Mesh LoRa Node Design with Reactive Ad-Hoc Routing Protocol

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ABSTRACT

Currently, the Internet of Things (IoT) and Artificial Intelligence (AI) are influential technology fields that have a wide impact and hold an important position in the future. Contributing to the wide network of physical devices linked together, the long-range (LoRa) network control system has become very popular and widely applied in many fields. With low power consumption and transmission distance between 2 nodes up to 5km, LoRa is very suitable in IoT applications, smart home, or reading temperature, humidity, water level values, etc. in areas with difficult terrain and low energy consumption. However, the LoRa hardware architecture is only for point-to-point connectivity and does not support mesh multipoint connections. For this reason, this article presents hardware and algorithm development for LoRa that supports mesh architecture. Through the microprocessor, routing algorithms are embedded in the hardware to route packets through multiple intermediate nodes from the source node to the destination node. Data packet will automatically find the shortest path through the continuously updated routing table. Thereby, data is sent from the sensors to the Internet Gateway in the fastest way. Compared with the LoRa network, besides the advantage of extending the wireless transmission distance, mesh networking also helps to limit the rate of packet loss because the packet has many paths between the source node and the destination node.

KEYWORDS: IoT, LoRa, Reactive routing, AODV, packet loss.

1. Introduction

A long-range (LoRa) network is a type of wireless network that consumes little power and is capable of transmitting data over long distances. The LoRa network uses asynchronous communication technology and spread-spectrum communication algorithms to transmit data over long distances up to several kilometers, even in crowded inner-city environments. LoRa network operates in the Industrial, Scientific, and Medical (ISM) band without licensing and uses multiple channels to transmit data, allowing simultaneous connection of multiple devices. This makes LoRa suitable for Internet of Things (IoT) applications and applications that require long data transmission distances, low energy consumption, and low costs. One of the characteristics of LoRa is that the data transfer rate is quite slow, usually ranging from a few kbps to about 50kbps. However, data transmission over long distances up to several kilometers and low power consumption are significant advantages of the LoRa network. In addition, the LoRa network has security features to ensure the safety of data transmission. LoRa's data transmission protocols are encrypted to prevent hacking and unauthorized access (Falanji et al., 2023).

The LoRa network is an IoT networking solution that consumes less energy, is capable of transmitting data over long distances, and has high security. It has been widely used in many IoT applications and continues to be developed and researched to improve new features and applications (Kietzmann et al., 2022). In most current IoT system designs, to link and transmit information between two points A and B together, point-to-point connections currently focus mainly used to connect two endpoints directly via a single link. However, this network structure has the following disadvantages:

- The connection distance is not so far, making it more inconvenient and limited in data transmission.
- This structure has only one link, so when something goes wrong, that link will be interrupted and interrupt the connection in the system.

Because of the above disadvantages, we should replace the point-to-point structure in LoRa with a mesh network structure. The mesh structure in LoRa uses many endpoints and when one of the links fails, the mesh structure will route itself and follow another path. For this reason, two points A and B will always have a backup path, and ensure the link always exists.

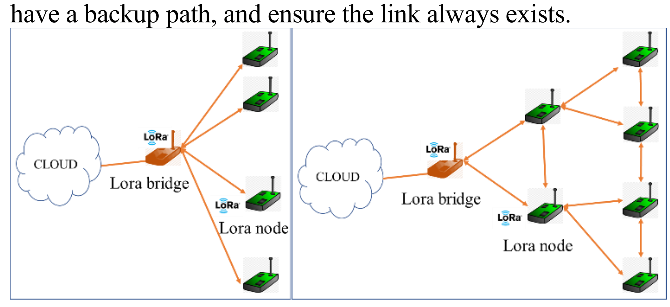


Figure 1. LoRa with a mesh network structure

LoRa Mesh is an extended version of the LoRaWAN network as shown in Figure 1, in which devices can not only communicate directly with the gateway but also have the ability to link together into a mesh network. LoRa Mesh provides network scalability, increased coverage, and improved reliability for LoRaWAN networks. In a LoRa Mesh network, devices can transmit data to each other, which allows the LoRaWAN network to act as a mesh system, increasing coverage and improving network reliability. Devices in a LoRa Mesh network can be configured to act as routing nodes, helping to optimize data transmission and increase network scalability. LoRa Mesh in ad hoc is a type of self-organizing wireless network, in which devices in the network automatically form and maintain connections with each other without the intervention of a control center (Cotrim et al., 2022, Nguyen et al., 2022).

