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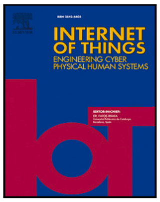

Research article

LPWC: Long preamble wake-up communication protocol for a LoRa network

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ABSTRACT

LoRa is widely used in various applications, which has gained increasing popularity in the field of Internet of Things (IoT). However, in legacy LoRa protocols, bidirectional communications and low power consumption cannot be achieved simultaneously, hindering the further development of LoRa. In this study, a long preamble wake-up communication (LPWC) protocol is proposed to alleviate the aforementioned issue. This scheme is performed at both sides of communication: (1) LoRa nodes are designed to sleep periodically to save more power; (2) LoRa gateway must send packets with long preamble to maintain the reliability of downlink communication. In addition, an energy model is built to prove that an optimal cycle period exists for LoRa nodes to save more energy. Then we implement simulations to evaluate the performance of the proposed method in various cases. Results show that LPWC outperforms LoRaWAN Class B mode in terms of power conservation and packet latency.

1. Introduction

Low Power Wide Area Network (LPWAN) is currently a typical wireless communication technique that is usually adopted in the field of the Internet of Things (IoT); it exhibits the advantages of wide coverage and low power consumption [1]. The applications of LPWAN are ubiquitous in daily life, including smart homes [2], smart buildings [3] and smart cities [4], providing people with more convenience. Benefited by the rapid growth of IoT, LPWAN has also obtained extensive attention. To date, research has shown that the chipsets of LPWAN has reached over 100 million in the market, and the growing tendency will continue in the next 5 years [5]. Several radio technologies are contained in LPWAN, including LTE-M [6], NB-IoT [7], Sigfox [8] and LoRa [9]. In terms of energy consumption and deployment cost, LoRa is the most prominent among the aforementioned technologies. LoRa is developed by Semtech Company, which utilizes chirp spread spectrum (CSS) as its modulation technique. Three adjustable parameters are provided in the physical layer of LoRa, namely, spreading factor (SF), bandwidth (BW), and coding rate (CR) [10]. In accordance with specific conditions, these parameters can be given with different values to improve network flexibility and reliability.

As a typical LPWAN technology, power conservation is frequently considered as the first priority in a LoRa network. Therefore, a LoRa end device is usually expected to remain in sleep mode as long as possible in an application. Accordingly, two-way communications are difficult to achieve between a LoRa gateway and a node, because a sleeping node cannot proactively receive

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downlink communication. Meanwhile, downlink communication is required in many cases [11], and thus, this issue may pose a limitation to further extending LoRa applications. In smart city scenarios, for example, street lights must send uplink data to report their status, while simultaneously receiving downlink communication, which includes control commands [12]. Always keeping an end device on can assure reception of downlink communication but consumes too much energy. Therefore, finding an effective approach for enabling bidirectional communications in a LoRa network while maintaining low power consumption is urgently required.

As the most popular LoRa protocol in medium access control (MAC) layer, LoRaWAN provides three methods for establishing bidirectional communications [13], but it cannot simultaneously meet the requirements of real-time downlink transmission and low power consumption. In [14], a transmitter initiated cycled receiver (TICER) approach was proposed to save more power in wireless sensor networks. In this method, the receiver was designed to sleep and wake up periodically. Meanwhile, the transmitter should send RTS (request to send) packet frequently and expect to get CTS (clear to send) from the receiver. To ensure that the receiver could get RTS packet timely when it wakes up, the interval time between two RTS packets at the transmitter side must be less than the wakeup period at the receiver side. Simulations indicated that the TICER strategy can reduce total power consumption effectively. However, several kinds of control packets are introduced in this method, including RTS, CTS and ACK, thus it leads to additional communication overhead, which may not be applicable to LoRa communication with low data rate.

In response to the above issues, we propose a long preamble wake-up communication (LPWC) protocol for LoRa in the current study. This method is designed with two aspects. (1) LoRa nodes remain asleep most of the time and wake up periodically to check the channel. (2) A LoRa gateway must send packets with a long preamble to make the communication detectable by end devices. In this manner, we can simultaneously achieve the goals of low power consumption and real-time communication. In addition, a mathematical model is developed to calculate the energy consumption of nodes. On the basis of this model, we prove that sleep periodicity may exert the most significant influence on power consumption, and an optimal value is derived to save more energy. In summary, LPWC is an energy efficient method for establishing two-way communications between LoRa nodes and gateway.

In summary, the main contributions of our work are as follows:

(1) We propose a LPWC protocol that any LoRa nodes could communicate with each other with low power consumption regardless of any prior synchronization. In this method, the transmitter sends packet with long preamble, meanwhile the receiver can sleep periodically to conserve energy.

(2) We build an energy model for LoRa nodes which better describes the total power consumption. In this model, the LoRa chip is classified with several working states, which are configured with different operating currents. By doing this, the energy consumption of each state is calculated accurately.

(3) We calculate an optimal cycle period for LoRa nodes which can save energy to the furthest extent. By comparing with traditional LoRaWAN protocol, the proposed method shows superior energy efficiency via simulations.

