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Fast and Reliable LoRa-based Data Transmissions

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***Abstract*—LoRaWAN is a recently proposed MAC layer protocol which manages communications between LoRa-based gateways and end-devices. It has attracted much scientific attention due its physical layer characteristics, but mainly due to its versatile configuration parameters. However, it is known that LoRaWAN-based transmissions suffer from extensive collisions due to the unregulated access to the medium. For this reason, various techniques that alleviate the burst of collisions have been proposed in the literature. In this paper, we deal with the problem of fast data delivery in LoRa-based networks. We model a network where transmissions follow a Poisson process. We compute the average packet success probability per Spreading Factor (SF) assuming orthogonal transmissions. We, then, formulate an SF optimization problem to maximize the success probability given an amount of data per node and a maximum data collection time window. We show – both theoretically and using simulations – that the overall success probability can be improved by approximately 100% using optimal SF assignments. We validate our findings using a 10-node testbed and extensive experiments. Despite that experiments reveal the existence of inter-SF interference, our solution still provides the best performance compared to other LoRaWAN configurations.**

I. Introduction

LoRa is a new physical layer communication protocol designed for low-power, long range, and low bandwidth IoT applications. It operates on the sub-GHz licence-free band and allows multiple parallel pseudo-orthogonal transmissions (spreading factors). LoRa trades data rate with distance. This means that long range transmissions are performed with lower data rate (higher SFs) than short range transmissions (lower SFs). Moreover, LoRa has been recently enhanced with an upper layer stack to manage communications between gateways and end-node devices, called LoRaWAN. LoRaWAN is also responsible for managing communication parameters like the data rate and the power of end devices, through the Adaptive Data Rate (ADR) mechanism [1].

The main drawback of LoRaWAN is its unregulated transmission policy; the transmissions are treated as pure ALOHA transmissions. As it has been shown by many recent studies [2], [3], this policy leads to a high probability of collisions and, thus, to poor performance – both in terms of throughput and fairness – when the traffic in the network is high. In order to increase fairness, LoRa transmissions are regulated by either an upper duty cycle limit (i.e., 1% for uplink transmissions in the EU868 band) or by a maximum transmission time per channel (US regulations for sub-GHz bands) [4]. Nevertheless, these rules do not apply when a *Listen Before Talk* technique is used.

This paper is part of a project aiming at reducing the operating costs in the agricultural domain by using Internet of Things (IoT) network technologies. In this context, we consider an application where the nodes store data and transmit it in bulk when a gateway becomes available. This is a typical application in the agricultural domain (e.g., animal and field monitoring) where seamless connectivity is not guaranteed due to the often times poor rural coverage or due to the absence of a main power supply. As a consequence, gateways may be deployed in a near farm or can be carried by mobile vehicles [5] and become available at regular intervals in order to collect the data gathered and stored by the nodes. In this type of applications, it is important to collect the data as fast as possible without compromising the system reliability. Thus, it is important to develop solutions that alleviate the collisions and increase the throughput. In the current work we propose an approach to minimize the collection time to data delivery ratio, a desirable reliability feature of many applications like the agriculture and the industrial IoT [6]. LoRa's long range capabilities and independence of third-party providers, makes it the best candidate to achieve the objectives mentioned above.

In this paper, we assume that the nodes are uniformly placed in a not very large area (e.g., animals in a farm) and are capable of taking measurements every few minutes and of storing the data in their memory. The nodes upload their data once the gateway becomes available. To do so, they send it (in packets) at random times within a maximum predefined time window. Following the default LoRaWAN operation, the nodes that are close to the gateway will all use similar SF to save energy. However, having many nodes on the same SF leads to a high number of collisions. Hence, this brings up the following question: *is there any particular SF arrangement that could eventually decrease the number of collisions?*

In order to answer this question we model the arrival of the packets at the gateway as a Poisson process and we compute the average success probability per SF as a function of the percentage of the nodes having the same SF, the capture effect power threshold, and the packet arrival rate. Next, we examine the trade-off between traffic density and transmission time as well as its effect on the overall success probability. In particular, we examine whether by moving some nodes to higher SFs, could lead to a higher overall success probability and, thus, to faster delivery times. We maximize that probability by playing on the proportions of nodes using each SF. For this reason we formulate the *Optimal SF configuration problem* given a specific number of nodes as well as a mean packet arrival rate. Finally, we compute the minimum data collection time required to achieve a minimum overall packet success probability in the network by formulating the *Optimal Data Collection Time* problem. We evaluate and validate the theoretically computed performance of the optimal SF configuration through simulations and experiments.

