Large Scale LoRa Networks: From Homogeneous to Heterogeneous Deployments

Moises Nunez Ochoa *†, Luiz Suraty*, Mickael Maman * and Andrzej Duda†
*CEA, LETI, Minatec Campus, 17 rue des Martyrs, 38054 Grenoble, France
{moises.nunezochoa, luiz.suratyfilho, mickael.maman}@cea.fr
†Univ. Grenoble Alpes, CNRS, Grenoble INP, LIG, F-38000 Grenoble France
andrzej.duda@imag.fr

***Abstract*—LoRa technology has emerged as an interesting solution for Low Power Wide Area (LPWA) applications. The main LPWA research directions are about large scale networks to support massive number of devices, interference issues, link optimization and adaptability. Thus heterogeneous network deployments and Spreading Factor (SF) allocation strategies need to be studied. In this paper, we investigate the performance of homogeneous networks (i.e. when all the nodes select the same LoRa configuration) and heterogeneous networks (i.e. when each node selects its LoRa configuration according to its link budget or their needs) for large scale deployments (up to 10000 nodes per gateway). For that purpose we have developed a LoRa Module, based on improved WSNet simulator, including a spectrum usage abstraction, the co-channel rejection due to the quasi-orthogonality of SFs and the gateway capture effect. Simulation results show the performance comparison in terms of reliability, network capacity and power consumption for homogeneous and heterogeneous deployments as a function of the number of nodes and the traffic intensity. The comparison shows the benefits of the heterogeneous deployment where each node selects its configuration according to its link budget.**

I. Introduction

Over the past few years, new approaches called Low Power Wide Area (LPWA) networking technologies have emerged. These technologies define a new air interface that provides low power connectivity alternative to current generations of cellular systems (2G, 3G, and 4G), while covering large areas (typical range of 10 km). Several papers have reviewed the different LPWA technologies. For example, Raza et al. [1] surveyed standardization activities (IEEE, IETF, 3GPP, ETSI) as well as industrial ones around LPWA technologies (LoRa alliance, Weightless-SIG, Dash7 alliance). They identified potential research directions to address limitations and challenges of LPWA technologies such as a massive number of devices, link optimization, and adaptability. After giving an overview of LPWA and cellular technologies for IoT [2], the authors discussed the capabilities and limitations of LoRaWAN. Nevertheless, the potential of an adaptive LoRa solution in terms of spreading factor, bandwidth, transmission power, and topology is still not well studied or exploited. Thus, new protocols and strategies are required to improve LoRa scalability. The first step is to understand heterogeneous network deployments when devices use different spreading factor.

In this paper, we investigate homogeneous (i.e. when all the nodes select the same LoRa configuration) and heterogeneous deployments (i.e. when each node selects its LoRa configuration according to its link budget or their needs) for a large number of devices (up to 10000 nodes per gateway).In order to evaluate performance, we have developed an accurate model of the PHY/MAC LoRa based on the extended WSNet simulator. The LoRa model takes into account spectrum usage, co-channel rejection due to quasi-orthogonality of the LoRa spread-spectrum modulation, and the gateway capture effect. The simulation results give an insight on reliability, network capacity, and energy consumption for homogeneous and heterogeneous deployments as a function of the number of nodes and traffic intensity.

The article is organized as follows. Section II gives a short overview of the LoRa technology and provides the state of the art on LoRa experimental measurements and simulations, LoRa limitations, and network deployment strategies as well as motivations. Section III presents the developed LoRa WSNet based simulator and the deployment scenarios. Section IV analyzes performance in terms of packet delivery ratio, throughput, and power consumption. Section V concludes the article and gives some ideas for future work.

II. Related Work

A. LoRa Overview

In this section, we give a short overview of the LoRa physical layer parameters. LoRa specification [3], [4] and technical documents [5], [6], [7], [8] contain more detailed information.

1) Bandwidth (BW): is the range of frequencies available for transmission. Larger BW increases the data rate but decreases sensitivity. Typically, BWs are 125 kHz, 250 kHz, and 500 kHz. However, Semtech SX1276 offers BW configurations from 7.8 kHz to 500 kHz.

2) Carrier Frequency (CF): is the central frequency in a band. For our study, we consider the 868 MHz band.

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3) Coding Rate (CR): characterizes resilience to transmission errors. Higher CRs result in better robustness, but increases the air time. LoRa supports CR of 4/5, 4/6, 4/7, and 4/8.

