Time-Slotted ALOHA-based LoRaWAN Scheduling with Aggregated Acknowledgement Approach

Gokcer Yapar, Tuna Tugcu
Bogazici University
Istanbul, Turkey
{gokcer.yapar, tugcu}@boun.edu.tr

Orhan Ermis
EURECOM
Sophia-Antipolis, France
ermis@eurecom.fr

Abstract—**Long range (LoRa) wide-area network (LoRaWAN) protocol is a promising candidate for Internet of Things devices that operate on Low Power Wide Area Networks (LPWAN). Recent studies on this protocol are mostly focused on uplink (UL) communication. In particular, the performance of the pure ALOHA type MAC protocol used in this protocol is not fully observed. Investigations have revealed that the pure ALOHA type MAC protocol and downlink (DL) traffic may cause significant negative impacts in terms of the scalability and the reliability of the network. For this respect, in this paper, we propose an extension to LoRaWAN MAC layer, called Aggregated Acknowledgment Slotted Scheduling LoRaWAN (A2S2-LoRaWAN), to improve the scalability and reliability of LoRaWAN. A2S2-LoRaWAN contains time-slotted ALOHA-based periodic frame structure, which is supported by aggregated acknowledgment methods, for scheduling transmissions. A2S2-LoRaWAN reduces UL-DL traffic and increases the scalability of LoRaWAN. For instance, while A2S2-LoRaWAN decreases UL-DL traffic five times compared to LoRaWAN, its success rate with 10,000 End-Devices (EDs) transmitting 10-byte payload is twice better than the success rate of LoRaWAN with a single gateway (GW).**

I. Introduction

While Internet of Things (IoT) promises significant changes in our daily lives, it also poses significant challenges to the communications infrastructure. IoT devices and services substitute monotonic human tasks as generating data, sensing information, or maintaining request-based services [1]. According to a prediction by Cisco, there will be 12 billion connected devices until 2020 for various purposes such as monitoring [2]. Such increase in the connected devices will bring a burden in terms of the uplink data since these devices are also considered as data generators [3].

In [4], Long range wide-area network (LoRaWAN) is composed of three main network components: end devices (EDs), gateways (GWs) and centralized Network Server (NS). These components forms the LoRaWAN network in a start-of-stars topology. In other words, there is not a direct connection between the EDs and the NS. The communication is established over the GW, which relays the message of ED to NS through a reliable and high throughput link indirectly. In addition, the transmissions on the wireless communication channel between ED and GW are modulated by using LoRa or Frequency Shift Keying (FSK) modulation. There is no rule for ED that it should send its message to an attached GW, because there is no terminal attachment for the network. Therefore, EDs transmits to the most available GWs. After receiving a message from the ED, each GW forwards it to a centralized NS that is responsible for selecting the best GW to transmit DL communications to the ED and filtering duplicate messages. For the purpose of maximizing the resilience of the network to interference and to make it robust against distortions in the wireless channel, multiple logical channels are determined for the entire network. Moreover, EDs are expected to choose a channel in a pseudo-random fashion. In order to get an ED connected to LoRaWAN, it has to first register to the network. There are two types of registration methods in LoRaWAN: Over-The-Air Activation (OTAA) and Activation By Personalisation (ABP). Indeed, there are three types of devices for the use cases of the EDs: Class A, Class B, and Class C, which are mainly distinguished with respect to their different behaviors against power consumption and transmission schedule. Enforced by the standard, all LoRaWAN EDs must implement Class A features, and the implementations of the other two classes are optional. In Class A, transmission schedule is based on the communication needs of the ED whose communication channel is bi-directional. An ED of Class A opens its receive window after transmitting the message to GW. DL communication is not initialized by the NS; in other words, it could be active after a UL communication initiated by the ED. Furthermore, the ED waits to receive an acknowledgment (ACK) message after sending a confirmed message. If the ED does not receive the ACK message, it retransmits its message until reaching the upper limit of retransmissions.

LoRaWAN is a promising IoT technology due to its low power consumption and long distance transmission capability [5]. Yet, LoRaWAN also has its shortcomings, especially in the number of supported EDs. Such shortcomings are rooted in the contention of the medium shared by the end devices, and also in the uplink (UL) and the downlink (DL) traffic. While the UL traffic carries the data from the end devices towards the network servers, the DL traffic constitutes mainly from the ACK packets. Unfortunately, uplink data must compete with their corresponding downlink ACKs, subject to collisions, backoffs, retransmissions, and frame separations. To the best of our knowledge, this problem has not been addressed in the literature and further it is our main motivation for this study.

