same area of interest and without decreasing the LoRa network performance. Our study assumes that a spectrum map is periodically given by a network of sensors having cognitive radio capabilities, in such a way that the LoRa network has the ability to use a different set of frequencies in every geographical sub-zone. We show that the overall LoRaWAN network throughput can be improved when the communication parameters in terms of frequencies and spreading factors are dynamically allocated. An optimization problem is formulated, taking in account both the spectrum map and the radio conditions of the LoRa end nodes, and generating an optimal resource allocation. Numerical results and system level simulations confirm that a LoRaWAN network with such spectrum-aware capabilities outperform the classical static deployment.**

Keywords—IoT, LPWAN, LoRa, Optimization, CR.

I. Introduction

Wireless spectrum is a scarce and precious communication resource. Radio spectrum regulators are facing several challenges due to spectrum scarcity caused not only by increased demand but also by inefficient management of this resource. Cognitive radio (CR) technology has been proposed as a means to improve the spectrum utilization by allowing a secondary network to share the wireless spectrum without purchasing the spectrum license of a primary network. In addition, users of the secondary network can reuse the unused chunks of a primary licensed spectrum (spectrum holes) under the condition of not introducing a harmful interference to the primary services.

On the other hand, the rapid growth of the internet of things (IoT) will necessitate in the near future, the connection of more than 20 million devices through wireless communications. Many innovative technologies, like Low Power Wide Area Network (LPWAN), are flourishing to satisfy the requirements of the upcoming increase of IoT devices. One of the most adopted LPWAN solutions is the long-range (LoRa) technology, which is considered by a large number of industries as a base for their IoT applications. LoRa has advantages in terms of battery lifetime (around 10 years), long communication range (2-5 km in urban areas and 15 km in suburban areas) and cost. Thus, LoRa is perfectly suitable for the IoT applications that only need to transmit tiny amounts of information in a long-range.

Many operators aim to convert the unlicensed frequency band where LoRa is operating, to a licensed band in order to exploit the newly vacant spectrum for new applications and services. In fact, the Federal Communications Commission (FCC) issued during 2013, an Order authorizing Progeny LMS, LLC (Progeny) to commence commercial operation of its position location service network in the 902-928 MHz band, to deploy a highly accurate location service to improve the delivery of emergency services (911) that can bring significant public safety benefits [1]. After obtaining the authority, Progeny can transmit with much higher power levels and therefore may cause interference to a variety of unlicensed operations in this band, such as automatic meter reading (AMR) systems, LoRa end-devices, and others. The FCC action came under vigorous objection from the companies that use this unlicensed band, even though the FCC stated that the use of this band will be subject to constraints of not causing "unacceptable levels of interference" to licensed and unlicensed devices.

We should think about the co-existence between licensed and unlicensed users within the same band with respect to the legal right of licensed users (Primary Users). LoRa unlicensed devices are expected to be tremendously affected by the new regulation if it becomes a reality. Therefore, LoRa regulators will be urged to take reasonable steps to minimize, avoid, or remedy interference that their devices could introduce or receive. The viewpoints of several key players; regulators, standardization bodies, economic/business communities, industrial partners and companies, present a conflict of interest

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that could be compromised by the use of CR technology. Briefly, CR allows a secondary user (SU) to scan and search the licensed spectrum for spectrum holes that might be available for opportunistic usage. In this context, the LoRa network could benefit from CR technology to be tightly coupled with real-time spectrum awareness in a way that allows LoRa end-devices to operate alongside the primary user (PU) systems. Primary system can be any licensed service having the regulatory authority to work within the 868 MHz or 915 MHz bands.

The goal of this paper is to investigate the performance and scalability of LoRa technology in a predicted situation where LoRaWAN shares frequency bands with a primary system. Section II provides a preliminary description of LoRaWAN technology. Section III represents some contributions to the literature relevant to LoRaWAN performance evaluation and design. In Section IV, we describe our theoretical model and its corresponding network components, which will be used in Section V for problem formulation. Section VI outlines and discusses the experimental results. Finally, Section VII concludes the paper.

