

LoRa-based Mesh Network for IoT Applications

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Abstract—In this paper, we study LoRa-based private networks for IoT applications. First, we consider the problems that may arise when LoRa devices are deployed in a private network with special operation scenarios (other than commercial networks) based on the standard LoRaWAN. We propose an improved LoRa protocol that can replace LoRaWAN. The proposed LoRa protocol overcomes the shortcomings of the existing LoRaWAN and can be effectively deployed in private networks of various applications. The proposed LoRa protocol employs mesh networking to improve the network coverage and a new multiple access scheme (other than Aloha) to reduce the data collision rate.

Index Terms—Internet of things, wireless sensor networks, mesh network, multiple access, low-power wide-area network (LPWAN), environmental monitoring system

I. INTRODUCTION

Since the terminology, Internet of things (IoT), was coined in the late '90s, IoT has evolved considerably and has had a significant impact on our daily life [1], [2]. Initially, IoT simply meant connecting things through the internet, similar to machine to machine (M2M) communication. Recently, it also refers to the value-chain created by connecting things, data, humans, and services. The fourth industrial revolution, which has become a huge trend in recent years, is based on cyber-physical systems (CPSs) [3]. A CPS is implemented through a deep connection between the real world and the virtual world through IoT. Thus, IoT is recognized as a key enabler of CPS.

Currently, various communication technologies applicable to IoT systems are competing to expand their influence. They can be grouped into three categories depending on the data rate and coverage. Bluetooth, Zigbee, and WiFi are widely employed standards for local area networks (LANs) and serve various applications for short-range communication [4]. A cellular network is suitable for high data rate applications. Low-power wide-area networks (LPWANs) offer low-power consumption and long-distance communication, though the supported data rate is relatively low [5]–[8].

LoRa was developed as an air interface technology for LPWANs [9]. LoRa often refers to a proprietary physical layer specification based on chirp spread spectrum (CSS). LoRa addresses many challenges in IoT use cases by employing CSS

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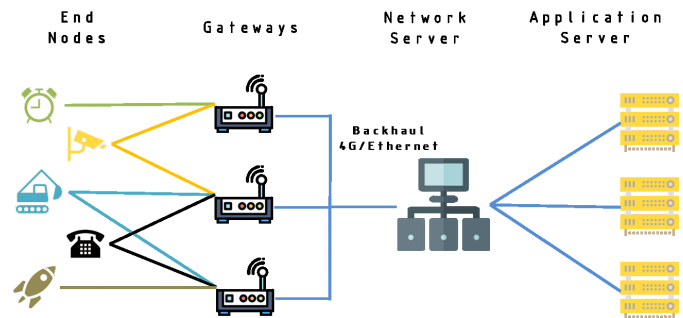


Fig. 1. LoRa network topology.

[10]. LoRa modulation provides scalability of the bandwidth and frequency. LoRa consumes less power owing to constant envelope of the CSS. Moreover, LoRa provides long-range communication with a higher link budget and high sensitivity of the receiver. In this paper, we study the problems that may arise when LoRa devices are deployed in a private network with special operation scenarios based on the standard LoRaWAN [11]. We propose an improved LoRa protocol that can replace LoRaWAN and overcome the shortcomings of the existing LoRaWAN.

The remainder of this paper is organized as follows. A brief review of LoRaWAN is given in Section II, and the development of a modified LoRa protocol is explained in Section III. The application cases of the proposed LoRa protocol are given in Section IV. Finally, discussions and concluding remarks are presented in Section V.

II. LORAWAN OVERVIEW

LoRaWAN is an open protocol stack proposed by LoRa Alliance and employed for public LoRa networks deployed by network operators [11]. It defines network topology and medium access control (MAC) on top of the LoRa physical layer. The three main components of the LoRaWAN network are LoRa end-nodes, gateways and a network server. Fig. 1 shows the LoRaWAN network topology [9], [11].

