A LoRaWAN-Based Adaptive Multi-Frame Efficient Transmission Method (Postprint)

Authors: Ren Zhi, Qin army, Jiang Nan, Kunlong Wang

Date: 2019-04-01T00:00:00+00:00

Abstract

To address the problem of large control overhead and transmission delay in the multi-frame data transmission scheme between LoRa gateways and LoRa terminals in the LoRaWAN (long range wide area network) protocol, this paper proposes an adaptive multi-frame efficient transmission (AMFET) method based on LoRaWAN, which includes an adaptive multi-frame transmission mechanism, an adaptive multi-frame reception acknowledgment mechanism, and a frame loss identification mechanism. The adaptive multi-frame transmission mechanism sets priority levels for confirmed data messages, performs immediate acknowledgment for high-priority confirmed data messages, while low-priority confirmed data messages are acknowledged collectively after the adaptive transmission mode ends, and simultaneously introduces the Fpending mechanism into LoRaWAN uplink multi-frame transmission; the adaptive multi-frame reception acknowledgment mechanism records received data frame information through bit vector compression technology, thereby enabling consolidated acknowledgment of multiple confirmed data messages in a single operation; the frame loss identification mechanism utilizes the confirmed data identity (CDID) to identify whether low-priority confirmed messages are lost, preventing terminals from abnormally entering sleep mode. Through mathematical analysis and experimental testing, the performance of the AMFET method was theoretically and experimentally validated respectively. The validation results demonstrate that, compared with the original LoRaWAN multi-frame transmission scheme, the AMFET method effectively reduces data transmission delay and energy consumption while ensuring data transmission reliability.

Full Text

Preamble

Vol. 37 No. 5
Application Research of Computers (ChinaXiv Partner Journal)

An Adaptive Multi-Frame Efficient Transmission Method Based on LoRaWAN

Ren Zhi, Qin Jun†, Jiang Nan, Wang Kunlong
(School of Communication & Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China)

Abstract: The multi-frame transmission mode between LoRa gateways and LoRa terminals in the LoRaWAN (long range wide area network) protocol suffers from high control overhead and transmission delay. To address this issue, this paper proposes an adaptive multi-frame efficient transmission method (AMFET) that comprises three key mechanisms: an adaptive multi-frame sending mechanism, an adaptive multi-frame receiving confirmation mechanism, and a frame loss recognition mechanism. The adaptive multi-frame sending mechanism assigns priority levels to confirmed data messages, requiring immediate acknowledgment for high-priority messages while deferring acknowledgment for low-priority messages until the end of the adaptive sending mode. It also introduces the Fpending mechanism into LoRaWAN uplink multi-frame transmission. The adaptive multi-frame receiving confirmation mechanism employs bit vector compression technology to record received data frame information, enabling consolidated acknowledgment of multiple confirmed data messages in a single transmission. The frame loss recognition mechanism utilizes a confirmed data identity (CDID) to identify whether low-priority acknowledgment messages have been lost, preventing terminals from abnormally entering sleep mode. Through both mathematical analysis and experimental testing, the performance of the AMFET method is theoretically and empirically validated. Results demonstrate that compared to the original LoRaWAN multi-frame transmission scheme, AMFET effectively reduces data transmission delay and energy consumption while guaranteeing data transmission reliability.

Keywords: LoRaWAN protocol; Fpending mechanism; bit vector compression; adaptive multi-frame transmission; merged confirmation

Classification: TN915.06
DOI: 10.19734/j.issn.1001-3695.2018.11.0840

---

0 Introduction

Low Power Wide Area Network (LPWAN) is an IoT technology designed to address the long-range, low-power communication requirements of the Internet of Things. Its emergence has compensated for the limitations of traditional M2M technologies and wireless sensor network technologies, enabling widespread IoT applications and interconnectivity among IoT devices. LoRa technology, as a novel LPWAN wireless communication technology, employs linear spread spectrum modulation and achieves variable data rate transmission by adjusting orthogonal spreading factors, offering long-range, low-power, and anti-interference communication capabilities.

