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Performance Evaluation of LoRaWAN for Green Internet of Things

ZULFIQAR ALI[1], SHAGUFTA HENNA[2], ADNAN AKHUNZADA[1], MOHSIN RAZA[3], AND SUNG WON KIM[4]

[1]Department of Computer Science, COMSATS University Islamabad, Islamabad 45550, Pakistan
[2]Telecommunications Software and Systems Group (TSSG), Waterford Institute of Technology (WIT), Waterford, X91 KOEK Ireland
[3]Design Engineering and Mathematics Department, Middlesex University, London NW44BT, U.K.
[4]Department of Information and Communication Engineering, Yeungnam University, Gyeongsan 38542, South Korea

Corresponding author: Sung Won Kim (swon@yu.ac.kr)

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ABSTRACT LoRa is a long-range, low power and single-hop wireless technology that has been envisioned for Internet of Things (IoT) applications having battery driven nodes. Nevertheless, increase in number of end devices and varying throughput requirements impair the performance of pure Aloha in LoRaWAN. Considering these limitations, we evaluate the performance of slotted Aloha in LoRaWAN using extensive simulations. We employed packet error rate (PER), throughput, delay, and energy consumption of devices under different payload sizes and varying number of end devices as benchmarks. Moreover, an analytical analysis of backlogged and non-backlogged under slotted Aloha LoRaWAN environment is also performed. The simulation shows promising results in terms of PER and throughput compared to the pure Aloha. However, increase in delay has been observed during experimental evaluation.Finally, we endorse slotted aloha LoRaWAN for Green IoT Environment.

INDEX TERMS LPWAN, LoRa, LoRaWAN, IoT, SF, FEC, DER, ADR.

I. INTRODUCTION

Recently, an advent to the Internet of Things (IoT) has demonstrated significant applications in industry, healthcare, smart agriculture, smart cities, connected vehicles and environmental monitoring [1]. Long Range Wide Area Network (LoRaWAN) is considered one of the popular low power wide area network technologies, which provides long range, low power, low cost, and secure bi-directional communication. A recent advancement in virtualization and cloud computing has motivated the telecommunication industry to rethink the conventional proprietary approaches to networking. The primary infrastructure used by the telecommunication industry lacks the capabilities which we wish should be enabled with the 5G [2]. The next era of IoT is expected to bring along a range of flexible and automated applications for the end users. In order to make 5G a reality, LoRaWAN due to its capability and feasibility in IoT can be considered as one of the strong candidate enabler which can be integrated with the 5G [1]. A massive increase in the number of IoT devices in the decade to come is expected to impose huge capacity requirements on the backbone connectivity provided by the low power wide area network (LPWAN) technologies. LoRaWAN due to its low power, long range, and low cost is expected to out stand other LPWAN technologies.

By 2020 [1], MTC is expected to surpass the number of human subscribers by taking over more than 28% of connections. MTC traffic requirements are more challenging due to its dynamic nature [3]. Typically, the MTC devices generate short and bursty traffic at regular intervals [4]. Millions of these devices may result in massive traffic resulting in a bottleneck at the network degrading its performance [5]. Current wireless communication technologies need to be capable to cope the challenges of massive traffic loads and unpredictable traffic situations in order to exploit IoT capabilities [6]. Although LoRaWAN deployment promises to ease these situations by devising different congestion mitigation techniques including dynamic channel assignment [7] and orthogonal

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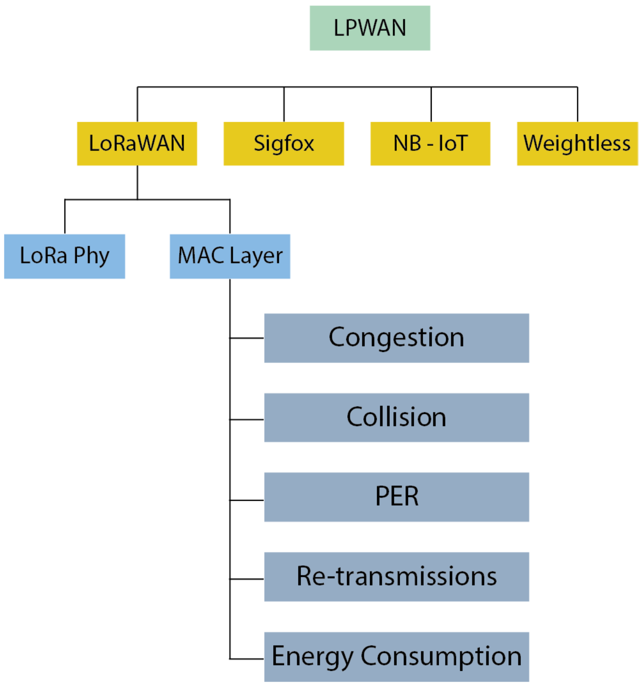

FIGURE 1. Taxonomic View of MAC issues in LoRaWAN.

spreading factors, however LoRaWAN environment still rely on a simplest Aloha-based due to limited requirements of end devices, whose major constraints are well-known in other networks [1], [8].

Majority of the LPWAN technologies support extremely low data rate, where a very large time on air (ToA) for the transmission may drastically increases the number of collisions even under 1% duty cycle regulations [9]. This higher number of collisions incurs extra energy due to retransmissions by the end devices. A medium access mechanism can be related to the applications and dynamics of environment operating in a low power wide area network, where a change in payload size or number of end devices can severely impair network's performance [10]. In [11], authors discuss that IEEE 802.11based multiple access schemes are not suitable for transmission of data in low duty cycle technologies due to idle listening. In [12], authors demonstrates that over a distance of approximately 2 km, 95.5 % of packets are successfully received. LoRaWAN is specifically designed for nodes that are static but in [13] authors studies the performance in LoRaWAN by deploying mobile nodes.Authors in [14] introduce a distributed queuing (DQ) algorithm that can operate efficiently for infinite number of nodes in low duty cycle networks. Further, the same authors have provided an overview of different MAC layer performance metrics in LPWAN, and analytical solutions to them as illustrated in Figure 1.

