

Energy harvested end nodes and performance improvement of LoRa networks

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Abstract

LoRa technology is derived from chirp spread spectrum (CSS) having embedded forward error correction (FEC). A wide band is used for transmissions to counter interference and to handle frequency offsets. The paper investigates low power wide area networks (LPWAN) transmissions in the uplink, where the end nodes are powered by using energy harvested from the surroundings. Long-range (LoRa) networks demonstrate their capability to support Internet of Things (IoT) applications, where the end nodes utilize the harvested energy for transmission to gateways using different spreading factor (SF) codes. The work fairly improves the throughput of the LoRa nodes while keeping the other parameters, like time duration of the energy harvesting (EH), SF , and transmit power, optimally. Initially, a mathematical expression is derived for collisions between packets of the end nodes; keeping this as an important factor, an algorithm is proposed that fairly assigns SFs to the nodes. Simulation results confirm the improvement in packet error rate and time on air when fewer LoRa nodes are used for lower SFs , as compared to higher SFs . The number of LoRa nodes that can communicate using $SF=7$ is almost four times as compared to using $SF=11$, while maintaining a low packet error rate. Also, for $SF=7$, changing the coding rate from 1 to 4 increases time on air by around 20ms, while time on air increases by 1,200ms for $SF=12$. The energy efficiency is also compared for different SFs and different transmission powers. A lower SF and lower transmission powers are more suitable for smaller distance and provides better energy efficiency.

Keywords

LoRa, IoT, Energy harvesting, LoRaWAN, ToA, Gateway, Smart sensors.

The evolution of the Internet of Things (IoT) has taken the idea of connectivity to a very different level due to the rapid development of the platforms that will connect billions of the devices (Bor et al., 2016). With the merger of pervasive sensing along with remote power computations on these platforms, it is possible to collect and process data of numerous applications related to smart cities, agriculture, healthcare, and logistics. The utilization in numerous applications

increases proportionally to the requirement on the network side (Gubbi et al., 2013). The network infrastructure, which services these IoT applications, must be able to provide services that these applications demand as they might have different latency requirements, mobility levels, and reliability. Also, security should address the demand for different levels of mobility, latency tolerance, security, and reliability. Another important factor that affects demand is

the range of communication: long and short. It is impossible for a single network architecture to address these diverse demands. The demands are divided among the different types of service providers. The mobile communication operators perceive the need to adjust the systems to serve short-extent machine-to-machine (M2M) communication applications. The legacy networks, which were originally deployed for voice communication, and later used for multimedia applications, serve the delay-sensitive IoT applications at the expense of higher protocol overhead. However, energy efficiency improvement of connected devices is one of the major challenges to be addressed (Dhillon et al., 2017). The development of a low power wide area network (LPWAN) standard also uses narrow band IoT, termed LTE-2M, which enhances the performance of the existing mobile network to provide wide range coverage to IoT devices (Adhikary et al., 2016; Balyan and Groenewald, 2016; Balyan and Saini, 2011; Pana et al., 2018).

An overview of LPWAN techniques is given in the studies of Petäjälä et al. (2017) and Raza et al. (2017). A solution given for LPWAN is the LoRa™ platform, which enables lower power and lower cost end devices, with a reliable backup system. The end-users (EU) communicates in sub-GHz bands (different in every country) and uses frequency shift keying (FSK) modulation, or a chirp spread spectrum (CSS) modulation, in which the signal is spread over a wide band channel, with the ability to recover quickly from noise and interference. The research community is attracted towards LoRa™ to address complex scenarios of IoT. The work in the study of Georgiou and Raza (2017) questioned scalability together with the number of connected devices. The collisions between the EUs transmitting at the same time with the same *SF* have been analyzed. The results indicate that more gateways can be deployed in more crowded areas. The propagation range of links between EUs and the gateway is analyzed in the study of Petäjälä et al. (2017), and a real network that is ideal for small area or town is deployed for analysis. The channel attenuation model is also valid for propagation near water surfaces. The results in the study of Petäjälä et al. (2017) help in network deployment of base stations with respect to density of the EUs.

The applications, which are delay-sensitive and use lower data rates, utilize LoRa™ to provide a promising solution. The choice of *SF* with respect to the range of communication is an important trade-off. In addition, no research has been conducted for energy efficiency and the device's lifespan using LoRa™ in an LPWAN. To perceive the significance

of these performance parameters and trade-offs, in Ireland implementations are being tested in real scenarios using test-beds (Costa et al., 2017).

The work reported in the studies of Centenaro et al. (2016), Goursaud and Gorce (2015), Vangelista et al. (2015) explains LoRa briefly; the main focus is on physical layer (PHY) and applications, with little attention paid to medium access control (MAC) protocol. Using a lower number of devices in a scenario, a testbed and its simulation results are presented in the study of Augustin et al. (2016). A traditional protocol similar to ALOHA is presented in the study of Adelantado et al. (2016) to assess the performance of LoRaWAN in a scenario with a higher number of devices, the work is not using any testbed or simulation for validation.

The way by which LoRa nodes communicate with one another, together with a reduction in energy consumption or using energy harvesting for LoRa nodes, will result in the development of sustainable and strong IoT in future. The related work presented in the next section, reviews work that has already been reported in the literature. The main contributions of this paper are as follows:

1. The resource allocation used maximizes the LoRa user rates, and the LoRa users harvest energy from external sources.
2. The total time taken, including harvesting, transmission, and reception time at the gateway, is used for avoiding the collisions between transmissions between LoRa nodes.
3. A priority LoRa algorithm is proposed, which assigns specific *SF* to nodes having priority over other nodes.
4. LoRa technology scalability is also analyzed.

Related work

Wireless sensor networks and LoRa

A wireless sensor network (WSN) is comprised of sensors that are connected wirelessly. The performance of the network depends upon its nodes' capability to sense, process, and communicate with the destination sensor node. This depends upon two factors; how it is routed and the energy used for transmission (Gupta et al., 2020; Tanwar et al., 2014, 2019). LoRaWAN is gaining astounding equal ground in industry and small businesses. As of late, it has pulled incomparable degrees of consideration from the scholastic and exploration network. In the studies of Petäjälä et al. (2017), Augustin et al. (2016),