4) Spreading Factor (SF): is the ratio between the chip rate and the symbol rate. For a given SF, there are 2^{SF} chips per symbol. SF can be selected between 6 and 12, where SF12 presents the highest sensitivity and the longest range, but the lowest data rate.

B. From Experimental Measurements to Simulations

Some authors deployed LoRa networks and experimentally studied its performance [9] [10] [11] [12] [13]. The measurements were done in city centers, tactical troop tracking, and sailing monitoring systems. Nevertheless, experimental results in real life networks are not reproducible and MAC layer optimization is difficult. Blenn et al. [14] performed simulations based on traces from experiments and analyzed results based on real life and large scale measurements from The Things Network but their simulations are limited to the deployed scenario. To and Duda [15] presented LoRa simulations in NS-3 validated in testbed experiments. They considered the capture effect and showed the reduction of the packet drop rate due to collisions with a CSMA approach. In a system level simulator, Haxhibeqiri et al. [16] studied the scalability for LoRaWAN deployments in terms of the number of nodes per gateway. Simulations are performed for a duty cycle of 1% but they are limited to 1000 nodes.

We developed a LoRa simulator to compare the performance in different deployment scenarios for large scale networks based on an accurate model of the LoRa PHY/MAC layers. We simulate several deployment scenarios varying traffic intensity and the number of nodes.

C. LoRa Evaluation and Limits

Several authors evaluated performance and limits of LoRa networks. Reynders et al. [17] evaluated Chirp Spread Spectrum (CSS) and ultra-narrow-band networks. They proposed a heuristic equation that gives Bit Error Rate (BER) for a CSS modulation as a function of SF and Signal to Noise Ratio (SNR). Cattani et al. [18] evaluated the impact of the LoRa physical layer settings on the data rate and energy efficiency. They evaluated the impact of environmental factors such as temperature on the LoRa network performance and showed that high temperatures degrade the Packet Delivery Ratio (PDR) and Received Signal Strength (RSS). Goursaud et al. [19] studied the performance of the CSS modulation. They showed the possibility of interference between different SFs and evaluated co-channel rejection for all combinations of SFs. Feltrin et al. [20] discussed the role of LoRaWAN for IoT and showed its application to many use cases. They considered the effect of non perfect orthogonality of SFs for a link level analysis. Petajajarvi et al. [21] analyzed the scalability of a LoRa wide area network and showed its good coverage (e.g. until 30km on water for SF12 and transmit power of 14 dBm). They also showed the maximum throughput for different duty cycles per node per channel. Mikhaylov et al. [22] discussed LoRa performance under European frequency regulations. They studied the performance metrics of a single end device, then the spatial distribution of several end devices. They showed LoRa strengths (large coverage and good scalability for low uplink traffic) and weaknesses (low reliability, delays, and poor performance of downlink traffic). Bor et al. [23] presented a capability and performance analysis of a LoRa transceiver and proposed LoRaBlink protocol for link-level parameter adaptation. Nunez et al. [24] analytically showed the potential gain of adaptive LoRa solutions that choose suitable radio parameters (i.e., spreading factor, bandwidth, and transmission power) to different deployment topologies (i.e., star and mesh).

These studies provide a first view of LoRa performance and its limitations. As a conclusion we need to take into account the capture effect and imperfect orthogonality of SFs. We contribute with an accurate LoRa simulation model considering the co-channel SF interference and the gateway capture effect, allowing accurate performance analysis in large scale simulations for different deployment scenarios. Our study extends the previous evaluations of LoRa limits with the evaluation of reliability, network throughput, and power consumption from sparse to massive access deployment scenarios.

D. LoRa Network Deployment Strategies

Some authors studied LoRa network deployments and SF allocation strategies. Bor et al. [25] studied LoRa transceiver capabilities and the limit supported by LoRa system. They showed that LoRa networks can scale if they use dynamic selection of transmission parameters. Georgiou et al. [26] investigated the effects of interference in a network with a single gateway. They studied two link-outage conditions, one based on SNR and the other one based on co-SF interference. They showed, as expected, that performance decreases when the number of nodes increases and highlighted the interest of studying spatially heterogeneous deployments. Croce et al. [27] showed the effect of the quasi-orthogonality of SFs and found that overlapped packet transmissions with different SFs may suffer from losses. They validated the findings by experiments and proposed SIR thresholds for all combinations of SFs. They remarked that LoRa networks cannot be studied as a superposition of independent networks because of imperfect SF orthogonality. Abeele et al. [28] studied the capacity and scalability of LoRaWAN for thousands of nodes per gateway. They showed the importance of considering the capture effect and interference models. They proposed an error model from BER simulations to determine communication ranges and interference. They also analyzed three strategies of network deployments (random SF allocation, a fixed one, and according to related PDR), the last one presenting the best performance. Lim et al. [29] analyzed the LoRa technology to increase packet success probability and proposed three SF allocation schemes (equal interval based, equal area based, and random based). They found that the equal area scheme results in better performance compared with other schemes because of the reduced influence of SFs.

