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An Adaptive and Lightweight Spreading Factor Assignment Scheme for LoRaWAN Networks

Shumaila Farhad[1], M. Ali Lodhi[2], Wajid Ullah Khan[1], and Fahad Masood[1]
[1]Department of Computing & Technology, Abasyn University
Peshawar, Pakistan
[2]School of Software Technology, Dalian University of Technology
Dalian, China
shumailafarhad@codeforpakistan.org, alilodhi30@mail.dlut.edu.cn

***Abstract*—** Presently, a long-range wide area network **(**LoRaWAN) uses an adaptive data rate (ADR) by aiming to provide consistent and energy-efficient communication to the Internet of Things devices. The ADR manages both the spreading factor (SF) and transmit power at the end device (ED) and network server-sides. However, the performance of ADR is severely affected by the variable channel conditions, resulting in massive packet loss. Therefore, we propose two schemes: the initial SF assignment scheme (I-SFA) during the deployment phase and a recovery method called adaptive SF assignment based on the interference (A-SFA). The I-SFA assigns the best SF to EDs based on the received power that a gateway would receive from ED. Whereas A-SFA is used as a recovery method when a collision between two packets of the same SF occur, the A-SFA changes the SF. Hence, it reduces the chances of future interference and thus improves the packet delivery ratio. Simulation results show that the proposed schemes perform better in terms of packet delivery and energy consumption compared to the existing methods.

Keywords—LoRaWAN; adaptive data rate; resource allocation; interference;

I. Introduction

Long-range wide area networks (LoRaWANs) [1] is one of the Low power wide area networks (LPWANs) technologies. LoRaWAN has been adopted as one of the substitutes for the Internet of Things (IoT) applications due to long-range, energy-efficient, and low data rates [2]. LoRaWAN provides practical solutions to meet a wide range of IoT application requirements [3]. These include packet length, packet delivery ratio, reliability, and mobility characteristics. To fulfill IoT application requirements, LoRaWAN uses class *A* end devices (EDs).

Fig. 1 shows the LoRaWAN architecture, where class *A* EDs always initiate uplink packets to a gateway (GW). GW is responsible for forwarding the received packet to a network server (NS) via Cellular/Ethernet. The NS is responsible for managing resources such as transmit power and data rate. Class *A* EDs are more energy-efficient and support bi-directional communication. When a class *A* ED transmits an uplink packet to a GW, it open two receive windows for the downlink packet. The NS transmits a downlink packet (i.e., acknowledgment) to the corresponding ED [4]. If acknowledgment (ACK) is missed in both of the receive windows, an ED retransmits the previous packet by choosing a random time between 1 to 3 seconds to avoid further collision.

Class *A* EDs employ an adaptive data rate (ADR) scheme for reliable and energy-efficient communication [5]. ADR consist of two methods implemented at the ED and NS-sides. The ADR implemented at ED-side is only responsible for incrementing the spreading factor (SF) to regain GW connectivity. Whereas the NS-side ADR is accountable for managing both SF and transmit power (TP) based on the past 20 packets received at the NS. When the NS reconfigures both SF and TP, a downlink MAC command is transmitted to ED containing SF and TP.

