Sensitivity-Aware Configurations for High Packet Generation Rate LoRa Networks

Hanan Alahmadi, Fatma Bouabdallah
Faculty of Computing and Information Technology
King AbdulAziz University
Jeddah, Saudi Arabia
hjalahmadi1,fothman1@kau.edu.sa

Baraq Ghaleb, Ahmed Al-Dubai
School of Computing
Edinburgh Napier University
Edinburgh, UK
Email: B.Ghaleb, A.Al-Dubai@napier.ac.uk

***Abstract*—In this paper, we introduce Sensitivity-Aware LoRa Configuration (SAL), a new algorithm for efficient autonomous and distributed selection of LoRa physical layer transmission parameters. The aim is to address the limitations of the currently adopted MAC algorithm in LoRaWAN networks (i.e., Adaptive Data Rate - ADR). The selection of the transmission parameters in ADR is done randomly by the gateway node, an approach that may result in the gateway reaching its Duty Cycle Limit, consequently hindering it from sending the configuration information to the end points under large-scale networks negatively affecting the network performance. Unlike ADR, SAL uses a decentralized approach to select node's transmission parameters without any need for gateway's control packets and it only considers a combination of parameters that is guaranteed to be received successfully by the gateway. The performance of the proposed algorithm is validated through extensive simulation experiments under different scenarios and operation conditions. In particular, SAL is compared to LoRaWAN configuration algorithm in terms of Packet Error Rate (PER), Capture effect Probability, Collision Probability, End-to-end Delay, Packet Delivery Ratio (PDR), Throughput and Energy Consumption showing promising results in this context.**

***Index Terms*—LoRaWAN, Duty cycle limitation, SF distribution, channel allocation**

I. Introduction

Internet of Things (IoT) is the main component to enable smart scenarios such as smart cities, environmental monitoring, and industrial management. In such scenarios, things should interact with the surroundings widely with minimum power consumption, as they are usually equipped with limited battery resources. For that mission, Low Power Wide Area (LPWA) network technologies were proposed. LPWA networks can be divided into two main categories depending on the operational band, licensed and unlicensed networks. In licensed networks, nodes communicate with each others through Cellular networks. In unlicensed networks, on the other hand, sensor motes are connected through the Industrial, Scientific, and Medical (ISM) band. Although the unlicensed band does not charge any cost for the usage, it imposes strict usage regulations. In other words, in order to regulate the access to the shared medium, nodes must use either Listen Before Talk (LBT) mechanism or follow duty cycle regulations [1] [2]. Two common technologies use the unlicensed band, which are LoRa [3] and SigFox [4]. This paper supposes the usage of LoRa networks. LoRaWAN protocol, which is the MAC protocol used by LoRa network, uses Duty Cycle (DC) regulations to regulate the access to the medium. DC denotes the proportion of time during which a node or a gateway is allowed to transmit.

In this study, we select LoRa among other technologies as it provides the longest coverage range due to its physical layer modeling technique. Moreover, LoRa physical layer supports different transmission parameters that highly affect the overall performance of the network. These parameters include the support of multi-channel communication, different Spreading Factors (SFs), different transmission power levels, different channel bandwidths, and different Coding Rate (CRs). In fact, transmissions with different SFs are considered orthogonal, which means that if there are two or more packets that are transmitted on the same channel with different SFs, the receiver can decode all of them. However, if one of the simultaneously transmitted packets was received with much higher power (above a threshold), that packet will only be decoded by the receiver.This phenomenon is called the capture effect, and it is considered as a main challenge in LoRa networks due to the long-range coverage. In fact, by using different SFs we may increase the number of parallel packet transmissions per channel. However, without wise controlling of node's transmission powers, the network throughput will be limited due to the capture effect.

Indeed, controlling node's transmission parameters could be done centrally, through the network server, or locally through the node itself. In centralized approach, the server is responsible of sending control packets to manage node's transmission parameters. Since the server may have full knowledge about the networks, the suggested transmission parameters by the server could be more accurate. However, with large number of connected nodes, the server may not be able to deliver all needed control packets to nodes since it is constrained by a Duty Cycle Limit (DCL). To overcome that, decentralized approaches can be used, where nodes autonomously determine its transmission parameters without any required downlink traffic from the server.

This research work was funded by Institutional Fund Projects under grant no (IFPRC-065-612-2020). Therefore, authors gratefully acknowledge technical and financial support from the Ministry of Education and King Abdulaziz University, Jeddah, Saudi Arabia.