The remainder of the paper is organized as follows: in Section II we briefly report the related work. In Section III we compute the success probability per SF, and in Section IV we formulate the optimal SF and time optimization problems. Extensive series of simulations and experiments are presented in Section V and they are compared to theoretical results. Finally, Section VI concludes the paper and presents ideas for future work.

II. Related work

Recent works have shown that LoRaWAN networks cannot scale due to the nature of the MAC layer which causes a high increase in collisions even for a moderate number of transmissions [2], [7], [8]. Moreover, the capture effect and the inter-SF interference can further decrease the network capacity [3], [9].

Several works have been presented in the literature over the past year, targeting to decrease the collisions and, thus, improve the performance. A lightweight scheduling approach is proposed by Reynders *et al.* [10]. This work divides the nodes into groups where similar transmission powers are used in each group to reduce the capture effect. The schedule moves some nodes to higher SFs in order to allow collision-free simultaneous transmissions. More sophisticated scheduling schemes are proposed in [11] and [12]. In the first work the authors present an on-demand time division protocol to assign slots to the nodes. The solution improves the network performance but does not completely eliminate collisions. The latter work presents a two-phase collision-free approach to schedule spreading factors, transmission powers, frequency channels, timeslots, and slot positions in frames for LoRaWAN end-devices. The authors report much better results compared to LoRaWAN but high communication overhead for time-limited applications. In general, slotted communications require additional communication and time overhead to synchronize the nodes or compute the schedules [13] and they cannot fit in all the scenarios. However, our proposed work can be enhanced with some soft synchronisation characteristics with low overhead as the one presented in [14], where slotted-LoRaWAN transmissions are studied.

Applying CSMA techniques to LoRa networks has been also investigated in the literature [15], [16] and can eventually reduce the data collection time since the number of collisions is decreased. However, the superiority of CSMA over other access protocols has been shown only for a single SF scenario [17]. Listen Before Talk solutions cannot detect the ongoing SF on the channel activity and would lead to either sub-optimal use of the SFs or diminish the capability of parallel transmissions.

III. Probability of successful reception

We assume that there are N nodes uniformly distributed over a disk area of radius d centered at the gateway. Every node has to transmit data of volume V within a data collection time window τ. To do so, the data is divided in packets of equal size pkt, thus, $k = \lceil V/\mathrm{pkt} \rceil$ packets will be transmitted within τ amount of time. Assuming orthogonality of transmissions, our goal is to express the average probability of successful packet reception per SF.

We consider the LoRa MAC layer (per SF) as an ALOHA MAC without acknowledgments, and assume that the nodes emit packets independently of each other and of their location, with an intensity $\theta = k/\tau$. We denote with α_f the percentage of nodes configured with SF f, where $\sum_{f=7}^{12} \alpha_f = 1$ (SF ranges from 7 to 12). The packet generation of nodes in the disk therefore follows a Poisson distribution with rate $\theta\alpha_f N$.

Now, let us consider a node at distance x from the gateway, emitting a message with SF f. Taking into account the capture effect, a node's packet transmission is successful if (a) no other packet with the same SF overlaps with the current one within the transmission time T_f, or (b) the power at the gateway of any other packet with the same SF exceeds the current one by at least P_{thld} [2]. Assuming that all the nodes have the same transmission parameters, due to the path-loss properties of the signal the potential interferers are those whose distance from the gateway is below xR with $R = 10^{\frac{P_{\text{thld}}}{10\gamma}} > 1$ [18], where γ is the path loss exponent.

