How to Select SF and BW for 2.4 GHz LoRa Ad-Hoc Communication: From Energy Consumption Perspective

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Abstract. LoRa modulation is a narrowband, long-range wireless communication technology. At present, Sub-GHz LoRa is mainly used to build LoRaWAN and is applied to data collection of Internet of Things. However, the latest 2.4 GHz LoRa can be applied to point-to-point and self-organizing networks. In this paper, the impacts of bandwidth (BW) and spreading factor (SF) on the energy consumption is evaluated for the first time. In general, to reach the target transmission distance, a larger SF or a smaller BW can be selected to reduce transmitting power (but the ToA time will increase in this case), or the desired transmission distance can be achieved by increasing the transmitting power and keeping a smaller SF or a larger BW. obviously, both of them will increase the power consumption of transmission. We analyze which method is more energy-efficient by constructing an energy consumption model for LoRa communication. The energy model is suitable for the adaptive data rate (ADR) of LoRa and establishes the foundation for building low-energy node-to-node and Ad-hoc LoRa networks.

Keywords: 2.4 GHz LoRa · Energy consumption · Node to node communication

1 Introduction

LoRa is a new low-rate modulation technology for wireless communication, which uses spread spectrum communications to increase the transmission distance. It can dynamically adjust the data rate and efficient transmission distance by adjusting the spreading factor (SF) and bandwidth (BW). The existing sub-GHz LORA network is used for campus networking and coverage of LoRaWAN standard protocol network through the deployment of terminals, gateways and Network Servers (NS). For example, we can use Semtech's SX1276 chip to build a 470 MHz terminal device, use the SX1301 chip to set a gateway, and deploy a network server in the cloud. Sub-GHz LoRa relies on multiple

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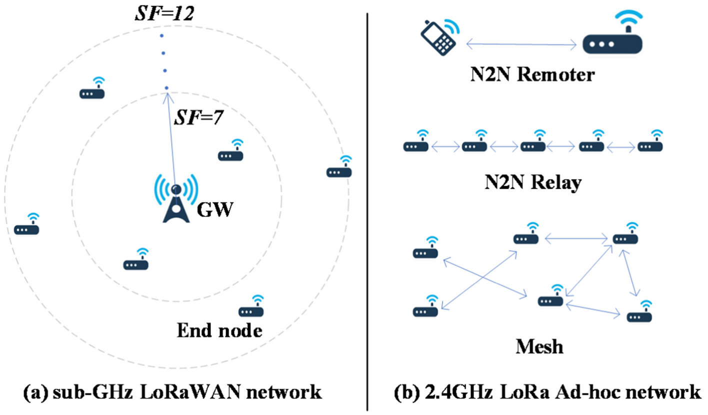
parallel channels inside the SX1301 and can receive and parse up to 8 LoRa signals with different spreading factors simultaneously, thus enlarging the system capacity. In LoRaWAN networks, NS must be deployed in the cloud platform, in which protocols run. NS dynamically adjusts the parameters of terminals such as BW, SF and transmission power by issuing commands [1]. The standard LoRaWAN network is a star topology, with its gateway the central node through which other nodes must pass messages, as shown in Fig. 1(a).

To simplify network deployment and save the cost of deployment and maintenance, some applications can directly use LoRa point-to-point communication or multi-hop network communication, without deploying LoRaWAN gateways, NS and LoRaWAN networking. For example, Fig. 1(b) shows (1) Point-to-point communication: remote control device; (2) Multi-hop relay; (3) Self-organizing multi-hop ad-hoc network. Through the LoRa ad-hoc network, the coverage of LoRa can be further expanded, such as monitoring oil pipelines of tens of kilometers or wild rivers without any cellular signal. The preceding networking methods are more private and flexible, which can use LoRa as a physical layer technology to build MAC, transmission protocols and application topologies suitable for specific applications.

In particular, besides the well-known sub-GHz LoRa communication technology, Semtech has recently introduced LoRa technology and chip (SX1280) that work in the 2.4 GHz ISM frequency band [2]. The application scenarios of 2.4 GHz LoRa technology will be more inclined to use self-organizing methods for networking. Compared with sub-GHz LoRa, 2.4 GHz LoRa will be very conducive to constructing global universal Internet of Things (IoT) solutions.