In the LoRa Mesh network, each device is installed with a routing function; that is, the device is capable of relaying information between other devices in the network, helping to increase the scalability and reliability of the network. Each router in the LoRa Mesh network uses dynamic routing algorithms that automatically adjust to optimize transmission and minimize latency. The LoRa Mesh network also supports auto-networking, allowing new devices to automatically join the network without the need for manual configuration. This feature simplifies network deployment and management. The LoRa Mesh network is also designed to save energy, as devices in the network can go into a deep sleep and wake up automatically when there is data to transmit. This helps to increase the battery life of devices and reduce battery replacement costs. The LoRa Mesh network has many applications in various fields, including animal monitoring and management, monitoring and control of smart home devices, energy management in power grid systems, etc (Solar et al., 2022, Wu and Liebeherr, 2023).

The main objective of this article is to build a mesh structure for LoRa based on applying the AODV algorithm to the existing LoRa module, which is cheap and multi-application in control. The application of advanced technologies to control protocols to improve the quality and efficiency of network resource exploitation is essential and very important in the era when IoT technology is rapidly developing.

2. Literature Review

2.1 Low-cost Low-power Wireless Technology

A bell wave is a waveform in which the frequency increases or decreases over time, creating a bell-like appearance. In LoRaWAN, bell waves are used as a method to transmit data over wireless channels with long distances and low energy consumption. The bell waves in LoRaWAN are generated using the Chirp Spread Spectrum (CSS) technique. In CSS, bell waves are used to transform Radio Frequency (RF) signals to produce a special type of signal called a chirp signal. When a bell wave is emitted, the data signal is encoded into different bell waves to form a data sequence. During data transmission, bell waves are used to encode data and transmit it over RF channels. The bell wave in LoRaWAN can be customized to meet the requirements of different applications, including transmission frequency, length, and distance (Falanji et al., 2023).

When a bell wave is transmitted, the signal experiences environmental effects such as attenuation, distortion, and noise, resulting in a change in the signal's frequency. However, thanks to the characteristics of the bell wave, the signal can be decoded and reconstructed by suitable signal processing algorithms at the receiver. Bell waves are used in many communication applications, including radar, medical imaging, and wireless communications. Using bell waves in wireless communications has many advantages, including tolerance to interference, reduced signal loss, and increased detection of weak signals. In addition, bell waves can also be used to create a multi-path channel, enhancing communication in environments with many reflecting objects.

One advantage of the bell wave in LoRaWAN is its ability to transmit data over long distances with low energy consumption. This is especially useful in IoT applications where energy consumption is a critical factor. In addition, the bell wave is also resistant to interference, allowing LoRaWAN to transmit data in high-noise places such as cities with high accuracy, making LoRaWAN meet the requirements of demanding applications with high precision.

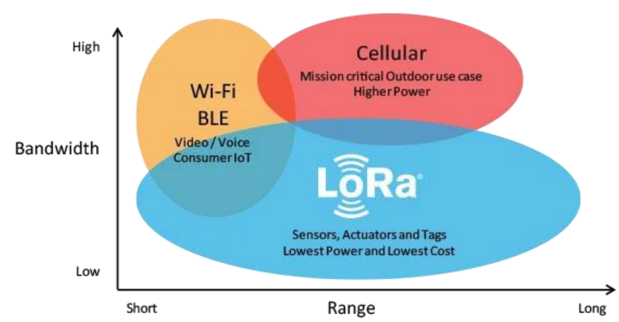


Figure 2. CSS in LoRa in comparing with other wireless technology of Bagur and Chung (2023)