II. LoRa Technology Description

LoRa (short for long range) is a proprietary digital communication technology developed by Cycleo of Grenoble, France, and acquired by US-based Semtech in 2012 [2]. From a technical point of view, the LoRa solution is divided into two major components. The first one is the LoRa physical layer, which describes a special modulation technique based on CSS (Chirp Spread Spectrum). The second component is the LoRaWAN protocol, which is an open LPWAN standard defining the medium access (MAC) and network layer and is maintained by the LoRa Alliance.

A. LoRa physical level

The LoRa modulation is located at the physical layer of the LoRaWAN protocol. This modulation operates in the Sub-GHz ISM (Industrial, Scientific, and Medical) band at 868 MHz (Europe) and 915 MHz (North America) unlicensed bands and provides bidirectional communication. Several parameters are available to customize the LoRa modulation: **(1)** ***Channel Bandwidth (BW)*** typical values are 125, 250 and 500 kHz in the HF ISM 868 MHz (Europe) and 915 MHz (North America) bands [3]. **(2)** ***Spreading Factor (SF)*** defines the ratio between the chip rate and symbol rate, i.e., $SF=\log2(Rc/Rs)$. The SF tells "how much" the reference signal is spread in time. The higher the spreading factor, the longer the range but the slower the transmission. Accordingly, there is a trade-off between SF and communication range. There are six configurable spreading factors: SF=7 (128 chips/symbol) to SF=12 (4096 chips/symbol) [4]. **(3)** ***Coding Rate (CR)*** is introduced optionally to improve the robustness of the transmitted signal and can be chosen from a set of different values (4/5, 4/6, 4/7, 4/8). **(4)** ***Transmission Power (Ptx)*** must comply with rules and restrictions specified by regional regulators, e.g., in Europe maximum *Ptx* is limited to 14 dBm, whereas in the USA it is limited to 20 dBm.

B. LoRaWAN Network Architecture

LoRaWAN is an open communication protocol developed by the LoRa Alliance that uses the LoRa modulation at the physical level. The architecture of the LoRa communication system includes the end-nodes, gateways, network server and the application server with which the user is interacting. LoRaWAN networks are organized in a star-of-stars topology, where gateways collect packets transmitted by end-nodes and forward them to the network server. These main components are defined in the specification and are required to form the LoRaWAN network: **(1)** ***End nodes/devices*** are the low-power sensors that send data to multiple gateways over single-hope LoRa communication. Thus, they are not associated with a specific gateway. **(2)** ***Gateways*** are the intermediate devices, which serve simply as a link-layer relay and forward the received packets to the core network. **(3)** ***Network server*** is assigned the management responsibility of the data flows, as it holds all the intelligence of the network. It filters the duplicated packets which can be received by multiple gateways, checks security by authenticating the data to make sure that there are no replay attacks, sends ACKs to the gateways, forwards the packets to the corresponding application server and chooses the appropriate gateway for sending back a reply if any. **(4)** ***Application Server*** is responsible for the device "inventory" part of a LoRaWAN infrastructure, handling of join-request and the encryption of application payloads.

C. Medium Access Technique

The mechanism of access adopted by LoRaWAN is a specific ALOHA type access. Hence, there is no collision avoiding mechanisms like Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) used by LoRaWAN MAC protocol. Instead, the collision mitigation mechanism is implemented through regulation by defining the transmitter duty-cycle (channel occupancy) limits and by implementing a pseudo-random channel-hopping technique.

LoRaWAN defines three types of end nodes with different capabilities to address the various needs of applications. These classes present different trade-offs between network downlink communication latency versus battery life; ***Class A end-devices*** are battery-powered sensors, use pure Aloha channel access for the uplink and can only receive downlink data immediately after a successful uplink transmission. ***Class B end-devices*** are battery-powered actuators, they can receive additional downlink data at a scheduled fixed time interval. ***Class C end-devices*** are typically mains-powered actuators and open a continuous receive window except when they transmit.