(a) sub-GHz LoRaWAN network (b) 2.4GHz LoRa Ad-hoc network

Fig. 1. Comparation of LoRaWAN and LoRa Ad-hoc network topology

2 LoRa Technology and Related Works

The rapid development of the IoT has put forward higher requirements for wireless communication technology. The low-power Wide-Area Network (LPWAN) specially designed for low-bandwidth, low-power, long-distance, and massively connected IoT applications is also rapidly emerging. LoRa, which is an ultra-long-distance and low-power data transmission technology below 1 GHz, is a wireless communication technology dedicated to long distance and low power. It uses chirp-spread-spectrum modulation technology, which not only maintains the same low power consumption characteristics as Frequency-Shift Keying (FSK) modulation, but also significantly increases the communication distance, while improving network efficiency and eliminating interference. It means that terminals with different spreading sequences will not interfere with each other even if they use the same frequency to send signals simultaneously. Therefore, the Concentrator/Gateway developed on it can parallelly receive and process data from multiple nodes, which markedly expands the system capacity. The data transmission rate of LoRa is dynamically adjustable and decreases with the increase of its SF ranging from 6 to 12. The receiving sensitivity of LoRa communication has reached an astonishing -148 dbm. Compared with other advanced sub-GHz chips in the industry, its highest receiving sensitivity is improved by more than 20 db, ensuring a reliable network connection. Meanwhile, its link budget is as high as 157 db, making its communication distance up to 15 km (related to the environment), while its receiving current is only 10 mA, and its sleeping current is 200 nA, which greatly extends the battery life. Now LoRa mainly operates on free frequency bands (unlicensed frequency bands) all over the world, including 433, 868, 915 MHz, with different standards different countries and regions.

With the rapid development of the IoT, researchers pay increasing attention to LPWANs technology. Firstly, in terms of LoRa basic performance, Ruben M. Sandoval et al. [3] proposed that the average throughput per node of LoRa-based network has been mathematically formulated and the optimal network level configuration has been derived. Zhijin Qin et al. [4] investigated the uplink transmission performance of low-power-wide-area (LPWA) networks with regards to coexisting radio modules and showed how the performance of LPWA networks could be enhanced by adjusting the density of LoRa nodes around each LoRa receiver. Orestis Georgiou et al. [5] analyzed and formulated unique peculiarities of LoRa, showing that the coverage probability drops exponentially as the number of end-devices grows due to interfering signals using the same spreading sequence. Jansen C. Liando et al. [6] proposed that LoRa is capable of communicating over 10 km under line-of-sight environments. Kais Mek ki et al. [7] gave a comprehensive analysis of the LoRa modulation, including the data rate, frame format, spreading factor, and receiver sensitivity. Secondly, in terms of energy consumption, Binbin Su et al. [8] investigated energy efficiency for uplink LoRa, and formulated a nonconvex optimization problem for maximizing the system energy efficiency. Taou fik Bouguera et al. [9] presented a sensor node energy model using LoRa technology which allowed estimating the consumed power and the battery life of the sensor node for a target application. Lastly, in terms of positioning and ranging, Emanuele Goldoni et al. [10] presented a complete experimental data set of received signal strength indicator (RSSI) measurements collected in different indoor and outdoor environments using LoRa radios. However, these studies mainly focused on the basic performance of LoRa (such as optimal parameter configuration of the network, communication coverage ability, positioning and ranging capabilities, etc.) and the power consumption of nodes under the LoRaWAN network, without in-depth study on the LoRa self-organizing network.

LoRa is widely used now. To meet the requirements of long range, a small amount of data transmission, low power, and low cost of the IoT in actual applications, a low-power wide-area network information monitoring approach based on NB-IoT and LoRa was proposed by Xihai Zhang et al. [11]. Dario Madeo et al. [12] discussed the architecture of a low-cost unmanned surface vehicle (USV) to be employed for the collection of crucial parameters about water quality in rivers, lakes, or seas. Fan Wu et al. [13] presented a hybrid wearable sensor network system for the IoT connected with safety and health monitoring applications. Mauricio de Castro Tomé et al. [14] studied the application of Lora technology in smart meters, using LoRa module to send the average power required by their families in a given time. He sheng Zhang et al. [15] studied the well-covered monitoring device based on Lora and accelerometer and designed a 433-MHz whip antenna to overcome the shield of manhole cover and the absorption of electromagnetic waves of the earth. Shengwei Lin et al. [16] proposed a new mechanism to collect and transmit monitoring information based on LoRa technology. In summary, at present, most of these applications are developed on LoRaWAN networks constructed by sub-GHz LoRa, with few studies on 2.4 GHz LoRa applications.