Reynders et al. (2016, 2017), an overview of the performance and detailed analysis of its operational requirements is given, aimed at scalability with respect to the simple ALOHA access techniques. The work done in the studies of Petäjärvi et al. (2017) and Georgiou and Raza (2017) is focused on end-user distance from the gateway using the highest data rate and ensuring correct demodulation. The work in the study of Adelantado et al. (2016) assumes a distribution of all end-users that ensures maximum coverage distance using the highest SF. In the study of Gupta et al. (2020), the proposed work provides new resource allocation, which enhances LoRa's capacity and improves its performance. A small cell network with a small radius is considered in the studies of Augustin et al. (2016) and [21] such that all end-users can communicate with the gateway directly using available SFs. A three layer IoT architecture is employed in the study of Bandopadhyaya et al. (2020) for healthcare monitoring of soldiers working in adverse environmental conditions. The integration of NOMA with LoRa is also getting attention for resource allocation (Balyan, 2020; Balyan and Daniels, 2020; Bandopadhyaya et al., 2020; Li et al., 2019). The work in the study of Sherazi et al. (2020) proposed a model to evaluate the energy consumption and predict the LoRaWAN monitoring devices' battery life. In the study of Delgado et al. (2020), the viability of LoRaWAN battery-less Class A devices is considered for both downlink and uplink transmissions. A model using a Markov chain is proposed, which uses granularity parameters and verified after comparing with a simulation model. It also checks applications-specific viability of battery-less LoRaWAN devices. The effect of the transmission interval and packet size is also analyzed, which concludes that the performance of the downlink is influenced when, especially, the second reception window is open. This work also proposes to use small size packets. The work in the study of Farooq (2020) proposes a multi-hop communication scheme for the uplink, which uses LoRa's PHY layer parameters to extend the network's coverage and throughput simultaneously.

Energy harvesting and scheduling

The requirements of high-speed networking in all the sectors is putting a burden in the form of resources to store and means to conserve energy, which is further growing due to massive sizes (Khargharia et al., 2007). The LoRa flexibility is limited when the devices are powered by energy sources (batteries). The deployment of such devices further limits the performance of the LoRa, as the battery replacement

cost and distance of location or dangerous environment is another factor which needs to be considered. This clearly indicates that addressing energy efficiency is not sufficient. Another solution is to use energy harvesting, which is used to provide power to remote sensors or LoRa nodes. The harvested energy can be taken from solar energy, radio frequency energy, electromagnetic energy, or wind energy (Clerckx et al., 2019). The radio frequency energy can be derived from dedicated transmitters, for example WiFi. The work reported in the study of Orfei et al. (2017) uses a battery-less LoRa wireless sensor that monitors road conditions. Mechanical vibrations are harvested electromagnetically, using energy harvester with Halbach harvesting configuration for harvesting. The work in the study of Lee et al. (2018) proposes a novel floating device that harvests thermoelectric and solar energy. The work presented in the study of Hasanloo et al. (2020) uses a system model that has a real-time periodic task set, an energy harvester, and a hybrid energy storage system (HESS). The HESS is described in two parts: instantly available charge (IAC) and instantly unavailable charge (IUC). These two parts intelligently controls the flow of charge in HESS and prolongs the lifetime of the system. Furthermore, the combination of the HESS and task scheduling leads to lifetime improvements of up to 20% provides as compare to other classical algorithms. The work in the study of Sherazi et al. (2020) uses available resources of renewable energy in a smart industry environment to highlight the importance of energy harvesting compared to the replacement cost of battery and associated damages. In our analysis of the literature review on LoRaWAN and EH together, we found that the performance of LoRaWAN is limited due to:

1. The devices that are powered by battery; and
2. Use of resource allocation algorithms, which are prone to collisions.

The work is done in the paper to address above mentioned issues. The remainder of the paper is organized as follows; an overview of LoRa specifications are given in the third section, energy harvesting and collision detection methods for LoRa nodes is explained in the fourth section, simulation results for performance evaluation are given in the fifth section, and finally, the conclusions are drawn in the sixth section.

LoRa specifications

LoRa technology is derived from chirp spread spectrum (CSS) having embedded forward error

correction (FEC). A wide band is used for transmissions to counter interference and to handle frequency offsets. A LoRa receiver is sensitive to decoding transmissions which are 19.5dB below the noise floor (Bor et al., 2016), which enables larger communication distances. The main benefits of LoRa include long-range links, robustness, low power, doppler, and multipath resistance. The available LoRa transceivers can operate between 137 and 1,020MHz. They are used in ISM bands. The physical layer of LoRa can be used with any MAC layer; however, LoRaWAN is the MAC for LoRa using a star topology.

LoRaWAN

The LoRaWAN provisions are maintained by the LoRa alliance, which is a non-profitable organization. The devices in LoRaWAN transmit packets directly to the nearby gateway(s), denoted as GW, which transparently forward the packets to a network server (NS). The NS uses the best packet and removes multiple duplicate messages, which might arrive due to multiple gateways, and forwards the packet to the application server. The devices and application servers are supplied by the end-user (EU), while the network provider provides the gateways and network server.

The three types of end devices are defined by LoRaWAN: classes A, B, and C. Class A devices send the packet randomly to the gateway and after a waiting time opens a receive window to receive any acknowledgment or pending messages from the gateway. Class B devices work on top of Class A devices with an additional scheduled receive window. Class C devices extend Class A by leaving the receive window open until it is transmitting. Classes A and B devices are mainly battery-powered, while Class C devices are mains powered.

As stated earlier, LoRaWAN operates in the ISM band (license exempt band). The frequency depends upon the country of deployment and operates using on the following frequencies 433,868 or 915MHz. There are eight physical layers used for this band; six with spreading factor (SF $7 \leq SF \leq 12$) using 125kHz bandwidth, 1 with $SF=7$ at 250 kHz bandwidth and the eighth operates with Gaussian frequency shift keying (GFSK) and supports 50kbps data rate. In order to extend the battery life of end node devices and the capacity of the network, the data rate and RF output of end nodes can be controlled independently by using an adaptive data rate (ADR) scheme. The chip rate, chip duration, bandwidth, symbol rate, symbol duration, and data rate are denoted by R_c , T_c , BW , R_s , T_s and R_b , respectively. The notations are

given in Table 1. The relation between them are as follows:

$$R_c = BW \text{ chips/s} \quad (1a)$$

$$T_c = \frac{1}{BW} \quad (1b)$$

$$R_s = \frac{BW}{2^{SF}} = \frac{R_c}{2^{SF}} \text{ symbols/s} \quad (1c)$$

$$T_s = \frac{2^{SF}}{BW} \quad (1d)$$

where $R_c > R_s$.

$$R_b = SF \times \frac{BW}{2^{SF}} \times \frac{4}{4 + CR} \quad (2)$$

where CR is the coding rate for forward error correction (FEC), $1 \leq CR \leq 4$.

With an increase in SF , R_b decreases and vice versa. The main impact of increasing SF will be on time on air (ToA), which means more time will be used to send the same amount of data. This in effect increases the power consumption too. Therefore, a higher SF value is used for a weak signal or in case of higher channel interference.

Time on air

The time on air (ToA) that not only depends upon the size of the payload, but also on the selection of BW , SF and CR . It can be calculated using the Semtech LoRa modem calculator [2]. The selection of communication parameters hugely affects the

Table 1. Notations.