The LoRa end-nodes communicate with the gateways using the LoRa physical layer. The gateways are connected to a network server over IP-backhaul with a high throughput, such as Ethernet or a cellular network. The gateway relay packets transparently between the LoRa end-nodes and the network

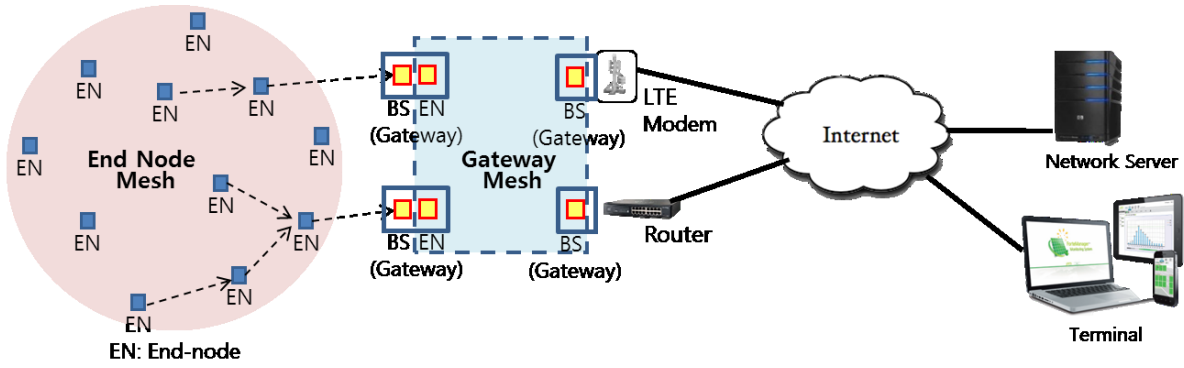


Fig. 2. LoRa mesh networking

server. Unlike a conventional cellular system, there is no initial gateway search procedure at the end-nodes, and each node is not associated with a specific gateway [9].

A packet from a particular node is delivered to the network server through multiple gateways. The network server decodes duplicate packets relayed from the multiple gateways and chooses the best reliable packet. If necessary, the network server sends back an acknowledgment to the end-node through the corresponding gateway. LoRaWAN uplink achieves diversity gain and hand over for mobile end-nodes implicitly [11].

The working scenario of LoRaWAN assumes the preliminary condition that there are enough well-planned gateways such that each node can reach one or multiple gateways in a single hop of LoRa communication. Optimal cell-planning may not be an issue for public networks run by network operators. However, for a temporarily run private ad-hoc network (e.g., in construction fields), the network deployment should be simple, reliable, and scalable. In fact, there are many use cases where private networks are preferred over public networks that require subscription and monthly fee for every node.

In the LoRaWAN topology, direct communication is not supported between the LoRa nodes. Any node-to-node communication must be through the network server via two-gateway transmission. In LoRaWAN, there is no multiple access scheme to prevent the collision between the packets coming from the end-nodes, whereas carrier-sense multiple access (CSMA) is employed in conventional wireless networks, such as 802.11, to mitigate the collision rate. The link capacity of LoRaWAN decreases to that of pure Aloha when a significant number of node transmissions occur simultaneously [12].

In summary, there are two problems when LoRaWAN is used to serve applications in a poorly cell-planned private network: 1) Presence of end-nodes that are disconnected from the network. 2) A high collision rate because of the interference among the end-nodes.

III. MODIFIED LORAWAN

To address the problems associated with standard LoRaWAN when employed in ad-hoc private networks, we

developed a modified LoRa protocol stack that supports mesh networking and time-division multiple-access. Because conventional network topologies, such as star-and-tree topologies, are well established, highly standardized and vendor-neutral, they are often used for public networks. Common standard and interoperability are not well-defined for mesh networks, which are often used for private networks with specific application scenarios [13].

A. LoRa Mesh Network in ISM Band

Fig. 2 shows the LoRa mesh network architecture. As there is no hierarchy in a mesh network, every node can relay a packet and cooperate with other nodes to efficiently route a packet to the gateways. Mesh networks dynamically connect end-nodes together and self-configure the routing paths [14].

In LPWAN-based IoT systems, the end-nodes are low-powered devices and need to operate for many years on a coin-cell battery. Therefore, the transmission power of the end-nodes is usually maintained lower than that of the gateways. In some countries, different maximum transmission powers are designated for uplink and downlink by regulation. This imbalance causes a problem in a real mesh network.

Generally, a mesh network can be self-configured using flooding algorithms. Flood-based networking can be summarized as follows [14]. First, a gateway broadcasts a beacon message. The end-nodes receive the message and relay it with a reception history. When the flooding process ends, most of the end-nodes would have received the beacon message several times either directly from the gateway or through other end-nodes. Thereafter, a mesh table is prepared for each end-node based on the reception history and received signal strength indication (RSSI) of the beacon message.