III. Related Work

Over the past few years, trends were shifting to the adaptability of cognitive radio technology into the IoT concept. Many researchers envisioned that future IoT objects should have a cognitive capability to search for opportunistic spectrum access while protecting primary users from interference. In this context, Khan et al. [5] discuss how CR technology could sustain the growing challenge of IoT paradigm by providing continuous spectrum functionalities, as long as requirements such as channel allocation, protocol design, energy harvesting and resource management are satisfied. It means that IoT objects should have the cognitive capability to think, learn, and capture the spatio-temporal spectrum usage.

Paradoxically, Debroy et al. [6] found useless to incorporate the traditional CR capability into IoT devices as the level of spectrum sensing adds a considerable time and power overhead on the already constrained IoT devices. Thus, dynamic spectrum access and sharing based protocols have been proposed to meet the growing demands of the emerging IoT networks, by exploiting dedicated spectrum sensors that capture the presence of primary incumbents and draw periodically a spectrum map to aid secondary IoT communications.

On the other hand, most of the studies in the literature concerning the LoRaWAN network mainly target the performance level assessment, by analyzing the number of packet collisions and thus find out the capability of this technology to form the high density, large-scale architecture related to the number of nodes that could be supported.

Mikhaylov et al. [7] analyzed and assessed the strengths and weaknesses of LoRaWAN technology in terms of key performance metrics defined by energy efficiency, scalability, and coverage. Authors show that following the current specification release, LoRa can effectively assure high coverage and acceptable scalability under low uplink traffic and finally concluded that LoRa is suitable for applications that do not impose strict latency and need very low traffic devices.

The work in [8] introduces a simulator for LoRaWAN named LoraSim. Experiments that describe LoRa communication behavior, were used to parameterize the LoraSim in order to study network performance including transmission latency and data extraction rate, besides the limit regarding the number of nodes a LoRa system can support. It has been shown that dynamic transmission parameters selection and the introduction of more gateways could considerably enhance the scalability. The simulator LoraSim is further adapted and modified by Lavric et al. [9] to assess the performance level of the LoRaWAN technology by analyzing the number of packet collisions that can occur, and subsequently determine the maximum number of nodes that can communicate on a channel considering the duty cycle restrictions. On the other hand, Cesana et al. [4] introduced a mathematical framework that could be adopted by LoRaWAN network providers to optimize the network cost layout as a wireless segment and backhaul links at design time.

Finally, Ferran et al. [3] provided an impartial and independent overview of what are the capabilities and limitations of LoRaWAN networks, in order to avoid the over-use of the technology in scenarios where it does not fit. From the authors' point of view, LoRaWAN could not meet the requirements of all use cases as each application has specific constraints in terms of reliability, maximum latency, and transmission pattern. Furthermore, the authors considered that many factors could limit LoRaWAN large-scale deployments, particularly the duty-cycle regulations and the non-guaranteed Aloha-based access.

The aforementioned articles pay particular attention to the current LoRaWAN state-of-the-art in terms of performance evaluation and capacity optimization, where a pseudo-random channel hopping method is natively used to distribute transmissions over the pool of available channels, in order to reduce the collision probability. However, in this work, we verify that an adaptive channel hopping sequence could increase the throughput by distributing the available channels according to an optimized method.

IV. System Model And Network Components

The proposed system consists of a large geographic area where IoT LoRa devices coexist with a primary system. To visualize the spectrum utilization at the geographical region, an independent collection of sensors with cognitive radio capabilities (CR sensors) are deployed to periodically sense primary activity and create a spectrum map (Fig. 1).

A. *Primary network*

In this work, the primary network is organized in small cells where each one is served by a base station that assures the communication of primary users over the expected licensed band 868 MHz or 915 MHz. The primary network has prioritized access to the licensed spectrum and operates independently of the secondary devices.