Notation	Definition
R_c	Chip rate
T_c	Chip duration
R_s	Symbol rate
T_s	Symbol duration
R_b	Data rate
SF	Spreading factor
CR	Coding rate
t_{ai}	Time on air of i th node

performance and scalability of LoRa. The ToA denoted as t_{a_i} is given as follows:

$$t_{a_i} = \frac{S}{R_s} = s \times T_s \quad (3)$$

where s denotes the number of symbols.

The work in this paper considers the frequency regulations on duty cycle is between 0.01 and 10% of Europe for the 868MHz sub-band, which is also known as ISM sub-GHz band. If the duty cycle is denoted by T , then $(1-T)\%$ denotes the off-time for the node, after a packet transmission, when $T=1\%$. The T_i is the on-time for the i^{th} node during transmission, after which $T_i^{off} = \frac{(1-T_i)}{T_i} t_{a_i}$ is the off-time for the LoRa node. LoRa nodes are battery-less and uses harvested energy to power up, the harvested energy is from external sources.

Energy harvesting and collision detection methods for LoRa nodes

The model of LoRaWAN is shown in Figure 1. Each LoRa node is battery-less and is powered by harvested energy from external sources of energy. The energy can be harvested from any external source, which will not interfere with the LoRa nodes' frequencies. For a harvested energy per unit time denoted as E_i for the i^{th} node, which depends upon external conditions and is independent of time like distance from the energy sources. The transmission by a LoRa node is only possible after harvesting sufficient energy. Therefore, transmission is carried out after harvesting. Let the

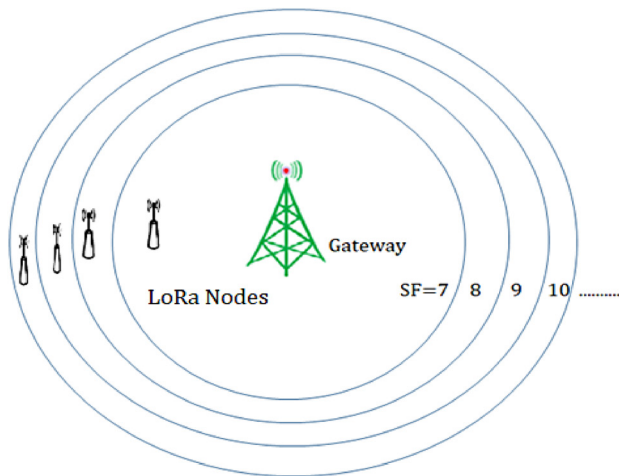


Figure 1: Model of LoRaWAN.

total time taken from harvesting, transmission, and reception at the gateway for the i^{th} node be:

$$T_i = t_{h_i} + t_{a_i} + t_{r_i} \quad (4)$$

where $t_{h_i} = T_i^{off}$ denotes the time of harvesting energy and t_{r_i} denotes the time required for complete reception of the packet. Therefore, the harvested energy for the i^{th} node is given by:

$$E_{h_i} = t_{h_i} \times E_i \quad (5)$$

Also, let the reception starts and ends at $t_{r_{is}}$ and $t_{r_{ie}}$, respectively, for the i^{th} node. The t_{r_i} for the i^{th} node is then given by:

$$t_{r_i} = t_{r_{ie}} - t_{r_{is}} \quad (6)$$

The midpoint of length and midpoint of reception time t_{r_i} is given by:

$$t_{r_{im}} = \frac{t_{r_{ie}} - t_{r_{is}}}{2} \text{ and } t_{r_{im}} = \frac{t_{r_{ie}} + t_{r_{is}}}{2} \quad (7)$$

The two packets i and j will collide during the reception time for:

$$|t_{r_{im}} - t_{r_{jm}}| < t_{r_i} + t_{r_j} \quad (8)$$

The LoRa nodes are required to transmit at maximum power, denoted by P_{max} , and which is known in advance. A LoRa node decides its transmission time after harvesting the energy required for transmission. If the harvested energy is more than required, it will not be stored.

A collision may occur between nodes with the same SF or different SFs. The work in this paper considers both these scenarios. Ideally, the nodes with different SFs must not interfere with each other due to orthogonality conditions; however, the imperfect orthogonality leads to inter-SF interference between these nodes.

The calculations are done taking node i as reference. The collision possibilities depend upon harvesting time, time on air, and time of reception. The delay between harvesting time and transmission is considered to be zero. For any two nodes i and j :

- t_{h_i} and t_{h_j} denotes harvesting time.
- T_{a_i} and T_{a_j} denotes time on air.
- t_{r_i} and t_{r_j} denotes reception time.

Let the collision time between two nodes i and j be denoted by $t_{i,j}^c$.

Case 1: If $[(t_{h_i} > t_{h_j}) \& (T_{a_i} > T_{a_j}) \& (t_{r_i} > t_{r_j})] | (t_{h_i} > t_{h_j} + T_{a_j} + t_{r_j})$

$$t_{i,j}^c = 0 \quad (9)$$

This case considers that the harvesting time, time on air and reception time of node i is greater than that of node j . Also, the harvesting time of node i is greater than the total time taken by another node j . In this case, collision time between nodes is zero, as shown in Figure 2A.

Case 2: $[(t_{h_i} > t_{h_j}) \& (T_{a_i} > T_{a_j}) \& (t_{r_i} > t_{r_j})] | (t_{h_i} < t_{h_j} + T_{a_j} + t_{r_j})$

$$t_{i,j}^c = t_{h_j} + T_{a_j} + t_{r_j} - t_{h_i} \quad (10)$$

This case considers that the harvesting time, time on air and reception time of node i is greater than of node j . However, with the harvesting time of node i less than the total time taken by node j , the collision time between nodes is given in Equation (10), as shown in Figure 2B.

Case 3: $[(t_{h_i} > t_{h_j}) \& (T_{a_i} < T_{a_j}) \& (t_{r_i} < t_{r_j})] | (t_{h_i} > t_{h_j} + T_{a_j} + t_{r_j})$

$$t_{i,j}^c = 0 \quad (11)$$

When harvesting time of node i is greater than of node j , the time on air and reception time of node j is greater than of node i . However, the harvesting time of node i is greater than the total time taken by

another node j , then collision time between nodes is zero as shown in Figure 2C.

Case 4: $[(t_{h_i} > t_{h_j}) \& (T_{a_i} < T_{a_j}) \& (t_{r_i} < t_{r_j})] | (t_{h_i} < t_{h_j} + T_{a_j} + t_{r_j})$

$$t_{i,j}^c = t_{h_j} + T_{a_j} + t_{r_j} - t_{h_i} \quad (12)$$

When harvesting time of node i is greater than of node j , the time on air and reception time of node j is greater than of node i . However, the harvesting time of node i is lesser than the total time taken by another node j , then collision time between nodes is given by Equation (12) as shown in Figure 2D.