As shown in Figure 2, the LoRa network uses a wireless communication method called CSS to transmit data. CSS is a wireless communication technique that allows for increased immunity to interference and reduces the impact of interference signals on transmitted waves. The signals emitted by the nodes will be encoded with CSS and then emitted as radio waves on the ISM band at 433MHz or 868MHz. Since these signals have a very narrow bandwidth (about 125kHz), they can effectively pass through obstacles such as walls or other obstructions. However, wave propagation in the LoRa network can also occur due to other factors such as antenna heights, topographical structures, and different densities of objects. In CSS, the data signal is encoded with a bell wave, increasing the signal's width compared to the original bell wave, and then divided into multiple blocks and distributed over multiple frequencies. The number of frequencies to allocate depends on the bandwidth of the bell wave and the resolution of the signal. Each frequency will carry a portion of the data, and all these frequencies will be combined to form the CSS signal. To transmit a CSS signal, the frequency of the signal is changed continuously in a specific order, called a frequency hopping sequence. This sequence is generated using a predefined algorithm and is divided into several segments. When transmitting a signal, the frequency of the signal will change continuously in the order in which the segments of the sequence change in frequency. With CSS, the signal is distributed over multiple frequencies and changes frequencies continuously, so the signal's tolerance to noise is greatly improved.

Table 1. Comparison of low-power wireless technology

Criteria	Chirp (CSS)	UWB	BLE	Wi-Fi
Location accuracy	1-2 m	+/- 40 cm	< 5 m	< 10 m
Range	Optimal: 10-500 m Max: 1000 m	Optimal: 0-50 m Max: 200 m	Optimal: 0-25 m Max: 100 m	Optimal: 0-50 m Max: 500m
Delay	< 1 ms	< 1 ms	3-5 s	3-5 s
Power Consumption	Very low, for portable batteries embedded in hardware options	Low, for portable batteries embedded in hardware options	Very low, for portable batteries embedded in hardware options	Medium
Cost	$	$$	$$	$$$
Frequency band	ISM: 2.4 GHz (2.4 – 2.4835)	3.1 - 10.6 GHz	2.4 GHz	2.4; 5 GHz
Data rate	Up to 2 Mbps	Up to 27 Mbps	Up to 2 Mbps	Up to 1 Gbps

In addition, frequency allocation and continuous frequency change also increase the security of the signal since it is difficult for others to decipher the signal without knowing the frequency shift sequence. CSS technology is used in many communication applications, including GPS navigation systems, LoRa networks, and IoT applications.

2.2 Common Ad-hoc Wireless Network Routing Protocols

Figure 3 shows an overview of classical routing protocols divided into three main groups: proactive, reactive and hybrid. Within the scope of this paper, we use the reactive group to design and experiment with the LoRa Mesh network.

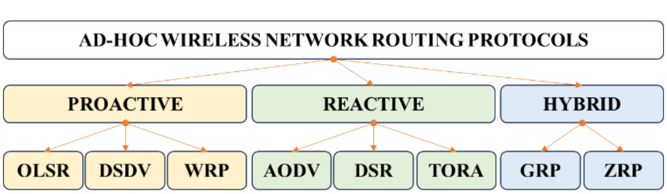


Figure 3. Classification of classical routing protocols

Dynamic Source Routing (DSR) is a simple and efficient routing protocol specifically designed for use in Multi-Hop Wireless ad hoc networks of wireless nodes. DSR can allow the network to self-configure, organize for itself, without the need for any other existing infrastructure or management. It is a reactive protocol and all components are fully on-demand. It works on source routing concept in which the Sender of a packet defines the complete sequence of nodes through which packets are forwarded.

Temporally Ordered Routing Algorithm (TORA) is a source initiated on the on-demand routing protocol. TORA is a highly adaptive, efficient, loopless and scalable routing protocol based on a link reversal algorithm. The main goal of TORA is to limit message transmission in highly dynamic mobile computing environments. It means, it is designed to reduce communication costs by adjusting to local topology changes in the ad hoc network. Another key feature of the TORA routing protocol is the localization of control packets to a small area (set of nodes) near the occurrence of topology changes due to route breaks. Thus, each node of the requesting network contains its local topology and routing information about the adjacent nodes. TORA supports multiple routes for packet transmission between the source and destination nodes of the mobile ad hoc network. In short, TORA represents multipath routing capabilities. TORA's operation can be compared to that of water flowing downhill towards a sink node through a network of pipes that model routes in a real-world network. Pipe joints represent nodes, pipes themselves represent route links between nodes, pipe water represents packets flowing between nodes through route links to destination.