Expected growth of smart IoT devices is 32% annually with a claim by most of the well reputed research papers that over 21 billion [15] devices will be there to transmit and receive data. Authors in [16], elaborate different approaches for connectivity of smart devices in large scale. It also discuss pros and cons of smart devices and its design aspects specifically in terms of smart applications used in urban areas.

In this article [17] authors analyze automobile accidents and there prevention by using smart IoT devices. IoT enable users to communicate with vehicle and think in terms of intelligent transportation system. Authors in [18] proposed categorization of various communication technologies possibly in two broad categories: LPWAN and Bluetooth technologies. Detail of various LPWAN and Bluetooth technologies are discussed with its applications.

Since 1970's Slotted-Aloha is one of the most efficient protocol practically used in different communication scenarios [19]. Channels in Slotted Aloha is divided in to slots, having fixed length T. Internally channels operates in two different portions i.e transmission time T_r and tolerance interval T_b. Approximately 37% of throughput is achieved when Slotted Aloha is operated in his full potential. Authors in [20] rigorously analyzed scalability in LoRaWAN. Results depicts that total of 120 end devices having static configuration with 22 minutes of transmission each, can be managed successfully. With dynamic configuration of end devices, number of nodes reached up to 1600. Authors in [21] evaluates performance of LoRaWAN by deploying end devices inside the building. The gateway is places outside the building. Almost 95% packets are succefully received having path loss factor ranges from 97 dB to 146 dB. In [22], authors analyzed propagation in indoor environment. Different models like ITU model, multi-wall model, ray tracing model) is used by author and it was found that multi-wall model gives much better results than others.

In another study [23], authors analyze performance of LoRaWAN in indoor environment. In this paper, LoRaWAN network was deployed by keeping gateways at indoor vicinity. Total indoor area consists of 34000 m^2 having one gateway with SF7.

It was observed that outdoor area is reachable only with SF12. Authors in [24], implemented an NS3 based LoRaWAN module with extra features of CSMA.

In literature, different studies have evaluated the transmission capacity and outage probability of slotted Aloha by modeling the transmitters under Poisson distribution [25]. In another study, authors have evaluated the capacity of slotted Aloha under different transmission densities and have demonstrated almost double performance over CSMA [26]. Yang et al. have also analyzed the performance of a random-access mechanism similar to Aloha in LTE [27]. Similar to Yang et al., Nielsen et al. have studied the outage probability of Aloha-based access under Bianchi model [28]. In another work, authors analyze the collision probability of Aloha by using stochastic geometry approach. Further, they also have analyzed the maximum load capacity under various packet loss rate. Goursaud et al. [29] investigates the performance of carrier frequency under slotted Aloha. In another recent work [30], authors analyze the throughput of slotted Aloha in cognitive radio networks with constant power under Rayleigh fading.

Given the future uptake of LoRaWAN for innovative IoT applications, recently a significant research has been dedicated to the strengthen the robustness of medium access mechanisms in LoRaWAN. Although the performance of slotted Aloha has been well studied in different literature for LTE, wireless networks, and cognitive radio networks. However, to the best of our knowledge no work about the performance analysis of slotted Aloha for the backlogged and non-backlogged nodes has been considered for LoRaWAN. In this paper, we propose an analytical model to study backlogged and non-backlogged under slotted Aloha LoRaWAN environment. In the analysis, the main objective is to analyze the probability of collisions for both the backlogged and non-backlogged nodes. We then perform simulations to analyze the performance of slotted Aloha in terms of energy efficiency, throughput, and packet error rate, and delay under varying packet load sizes and number of end devices.

To fulfill the channel access requirements of end devices in LoRaWAN, we devise certain rubrics for MAC layer. Our aim is to develop a multiple access scheme for LoRaWAN. The contributions of the paper are manifold:

- Easy implementation having small code with fewer calculations
- Enhance throughput in LoRa network
- Mitigate packet error rate
- Efficient utilization of network capacity with both high and low data rate
- Perform operations at low power

The structure of paper is organized as follows: Sec. II provides overview of uncoordinated medium access, i.e., Aloha and unslotted Aloha. Sec. III presents different MAC schemes in different LPWAN platforms. Challenges in LPWAN channel access schemes are discussed in Sec. IV. The markov chain based slotted Aloha model for backlogged and non-backlogged nodes is proposed in Sec.V. Sec. VI explores how nodes adjust its data rate adaptively in LoRa network. Sec. VII elaborates the performance of slotted Aloha with simulation results in LoRaWAN under varying payload sizes and number of end devices. Finally, Sec. VIII concludes this article with some future directions.

II. UNCOORDINATED CHANNEL ACCESS SCHEMES

Pure Aloha is one of the simplest multiple access protocol for medium access, where a node transmits data without any coordination. When two or more nodes transmit data simultaneously, it results in a collision. After transmitting data, a node waits for an acknowledgment. If it does not receive any acknowledgement for a specific amount of time, it assumes that the packet is lost. After a collision, node waits for a random amount of time and retransmits data again [14].

Figure 2 explains the design of pure ALOHA. Suppose we have four stations that have frames to transmit. Let Station 1 transmits a frame (Frame 1.1). After some time, Station 3 also transmits data as Frame 3.1. In the meanwhile, Stations 1 and 2, have frames to transmit. The overlapping region in Figure 2, shows the collision as more than one nodes transmit frames at the same time.

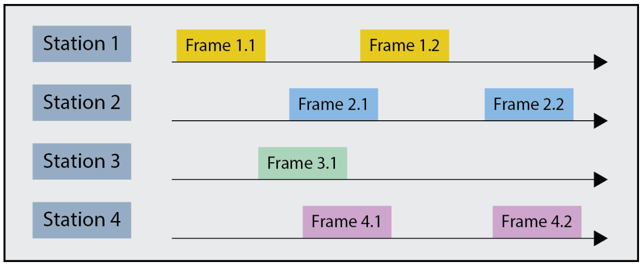

FIGURE 2. Design of pure ALOHA.