The LoRaWAN protocol, introduced by the LoRa Alliance, is an open-source MAC layer protocol standard for low-power wide area networks. It specifies the network topology, device roles, and transmission schemes for LoRa networks, representing a relatively complete and reliable MAC layer solution for LoRa networks to date. Based on different application requirements, LoRaWAN classifies terminal devices into three classes: A, B, and C. Class A is the default mode supported by LoRa terminals, where terminals initiate communication using ALOHA-based message transmission and immediately enter sleep mode after sending, resulting in the lowest power consumption. Class B mode synchronizes gateways and terminals through beacons, allowing terminals to open additional receive windows during scheduled intervals to improve downlink transmission efficiency. Class C mode operates on a simpler principle, with terminals continuously keeping receive windows open to reduce downlink transmission delay. Class A terminals can switch to Class B or Class C modes based on actual requirements. This paper focuses on the Class A transmission mode of LoRaWAN.

In Class A mode, the LoRaWAN protocol proposes an Fpending mechanism for multi-frame transmission between LoRa gateways and LoRa terminals. This mechanism marks the Fpending control bit as 1 (default is 0) in messages to instruct terminal devices to open additional receive windows for incoming data messages from the gateway. While this mechanism provides certain optimizations for multi-frame transmission, it suffers from relatively high control overhead and delay, resulting in low transmission efficiency.

1 LoRaWAN Multi-Frame Transmission and Problem Description

1.1 LoRaWAN Multi-Frame Transmission Principle

In LoRaWAN multi-frame transmission, as illustrated in [Figure 1: see original paper], the downlink employs the Fpending mechanism to trigger terminals to open additional receive windows via the Fpending control bit. In the uplink, after sending a message, the terminal either waits for two receive windows before transmitting the next message or immediately sends the next message upon receiving a downlink message. The multi-message transmission mechanism can be categorized into confirmed multi-message transmission and unconfirmed multi-message transmission from a reliability perspective, and into uplink multi-message transmission and downlink multi-message transmission from a link direction perspective.

When the gateway transmits downlink messages, if it has continuous data to send, it sets the Fpending bit to 1 and waits for the terminal' s response after sending the message. The terminal detects the preamble and receives the downlink message. If the message is a confirmed data message type, the terminal immediately sends an acknowledgment message, enters sleep mode, and then opens two receive windows. If the message is an unconfirmed data message type, the terminal immediately sends an empty message, enters sleep mode, and subsequently opens receive windows. After receiving the terminal' s response (acknowledgment or empty message), the gateway can choose to transmit the next message in either of the two receive windows.

During terminal uplink message transmission, messages are similarly divided into confirmed data messages and unconfirmed data messages. For confirmed data messages, the terminal enters sleep mode after sending data, then opens two receive windows to wait for acknowledgment. If an acknowledgment is received, the terminal immediately transmits the next message. If no acknowledgment is received in either receive window, the terminal retransmits the message after a timeout. For unconfirmed data messages, the terminal opens two receive windows after sending data. If a message from the gateway is received in either window, the terminal immediately switches to transmission mode for the next message; otherwise, it must wait until the end of the second receive window to transmit the next message.

1.2 Problem Description

Our research identifies several issues in the LoRaWAN protocol' s multi-frame transmission scheme:

a) In the uplink transmission scheme, terminals open two receive windows after each uplink message to receive potential downlink messages from the gateway. If the gateway has no downlink data to transmit, the terminal wastes time waiting for these two receive windows, reducing transmission efficiency and increasing both transmission delay and energy consumption.

b) In the downlink transmission scheme, when a terminal receives a message with Fpending bit set to 1, it must send an empty message to trigger the opening of its receive windows for subsequent gateway data. This transmission approach not only increases control overhead but also affects downlink data message transmission delay.

c) In the LoRaWAN transmission scheme, for multiple confirmed data messages, the gateway/terminal only sends the next data message after receiving an acknowledgment for the current one. However, in some application scenarios where data timing requirements are not strict, these messages do not require immediate acknowledgment. This wait-for-acknowledgment-before-sending mechanism increases overall data message transmission delay.

