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LoRaWAN Performance Evaluation with Optimized Configuration

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Abstract

LoRaWAN is an access technology coupled with protocol stack specification which is exclusively presented to serve IoT application. IoT application commonly has small data and infrequent transmission. However, the challenge in presenting wireless access technology for IoT lies in its characteristic of massive node deployment and power-constrained transmission. Among several technologies, LoRaWAN promises the ability to handle massive number of nodes, longer transmission range, lower power consumption, as well as cheaper communication module. This paper presents a performance evaluation of LoRa network in respect to those claims. The performance of the network in term of packet delivery ratio, average energy consumption per transmission and average energy wasted in collision per nodes are investigated. A realistic scenario is considered, and the scalability study is also conducted via computer simulation. The result shows that the performance of LoRa network is highly dependent to the configuration of spreading factor, coding rate, and frequency selection. The performed experiment shows that the limitation inherited from pure ALOHA access strategy can be alleviated by randomizing frequency selection and node-specific optimization to maximize data rate relative to its location (i.e. channel condition) and contention severity.

Keywords: *LoRa, LoRaWAN, LPWA, IoT*

1. Introduction

Today's Internet of Things (IoT) is characterized by cloud-connected nodes which are mostly low-cost microcontroller having one or more sensors or actuators with constrained battery life, some of which may be located in remote locations, reporting small amount of data at a time over a communication link to a backend system. Compared to the current traditional Internet, IoT nodes has less memory, less processing power, less bandwidth, and less available energy. Numerous services are envisioned for IoT. IoT, which is also called Low Power Wide Area Network (LPWAN), is expected to be the next revolution in the mobile ecosystem.

Many LPWA networks are currently in trial phases or in commercial rollout worldwide because of the attractiveness to create a rapid route to market innovative IoT services. The two leading network technologies contributing to the fast development of LPWA IoT markets are LoRaWAN, and Ultra-Narrowband (UNB). Other LPWA technologies such as Weightless-N, Weightless-P from Weightless SIG and RPMA (Random Phase Multiple Access technology) from Ingenu are also commercially deployed and used to support specific vertical use cases. There are also several new 3GPP standards such as EC-GSM, LTE-M and NB-IoT [1] that are currently being specified to enable future 3GPP networks to support the specific requirements and use cases of the fast growing IoT markets in upcoming years.

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LoRaWAN targets key requirements of Internet of Things such as secure bi-directional communication, mobility and localization services. The LoRaWAN specification provides seamless interoperability among smart Things without the need of complex local installations and gives back the freedom to the user, developer, and businesses enabling the roll out of Internet of Things.

An important feature of the LoRa modem is its increased immunity to interference. The LoRa modem is capable of co-channel GMSK rejection of up to 25 dB. This immunity to interference permits the simple coexistence of LoRa modulated systems either in bands of heavy spectral usage or in hybrid communication networks that use LoRa to extend range when legacy modulation schemes fail.

The LoRaWAN protocol has several advantages over other LPWA technologies, particularly when compared with currently available one. LoRa's data rate ranges from 300 bps up to 5 kbps (with 125 kHz bandwidth) and 11 kbps (with 250 kHz bandwidth) allowing for better time-on-air and better battery life. Communication in LoRa is natively bidirectional and unlimited (with respect to ISM band local regulations) and natively supports payload encryption. The ADR (Adaptive Data Rate) enables an easily scalable network as base station addition will lower the average ADR and time-on-air around it, allowing for more nodes to communicate. The time difference on arrival (TDoA) in LoRa can be utilized for localization instead of GPS which uses more power. Technically, LoRa vendors are also providing wide variety of gateways: macro-gateways, indoor gateways, pico-gateways, *etc*.

Given the fact that a wide area is covered and that all nodes communicate directly to a few gateways, a large number of nodes have to share the communication medium. LoRa provides for this reason a range of communication options (center frequency, spreading factor, bandwidth, coding rates) from which a transmitter can choose. Many combination settings are orthogonal and provide simultaneous collision free communications. While the benefits of these technologies are known and are often considered as the key enablers for some applications, their limitations are still not well understood [2-4]. Additionally, the promise of LoRaWAN technologies to wirelessly connect massive numbers of geographically dispersed nodes at a low cost continues to attract a great deal of attention in the academic and commercial communities. Several rollouts are already underway even though the performance of these technologies is yet to be fully understood.

This paper aims to thoroughly evaluate the performance of LoRaWAN under different scenarios. An experimental testbed is constructed and analyzed while the scalability-related issues are evaluated via computer simulation by taking into account realistic LoRa deployment environment. This allows the result to be benchmarked with similar model in the future works. Notice that several existing works evaluate the system based on different testbed equipment, which makes it hard to be compared with others, as the main focus is to compare the protocol instead of hardware-related performance.

2. LoRaWAN Overview

LoRaWAN network architecture is typically laid out in a star-of-stars topology in which gateways is a transparent bridge relaying messages between nodes and a central network server in the backend. Gateways are connected to the network server via standard IP connections while nodes use single-hop wireless communication to one or many gateways, which is distinct from multi-hop transmission in ad-hoc networks [5]. All end-point communication is generally bi-directional, but also supports operation such as multicast enabling software upgrade over the air or other mass distribution messages to reduce the on-air communication time.

Communication between nodes and gateways is spread out on different frequency channels and data rates. The selection of the data rate is a trade-off between communication range and message duration. When designing the wireless link using

LoRa, there are three main parameters to be carefully considered. Each one permits a tradeoff between link budget, immunity to interference, spectral occupancy and nominal data rate. These parameters are spreading factor, modulation bandwidth and error coding rate.

- Spreading Factor. The spread spectrum LoRa modulation is performed by representing each bit of payload by multiple chips of information. The rate at which the spread information is sent denotes the symbol rate. Ratio between the nominal symbol rate and chip rate denotes the spreading factor, which also represents the number of symbols sent per bit of information. The spreading factor must be known in advance on both transmit and receive sides of the link as different spreading factors are orthogonal to each other.
- Coding Rate. To further improve the robustness of the link, LoRa modem employs cyclic error coding to perform forward error detection and correction. Note that such error coding incurs a transmission overhead. Forward error correction is particularly efficient in improving the reliability of the link in the presence of interference. The coding rate can optionally be included in the packet header for use by the receiver.
- Signal Bandwidth. An increase in signal bandwidth permits the use of a higher effective data rate, thus reducing transmission time at the expense of reduced sensitivity improvement. There are of course regulatory constraints in most countries on the permissible occupied bandwidth. Contrary to the FSK modem, which is described in terms of the single sideband bandwidth, the LoRa modem bandwidth refers to the double sideband (*i.e.*, total) bandwidth.