A. Related Work

Related work of LoRa networks can be categorized into two main categories, researches that are interested in analyzing the performance of LoRa networks with variant network conditions and configurations [5] [6] and researches that are interesting in finding the most efficient distribution mechanism of the transmission parameters [7] [8] [9] [10] [11].

With regard to the first category, in [5], they perform a systematic simulation analysis of LoRaWAN MAC protocol by changing some of its build-in parameters to show how minor modifications could significantly affect the performance of LoRa networks. Among the parameters they had modified is turning off the DC restriction on the downlink traffic from the gateway to nodes. According to their simulation results, they achieve higher Packet Success Ratio (PSR) since gateway can freely acknowledge the uplink packets, which will result in less retransmission rate. Furthermore, they had switched the recommended channels for downlink transmissions of RX1 and RX2 receiving windows. In other words, they use the default channel of RX2 receiving window in LoRaWAN standard, which is the channel with 10% DC, in RX1 receiving window and use the channel of the uplink transmission in RX2 receiving window. Hence, they achieve more DC for downlink transmissions in the first receiving window RX1. They have also changed the default settings of SFs for the downlink transmissions of RX1 and RX2 by adopting higher data rates, and hence less consumption of gateway DC. Based on their simulation results, better Packet Delivery Ratio (PDR) was achieved with these minor modifications. This in fact highlights the fact that the DC regulations could be the bottleneck of the system especially with high number of connected nodes.

Regarding the second category, a wide variety of algorithms was proposed in the literature to tackle the problem of distributing transmission parameters among nodes [7] [8] [9] [10] [11]. Some of these researches focuses only on the distribution of spreading factors among nodes. In other words, they assume fixed transmission power levels for all nodes. Consequently, these algorithms may suffer from collisions due to the capture affect, especially with long-range coverage, as the signals of closer nodes dominant on the signal of farther nodes. [7]. Other researches address the distribution of both spreading factors and transmission power levels [9] [10]. Specifically, in [11], they propose a model to determine the optimal range for each SF that maximize the Packet Delivery Ratio (PDR). Based on the proposed model, each node will select an SF that satisfy two conditions: i) the received power at the gateway of a transmission using a given SF must be above the sensitivity level of the gateway for that SF and ii) the Signal to Interference (SIR) of the received signal at the gateway must be above a given threshold. If a node could not satisfy both conditions, which is an expected case in dense networks, the model sacrifices the first condition and allows nodes to satisfy condition II only. They found that satisfying the second condition will result in higher PDR than satisfying the first condition. According to that, although the PDR could be high, some nodes could have transmissions that are received below the sensitivity level of the gateway. As a result, the packet retransmission rate could be increased and that will affect the energy efficiency of these nodes. Alternatively, instead of sacrificing condition I, which is vital and essential in order for transmissions to be decoded by the gateway, we can assign different frequency for nodes to maintain a given PDR. This, in fact, highlights the importance of exploiting the multi-channel communication that is supported by the physical layer of LoRa. Moreover, the proposed model does not consider the different transmission power levels that affect the estimated SF ranges. To sum up, none of these research studies consider the full advantage of the multi-channel communication provided by LoRa physical layer. In fact, they all use the default channels on the default sub-band.

B. Contributions

In this paper, we propose Sensitivity-Aware LoRa Configuration (SAL) algorithm that autonomously allows nodes to select its transmission parameters in order to maximize the Packet Delivery Ratio (PDR). In other words, nodes independently determine the set of transmission parameters that ensure the transmitted packets using these parameters will not be received below the sensitivity level of the gateway. Assuming that each node knows its coordinates as well as the gateway ones, they can independently determine the optimal combination of Spreading Factors (SFs), Transmission Power (TX), and Channel Frequencies (CFs) based on their distance from the gateway. Furthermore, since the proposed algorithm uses all CFs from all ISM sub-bands and not just the CFs of the default sub-band, the proposed algorithm at least double the available Duty-Cycle (DC) by exploiting the channels of other sub-bands. To the best of the authors knowledge, this is the first LoRa algorithm that considers the distribution of (SF, TX, CF) taking into account the duty cycle of channel's sub-bands. Extensive simulation has been performed on OMNET++ [12] under FLoRa framework [13] showing promising results especially in terms of PDR and throughput.