Case 5: $(t_{h_i} + T_{a_i} + t_{r_i} < t_{h_j} + T_{a_j} + t_{r_j})$

$$t_{i,j}^c = T_{a_i} + t_{r_i} \quad (13)$$

When total time of node i is lesser than the total time taken by another node j , then collision time between nodes is given by Equation (13) as shown in Figure 2E.

The allocation of the SF to an EU is an important decision for the LoRaWAN for many reasons, for example, a higher value of SF provides higher coverage distance for better reception and suffers from lower bit rate and longer ToA. Therefore, for higher SF values the communication channels are busy for longer durations, which increases the probability of collisions between the packets transmitted concurrently. As the different SFs are orthogonal to each other, this allows more communication using the same channel. The number of devices d_{total} is usually very large, the minimum data rate will do exhaustive search equal to $6^{d_{total}}$. Therefore, an exhaustive search is not used due to complexity. To reduce the complexity, the algorithm explained below is used.

The proposed PRIORLoRa algorithm assigns SF on the basis of the priority of nodes to send data. To the best of the author's knowledge, this paper is the first to assign SF to the EU with priority. Most of the algorithms in literature assign SF on the basis of radio visibility only. The algorithm is given below.

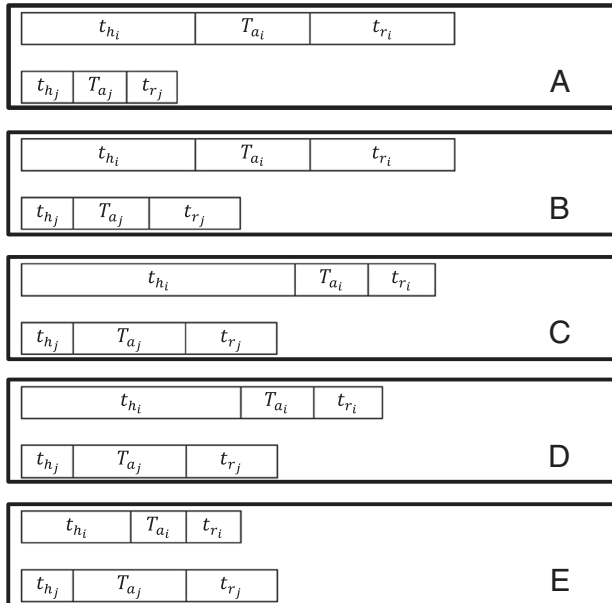


Figure 2: Illustration of collision time for nodes as a function of their harvesting time, time on air and reception time.

Algorithm PRIORLoRa

1. **Input:**
2. d_{total} – number of devices covered by a gateway
 $SF_s, 7 \leq s \leq 12$: denotes number of SF of value s ,
 $SENS$: denotes sensitivity of the devices,
 $RSSI$ – nodes power levels.
 $PRSSI$ – priority nodes power levels.
3. **Output:** SF_o

```

4. function PRIORLoRa-SF ( $[PRSSI]_{m \times n}$ ,  $[SF]_{1 \times n}$ ).
5.  $[SF]_{1 \times n} = [7 \dots 12]$  of  $n$  end devices.
6. for  $l = 1$  to  $\text{length}(SF_s)$ 
7.  $c = \text{count}(PRSSI(l) > SENS)$ 
8. if  $c > \frac{d_{total}}{\text{length}(SF_s)}$ 
9.  $r = \frac{d_{total}}{\text{length}(SF_s)}$ 
10. else
11.  $r = c$ 
12. End if
13. for  $k = 0$  to  $r$ 
14.  $[p, q] = \max(PRSSI)$ 
15.  $SF_o[q] = [SF[l]]$ 
16.  $PRSSI[:, q] = -200 \text{ dBm}$ 
17. End for
18. End for
19. return  $SF_o$ .

```

The complexity is reduced by searching for r devices only. The complexity in searching SF for a node (user) using the algorithm is $6^r < 6^{d_{total}}$ (the number of SF used are 6 in this algorithm). For m , SFs used complexity will be $m^r < m^{d_{total}}$. The flowchart of proposed PRIORLoRa algorithm is shown in Figure 3.

The energy consumed by LoRa node during transmission of packet is found using the current levels given in the study of Gubbi et al. (2013). This energy needs to be minimize even though energy harvesting is used for LoRa nodes. The energy spent (Joules) in transmission for i^{th} node for a supply voltage V volts and current I mA can be calculated from:

$$E_i = V \times I \times t_{a_i} \quad (14)$$

The energy spent during transmission plays an important role in improving the performance of the network. The energy efficiency (EE) for i^{th} node is defined as:

$$EE_i = \frac{\text{Payload in bits} \times p_s}{BW \times E_i} \quad (15)$$

where p_r denotes the probability of packet received without error.

The number of transmitted packets by a node depends upon SF , bandwidth of channel used and the payload. If the payload is large, the packets become larger which leads to lesser transmission in

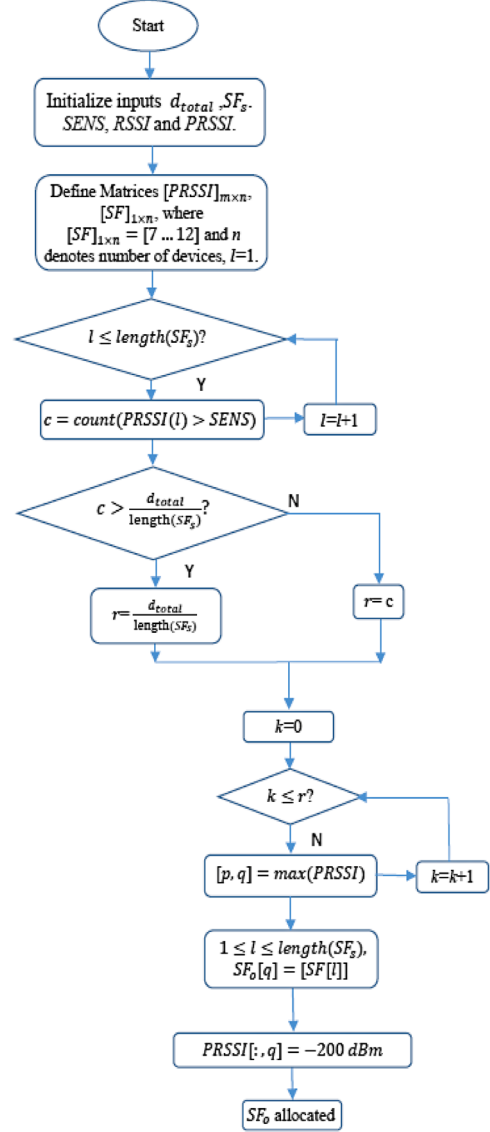


Figure 3: Flowchart of PRIORLoRa algorithm.

a day. One way to use the battery or the harvested energy of a LoRa node for a long time is utilization of longer SF , which increases time on air.