3. Related Works

As the emerging networking technology for IoT, LoRaWAN has gained considerable amount of focus by researcher around the world. In this section we briefly review the existing studies about LoRaWAN performance.

A study in [6] provides an overview of LoRa and an in-depth analysis of its functional components. The physical and data link layer performance is evaluated by a testbed and simulations. Based on the analysis and evaluations, several workable solutions for performance enhancements are proposed. The testbed uses Freescale KRDM-KL25Z development board with Semtech SX1276 MBED shield as the node and a Cisco910 industrial router as the gateway. The gateway is connected to the network server provided by Thingpark through standard Ethernet. This paper studies LoRa modulation, including the data rate, frame format, spreading factor, and receiver sensitivity. The results show that LoRa modulation offers good resistance to interference due to the chirp spread spectrum modulation and high receiver sensitivity. Field tests show that LoRa can offer satisfactory network coverage up to 3 km in a suburban area with dense residential dwellings. The spreading factor has significant impact on the network coverage, as does the data rate.

An evaluation testbet is also developed and studied in [7]. Indoor and outdoor placements of nodes are evaluated. This LoRaWAN network is designed to serve environment conditions monitoring and emergency alarm, backed with a commercial network and application server. Transmission performance from LoRa nodes to the LoRa gateway is investigated. The result shows how packet losses were affected by the distance between the node and the gateway, the transmit power, the payload length, the antenna angle, the time of day, and the weather conditions. The pattern of LoRa packet loss is also measured and it is found that more than 99% of LoRa packet losses occurred with three or less consecutive packet losses. It is observed that LoRa transmission may be severely interfered by nearby 4G base stations and suffer from a regular high packet loss rate pattern that is similar to human daily activities. Such a finding indicates that carrying three redundant LoRa packet is an effective method for higher reliability.

An experimental indoor testbed is developed and explored in [8]. From this study, the limits of LoRaWAN technology and the merits of using LoRaWAN for IoT communications in the context of 5G is investigated. In particular, it evaluates the performance of LoRaWAN unconfirmed uplink data frames in an indoor environment. The result shows the limitations in term of periodicity and size of data because of the ISM band regulation in a default channel configuration, which subsequently limits the maximum amount of data that can be sent per day. This work also evaluated the signal quality received from various locations, in order to verify the feasibility to cover an entire building with the LoRaWAN technology. It shows that while communication among nodes in the same floor is not affected by walls, communications with the basement do experienced degradations. Additionally, data rate and power consumption are also observed.

Another field test is also conducted by [9] with more simplified and affordable LoRa nodes. The testbed uses Arduino-based nodes and single-channel gateway. The performance is evaluated by measuring the RSSI level and delay of the data transmission in line-of-sight (LoS) and non-LoS scenario. In this test, 915 MHz ISM frequency is used in accordance to local regulation. The result is more of a proof-of-concept. Transmission delay is also discussed, highlighting the fact that NLoS transmission requires higher delay due to reflection, refraction, and scattering by obstacles. During the test, a maximum transmission range of 700 meters is observed, which is significantly less than the claimed maximal transmission range of the used LoRa module.

The study in [2] explored the limits of the technology, matching them to application use cases, and stating the open research challenges. According to the finding, A LoRaWAN gateway must be carefully dimensioned to meet the requirements of each use case. Thus, the combination of the number of nodes, the selected SFs, and the number of channels will determine if the LoRaWAN ALOHA-based access and the maximum duty cycle regulation fit each use case.

The study in [10] investigates the capacity limits of LoRa networks. Based on the conducted experiments, a model describing LoRa communication behavior is developed. This model is useful to parameterise a LoRa simulation to study the scalability. The experiments show that a typical smart city deployment can support 64 nodes per 3.8 ha, which is not sufficient for future IoT deployments. LoRa networks can scale quite well, however, if they use dynamic communication parameter selection and/or multiple gateways.

Limit of the access channel of LoRaWAN is also studied in [11], which surveys and analyzes LoRaWAN operation, focusing on performance evaluation of its channel access as the most crucial component for massive machine type communication. We reveal and point out weaknesses of the LoRaWAN specification and propose solutions to improve LoRaWAN performance. It is found that even with 3 main channels and 6 data rates (i.e. 18 virtual transmission channels) the network capacity is about 0.1 of 51-byte (frame payload) messages per seconds. It limits the possibility to use LoRaWAN in many scenarios of smart city.

The work in [12] investigates the bi-directional performance of LoRa network. It highlights the significant impact of the downlink traffic on the uplink throughput. The number of transmit attempts recommended in the LoRaWAN specification may not always be the best choice. This work also highlights the energy consumption versus reliability trade-offs associated with the choice of number of retransmission attempts. The result shows that duty cycle limited LoRaWAN gateways are easily overloaded by downlink traffic. Additionally, it also shows that these networks do not scale well if many nodes request acknowledgments, *i.e.*, downlink data.

4. Experiment Platform, Proposed Model and Optimization

4.1. Prototype

To realize the expected prototype system, four main components are developed. The first component is a LoRa node. This node comprises of a sensor or sensor set, microcontroller, RF module, battery, and housing enclosure. The sensor is used to generate the date based on the interest of the application. The microcontroller is chosen and programmed to control the attached sensor(s) and LoRa RF module. A LoRa RF module based on SX1278 is used to handle the connectivity and protocol stack (modulation, mutli-access scheme, *etc*.,) along with suitable antenna. As an IoT node, a sufficient battery and suitable housing enclosure can be employed by considering deployment and long-term maintenance strategy (*e.g.*, how and how often it should be checked/replaced, whether the node will be located in a place which is hardly reached by human, *etc.*).

The second component is LoRa gateway. Particularly for this work, a custom LoRa gateway is developed instead of using black-box commercial gateway, allowing for deeper inspection when necessary. The developed gateway consists of a controller (not necessarily microcontroller), a LoRa RF concentrator module, I/O toward the backbone Internet connectivity, and its housing. LoRa concentrator module based on SX1301 is used for this purpose. Unlike LoRa node, the gateway is deployed in a more controlled place with direct connection to power plug. Hence, no battery and special housing enclosure are required. The I/O toward the backbone is used to connect the gateway to the external network, *i.e.*, the Internet. We can use common protocols such as IEEE 802.3 or IEEE 802.11 family. LoRa gateway relays the data generated by LoRa nodes to the Internet for further processing in the network and respective application server.