2 Adaptive Multi-Frame Efficient Transmission Method

To address these issues, this paper proposes an Adaptive Multi-Frame Efficient Transmission method (AMFET) based on LoRaWAN, comprising three mechanisms: adaptive multi-frame sending mechanism, adaptive multi-frame receiving confirmation mechanism, and frame loss recognition mechanism.

2.1 Adaptive Multi-Frame Sending Mechanism

The adaptive multi-frame sending mechanism aims to improve data message transmission efficiency at the sender and reduce transmission delay. Its main concept involves classifying sender data messages into high-priority confirmed messages, low-priority confirmed messages, and unconfirmed messages, thereby reducing response delay for high-priority confirmed messages. It also improves downlink multi-frame data message transmission efficiency through the Fpending mechanism, avoiding control overhead caused by the "empty message" trigger mechanism.

The mechanism operates as follows:
a) Based on the receiver' s response requirements, sender messages are classified into three types: high-priority confirmed data messages, low-priority confirmed data messages, and unconfirmed data messages. High-priority confirmed messages have strict timing requirements and must be acknowledged immediately upon receipt. Low-priority confirmed messages have relaxed timing requirements and do not need immediate acknowledgment; instead, they are acknowledged collectively after multiple message frames are sent, with a single acknowledgment frame responding to multiple message frames. Unconfirmed messages do not require acknowledgment during transmission.

b) The reserved bit (RFU) in the frame control field of the original uplink message header is repurposed for Fpending control, enabling uplink transmission to also use the Fpending mechanism to control multi-frame message transmission, as shown in [Figure 2: see original paper].

c) Three reserved bits in the original MAC header (MHDR) are used as the Confirmed Data Identity (CDID) field for the sender to mark the sequence number of confirmed data messages, as shown in [Figure 3: see original paper].

The specific steps of the adaptive multi-frame sending mechanism are:
a) When the sender (gateway/terminal) needs to transmit a data message, it detects the message type. For low-priority confirmed data messages, the pending message frame counter Cnt is incremented by 1. For high-priority confirmed or unconfirmed messages, the Cnt value remains unchanged.

b) The CDID value is set to the current pending message frame counter Cnt value, and the process continues to the next step.

c) The mechanism checks whether the message is a high-priority confirmed data message. If so, the Fpending bit is set to 0, the data message is sent, and the process proceeds to step 5. If it is a low-priority confirmed data message, the process proceeds to step d).

d) The mechanism checks whether there are data messages in the transmission buffer. If messages exist, the Fpending bit is set to 1, the data message is sent, and the process returns to step a). Otherwise, the Fpending bit is set to 0, the data message is sent, and the process proceeds to step e).

e) The adaptive multi-frame sending mechanism terminates.

2.2 Adaptive Multi-Frame Receiving Confirmation Mechanism

The adaptive multi-frame receiving confirmation mechanism aims to reduce the number of acknowledgment message frames and lower transmission control overhead. Its main concept involves storing data message reception status information using a bit vector pattern, then using a single acknowledgment message frame carrying this bit vector value to acknowledge multiple data messages at once.

The mechanism operates as follows: A Data Receiving Status Vector (DRSV) records the reception status of successfully received confirmed data message frames. Each bit position in the vector corresponds to the ID of a confirmed data message frame, where a value of 1 indicates successful receipt of the corresponding frame and 0 indicates non-receipt, with a default value of 0, as shown in [Figure 4: see original paper]. The Data Receiving Status Mapping (DRSM) stores reception status information for confirmed data messages and can represent the status of up to 8 confirmed data messages. Therefore, a single adaptive multi-frame sending process allows transmission of at most 8 confirmed data messages.