Simulation results for performance evaluation

The simulation is done in MATLAB implementing the PRIORLoRa-SF algorithm described in the previous section. A LoRa network is implemented with end-users or nodes denoted as d_{total} and a single gateway centrally placed around which nodes are randomly distributed in circles as shown in Figure 1.

The density of the nodes is $Traffic_d = \frac{d_{total}}{\pi R^2}$, where R is the total radius of the network. The probability of node present at a distance x from the gateway can be found using probability density function defined as $f(x) = 2 \times \frac{y}{R^2}$, $0 \leq y \leq x$.

The SFs assigned to nodes SF_s , $7 \leq s \leq 12$. The index of assigned CR is from 0 to 4, which corresponds to coding rate 1, 4/5, 4/6, 4/7, and 4/8, respectively. The coding rate 1 indicates that no coding is applied. The nodes have same configuration and uses same transmit power 14dBm which is power allowed for the exempted frequency sub bands. Each i^{th} node selects a particular available frequency channel for transmission and then wait for T_i^{off} period before starting next transmission as per LoRaWAN specifications. The simulation parameters are taken from the study of El-Aasser et al. (2019).

In Figure 4, data extraction rate (DER) also known as success probability as a function of spreading factor (SF) is plotted for three different node densities, $10 \frac{nodes}{km^2}$, $20 \frac{nodes}{km^2}$, and $500 \frac{nodes}{km^2}$. It is clearly evident from result that as the node density and SF increase, the DER decreases significantly. The reason in sharp fall in DER when $SF \geq 10$ is longer time on air that increases number of transmission at the same time for all three density distributions. This decrease is more prominent for node density $500 \frac{nodes}{km^2}$, due to increase in more collisions.

The average received signal strength indication (RSSI) of the message received at the gateway plays

an important role in deciding a specific SF which depends upon the path loss propagation model. The SF assigned to an end user play an important role as the SF increases the coverage distance of end node communication with gateway improves. This comes at a cost of longer time on air and lower bit rate. Usually $10 \leq SF \leq 12$ are considered high SFs , which will have longer time on air and have higher probability of collisions. However, the use of different SF provides orthogonality in communication or in other words less interference. This leads to the inclusion of more number of nodes or higher spectral efficiency. The effect of payload of a packet is explored. The variation in packet error rate (PER) in a network that has increasing LoRa nodes and payload used are of 10, 25, 40, and 60 bytes are is done in this section. The PER is mainly affected by the number of collisions on the communication channel used by more than one node at a time. These collisions are influenced by the number of LoRa nodes that are using the same SF on the same channel.

In Figures 5 and 6, the rate of packet error is plotted against the number of LoRa nodes equal to 4,000 and 8,000, respectively, at constant $SF=7$, duty cycle 0.02%, and constant coding rate=4/5. These values are close to real-time IoT applications. A higher value of packet error rate indicates lesser packets are received with errors and vice versa. In Figure 5, the number of LoRa nodes used are 4,000, when the payload is 10 bytes the PER is more than

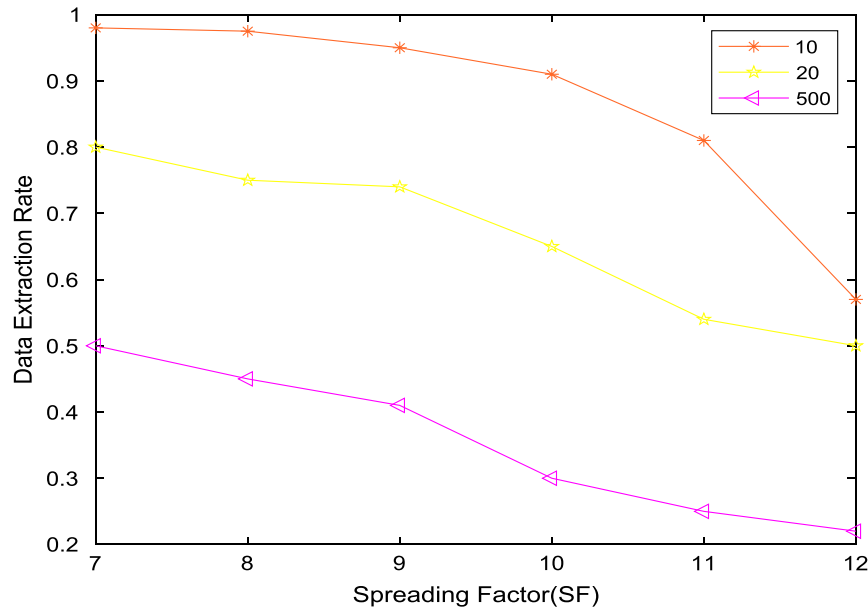


Figure 4: Data extraction rate vs spreading factor (SF) for three different densities $10 \frac{nodes}{km^2}$, $20 \frac{nodes}{km^2}$ and $500 \frac{nodes}{km^2}$ square km.

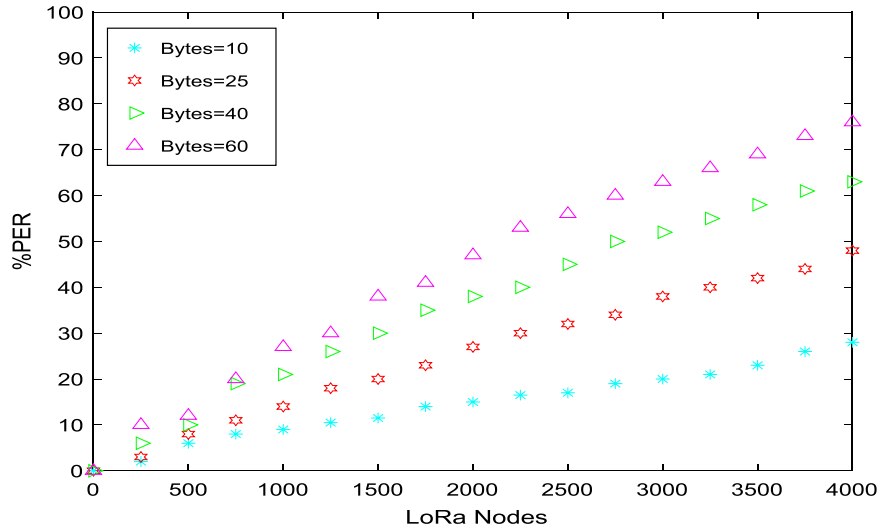


Figure 5: The rate of increase of packet error as a function of increase in number of LoRa nodes for constant $SF=7$.

25%, for an increase in the payload to 60 bytes the payload becomes almost thrice of it, i.e. close to 75%. Ideally, the packet error rate must be below 10%.