The third component is a network server. In this research, two network servers are employed: crowd-funded free service from The Things Network [13] and an open-source one based on LoRa Server [14]. While the former one is commonly used for DIY and non-profit community, we decided to also perform experiment with the latter one to be able to gain more control of the “Internet” side of this IoT system.

The last component is an application server. It subscribes to the specific application data that are pooled and filtered by the network server. In this work, simple job of recording/data logging and classifying the sensor data is performed by the application since the main purpose of the prototype system is to assess the network performance.

4.2. Optimal Gateway Location

LoRa uses ISM unlicensed band. Hence, it is crucial to limit its transmission power to avoid more severe interference. Nonetheless, at the same time, the transmission power should be governed to reach the required transmission coverage. Sufficient coverage allows more nodes to be served with less number of gateways, which in turn reduces the deployment cost.

Nodes are usually deployed at predefined locations of interest, specific to its job. In early stage of LoRa adaptation, mostly the infrastructure (*i.e.*, the gateways) is deployed to cover those nodes which are already in place. In this work, the optimal gateway deployment location is discussed.

It is assumed that all nodes are deployed within a 2-dimensional planar area. The location of m nodes are given as (x_1,y_1), (x_2,y_2),…, (x_m,y_m) with $x, y \in \mathbb{R}$. Our objective is to find the center point of the circle with minimum radius to contain all of nodes’ point. This center point is also known as Chebyshev center. In this center point we will deploy a gateway to effectively serve the nodes. Let (x_c,y_c) be the coordinate of the center point. In mathematical term, this problem can be written as

$$\min_{(x_c,y_c),r} r$$
$$\text{s.t. } |x_c - x_i, y_c - y_i| \le r, \text{ for } i = 1,2,...,m. \tag{1}$$

where $|x,y|$ denotes the Euclidean norm, *i.e.*, $(x^2+y^2)^{½}$. Notice that the function $|x,y|-r$ is convex as the translation of the norm function and linear function $–r$. This forms a convex optimization problem since it consists of minimizing a linear function subject to convex inequality constraint. Obviously, r is also constrained to be positive.

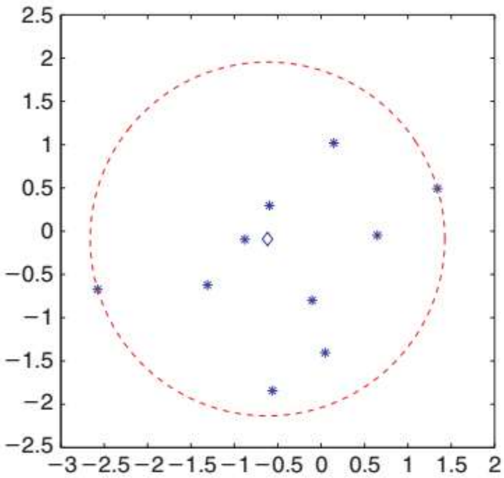

Figure 1. Illustration of the Optimal Location for the Gateway (denoted by a diamond marker) and its Coverage (denoted by dashed circle) which Includes all Nodes (denoted by asterisks) [15]

The deployment area is illustrated in Figure 1. To better represent the real deployment environment in which signal power attenuation occurs, we introduce a normally-distributed position uncertainty for the ith node as e_i. In this case, distance of the ith node to the gateway (*i.e.*, as perceived based on the received power) has an offset of $|x_c-(1\pm e_i)x_i , y_c-(1\pm e_i)y_i|$. Our problem is hence translated to

$$\min_{(x_c,y_c),r} r$$
$$\text{s.t. } |x_c - (1\pm e_i)x_i, y_c - (1\pm e_i)y_i| \le r,$$
$$\text{for } i = 1,2,...,m. \tag{2}$$

This problem can be solved using existing optimization approaches relevant to Chebyshev center of a set of points. The obtained optimal center point will ensure that all nodes are connected. In subsequent discussion, an optimal gateway location is assumed such that the signal quality between each nodes and gateway is always in acceptable condition to ensure good reception.

4.3. Modeling of LoRaWAN Access Mechanism

The optimal gateway placement discussed in the previous subsection ensures that all nodes can establish acceptable wireless link quality. In this case, mechanisms in the physical layer can be modelled easier. In this subsection, we discuss the behavior of LoRaWAN protocol in term of access mechanism, *i.e.*, how to handle the collision.

Collision happens if two or more non-orthogonal transmissions overlap at the receiver. Transmissions with different spreading factor are orthogonal and they do not interfere (*i.e.*, collide) each other although they happen at the same time. For transmission which is conducted at the same time with similar spreading factor, they may still be decoded separately (*i.e.*, not considered as collision) when they are using different carrier frequency with absolute offset larger than a certain threshold. For example, let f_1 and f_2 be the carrier frequency of the first and second transmission, respectively. In this case, they will be able to be decoded by gateway if the following condition is satisfied

$$| f_1 - f_2| \geq f_{\text{thresh}} \quad (3)$$

where f_{thresh} denotes the frequency offset threshold. The minimum tolerable frequency offset for different carrier frequency in LoRa is different. In this work, f_{thresh} of 60 kHz for 125 kHz bandwidth, 120 kHz for 250 kHz bandwidth and 240 kHz for 500 kHz bandwidth is adopted herein [16].