Most of the research in this field deals with different MAC layer protocols based on Aloha. The performance of these protocols is satisfactory when limited number of devices are transmitting simultaneously. However, if the number of devices increases exponentially, it results in severe congestion [14]. Some researchers also adopt random access methods to share the communication channel. All these influential approaches are summarized in Table 1. With 50% of PER, Aloha is not an overwhelming choice for industrial environment where we need immediate response from nodes.

TABLE 1. Channel access schemes in different IoT-enabled wireless technologies.

Multiple Access Schemes	Technologies
Pure Aloha	SigFox, LoRa
Slotted Aloha	RFID, NB-IOT, Weightless
Non-Slotted CSMA/CA	ZigBee, WiFi
Slotted CSMA/CA	ZigBee

Nodes belongs to Class A use pure Aloha to transmit packets. Mention technique is appropriate for applications, which wait for downlink acknowledgment immediately after transmitting data [14]. Another drawback of pure Aloha is energy consumption of end devices incurred due to PER. With over 50% PER, most of the packets must be retransmitted by end devices, which affects LoRaWAN capacity.

III. SUPPORT OF MAC SCHEMES IN UBIQUITOUS IOT TECHNOLOGIES

Wide variety of IoT applications are supported by several wireless technologies. The performance of these wireless technologies highly depends on MAC implementation. Some of these wireless technologies rely on hybrid multiple access schemes. Hybrid MAC techniques use a combination of contention-based and scheduled medium access. Several wireless technologies are based on spread spectrum multiple access, in which multiple users can access the channel by using same frequency band. Regardless of different MAC protocols available for wireless technologies, researchers in academia and industry are both interested in variants of Aoha and CSMA due to their simplicity and low cost. Wireless technologies meant for IoT applications like LoRaWAN are

TABLE 2. Overview of multiple access methods in different wireless technologies.

	Pure ALOHA	Slotted ALOHA	Slotted CSMA/CA	FDMA	TDMA	CDMA	CSS	FHSS	DSSS
LoRaWAN	☑						☑		
Sigfox	☑								
NB-IoT		☑		☑		☑			
Weightless		☑		☑	☑			☑	☑
Zigbee			☑				☑		☑
WiFi				☑					☑
RFID		☑							

also based on a mechanism similar to pure Aloha as a multiple access mechanism. Table 2 presents an overview of wireless technologies with their relevant MAC access scheme.

Brief description of some popular wireless networks and LPWAN standards, in terms of channel access capabilities are as follow:

A. ZIGBEE

The IEEE 802.15.4 constitutes the foundation of ZigBee Alliance specification. Two different methods are used by ZigBee for accessing channels. ZigBee operates in two different modes, beacon-enabled mode and non-beacon mode. First one is used in star topology whereas later one is based on multi-hop topology. Beacon-enabled star topology networks access is based on hybrid MAC which uses CSMA/CA as a medium access to delay-tolerant application data and a reservation-based access for time critical data. However, to get access of channel, end device must perform beacon synchronization. Non-beacon multi-hop deployments use contention-based MAC which uses unslotted CSMA/CA for channel access equipped with a binary exponential back off mechanism. End device that have some data to transmit, should wait for random time. Once sensed channel become idle, it proceeds with transmission else backoff for random amount of time.

B. RADIO FREQUENCY IDENTIFICATION (RFID)

RFID operates in ISM frequency bands and identify packets with RFID codes. RFID depends on uncoordinated slotted Aloha scheme like (FSA). One approach applied to reduce tag collision issue is dynamic adaption of total number of slots per frame according to the total number of collided tags. Another mechanism based on query tree reduces the number of collisions experienced by RFID.

C. LTE

Long Term Evolution (LTE) is more useful in terms of mobility and coverage. Random Access Channel (RACH) is used by nodes to establish connection with base station. Contention-bases LTE involve a handshake of four messages between a User Equipment (UE) and base stations and are based on FSA access. In contention-free LTE, the base station allocates specific medium access resources to delay-constrained requests.

D. SIGFOX

Sigfox technology achieves long range communication by operating at ultra-narrow band frequencies. The applications based on Sigfox operate on low data rate of 100 bps and use binary phase shift keying (BPSK) as a modulation scheme [31].

Owing to ultra-narrow band operation, it performs better due to reduced noise level which provides better sensitivity on receiver's end. Sigfox uses Random Frequency-Time Division Multiplex (R-FTDMA) scheme to transmit data packets. There is no synchronization required for nodes, as it randomly selects any available frequency for transmission. As in Aloha, end devices in R-FTDMA transmit data without sensing the channel. Similar to pure Aloha, this scheme requires no synchronization with the gateway prior to transmission, and therefore consumes less energy consumption. However, random selection of frequencies may lead to collisions due to an increase in co-channel interference.

E. LORAWAN

Long Range (LoRa) is based on Chirp Spread Spectrum (CSS) technology and Frequency Shift Keying (FSK) as modulation scheme. The CSS is used to recover data from weak signals through controlled frequency diversity. LoRaWAN uses three classes at data link layer to address three different requirements. Class A end devices allow bi-directional communication and uses pure Aloha as multiple access scheme. With this scheme, collision rate is extremely high when traffic load increases, which in turn affects the performance of network. Class B end devices perform similar to Class A with an extra receiving window to provide synchronization with the network server. Class C end devices are always ON to transmit or receive data which leads to immense power consumption. Class C is an attractive choice for IoT applications which require low latency communication with no energy constraints.

F. WEIGHTLESS

Weightless technology provides affordable MTC by using low frequency spectrum. Depending on the requirements, two different access modes are considered, i.e., narrow band and wide band FDMA. Both use FDMA and TDMA schemes. Weightless is based on the master-slave architecture with three different connectivity standards at data link layer to reduce number of collisions.

- Weightless-W: is based on time division duplexing (TDD) that minimizes interference.
- Weightless-N: is used for secure, low power, cost efficient devices for one-directional exchange of data.
- Weightless-P: It allows bi-directional communication by using both TDMA and FDMA as channel access schemes.