As the number of LoRa nodes increases the packet error rate increases drastically. Also, an increase in payload brought a higher packet error rate when fewer LoRa nodes are employed as shown in Figure 6. Clearly from Figure 6, the number of LoRa nodes that lead to a 10% packet error rate is around 2,000, 1,000, 500, and 200, respectively, for 10, 25, 40, and 60 byte payloads. At 8,000 LoRa nodes,

more than 90% are received with error for a payload of 60 bytes. The higher packet error rate is due to the larger number of LoRa nodes in Figure 6.

In Figures 7 and 8, the effect on packet error rate is compared with the number of LoRa nodes. The maximum number of LoRa nodes employed are 800 and 1,800 in Figures 7 and 8, respectively, keeping constant $SF=11$. An increase in SF leads to a very high packet error rate due to a longer time on air. For a payload of 60 bytes, the packet error rate is around 97% and more than 100% for 800 and 1,800

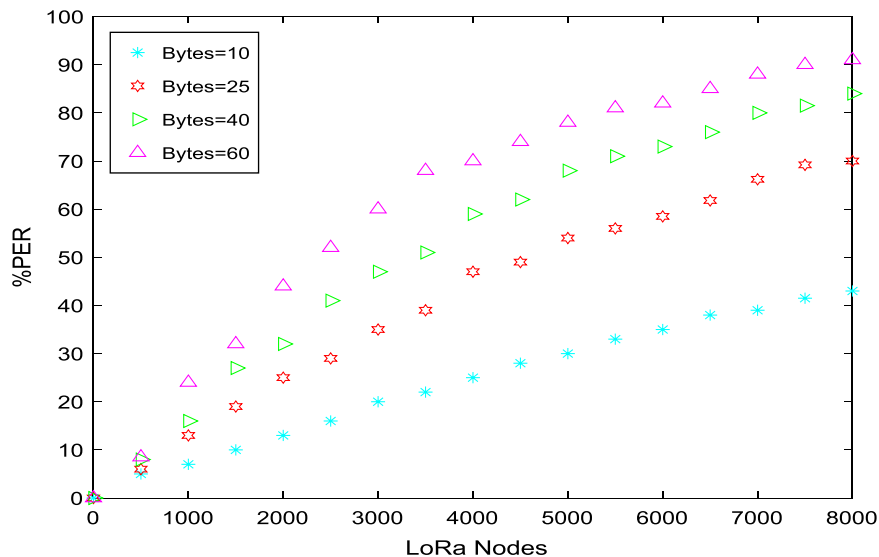


Figure 6: The rate of increase of packet error as a function of increase in number of LoRa nodes for constant $SF=7$.

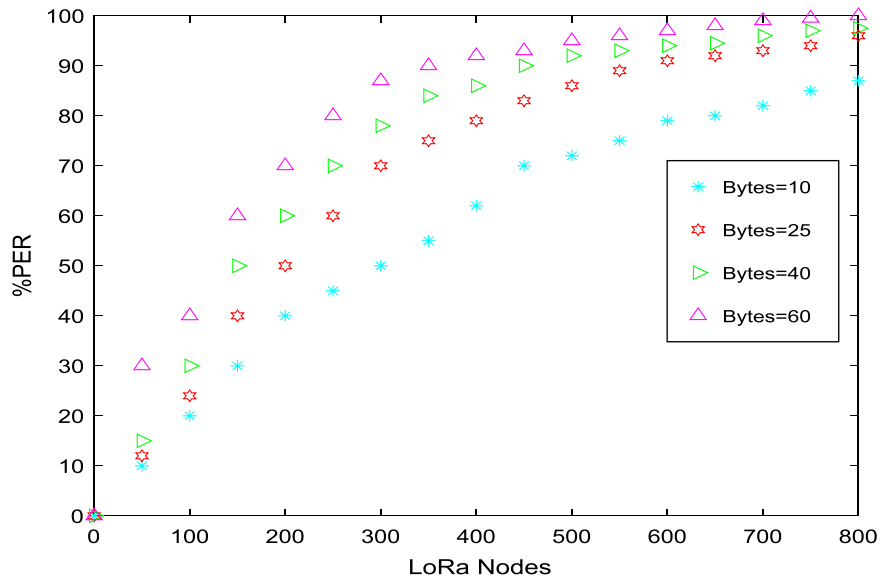


Figure 7: The rate of increase of packet error as a function of increase in number of LoRa nodes for constant $SF=11$.

LoRa nodes, respectively. Compared to the results of Figures 5 and 6, where $SF=7$ is used for a payload of 60 bytes the packet error rate is around 75 and 92%, respectively, for 4,000 and 8,000 LoRa nodes. It is due to the higher time on air which is due to more collisions affected by the payload of packets and SF .

In Figure 9, the packet error rate is compared for two different duty cycles 0.2 and 0.5%, while keeping SF constant at 7. A higher duty cycle means longer

time on air, the effect of which is evident from the plot of Figure 9, that packet error rate reaches 100% for around 600 LoRa nodes for 0.5% duty cycle as compared to 82% packet error rate for 800 LoRa nodes when 0.2 duty cycle is employed. The result indicates the importance of selecting an appropriate duty cycle for a specific SF . It is also important to consider regulations imposed by the ISM operational band which allows a maximum of 1% duty cycle.

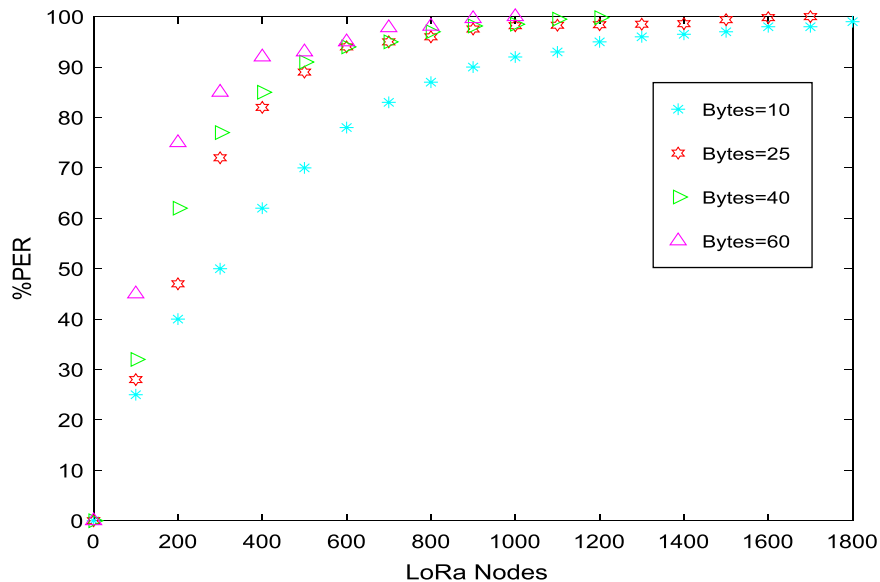


Figure 8: The rate of increase of packet error as a function of increase in number of LoRa nodes for constant $SF=11$.