The remainder of this paper is organized as follows. In Section 2, we introduce the background and related works of LoRa technology. In Section 3, LPWC protocol is proposed, and an optimal cycle period is calculated for this method. In Section 4, simulations are carried out to demonstrate the superior performance of LPWC, and limitations are also discussed. Finally, conclusions are drawn in Section 5.

2. LoRa and LoRaWAN

2.1. LoRa parameters

LoRa, as a typical low-speed wireless communication technology, the range of data rate is 0.018 to 37.5 kbps. Three configurable parameters including spreading factor (SF), bandwidth (BW) and coding rate (CR) are used to calculate data rate in LoRa communication. The equation is presented below [10]:

$$R_b = SF\frac{BW}{2^{SF}}CR. \tag{1}$$

It can be seen that LoRa communication with smaller SF, larger BW and CR can have higher data rate, with a cost of lower communication range. Moreover, packet airtime is also related with the preceding parameters and the formulas are listed as follows [10]:

$$\begin{aligned} &T_s = \frac{2^{SF}}{BW}, \\ &T_{prea} = n_{prea} * T_s, \\ &T_{pay} = n_{pay} * T_s, \\ &T_{air} = T_{prea} + T_{pay}, \end{aligned} \tag{2}$$

where n_{prea} and n_{pay} are the lengths of the preamble and payload, T_s, T_{prea} and T_{pay} denote the airtimes of LoRa symbol, preamble and payload. The equations above will be used to obtain the airtime of a packet with different settings.

Table 1
Current in CAD mode with different settings.

BW (kHz)	Full current state (mA)	Reduced current state (mA)
7.8–41.7	11	5.2
62.5	11	5.6
125	11.5	6
250	12.4	6.8
500	13.8	8.3

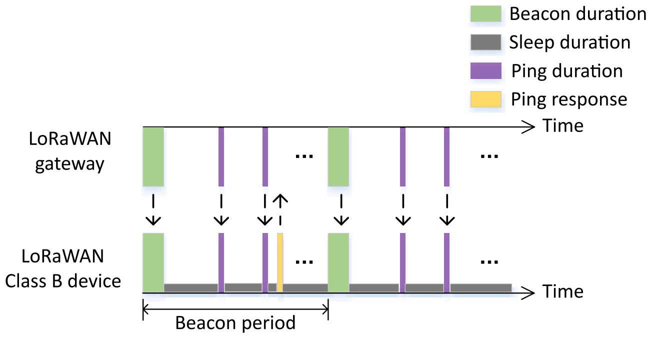

Fig. 1. Illustration of LoRaWAN Class B mode.

2.2. LoRa CAD mode

In wireless sensor network, the detection of a target signal whose power is lower than noise is a technical challenge. In LoRa communication, a channel activity detection (CAD) mechanism is specially designed to address this issue. In this mode, a LoRa chip can find useful signal quickly with minimum energy, thus it is applicable to low power applications in LoRa network. The duration of CAD mode is about two symbols time, which is divided into two phases, namely, full current and reduced current state. Each of the two states is about one symbol time. In addition, the energy consumption in different states are listed in Table 1 [10].

From the above table, it can be seen that the current varies as BW changes. Assuming that the BW is set to 125 kHz, thus the current is 11.5 mA in full current state and 6 mA in reduced current state. Therefore, the average value is calculated with 8.75 mA. Moreover, in this study, LoRa node is devised to switch into CAD mode once it wakes up, so as to check the target channel in a short time.

2.3. LoRaWAN

LoRa provides a low power and long range radio communication technique in the physical layer. Protocols above the physical layer in the Open Systems Interconnection (OSI) layer model are required for a complete system (network). LoRaWAN is an open standard developed by the LoRa Alliance, which defines the MAC and network protocol for LoRa radio [13]. In LoRaWAN standard, an end device is defined to work with one of the following three modes:

1. Class A: Class A mode is specifically developed for ultra-low power consumption applications. Thus, even a battery-powered LoRa node is expected to work for several years. To save more energy, a Class A device remains sleeping for most of its lifetime. When uplink communication is required, node starts transmission, and then it will listen on the corresponding channel for two times to receive response.
2. Class B: Both energy conservation and two-way communications are considered in Class B mode. Similar to Class A, LoRa nodes are designed to enter sleep mode in idle state. Meanwhile, time synchronization is utilized to produce predictable opportunities for a gateway to transmit downlink packets to the end device. Fig. 1 illustrates the workflow of LoRaWAN Class B mode. A LoRaWAN gateway periodically broadcasts beacons, and thus, an end device can take the beacons to implement timing calibration to remain synchronized with the gateway. In addition, numerous "ping slots" are defined between two consecutive beacons, as agreed upon by the gateway and end device. Meanwhile, the end device should switch to listening mode in the beginning of each ping slot to receive possible packets from the gateway.
3. Class C: LoRa nodes in this mode remain in receiving state unless they are required to send uplink packets. In this manner, downlink communication can be accomplished with low latency.

Given the extensive applications of LoRaWAN, Class B mode is set as the baseline in the subsequent sections.

Table 2
Summary of LoRa energy saving technologies.