The state of the art indicates the interest in heterogeneous deployments and SF allocation strategies. Thus, we analyze homogeneous and heterogeneous deployments with different SF allocations as a function of the number of nodes and traffic intensity in order to show network performance and the benefits of heterogeneity for large scale networks.

III. LoRa Simulation Model in WSNet

We use an accurate and realistic WSNet-based simulator [30] written in C/Modern C++ under CeCILL free license. WSNet is a modular event-driven wireless network simulator that implements the required communication protocol layers and simulates the network behavior with a high level of accuracy. We have extended the simulator in several aspects (e.g., spectrum use, interference, capture effect) to take into account flexibility and specificity of the LoRa PHY/MAC layers.

A. Spectrum

To support PHY layer heterogeneity and flexibility, we have modified the core of the WSNet simulator by including a spectrum model. This new core is inspired by Baldo et al. [31] to provide a support for modeling the frequency-dependent aspects of communications. Moreover, it exploits the spectrum in terms of spectral resources instead of logical channels. It provides more accurate PHY models (several waveforms with different configurations) and a more accurate interference model for heterogeneous simulations. Thus, we can evaluate different configurations of LoRa network (e.g., SF, BW, channel) for different homogeneous and heterogeneous deployments. Furthermore, it permits the evaluation of inter-technology interference (from a non LoRa technology), not presented in this article for space reasons.

B. LoRa Modulation

The LoRa modulation is an adaptation of the CSS modulation. Its advantages are low power transmissions and channel robustness. LoRa features seven orthogonal SFs from SF6 to SF12. Symbol duration T_s and bit rate R_b are defined as follows:

$$T_\mathrm{s} = \frac{2^{SF}}{BW} \tag{1}$$

$$R_\mathrm{b} = \frac{SF}{T_\mathrm{s}} CR = \frac{SF.BW}{2^{SF}} CR \tag{2}$$

We have developed a LoRa modulation module inspired by the Equation 3 presented in [17]. This equation shows BER as a function of SF and the energy per bit to noise ratio $\frac{E_\mathrm{b}}{N_0}$:

$$BER_\mathrm{CSS} = Q(\frac{log_{12}(SF)}{\sqrt{2}} \frac{E_\mathrm{b}}{N_0}) \tag{3}$$

where $Q(x)$ is the Q-function.

C. Spreading Factors Orthogonality

We have developed an interference module taking into account the effect of the quasi-orthogonality of SFs. It uses the values for co-channel rejection for all combinations of the desired signal SF_d and the interferer signal SF_i [19] presented in Table I.

TABLE I
Co-channel rejection [dB] for all combinations of SFs.

$SF_d \backslash SF_i$	6	7	8	9	10	11	12
6	-6	12	14	16	16	26	18
7	21	-6	16	18	19	19	20
8	24	24	-6	20	22	22	22
9	27	27	27	-6	23	25	25
10	30	30	30	30	-6	26	28
11	33	33	33	33	33	-6	29
12	36	36	36	36	36	36	-6

D. LoRa SX1276 and SX1301 Transceivers

The Semtech SX1276 transceiver provides high interference immunity while minimizing energy consumption [7]. Sensitivity ρ_dBm is defined according to the Semtech designer guide [5] as:

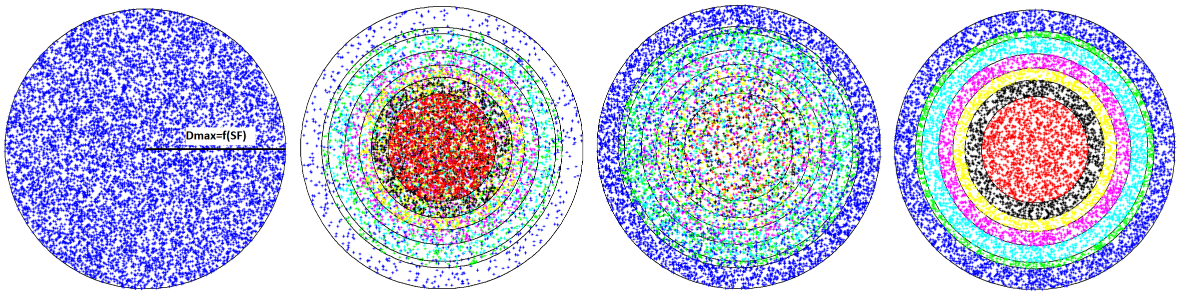
$$\rho_\mathrm{dBm} = -174 + 10log_{10}(BW) + NF + SNR, \tag{4}$$