The rest of the paper is structured as follows: section II highlights the problem statements and describes in details the proposed algorithm. Section III summarizes the performance evaluation of SAL algorithm. Finally, section IV concludes the paper and provides insights about possible future research works.

II. Sensitivity-Aware LoRa Configuration Algorithm

This section describes the proposed Sensitivity-Aware LoRa Configuration algorithm (SAL) to mitigate the effect of the limited duty cycle of nodes.

A. Overview

Indeed, according to LoRa, each node has a set of eligible spreading factors (SFs) where the transmission of packets using such factors is not received below the sensitivity of the gateway [3]. However, in the legacy LoRaWAN, nodes select randomly a channel (CF), a transmission power level (TX), and a spreading factor (SF) for each new transmission without considering whether the transmission using the selected SF will be received by the gateway. In fact, the number of available frequencies and transmission power levels depends on the region in which the LoRaWAN network is deployed. In Europe region, the assumed deployment region in this study, there are five transmission power levels, eight channels, and six SFs providing us with a search space of $(8CFs \times 6SFs \times 5TXs)$or 240 different combinations for each node. However, LoRaWAN uses three channels only by default leaving us with 90 options out of the 240 available. In addition, depending on the node's distance from the gateway, some of these options are not eligible to be used by a given node, as packets using these combination of transmission parameters might be received below the gateway's sensitivity. In other words, LoRaWAN nodes are not aware of whether the selected combination of (SF and TX) is eligible or not. Indeed, reducing the research space to include only the combination of transmission parameters (SFs, TXs) that are eligible according to node's distance to the gateway is vital to decrease the number of packets received below the sensitivity at the gateway. Consequently, enhancing the throughput as well as the energy efficiency. LoRaWAN uses a centralized approach called the Adaptive Data Rate (ADR) to choose a combination of (SF, TX) such that the Received Signal Strength Indicator (RSSI) of packets are above a pre-determined threshold. However, with a large number of connected nodes, the gateway may reach soon its Duty Cycle Limit (DCL) and cannot send control packets specifying nodes optimal transmission parameters. To overcome such an issue, this paper proposes a decentralized approach of determining node's transmission parameters without any need for gateway's control packets. The following section describes in details the proposed SAL algorithm.

B. Network setup

As mentioned earlier, a LoRa network has 240 different transmission parameters combinations with some that can worsen the network performance as they may result in packet transmissions below the sensitivity of the gateway. Thus, a more efficient approach is to have the network acts wisely and only considers a combination of parameters that is guaranteed to be received by the gateway. The following equation shows how to calculate the receiver sensitivity S of packets given the channel bandwidth BW and the Signal to Noise Ratio of each spreading factor SF SNR [14]

$$S = -174 + 10\log_{10} BW + NF + SNR \qquad (1)$$

Where the constant (-174) is the thermal noise of the receiver at room temperature and NF is the Noise Figure at the gateway and is fixed to (6 dB). Table I shows the gateway sensitivity level according to each SF when the $BW = 125kHz$. In order for the gateway to successfully decodes a packet, the received power of that packet must be higher than the receiver sensitivity for a given SF. Indeed, the received power

TABLE I
SNR AND S FOR EACH SPREADING FACTOR SF [15]

SF	SNR	Sensitivity (S)
7	-7	-124
8	-10	-127
9	-13	-130
10	-16	-133
11	-18	-135
12	-20	-137

depends on the transmission power and the path loss due to the signal attenuation and shadowing. In this study, we use the well-known log-distance path loss model with shadowing [16], which is used by different studies in LoRa [13] [17] [7] [8] [10]. Eq.2 shows the path loss PL formula

$$PL(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d0}\right) + X_\sigma \qquad (2)$$

where $\overline{PL}(d_0)$ is the mean path loss for distance d_0, n is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. Knowing that the received power is the node's transmission power subtracted by the path loss PL, we can estimate the maximum distance d such that the resulting received power will be above the sensitivity level of the gateway. In fact, two transmission parameters affect the received power at the gateway, the transmission power parameter (TX) and the spreading factor parameter (SF). Table II shows the estimation of the maximum distance in meters in which it is eligible to use a given combination of SF and TX. For example, if the distance between a node and the gateway $d = 2500m$, then we have the following eligible set of transmission parameters (SF7,TX14), (SF8,TX11), (SF9,TX8), (SF10,TX5), (SF11,TX2), and (SF12,TX2). By using any of these combinations, the received power of the packet will be above the gateway sensitivity. Note that, we use the first maximum distance greater than the target distance in order to improve the energy efficiency of the algorithm by either reducing the time on air or the transmission power.