Category	Name	Description	Limitation
Optimization in physical layer	ICS-LoRa [15]	Every LoRa symbol can carry more information	Implementation in real chip requires further study
	Lora-backscatter [16–18]	Backscatter is combined with LoRa technology	
Additional hardware is used	[20]	Hybrid power system is employed	Increase the cost of hardware
	[21]	A wake-up receiver is introduced	
Various modes are designed according to energy consumption	LoRaWAN [13]	Three kinds of modes are proposed	Energy conservation and real-time communication are incompatible

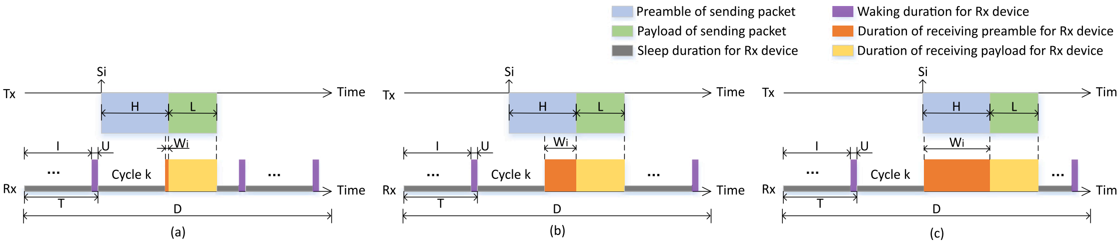

Fig. 2. Illustration of the LPWC protocol with three examples. (a) A node wakes up at the end of preamble transmission, and thus, nearly no preamble is required to be received. (b) A node wakes up in the middle of preamble transmission, and thus, half of the preamble is required to be received. (c) A node wakes up in the beginning of preamble transmission, and thus, the whole preamble is required to be received.

2.4. Related works about LoRa technology with energy conservation

Several works have been done to address the issue of power conservation for LoRa technology. In [15], an ICS-LoRa method was proposed by optimizing the modulation technique of LoRa. Comparing with the original LoRa technology, every LoRa symbol in this method can carry more information. Thus, the airtime of a given packet was reduced and less energy was consumed. In [16–18], the authors combined LoRa technology with the backscatter method. The main idea of backscatter is that the transmitter can send data via reflecting signals from others, thus no energy was required at the transmitter side theoretically [19]. Simulations have shown that all the above methods can achieve superior power-saving performance, but how to implement these ideas into real chip requires further study. In [20], a hybrid power system was proposed to provide energy for LoRa nodes. In this method, a photovoltaic panel was mostly used as the main source, meanwhile a supercapacitor and a Lithium battery were both employed as the backup power supply. By doing this, the lifetime of nodes was increased from two years to ten years. In [21], an on-demand communication method was developed to reduce data latency and increase node lifetime. Meanwhile, the authors utilized a microwatt wake-up receiver (WuRX) to check the wireless channel with ultra-low power. Results showed that the lifetime of the end device can be extended by up to 3 years. However, these two methods rely on additional hardware, which may increase the cost of LoRa node. In LoRaWAN network, three kinds of LoRa devices are proposed with the consideration of energy conservation, including Class A, B and C [13]. When the end device is in Class A mode, it cannot receive data until an uplink communication is issued. For a device with Class B mode, downlink communication is only allowed in scheduled time slots, and additional power is consumed due to time synchronization. A device in Class C mode can receive packets at any time by having the receiver always on without considering energy preservation. But none of these modes can achieve real-time communication and energy conservation simultaneously.

All the power-saving researches about LoRa communication are summarized in Table 2. None of these existing technologies can achieve energy saving and real-time communication simultaneously without involving additional hardware. To fill the aforementioned gap, the proposed method has the simplicity of implementation, moreover it can achieve the objective of two-way communications in nearly real-time.

3. LPWC protocol

3.1. Overview of LPWC protocol

The LPWC protocol is illustrated in Fig. 2, which is designed for bidirectional communications with two components: (1) a receiver (i.e., a LoRa node) that sleeps and wakes up periodically to save power, and (2) a transmitter (i.e., a LoRa gateway) that must send packets with a long preamble. Notably, the preamble duration at a gateway must be longer than the sleeping period of the end device. Thus, although a downlink communication is issued randomly, an end device is able to receive the preamble when

Table 3
Parameters employed in this part.

Parameter	Symbol
Whole duration	D
Cycle period of Rx device	T
Sleep period of RX device	I
Wakeup period of Rx device	U
Preamble time of sending packet	H
Payload time of sending packet	L
Number of generated packets in this duration	M
Index of generated packets and its range is $(1-M)$	i
Number of full wake-up cycles for Rx device	N
Generating moment of packet i	S_i
Waiting time for node to receive payload of packet i	W_i

it wakes up, and then switches into the receiving mode. By doing this, the successful reception of downlink communication can be assured. In the following sections, an optimal cycle period which can save energy to the greatest extent is derived for the end devices.

3.2. Overhead of the long preamble for LPWC protocol

In the preceding paragraphs, a sleep–wake mechanism is proposed for a LoRa node to save power. However, this scheme will lead to additional energy consumption because of receiving the long preamble. In particular, when a gateway transmits a packet i, a LoRa node has to wait W_i until the end of the long preamble. Then, W_i is defined as the overhead of the long preamble because a node must remain in listening mode during the time of W_i. In Fig. 2, three examples are provided to demonstrate that W_i has different values as packet transmission time varies. In this section, the average value of W_i is expected to be derived, such that we can determine the overhead of LPWC. In addition, the parameters of LPWC are listed in Table 3.