Hence, from the assumption of a uniform distribution of nodes with SF f, the number of potential interferers is $\alpha_f N \frac{(\min(Rx,d))^2}{d^2}$, where d is the disk range. The probability of successful transmission $P_{\text{success}}(x)$ is that within a vulnerability period of duration $2T_f$, none of those potential interfering nodes starts a transmission. Hence, we have:

$$P^f_{\text{success}}(x) = e^{-2T_f\theta\alpha_f N \frac{(\min(xR,d))^2}{d^2}}. \tag{1}$$

Given Eq. (1), we compute the average success probability among nodes for the given SF. We must note that some nodes may have a success probability below the average, but because of a potential node mobility (e.g. animal monitoring), that success probability will evolve over time so that the individual time-average equals the average among nodes. Assuming a uniform distribution of nodes over the disk, the infinitesimal number of users within distance $[x, x + \mathrm{d}x]$ from the gateway is $2\frac{\alpha_f N}{d^2} x\mathrm{d}x$. Thus, the average success probability in the disk for SF f nodes is given by the following equation:

$$\begin{aligned} P^f_{\text{avg}} &= \frac{1}{\alpha_f N}\int_{x=0}^{d} 2\frac{\alpha_f N}{d^2} e^{-2T_f\theta\alpha_i N\frac{(\min(Rx,d))^2}{d^2}} x\mathrm{d}x \\ &= \frac{1 - e^{-2\alpha_f T_f\theta N}\left(1 - 2(R^2-1)\alpha_f T_f\theta N\right)}{2\alpha_f T_f \theta N R^2}. \end{aligned} \tag{2}$$

We can observe that, since the transmission time is fixed given a certain SF and a specified channel bandwidth [1], the average probability depends only on the transmission rate (i.e., θ) and the number of nodes.

IV. SF AND TIME OPTIMIZATION PROBLEMS

As our objective is to reduce the data collection time (thus, the number of collisions), we need to find SF configurations that optimize the average success probability. Hence, we formulate the "Optimal SF configuration Problem" (OSFP) to optimally assign SFs to the available nodes N, so that the overall average success probability is maximized. This can be done by adjusting the percentage of nodes α_f, with $f \in [7, 12]$. We must note that, for simplicity reasons, we restrict the formulation for nodes which can reach the gateway using SF7 so that they can be switched to higher SFs. Otherwise, a minimum SF per node must be defined according to its distance to the gateway [5].

$$\max_{\alpha_7,...,\alpha_{12}} \left(\sum_{f=7}^{12} P_{\text{avg}}^f \alpha_f \right) \tag{3}$$

$s.t.$

$$P_{\text{avg}}^f = \frac{1 - e^{-2\alpha_f T_f \theta N} \left(1 - 2(R^2 - 1)\alpha_f T_f \theta N\right)}{2\alpha_f T_f \theta N R^2}, \tag{4}$$

$$R = 10^{\frac{P_{\text{thld}}}{10\gamma}}, \tag{5}$$

$$\alpha_f \in [0, \rho, 2\rho, ..., 1], \forall\ f \in [7, 12], \tag{6}$$

$$\rho N \in \mathcal{N}, \tag{7}$$

$$\textstyle\sum_{f=7}^{12} \alpha_f = 1. \tag{8}$$

Since $\alpha \in \mathcal{R}$, we discretize it by considering a step $\rho \in \mathcal{R}$ as described in (6). Eq. (7) ensures that the number of nodes having a particular SF is an integer number and Eq. (8) requires that the sum of the percentages is 1. A computation of T_f is given in [1].

In this paper we also formulate the reverse problem; given an assignment of SFs $[\alpha_7, ..., \alpha_{12}]$, we determine the minimum required data collection time, while achieving a minimum average success probability P_{min}. Thus, we introduce the "Optimal Data Collection Time" (ODCT) problem as a problem of minimizing the data collection time τ of N nodes, each of them transmitting a volume of data V. The problem can be formulated as follows:

$$\min \tau, \tag{9}$$

$s.t.$

$$\frac{1 - e^{-2\alpha_f T_f \theta N} \left(1 - 2(R^2 - 1)\alpha_f T_f \theta N\right)}{2\alpha_f T_f \theta N R^2} \geq P_{min}$$