We may define the details of the problem as follows. LoRaWAN operates in sub-GHz ISM bands [6]. Thus, LoRaWAN devices must comply with wireless communication policies defined by ETSI [7], for Europe, enforcing restrictions on its transmission on the unlicensed bands. Since it lacks Listen-Before-Talk (LBT) mechanism, a LoRa device can transmit

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for 36 seconds per hour in a subband at most with 1% Duty Cycle (DC) constraint. This is valid also for DL. Due to collisions or the DC constraints, ACK messages may not be received by EDs, which results in the retransmission of the same messages. Consequently, the number of collisions in the network increases with growing number of EDs and UL traffic. Since LoRaWAN devices transmit using ALOHA-based approach subject to regional DC regulations ([8]), the increase in traffic hampers the scalability of the LoRaWAN network. LoRaWAN's scalability problem is due to the negative impact of DL on the UL [9]. In LoRaWAN networks with large number of EDs, requiring ACK does not scale [10]. The main reason is the ALOHA type MAC protocol used by LoRaWAN and the DC restrictions on DL [11]. In other words, not using a DC-friendly MAC protocol in LoRaWAN causes a significant problem for network scalability.

Several scheduling solutions are proposed in the literature to reduce collisions and increase network performance. In [12], a new MAC layer is proposed as a two-step lightweight scheduling, which divides EDs to groups. Also, EDs are directed to choose different spreading factors (SFs) to improve reliability and scalability. On the other hand, the system model of the solution could be improved by considering the DC restriction on GW for avoiding retransmission and accessing the resource in the subframe could be in a slotted manner for increasing the network reliability. The study in [13] implements an on-demand scheduling approach, where the nodes demand time slots from GW. Then, GW sends selected time slot indices encoded in a bloom filter, a probabilistic data structure, by which DL traffic is reduced. However, collisions still occur since the probabilistic data structure can have false positives. After running test scenarios with the solution, 7% to 30% increases in packet delivery ratio for SF7 and SF12 occur for Class A of LoRaWAN. In [14], two offline algorithms for the allocation of SFs mechanism are proposed for minimizing the total time of data collection at the nodes. Although these algorithms considers DC limitations, the test scenarios that were run with 1000 nodes, which is not a realistic number and also, the packet size of some EDs used in the scenarios is not approved by LoRaWAN specifications. The proposed study in [15] implements slotted ALOHA for LoRaWAN and further presents performance evaluations on real devices. Thus, the success of slotted ALOHA LoRaWAN noticed compared to pure ALOHA LoRaWAN.

Unlike most of the previous work in the literature, we design our system model subject to DC restrictions on GW. Moreover, our proposed solution, Aggregated Acknowledgment Slotted Scheduling LoRaWAN (A2S2-LoRaWAN), is evaluated with 10,000 EDs in a cell and with different packet sizes supported by all SF EDs. In this paper, the following contributions are proposed for solving the scalability problem of the LoRaWAN:

- We propose a DC-friendly time-slotted ALOHA-based LoRaWAN scheduling for improving network scalability and decreasing UL message traffic.
- We propose Naive Aggregation (NA) method to decrease traffic of DL messages by aggregating ACK messages.
- We derive a formal mathematical representation of A2S2-LoRaWAN scheduling model to validate the proposed system performance.
- We present performance evaluations based on simulation scenarios that consider the increasing number of devices in the network, increasing the load of message payload sent from EDs to GW and changing the SF-based distribution of the EDs inside the network.

II. System Design

In this section, we introduce the system design of the A2S2-LoRaWAN. The proposed model has three phases: the system model, the medium access scheduling, and aggregated acknowledgment as shown in Fig. 1. A2S2-LoRaWAN operates as follows. First, ED registers to the Network Server (NS), then sends a request to get scheduling parameters. Upon receiving these parameters, ED synchronizes its UL traffic and DL traffic.

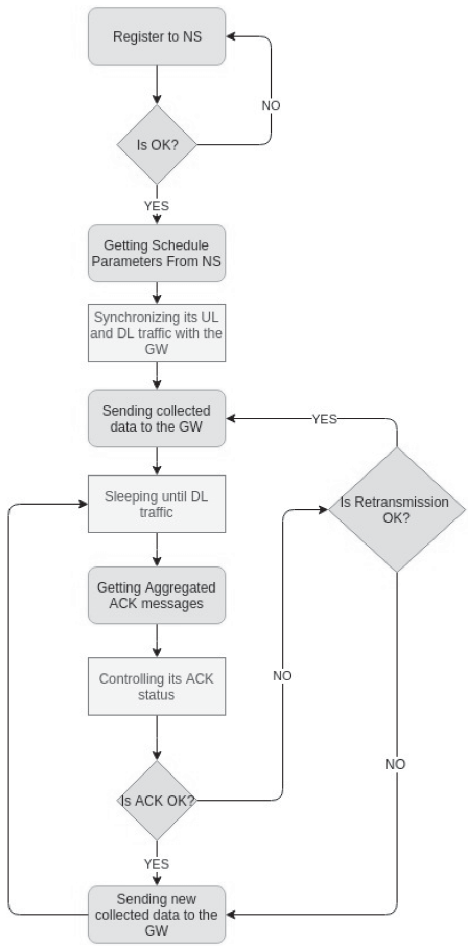

Fig. 1. An ED lifecycle in the A2S2-LoRaWAN solution as a state diagram

A. System Model

In A2S2-LoRaWAN, the entire available channel is divided into repetitive frames, called super-groups, with the duration of t_G. Each SF has its own super-group overlapping in time with the super-groups of the other SFs and each super-group consists of several groups. Therefore, each group starts with

UL slots followed by one DL slot of which time-on-air is equal to one UL slot in the group. Moreover, there is a constant time, which is the active period of the GW, between the DL slots of each group in a super-group. According to the system model, the system is designed as a periodic two dimensional array, whose rows correspond to the super-groups and columns match the groups, as shown in Fig. 2.