Fig. 3 shows the LoRa network with power imbalance [15]. The mesh network assumes a maximum of three hops, and the one-hop coverage of the gateway is up to the imbalance region denoted by the gray area. To initiate mesh networking, a gateway broadcasts a beacon. If a node is located outside the gateway coverage, it tries to connect with a neighboring node for uplink transmission. The end-node, indicated using a red circle, is within the coverage of the gateway and can receive the downlink beacon directly from the gateway. Accordingly,

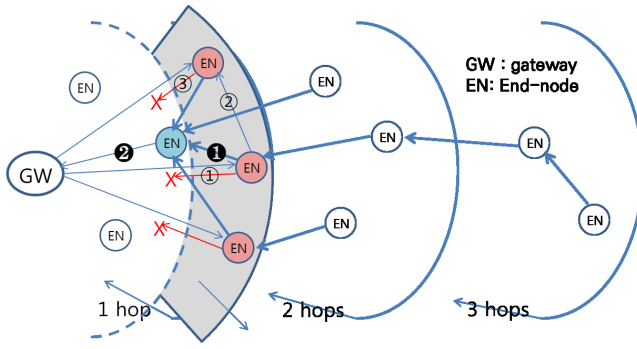


Fig. 3. Mesh networking with the imbalance in uplink and downlink transmission powers.

the gateway and neighboring end-nodes indicated using the other red circles are on top of its mesh table. However, an uplink packet transmitted by the end-node in the imbalance region can not be delivered to the gateway neither directly nor through the neighboring nodes indicated using the red circles. This imbalance may lead to a time-out or looping in the routing procedure when using the conventional flooding mesh algorithm.

To overcome the aforementioned issues, we remove the gateway and the neighboring end-nodes from the mesh table and place the end-node, indicated using a blue circle, on top of the mesh table in our modified LoRa protocol if the current end-node is in the imbalance region, as shown in Fig. 3.

Following are the characteristics of the proposed mesh network:

- There is no need for cell-planning with the gateways, and the end-nodes can be deployed in a relatively simple and flexible manner.
- The routing paths are established automatically among the end-nodes. If there is a failure in the existing routing path, re-routing is done in the network, and new paths are reconfigured.
- The network is optimized for low-rate communication at sub-GHz ISM bands.
- N:1 and 1:N bidirectional communications are possible.
- The network is suitable for smart metering, building energy management systems (EMSs), and safety monitoring in construction fields.

B. Time-slotted event-driven system (TEDS)

For systems that have many end nodes in less than one hop (direct coverage area) and need to collect event-driven data rather than polling, we developed a TEDS stack to reduce the data collision rate. This prevents the simultaneous increase in the load due to event processing signals and data corruption. In particular, it is suitable for water/gas remote metering systems that operate on a battery, simulated combat systems that require near real-time capabilities, and street light control that requires fast response of many nodes.

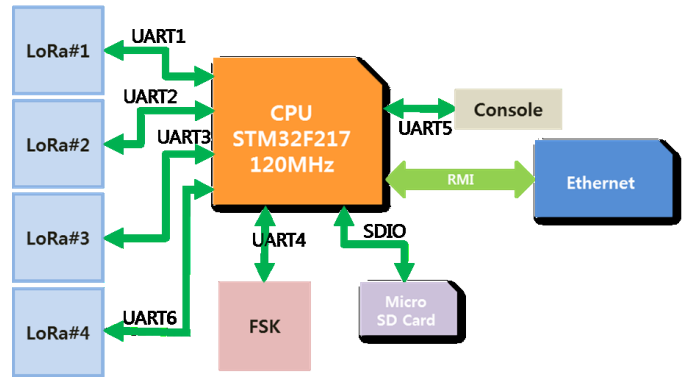


Fig. 4. The developed gateway supporting a LoRa mesh network.

C. Gateway development

We developed a gateway for the proposed LoRa protocol. Fig. 4 shows the system architecture of the gateway. Following are the advantages of the gateway:

- Applicable to most IoT operation scenarios
- Supports a maximum of four LoRa channels (end-node mesh network)
- Additional wireless backhaul with 38.4kbps frequency-shift keying (FSK)
- Ethernet (WAN connection)
- Indoor and outdoor use (waterproof / dust proof design)

IV. USE CASES OF THE MODIFIED LORAWAN

In this section, we present three use cases of the proposed LoRa protocol, which can be implemented in a private network.