B. *Secondary LoRa network*

The LoRa end-devices are connected through a single-hop to one gateway, which in turn is connected to a core network server via a standard IP network. LoRa devices try to use channels not being used by primary users (white spaces). Therefore, these devices should have a clear knowledge of the spectrum map in the area of interest, which poses significant challenges and requires careful considerations. Subsequently, providing LoRa devices with cognitive radio sensing capabilities can deteriorate the primary characteristic of this technique concerning the battery lifetime, as the sensing operation consumes a lot of energy. For this reason, the LoRa nodes are not cognitive radio enabled and thus have no spectrum sensing capability.

C. *Spectrum Occupancy Map*

The spectrum sensing capabilities will be dedicated to a collection of CR sensors which sense periodically the pool of channels used by primary users for any activity. The Spatio-temporal spectrum map captured periodically by CR sensors is a multi-dimensional representation of spectrum utilization [10-11], which divides the area of interest into zones where LoRa devices are allowed to use the spectrum holes for a specific period of time according to long-term measurements of spectrum occupancy characteristics. Spectrum map accuracy depends on the number and orientation of the sensor locations.

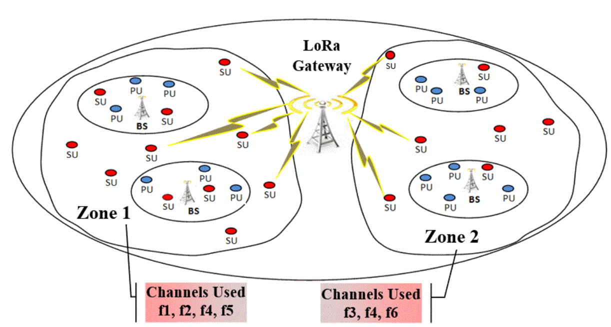


Fig. 1. Schematic terrain sample with Primary System and Secondary LoRa transmitter/receiver.

Although our system model will utilize any such map construction techniques, their design and implementation are beyond the scope of this paper.

A dedicated command control channel (CCC) could be used to ensure the establishment of sensor-to-sensor and sensor-to-device communication. The control channel's details in terms of frame structure are properties of a medium access control (MAC) protocol and can be integrated with any of the state-of-the-art wireless MAC protocols [6].

V. Problem Statement And Formulation

We address the problem from the perspective of a LoRaWAN network provider who seeks a way to optimize the overall throughput of its network, which works beside a primary network.

D. Success Probability

When a LoRa end-device has a packet to be sent, it randomly selects one of the available channels and transmits. This access mechanism is a specific Pure ALOHA type access and consequently, there is a need to define its throughput and the successful frames transmission rate. Thus, let T refers to the time needed to transmit one frame on the channel, and let's define "frame-time" as a unit of time equal to T. We define G as the average number of packets generated during the considered frame-time interval by a group of end-devices which collectively form an independent Poisson source with an aggregate mean packet generation rate of λ packets/s.

$$G = \lambda T \tag{1}$$

In Pure ALOHA, the probability that a single transmission is successfully performed is P_{suc} as it was shown in [12]:

$$P_{suc} = e^{-2G} \tag{2}$$

Hence, the normalized throughput S is given by:

$$S = G\, e^{-2G} \tag{3}$$

This model generates results that approximate the real deployments for LoRaWAN with an unacknowledged configuration when there is only uplink transmission without the answer from the gateway [13], and therefore, the LoRa layer is considered as a protocol without retransmissions where nodes emit packets independently of each other.

The throughput is limited by the collisions of simultaneous transmissions under the condition of selecting the same SF, BW and carrier frequency (CF); no capture effect is considered. Moreover, the SF parameters used during the LoRa modulation are orthogonal, making the simultaneous transmission of two end-devices with different SF (and same CF and BW) successfully decoded.

Let us consider that the gateway in collaboration with the implemented network of CR sensors is able to specify in each zone the allowed frequencies and to classify the traffic generated by end-devices according to their distance to the gateway. Moreover, we assume that each group of end-devices having the same distance to the gateway will be using the same SF, which is appropriate to that distance. An important consequence of using a higher spreading factor for LoRa is a longer frame-time transmission, aka Time on Air (ToA). Therefore, the LoRa radio module needs more time to send the same amount of data. Our effort will be focused on optimizing the distribution of traffic among available frequencies and seek an adaptive way to assign spreading factors.