where -174 accounts for the thermal noise effect,BW is the receiver bandwidth, NF is the receiver noise factor for a given hardware implementation, and SNR is the minimum ratio of the desired signal power to noise that can be demodulated. Table II shows sensitivity and the data rate for the SX1276 transceiver.

TABLE II
Receiver sensitivity and data rate for a bandwidth of 125 kHz and coding rate of 4/5. [7]

SF	Sensitivity[dBm]	Data Rate[kb/s]
6	-118	9.38
7	-123	5.47
8	-126	3.13
9	-129	1.76
10	-132	0.98
11	-133	0.54
12	-136	0.29

The Semtech SX1301 offers breakthrough gateway capabilities with a multi-channel high performance trans-



(a) SF_i Homogeneous (b) Multi-Homogeneous (c) Heterogeneous Random (d) Heterogeneous f(Dmax)

Fig. 1. Network Deployment Scenarios

mitter/receiver designed to simultaneously receive several LoRa packets with different SFs and up to 8 channels [8]. It enables robust communications for a large number of nodes spread over a wide range. In our simulator, we consider the gateway capture effect based on SX1301. The gateway may receive, depending on the reception power, several packets with different SFs because they are quasi-orthogonal with respect to each other. If the gateway receives two packets overlapped with the same SF, the gateway will receive the first detected packet if it is stronger by 6 dB.

E. MAC and Application Layers

Our simulator considers a LoRa random access method that basically behaves like ALOHA. The application layer manages the data traffic generation at each node inside a time window ”Application Period (AP)”. At every AP occurrence, each node picks randomly a time instant inside the current window, and a data packet is generated and sent to the lower layer (network or MAC). Hence, each node can generate only one data packet per AP. We vary AP between 60 s and 40 min to evaluate performance for different application use cases.

F. Deployment Scenarios

In this subsection, we present the network deployment scenarios and the SF allocation strategy in each scenario.

- In $\mathbf{SF_i}$ **Homogeneous**, nodes are uniformly deployed in a disk of radius equal to $D_{max}(SF_i)$, the maximum transmission range of SF_i (Figure 1(a)), and select the same LoRa configuration SF_i.
- **Multi-Homogeneous** is the superposition of independent SF_i homogeneous deployments (i from 6 to 12 and the corresponding radius $D_{max}(SF_i)$) with a single gateway at the center. The number of nodes are equally distributed between homogeneous networks. As each SF_i homogeneous deployment is independent and uniform, we can see in Figure 1(b) higher density close to the gateway.
- In **Heterogeneous f(Dmax)**, nodes are uniformly deployed in a disk of radius equal to $D_{max}(SF_{12})$, the maximum transmission range of SF12 and then, each node selects its configuration according to its link budget (i.e., with the maximum data rate or the minimum SF). As shown in Figure 1(d), some rings naturally appear. Nodes in the farthest ring are configured with SF12, in the next ring with SF11, and so on until the last disk with SF6.
- In **Heterogeneous Random**, nodes are still uniformly deployed in a disk of radius equal to $D_{max}(SF_{12})$ but they randomly select their configuration among the ones available according to their link budget. Hence, each node selects its LoRa configuration according to its budget link and its needs. For example, nodes in the third ring can randomly select their SF between SF10 and SF12 depending on their optimization criteria (e.g., energy consumption, data rate, reliability).

IV. Simulation Results

A. Deployment Scenarios and Assumptions

In this study, we have simulated the deployment scenarios described in Section III.F with a SX1301 gateway, at the center, configured with one single channel of 125 kHz and up to 10000 SX1276 nodes. Hence, the gateway can simultaneously receive up to 7 packets configured with different SF each (SF6 to SF12). Packets are dropped according to the modulation and interference models. Table III presents the simulation parameters. For sake of simplicity, we have considered the 868 MHz band and the Okumura Hata pathloss model.