According to LoRaWAN networks, node transmissions are regulated by defining a Duty Cycle Limit (DCL) for every channel per sub-band. DCL is the fraction of time per sub-band for which a node is allowed to transmit on channels of

TABLE II
ESTIMATION OF THE MAXIMUM DISTANCE IN METERS PER EACH (SF,TX)

SF \ TX	2	5	8	11	14
7	910	1225	1650	2220	2950
8	1220	1650	2200	2900	4000
9	1650	2200	2900	4000	5400
10	2200	2900	3900	5400	7300
11	2700	3600	4900	6600	8900
12	3300	4400	5900	8000	10800

that sub-band. In Europe region [18], there are 2 sub-bands that are used for uplink transmissions of LoRa nodes, named g and g1 [19]. Each sub-band has a set of channel frequencies as listed in Table III. According to Table III, each node has a maximum of 1% DC for every sub-band, which corresponds to 36s of dwell time per hour. Dwell time is the time a node consumed for packet transmission. In other words, if a node consumes all the DC on one channel of a sub-band, it cannot send any further packets on any other channel from the same sub-band [20]. In the proposed algorithm, we uniformly divide the DC of each sub-band on channels belonging to that sub-band, as described in the last column of TableIII. In other words, the time is divided into frames of 1 hour period. At the beginning of each frame, all channels will be resetting its DC to the maximum as shown in the last column of TableIII. By doing that, each channel has its own DC. Hence, whenever a node reaches its DC on a channel, it will not be blocked from using other channels of that band. This will enable the parallel transmissions on different channel frequencies. To the best of the authors knowledge, there is no research work that considers the duty-cycle per sub-band.

Regarding channels allocation, we assign at most two adjacent transmission power levels for a given channel to avoid the capture effect problem, which is a common challenge in LoRa networks due to the wide area coverage. In other words, all nodes that are within the same distance range and using the same channel will use either the same transmission power or at most two adjacent power levels such that the difference between the reception power of their transmitted packets on the same channel is less than 6 dBm. In other words, if two signals were received on the same channel at the gateway, the dominant one will be decoded, which is the signal with a received power greater than the received power of the other signal by at least 6 dB [21]. According to that, tableIV shows our distribution of the transmission power levels on different channels. By considering the channel frequencies CFs in the set of eligible transmission parameters, we almost double the number of these configurations. However, the total number of eligible combinations of transmission parameters still very small compared to the actual research space. More importantly, the upper limit and the lower limit of the number of available combinations according to the node's distance is fixed regardless of node's distance to the gateway. As a consequence, only a very limited memory storage is required to store these combinations in each node.

TABLE III
DUTY CYCLE PER CHANNELS

Sub-band	**Sub-band duty cycle**	**Channels (MHz)**	**Channel's duty cycle**
g1	1%	868.1	0.33%
		868.3	0.33%
		868.5	0.33%
g	1%	867.1	0.20%
		867.3	0.20%
		867.5	0.20%
		867.7	0.20%
		867.9	0.20%

TABLE IV
DISTRIBUTION OF THE TRANSMISSION POWER LEVELS ON DIFFERENT CHANNELS

Channel ID	Channel Frequency (CF) MHz	Transmission power (TX) dBm
1	868.1	2, 5
2	868.3	8, 11
3	868.5	14
4	867.1	11
5	867.3	14
6	867.5	2
7	867.7	5
8	867.9	8

1) The initialization phase: In the proposed algorithm, we assume that each node can independently derive its Euclidean distance to the gateway by knowing its coordinates as well as the gateway's coordinates. Once a node has determined its distance to the gateway, it can calculate the set of tuple transmission parameters (CF, TX, SF) that guarantee the successful reception of its packets at the gateway. According to our example, when the distance d equals 2500 m, for instance, the set of eligible transmission configuration will be as follows: (CF5, SF7,TX14), (CF3, SF7,TX14), (CF4, SF8,TX11), (CF2, SF8,TX11), (CF2, SF9,TX8), (CF8, SF9,TX8), (CF1, SF10,TX5),(CF7, SF10,TX5), (CF1, SF11,TX2), (CF6, SF11,TX2), (CF1,SF12, TX2), and (CF6,SF12, TX2). In fact, this example shows the upper limit of the number of available options that a node could have, which is 12. The lower limit of the number of available options is 2, which is the case when the distance is less than 910 m or greater than 10800 m. By doing that, we reduce the selection space of nodes from 240 options to a maximum of 12 options regardless of node's distance to the gateway. Once a node determines its transmission parameter options, it will sleep until it has a packet for transmission.