LoRa modulation also has exhibits capture effect. It is the situation where at most one of the collided signals can be recovered and detected properly. This happens when there is one signal that has transmission power higher than the other. In particular, let us assume three signal with received power of $P_1 > P_2 > P_3$ respectively. The first transmission can take benefit from capture effect and being recovered from the collision if the power difference between two signals with the highest power is higher than certain threshold P_{thresh}. In other word, the first transmission will be recovered if the following condition is satisfied

$$| P_1 - P_2| \geq P_{\text{thresh}} \quad (4)$$

Collision probability of the basic access mechanism in LoRa media access control (MAC) protocol follows pure ALOHA access mechanism. In pure ALOHA, when there are G transmission attempts in a transmission interval, the probability of there is k transmissions during a such interval is

$$\frac{1}{k!} G^k e^{-G} \quad (5)$$

Therefore, when the transmission interval is T, the probability that during any particular period from t=2nT to t=(2n+1)T, (that is for any particular non-zero integer value of n) exactly one node will begin transmission is

$$G^k e^{-G} \quad (6)$$

and the probability that during any particular period t=(2n+1)T to t=(2n+2)T, no node will begin transmission is e^{-G}. For successful transmission of a frame, both the events should occur simultaneously. That is during period t=2nT to t=(2n+1)T, exactly one node begins transmission and during t=(2n+1)T to t=(2n+2)T no node begins transmission. Hence the probability that both the independent events will occur simultaneously is

$$G^k e^{-2G} \quad (7)$$

which gives the packet delivery ratio in pure ALOHA, as well as the default LoRaWAN. When f frequencies can be used in LoRaWAN, and each transmitting node can randomly choose one of them for its uplink transmission, the packet delivery ratio can be improved by factor of f, such that

$$\text{PDR} = fG^k e^{-2G} \quad (8)$$

Each LoRa transmission is started with a preamble before its main payload. A recent experiment in [10] yields that when the ending part of a transmission collides (*i.e.*, overlap) with the first 5 symbols of the preamble from one other transmission, both of these transmissions can still be recovered correctly by the gateway although they are using similar spreading factor and carrier frequency. This fact requires us to revise the critical interval in LoRa transmission from T to become T-5T_{sym}, where T_{sym} denotes the duration of ne preamble symbol.

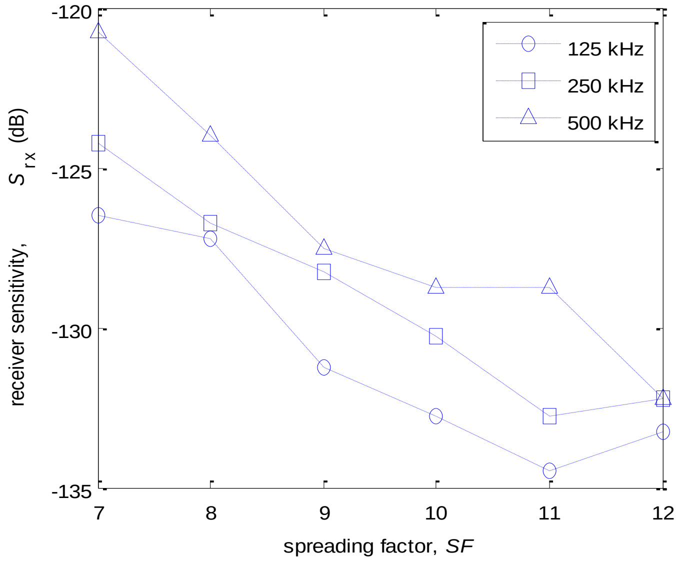

Figure 2. Receiver Sensitivity in Respect to the Carrier Frequency and Spreading Factor

The amount of energy spent for LoRa transmission in this work is calculated by multiplying node's airtime and its transmission power, P_{tx}. For a transmission in LoRa to be successfully detected by the receiver, the received power P_{rx} must be larger than the receiver sensitivity S. Note that this relation implicitly dictates the feasible transmission distance d. P_{rx} can be calculated as

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{tx} - L_{rx} - L_{ch} \tag{9}$$

where G_{tx} and G_{rx} denotes transmitter's and receiver's gain, respectively, L_{tx} and L_{rx} denotes transmitter's and receiver's loss, respectively, and L_{ch} denotes combined losses of the channel. This work adopts log distance loss model such that

$$L_{ch}(d) = L_0 + 10\gamma \log(d/d_0) + X_g \tag{10}$$

where L_0 be the path loss at reference the distance d_0, γ be the path loss exponent, and X_g be a normal (or Gaussian) random variable with zero mean to represent fading.

The receiver sensitivity obtained by the measurement in [10] is adopted, as shown in Figure 2.

5. Evaluation

The system is evaluated using custom based simulation following [10]. This evaluation focuses on the overall network performance instead of per-node performance. The most economical scenario where m nodes are served by one gateway is observed, presumably to give more insight for early adopter of LoRaWAN technology which is usually not backed up by large amount of funding. The gateway is capable of decoding 8 concurrent orthogonal signals.

In the simulation, the nodes are configured with 5-tuples of settings which specifies the transmission power, carrier frequency, spreading factor, bandwidth, and coding rate. Each node has an average data arrival rate of 10 minutes and a uniform data size of 20 bytes, which is always being transmitted using preamble which consists of 8 symbols. The evaluation is conducted for 2 months.

5.1. Performance Metrics

The performance of the network is measured in term of throughput S and total power consumption *P*. The throughput *S* denotes the ratio between number of successfully decoded packet and the total number of transmitted packet. This metric is importance since in the effective LoRaWAN environment all transmitted packet should be received by the backend system. The total power consumption P denotes the number of energy, in Joule (J), spend by the RF module in all transmitting nodes during evaluation.

The performance of the network is measured in term of packet delivery ratio (PDR), average energy consumption for each successful transmission *E*, and average wasted amount of energy per nodes *W*. The packet delivery ratio denotes the ratio between number of successfully decoded packet and the total number of transmitted packet in the system. This metric is importance since in the effective LoRaWAN environment all transmitted packet should be received by the backend system. Only uplink packet is considered which is consistent with most of the simplified sensor networks in IoT application.

The average energy consumption for each successful transmission *E* denotes the number of energy, in Joule (J), spend by the RF module in all transmitting nodes during evaluation normalized by number of nodes in the network. With this metric, one can immediately picture the energy cost per data transmission, which can be useful for application designer to decide the frequency of data transmission of the nodes.

The average wasted energy consumption per nodes *W* denotes the number of energy, in Joule (J), spend by the RF module in each node to transmit the collided packets. It is calculated by multiplying the amount of energy for transmitting one packet and the number of collided packets. With this metric, one can picture how much the energy is wasted and can be useful for application designer to estimate the battery longevity of nodes in respect to the timeliness of its uplink data transmission.

5.2. Baseline Case

For the sake of comparison with other cases, a baseline case is introduced herein. The baseline case is when all nodes are configured with LoRa common configuration consisting of transmission power of 14 dBm, carrier frequency of 915 MHz, spreading factor of 12, bandwidth of 125 kHz, and coding rate of 4/5. Except for the carrier frequency, this setting is similar to the baseline used in [10] and [13]. This baseline case is denoted as “default” in subsequent result figures.