Ad-hoc On-demand Distance Vector (AODV) is a routing protocol designed for wireless networks and ad hoc mobile phones. This protocol establishes routes to locations on demand and supports both unicast and multicast. It is designed to work efficiently in networks with a large number of nodes that are unevenly distributed.

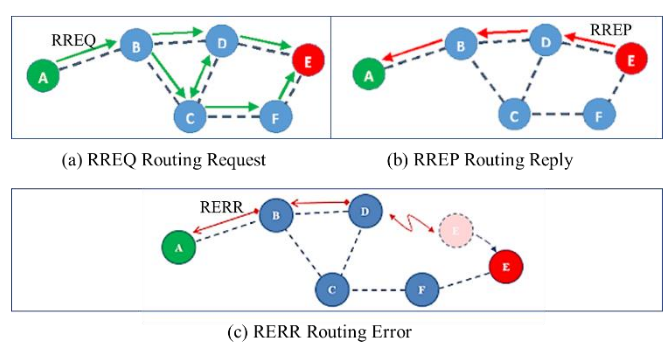


Figure 4. Example of AODV algorithm

As shown in Figure 4, AODV uses an on-demand mechanism to find routes between nodes in the network. This means that when a node needs to send a packet to another node, it will ask for a route to that node. In Figure 4(a), AODV will send a Route Request (RREQ) message to neighboring nodes to find the route to the destination node. If the neighboring node already knows the route to the destination node or knows another node that has the route information to the destination node, it sends back a Route Reply (RREP) message to the requesting node as shown in Figure 4(b). The requesting node will use the path found to send the packet. If the path is broken or no longer usable, AODV will update the routing table to find a new route (Perkins et al., 2003, Hong et al., 2022).

In Figure 4(c), when the source node fails to send the packet to the destination node, it sends a Route Error (RERR) message back to the source node. The RERR message includes the address of the unreachable destination node and some other information such as the node's current routing sequence number. The RERR message can also be used to notify other nodes that a path has been lost or is no longer valid. The RERR message is retransmitted from the source node to the node causing the problem to re-update the routing table of the nodes in the network. Nodes that receive the RERR message will delete the routing record associated with the lost destination node from their routing table. The use of RERR messages helps nodes in the network to update routing information accurately and timely, thereby minimizing the situation of packets being lost or corrupted during transmission in the Ad-hoc network.

Thus, in the reactive algorithms presented above, the AODV algorithm is the most suitable when applied to the LoRa Mesh network model. Advantages as well as features of AODV include:

- Save bandwidth: AODV uses an on-demand mechanism to find the route only when there is a request node to send the packet to find the route.
- Capable of responding to networks with a large number of nodes and an uneven distribution.
- Capable of self-healing when the network is changed by deleting unusable paths and finding new ones.
- Capable of supporting multipath to reduce load and increase transmission efficiency.
- Capable of supporting high reliability and low latency.

The main components of the AODV algorithm include:

- Node: These are devices in the MANET network, such as laptops, mobile phones, or mobile routers. Each node will need to implement the AODV algorithm to perform routing.
- Route Request (RREQ): This is a message sent from the source node to request a route to the destination node. If a node does not know the path to the destination node, it broadcasts the RREQ to all its neighbors.
- Route Reply (RREP): When a node receives a RREQ, if it knows the route to the destination node, it will send the RREP back to the source node through its neighbors. Otherwise, it will forward the RREQ to its neighboring nodes.
- Route error (RERR): When a node cannot send a packet to the destination node, it sends a RERR message back to the source node.
- Routing Table (RT): The routing table stores information about neighboring nodes and the path to them.
- Sequence Number: Each node in the network has a unique sequence number to ensure the consistency of messages sent.
- Hop Count (HC): This is the number of intermediate nodes that need to be passed through to reach the destination node. Each time the RREP is forwarded, the hop count value will be updated.
- Active Route Timeout (ART): The time between updates to a node's routing table.
- Hello Message (HM): This is a message sent periodically between nodes to maintain network connectivity. If a node does not receive a hello message within the specified time, it considers that node to have lost its connection and removes it from its routing table.
- Destination Sequence Number (DSN): The sequence number assigned to the destination node, updated each time a RREQ is sent to the destination node.