A. Fire Pipe Freeze Monitoring System

Fig. 5 shows the deployment site. There are more than 600 fire-pipe temperature sensors in an area covering $2.3\text{km} \times 4.8\text{km}$. In an environment such as this, it was difficult to find sufficient sites for gateway installation. Because of the severe radio interference and channel variation, we reconfigured the routing path periodically. The proposed LoRa mesh network worked successfully.



Fig. 5. LoRa mesh network for freeze protection of fire water pipes in a big plant.

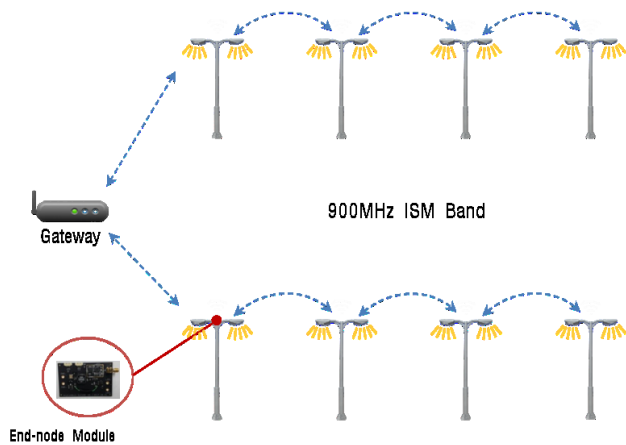


Fig. 6. LoRa mesh network for street light control.

B. Street light smart control system

Thousands of street lights were installed in a private network with a single gateway (hybrid TEDS and Mesh technology applied) as shown in Fig. 6. With this network structure, only one backhaul was necessary. There was no need for cellular subscription and telecommunication fees. As internet connection is not necessary for gateways, investments in network facilities and maintenance were not required. This self-network solution enables additional services such as water metering and emergency call processing implemented in private networks.

C. Toxic gas monitoring during big ship building

A safety management system is very important during ship construction. In this context, LoRa tags were attached to the harnesses of worker's in a ship construction site. The work paths and current job locations along with environmental air condition were monitored. In case of an emergency, the workers can press an emergency call button attached to the LoRa tag and it will be immediately notified to the control room. The network is designed to operate over six months without battery replacement. In this case, as the installation of internet facility for gateway backhaul is costly, LoRa mesh networking can be the best alternative. Fig. 7 shows the system development (LoRa tag, LoRa end-nodes, and gateways).

V. CONCLUSIONS AND DISCUSSION

In this paper, we analyzed LoRa-based private networks for IoT applications. Some problems were encountered when using standard LoRa in private networks with special working scenarios. Therefore, we proposed a modified LoRaWAN that supports mesh networking and TEDS. Mesh networking improves the coverage and makes network deployment easier. With the TEDS, the collision rate in the network systems was reduced. In the future, we plan to apply the proposed LoRaWAN to real networks and evaluate the performance from various perspectives.

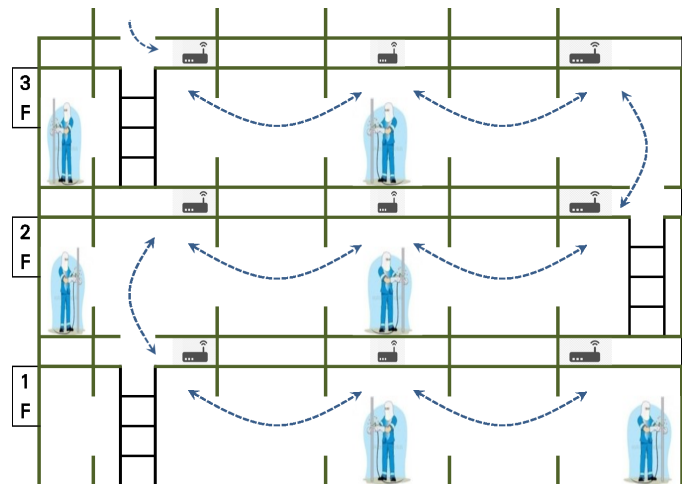


Fig. 7. LoRa mesh network for ambient air quality monitoring at shipbuilding sites

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