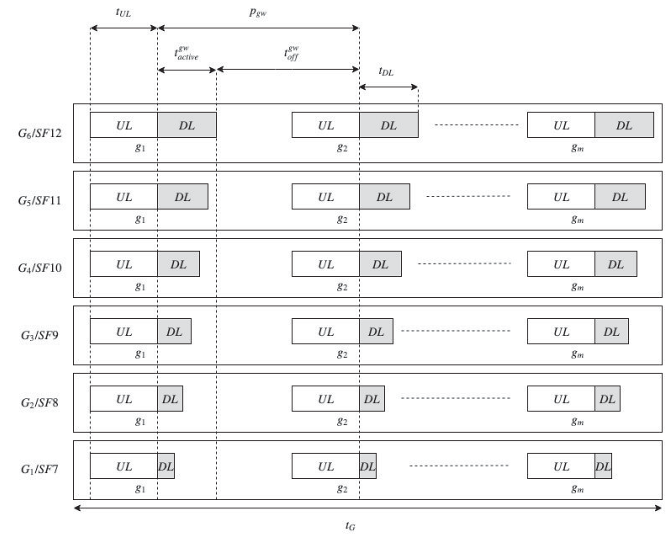

Fig. 2. System model repetetive frame structure contains six super-groups, which consist of identical time-slotted groups

TABLE I. TIME DEFINITIONS IN THE SYSTEM MODEL

Symbol	Description
t_{DL}	Time duration of one slot DL in a group (differs by each super-group)
t_{UL}	Time duration of the entire UL slots in a group (same for each super-group)
t_G	Time duration of the each super group (same for each super-group)
t^{gw}_{off}	Time off duration of gateway "gw" (same for each super-group)
t^{gw}_{active}	Active time duration of gateway "gw" (same for each super-group)
p_{gw}	Transmission period of gateway "gw" (same for each super-group)

The groups in each super-group have group ids and different groups in each super-group have the same number of groups. In addition, the time duration of the UL slots in each group, and the time duration of each super-group are equal. Moreover, we assume that transmission time of the groups with the same group id in the different super-groups is the same. Thus, GW can transmit ACK to each ED inside the groups with the same group id in each super-group at the same time.

B. System Scheduling

As shown in Fig. 2, a group consists of two communication partitions. According to Fig. 3, the UL section is divided into identical time slots, which differ for each super-group. ED in the group can randomly select a time slot while making a transmission. Once the message is transmitted, ED opens its receive window at the DL section of the group. For realizing the system model, EDs should know the schedule parameters for their group, time slot duration of the group, and the first group transmission time in their own super-groups. After getting the schedule parameters from NS, ED is synchronized with the system.

TABLE II. SYNCHRONIZATION PARAMETERS RECEIVED BY AN ED FROM THE NS

Symbol	Description
$subscription\_id$	Subscription id of the ED (It is used for describing its transmission time and is used to check its) ACK status by controlling the received ACK message.
l_{type}	The payload type used in the network
T_1	The transmission time of the first group in its super-group as shown in Fig. 3
t_G	Described as in Table I

Once registered to the network, ED sends a request to NS for getting l_{type}, subscription_id, T_1, and t_G to synchronize itself with GW according to the system model design in Fig. 3.

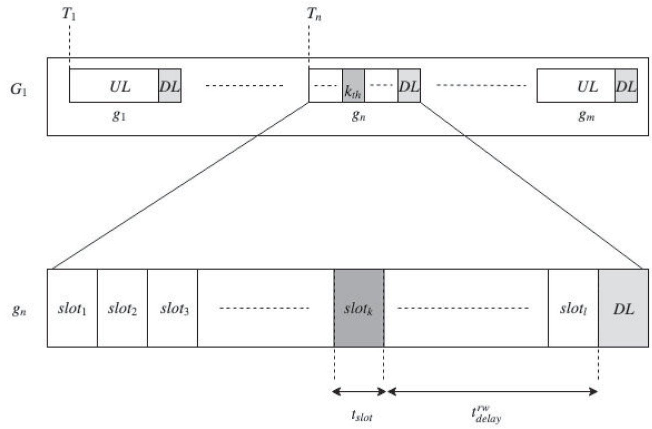

Fig. 3. ED in g_n, which is a group with the id n of G_1 super-group, transmits a message at $slot_k$. After transmitting the message, ED opens its receive window end of t^{rw}_{delay} time

Upon receiving the parameters in Table II, ED should calculate own transmission schedule. According to the scenario in Fig. 3 and the model in Fig. 2, ED should consider the steps in Algorithm 1.