IV. CHALLENGES IN LPWAN CHANNEL ACCESS SCHEMES

In literature, a significant analysis of contention-based MAC techniques has been performed. Several IoT applications as discussed in recent literature are based on Aloha [32]. In [31], authors analyze the performance of Aloha in homogenous networks, where nodes generate traffic according to random distribution. Authors analyze the throughput performance of the work along with delay incurred due to path loss. However, with the evolution of *IoT* enablers, in particularly *LoRaWAN*, the random packet generation models must be revised according to the requirements of user and dynamics of system. For example, large number of sensors is deployed to monitor vibration of infrastructure like buildings etc. These sensors generate packets on a regular basis to provide feedback, which will lead to congestions. Smart metering is another example of delay tolerant application, which generates short messages of readings from water, gas, electricity at regular intervals. Although, *LoRaWAN* is one of the emerging technologies used for IoT applications nowadays. However, there are number of challenges including massive number of collisions, re-transmissions, low throughput, energy consumption, packet error rate (*PER*), and delay etc. that we should be addressed, effectively. Most of *LPWAN* technologies used for *IoT* applications are based on ALOHA type multiple access mechanism. Although, Aloha appears an attractive choice for limited number of end devices. However, massive number of M2M devices may qualify it as an unwise channel access mechanism. We, therefore, need an access mechanism in LoRaWAN which can have go slightly wiser than Aloha, while still keeping the essence of its simplicity.

Majority of the research in wireless communication based on the variants of Aloha and *CSMA* as a channel access scheme [33]. These channel access schemes experience severe issues of performance degradation due to contention-based medium access with exponential backoff delays under massive traffic. In [34], authors optimized the performance of Aloha and *CSMA* by tuning desired parameters, intelligently. However, once end devices grows exponentially it contribute significantly in backoff delay, thus degrading the network throughput. In another study, authors propose an Aloha-based protocol called Collision Resolution Algorithm (*CRA*) [34] to improve throughput of overall system. *CRA* algorithm demonstrates better performance for delay tolerant applications. Once a collision is detected, CRA keeps the delay constant for re-transmissions.

V. MARKOV CHAIN MODEL FOR SLOTTED ALOHA

Assume that we have m users that are sharing a channel using slotted Aloha (*SA*). To analyze the impact of backlogged (*BL*) and non-backlogged (*NBL*) nodes on SA, it is important to understand the terms *BL* and *NBL*. *BL* nodes are those who always have packet to transmit, as these users experience collisions or packet loss in their first attempt. *NBL* nodes are those who either successfully transmit packets in first attempt or do not have any packet to transmit. It means in case of *NBL*, no queues buildup.

Assume that out of these m users, n users are in *BL* state. So $(m-n)$ remains in *NBL* state. Let a denotes the probability of *NBL* nodes to transmit packet in a particular slot. Value of a is usually very small because in wireless networks like LoRaWAN users are in *BL* state most of the time. Let b be the probability of *BL* nodes, which have packet to transmit. It is important to understand that probability b is not generation of new packets. It is similar to re-transmission of a packet. Network performance highly depends on the value of b. We can optimize the value of b for our system. However, we do not have any control on the value of a. Given values of m, n, a and b describes throughput of our system.

Assume, A(i,n) is the probability of exactly i *NBL* nodes, that can transmit in a slot as given in Equation No 1.

$$A(i,n) = \sum_{i=0}^{m-n} \binom{m-n}{i} a^i (1-a)^{m-n-i} \tag{1}$$

Let B(i,n) is the probability that exactly i *BL* nodes will re-transmit in a slot as represented in Equation No 2.

$$B(i,n) = \sum_{i=0}^{n} \binom{n}{i} b^i (1-b)^{n-i} \tag{2}$$

Let n represents the process state. As can be seen in Figure 3, in the start we have no *BL* nodes so our system states will start from $n = 0$, which becomes our starting state and then we have one *BL* node and so on. Figure 3 shows the states of our system.

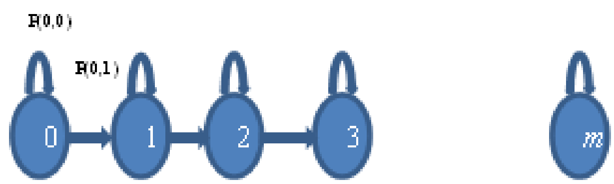

FIGURE 3. State transition diagram for BL nodes.

In Figure 3, P(n,n) denotes the probability that node remains on the same state n after occurrence of any transaction, and P(0,1) is the probability that a node moves from state 0 to state 1.

For slotted Aloha P(n,n) indicates same number of BL nodes in the beginning and end of timeslot as shown in Equation No. 3.

$$P(n,n) = [A(1,n) * B(0,n)] + [A(0,n) * (1 - B(1,n))] \tag{3}$$

In the Equation No, A(1,n) denotes only one NBL node in transmit state, and B(0,n) means none of the BL nodes is in transmit state. A(0,n) represents that no NBL node has data to transmit, and 1-B(1,n) indicates an exactly one BL node in transmit state.

Similarly P(n,n+1) becomes,

$$P(n, n+1) = [A(1, n) * (1 - B(0, n))] \tag{4}$$

In Equation No 4, A(1,n) indicates that only one NBL node can transmit packet and B(0,n) depicts at least one BL node that will try to send.

We can also find the probability P(n,n − 1) as,

$$P(n, n-1) = [A(0, n) * B(1, n)] \tag{5}$$

According to the above equation exactly one *BL* user will transmit.

We can also generalize the case when we have more than one *NBL* node who wants to transmit. Such a case is translated as follows:

$$P(n, n+i) = [A(i, n)] \tag{6}$$

where, $2 \leq i \leq m-n$

With every state n in Figure 3, we have a reward r that determines that either packet is successfully transmitted or not. The throughput of system highly depends on reward r.

Let, r_n indicates reward of state n, which determines probability of successful transmission at state n as given in Equation No 7.

$$r_n = [A(0, n) * B(1, n)] + [A(1, n) * B(0, n))] \tag{7}$$

The above expression r_n indicates that for successful transmission either one BL node or NBL node can be in the transmit state.