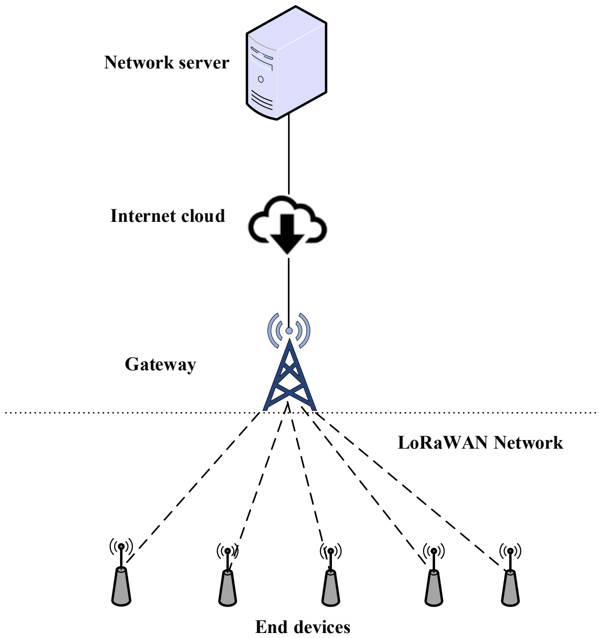

Figure 1. The underlying architecture of LoRaWAN.

Moreover, the ADR method described in LoRaWAN has been primarily designed for static EDs [5]. However, the performance of ADR is severely affected owing to the channel conditions, such as shadowing and fading [6]–[9]. Therefore, the ADR method suffers from massive packet loss and retransmissions. Moreover, ADR uses SF=12 during the initial network deployment, which increases the interference among the packets of other EDs. As a result, interference forces EDs for retransmissions. It is because high SFs are highly vulnerable to interference, and it causes an avalanche effect. Therefore, to resolve this issue, we propose two schemes: the initial SF assignment scheme (I-SFA) during the deployment phase and a recovery method called adaptive SF assignment based on an interference scheme (A-SFA).

The primary aim of the I-SFA scheme is to assign the best SF to EDs based on the received power that a GW would receive from ED to lower the impact of interference. Whereas A-SFA is used as a recovery method when a collision between two packets of the same SF occur, A-SFA changes the SF. Hence, it reduces the chances of future interference and thus improves the packet delivery ratio.

The rest of the paper is organized as follows: Section II provides an in-depth overview of the published work. Section III elaborates on the proposed methods. Experimental results and analysis of the proposed schemes compared with ADR, ADR+ [10] are presented in Section IV, while the last section concludes this paper.

II. Literature Review

In the existing literature, researchers mainly focus on enhancing the PDR. This section presents the published work in the area of resource allocation to EDs in the LoRaWAN network.

To allocate resources (i.e., SF) to EDs, the authors present an SF scheme [11]. They aim to optimize the packet error rate by considering a single GW cell. The main idea behind their scheme is that it allocates the SFs to each ED to avoid the near-far issue and assign distinct EDs to different channels. Thus, it reduces the chances of interference and collision. As a result, their scheme enhanced the error rate by up to 50%.

Paper in [6] presents the performance assessment of the ADR scheme by highlighting the limitations such as convergence period under variable channel conditions. It is further enhanced by [10], which averages the SNR of the 20 received packets at the NS. Their solution shows an increase in performance as compared to the typical ADR. However, ADR+ has been only evaluated with the typical ADR in the absence of a realistic urban environment.

Authors in [12] further enhance the ADR scheme in terms of reducing the convergence period. It is shown in [12] that ADR suffers from a high convergence period in variable channel conditions. The ADR is inefficient to lossy channel links, which forces ADR to converge to a stable state in hours [13]. Therefore, ADR suffers from high packet loss, and in return, the retransmission is increased from the EDs. Their method is simple, which calculates the SF and TP based on the five uplink packets instead of considering the 20 uplink packets received at the NS.

Recently, the performance of ADR has been evaluated under the mobility environment [14]. It is shown in [14] that the ADR mechanism is not efficient in mobility because it is only applicable to static EDs.

To improve the performance of ADR in terms of packet delivery ratio by reducing the impact of interference, in this paper, we propose two schemes: I-SFA during the deployment phase and a recovery method called A-SFA. Both the proposed methods do not modify the rest of the ADR mechanism at the ED and NS. Moreover, the proposed methods improve the performance in terms of packet success ratio and decrease the packet loss caused by interference.

III. The Proposed Schemes

In this section, we present the proposed schemes called I-SFA and A-SFA. I-SFA mainly allocates the SF to EDs during the initial deployment phase. In contrast, A-SFA is a recovery scheme that assigns a new SF based on collision between the two packets transmitted with the same SF on the same channel. In the remainder of this section, we explain the proposed schemes in detail.