As mentioned in Section 3.1, preamble duration must be longer than the cycle period, i.e., $H \geq T$. To save more energy, H and T are set with the same value in this study. Thus for any packet i, the moment when its preamble ends can be indicated as $S_i + H$. Meanwhile, a corresponding cycle period $[kT, (k+1)T]$ (k is an integer) occurs at the node side, during which the packet payload is received successfully. Accordingly, we have the following expressions:

$$W_i = \begin{cases} S_i - (k-1)T & (0 \leq (S_i + H)\%T < I) \\ I & (I \leq (S_i + H)\%T < T). \end{cases} \tag{3}$$

Then the expectation of W_i can be derived as follows:

$$\begin{aligned} E(W_i) = {} & V(W_i^1)P\{0 \leq S_i - (k-1)T < I\} \\ & + V(W_i^2)P\{I \leq S_i - (k-1)T < T\}, \end{aligned} \tag{4}$$

where $V(W_i^1)$, $V(W_i^2)$ are the average values of W_i in different conditions.

In accordance with the arrival times for the Poisson Process, the generating moments S_i are distributed independently under the condition that M packets are transmitted in this duration [22]. Moreover, $S_1, S_2, \ldots$ follow a uniform distribution when they are regarded as unordered random variables. Thus, the value of S_i is also distributed uniformly in any time segment. Then we can have the following results:

$$\begin{aligned} & V(W_i^1) = E(S_i - (k-1)T) = \frac{I}{2}, \\ & P\{0 \leq S_i - (k-1)T < I\} = \frac{I}{T}, \\ & P\{I \leq S_i - (k-1)T < T\} = \frac{U}{T}. \end{aligned} \tag{5}$$

Thus, Eq. (4) can be expressed as follows:

$$E(W_i) = \frac{I}{2} * \frac{I}{T} + I * \frac{U}{T}, \tag{6}$$

The wakeup time is the CAD period, and it only requires two symbols time as mentioned in Section 2.2. In this study, the LoRa node is mainly designed to sleep long time during every cycle period to save more energy. Thus, the wakeup time is omitted for simplicity and the cycle period is approximately equal to the sleep period (i.e., $I \approx T$). Finally, we can get the following result:

$$E(W_i) \approx \frac{T}{2}. \tag{7}$$

That is, the node is required to wait $\frac{T}{2}$ on average before receiving packet payload.

Table 4
Current in different modes.

Mode	Sleep	CAD	Receive	Transmit
Current (mA)	0.0002	8.75	11	29

3.3. Optimal cycle period

In this section, an energy model is built to calculate the total power consumption E_w^{lpwc} for a LoRa transceiver node (including transmission and reception), which is represented as follows:

$$E_w^{lpwc} = E_s + E_c + E_r + E_t, \tag{8}$$

where E_s, E_c, E_r and E_t are the total energy consumption in the sleep, CAD, reception and transmission modes, respectively. Considering that sleep current is less than 1 uA, which is considerably smaller than those in other modes, and thus, the corresponding power consumption E_s in this state can be ignored. The current in the other three modes are denoted with I_c, I_r and I_t, meanwhile the chip voltage is V. Then we can obtain the following equations:

$$\begin{aligned} E_c &= V * I_c * T_c, \\ E_r &= V * I_r * T_r, \\ E_t &= V * I_t * T_t, \end{aligned} \tag{9}$$

where T_c, T_r and T_t are the sum of the periods in CAD, receiving and transmission process. These values can be denoted as follows:

$$\begin{aligned} T_c &= (N - M) * t_{cad}, \\ T_r &= M * (t^r_{pre} + t_{pay}), \\ T_t &= M * (t^t_{pre} + t_{pay}), \end{aligned} \tag{10}$$

where t_{cad} indicates the single period of CAD process, which is about $2(2^{SF}/BW)$. Meanwhile, t^r_{pre} is the single period required to receive preamble, and it is $\frac{T}{2}$ on the basis of Section 3.2. Moreover, t^t_{pre} and t_{pay} indicate the single period to send preamble and payload, their values are T and L, respectively. Thus, we obtain the following results:

$$\begin{aligned} T_c &= 2(N - M) * \frac{2^{SF}}{BW}, \\ T_r &= M * (\frac{T}{2} + L), \\ T_t &= M * (T + L), \\ N &\approx \frac{D}{T}. \end{aligned} \tag{11}$$

Then the power model is developed as follows:

$$E_w^{lpwc} \approx \underbrace{2V * I_c * \frac{2^{SF}}{BW} * (\frac{D}{T} - M)}_{E_c} + \underbrace{V * I_r * M * (\frac{1}{2}T + L)}_{E_r} + \underbrace{V * I_t * M * (T + L)}_{E_t}. \tag{12}$$