C. Aggregated Acknowledgment

When the message is transmitted, ED opens its receive window in the DL section of its group for retrieving the DL message, which is an aggregated ACK message. GW can create the aggregated ACK message by using a NA method. After getting the DL message, ED checks the received aggregated ACK message for subscription_id to find the DL message containing its ACK. On the other hand, if a device does not find its subscription_id inside the aggreagated ACK message, then it should retransmit its message in the next super-group iteration to comply with the specifications of LoRaWAN.

In NA, the GW collects subscription_id of the successful transmitters. After collecting subscription_id for all EDs, GW creates an aggregated ACK message for the active group in each super-group. The created the ACK messages for a group with id eight are shown with in Table III.

Algorithm 1 Synchronization between ED and GW

1: ED calculates t^{gw}_{active} for equals time-on-air of one time slot in $G_6/SF12$ super-group using l_{type}.
2: ED calculates the GW transmission period p_{gw} as a summation of the t^{gw}_{active} and t^{gw}_{off} (using time-off equation specified in LoRaWAN specification document [4], [16].)
3: ED finds number of groups, m, in the super-group G_j by m=$2^{\left\lfloor \log_2 \frac{t_G - T_1}{p_{gw}} \right\rfloor}$.
4: ED uses $log_2 m$ as the right-most bit of the subscription_id for the group id. n is found by converting the binary representation of the group id to decimal.
5: ED calculates T_n, which is the transmission start time of g_n by T_n=T_1+$(n$–$1) \cdot p_{gw}$.
6: ED calculates t_{slot} , which equals to time-on-air of one time slot in G_j super-group, by using l_{type}.
7: ED transmits on $slot_k$ by choosing slot k randomly in the range of [1, l], after finding the slot number l in the UL section of the group g_n by $l = \frac{t_{UL}}{t_{slot}}$.

TABLE III. NA EXAMPLE WITH $m = 8$ (TAKING RIGHT-MOST 3 BITS OF THE SUBSCRIPTION_ID, WHICH IS 010)

Super-Group	Successful subscription_id	Aggregated ACK
$G_1/SF7$	1000010, 1100010, 0100010	010100011000100
$G_2/SF8$	1110010, 1101010, 0110010	010111011010110
$G_3/SF9$	1001010, 1111010, 0101010	010100111110101
$G_4/SF10$	1100010, 1110010, 1001010	010110011101001
$G_5/SF11$	0001010, 1010010, 0010010	010100010100010
$G_6/SF12$	1011010, 1110010, 0101010	010101111100101

In Table III, an aggregated ACK starts with the binary notation of the group id, followed by the compressed successful subscription_id of the devices by extracting group id from them. Moreover, created aggregated ACK by NA method details for $G_1/SF7$ super-group are represented by the following notation:

$$NA\left(\begin{array}{c} \overbrace{\underbrace{1000}_{id_1}\ \underbrace{010}_{group\_id}}^{sub\_id_1}, \\ \overbrace{\underbrace{1100}_{id_2}\ \underbrace{010}_{group\_id}}^{sub\_id_2}, \\ \overbrace{\underbrace{0100}_{id_3}\ \underbrace{010}_{group\_id}}^{sub\_id_3} \end{array}\right) = \overbrace{\underbrace{010}_{group\_id}\ \underbrace{1000}_{id_1}\underbrace{1100}_{id_2}\underbrace{0100}_{id_3}}^{AggregatedAck_{NA}}$$

III. MATHEMATICAL MODEL

TABLE IV. DESCRIPTIONS OF THE SYMBOLS USED IN THE MATHEMATICAL MODEL

Symbol	Values	Description
I	$\{i \mid 1 \leq i \leq m\}$	$Group\ ids$
J	$\{j \mid 1 \leq j \leq n\}$	$SuperGroup\ periods$
K	$\{k \mid 7 \leq k \leq 12\}$	$Spreading\ Factors$
t_{ijk}	$(i \in I,\ j \in J,\ k \in K)$	$Transmission\ count$
S_k	$(k \in K)$	$Time\ slot\ count$
G_{ijk}	$(i \in I,\ j \in J,\ k \in K)$	$Offered\ load$
P_{ijk}	$(i \in I,\ j \in J,\ k \in K)$	$Probability\ of\ success$

In Table IV, I is a group id set between the values 1 to m. The maximum group number in all super-groups, m, is calculated by Step 3 in Algorithm 1. J is a period number set between 1 and n. n is related to the super-group duration t_G while the system run time is t_R seconds. If the system is running indefinitely, n converges to infinity. P_{ijk} in Equation 1 gives the probability of success of A2S2-LoRaWAN since it uses time-slotted ALOHA-based MAC protocol. In more details, A2S2-LoRaWAN consists of repetitive or periodic frames, where each frame contains identical groups and each group works with time-slotted ALOHA, when EDs access the medium. The probability of success in time-slotted ALOHA is equal to e^{-G} - [17]. Thus, the probability of success of A2S2-LoRaWAN is equal to $e^{-G_{ijk}}$.