A. I-SFA scheme

The working procedure of the proposed I-SFA scheme is presented in Fig. 2. The first step in the proposed I-SFA scheme is to find the received power (P_{rx}) at GW (that is a GW can receive from ED). The primary aim of this scheme is to assign a suitable SF based on the GW sensitivities (S_g, as shown in Table 1) to avoid packet loss arriving under the sensitivity at GW. Table I shows the SF sensitivities of GW (S_g) and ED (S_e), respectively.

TABLE I. Sensitivities of EDs and GW [15], [16].

SF	BW [kHz]	S_g	S_e
12	125	-142.5	-137.0
11	125	-140.0	-135.0
10	125	-137.5	-133.0
9	125	-135.0	-130.0
8	125	-132.5	-127.0
7	125	-130.0	-124.0

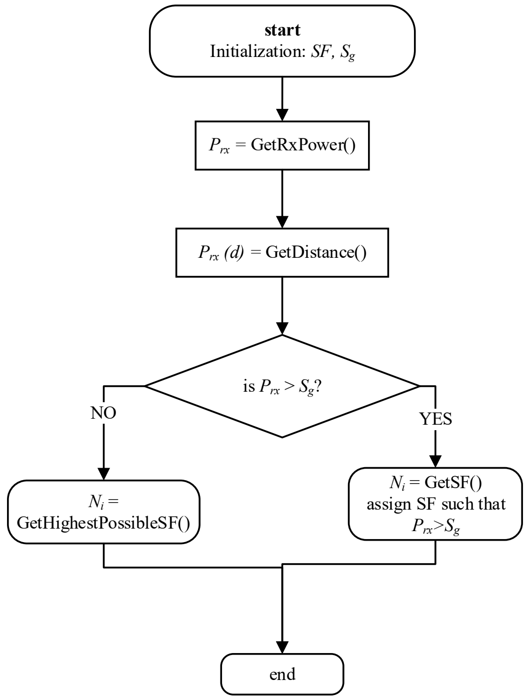

Figure 2. Working procedure of I-SFA.

When the ED transmits a packet to GW, it can be detectable if P_{rx} is above the sensitivity level for a specific SF. In this paper, we assume that the P_{rx} of a packet is constant during the whole simulation period. If the P_{rx} is sufficient, then the GW can start the decoding process and can receive a packet correctly. Once a proper is SF identified based on the P_{rx}, the proposed scheme I-SFA computes the distance between an ED and a GW using Euclidean distance.

After the P_{rx} estimation, the distance can be computed using equation (1) (i.e., Euclidean distance), as presented in [17].

$$P_r(d) = A - 3.76n \times \log_{10}(d) \tag{1}$$

where $P_{rx}(d)$ represents the received power in dBm at distance d, A represents the received power at 1 meter, and n is the exponent called path loss exponent. The value of n in LoRaWAN is much dependent on the antenna height of the gateway. Here n=3.76, which is based on an antenna height of 15 m.

The I-SFA scheme compares the computed P_{rx} value against the S_g. If the condition holds, then a proper SF is assigned. Otherwise, if EDs are out of range, then SF 12 is set. The process is continued until all EDs involved in the communication gets SF. When the SFs are assigned to all EDs, the EDs start transmitting packets in uplink direction to a GW. If interference between the two packets of two different EDs with the same SF occur, the A-SFA is responsible for assigning a new SF to decrease further collision.

B. A-SFA scheme

The working of the proposed A-SFA scheme is shown in Fig. 3.