Under certain circumstances, all the parameters in Eq. (12), except for T, are employed with fixed values. Thus, power consumption is dependent upon the cycle period (i.e., airtime of the preamble). In accordance with Eq. (12), if T is large, then more energy is used for transmitting and receiving preamble because of its long duration, but less power will be consumed in the CAD state. By contrast, a node is required to wake up frequently and energy will be mainly exhausted in the CAD mode. In conclusion, an optimal value of T that can better balance the trade-off between E_c, E_r and E_t is available, and thus, minimum power consumption is achieved. By deriving both sides of Eq. (12), the results are shown below:

$$\frac{\partial E_w}{\partial T} \approx -2V * I_c * \frac{2^{SF}}{BW} * D * T^{-2} + \frac{1}{2}V * I_r * M + V * I_t * M. \tag{13}$$

Then we set $\frac{\partial E_w}{\partial T} = 0$. Eventually, the optimal result is presented as follows:

$$T_{opt} = \sqrt{\frac{4I_c}{I_r + 2I_t} * \frac{2^{SF}}{BW} * \frac{D}{M}}, \tag{14}$$

Assuming Sx1276/77/78/79 transceiver is utilized in this study, meanwhile the transmission power is set to 13 dBm and the chip voltage is set to 3.3 V. According to the LoRa specification [10], the rough values of the current in different modes are enumerated in Table 4. Thus a further result of Eq. (14) is shown as follows:

$$T_{opt} = \sqrt{\frac{35}{69} \frac{2^{SF}}{BW} \frac{D}{M}}, \tag{15}$$

which indicates that the cycle period should be set by considering LoRa parameters (i.e., SF, and BW). Meanwhile, given that $\frac{D}{M}$ is the average transmission interval, this result also suggests that we should adjust the value of T in accordance with the packet rate.

Table 5
General parameters for the simulations.

BW	SF	Average packet interval
125 kHz	9	100 s
CR	Payload length	Battery capacity
4/5	30 bytes	3000 mA∗h

Table 6
Different T values and the corresponding preamble lengths.

Cycle period (s)	0.3	0.4	**0.45**	0.5	0.6
Preamble length (symbols)	69	94	**106**	118	143

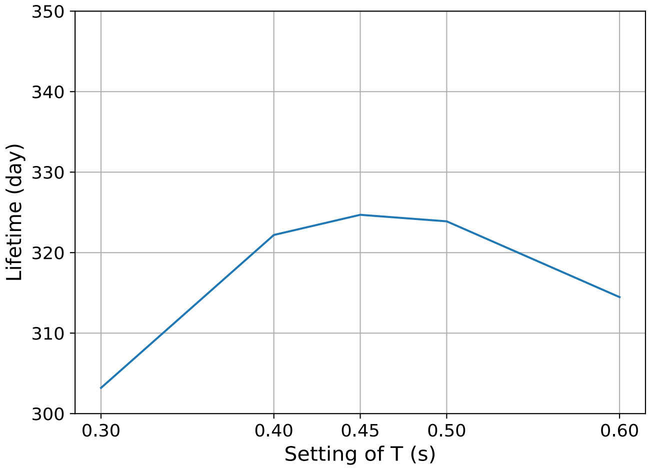

Fig. 3. Lifetime of node changes as T varies.

4. Simulations

4.1. Overview of the simulations

In this section, simulations will be performed to evaluate the performance of the proposed protocol. We use LoRaSim as the simulation tool which is widely employed in various LoRa studies [23]. LoRaSim is a lightweight simulator programmed with python. In LoRa network, this simulator is mainly used for investigating packet collisions and it is expanded to calculate energy consumption in this part. Simulations will be performed in two steps: (1) We verify that the cycle period configured with an optimal value can save more energy. (2) We set LoRaWAN as the baseline to compare it with LPWC. Related parameters with default values are listed in Table 5. In addition, the lifetime of a node is utilized as the indicator for measuring the energy efficiency of different methods in the following simulations.

4.2. Verification of the optimal cycle period

In this section, simulation is carried out to explore the relationship between cycle period T and energy consumption. In Table 6, T is given with several values, which ranges from 0.3 s to 0.6 s, and the optimal cycle period is also included. On the basis of Eq. (15), the optimal value is about 0.45 s. Meanwhile, in Section 3.2, an assumption is proposed that the preamble duration of a packet is the same as the cycle period, and thus, preamble lengths should be adjusted in accordance with different T values. By using Eqs. (1) and (2), the corresponding preamble lengths are calculated with given airtimes, which are also provided in Table 6.

Fig. 3 shows that the lifetime changes as T is provided with different values. When T reaches the optimal value, the corresponding node has the longest lifetime. This result proves the finding in Section 3.3, i.e., any node configuring with the optimal periodicity can survive for a longer time. In addition, we note that the longest lifetime is about 324 days, indicating that a LoRa node which is capable of real-time communication can work for about 1 year by utilizing our method.

4.3. Comparison with LoRaWAN

As described in Section 2.3, LoRa devices in Class B mode are set as a baseline to make comparisons. In the following simulations, a LoRaWAN device denotes a node in Class B mode unless otherwise specified. In addition, it should be noted that star network

Table 7
Simulation parameters of LoRaWAN.