TABLE III
Simulation parameters

Path-Loss Model	Okumura Hata
Frequency	868 MHz
Environment	open rural
Transmission Power	14 dBm
Spreading Factor	SF6 to SF12
Bandwidth	125 kHz
Coding Rate	4/5
Application Period (AP)	from 1 min to 40 min
Simulation Duration	100*AP
Number of Nodes	up to 10000
Payload Length	50 Bytes

B. Homogeneous Deployments Scenarios

In this subsection, we present the results of simulations for homogeneous deployments with different SFs as a function of the number of nodes (up to 10000) with AP set to 60 s (i.e., each node transmits a packet every minute). We have to emphasize that nodes are deployed in a disk of radius equal to the maximum transmission range of SF_i for each scenario, i.e. the Homogeneous SF6 in a disk of radius $D_{max}(SF_6)$ and so on.

Figure 2 shows PDR for homogeneous deployments with different SFs from 6 to 12. We can see that PDR decreases when the number of nodes increases. The SF6 Homogeneous deployment has better PDR compared with the others due to its short air time but its range is reduced.

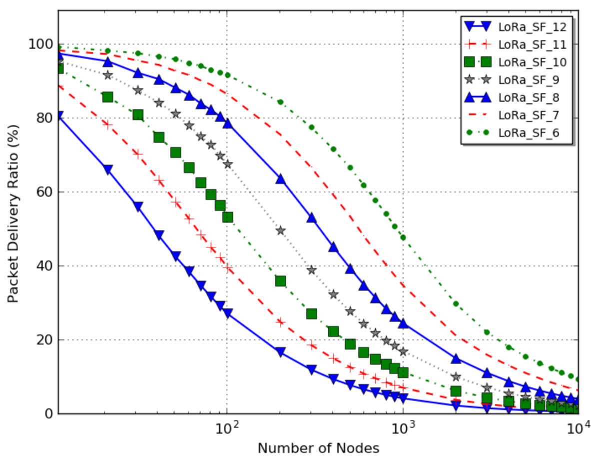


Fig. 2. PDR for Homogeneous deployments as a function of the number of devices generating a 50 Bytes packet each 60 s.

Figure 3 shows the throughput in packets per second for homogeneous deployments with different SFs. We can see that when the number of nodes increases, the throughput becomes saturated. The SF12 Homogeneous deployment converges faster and presents the lowest throughput due to its low data rate. Nevertheless, it presents the longest range.

We have extended the previous analysis by varying AP up to 40 min and we set the number of nodes to 10000. As shown in Figure 4, increasing the Application Period reduces the probability of collision, then PDR increases.

Figure 5 shows the throughput as a function of the Application Period. As we can observe, the throughput is higher when nodes use lower SF. Thus, in dense networks with high intensity traffic, we have to prioritize the use of the SF6 configuration. Nevertheless, it reduces the range and therefore, multi-hop communications or denser deployment with several gateways may be necessary to cover the same area.

Figure 6 compares the average power consumption per node for the homogeneous deployments as a function of the Application Period for a simulation time of

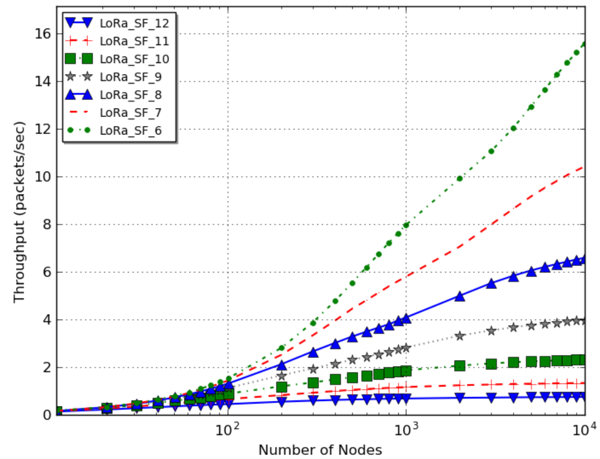


Fig. 3. Network Throughput for Homogeneous deployments as a function of the number of devices generating a 50 Bytes packet each 60 s.