2) SAL operational modes: There are two operational modes in SAL that determine how a node selects a tuple of transmission parameters from the list that is created during the initialization phase, namely, the Round-Robin mode and the Random mode. In the Round-Robin mode, nodes initially select the first option in the list and keep using it until no more DCs are available on the channel of that option. In this case, it will select the second next option in the list, and continue until no more DCs are available on its channel, and so on. It is worth pointing out that the list is organized such that the options with the smallest SFs will be used first since the transmissions with small SFs will have less Time on Air (ToA). Hence, nodes will consume less of its DCs. In the Random mode, a node selects an option randomly from the list for each transmission regardless of whether more DCs are available. In other words, on each new transmission, a node selects a new option even if there are DCs available on the current selected channel. Consequently, we guarantee for each new transmission, nodes will select a new option even if the DC limit on the current selected channel is not yet reached. In both modes, if the DC limit on all the channels is reached, packets will be dropped until the beginning of the next frame (hour) where the DC is recharged and become at its maximum level. Algorithm 1 describes the Round-Robin approach of SAL algorithm.

Algorithm 1 Check DCL for current transmission options

Input: A new generated packet with $< CF_i, TX_i, SF_i >$
$DCperCF \leftarrow [DC_{CF1}, DC_{CF2}, DC_{CF3}, .., DC_{CF8}]$
$ToA \leftarrow TimeonAir(PL, SF_i, CR_i)$
while $ToA > DCperCF[CF_i]$ **do**
    $i++$
    if $i < TransOptions.size()$ **then**
        $CF_i \leftarrow TransOptions[i][0]$
        $TX_i \leftarrow TransOptions[i][1]$
        $SF_i \leftarrow TransOptions[i][2]$
    else
        break;
    end if
end while
if $i < TransOptions.size()$ **then**
    $sendPacket()$
    $updateDCperCF()$
else
    $droppedPackets++$
end if

3) Data transmission phase: At the beginning of each frame (hour), the duty cycle of all channels is recharged. Once a node has a packet to transmit, it will select an option from the list it has created during the initialization phase based on the operational modes, that were discussed earlier, to configure the transmission parameters of the packet. Once a node finishes its transmission, it will enter DELAY1 period, similar to LoRaWAN, and update the DC of the used channel by subtracting the Time on Air (ToA) of the transmission from the DC of that channel.

III. Performance Evaluation

This section evaluates the two modes of SAL algorithm (Round-Robin and Random) in comparison with the LoRaWAN protocol using several metrics including Packet Error Rate (PER), Capture effect Probability, End-to-end delay, Packet delivery Ratio, (PDR), Throughput and Energy Consumption. SAL algorithm is implemented and evaluated in OMNET++ simulator [12] under FLoRa framework [13]. Specifically, our proposed algorithm is implemented in the application layer of LoRaWAN end nodes within the FloRa framework. Hence, no required modifications were needed at the network server entity of FLoRa framework, as SAL algorithm is completely distributed. However, since FLoRa framework uses only the default channels, we have modified the framework to support channels from all the available subbands and not just the default one. We made the assumptions in relation to the network that simultaneous transmissions with

TABLE V
Simulation Parameters

Parameter	Value	Comments
CF	{868.1, 868.3, 868.5, 867.1, 867.3, 867.5, 867.7, 867.9}	Carrier Frequencies (MHz)
SF	7 to 12	Spreading factors
TP	(2, 5, 8, 11, 14) dBm	Transmission powers
CR	4/5	Coding rate
BW	125kHz	Bandwidth
R	10 km	Field radius
N	1000	Number of nodes
Simulation time	5	Days

different SFs are considered orthogonal and the used network topology is the star topology. Since the proposed algorithm intended for large-scale networks, we evaluate the algorithm under a relatively large number of nodes (i.e., 1000 nodes) that are randomly distributed within a radius of 10 Km from the gateway and with each node generating a 20-byte packet with an exponential inter-arrival time. Table V Summarizes the used simulation parameters.