Parameter	Value
Beacon periodicity	128 s
Receiving duration for beacon	2.12 s
Ping periodicity	8 s
Ping duration	0.03 s

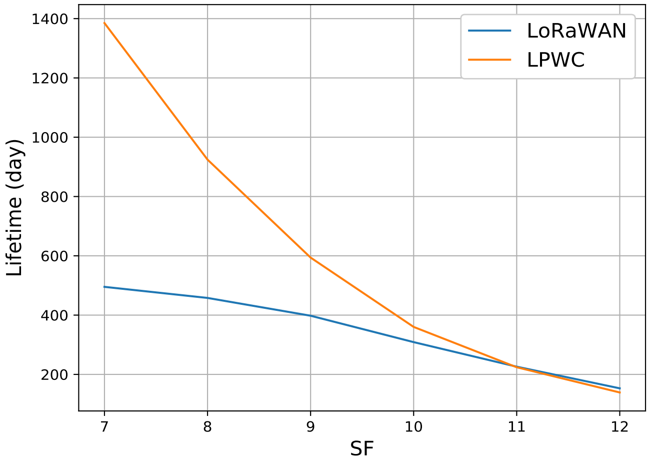

Fig. 4. Comparison of lifetime of LoRaWAN and LPWC as SF increases.

structure is adapted in LoRaWAN network. In this network, all nodes communicate with gateways directly. LoRa gateways are generally configured with mains power which can receive packets at any time. Then power-saving performance is not the main factor to be considered at the gateway side, and it is unnecessary for the nodes to send packet with long preamble in uplink communication. Thus, in star network, the energy model is slightly different with those in Eq. (12) when utilizing LPWC method. The short preamble length is denoted with F when the nodes send packets to gateway, and it is set to 8 symbols in this section. The new power model for the nodes is listed as follows:

$$E_w^{lpwc} \approx \underbrace{3.3 * (17.5\frac{2^{SF}}{BW}\frac{D}{T} - 17.5\frac{2^{SF}}{BW}M)}_{E_c} + \underbrace{3.3 * (5.5MT + 11ML)}_{E_r} + \underbrace{3.3 * (29MF + 29ML)}_{E_t}. \tag{16}$$

On the basis of the above equation, the corresponding optimal cycle period can be calculated below:

$$T_{opt} = \sqrt{\frac{35}{11}\frac{2^{SF}}{BW}\frac{D}{M}}. \tag{17}$$

And the new optimal cycle period would be used in the following simulations when comparing with LoRaWAN.

Similarly, we also establish an energy model for LoRaWAN devices, and the energy consumption $E_w^{lorawan}$ is shown as follows [24]:

$$E_w^{lorawan} = E_s + E_b + E_p + E_r + E_t, \tag{18}$$

where E_b and E_p represent the energy consumption of the beacon and ping period, respectively. In accordance with the research on LoRaWAN Class B devices [25], the related parameters are presented in Table 7. Then, we can calculate the energy consumption of the LoRaWAN nodes in detail.

Figs. 4 and 5 show the relationship between lifetime and LoRa parameters, including SF and BW. In general, the LPWC outperforms LoRaWAN in terms of lifetime in most of the cases. The reason may be that a node of LoRaWAN consumes additional energy in both beacon period and ping period, while extra energy is only required to receive the long preamble for a node of LPWC.

Packet latency is also an important indicator to evaluate network performance. In Figs. 6 and 7, the packet delay of LoRaWAN is longer than that of LPWC in all the cases. For LoRaWAN, packets from a gateway cannot be transmitted until a ping slot starts at the node side, and thus, packet delay is a random value that ranges from 0 to ping periodicity. According to [25], the average packet latency for LoRaWAN is half of the ping periodicity, which remains at 4 s during this simulation. For LPWC protocol, packet delay depends on preamble airtime. Based on Eq. (15), a larger SF or a smaller BW may lead to a longer cycle period (i.e., preamble time), and thus, the packet latency grows. The maximum latency is about 3.2 s in Figs. 6 and 7 when SF is set to 12. Nevertheless, the packet delay of a LPWC node is still shorter than that of a LoRaWAN node.

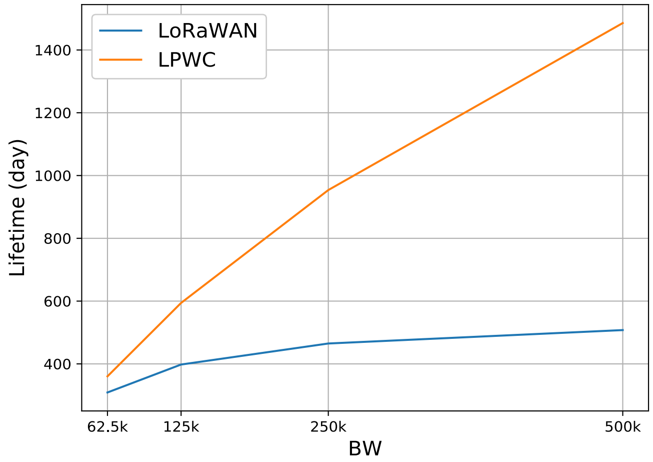

Fig. 5. Comparison of lifetime of LoRaWAN and LPWC as BW increases.