The specific steps of the adaptive multi-frame receiving confirmation mechanism are:
a) The receiver receives a data message and detects its type. For confirmed data messages, it extracts the CDID value from the message frame header (MHDR) and sets the corresponding element in DRSV to 1. For unconfirmed data messages, it directly passes them to the upper layer for processing.

b) The mechanism checks the Fpending bit value. If the value is 1, indicating the sender still has data messages to transmit, the receiver continues to open receive windows and returns to step a). If the value is 0, indicating no subsequent data messages, the process proceeds to step c).

c) The mechanism checks the DRSV value. If DRSV is 0, indicating no confirmed data messages were received, the node directly enters sleep mode or performs other operations after message reception completes, and proceeds to step e). Otherwise, it proceeds to step d).

d) The acknowledgment message frame’ s data receiving status mapping field is set to the DRSV value, and the ACK bit in the frame control field (FCtrl) is set to 1, then the acknowledgment message frame is sent.

e) The adaptive multi-frame receiving confirmation mechanism terminates.

2.3 Frame Loss Recognition Mechanism

The receiver only needs to record message frame reception status via the DRSV vector when receiving low-priority confirmed messages. If the DRSV value is 0, it indicates no low-priority confirmed messages were received. However, if all confirmed messages are lost during transmission while the DRSV value is also 0, the receiver determines that no acknowledgment message frame needs to be sent. If the receiver is a terminal, it will directly enter sleep mode, causing the sender (gateway) to remain in a perpetual waiting state for acknowledgment frames.

Therefore, we propose a frame loss recognition mechanism for low-priority confirmed messages based on CDID. The CDID field in message frames is used by the sender to mark the sequence number of the current confirmed data message being sent, with its value consistent with the sender’ s pending data message frame counter Cnt. After receiving a data message frame, the receiver can determine whether the sender transmitted confirmed data messages during transmission and how many such frames were sent by examining the CDID value. If the sender transmitted N low-priority confirmed data message frames and M high-priority confirmed messages, but all N low-priority confirmed message frames were lost during transmission, although the DRSV value would be 0, the CDID value in the last received message frame would not be 0. This confirms that the sender did transmit confirmed data messages, requiring the terminal to reply with an acknowledgment frame rather than immediately entering sleep mode, which would affect subsequent data message reception.

3 Mathematical Analysis of Algorithms

This section provides mathematical analysis of the energy consumption and time complexity of multi-frame transmission for the AMFET mechanism.

Lemma 1. The multi-frame transmission energy consumption of the AMFET mechanism is lower than that of the original LoRaWAN transmission mechanism.

Proof. Assume the gateway node sends a total of N_{unconf} unconfirmed messages and N_{conf} confirmed messages. Let E_{unconf}^L and E_{conf}^L represent the energy consumption for transmitting unconfirmed and confirmed messages under the LoRaWAN mechanism, respectively, while E_{unconf}^A and E_{conf}^A represent the corresponding energy consumption under the AMFET mechanism.

In the AMFET mechanism, a single transmission process can send at most 8 message frames. Therefore, the transmission of N message frames can be divided into k sending processes (where k is the integer division of N by 8), giving:

$$E^{A}_{unconf} = k \times (E_{st} + E_{tx} + E_{sleep} + E_{sr} + E_{rxnack}) \tag{1}$$
$$+ (N - 8k) \times (E_{tx} + E_{sleep} + E_{sr} + E_{rxnack}) \tag{1}$$

$$E^{A}_{conf} = k \times (E_{st} + E_{tx} + E_{sleep} + E_{sr} + E_{rxack}) \tag{2}$$
$$+ (N - 8k) \times (E_{tx} + E_{sleep} + E_{sr} + E_{rxack}) \tag{2}$$

where E_{st} represents the energy consumption for switching from sleep mode to transmission mode, E_{tx} represents transmission energy, E_{sleep} represents sleep energy, E_{sr} represents the energy for switching from sleep mode to reception mode, E_{rxnack} represents the energy for receiving unconfirmed messages, E_{rxack} represents the energy for receiving confirmed messages, and r represents the number of retransmissions.