A. Packet Error Rate (PER)

The PER is the ratio of the total number of packets that is received under the gateway sensitivity to the total number of packets that is transmitted by end nodes. Fig. 1 shows the PER as function of the packet inter-arrival time. Both modes of the proposed algorithm achieve lower PER compared to LoRaWAN. Specifically, the average PER of SAL is only 8% compared to that of LoRaWAN that stands at 83%. This can be attributed to the fact that SAL algorithm selects the combination of (CF, TX, SF) such that the estimated received power at the gateway will be above its sensitivity level. However, in LoRaWAN, nodes select randomly the combination of transmission parameters regardless of their distance to the gateway.

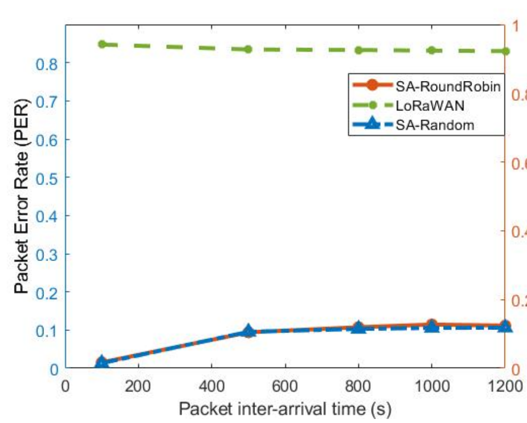

Fig. 1. Packet Error Rate (PER).

B. The probability of the Capture effect

Fig. 2 shows the probability of the capture effect as a function of the packet inter-arrival time. As shown in Fig. 2, SAL algorithm outperforms LoRaWAN, thanks to the wise distribution of transmission powers among the channels. In other words, nodes that use same channel will use similar transmission power levels as they are within the same distance from the gateway. Hence,their transmissions will be received nearly with the same power which will allow their successful decoding at the gateway. Unlike LoRaWAN, where a node can use a random transmission power on any channel regardless its distance to the gateway.

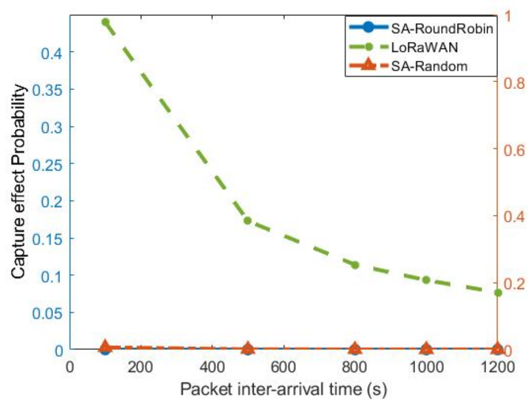

Fig. 2. The probability of the capture effect.

C. End-to-end Delay

Fig. 3 shows the end-to-end delay as a function of the packet inter-arrival time. As shown in Fig. 3, SAL-RoundRobin achieves the lowest delay since it allows nodes to use firstly the smallest eligible SF in their options list and keep using it till no more DC on the associated frequency. In other words, nodes use firstly the smallest eligible SFs in their lists. On the other hand, LoRaWAN and SAL-Random have longer delay than the SAL-RoundRobin as they select their SFs randomly. As a result, they select randomly SFs for their transmissions and hence they may select more frequent larger SFs with higher ToA and hence higher delay. It is worth pointing out that, although SAL-Random achieves the highest end delay, especially with high packet generation rate, it achieves the highest Packet Delivery Rate (PDR) and throughput as demonstrated in the following sections.

D. Packet Delivery Ratio (PDR)

Packet Delivery Ratio (PDR) is the ratio of the number of successfully received packets at the network server to the total number of packets that is transmitted by end nodes. Fig. 4 shows the PDR as function of the packet inter-arrival time. Obviously, SAL algorithm shows a superior performance in terms of the PDR with 64% compared to that of LoRaWAN with a PDR of only 15%. Indeed, as shown in Fig. 2 and Fig. 1. LoRaWAN has higher packet error rate and higher capture effect ratio which explains its low PDR.

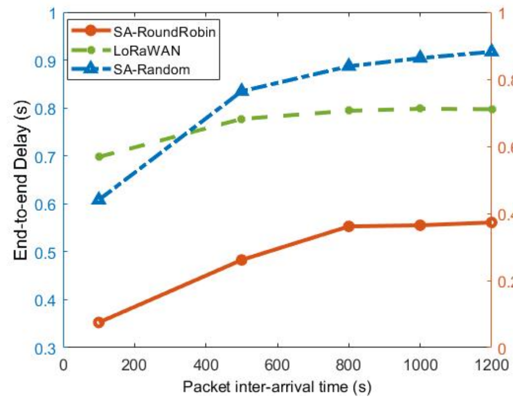

Fig. 3. The end-to-end delay.