E. Optimization Model

Let us define $I = \{1, 2, \dots, m\}$ to be the set of zones indices defined periodically by the network of CR sensors after drawing the spectrum map. LoRa end-devices that coexist in each zone are allowed to use some frequencies that do not affect the licensed primary user. Let us define $J = \{1, 2, \dots, n\}$ to be the pool of frequencies. Traffic created by these end-devices is classified in each zone depending on their geographical position. Each end-device performs uplink transmissions using one spreading factor in the set $SF = \{7, \dots, 12\}$ which corresponds to the six SF values defined in LoRaWAN specification. Accordingly, the ToA is directly affected by the choice of LoRa modulation parameters such as SF, BW and CR. Without loss of generality, we assume that the packet size used in the uplink transmissions is fixed and common to all the LoRa end-devices, besides fixed values for BW and CR. Subsequently, the transmission delay depends only on the assigned SF and is characterized by a T_k delay for $k \in SF$ (see Table I).

It is further convenient to define the set λ_i, which indicates the packet arrival rate in zone i. Sets I, J and λ_i are generally known by the network provider due to the spectrum map drawn by CR sensors comprising the environmental sensing capability. Let us further define decision variables $\boldsymbol{a_{ijk}}$ to model the assignment of a portion of traffic rate $\boldsymbol{\lambda_i}$ in zone $\boldsymbol{i}$ over the frequency $\boldsymbol{j}$ using spreading factor $\boldsymbol{SF_k}$. Accordingly, we could approximate the LoRaWAN network throughput by the superposition of a set of independent Aloha-type access networks characterized by the number of channels and the SFs. Based on this, we could build the objective function that represents the throughput over all the area of interest, by first considering the traffic generated during the transmission time interval, within all zones when it is assigned and transmitted over an allowed frequency and a suitable spreading factor.

$$G_{jk} = \sum_{i=1}^{m} a_{ijk}\, \lambda_i\, T_k \tag{4}$$

According to Equation (3), the total throughput (successful traffic) will be as follows:

$$\sum_{j=1}^{n} \sum_{k=7}^{12} G_{jk}\, e^{-2G_{jk}} \tag{5}$$

Consequently, the problem of maximizing LoRa throughput (packets/s) over the geographical area could be achieved by maximizing the objective function formulated as follows:

TABLE I
LoRa Time on Air example[1]

BW = 125KHz	**Spreading Factor**	**Time on Air, T_k (ms)**
CR = 1	7	56.58
Payload Length = 20 bytes	8	102.91
CRC enabled	9	185.34
Explicit Header enabled	10	370.69
$n_{preamble} = 8$	11	741.38
	12	1318.91

[1]Online tool to calculate Time on Air: *https://www.loratools.nl/#/airtime*

- Objective function:

$$max\ \sum_{j=1}^{n}\sum_{k=7}^{12}\left(\sum_{i=1}^{m} a_{ijk}\lambda_i\right)e^{-2T_k\sum_{i=1}^{m} a_{ijk}\lambda_i} \quad (6)$$

- Subject to:

$$\sum_{j=1}^{n}\sum_{k=7}^{12} a_{ijk} = 1 \quad \forall i \in I \quad (7)$$

$$a_{ijk}=0 \quad \text{if } f_j \text{ is not allowed in Zone } i, \quad \forall i \in I,\ \forall j \in J \quad \text{for } 7 < k < 12 \quad (8)$$

$$a_{ijk}=0 \quad \text{if } k < \text{Allowed } SF_i \quad \forall i \in I,\ \forall j \in J \quad \text{for } 7 < k < 12 \quad (9)$$

The objective function (6) tends to maximize the overall LoRa network throughput by assigning values to the decision variables aijk that are subject to a set of constraints. The set of constraints (7) enforces that the summation of all partial traffic rate ratio aijk created in zone i is equal to one for each zone. Constraints (8) further prevent the use of a set of frequencies in particular zones, and consequently their corresponding spreading factors. Constraints (9) enforce each group of nodes in zone i, located at a certain distance from the gateway, to use a spreading factor SFk or all its greater values. The last constraints are built on the fact that the sensitivity of a radio receiver increases if the SF increases [8], and thus if an SF could be used then all its greater values could also be used at the cost of having greater ToA, hence more probable collisions.