The baseline case and the other cases will be compared under two radio models: the basic model which does not consider capture effect and the one which consider capture effect which is more consistent with LoRa modem. Without capture effect, any two or more transmissions conducted at the same time using the same carrier frequency, spreading factor and bandwidth will collide and none of them will be successfully decoded. However, with capture effect, there can be at most one transmission can be recovered from the collision when the difference in timing and strength of the transmitted signals received by gateway is sufficient.

5.3. Results and Discussions

As stated earlier, combinations of nodes configuration play important role in deciding the performance, especially in term of the three metrics used in this paper.

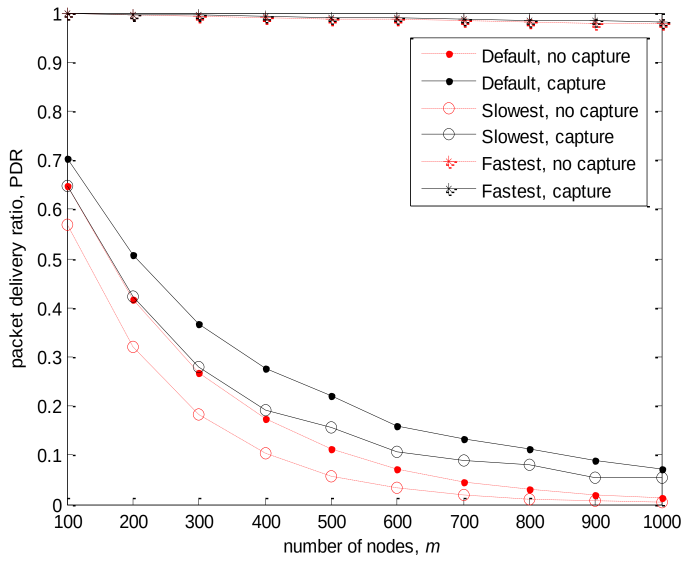

Figure 3. PDR of Experiment 1

Experiment 1. In this experiment, we compare the configuration which favors robustness and the one which favors higher uplink data rate. Notice that these two configurations are the extreme opposite as the most robust configuration has the lowest data rate and the highest data rate has the worst signal quality. The slowest configuration uses spreading factor of 12, bandwidth of 125 kHz, and coding rate of 4/8. The fastest configuration uses spreading factor of 6, bandwidth of 500 kHz, and coding rate of 4/5. Both of them use transmission power and carrier frequency similar to the one used by the baseline case.

The result of PDR from Experiment 1 is shown in Figure 3 along with the default case. Each case is evaluated with and without capture effect. Overall, the cases with capture effect obtain higher PDR compared to the respective cases without capture effect. This is because with capture effect there may be one transmission which can be recovered from each collision. The difference between the fastest case with and without capture effect is not noticeable as both of them are almost visually overlap.

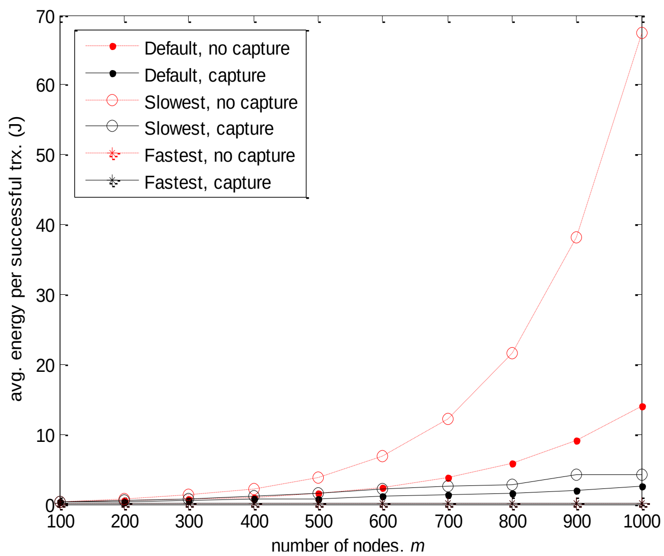

Figure 4. Average Energy Consumption for each Successful Transmission in Experiment 1

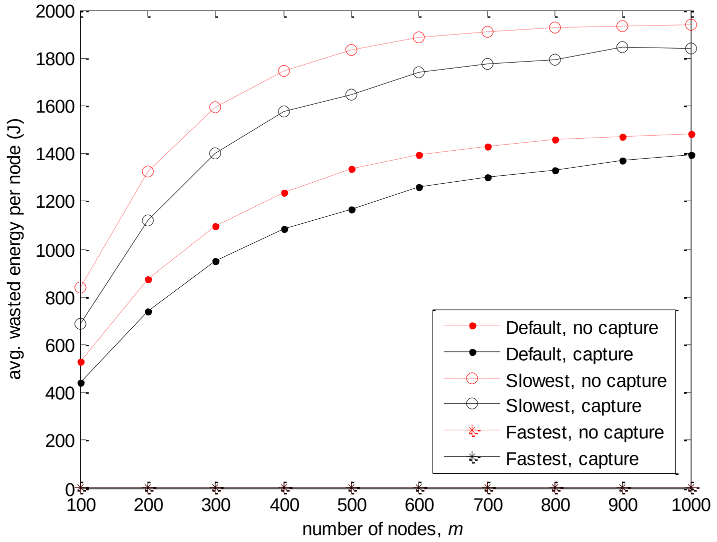

Figure 5. Average Amount of Energy Wasted in Collided Transmissions for each Node in Experiment 1

As the name suggest, the slowest configuration delivers lower PDR among the three depicted cases. However, it is closer to the baseline case. Meanwhile, the fastest case delivers the highest PDR out of the three depicted cases. This is because when every transmission signal is received perfectly by the received end, the fastest configuration has shortest airtime or transmission duration. This is important as LoRa has similar access mechanism to pure ALOHA. The longer transmission duration, the more collision can happen. With shorter transmission duration, other newly-arrived transmission has less chance to overlap with the existing transmission. Hence, with the fastest configuration, more transmission can be successfully received by the gateway which translates to higher PDR.