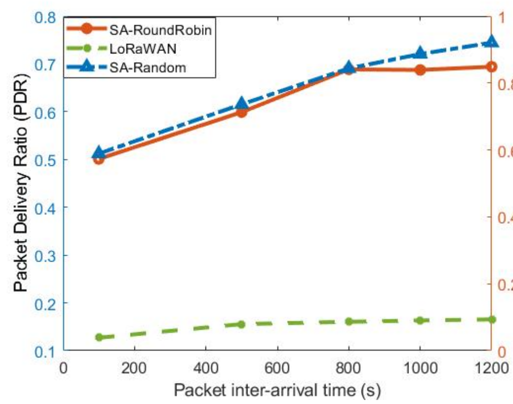

Fig. 4. The packet Delivery Ratio.

E. Throughput

Fig. 5 shows the network throughput as function of the packet inter-arrival time. Firstly, it is worth pointing out that both operational modes of the SAL algorithm achieve higher throughput than LoRaWAN. More importantly, the throughput of the proposed algorithm is much higher than LoRaWAN especially when the network has a high packet generation rate thanks to the efficient distribution of channels, SFs, and transmission powers among nodes. In fact, with high packet generation rate, LoRaWAN performs the worse due to the high PER (Fig. 1) and high capture effect ratio(Fig. 2).

F. Energy per Bit (EpB)

Fig. 6 shows the average energy consumed by nodes to successfully deliver one bit as a function of the average packet inter-arrival time. In general, LoRaWAN has the highest energy consumption since it has the highest PER and capture effect ratio. Specifically, when the network has high packet generation rate (i.e 1 per 100 seconds), LoRaWAN consumes more energy compared to the proposed algorithm.

IV. CONCLUSION

This paper proposed Sensitivity-Aware LoRa (SAL) algorithm that allows nodes to autonomously determine different

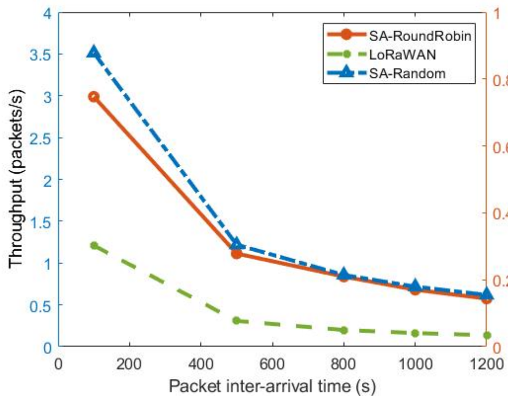

Fig. 5. Network throughput.

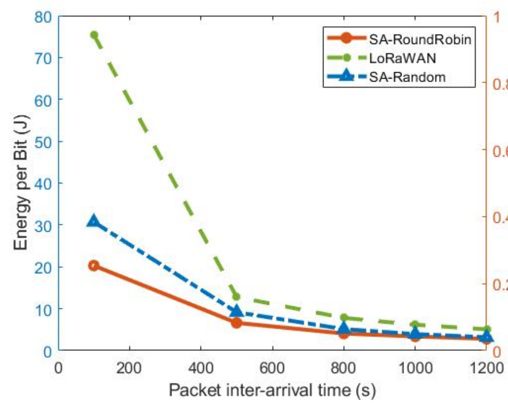

Fig. 6. Energy consumed per bit.

combinations of transmission parameters such that the packet error rate (PER) is minimized. Furthermore, SAL algorithm exploits all channels, SFs and transmission power levels provided by LoRa physical layer to increase the number of parallel transmissions and hence increase the network throughput without violating the duty cycle. To fully taking advantage of the multichannel communication provided by LoRa, the duty cycle of sub-bands was distributed among the channels of each sub-band. To the best of the authors knowledge, no research work has been proposed that exploit the multichannel communication considering the duty cycle limitation. SAL algorithm provides a limited set of possible transmission parameter options regardless of node's context. Hence, only a small storage space is needed to store these options. The proposed algorithm was evaluated using extensive simulations that emulate the real environment. Simulation results show that the average PER was enhanced by an almost 90% compared to LoRaWAN. Hence, the average throughput using SAL algorithm was tripled compared to the average throughput of LoRaWAN. As a future work, we will implement the proposed algorithm on real testbed to evaluate its performance in real environments.