$$P_{ijk} = e^{-G_{ijk}} \tag{1}$$

The offered load G in Equation 1 is evaluated by Equation 2. The offered load of Group i of Super-group k during the j_{th} period, G_{ijk}, depends on the current transmission count t_{ijk}, the summation of each failed transmission count until the j_{th} period, and the slot number in any group of super-group k.

$$G_{ijk} = \begin{cases} \frac{\sum_{a=0}^{j-1} \left\{ t_{iak} \cdot \prod_{b=a}^{j-1} (1 - P_{ibk}) \right\} + t_{ijk}}{S_k}, & \text{if } j > 0; \\ \frac{t_{i0k}}{S_k}, & \text{if } j = 0; \end{cases} \tag{2}$$

The initial offered load for $j = 0$ is calculated by Equation 2. Moreover, the second offered load depends on the first offered load. The recursive offered load in Equation 3 is derived by using equations 2 and 1. In the derivation of Equation 3, only $j \in J$ value changes therefore, $i \in I$ and $k \in K$ values are omitting in some steps of the derivation for the simplicity.

$$G_{ijk} = \frac{\sum_{a=0}^{j-1} \left\{ t_{iak} \cdot \prod_{b=a}^{j-1} (1 - P_{ibk}) \right\} + t_{ijk}}{S_k}$$

$$\begin{aligned} G_{i1k} &= \frac{t_{i0k} \cdot (1 - P_{i0k}) + t_{i1k}}{S_k} \\ S \cdot G_1 &= t_0 \cdot (1 - P_0) + t_1 \\ &= [S \cdot G_0] \cdot (1 - P_0) + t_1 \end{aligned}$$

$$\begin{aligned} G_{i2k} &= \frac{t_{i0k} \cdot (1 - P_{i0k}) \cdot (1 - P_{i1k}) + t_{i1k} \cdot (1 - P_{i1k}) + t_{i2k}}{S_k} \\ S \cdot G_2 &= t_0 \cdot (1 - P_0) \cdot (1 - P_1) + t_1 \cdot (1 - P_1) + t_2 \\ &= [t_0 \cdot (1 - P_0) + t_1] \cdot (1 - P_1) + t_2 \\ &= [S \cdot G_1] \cdot (1 - P_1) + t_2 \\ &\ \ \vdots \end{aligned}$$

$$\begin{aligned} G_n &= \frac{S \cdot G_{n-1} \cdot (1 - P_{n-1}) + t_n}{S} \\ &= \frac{S \cdot G_{n-1} \cdot (1 - e^{-G_{n-1}}) + t_n}{S} \\ &= \frac{S_k \cdot G_{in-1k} \cdot (1 - e^{-G_{in-1k}}) + t_{ink}}{S_k} \end{aligned}$$

$$\therefore G_{ijk} = G_{ij-1k} \cdot (1 - e^{-G_{ij-1k}}) + \frac{t_{ijk}}{S_k} \tag{3}$$

IV. Performance Evaluation

In this section, we present performance evaluation in order to compare the performance of A2S2-LoRaWAN with LoRaWAN. For this respect, we present several simulations by considering the following application scenarios:

- Increasing number of end devices
- Changing spreading factor distribution and increasing message load
- Increasing message load and increasing number of devices

A. Simulations

Understanding the network performance of A2S2-LoRaWAN requires a comparison with the traditional LoRaWAN. The simulators were carried out by Python for realizing the A2S2-LoRaWAN and LoRaWAN. Moreover, we have run our simulations on synthetically generated network traffic. In A2S2-LoRaWAN, EDs are uniformly distributing within the groups of each super-group. Furthermore, the transmission of each ED in a group is distributed uniformly through each super-group period.

LoRaWAN simulator has been implemented based on the specifications of LoRaWAN and by considering the following assumptions:

- Communication is on a single bidirectional channel for a single GW.
- Retransmissions for unsuccessful transmissions are implemented.
- GW transmits ACK messages on the first receive window or the second receive window of each ED.
- Transmitting ACKs has higher priority over other transmissions at GW.
- ACK transmission is canceled when GW is in time-off duration due to the DC restriction.
- A collision in UL occurs when the same SF EDs overlap in time and space.

A2S2-LoRaWAN and LoRaWAN simulators run with the same system parameters. The Super-group duration, t_G, is defined as 3600 seconds, T_1 is set to 0, and UL section duration of a group, t_{UL}, is set to 15 seconds in A2S2-LoRaWAN simulator. The remaining system environment parameters are as shown in Table V.