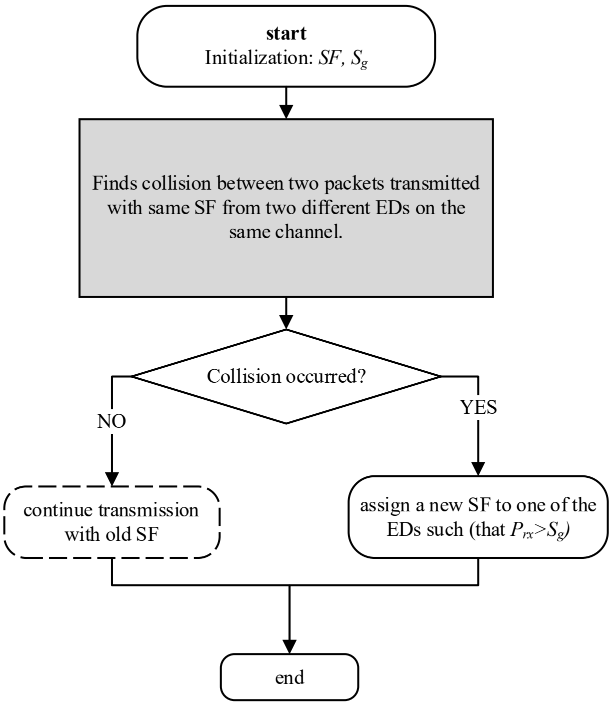

Figure 3. Working procedure of the A-SFA scheme.

A-SFA scheme deals with identifying the interference with two packets being transmitted with the same SF, where the interference model is based on [18]. We assume that a packet is always correctly decoded and received if it is above the sensitivity threshold [19], and we also assume that this packet survived interference. Otherwise, the packet is lost and retransmitted. When the collision has occurred between two same SF (e.g., SF 12) over the same channel, the proposed A-SFA will change the SF of one of the two EDs involved in the collision. If the collision has already occurred, the proposed A-SFA scheme checks if the condition is true, then a new SF is assigned. Otherwise, the communication continues with the old SF.

IV. Experimental Results

This section evaluates the performance of ADR, ADR+, and proposed schemes (I-SFA and A-SFA) using NS-3 [20].

A. Simulation Background

In the simulation, every ED transmits an uplink packet to NS via GW and expects an acknowledgment in response from the server. The rest of the simulation parameters are shown in Table II.

TABLE II. Simulation Parameters.

Parameter		Value
Simulation time [h]		1
Uplink time [min]		30
Circular radius [m]		7500
Gateway		1
Size of a packet [bytes]		51
EDs		200-1000
Number of default channels [Europe region 868 MHz]		3
GW antenna height [m]		30
EDs antenna height [m]		1.5
Path loss exponent		3.52
Mode of communication		confirmed
Propagation loss model		log-distance
Shadowing model	correlated shadowing	110 m [21]
	variance	6 dB
ED power		14 dBm
ED distribution		circular

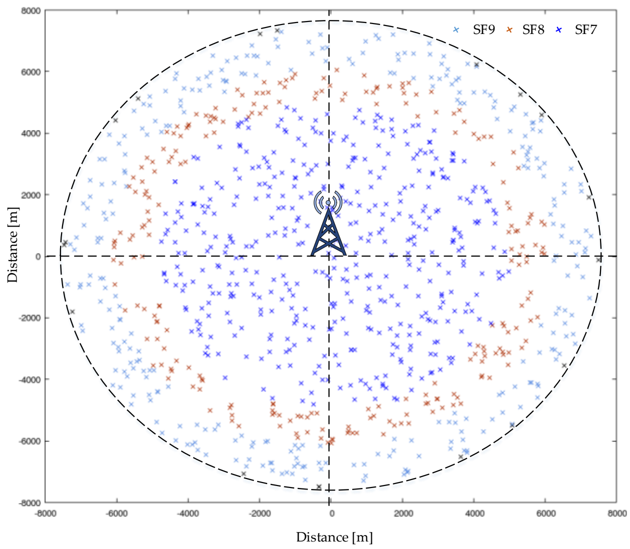

Figure 4. The SF assignment using the proposed algorithm (I-SFA).