References

[1] J. P. S. Sundaram, W. Du, and Z. Zhao, "A survey on lora networking: Research problems, current solutions, and open issues," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 371–388, 2019.

[2] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the Limits of LoRaWAN," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 34–40, 2017. [Online]. Available: 10.1109/mcom.2017.1600613; https://dx.doi.org/10.1109/mcom.2017.1600613

[3] S. Corporation, "What is LoRaWAN® | LoRa Alliance®." [Online]. Available: https://lora-alliance.org/resource-hub/what-lorawanr

[4] A. Ikpehai, B. Adebisi, K. M. Rabie, K. Anoh, R. E. Ande, M. Hammoudeh, H. Gacanin, and U. M. Mbanaso, "Low-power wide area network technologies for internet-of-things: A comparative review," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2225–2240, 2019.

[5] D. Magrin, M. Capuzzo, and A. Zanella, "A thorough study of lorawan performance under different parameter settings," *IEEE Internet of Things Journal*, vol. 7, no. 1, pp. 116–127, 2019.

[6] J. Finnegan, R. Farrell, and S. Brown, "Analysis and enhancement of the lorawan adaptive data rate scheme," *IEEE Internet of Things Journal*, vol. 7, no. 8, pp. 7171–7180, 2020.

[7] F. Cuomo, M. Campo, A. Caponi, G. Bianchi, G. Rossini, and P. Pisani, "Explora: Extending the performance of lora by suitable spreading factor allocations," in *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. IEEE, 2017, pp. 1–8.

[8] B. Reynders, W. Meert, and S. Pollin, "Power and spreading factor control in low power wide area networks," in *2017 IEEE International Conference on Communications (ICC)*. Paris, France: IEEE, May 2017, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/document/7996380/

[9] B. Reynders, Q. Wang, P. Tuset-Peiro, X. Vilajosana, and S. Pollin, "Improving Reliability and Scalability of LoRaWANs Through Lightweight Scheduling," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 1830–1842, Jun. 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8315103/

[10] K. Q. Abdelfadeel, V. Cionca, and D. Pesch, "Fair Adaptive Data Rate Allocation and Power Control in LoRaWAN," in *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*. Chania, Greece: IEEE, Jun. 2018, pp. 14–15. [Online]. Available: https://ieeexplore.ieee.org/document/8449737/

[11] J.-T. Lim and Y. Han, "Spreading Factor Allocation for Massive Connectivity in LoRa Systems," *IEEE Communications Letters*, vol. 22, no. 4, pp. 800–803, Apr. 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8268120/

[12] OMNeT++ Discrete Event Simulator, 2018. [Online]. Available: https://omnetpp.org/

[13] M. Slabicki, G. Premsankar, and M. Di Francesco, "Adaptive configuration of lora networks for dense iot deployments," in *NOMS 2018-2018 IEEE/IFIP Network Operations and Management Symposium*. IEEE, 2018, pp. 1–9.

[14] S. Corporation, "Sx1272/3/6/7/8: Lora modem. designer's guide," 2013. [Online]. Available: shorturl.at/hwzHY

[15] ——, "Sx1272/73 datasheet rev 3.1," 2017. [Online]. Available: shorturl.at/klBDI

[16] T. S. Rappaport, "Wireless communications–principles and practice, (the book end)," *Microwave Journal*, vol. 45, no. 12, pp. 128–129, 2002.

[17] M. C. Bor, U. Roedig, T. Voigt, and J. M. Alonso, "Do lora low-power wide-area networks scale?" in *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, 2016, pp. 59–67.

[18] E. Standard, "Final draft etsi en 300 220-1, v2.4.1," 2012. [Online]. Available: shorturl.at/bnuL5

[19] T. T. Network. Duty cycle. [Online]. Available: https://www.thethingsnetwork.org/docs/lorawan/duty-cycle/

[20] ——. Frequency plans. [Online]. Available: https://www.thethingsnetwork.org/docs/lorawan/frequency-plans/

[21] C. Goursaud and J.-M. Gorce, "Dedicated networks for iot: Phy/mac state of the art and challenges," *EAI endorsed transactions on Internet of Things*, 2015.