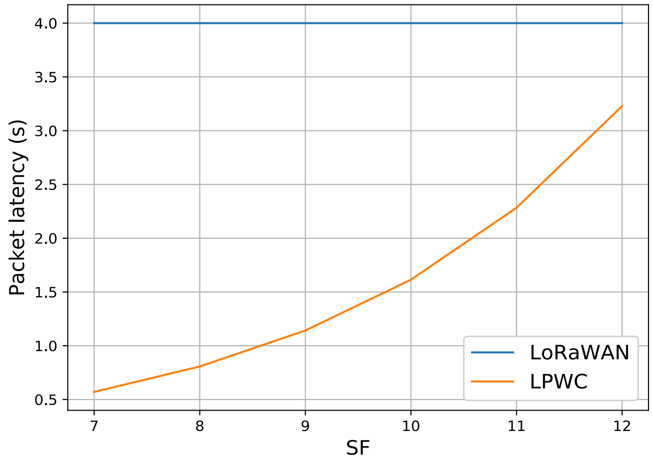

Fig. 6. Comparison of packet latency between LoRaWAN and LPWC as SF increases.

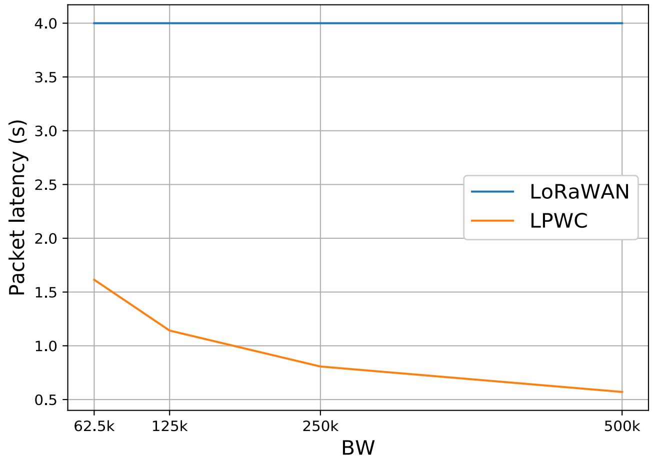

Fig. 7. Comparison of packet latency between LoRaWAN and LPWC as BW increases.

In Fig. 8, the average packet interval is changed from 50 s to 300 s to measure the lifetime of the nodes. As packet interval is extended, less packets are generated, and thus, the lifetime increases for both of the methods. Meanwhile, given the current

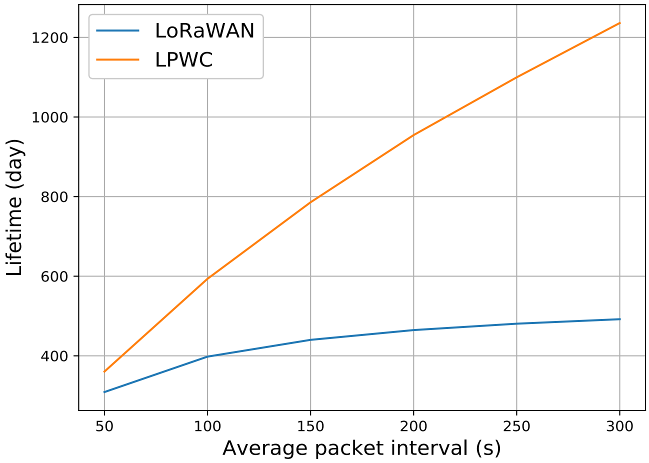

Fig. 8. Comparison of lifetime of LoRaWAN and LPWC as packet interval varies.

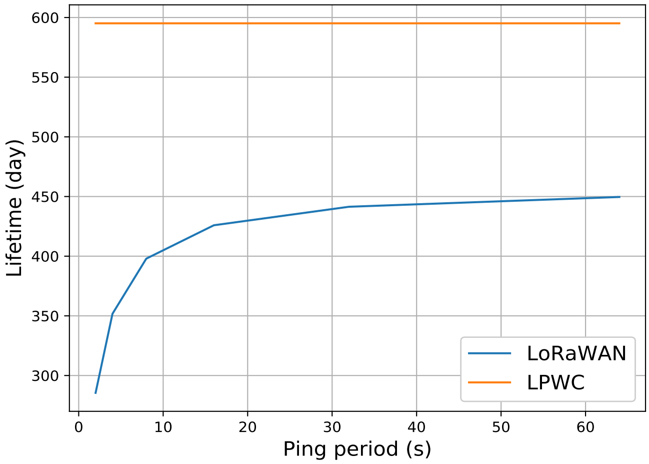

Fig. 9. Comparison of lifetime of LoRaWAN and LPWC as ping period changes.

settings, LPWC exhibits an advantage over LoRaWAN in terms of energy consumption, and the gap becomes larger when transmission frequency is reduced.

The ping period is a critical factor in power depletion for a LoRaWAN network. In this section, the ping period is provided with different values that ranges from 2 s to 64 s. Fig. 9 presents the comparison of lifetime between the two methods. For LoRaWAN protocol, a longer ping period leads to a longer lifetime. As illustrated in Fig. 9, the longest lifetime of a LoRaWAN node is about 450 days when the ping period is 64 s. Meanwhile, a node that employs LPWC can last for 595 days. In summary, a sizable gap remains between the two methods in terms of power conservation.