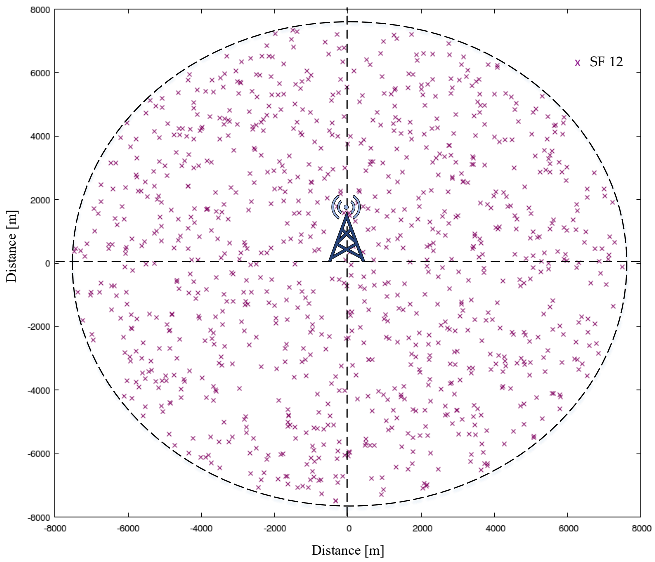

Figure 5. The SF assignment using the ADR scheme (with SF = 12).

Further, the simulation scenarios under log-distance are shown in Figs. 4, and 5. Fig. 4 shows the SF distribution using the proposed I-SFA scheme, where the EDs get SF based on the received signal strength during the initial network deployment, while Fig. 5 shows the SF assignment using SF=12 (ADR-based). Generally, ADR uses SF=12 and transmit power =14 dBm during the initial deployment. Therefore, it suffers from high interference because higher SF generates more interference [4], [13].

B. *Performance evaluation*

1) Packet delivery ratio: The average packet delivery ratio of the proposed algorithm compared with ADR and ADR+ is presented in Fig. 6. ADR has the worst performance in PDR because the network server-side ADR changes SF and transmit power based on the highest signal-to-noise (SNR) value among the last 20 packets received. On the other hand, ADR+ takes the SNR of the previous 20 packets received at the network server, resulting in a better PDR compared to ADR.

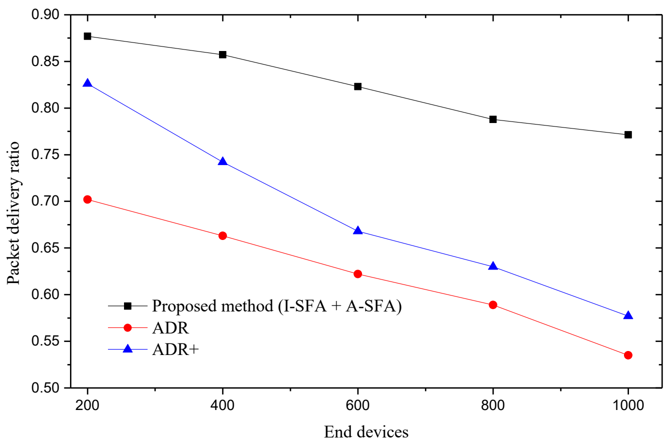

Figure 6. Average packet delivery ratio.

TABLE III. PDR IMPROVEMENT FOR THE PROPOSED SCHEMES (I-SFA AND A-SFA) IN COMPARISON WITH ADR AND ADR+.

EDs	Improvement in PDR	
	improvement than ADR	**improvement than ADR+**
200	24.9%	6.1%
400	32.3%	18.2%
600	32.3%	23.2%
800	33.7%	25.0%
1000	49.7%	33.6%
average improvement	**34.6%**	**21.2%**

However, in Fig. 6, the proposed scheme outperforms the remaining algorithm due to its efficient SF allocation during the deployment and recovery algorithms. The recovery algorithm assigns a new best possible SF (based on the GW sensitivity) when interference between the two packets of the same SF over the same channel occurs. Therefore, it increases the PDR. The PDR improvement for the proposed scheme in comparison with ADR and ADR+ is highlighted in Table III.