For the original LoRaWAN mechanism:

$$E^{L}_{unconf} = N \times (E_{st} + E_{tx} + E_{sleep} + E_{sr} + E_{rxnack}) \tag{3}$$

$$E^{L}_{conf} = N \times (E_{st} + E_{tx} + E_{sleep} + E_{sr} + E_{rxack}) \times (r + 1) \tag{4}$$

From equations (1) and (3), we obtain:

$$E^{L}_{unconf} - E^{A}_{unconf} = (N - k) \times E_{st} > 0 \tag{5}$$

From equations (2) and (4), we obtain:

$$E^{L}_{conf} - E^{A}_{conf} = (N - k) \times E_{st} + N \times r \times E_{st} > 0 \tag{6}$$

Therefore, the AMFET mechanism achieves energy optimization compared to the original LoRaWAN transmission mechanism.

Lemma 2. The multi-frame transmission time of the AMFET mechanism is less than that of the original LoRaWAN transmission mechanism.

Proof. Let t represent the transmission time for a single message packet (with fixed packet length and transmission rate). Let T_{unconf}^L denote the duration for transmitting multiple unconfirmed message packets under the LoRaWAN mechanism, and T_{unconf}^A denote the corresponding duration under the AMFET mechanism. Then:

$$T^{L}_{unconf} = t_0 + t_1 + t_2 + t_3 + t_4 \times N \tag{7}$$

$$T^{A}_{unconf} = t_0 + t_1 + t_2 + t_3 + t_4 \times (N - k) \tag{8}$$

where t__0 represents mode switching time, t__1 represents transmission window duration, t__2 represents sleep window time, t__3 represents receive window time, and t__4 represents the sending process duration for N message packets.

From equation (8), we derive:

$$T^{L}_{unconf} - T^{A}_{unconf} = k \times t_3 > 0 \tag{9}$$

Therefore, the AMFET mechanism effectively reduces overall transmission duration in multi-frame transmission, indicating its time complexity is lower than that of the original LoRaWAN transmission mechanism. By similar reasoning, this also holds for multiple confirmed message transmission scenarios.

4 Experimental Testing and Analysis

4.1 Experimental Test Scenario and Platform

This experiment evaluates the performance of the proposed adaptive multi-frame efficient transmission method for LoRaWAN from three perspectives: transmission energy consumption, transmission delay, and transmission success rate. Data collection is based on the network topology shown in [Figure 5: see original paper].

The hardware for both terminal nodes and gateway nodes in the topology uses LoRa wireless development boards provided by RuiMi Communication Technology, primarily consisting of STM8L151C8T6 microcontrollers and SX1278 RF modules. All nodes in the network topology are connected to PCs via serial conversion cables during testing, with programs downloaded and debugged through ST-Link V2, and communication data frame reception monitored through serial debugging software. Gateway and terminal nodes in the topology communicate via LoRa wireless technology within single-hop range.

4.2 Transmission Energy Consumption Testing and Analysis

Based on the operating modes of the STM8L151 and SX1278 RF chips, the terminal node’ s entire communication process is divided into four parts: standby mode, transmission mode, reception mode, and sleep mode. This experiment measures the operating current values of nodes in different modes using a multimeter. Test results show average currents of 23.57 mA in standby mode, 84.37 mA in transmission mode, 33.87 mA in reception mode, and 10.24 A in sleep mode.

According to LoRaWAN protocol specifications, the duration of windows in each mode is shown in .

Table 1. Window Duration in Operating Modes

Mode	Duration
Receive Window 1 (with ACK)	1742.28 ms
Sleep Window 1	1495.08 ms
Receive Window 1 (without ACK)	1000.00 ms
≥	247.08 ms

Since the voltage remains constant (3.3 V) during testing, this experiment reflects terminal energy consumption by calculating charge quantity Q = I × t. The switching time from sleep mode to normal operation mode requires 240 s, and a complete message transmission process typically involves two switching operations.