The result of average energy consumption for each successful transmission *E* from experiment 1 is depicted in Figure 4 along with the default case. Each case is evaluated with and without capture effect. Notice that *E* is expected to grow along with number of collision. Since collision rate is the opposite of PDR by the definition, the case which has higher PDR consequently obtains lower *E*. One thing to be noticed in this figure is that *E* grows exponentially and a small difference in low PDR translates into significant difference of *E*. For example, this happens at *m*=1000 between the "Default, no capture" and "Slowest, no capture" cases. In these particular situations, total energy consumption of the default case is somewhere around 1.9 MJ while the slowest case is around 1.5 MJ. Although seemingly both of them have almost similar PDR, the actual number of successful transmission in the default case and slowest case are around $107\text{x}10^3$ and $28\text{x}10^3$, respectively. Thus, their difference in *E* is large.

The result of average wasted energy consumption per nodes *W* from experiment 1 is depicted in Figure 5 along with the default case. Each case is evaluated with and without capture effect. From this figure, one can observe that the case with higher PDR yields less wasted energy since there is less number of collided transmissions. The fastest case has the minimum *W* of 8 mJ and the maximum *W* of 0.16 J which are depicted as almost 0 in this figure. Meanwhile, the default and the slowest cases obtain significantly higher *W*, compared to the fastest case, which plots like logarithmic function. With these conditions, the nodes are less effective in using their battery power as it will be consumed a lot by collision.

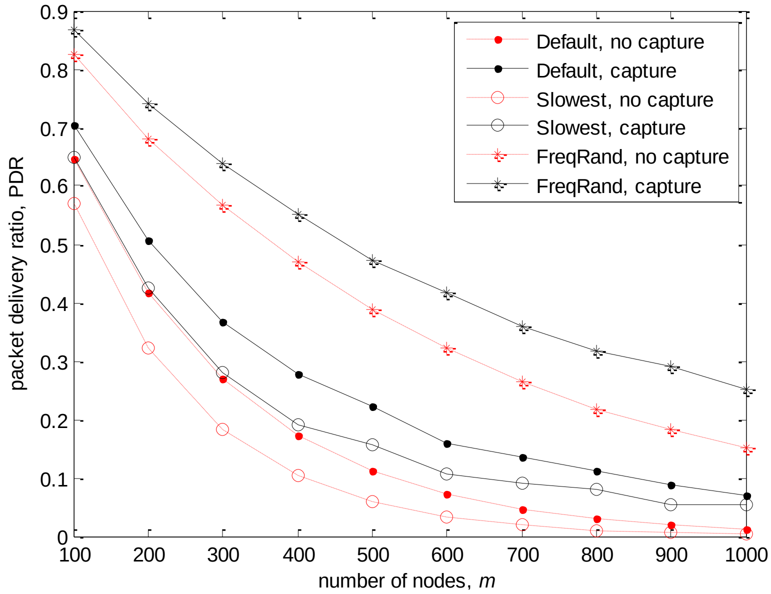

Figure 6. PDR of Experiment 2

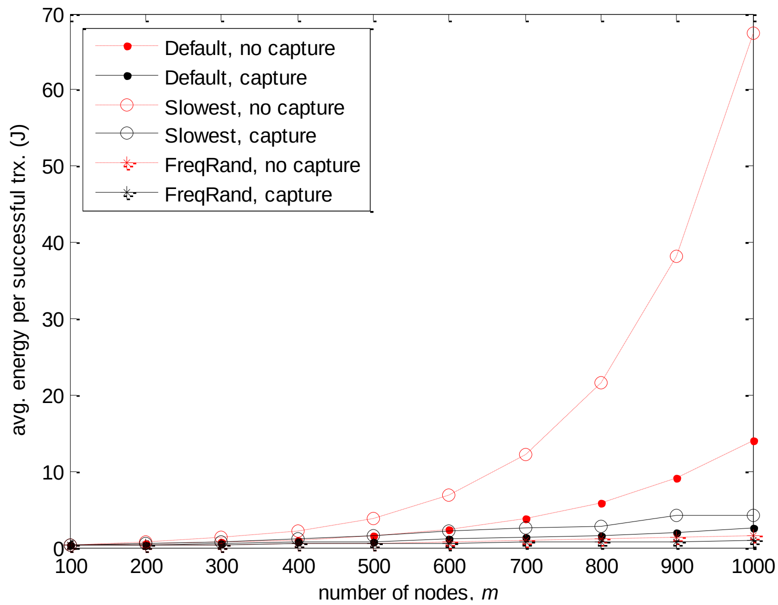

Figure 7. Average Energy Consumption for each Successful Transmission in Experiment 2

Experiment 2. In this experiment, we incorporate multiple frequency randomizations which can be employed in LoRa modem to minimize the collision. In this experiment, node will randomly choose one among three frequencies for it to use in transmitting its uplink data. Collision happens when there is two or more transmission conducted using similar frequency. For this experiment, the slowest case from Experiment 1 is adopted. Hence, three cases are compared: the default case, the slowest case, and the slowest case with frequency randomization.

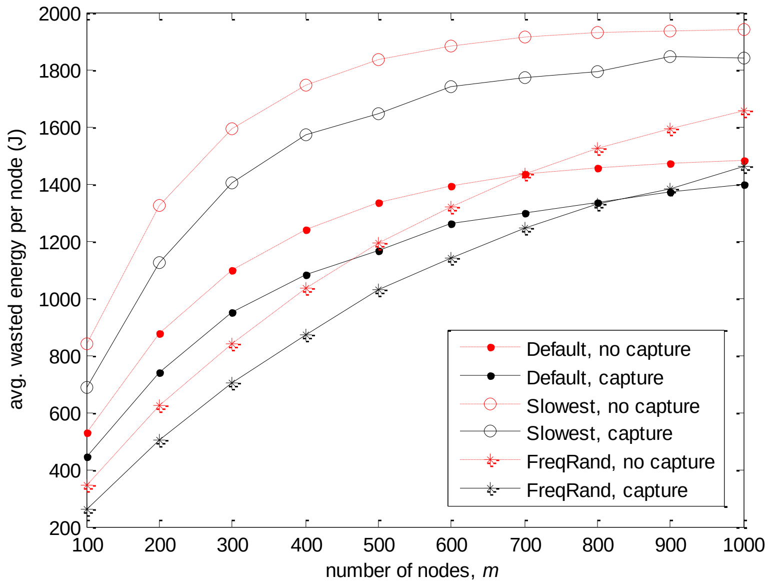

Figure 8. Average Amount of Energy Wasted in Collided Transmissions for each Node in Experiment 2

The result of PDR from Experiment 2 is shown in Figure 6. Each case is evaluated with and without capture effect. Overall, the cases with capture effect obtain higher PDR compared to the respective cases without capture effect. The result shows that the introduced frequency randomization can increase the PDR of the slowest case. The result of average energy consumption for each successful transmission E from experiment 2 is depicted in Figure 7 along with the default case. Similarly, each case is evaluated with and without capture effect. This figure depicts similar situation as the one shown in Figure 4, where the case with lower PDR exhibits higher E. The result of average wasted energy consumption per nodes W from experiment 1 is depicted in Figure 8 along with the default case. The influence of capture effect is also depicted. From this figure, one can observe that the case with higher PDR yields less wasted energy since there is less number of collided transmissions. Notice that the case with frequency randomization has less wasted energy than the default case when $m \leq 800$, which is even lower than the slowest case at all m values.