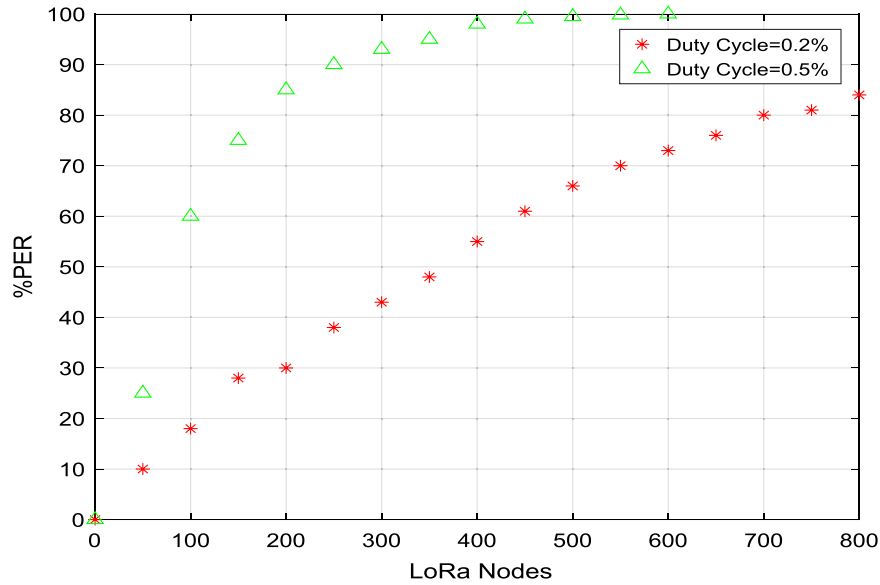


Figure 9: The rate of increase of packet error as a function of increase in number of LoRa nodes and duty cycle for constant $SF=7$.

In Figure 10, time on air is compared for different payloads using different coding rates for constant $SF=7$. The different coding rates used here are due to the different distances between LoRa nodes and gateway. The lower coding rate means a larger distance between LoRa node and gateway. The change of coding rate at constant SF improves the packet error rate as the number of encoding bits are

increased. However, it is achieved at the expense of increase in the time on air.

In Figure 11, time on air is compared for different payloads using different coding rates for constant $SF=12$. From Equations (1) and (3), using time on air which is directly proportional to 2^{SF} , increasing SF from 7 to 12, for a payload of 10 bytes increases ToA to around 8,000ms for $SF=12$. The use of a higher

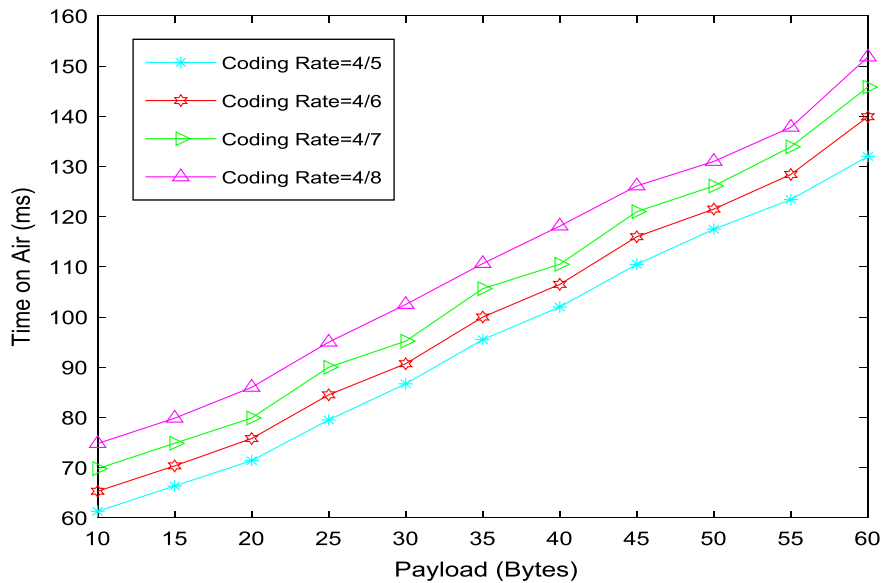


Figure 10: Time on air (ms) as a function of payload (bytes) for different CR and constant $SF=7$.

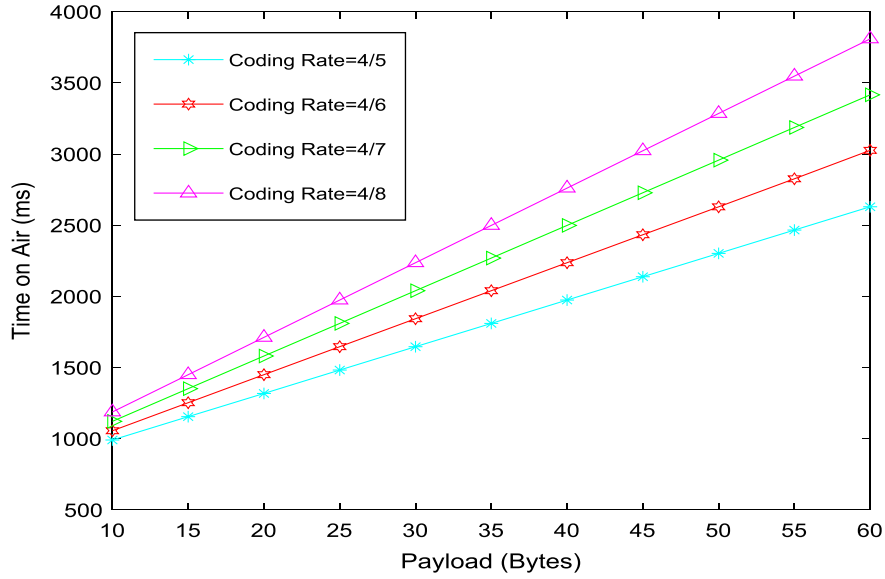


Figure 11: Time on air (ms) as a function of payload (bytes) for different CR and constant $SF=12$.

coding rate makes transmission more robust. A higher coding rate must be used when the interferences present are too many.

For the illustration of the energy efficiency is expressed in bits per Hertz per Joule and the voltage used is 3.3 volts. The energy spent depends upon

the current given by in [2] and is calculated using (14). A payload of 10 bytes and the bandwidth used is 125kHz for analysis of EE .