Calculated results show: transmission energy consumption E_{tx} is 147 mC, sleep energy consumption E_{sleep} is 10.24 C, reception energy consumption for Receive Window 1 (without ACK message) is 8.37 mC, reception energy consumption for Receive Window 1 (with ACK message) is 50.6 mC, energy consumption for switching from sleep to transmission mode E_{st} is 10.1 C, and energy consumption for switching from sleep to reception mode E_{sr} is 4.1 C.

This experiment tests the total energy consumption for transmitting 100 confirmed data messages (Q_{ACK}*{MSG}) and 100 unconfirmed data messages (Q*{NACK}_{MSG}) under both LoRaWAN and AMFET mechanisms. Through experimental measurements and computational analysis, node energy consumption values are obtained as shown in .

Table 2. Node Energy Consumption Measurement Results

Message Type	Original Mechanism	AMFET	Energy Savings
NACK_{MSG}	15538 mC	14809 mC	11.6%
ACK_{MSG}	20228 mC	17885 mC	11.6%

The results indicate that AMFET saves energy during multi-message frame transmission compared to the original LoRaWAN mechanism, with more significant energy savings when transmitting confirmed data messages. This is primarily because AMFET uses bit vector compression technology to store reception status of multiple low-priority confirmed data messages, enabling consolidated acknowledgment of multiple confirmed messages and reducing the number of acknowledgment messages, thereby lowering transmission energy consumption. Additionally, AMFET optimizes the uplink multi-frame transmission scheme, preventing terminals from opening unnecessary receive windows and thus reducing energy consumption during the reception mode phase.

4.3 Transmission Delay Testing and Analysis

This experiment tests transmission delay for multiple unconfirmed data messages and multiple confirmed data messages (comprising both low-priority and high-priority confirmed messages). All message payloads consist of 50 bytes of data. Node operating parameters are configured as: spreading factor 12, bandwidth 125 kHz, coding rate 4/8, and transmission power 17 dBm. Test results for transmission delay in both scenarios are shown in [Figure 6: see original paper] and [Figure 7: see original paper].

As shown in the figures, AMFET reduces the total transmission time for both unconfirmed data messages (NACK_{MSG}) and confirmed data messages (ACK_{MSG}) during multi-frame transmission compared to the original LoRaWAN mechanism, thereby decreasing data transmission delay. This improvement primarily stems from introducing the Fpending mechanism into the LoRaWAN uplink multi-frame transmission scheme, optimizing the "empty message" triggered continuous downlink data transmission approach and enhancing downlink data message transmission efficiency.

In scenarios with multiple confirmed data messages, transmission delay increases compared to unconfirmed messages due to retransmission processes. AMFET classifies confirmed messages into high and low priority levels, enabling immediate acknowledgment for high-priority confirmed messages. Simultaneously, AMFET employs bit vector compression technology for consolidated acknowledgment of multiple low-priority confirmed messages, reducing the number of acknowledgment message frames. As the number of transmitted data message packets increases, the delay reduction effect of AMFET becomes more pronounced.

4.4 Transmission Success Rate Testing and Analysis

Data packet transmission success rate directly reflects the reliability of the AMFET mechanism. This experiment tests data message transmission success rates under different transmission distances and spreading factor conditions. Node operating parameters are configured as: spreading factor SF = 9, 11, 12, bandwidth 250 kHz, coding rate 4/8, and transmission power 17 dBm.

Test results for data packet transmission success rates under various conditions are shown in [Figure 8: see original paper] through [Figure 10: see original paper].

The results demonstrate that both transmission distance and spreading factor affect data packet transmission success rates. Under different spreading factor conditions, the maximum successful transmission distance varies, with larger spreading factors enabling greater maximum transmission distances. Moreover, under identical spreading factor and transmission distance conditions, the data packet transmission success rates of AMFET and the original LoRaWAN mechanism remain essentially consistent. This confirms that AMFET guarantees data message transmission reliability while reducing transmission energy consumption and delay.