$$\forall\ f \in [7, 12] \text{ and } \alpha_f N > 0, \tag{10}$$

$$\theta = \tfrac{k}{\tau}, \tag{11}$$

$$R = 10^{\frac{P_{\text{thld}}}{10\gamma}}. \tag{12}$$

V. PERFORMANCE EVALUATION

A. OSFP settings, simulation, and experiment setup

In this section we compare the theoretical results obtained by solving the OSFP and ODCT problems with simulation and experimental results. The OSFP is optimally solved using an exhaustive search approach. To do so, an ρ value of 0.1 was used for $N = 10$ and a value of 0.02 for node populations equal to or larger than 100.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Nodes	10 – 1000
Terrain range (disk)	500 m (∼3m for experiments)
Gateway coordinates	[0, 0, 10m] [0, 0, 0] for experiments
Bandwidth (BW) - Coding Rate	500 KHz - 4/5
Spreading Factors	7-12
Region	EU868
Preamble symbols	8
Packet size (pkt)	50 Bytes
Data per node (V)	2000 Bytes
Data collection window (τ)	3600 secs 40–200 secs for experiments
Path Loss model (see [2])	$\overline{L_{pl}}(d_0) = 95$dB $d_0 = 40$m, $\gamma = 2.08$, $\sigma = 3.57$
Capture effect threshold (P_{thld})	6 dBm
Receiver Sensitivities (per SF for BW500)	[-116, -119, -122, -125, -128, -129] dBm [19]
Transmission power	7 dBm (2 dBm for experiments)
Power consumption (transmission)	18 mA [19]

We assume a disk deployment area with 500 meters range and a variable number of nodes that are randomly and uniformly scattered in this area. All the scenarios use unconfirmed transmissions. We distinguish two versions of LoRaWAN. In the first version, we use the SF settings as they are computed by the OSFP solution (appears as "Sim-Optim" in the figures). In the second version, the SF of the nodes is determined based on their distance to the gateway. Since this approach is similar to the ADR mechanism of LoRaWAN, we denote it as "Sim-ADR" in the figures. We assume that two LoRa transmissions collide when they overlap in time, SF, bandwidth, and received power [2]. A packet-based LoRa simulator was developed with a proper signal path-loss model and capture effect[1]. We generate 50 instances per scenario and the average results are presented along with the 95% confidence intervals. Table I summarizes the values used for each simulated parameter.

We, also, created a small-scale testbed consisting of 10 LoRa nodes and a gateway[2]. The experiments were conducted in a $25m^2$ lab room at different timings during several days, using various random node positions. Each experiment was executed 20 times. The gateway was located in the middle of the room. In order to generate equivalent traffic scenarios with the previous examined scenario consisting of a higher number of nodes, we varied the data collection window (i.e., τ) from 40 to 200 seconds keeping the transmitted data size ($V = 2000$ bytes) and the packet length ($\text{pkt} = 50$ bytes) constant. We must note that not all values of τ comply with the 1% radio duty cycle restriction of EU. These values are chosen only for fair comparison purposes as well as for testing our method in high traffic density scenarios. All the experiments were carried out over the same channel, transmission power, and bandwidth

[1]The code will be soon available at https://github.com/deltazita/Bulk-LoRa
[2]We used a mix of Pycom lopy4 and fipy nodes (https://pycom.io/) and an Arduino LoRa gateway (https://store.arduino.cc/arduino-pro-gateway).

TABLE II
THEORETICALLY OPTIMAL SF SETTINGS FOR DIFFERENT NODE POPULATIONS

Nodes	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}
10	0.4	0.2	0.1	0.1	0.1	0.1
100	0.46	0.26	0.14	0.08	0.04	0.02
200	0.46	0.26	0.14	0.08	0.04	0.02
300	0.46	0.26	0.14	0.08	0.04	0.02
400	0.46	0.26	0.14	0.08	0.04	0.02
500	0.46	0.26	0.14	0.08	0.04	0.02
600	0.46	0.26	0.14	0.08	0.04	0.02
700	0.46	0.26	0.14	0.08	0.04	0.02
800	0.46	0.26	0.14	0.08	0.04	0.02
900	0.46	0.26	0.14	0.08	0.04	0.02
1000	0.46	0.26	0.14	0.08	0.04	0.02