VI. LORAWAN ADAPTIVE DATA RATE ALGORITHM

LoRaWAN end devices rely on an ADR mechanism as illustrated Algorithm to assign data rates to all end devices individually. The main purpose of using ADR is to optimize network performance and achieve scalability. End devices nearer to the gateway tune to high data rates, as compared to the farther away end devices [32]. By assigning high data rates to end devices nearer to the gateway, *LoRaWAN* avoids collisions between frames transmitted with the same data rates. Initially, an end device transmits data with an initial static configured data rate, which may result in massive congestion on the access point (*AP*) or coordinator adversely affecting the *LoRaWAN* capacity. An increase in the number of collisions increases the number of re-transmissions, which directly affects the energy efficiency of end devices. The data rates can be configured by both end devices and network. ADR bit is configured for this purpose. If the ADR bit is enabled or set in the frame control field, the network will manage the data rate for end devices through different *MAC* commands. If *ADR* bit is not set, it means network is not responsible to control the data rate of an end device. However, in order to extend the life time of end device and network capacity, the ADR scheme should be enabled. The control messages exchanged and extra computation required on end devices, affect the battery life time of end devices [35]. If *ADR* bit is enabled, it requires acknowledgments from the network towards end devices which may incur extra overhead. In case of loss of acknowledgments, the end device configures lower data rates and regains connectivity.

Algorithm:

1. Initial configuration:
 Band = EU-863-870
 Margin = 10
 ADR Status:
 DataRate = SF10BW125
 Trans Power = 14 dbm, NbTrans = 1.

2. To calculate Margin and Number of steps:
 Max. SNR from history of last 20 transmissions = 20.
 SNR required for SF10BW125 = −15.
 Device Margin = 10.
 New SNR Margin = 7.

3. Now for SNR Margin calculate:
 Number of steps = floor(Margin/3).

4. Increase data rate for each step:
 Until minimum = SF7BW125.
 New data rate = SF8BW125.

5. Dec/Inc Transmit Power by 3 for each remaining step:
 Untilminimum = 2 and maximum = 14.
 Transmit Power = 14.

Case 1:
 If Number of steps < 0, then power will be automatically increased by 03 in each step until it reaches maximum. (Tx Max = 14 dbm).

Case 2:
 If Number of steps > 0, then firstly data rate will be increased in each step until it reaches maximum data rate (DR5) and power will be decremented until it reaches lowest level of transmitted power (Tx min = 2dbm).

VII. SIMULATION RESULTS

This section presents simulation results of slotted Aloha for LoRaWAN. Each LoRaWAN gateway covers 100 to 100 nodes, where each node selects a random payload size.The distance between end devices and gateway varies from 500m to 1000m. Several numbers of packets (in bytes) are transmitted by end devices per simulation, to know its impact on LoRa network. Each simulation is performed at least 100 times to get average values of all parameters.

All the possible cases are taken in to considerations to analyze the performance of slotted Aloha in LoRaWAN. LoRa technology defines 3 data channels for the european standard, i.e., 868.1, 868.3, 868.5 for end devices transmit its data towards gateway with 6 SFs, i.e., 7,8,9,10,11,12 [35]. Some of the simulations results are taken over single SF like for SF=12 and so on. ADR must be disabled if we want to perform simulation with single SF. With 3 data channels and 6 SF, logically we have 18 virtual channels that can be used simultaneously without any interference. For the scenarios

TABLE 3. Numerical analysis of PER with varying parameters.

Spreading Factor	Bandwidth	End devices	PER (in percentage)	Distance (m)	ADR	Payload Size	Duty Cycle
SF12	125 Khz	500	25%	500m	Disabled	20	1%
SF11	125 Khz	500	13.5%	500m	Disabled	20	1%
SF10	125 Khz	500	12%	500m	Disabled	20	1%
SF9	125 Khz	500	8%	500m	Disabled	20	1%
SF8	125 Khz	500	5%	500m	Disabled	20	1%
SF7	125 Khz	500	5%	500m	Disabled	20	1%

where we obtain results by using single SF, transmit power remains constant with a value 14 dbm for the time of simulation. In all other scenarios, we keep the ADR enabled. The simulations results clearly shows for all the above scenarios that slotted Aloha is more suitable for delay tolerant applications. PER is observed for different SF's for varying payload sizes. The curves for different SFs are plotted to get exact information from simulations. By keeping ADR enabled, we analyze the average throughput in bits per second for LoRaWAN using slotted Aloha. Further, we also evaluate the slotted Aloha in terms of slotted Average delay for different SFs under varying payload sizes.

A. LIMITATIONS OF 1% DUTY CYCLE IN SLOTTED ALOHA

As LoRaWAN is a constrained technology by respecting duty cycle of 1% imposed by regulations. Duty cycle indicates that each LoRa end device can use a channel or subchannel (sub-band) for 1% of the time in 24 hours. This duty cycle limitation prevents LoRa network from collisions, and therefore PER. Due to duty cycle constraints, each node only transmits limited number of packets. In this article, all the simulations have been performed 1% duty cycle.

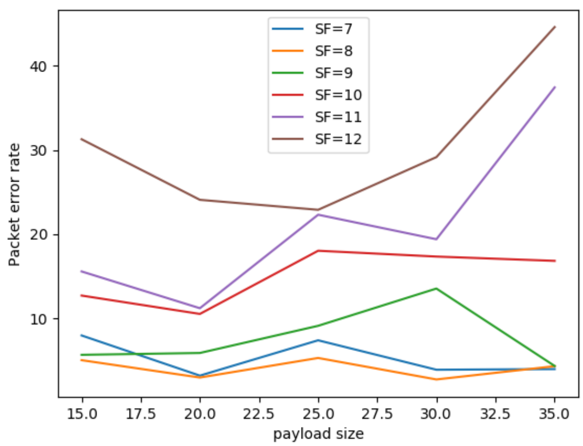

FIGURE 4. Analysis of packet error rate w.r.t payload size with varying SF's.

The simulation results in Figure 4 show PER (in percentage) in terms of different payload size (in bytes). We have used 3 data channels in this scenario and these channels are randomly assigned to end devices. Each end device is configured with a bandwidth of 125 khz. End devices and gateway are separated with distance of 500m. ADR is disabled for this simulation because we want to observe the performance of slotted Aloha under different SFs. If we observe the curve of slotted ALOHA in LoRaWAN for SF=12 and SF=7 with payload size of 20 bytes, we can observe that PER is almost 25% and 5%.