Semtech has released a Long Range (LoRa) chipset which operated at the globally available 2.4 GHz frequency band, on top of the existing sub-GHz and km-range offer, enabling hardware manufacturers to design region-independent chipsets. Compared with sub-GHz LoRa technology, 2.4 GHz LoRa has a wider range of SF from 5 to 12, but it has only four optional BW, namely 203 kHz, 406 kHz, 812 kHz and 1625 KH, which is not as flexible as sub-GHz LoRa. Table 1 is the Receiver Sensitivity of 2.4 GHz LoRa under different SF and BW conditions.

Table 1. Receiver Sensitivity [dBm] when using 2.4 GHz LoRa (in Low Power Mode, coding rate is 4/5), taken from [2].

BW	SF							
	5	6	7	8	9	10	11	12
203 kHz	−109	−111	−115	−118	−121	−124	−127	−130
406 kHz	−107	−110	−113	−116	−119	−122	−125	−128
812 kHz	−105	−108	−112	−115	−117	−120	−123	−126
1625 kHz	−99	−103	−106	−109	−111	−114	−117	−120

Due to the advantages of 2.4 GHz LoRa, researchers have also begun to study it. Thomas Janssen et al. [17] investigated the maximum communication range of LoRa in three different scenarios. Free space, indoor and urban path loss models were used to simulate the propagation of the 2.4 GHz LoRa modulated signal at different spreading factors and band widths. Frederik Rander Andersen et al. [18] determined the ranging capabilities of LoRa 2.4 GHz and the optimal settings for the SX1280 transceiver, depending on the distance.

However, no previous study has analyzed the energy consumption of 2.4 GHz LoRa in point-to-point and self-organizing networks, especially the impacts on energy consumption when choosing different SF and BW.

The main contributions of this paper are:

(1) According to the characteristics of LoRa communication, we modify the existing energy consumption model and propose a new one that is more suitable for the assessment; (2) For the potential point-to-point and self-organizing networking applications of 2.4 GHz LoRa, the impacts of choosing different SF and BW on energy consumption are evaluated for the first time.

3 Energy Model for LoRa N2N Communication

3.1 The Problem of Existing Energy Model

Existing works are usually based on the following energy consumption model:

$$\begin{cases} E_t = \left(E_T + E_{amp} \times d^{\tau}\right) \times k \\ E_r = E_R \times k \end{cases} \tag{1}$$

where E_T is the basic energy consumption of the node (such as the basic energy consumption of the MCU control unit), E_{amp} is the energy consumption of the radio frequency circuit, and E_R is the energy consumption of the receiving node. These three parameters are related to the hardware performance of the circuit. d is the transmission distance, k is the number of transmitted bits, and τ is the attenuation factor of the channel with a value range of 2–4.

The premise of using this energy consumption model is: (1) The air transmission rate of the radio frequency hardware is constant; (2) And the power amplifier circuit of the radio frequency transmission can be continuously and linearly adjusted according to the transmission distance. Transmission power of most RF chips including LoRa can only be set to several gears. For example, TI's CC2530 only defines 17 adjustment gears for transmission power: −28 dbm–+4.5 dbm [19]. However, LoRa can dynamically adjust the rate by setting SF and BW and changing the transmission distance accordingly. At the same time, its settable transmission power gear is also discrete-the sub-GHz SX1276 can be divided into 20 transmission power levels (−4 dbm–+15 dbm) and 17 transmission power levels (+2 dbm–+17 dbm and 20 dbm [20]) according to different radio frequency pins; While the 2.4 GHz SX1280 has 32 transmit power levels (−18 dbm–+12.5 dbm [2]). Obviously, neither of the premises mentioned above is satisfied.