TABLE III
BEST SIMULATED SF SETTINGS FOR DIFFERENT NODE POPULATIONS

Nodes	α_7	α_8	α_9	α_{10}	α_{11}	α_{12}
10	0.4	0.2	0.1	0.1	0.1	0.1
100	0.45	0.25	0.15	0.05	0.05	0.05
200	0.45	0.3	0.15	0.05	0.05	0
300	0.45	0.25	0.15	0.1	0.05	0
400	0.45	0.25	0.15	0.1	0.05	0
500	0.45	0.25	0.15	0.1	0.05	0
600	0.45	0.25	0.15	0.1	0.05	0
700	0.45	0.25	0.15	0.1	0.05	0
800	0.5	0.25	0.15	0.05	0.05	0
900	0.5	0.25	0.15	0.05	0.05	0
1000	0.5	0.25	0.15	0.05	0.05	0

as it is presented in Table I. Each node generated 40 packets of data following an exponential distribution with rate θ. Just for the needs of the experiments and in order to get statistically correct results, at the beginning of each experiment all the nodes were synchronized according to a precise global clock initiated by the gateway using WiFi[3].

B. Results

1) Determining the optimal SF settings: The results obtained by solving the OSFP are illustrated in Table II. We can observe that the solution includes nodes of all the SFs, while barely half of the nodes use SF7. We also conducted a series of simulations to verify the theoretical results. We tested the same network scenarios with various settings for α_f for all the available SFs looking for the settings that provide the best average PDR. Due to the high complexity of the approach we were able to obtain results with $\rho = 0.05$. The results are depicted in Table III and show almost constant α_f values for all the node populations. Comparing to the values of Table II, we can observe that they are very close to each other with an up to 0.05 units difference. Moreover, since the results of the two tables were generated using slightly different ρ values, we wanted to see what is the effect of a more precise ρ (i.e., 0.02 instead of 0.05) to the simulated PDR. Comparing each individual best simulated setting to the corresponding theoretically optimal one, we reported an only up to 0.1% difference in PDR.

[3]The time starts counting when the nodes (simultaneously) get an `init` command from the gateway.

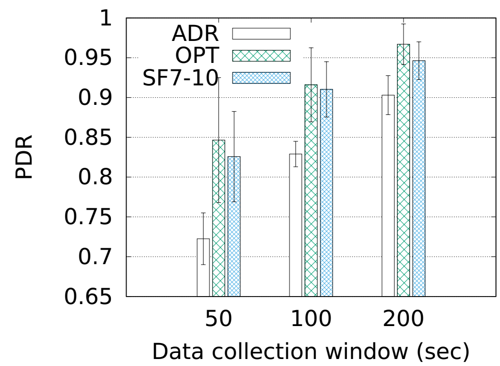
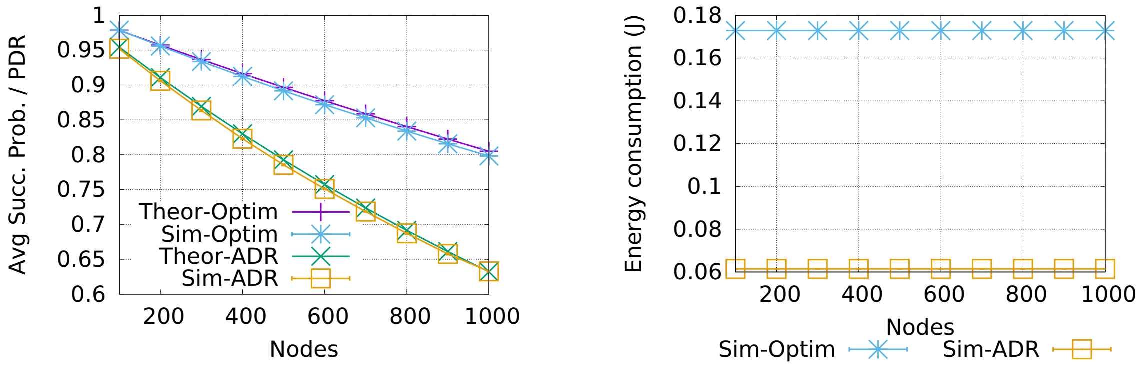


Fig. 1. Experimental results using the distance-based SF settings (ADR), the optimal SF settings (OPT), and [0.5, 0.3, 0.2, 0.1, 0, 0] α_f settings.