Another scenario presented in Fig. 7, showing the PDR in per-hour for the proposed ADR, and ADR+ algorithms. In Fig. 7, the results are presented for N=200 and under log-distance environment. Overall, it can be seen that the PDR of all algorithms fluctuates with time. However, the proposed scheme outperforms the ADR and ADR+ in terms of PDR. After 17 hours, the ADR algorithm PDR is decreased because it cannot assign the best SF and transmit power. Therefore, the packet arrives under the sensitivity at the GW. Hence, the packets are lost at GW.

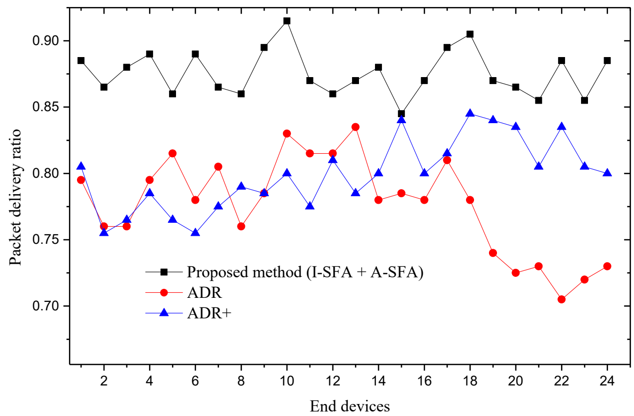

Figure 7. Per-hour packet delivery ratio.

2) Energy consumption: The average energy consumption in Joules for the proposed algorithm, ADR, and ADR+ is shown in Fig. 8. The energy consumption parameters are described in Table IV.

The energy consumption computed in Fig. 8 is based on the total energy consumed in the transmission state divided by the total number of packets successfully received at the GW. The energy consumption of ADR+ is higher than that of ADR because of retransmissions. When the packets are lost due to interference or arrived under the sensitivity at GW, they are retransmitted. Therefore, it uses more energy consumption.

However, on the other hand, the proposed scheme outperforms the existing methods in energy consumption due to its higher PDR, a low number of retransmissions, and interference. The energy consumption improvement for the proposed schemes in comparison with ADR and ADR+ is highlighted in Table V.

TABLE IV. ENERGY CONSUMPTION PARAMETERS [8], [22], [23].

Parameter	Value
Initial energy (J)	10000
Supply energy (V)	3.3 [24]
Standby (A)	0.0014
Current in transmission (A)	0.028
Sleep current (A)	0.0000015
Reception current (A)	0.0112

TABLE V. ENERGY CONSUMPTION IMPROVEMENT FOR THE PROPOSED SCHEMES (I-SFA AND A-SFA) IN COMPARISON WITH ADR AND ADR+.

EDs	Improvement in energy consumption	
	improvement than ADR	**improvement than ADR+**
200	14.1%	41.2%
400	71.4%	83.1%
600	63.8%	77.4%
800	64.5%	77.9%
1000	67.3%	78.7%
average improvement	**56.2%**	**71.7%**

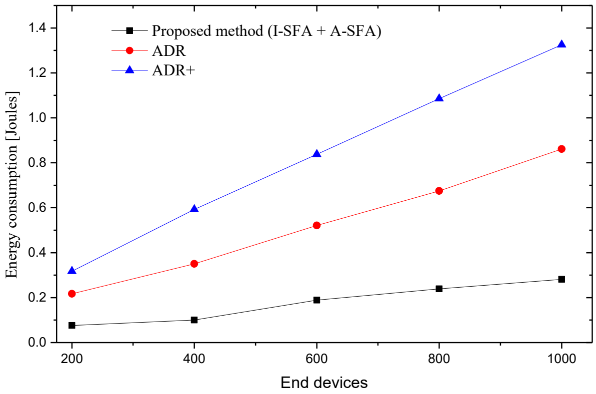

Figure 8. Average energy consumption in Joules.