For the same configurations in LoRaWAN using ALOHA, almost 78% of PER is observed with SF=12 and 60% with SF=7 [36]. Simulation runs for one hour each time (almost 50 tests).

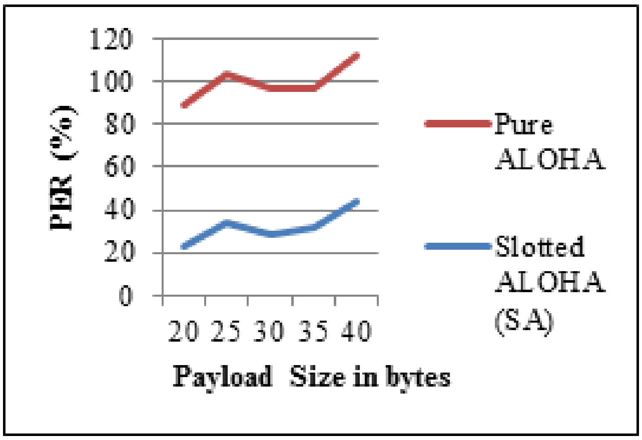

FIGURE 5. Payload Size w.r.t PER in percentage with ADR Enabled.

In Figure 5, the effect of PER is observed with respect to payload size with ADR enabled. Performance of both slotted ALOHA and pure ALOHA is rigorously analyzed in LoRaWAN. Significant amount of improvement is observed in case of slotted ALOHA, when compared with pure ALOHA. The performance of slotted ALOHA is ominously enhanced with ADR enabled. ADR is responsible for adjusting data rate and transmit power adaptively with the help of MAC commands. Initially, each end devices is configured with SF=12 and transmit power 14 dbm with 500 end devices, where distance between end devices and gateway is 500m. It can be observed from the Figure that when packets size is 20 bytes, PER is more reduced to 22%. We can see from the figure that for packet size of 30 bytes, PER is further reduced to 27%.

Comparison of PER, for both slotted ALOHA and pure ALOHA is performed and presented in Table 4. From numerical results we clearly observe that for discussed configuration, results of slotted ALOHA are better than pure ALOHA with 1% duty cycle limitation.

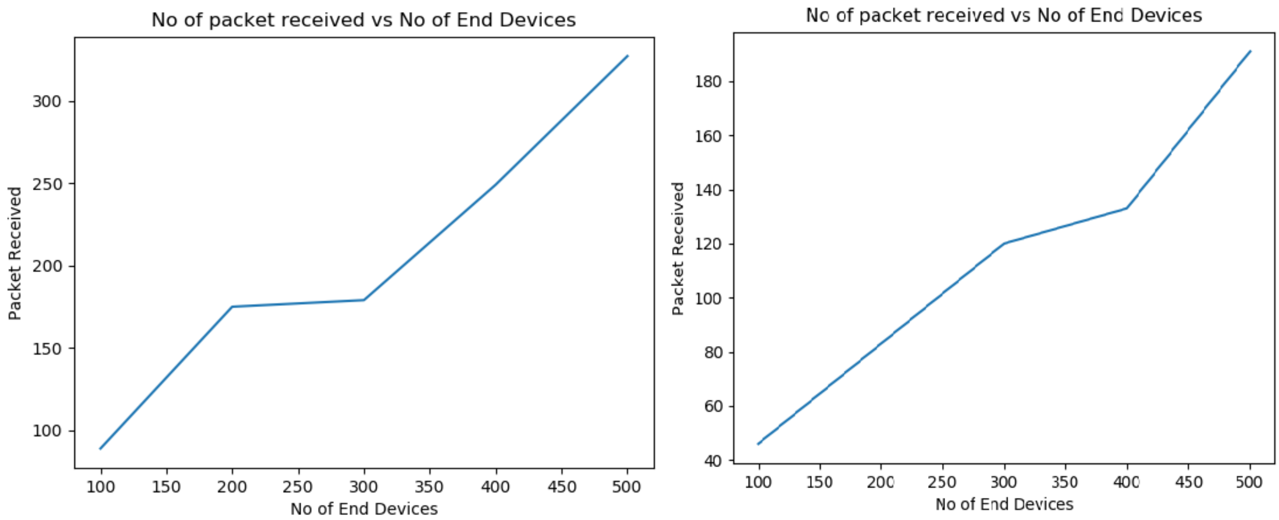

FIGURE 6. Average number of packets received w.r.t No. of end devices with ADR enabled. (a) d=500m (b) d=1000m.

TABLE 4. E = Enabled; Initial SF=12; Initial Transmit Power=14dbm.

DR	Bandwidth	End devices	SA PER (%)	Pure ALOHA PER (%)	Distance (m)	Payload Size	Duty Cycle
E/SF12	125 Khz	500	25%	500m	20	1%	
E	125 Khz	500	23%	66%	500m	20	1%
E	125 Khz	500	34%	70%	500m	20	1%
E	125 Khz	500	29%	68.3%	500m	20	1%
E	125 Khz	500	32%	65.5%	500m	20	1%
E	125 Khz	500	43.5%	69.4%	500m	20	1%

Algorithm below illustrates the steps which are involved in collisions and therefore in PER. There are three conditions that can cause collisions. These conditions include: If more than one nodes use same SF to transmit packet, or if more than one nodes access same slot at same time, or if they are using same channel. A packet loss occurs when received signal strength of a packet is below the sensitivity level at receiver or node takes at least 8 BEB. Otherwise signal is successfully transmitted and received. Algorithm below defines all the steps which are presented in Figure 6.