At this point, we would like to validate the results obtained by mathematical analysis and simulations, conducting a series of real experiments. We tested scenarios were the nodes should deliver the data within 50, 100, and 200 seconds. Since the experiments take a considerable amount of time, three different SF configurations were evaluated. The optimal one as it is computed by solving the OSFP (see Table II, row 1), the distance-based SF configuration where all the nodes are configured with SF7, and a configuration which completely omits the use of SF11 and 12 but moves the majority of the nodes to lower SF values. The results are depicted in Fig. 1 and confirm the theoretical and simulation outcome.

2) Optimal vs. distance-based SF settings: In the next study, we compute the theoretical and the simulated packet delivery ratio (PDR), as well as the energy consumption of the two different node arrangements for scenarios with 100 to 1000 nodes. Fig. 2a reports the average success probability of the theoretical solutions (optimal and ADR-based) and the corresponding PDR of the simulated ones. The first observation is that the simulated LoRaWAN versions present very similar results with the theoretical solutions. Apart from this, the results show the superiority of the optimal settings over the LoRaWAN version with the ADR-based SF settings. Indeed, the distance-based approach exhibits a weaker performance since almost all the nodes use SF7, thus increasing the probability of overlapping transmissions and resulting to an up to 31% difference compared to the optimal settings approach. Apparently, the throughput improvement comes with the expense of more energy since some nodes are switched to higher SFs (see Fig. 2b). However, if we normalize the energy consumption with the achieved PDR, we will observe that the energy consumption of the ADR-based version increases faster than the optimal version. This means that, at some point, it will reach and overtake the performance of the optimal settings.

In order to validate the theoretical and the simulation results of the previous scenarios, we experimentally evaluated the performance of the approaches using the 10-node testbed. The experimental results are depicted in Fig. 3 along with the corresponding theoretical and simulation ones. The error



(a) Average success probability / PDR

(b) Energy consumption per node

Fig. 2. A comparison between the theoretical and the simulated performance with ADR and optimal settings configuration.

bars of the experimental results show the minimum and the maximum captured values. We separate the outcomes in two subfigures for presentation purposes. Figure 3a depicts the performance of the approaches when the distance-based SF settings are used. We observe that all the three approaches achieve an almost identical performance. Figure 3b depicts the results using the SF settings as they are computed by solving OSFP. Switching to these settings, we can clearly observe the PDR improvement which varies from 6 to 29% for the experimental scenario. We must note that the experimental performance is slightly lower than the theoretically computed values since in practice LoRa transmissions are not completely orthogonal. Indeed, we expected an 100% PDR for the nodes with SFs 9-12 since no other nodes are assigned with these SFs. However, we captured, for instance, an average of about 33.5 delivered packets for SF10 and an average of 37 packets for SF9 when τ=40secs (out of 40 transmitted). Non-orthogonal transmissions led to 12.5% and 1.3% lower than expected performance for dense and sparse traffic scenarios, respectively.

3) Optimal data collection time: In this last study, we solve the ODCT problem given the theoretically optimal SF settings computed by solving OSFP (values of Table II). To do so, we use a brute force approach starting from $\tau = 10$ seconds and increasing it with a step of 1 second until P_{min} is achieved. The results are presented in Fig. 4a, where we see high performance gains when compared to the case where the distance-based SF settings are used. The improvement is close to 100% even for the low node numbers. The corresponding simulated scenarios using the theoretically computed data collection time, confirm a PDR of over 90% (see Fig. 4b). We must note that this performance was also confirmed by the experiments. Despite the slightly lower than expected performance due to the imperfect orthogonality when using multiple parallel SFs, we were able to collect 90% of the transmitted data in less than 90 seconds (on average), while we recorded over 90% PDRs in less than 30 seconds for some of the experiments. On the contrary, we needed more than 180 seconds (on average) with the distance-based SF settings, while the first instance with an over 90% PDR appeared within a time window of 140 seconds.