VI. Performance Evaluation

Our proposed model will be evaluated by considering a reference area where nodes are positioned around a single gateway. We assume that the independent CR sensors network, which draws periodically the spectrum map, splits the reference area at a given time into four zones and specifies for each zone the frequencies that are allowed to be used from a pool of six channels. The proposed framework is general and does not depend on specific assumptions on the propagation model, transmitted power and sensitivity model. Our model was first justified numerically by comparing the optimization output of our model vis-à-vis a simple and straight forward distribution of the generated traffic over the available frequencies. Afterward, the improvement introduced to the overall throughput was verified by simulation.

A. Numerical Evaluation

In the following evaluation, we formulate the objective function (Eq. (6)) by the use of Pyomo package [14] which is a collection of Python software packages used for formulating and solving optimization models. Among the dozens of solvers supported by Pyomo, the IPOPT (**I**nterior **P**oint **OPT**imizer) solver has been chosen, as it is dedicated to solving an optimization problem where some of the objective functions or the constraints are nonlinear.

As previously mentioned, some parameters are plugged into our optimization framework such as the number of zones and frequencies used in each zone. Nodes within each zone are grouped according to their distance to the gateway (sub-zone), subsequently, these nodes could use a specific spreading factor or its above values. Additionally, traffic generated in each sub-zone (λ_i), which reflects the number of nodes, is supposed to be known. The selected values are chosen arbitrarily and the numerical results obtained demonstrate that the proposed approach leads to a network configuration with superior performance in terms of system overall throughput.

Fig. 2 illustrates the throughput vs. traffic demand and reports the improvement introduced by the optimization method over the simple method of distributing the traffic equally among the available frequencies and SFs. The traffic demands were assumed to be identical in all zones. It is shown that this enhancement increases as the total packet arrival rate λ increases. Likewise, Fig. 3a & 3b illustrate the successful throughput while the traffic demand increases in sub-zones having higher SFs and lower SFs respectively. By increasing the number of users having higher SFs, the ToA of packets will increase, and then, the probability of having collisions will be definitely higher. Therefore, the successful throughput will decrease dramatically when the number of nodes increases in zones with higher SF. However, the optimization method outperforms in either scenario the classical distribution of traffic.

B. Simulation Evaluation

The proper assessment of the performance and scalability of LoRa networks was validated via simulations where the numerical results given by our proposed model were used to ensure that they are of practical relevance. Thus, the LoraSim simulator has been adapted and modified to comply with the designed scenarios. The LoraSim simulator was developed by M. Bor et al. [8]. It is a custom-build discrete-event simulator implement with SimPy. LoRaSim allows the placement of LoRa nodes in a 2-dimensional space with random distribution. Each LoRa node has a specific communication characteristic defined by transmission parameters; Transmission Power (TP), Carrier Frequency (CF), Spreading Factor (SF), Bandwidth (BW), and Coding Rate (CR). The simulation parameters used in the simulation model are shown in Table II. Furthermore, the evaluation of the scalability and performance of LoRa deployment is characterized by the Data Extraction Rate (DER). DER is defined as the ratio of the received messages to transmitted messages over a period of time [8], and therefore, it can be compared to the successful throughput delivered by our mathematical model.