3.2 Improve Energy Model for LoRa N2N Communication

Considering that LoRa communication can dynamically adjust the transmission data rate [21], combined with adjustment of the discrete gear on the transmission power, the above energy consumption model formula can be redefined as follows:

$$\begin{cases} E_t = \left(P_T + P_{amp}\right) \times ToA \\ E_r = P_R \times ToA \end{cases} \tag{2}$$

where P_T and P_R are the basic circuit power for sending and receiving, P_{amp} is the power of the radio frequency transmission circuit, and *ToA* is the air flight time of the data packet. In view of the preamble, CRC and spreading coefficients in wireless communication, it is more accurate and close to the actual situation to use Time on Air (ToA) to express the transmission time.

Calculation of P_{amp}. P_{amp} is the transmission power of the sending node. Under the same parameters, the longer the distance, the more the power is required. To determine the minimum transmission power required when the transmission distance is D, and considering the receiving sensitivity of LoRa modulation, the received signal energy needs to meet:

$$P_k g(d) \geq (S_{th}|sf, bw) \tag{3}$$

$g(d) = \lambda^2 / (4\pi d)^2$ represents the attenuation of the signal. For simplicity, this paper assumes that the environment is ideal, the gain of the receiving antenna is 1, and λ is the wavelength of the signal carrier. S_q represents the receiving sensitivity at a specific SF and BW, which is the lowest threshold of the signal reached. So the above formula can be transformed into:

$$P_k \geq \frac{S_{th} \times (4\pi d)^2}{\lambda^2} \tag{4}$$

Calculation of ToA. For LoRa communication, Time on Air for sending kbit data is the sum of preamble time and data load time:

$$T_{packet} = T_{preamble} + T_{payload} \tag{5}$$

According to the SX1280 data manual, the ToA calculation formula for 2.4 GHz LoRa is as follows (With CR as Legacy Coding Rate (ie. not Long Interleaving)):

$$T_{packet} = \begin{cases} \left[n_{preamble} + 6.25 + 8 + ceil\left(\frac{\max(8PL - 4SF + 16CRC - 20H, 0)}{4 \times SF} \right) \times (CR + 4) \right] \times T_s \; SF < 7 \\ \left[n_{preamble} + 4.25 + 8 + ceil\left(\frac{\max(8PL - 4SF + 8 + 16CRC - 20H, 0)}{4 \times SF} \right) \times (CR + 4) \right] \times T_s \; SF \in [7 - 10] \\ \left[n_{preamble} + 4.25 + 8 + ceil\left(\frac{\max(8PL - 4SF + 8 + 16CRC - 20H, 0)}{4 \times (SF - 2)} \right) \times (CR + 4) \right] \times T_s \; SF > 10 \end{cases} \tag{6}$$

where T_s is the symbol time, which satisfies:

$$T_s = 2^{SF} / BW \tag{7}$$

$n_{preamble}$ is the preamble length set by the system, and PL is the number of bytes in the payload. H is 0 in the explicit header and 1 in the implicit header. CR stands for encoding rate. The values of CR are 1, 2, 3 or 4, representing encoding rates of 4/5, 4/6, 4/7 or 4/8 respectively. CRC is the tail CRC check. If the check is turned on, CRC = 1, otherwise CRC = 0.

Combining the calculation of P_{amp} and ToA, we minimize the value of E_t by selecting SF and BW, which means making the transmission energy consumption of the sending node of LoRa reach the lowest. Obviously, it can be seen that for the receiving node, the receiving power consumption only depends on the ToA. The faster the rate, the smaller the ToA and the lower the receiving power consumption.

4 Performance Evaluation

We use Matlab to analyze the impact of SF and BW on energy consumption. Simulation parameters are set according to real hardware settings: packet payload length (PL) is 64, we choose the explicit header mode where H is 0, CRC is 1 to enable CRC verification, CR is 1 and coding rate is set to 4/5. Besides, we choose the corresponding SF (5–12) and BW (203 kHz, 406 kHz, 812 kHz, each 1625 kHz) to calculate the transmission energy consumption in different parameter settings. For ease of description, the form of (x, y) parameter group is used below to indicate that SF is currently set as x and BW is y.