3) Additional Analysis: Another scenario for PDR and packet losses is presented in Fig. 9, only for the proposed schemes.

Information presented in the legend of Fig. 8 is explained as follows.

- **I:** packet loss occurs due to the interference when two packets using the same SF collide.
- **S:** packet loss occurs when packets arrive under the sensitivity at GW (the sensitivities for different SFs, as shown in Table I).
- **R:** a packet is lost due to saturated receiver paths. In LoRaWAN, a single GW supports eight parallel reception paths for the default three channels in the European region (i.e., 868 MHz frequency). When all reception paths are busy receiving the packets, the other incoming packets arriving at the GW are lost [13].
- **T:** packets are lost due to the GW transmission procedure. By default, the GW in the LoRaWAN network suggests transmitting acknowledgment on a priority based. Therefore, when a GW is busy sending the acknowledgment to the concerned ED, the incoming packets from any other ED can be lost at the GW [8].

It can be seen in Fig. 9 that due to efficient SF allocation, there is no packet loss recorded for *S*. Therefore, it is evident that the proposed schemes jointly perform efficiently and produce significantly good results in terms of PDR.

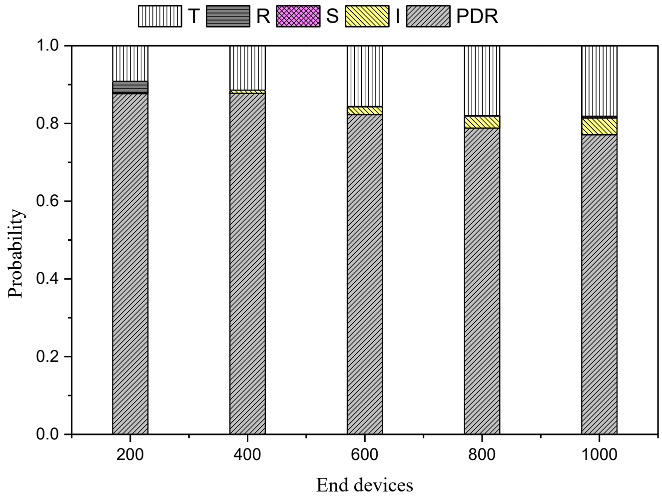

Figure 9. Probability of packet losses and PDR.

V. CONCLUSIONS

LoRaWAN employs an adaptive data rate for managing the SF and TP both at the ED- and NS-sides. The primary aim of the ADR is to provide reliable and energy-efficient communication to EDs. However, due to massive EDs in the network, the ADR performance is severely affected due to lossy links. As a result, the LoRaWAN network suffers from high packet loss due to increased interference. Therefore, we proposed two schemes I-SFA and A-SFA. The I-SFA scheme assigned a suitable SF to EDs based on the received power that a gateway would receive from ED. At the same time, the A-SFA scheme was used as a recovery method. When a collision between two packets of the same SF occurred during communication, the A-SFA scheme changed the SF to decrease further chances of a collision. Through simulation results, we showed that our proposed methods (I-SFA and A-SFA) enhanced the packet delivery ratio by lowering the impact of interference in comparison with ADR and ADR+. It was observed that the proposed scheme improved the PDR by (up to 34% and 21% than ADR and ADR+, respectively.

Moreover, due to the high packet delivery ratio, the proposed schemes significantly reduced the energy consumption on average, up to 56% compared to the ADR. We also observed that the duty cycle limitations and bi-directional communication limit the scalability of the LoRaWAN network substantially. In the future, we plan to advance the ADR mechanism (i.e., NS-side) by taking the moving average of the last 20 received packets at the NS under static and mobility environments.

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