Algorithm to determine packet collisions and packet lost in LoRaWAN Slotted ALOHA Initial Configurations:

Distance between end device and gateway (D) = 500m.
Payload Size (PL) = [20, 25, 30, 35, 40].
Number of transmitters (N) = 500.
Initial transmit power (Tp) = 14dbm.
Initial SF = 12.
ADR = Enabled.
Free space path loss model is used for channel modeling. Packets = [p1,p2].
ADR=Enabled.
If p1.SF = p2.SF AND p1.starttime = p2.starttime AND p1.channel = p2.channel.
Collision occurs and PER gets incremented.
If packets.RSSI $\leq$ Sensitivity[SF] AND backoffslots $\geq$ 8.
Packet lost. else
Packet transmitted successfully.

Figure 6 shows impact of successfully received packets by varying number of end devices. Data rate and transmit power of nodes are adaptively managed by LoRa network as ADR is enabled for this simulation. Packet size used for below simulation is 20 bytes. With 3 data channels and ADR enabled, we have 18 virtual channels that are simultaneously used by end devices to transmit data packets. Distance between end device and gateway are taken as 500m.

Figure 6 (a) is for d=500m and Figure 6 (b) is for d=1000m. Distance has significant effect on total number of average successfully received packets. Further to distance, the number of end devices also affect the number of received packets. If we increase the number of end devices from 500, the percentage of received packets are drastically decreased.

Figure 7, shows the behavior of average received packets with varying number of end devices. Having ADR enabled, number of packets received in slotted ALOHA is greater than pure ALOHA LoRaWAN. For this simulation payload size remains constant. A packet of 20 bytes are transmitted by varying number of end devices. Results clearly demonstrate that with payload size of 20 bytes and 500m of distance between end device and gateway, slotted ALOHA out-performs pure ALOHA. With 300 end devices, number of recieved packets in slotted ALOHA are significantly more

TABLE 5. E = Enabled; Initial SF=12; Initial Transmit Power=14dbm.

ADR	Bandwidth	End devices	Throughput	Payload Size	Duty Cycle	
E/SF12	125 Khz	100	86%	500m	20	1%
E	125 Khz	100	86%	500m	20	1%
E	125 Khz	200	95%	500m	20	1%
E	125 Khz	300	92%	500m	20	1%
E	125 Khz	400	50%	500m	20	1%
E	125 Khz	500	61%	500m	20	1%
E	125 Khz	100	47.65%	1000m	20	1%
E	125 Khz	200	49.5%	1000m	20	1%
E	125 Khz	300	49.0%	1000m	20	1%
E	125 Khz	400	48.65%	1000m	20	1%
E	125 Khz	500	45%	1000m	20	1%

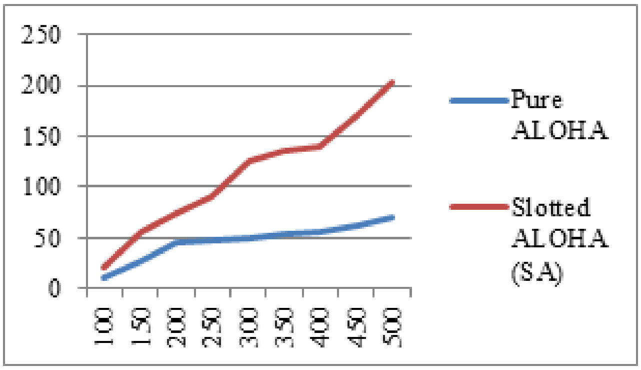

FIGURE 7. Average number of packets received w.r.t No. of end devices with ADR enabled.

than Pure ALOHA. Further, when we have 500 end devices per gateway transmitting packets simultaneously, average packets received in slotted ALOHA are greater than Pure ALOHA.

The throughput of slotted Aloha in LoRaWAN is presented in Figure 8. Initially, nodes configure their SF as 12 with a transmit power of 14 dbm, accordingly. As ADR is enabled, so after first transmission, the data rate and transmit power of a node is adaptively controlled. We perform simulations to analyze the throughput of slotted Aloha in LoRaWAN environment by varying distance between end device and gateway.

We have kept the packet size as 20 byte for the simulations. We can observe from Figure 8(a) that the throughput of slotted Aloha is 40% better than Aloha. We can observe that for 500 nodes having distance 500m between end device and gateway, transmitting a packet of 20 bytes will result in a 68% of throughput. In case of Aloha in LoRaWAN environment, the throughput for same set of parameters is 28% [36]. Further decrease in throughput is observed by increasing distance between end device and gateway from 500m to 1000m in Figure 8(b).

Figure 9 demonstrates the delay with respect to payload size. As LoRa nodes follow duty cycle limitation of 1%, the delay factor in LoRa network is really important to analyze rigorously. Before transmission of packets towards gateway, LoRa nodes have to select a random slot. This random slot duration is according to the SF used for transmission [35]. This slot selection by LoRa nodes causes delay, which will definitely increase time on air (ToA) for that packet. However, for the delay tolerant

IoT applications, this increase in delay generated by slotted Aloha is acceptable. We have kept the number of nodes for this scenario as 200. The delay showed in Figure 9 is in milliseconds. For SF 12, we have higher delay, which decreases significantly with the lower SF. One of the major factors in higher delay is BEB mechanism used for backoff in slotted Aloha.

LoRa end devices provide 10 years back up life time [35]. However, when it comes to real environment the situation is much more different. By default, LoRa end devices use Aloha for transmission of packets. Although, Aloha seems a simple choice to transmission, however it may lead to massive number of collisions affecting the LoRaWAN throughput. In this article, we have used slotted Aloha for transmissions. In case of slotted Aloha, end devices have to randomly select slot before transmission starts. However, unlike Aloha in slotted Aloha end device can only transmit data in the start of a time slot. Our results show that by using slotted ALOHA, energy consumption will be on a higher side as compared to Aloha due to the time spent by end devices in listening mode for most of its time for slot selection. In Figure 10, we analyze behavior of end devices that transmits different size of payload with different SFs. One interesting result in Figure 10 is for the payload size of 30 bytes. As the size of packet is large enough and with duty cycle limitation of 1%, it is not possible to transmit whole packet of size 30 byte in simulation time of 1 hour. This is the reason that energy consumption of LoRa end device