Experiment 3. In this experiment, we compare two simple optimizations. The first optimization, Opt1, configures the parameters in each node such that it minimizes transmission airtime (*i.e.*, transmission duration T), which is based on its distance to the gateway. The second optimization, Opt2, configures the parameters in each node to minimize its transmission time and energy consumption. Solutions for both optimizations are obtained via exhaustive search since the search space is considerably small. In other word, the second optimization tries to minimize the energy consumption of the solution obtained by the first optimization when possible. This experiment also includes the default case for comparison. Both conditions with and without capture effect are also included.

The result of PDR from Experiment 3 is shown in Figure 9. The result shows that both Opt1 and Opt2 obtain significantly higher PDR until the point where the difference between those cases with and without capture is barely noticeable visually. The result of average energy consumption for each successful transmission E from experiment 3 is depicted in Figure 10. Again, the result for Opt1 and Opt2 are overlapped and is very low in the figure. The Opt1 case has the minimum and maximum E of 2.348 mJ and 2.454 mJ, respectively. On the other hand, The Opt2 case has the minimum and maximum E of 1.703 mJ and 1.898 mJ, respectively, which are lower than those obtained by Opt1. This shows that the configuration used in Opt2 indeed can decrease energy consumption. The result of average wasted energy consumption per nodes *W* from experiment 3 is depicted in Figure 11. In this figure, Opt1 has the minimum and maximum *W* of 0.0536 J and 0.5292 J, respectively. Opt2 has the minimum and maximum *W* of 0.04238 J and 0.447 J, respectively. Meanwhile, the default case obtains significantly higher *W* compared to Opt1 and Opt2 cases. The results in Figures 9, 10 and 11 demonstrate that the performed optimization is able to yields higher PDR and lower power consumption, especially for Opt2.

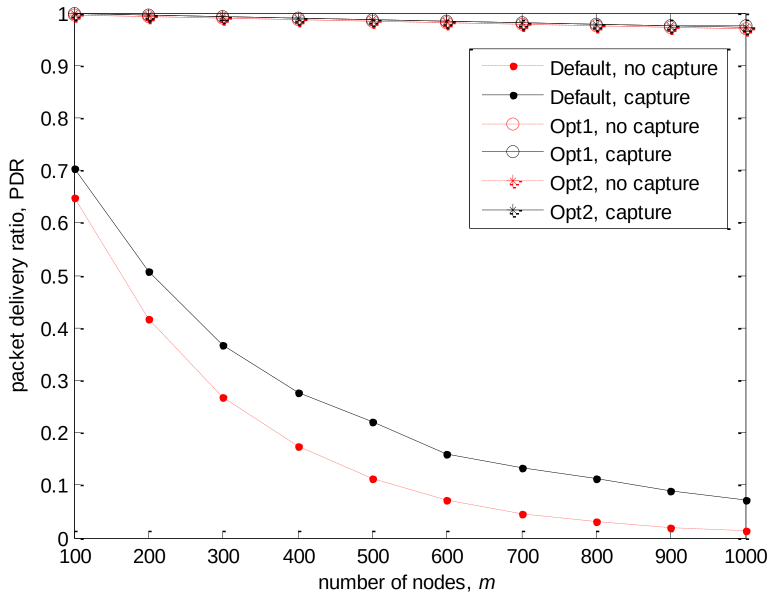

Figure 9. PDR of Experiment 3

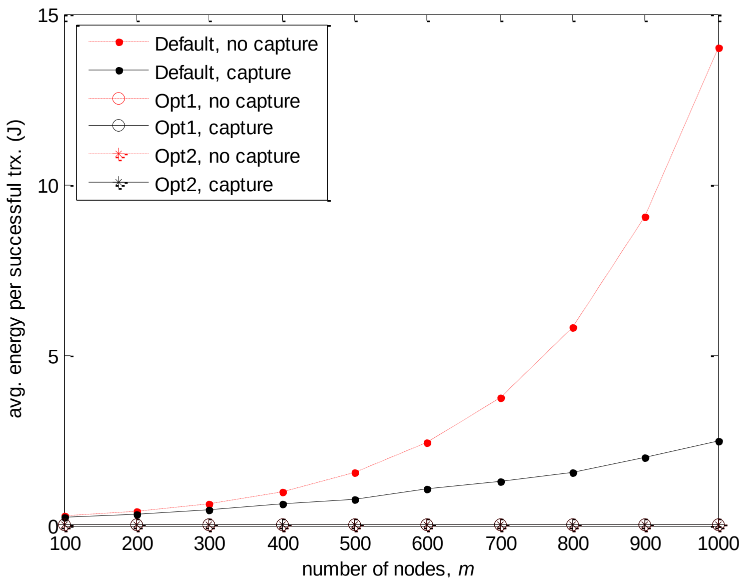

Figure 10. Average Energy Consumption for each Successful Transmission in Experiment 3