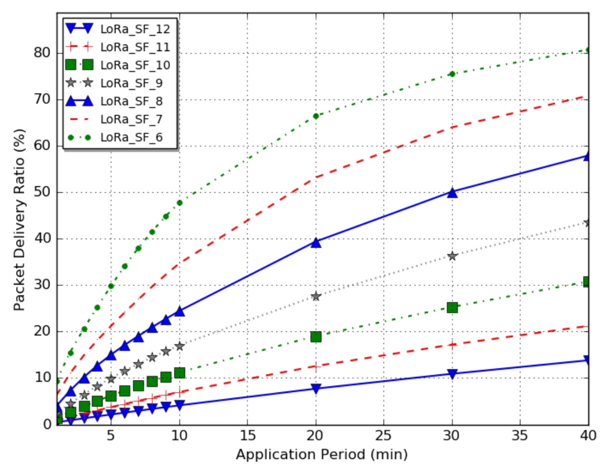


Fig. 4. PDR for Homogeneous deployments of 10000 nodes.

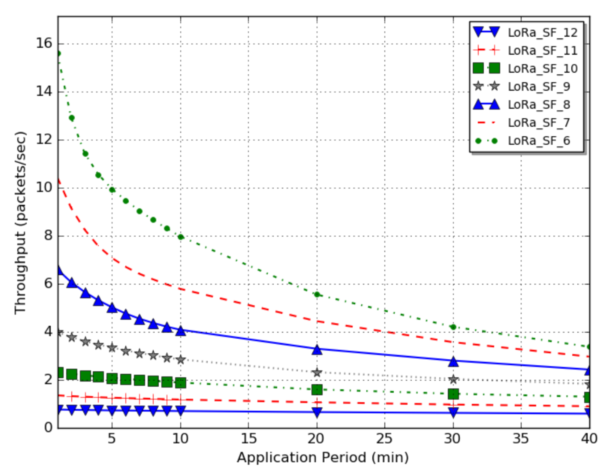


Fig. 5. Network Throughput for Homogeneous deployment of 10000 nodes.

100*AP. Increasing traffic intensity (e.g. AP from 40 min to 1 min) results in increased power consumption. SF6 configuration presents low consumption due to its shorter time on air. Higher consumption for the SF12 configuration due to its longer time on air.

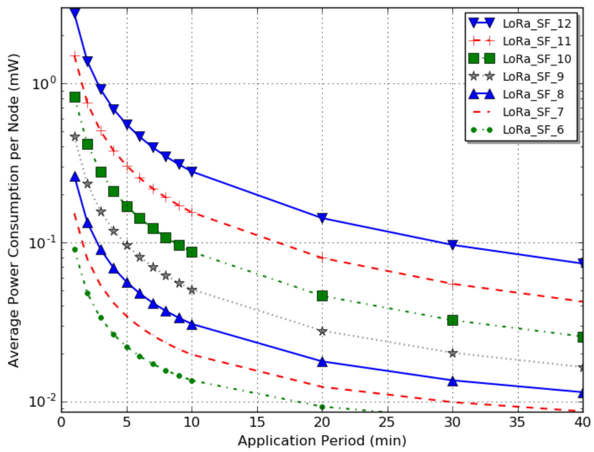


Fig. 6. Average Power Consumption for Homogeneous deployments configured with different SFs.

C. Heterogeneous vs. Homogeneous Deployment Scenarios

In this subsection, we compare the simulation results of the heterogeneous strategies with Homogeneous SF12 and Multi-Homogeneous deployments. Each deployment covers the same area (disk of radius $D_{max}(SF_{12})$). For homogeneous deployments, only Homogeneous SF12 is used for comparisons in order to keep the same cell coverage. We simulate the heterogeneous deployments with up to 10000 nodes and AP is fixed to 60 s.

Figure 7 compares PDR of homogeneous and heterogeneous deployments. The Heterogeneous f(Dmax) deployment presents the best performance. This is because in heterogeneous deployments we reduce packet-loss taking advantage of the quasi-orthogonality of SFs and the deployment strategy. For 100 nodes, the gain in terms of PDR for the Heterogeneous f(Dmax) deployment is 300% compared to the Homogeneous SF12 deployment. For the Multi-Homogeneous and Heterogeneous Random deployments, the gains are respectively 214% and 200%. A reliability of 20% is reached at 170, 360, 400 and 2600 nodes for the Homogeneous SF12, Heterogeneous Random, Multi-Homogeneous and Heterogeneous f(Dmax), respectively.

Figure 8 compares the network throughput for the homogeneous and heterogeneous deployments in received packets per second. When the number of nodes increases, the throughput saturates. The Heterogeneous f(Dmax) deployment presents better performance compared with others deployments up to 10000 nodes.