TABLE V. Common system environment parameters for the simulations

Parameter	Value
Simulation Runtime	86400 seconds (24 hours)
DC	1%
Network Topology	one GW, one channel

B. Increasing End Device Count Scenario

In this scenario, EDs are distributed inverse-exponentially from SF7 to SF12. Thus, the number of EDs in SF7 super-group is more than the number of EDs in SF12 super-group. Also, the number of EDs is increasing from 1000 to 10,000. Additionally, message load type is set to Min. According to Table VI, the load type input values are defined as Min, Avg, and Max. The load types differ by SFs; the meaning of the load type for each SF is described in Table VI.

TABLE VI. The byte value of Min, Avg, and Max load types for each SF

SpreadingFactors	Min	Avg	Max
SF7	10	125	250
SF8	10	125	250
SF9	10	60	123
SF10	10	30	59
SF11	10	30	59
SF12	10	30	59

In Fig. 4, P_{succ} of the proposed system model is almost equal to 1 and is not dependent on the increasing node count. The proposed mathematical model validates the proposed system model results. However, the success rate of LoRaWAN decreases while increasing the transmitter count in the network. The traffic load grows with the retransmissions and therefore, the total time-off duration of GW increases which corresponds to the increase in the number of collisions.

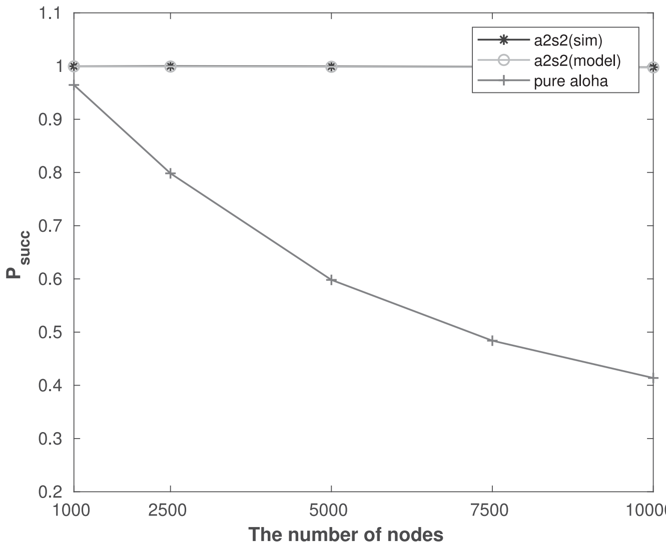

Fig. 4. The Probability of success of A2S2-LoRaWAN simulation model (a2s2(sim)), A2S2-LoRaWAN mathematical model (a2s2(model)) and LoRaWAN simulation (pure aloha) with respect to the increasing node count in the network (SFDistribution : $InverseExponential$, LoadType : min)

Table VII shows that the retransmission of each device count in LoRaWAN with inverse-exponential SF distribution (LoRaWAN (iexd)), which is bigger than in A2S2 with inverse-exponential SF distribution (A2S2 (iexd)). This is due to the fact that packet collisions occur more frequently in LoRaWAN (iexd), compared to A2S2 (iexd).

C. Changing Spreading Factor Distribution and Increasing Message Load Scenario

In this scenario, the distribution of EDs are changed from inverse-exponential to uniform distribution. Thus, the number

TABLE VII. UL AND DL PERFORMANCE OF A2S2-LORAWAN AND LORAWAN. $DevNm$ SHOWS DEVICE NUMBER IN THE NETWORK. $ULMsgNm$ AND $DLMsgNm$ SHOW THE TOTAL NUMBER OF TRANSMITTED MESSAGES IN UL AND DL (SFDISTRIBUTION : $InverseExponential$, LOADTYPE : min)

DevNm	A2S2 (iexd)		LoRaWAN (iexd)	
	ULMsgNm	DLMsgNm	ULMsgNm	DLMsgNm
1000	1004	863	1345	964
2500	2521	1484	5947	1995
5000	5100	1872	18122	2990
7500	7740	2101	32149	3629
10000	10440	2135	46573	4138

of EDs in SF7 super-group is decreasing, compared to that in inverse-exponential case. In contrast, the number of EDs in SF12 super-group is increasing. Also, message load is increasing from Min to Max. Additionally, ED count is set to 5,000.

In Fig. 5, P_{succ} of A2S2-LoRaWAN simulation model with uniform SF distribution (a2s2(sim)-ud) is lower than P_{succ} of A2S2-LoRaWAN simulation model with inverse-exponential SF distribution (a2s2(sim)-iexd) when the payload type is Max. The increase in the offered load of A2S2(sim)-ud is more than the load of A2S2(sim)-iexd. In more details, while the number of the groups in each super-group is decreasing, time slot duration in each super-group is increasing. Thus, the offered loads in A2S2(sim)-ud are increasing, compared to A2S2(sim)-iexd. P_{succ} of LoRaWAN simulation with uniform SF distribution (pure aloha-ud) is lower than P_{succ} of LoRaWAN simulation with inverse-exponential SF distribution (pure aloha-iexd) because the total time-on-air of the EDs is increasing in pure aloha-ud, compared to pure aloha-iexd. Therefore, retransmissions and collisions are inscreasing.