In the energy consumption evaluation, according to the requirements for receiving sensitivity when setting different SF and BW values in Table 1, then, calculating the minimum transmitting power of the starting node satisfying the communication distance according to Eq. (4), we can see that, if the minimum transmit power required is greater than the maximum value that the system can set (12.5 dBm), the current (SF, BW) setting is invalid and cannot meet the communication distance.

First, we set the communication distance d to 3000 m, and calculated and analyzed the transmission energy consumption of each (SF, BW) setting (E_t), as shown in Fig. 2 and Fig. 3 below. Figure 2 shows the minimum transmission energy consumption of different (SF, BW) configurations under theoretical parameter conditions (The corresponding energy consumption can be calculated according to the minimum receiving sensitivity value required by formula (4)). It can be seen from the figure that: (1) For the same BW, with the increase of SF, the overall trend of transmission energy consumption first drops and then rises, and the minimum energy consumption value is between 7 and 8. This indicates that when the BW is constant, although increasing SF increases ToA, the receiving sensitivity will also be improved at the same time, and sequentially, a smaller transmission power can be set, thus making a contribution to reducing the overall transmission energy consumption. But as SF continues to increase, ToA will grow rapidly, thus leading to an increase in overall transmission energy consumption; (2) In case of the same SF, with the increase of BW, the overall trend of transmission energy consumption also goes downward. But what is interesting is that when the BW reaches the maximum value of 1625 kHz, energy consumption faces a great increase, for the receiving sensitivity decreases markedly and the increase in the transmission power will seriously affect the overall power consumption when the BW reaches 1625 kHz. The above two points show that under ideal parameter conditions, large or small SF and BW are not conducive to reducing power consumption.

Then we used the actual power parameters of the module composed of SX1280 chip and MCU to simulate. Here we not only considered the minimum transmission energy consumption required for data transmission, but also the basic energy consumption required for the normal operation of the transmission module. The result is shown in Fig. 3. It can be seen from the figure that: (1) In case of the same BW, the transmission energy consumption continues to increase with the increase of SF; (2) In case of the same SF, the transmission energy consumption also continues to increase as the BW decreases. Therefore, it can be concluded that the basic energy consumption of the module plays a decisive role in the overall energy consumption. For formula (2), when the basic circuit power (P_T) is significantly greater than the gear adjustment power of power amplifier (P_{amp}), the transmission power of LoRa communication is mainly affected by ToA.

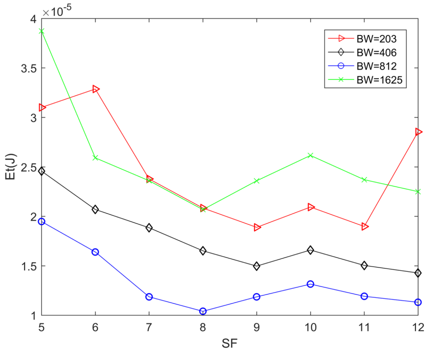


Fig. 2. Transmission power consumption using model parameters

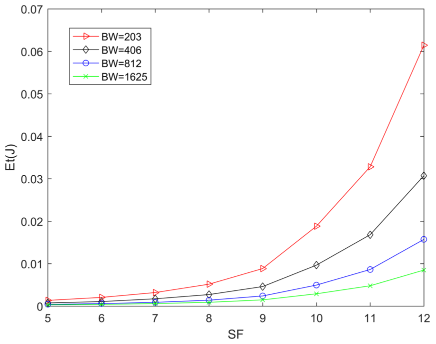


Fig. 3. Transmission power consumption using chip parameters

Secondly, the communication distance d was also set as 3000 m, but it was equally divided into 1–6 segments, and a LoRa node was added at each bisection point as a relay for forwarding data to form a multi-hop topology network. In case of different segments, two adjacent relay nodes set an (SF, BW) value that can minimize the transmission power according to the segment distance. Next, we counted and analyzed the energy (E_t) required by all nodes at different hops, as shown in Fig. 4 and Fig. 5 below.

Figure 4 shows the results under the theoretical parameter conditions. The best (SF, BW) value for different hop counts are marked on the top of the histogram. It can be seen from the figure that: (1) The overall transmission energy consumption will decrease as the number of hop counts increases; (2) Under the premise that the communication distance is 3000 m, the parameter SF of the lowest transmission energy consumption is 7 or 8, and the BW is 812 kHz, which is consistent with the result in Fig. 2 above. It is clear that the more the network hops, the lower the overall energy consumption of the network.