Figure 9 compares PDR as a function of traffic intensity (i.e. with AP from 1 min to 40 min). Decreasing traffic intensity reduces the packet loss, then

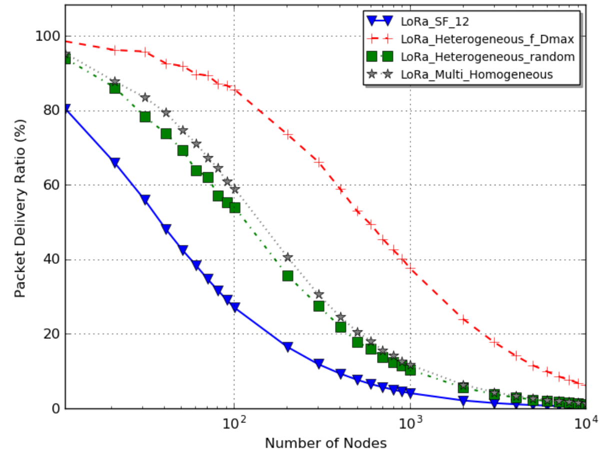


Fig. 7. PDR of Homogeneous and Heterogeneous deployments as a function of the number of devices generating a 50 Bytes packet each 60 s.

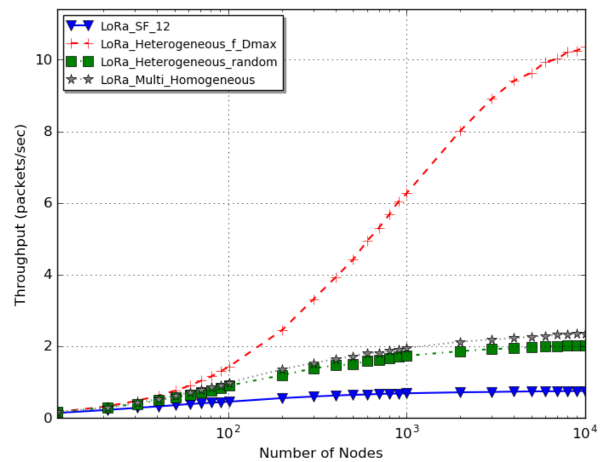


Fig. 8. Network Throughput for Homogeneous and Heterogeneous deployments as a function of the number of devices generating a 50 Bytes packet each 60 s.

PDR increases. The Heterogeneous f(Dmax) deployment presents better PDR because it takes advantage of the orthogonality of SFs reducing the interference, e.g., all nodes set up to SF12 are far from the gateway, then the interference to nodes close to the gateway set up to SF6 are reduced. The Homogeneous SF12 deployment presents lower PDR due to its long packet duration and the low spectral efficiency.

Figure 10 compares the throughput for homogeneous and heterogeneous deployments. When traffic intensity decreases, the throughput decreases. For high traffic intensity (e.g., 1 min Application Period), the Heterogeneous f(Dmax) deployment presents a throughput of 10 packets per second whereas other strategies have a throughput less than 2 packets per second.

Figure 11 compares average power consumption for the homogeneous and heterogeneous deployments for a simulation time of 100*AP. When increasing traffic intensity, power consumption increases. Taking the Homogeneous SF12 deployment as reference, the comparison shows that power consumption for the Heterogeneous

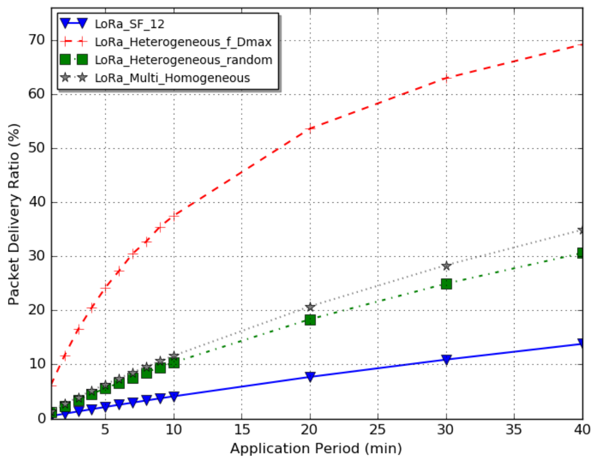


Fig. 9. PDR for Homogeneous and Heterogeneous deployments for 10000 Nodes.