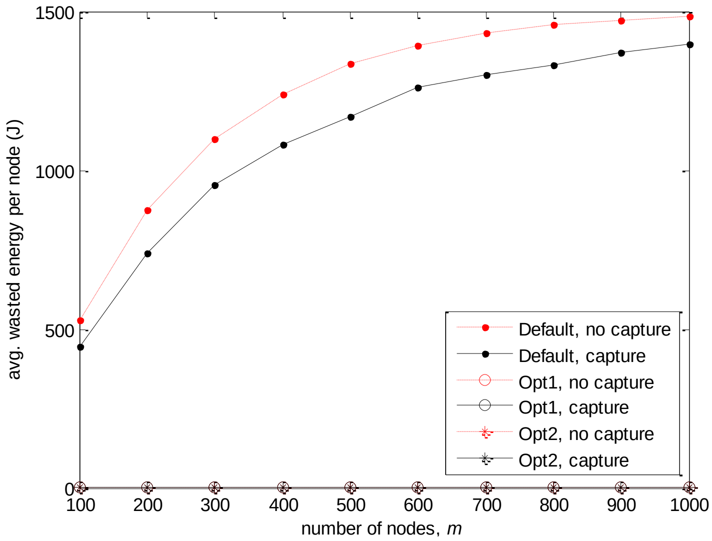

Figure 11. Average Amount of Energy Wasted in Collided Transmissions for each Node in Experiment 3

Impact of inter-arrival time. This experiment is conducted as an addition to the previous experiments with aim to observe the impact of inter-arrival time to the three performance metrics. In this case, decreasing inter-arrival time means increasing transmission frequency. This is important to represent various IoT applications and their transmission scenarios. In this experiment, we incorporate two numbers of nodes in the cell, *m*, namely 50 and 100, and varying the inter-arrival time from 1, 2, 3, up to 10 minutes. Since the capture effect has been discussed sufficiently in the previous three experiments, only results with capture effect are included in this experiment.

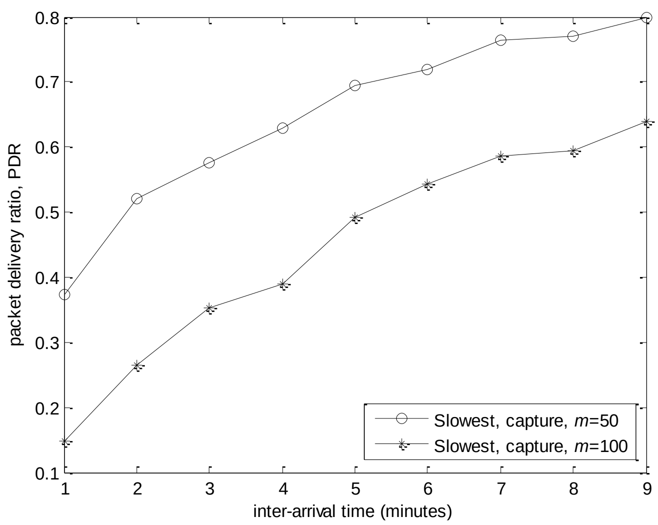

Figure 12. PDR

The result of PDR from this experiment is shown in Figure 12. For both values of *m*, the higher inter-arrival time, the higher obtained PDR is. This is because with higher inter-arrival time, the interval between two consecutive uplink transmission becomes larger, resulting in less frequent transmission. Hence, the contention is relaxed, which allows higher packet to be received correctly by the gateway. Thus, higher PDR is obtained.

The result of average energy consumption for each successful transmission *E* is depicted in Figure 13. As shifting to the right side on the x-axis denotes lower contention load, the amount of energy consumption is decreasing for both cases of *m*. With higher inter-arrival time, less transmission is collided, such that more energy is effectively used for successful transmissions. Hence, average amount of energy required for each successful transmission is also decreased. The effectiveness of energy usage is implicitly demonstrated in Figure 14. Figure 14 shows the average amount of energy wasted in collision which is calculated for each node, *W*. In this figure, the higher inter-arrival, the lower *W* is. Lower *W* means more energy can be used for successful transmission. This result is consistent with the result shown in Figure 13. With lower W, the nodes will be able to conserve more power relative to the amount of uplink transmission.

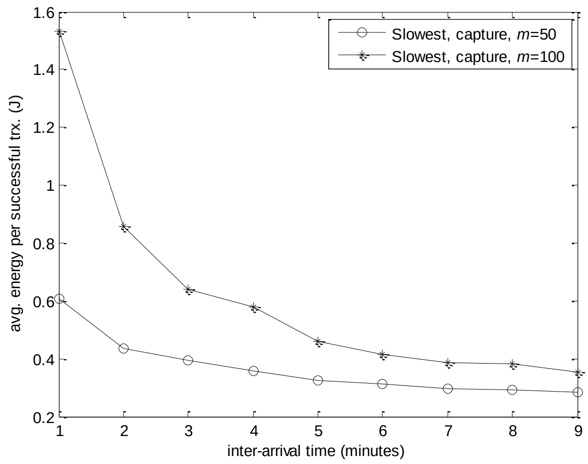

Figure 13. Average Energy Consumption for each Successful Transmission

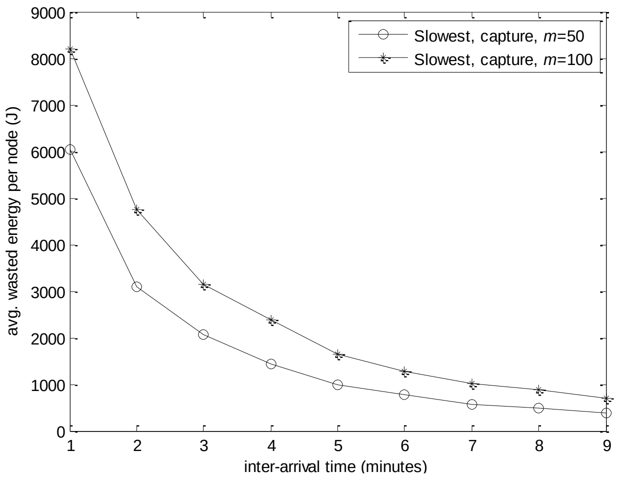

Figure 14. Average Amount of Energy Wasted in Collided Transmissions for each Node

6. Conclusion

This paper presents a performance evaluation of LoRa network to serve IoT application. The performance of the network in term of packet delivery ratio, average energy consumption per transmission and average energy wasted in collision per nodes are investigated. A realistic scenario is considered, and the scalability study is also conducted via computer simulation. The result shows that the performance of LoRa network is highly dependent to the configuration of spreading factor, coding rate, and frequency selection. The performed experiment shows that the limitation inherited from pure ALOHA access strategy can be alleviated by randomizing frequency selection and node-specific optimization to maximize data rate relative to its location (*i.e.*, channel condition) and contention severity. Additionally, interference from other ISM frequency users may also be crucial factor which affects the performance, which is interesting for further investigation. It is also important to study the effect of various classes of the node and its downlink transmission as well as the existence of multiple gateways in the vicinity.

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