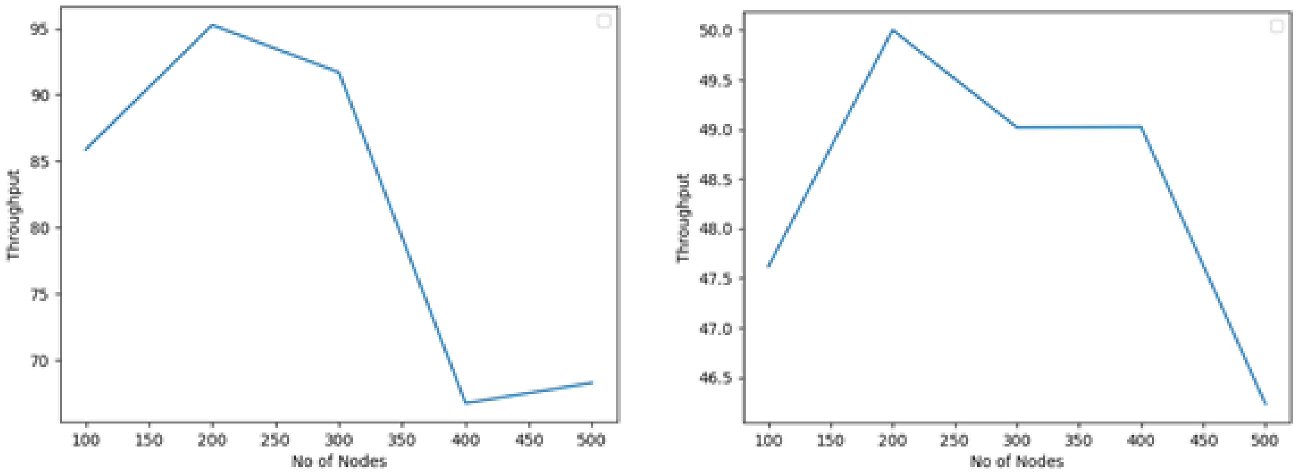

FIGURE 8. **Percentage Throughput w.r.t No of Nodes with ADR. (a) d=500m, (b) d=1000m.**

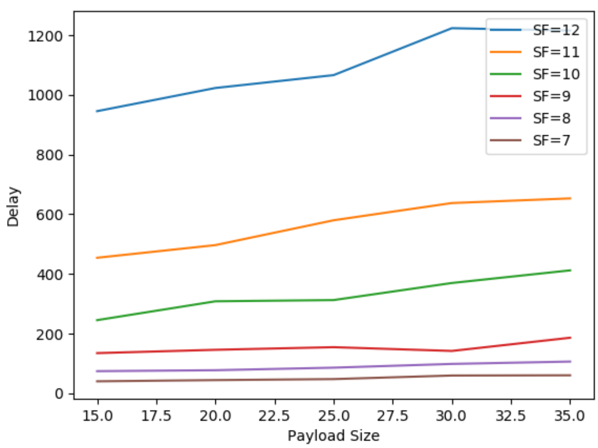

FIGURE 9. **Delay w.r.t Payload Size for different SFs.**

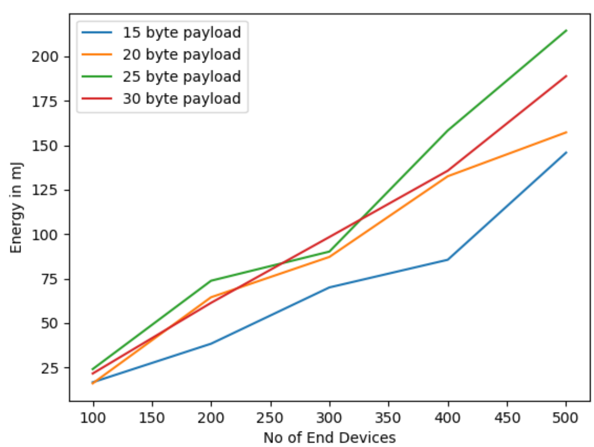

FIGURE 10. **Effect of No of end devices on energy (in milliJouls) having ADR Disabled.**

with 30 bytes payload is on a lower side as compared to others.

Results in Figure 11 shows the impact of varying payload size on energy with the ADR bit enabled. Initially end devices

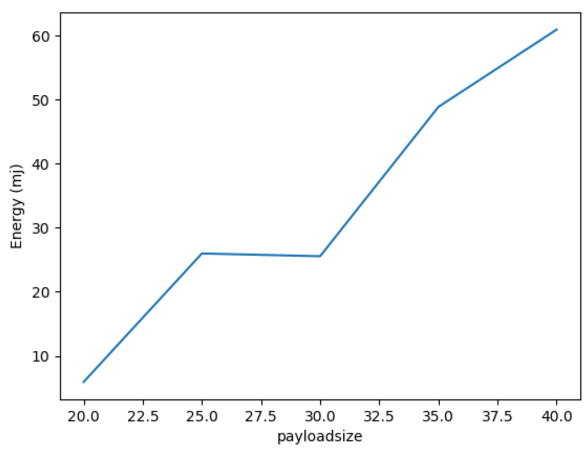

FIGURE 11. **Effect of No of end devices on energy (in milliJouls) having ADR Enabled.**

statically configures SF=12 and transmit power 14 dbm. After this both these parameters are adaptively controlled by LoRa network. By enabling ADR, energy of nodes is efficiently optimized.

VIII. CONCLUSION

Recently, IoT preferably use LPWAN as the most promising and prevalent technology for a wide range of applications such as smart homes, agriculture, and smart metering etc. Extant literature mostly focus on the use of LoRaWAN under pure Aloha that may not be suitable for certain delay tolerant applications. We rigorously evaluate the performance of slotted Aloha in LoRaWAN for delay tolerant applications. Results of slotted Aloha outperforms in terms of PER, collision, and throughput. Further, increase in delay has been observed; however, that is affordable by delay tolerant applications. The out-performance in terms of PER, throughput, collision, and reduced energy consumption can substantially lead towards Green IoT. Finally, we endorse slotted Aloha LoRaWAN for Green IoT. Further we plan to propose adaptive techniques to adjust duty cycle and channel allocation using adaptive reinforcement learning algorithms for dynamic Green IoT environments.

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