VI. Conclusions

In this paper, we examined the problem of the fast and reliable bulk data transmissions using the pure LoRaWAN protocol. We modeled the average success probability per SF in relation to the number of nodes and the packet arrival rate. We also examined the scenario of optimally configuring SFs, so that the overall success probability in the network is maximized. We computed the optimal SF configuration for a given group of nodes. Our simulation and experimental results confirmed that using the optimal settings the data collection time can be shrunk to the half compared to the case where the distance-based SF settings are used. However, this comes with some extra energy expense since some nodes are moved to higher SFs. The experimentation also revealed that LoRa transmissions are subject to inter-SF collisions which can degrade the performance by up to 12.5%. However, the inter-SF effect is very low for low traffic scenarios.

In the future, we plan to develop an adaptive mechanism executed at the gateway to optimally assign and download SF settings to the nodes. Since the current work trades energy for time, the problem of hybrid SF assignments that provide trade-offs between data collection time and energy consumption is also an interesting problem to explore. Moreover, since energy consumption is an important factor in IoT applications, the current work can be combined with some light time-slotted communication mechanism so that less nodes are moved to higher SFs. Finally, we intend to apply these data collection mechanisms to a real life agricultural scenario involving animals and drones.

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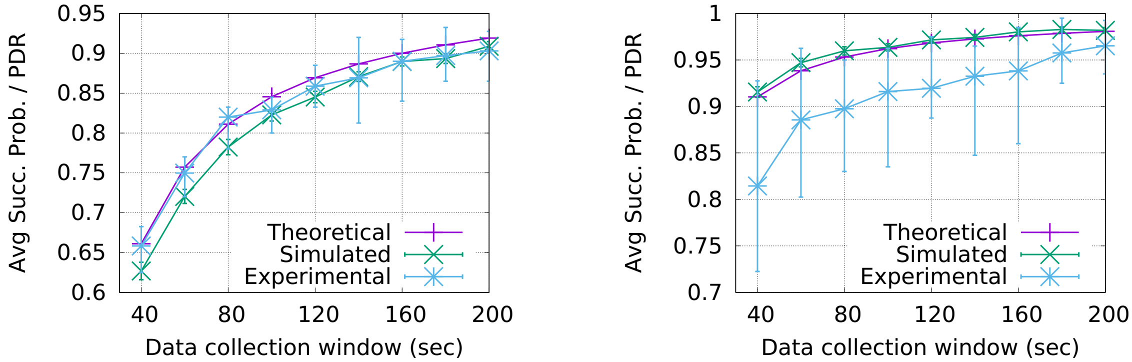
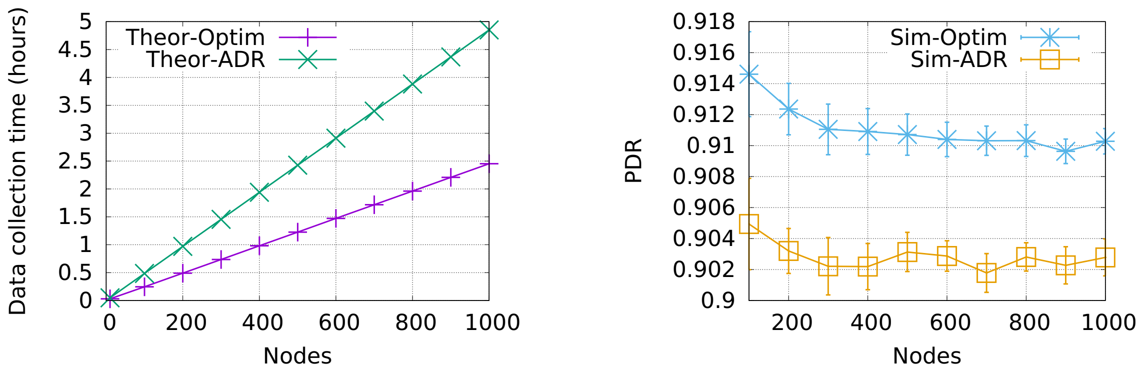


(a) Distance-based SF settings

(b) Optimal SF settings

Fig. 3. A comparison between the theoretical, the simulated, and the experimental performance for a scenario with 10 nodes and a variable data collection window.



(a) Theoretical data collection time

(b) Simulated PDR for the theoretically calculated data collection time of (a)

Fig. 4. Data collection time needed to achieve a P_{min} of at least 0.9.

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