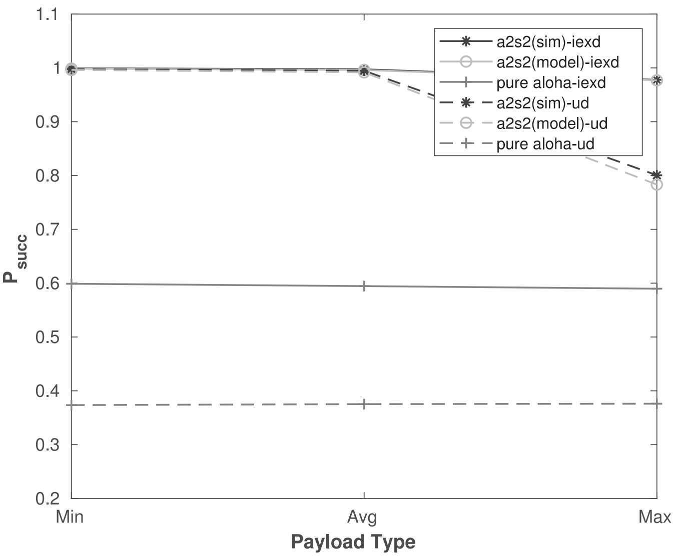

Fig. 5. The probability of success of a2s2(sim)-iexd/ud, a2s2(model)-iexd/ud and pure aloha-iexd/ud with respect to the increasing sent message size in the network (DeviceCount : $5,000$)

In Table VIII, UL-DL performance comparison of A2S2 and LoRaWAN with respect to the load type of the messages is provided. In A2S2 with uniform SF distribution (A2S2 (ud)), there is a slight increase in $ULMsgNm$ and decrease in $DLMsgNm$ when changing the load type from Min to Avg. However, sharp increase in $ULMsgNm$ and decrease in $DLMsgNm$ is observed when changing the load type from Avg to Max. The reason is the increasing number of collisions, therefore, retransmissions at Max load type are observed more frequently than the retransmissions at other load types. In LoRaWAN with uniform/inverse-exponential SF distribution (LoRaWAN (ud/iexd)), there are slight decreases in $ULMsgNm$ from Min load type to Max load type since the total time-off duration of the EDs increases. Therefore, the frequency of retransmissions decreases. On the other hand, $DLMsgNm$ remains almost the same. Furthermore, each SF distribution affects the results in Table VIII in different ways. In A2S2 (ud), collisions in SF11 and SF12 super-groups are more than the collisions in A2S2 (iexd). Therefore, the sum of $ULMsgNm$ in A2S2 (ud) is larger than the sum of $ULMsgNm$ in A2S2 (iexd). In addition to $ULMsgNm$, $DLMsgNm$ at Min and Avg is larger than $DLMsgNm$ in A2S2 (iexd). The reason is that P_{succ} of the two cases is almost same although collisions in A2S2 (ud) are more than collisions in A2S2 (iexd). Therefore, the GW in A2S2 (ud) sends much more ACKs than A2S2 (iexd).

TABLE VIII. UL AND DL PERFORMANCE OF A2S2-LORAWAN AND LORAWAN. $DevNm$ SHOWS DEVICE NUMBER IN THE NETWORK. $ULMsgNm$ AND $DLMsgNm$ SHOW THE TOTAL NUMBER OF TRANSMITTED MESSAGES IN UL AND DL (DEVICECOUNT : 5000)

LoadType	A2S2 (iexd)		LoRaWAN (iexd)	
	ULMsgNm	DLMsgNm	ULMsgNm	DLMsgNm
Min	5093	1865	18090	2994
Avg	5318	1866	17063	2972
Max	7230	1064	16354	2948
LoadType	**A2S2 (ud)**		**LoRaWAN (ud)**	
	ULMsgNm	**DLMsgNm**	**ULMsgNm**	**DLMsgNm**
Min	5280	2248	23093	1867
Avg	5581	2216	21847	1876
Max	11796	992	20686	1880

D. Increasing Message Load and Increasing Device Count Scenario

In Fig. 6, there are four critical points where the number of nodes is 1000, 5000, 7500, and 10000. All observations are almost equal at 1000 nodes. Later, the decrease in LoRaWAN simulation model with min/avg/max payload type (pure aloha-min/avg/max) is observed as inverse-exponential through the increase in the node count. Also, pure aloha is not adversely affected by the change of the message load, compared to A2S2 since pure aloha does not work on the time-slotted frame structure. On the other hand, there is a point of break between A2S2-LoRaWAN simulation-model/mathematical model with min/avg payload type (A2S2(sim/model)-min/avg) and A2S2-LoRaWAN simulation-model/mathematical model with max payload type (A2S2(sim/model)-max) at 5,000 nodes. The groups in A2S2(sim/model)-min/avg handle the load through the increase in the node count therefore, P_{succ} values of them are almost equal to one. However, after the breaking event at 5,000 nodes, A2S2(sim/model)-max cannot handle the traffic load because of the fact that the number of A2S2(sim/model)-max groups in its super-groups is lower than the number of A2S2(sim/model)-min/avg groups in their super-groups. Moreover, the number of time slots in A2S2(sim/model)-max groups is lower than the number of time slots in A2S2(sim/model)-min/avg groups. On the contrary, the differences between P_{succ} values of A2S2(sim)-max and A2S2(model)-max at