4.4. Discussion and limitations

In the previous simulations, we have demonstrated that LPWC exhibits better performance than LoRaWAN in terms of power-saving and packet delay under most scenarios. However, LPWC protocol also exhibits some limitations. One feature of LPWC is that a downlink packet has a long preamble, facilitating payload reception at the node side. However, this feature will simultaneously cause several problems. (1) The duration of a long preamble spans two time slots, which is introduced to keep a node alive, but it will result in a reduction of network throughput. As the packet preamble itself does not carry any information, thus more channel resource would be wasted when preamble is configured with a longer length. For example, assuming one packet has a long preamble, meanwhile the preamble and payload duration of this packet are both 0.5 s. Thus the data transmission efficiency is reduced to 50% comparing with other packets with no preamble, accordingly, the throughput of this network declines simultaneously. (2) When a gateway sends a packet, all the nodes around it have a chance to receive the packet. The overhearing issue may occur if a node is not the destination of the packet. This issue leads to additional energy consumption, and it will be aggravated by the long preamble with more end devices involved.

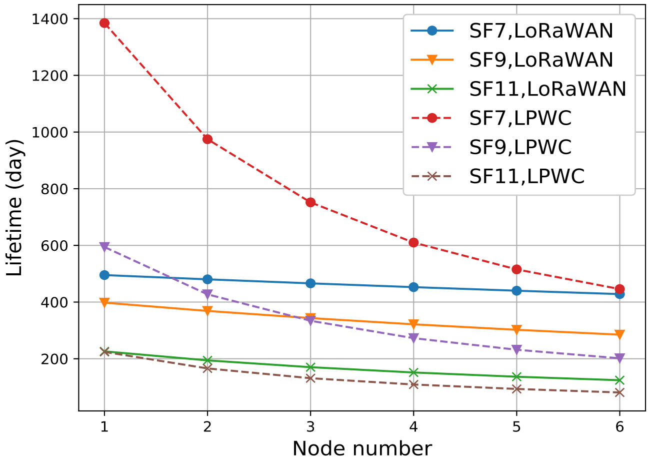

Fig. 10. Comparison of lifetime of LoRaWAN and LPWC as node number varies.

Several nodes will be utilized in the following simulations, and all of them are configured with the same parameters, including BW, SF and cycle period. Thus, we can fairly identify the overhearing problem which is purely caused by node number change. But, it should be noted that different nodes with various cycle periods are possible in LoRa network. Moreover, a given node that adjusts its cycle period dynamically in different periods is also permitted. In these situations, a specified field in the packet payload is designed to indicate the cycle period. When the cycle period is changed, the LoRa node is only required to incorporate the new cycle period into uplink packet. By receiving and analyzing the packet, the LoRa gateway then changes the packet preamble length when communicating with the corresponding node in the next time.

Fig. 10 shows comparison of lifetime in the two methods. As the node number is small, the LPWC method may be energy efficient at the node side in some cases. But more energy is consumed at the gateway side owing to the long preamble, and the additional overhead is about $3.3 * 0.029 * T_{opt}$ when transmitting one packet. In addition, when the node number exceeds 6, the LoRaWAN method can save more energy than LPWC with all SF settings. Under such circumstances, a possible solution is that more channel resources should be devoted, such as employing more frequency channels and SFs. As there is no interference when packets are transmitted in different frequency channels or SFs, thus the overhearing issue can be avoided. For instance, if a LoRa network has 15 nodes and 5 frequency channels are available to use, 3 nodes can be assigned to one channel. Then LPWC may also outperform LoRaWAN in some cases. In general, the proposed protocol is more applicable to a sparse network.

5. Conclusion

LoRa has recently obtained considerable attention in the field of IoT. With regard to the deployment of a LoRa network, power conservation and packet latency should be given with top priorities. To achieve the objectives, we propose a long preamble wake-up communication (LPWC) protocol. In this protocol, a LoRa node is designed to sleep and wake up periodically. Meanwhile, downlink packets from a gateway are equipped with a long preamble to ensure that the payload of packets can be received successfully. Then, we build an energy model and find an optimal cycle period for LoRa nodes. The simulation result verifies that nodes using the optimal sleep periodicity can survive for a longer time. In addition, we compare LPWC with LoRaWAN Class B in various cases, the former has lower power consumption and smaller packet latency than those of the latter. Moreover, we discuss the limitations of LPWC caused by the long preamble. In summary, as an energy efficient protocol, LPWC is suitable for a sparse LoRa network to achieve an extremely long lifetime.

As for future works, this paper can be promoted from the following aspects:

1. Receiving node is designed to sleep when it is idle in LPWC protocol, so it can save energy for LoRa communication. But the proposed method is only applied in one hop network, and it has the potentiality to be extended to LoRa-Mesh network in future study.
2. In Section 4.4, we have mentioned that LPWC is limited to small scale network owing to the long preamble. By providing more channel resources, nodes can send packets using different SFs or frequency channels without interference, thus the overhearing issue can be mitigated. So a method about how to assign the channel resource effectively deserves more attention in future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article

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