5 Conclusion

This paper addresses the defects of high control overhead, delay, and energy consumption in the LoRaWAN multi-frame transmission mechanism by proposing an Adaptive Multi-Frame Efficient Transmission method (AMFET). The method comprises three mechanisms: an adaptive multi-frame sending mechanism that classifies confirmed data messages into high and low priority levels, enabling immediate acknowledgment for high-priority messages while introducing the Fpending mechanism into uplink multi-frame transmission to improve efficiency; an adaptive multi-frame receiving confirmation mechanism that employs bit vector compression technology for consolidated acknowledgment of multiple low-priority confirmed messages, reducing acknowledgment message count and control overhead; and a frame loss recognition mechanism that uses CDID values to determine whether the sender has transmitted low-priority confirmed messages, preventing terminals from entering sleep mode due to loss of such messages.

Through mathematical analysis and experimental testing, results demonstrate that the AMFET method reduces multi-frame transmission delay and energy consumption while guaranteeing data transmission reliability, thereby validating the effectiveness of the improved mechanism.

References

[1] Wu S, Kang S, Chakrabarti C, et al. Low power baseband processor for IoT terminals with long range wireless communications [C]//Proc of IEEE Global Conference on Signal and Information Processing. Piscataway, NJ: IEEE Press, 2016: 728-732.

[2] Ali A, Shah G A, Farooq M O, et al. Technologies and challenges in developing Machine-to-Machine applications: A survey [J]. Journal of Network and Computer Applications, 2017, 83: 124-139.

[3] Hu X, Yang L, Xiong W. A novel wireless sensor network frame for urban transportation [J]. IEEE Internet of Things Journal, 2015, 2(6): 534-543.

[4] Stan V A, Timnea R S, Gheorghiu R A. Overview of high reliable radio data infrastructures for public automation applications: LoRa networks [C]//Proc of International Conference on Electronics, Computers and Artificial Intelligence, 2017: 1-4.

[5] Lavric A, Popa V. LoRa™ wide-area networks from an internet of things

perspective [C]//Proc of International Conference on Electronics, Computers and Artificial Intelligence. 2017: 1-4.

[6] Martin B, Utz R, Thiemo V, et al. Do LoRa low-power wide-area networks scale [C]//Proc of ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. New York: ACM Press, 2016: 59-67.

[7] Sornin N, Luis M, Eirich T, et al. LoRaWAN specification v1.0.2 [EB/OL]. (2016) [2019-01-08]. https://www.lora-alliance.org/.

[8] Lavric A, Petrariu A I. LoRaWAN communication protocol: The new era of IoT [C]//Proc of International Conference on Development and Application Systems. 2018: 74-77.

[9] Sun M, Zhang N, Jin L, et al. Study on MAC layer protocol based on LoRa standard [J]. Television Technology, 2016, 40(10): 77-81.

[10] Abeele F, Haxhibeqiri J, Moerman I, et al. Scalability analysis of large-scale LoRaWAN networks in ns-3 [J]. IEEE Internet of Things Journal, 2017, 4: 6.

[11] Goursaud C, Mo Y. Random unslotted time-frequency ALOHA: theory and application to IoT UNB networks [C]//Proc of International Conference on Telecommunications. 2016.

[12] Lavric A, Popa V. Internet of things and LoRa™ low-power wide-area networks: A survey [C]//Proc of International Symposium on Signals, Circuits and Systems. 2017: 1-5.

[13] Centenaro M, Vangelista L. Boosting network capacity in LoRaWAN through time-power multiplexing [C]//Proc of the 29th IEEE Annual International Symposium on Personal, Indoor and Mobile Radio Communications. 2018: 1-6.

[14] Xiao S, Quan H, Zhong X. Design and implementation of remote meter reading system based on LoRa [J]. Electronic Technology Application, 2018, 44(6): 31-34, 38.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.