7,500 nodes and 10,000 nodes are 0.05 and 0.03, respectively. The reason is that A2S2(sim)-max drops transmitters reaching the retransmission upper bound (eight transmission per message); however, this rule is not enforced in A2S2(model)-max mathematical model. Therefore, the number of collisions in A2S2(model)-max are more than the number collisions in A2S2(sim)-max. Finally, at 10,000 nodes, A2S2sim/model)-min/avg have best success rates, and pure aloha-min/avg/max is the worst.

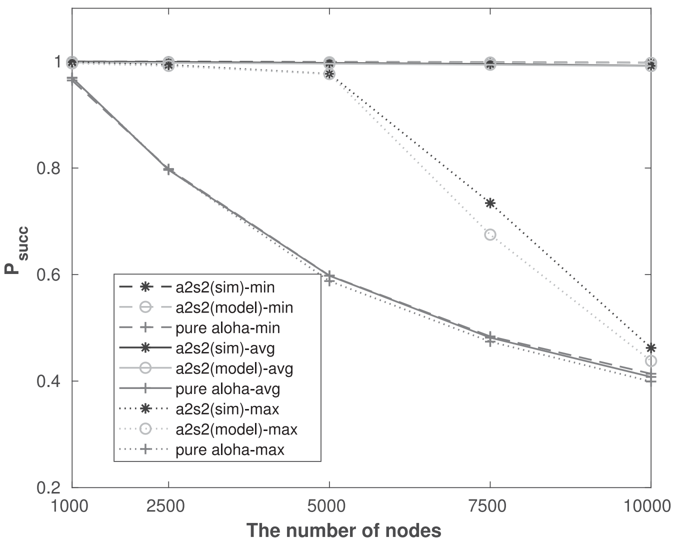

Fig. 6. The Probability of success of A2S2-LoRaWAN simulation model (a2s2(sim)), A2S2-LoRaWAN mathematical model (a2s2(model)) and LoRaWAN simulation (pure aloha) with respect to the increasing node count in the network and increasing sent message size in the network (SFDistribution : $InverseExponential$)

We perform simulations to compare the network performance of A2S2-LoRaWAN and LoRaWAN. According to the results, a GW in A2S2-LoRaWAN can work with 10,000 EDs at Min payload type with almost 100% success rate. However, GW in LoRaWAN can work with 1,000 EDs. While A2S2-LoRaWAN decreases UL-DL traffic five times compared to LoRaWAN, its success rate of it with 10,000 EDs at Min payload type is twice better than the success rate of LoRaWAN. On the other hand, A2S2-LoRaWAN is sensitive to the change of the payload type since the number of slots in the groups depends on the payload type. However, it still performs better than LoRaWAN. When SF distribution changes from inverse-exponential to uniform, A2S2-LoRaWAN shows lower performance for SF12 EDs; still, it has a better performance than LoRaWAN. Moreover, inverse-exponential distribution of SFs on EDs is expected for LoRaWAN in real life [18]. Furthermore, the NA method shows better performance than the BEA method for each case. Thus, A2S2-LoRaWAN generally has better performance on scalability and UL-DL traffic than LoRaWAN.

Although increasing the network performance of LoRaWAN with A2S2-LoRaWAN, there is a fixed latency due to the repetitive frame structure of the system model in A2S2-LoRaWAN. In other words, ED can send a message with a period of t_G. On the other hand, the energy consumption of the A2S2-LoRaWAN is better than LoRaWAN's when comparing the total UL and DL message count in Table VII and Table VIII. The retransmissions and failed transmissions are decreasing in A2S2-LoRaWAN compared to LoRaWAN.

V. Conclusion

Traditional LoRaWAN, which is based on pure ALOHA-type MAC protocol fails in scaling of the network. Therefore, we introduce a novel scheduling method for LoRaWAN, called A2S2-LoRaWAN to improve the scalability of the network. We have presented various scenarios to test A2S2-LoRaWAN and traditional LoRaWAN in order to analyze the network scalability and DL/UL traffic. According to the experiment results, there is a decrease in DL and UL traffic when using A2S2-LoRaWAN instead of LoRaWAN. In addition, using A2S2-LoRaWAN increases the scalability of the network when compared to pure-ALOHA LoRaWAN. Moreover, NA method helps minimize DL traffic of LoRaWAN.

As a future work, multi GW scenarios can be also included into the problem for improving the solution. Traffic types or application content types can be considered for improving the solution. Retransmission limit in LoRaWAN can be added to A2S2-LoRaWAN Mathematical Model as a constraint. Lastly, detailed energy consumption performance of A2S2-LoRaWAN can be investigated.

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