In Figure 12, the EE variation of different SFs with distance is compared. From the result, it is clear that small SFs are more suitable for small distances

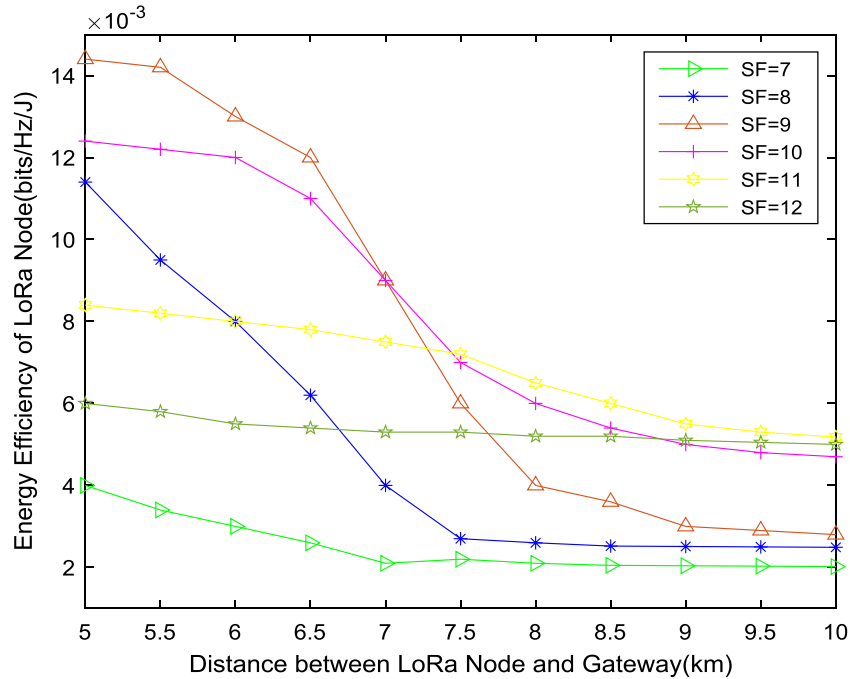


Figure 12: Comparison of energy efficiency of LoRa node versus distance between LoRa node and gateway for different SF .

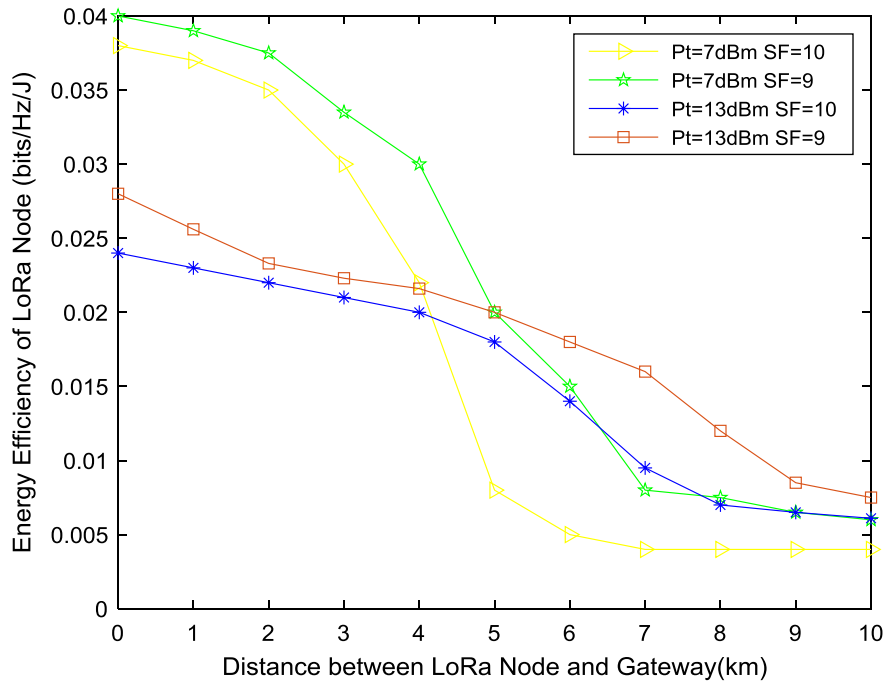


Figure 13: Comparison of energy efficiency of LoRa node versus distance between LoRa node and gateway for $SF=9$ and 10 with different transmission powers.

5–7 km, but their EE decreases due to higher number of transmissions with reduced probability of success. The higher SF provides better EE as compared to lower SF values due to longer time in air. The EE of $SF = 12$ is best, as its EE is almost a straight line due to longer time on air for all distances.

In Figure 13, the EE variation using two transmission powers 7 and 13dBm with distance are compared for $SF=9$ and $SF=10$. When the transmission power is less it is more suitable for smaller distances and EE is higher, however reducing SF from 10 to 9 increases EE slightly for both smaller and larger distances. When the transmission power increased to 13dBm, for both $SF=9$ and $SF=10$ the EE for performance is more suitable for small and mid-range distances.

The LoRa network can ensure the best performance when the number of retransmissions is minimum, which are directly proportional to the number of collisions. This can be achieved by keeping the packet error rate below 10%. One way to ensure this is by assigning SF to LoRa nodes depending upon their distance from the gateway. As the distance from the gateway increases, the SF assigned to a node increases. This will reduce the number of collisions.

Another way to ensure minimum retransmission is that the LoRa nodes must use the nearest gateway for communication, which increases the probability of

having a fewer number of nodes at larger distances. This in turn limits the number of nodes with higher SF . This also increases the existence of orthogonality between different LoRa nodes using the same channel but with different SF . The FEC can also be adopted to reduce the number of retransmissions also.

Conclusion

In this paper, the performance analysis of the LoRa technology is done which can be achieved by performing a scalability analysis. Thus, the main motivation was to determine the number of LoRa nodes that can be supported in an IoT like network. In other words, the scalability analysis is carried out, using different payloads, spreading factors, duty cycle, and coding rates. A packet is used for the transfer of information, a packet with error or collisions changes the performance of the network significantly. The packet error rate increases with an increase in payloads, duty cycle, spreading factors, and coding rate. A priority LoRa algorithm is proposed which provides priority to time-sensitive applications and ensures the allocation of SF is not only on the basis of radio visibility. The work also uses energy harvesting for LoRa nodes which are battery-less. This study is useful in choosing and configuring parameters of

LoRa/LoRaWAN. The parameters that are varied for analysis are SF , coding rate, network densities per square km, duty cycle, and payload. As the number LoRa nodes which can use the same channel using spreading factor 7 for communication purposes are around 1,300 for a payload of 10 bytes. The SF and coding rate must be on the basis of the distance of the LoRa node from the gateway. The EE of LoRa node is compared for different SFs and transmission power, the results indicate that higher power and higher SF are more suitable for larger distances.

In the future, work can be done to evaluate the performance under realistic conditions using different propagation models. Also, the effect of multi-user interference can be evaluated for better scalability analysis.

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