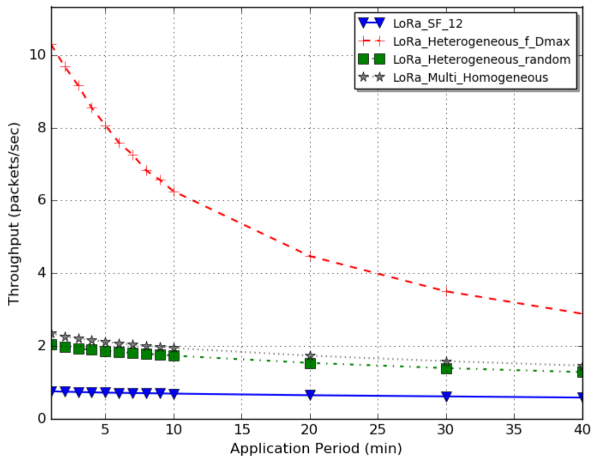


Fig. 10. Network Throughput for Homogeneous and Heterogeneous deployments of 10000 Nodes.

f(Dmax) deployment increases smoothly compared with the exponential increasing of the Homogeneous SF12 deployment.

D. Application Period and Packet Duration vs. ERC Regulations

In Europe, ERC regulates access to radio frequency bands. For most of the sub-bands in the 868 MHz band, the duty cycle must be lower than 1%. We analyze this constraint for a 50 Bytes packet configured with different SFs. Table IV shows the packet duration and the Application Period required to respect the regulation for different values of SF.

For an AP of 1 min, the packet duration must be lower than 600 ms to respect the duty cycle of 1%. Table IV shows that the constraint can be satisfied with all SFs except SF11 and SF12. APs for SF12 and SF11 must be longer than 2.6 min and 1.4 min, respectively, in order to respect the regulations.

V. Conclusion and Future Work

In this article, we have investigated homogeneous and heterogeneous networks for large scale deployments

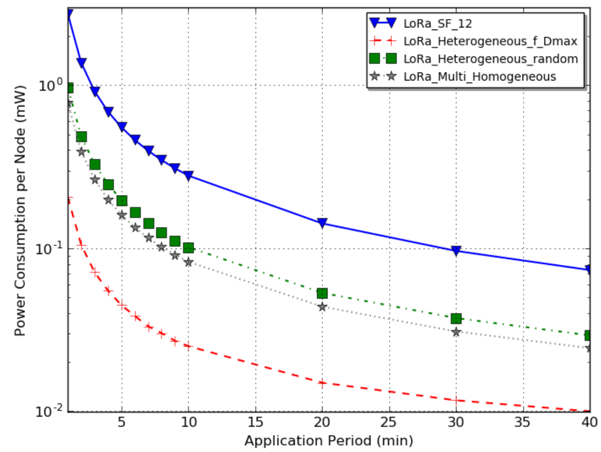


Fig. 11. Average power consumption for the Homogeneous SF12, the Multi-Homogeneous, the Heterogeneous f(Dmax), and the Heterogeneous Random deployments.

TABLE IV
50 Bytes Packet Duration and Application Period for 1% Duty Cycle.

SF	Packet Duration	AP
6	48.6 ms	4.86 s
7	83.3 ms	8.33 s
8	145.6 ms	14.5 s
9	259.1 ms	25.9 s
10	465.3 ms	46.5 s
11	844.4 ms	1.4 min
12	1572.4 ms	2.6 min

(up to 10000 nodes per gateway), SFs allocations, and performance in terms of PDR, throughput, and power consumption. We have developed a LoRa module in the WSNet simulator considering the co-channel rejection due to the quasi-orthogonality of SFs, the gateway capture effect based on the SX1301 transceiver, and a random access MAC to obtain accurate results for large scale deployments. Our simulations compare the performance for homogeneous and heterogeneous deployments as a function of the number of nodes and traffic intensity.

First, we have analyzed homogeneous deployments for different SFs from SF6 to SF12. Simulations show better performance for the SF6 deployment but reduced cell coverage. Second, we have compared heterogeneous and homogeneous deployments: the Heterogeneous deployment that selects its LoRa configuration according to its link budget results in the best PDR and throughput, as well as the lowest average power consumption compared to other deployments, for a different number of nodes and different traffic intensity. The results clearly show the benefits of heterogeneity for large scale network deployments and the need for adaptive SF allocation strategies.

In future work, we plan to define and simulate several decision modules to enable adaptive LoRa operation. The module will optimally select the configuration according to the scenario criteria (e.g., high data rate, energy efficiency, or network congestion) and the radio environment (e.g., link budget, level of interference, device mobility). It should minimize the overhead and the impact of bidirectional communications on performance.

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