Figure 5 shows the results under the actual operating parameters of the module. We not only considered the minimum transmission power required to transmit data, but also took into account the receiving power of each node (including relay nodes and receiving nodes) and the basic circuit power of the module to maintain the normal operation. It can be seen from the figure that as the number of hops increases, the overall energy consumption continues to increase. Besides, the best (SF, BW) value for all hops is (5, 1625 kHz), which is consistent with the result shown in Fig. 3.

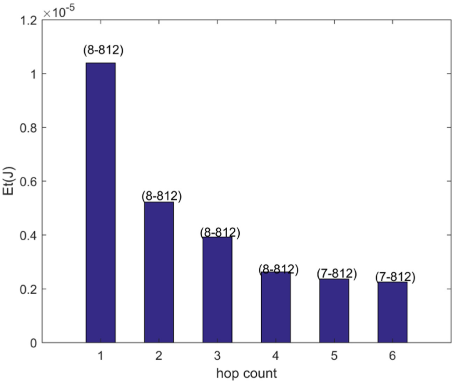


Fig. 4. Transmission power consumption under different hops (model parameters)

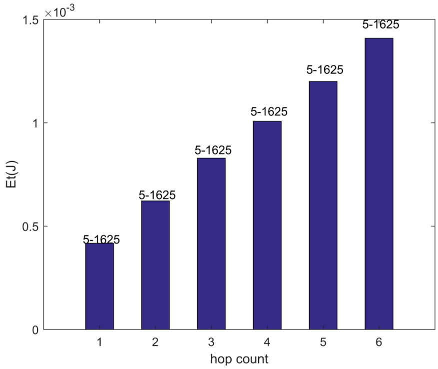


Fig. 5. Power consumption under different hops (chip parameters)

To further analyze the influence of distance and hop number on power consumption under actual working parameters, we fixed the communication distance as 10,000 m, and the remaining test conditions were consistent with the above working parameters. The total energy consumption for different hop counts was counted and analyzed, as shown in Fig. 6. It can be seen from the figure that: (1) The total energy consumption of the network is the smallest when the transmission is divided into three hops; (2) The energy consumption for different hop counts reaches the lowest when the SF is set to a lower value (5, 6 or 7) and the BW is set to 1625 kHz, which can ensure a faster transmission rate and reduce ToA.

In addition, comparing Fig. 5 with Fig. 6, we can come to an interesting conclusion: as the total transmission distance increases, the basic energy consumption of nodes is no longer a decisive factor that determines the total energy consumption of the network, which will also be affected by the transmission distance and the number of hops between single-hop transceivers.

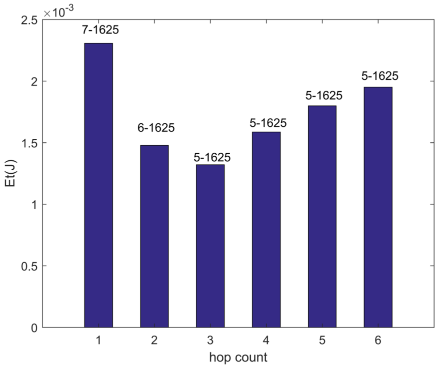


Fig. 6. Total energy consumption under different hops

5 Conclusion

Considering the characteristics of LoRa communication and the limitations of actual hardware conditions, this paper proposes an energy consumption model suitable for discrete adjustment of dynamic rate and transmission power. Based on the energy consumption model and combined with the ToA of LoRa communication, this paper analyzes the influence of different SF and BW settings on transmission energy consumption, as well as energy consumption under the conditions of model parameters and actual parameters. For model parameters (or hardware with base power equivalent to PA power), larger or smaller SFs and BWs will increase power consumption. For actual parameters, a faster rate configuration should be chosen as much as possible to shorten the ToA. Besides, the multi-hop transmission will be more conducive to reducing overall energy consumption when building a LoRa multi-hop relay network, especially when the distance is long. These conclusions can not only provide a reference for 2.4 GHz LoRa-based self-organizing networks but also be used for the potential applications of sub-GHz LoRa-based self-organizing networks.

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