TABLE II
LoRa Simulation Parameters

Simulation Parameters	Values
Carrier Frequency (*CF*)	868 MHz
Bandwidth (*BW*)	125 kHz
Spreading Factor (*SF*)	7 – 12
Coding Rate (*CR*)	4/5
Channel Pool	6 freq.
Payload (*PL*) Length	20 bytes
Header (*H*)	0
Preamble symbols (n_p)	8
Transmission power (P_{tx})	14 dBm
General Gains minus losses (*GL*)	0
Path loss exponent (γ)	2.08
Reference distance (d_0)	40 m
Path Loss at reference distance $Lpld_0$	127.41 dBm
Packet interval	20 secs
Individual Packet rate λ_{ind}	0.05 packet/s (1/20)
Simulation run / data point	86400000 ms (1 day)

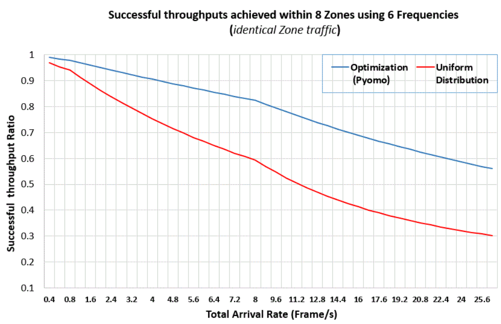
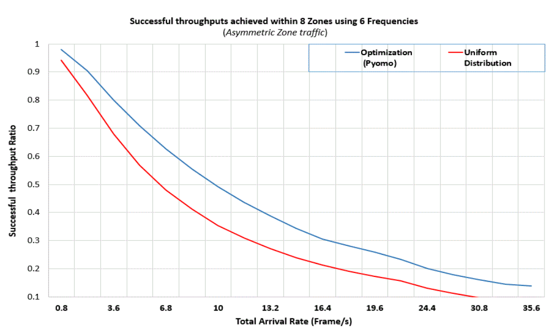


Fig. 2. Successful throughput ratio with identical zone traffic

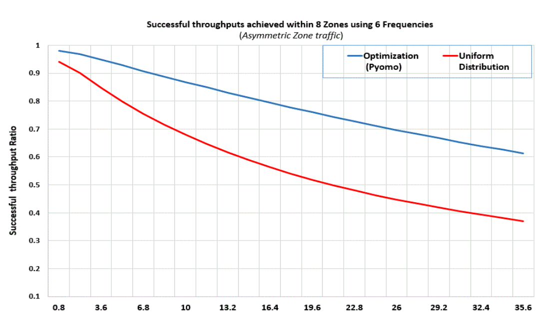
The Optimized traffic rate ratio (a_{ijk}) given by Pyomo were plugged into the simulator, to be used as weight (probability) for the selection of frequency and SF. The simulation results are identical to the numerical results, and precisely illustrate the better performance of LoRa network when the traffic is allocated according to the results of the optimization problem.

VII. CONCLUSIONS

Our study highlights the CR functionalities and analyses the performance level of a LoRa secondary system in terms of throughput and evaluating the number of nodes that can communicate using available primary channels while generating a total packet rate λ. We focused on LoRa as it is currently the most widely deployed emerging LPWAN technology and is considered by a large number of industries as a base for their IoT applications.



(a) Traffic generated in higher SF zones



(b) Traffic generated in lower SF zones

Fig. 3. Successful throughput ratio with asymmetric zone traffic

For this study, we modified the LoraSim simulator in order to integrate the optimization problem results formulated by the Pyomo package. In particular, we investigated the impact of selecting dynamic transmission parameters like carrier frequency and spreading factor based on Pyomo decision values output as the probability of selection. We verified the throughput improvement by simulation besides the numerical solution validation.

Adjusting the regulations related to ISM band by converting it to a licensed spectrum remains an open research issue. This modification will have a significant impact on the capacity of LoRa networks and will put into question their possible coexistence with a primary system within the same geographical area. Our future efforts will aim to explore new channel hopping algorithm instead of the native random hopping method used in LoRaWAN in order to distribute transmissions over the pool of available channels, in a way that maximizes the overall LoRa system throughput. Moreover, our simulation can be evolved by making it more realistic with the introduction of capture effect and duty cycle.

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