3. Hardware and Software Design

3.1 Layer structure of the mesh LoRa node

Similar to TCP/IP, the system is built on four layers including physical, datalink, network, application as shown in Figure 5.

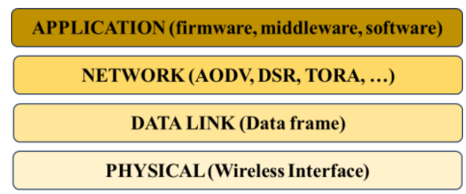


Figure 5. Layer structure of the mesh LoRa node

The physical layer defines the means of transmitting bits over the physical data link connecting the network nodes. The bitstream can be grouped into code words or symbols and converted into a physical signal to be transmitted over the transmission medium. The physical layer provides the electrical, mechanical, and procedural interfaces to the transmission medium. The shape and properties of the electrical connectors, the frequency to play on, the line code to use, and similar low-level parameters, are specified by the physical layer.

The datalink layer transfers data between nodes on a network segment on the physical layer. The data link layer provides the functional and procedural means for transferring data between network entities and can provide the means to detect and possibly correct errors that may occur in the physical layer.

The network layer is responsible for packet forwarding including routing through intermediate routers. Common application layer services provide semantic transitions between related application processes.

The application layer communicates directly with application processes and performs their usual services. This is an abstraction layer service that hides the rest of the application from transmission. The application layer relies on all the layers below it to complete its process. In this layer, the data or application is presented in a visual form that can be understood by the user.

3.2 Hardware Design

Each node uses the Arduino Nano as the main microcontroller as shown in Figure 6. The Arduino Nano is equipped with the ATmega328P microcontroller, just like the Arduino UNO. The power block uses an 18650 battery with a voltage of 3.7 volts connected to the charging circuit and the boost circuit from 3.7 volts to 5 volts to power the whole system, with the display using a 16x2 LCD screen and I2C connected to the Arduino by SDA and SCL pins. Using the LoRa E32 Module to communicate via UART with Arduino via TX and RX pins that connect to the computer uses the Arduino's dedicated cable to the computer's USB-A port (Pham et al., 2021, Pino et al., 2022).

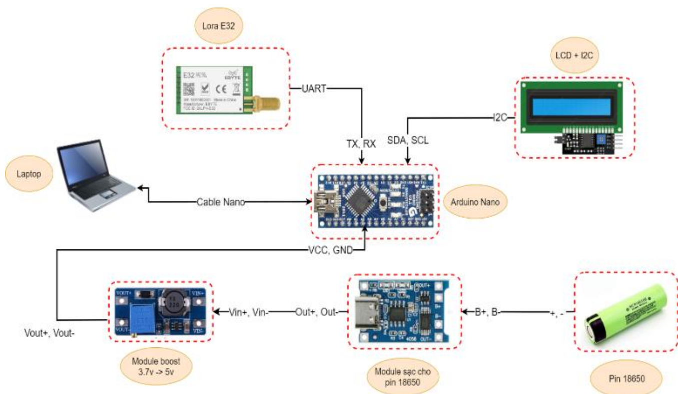
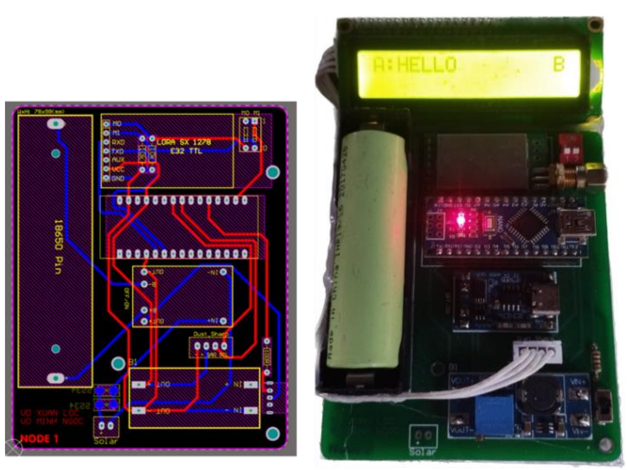


Figure 6. Block diagram of the mesh LoRa node

The LoRa SX1278 433MHz module is a wireless communication module that uses LoRa (Long Range) technology to transmit data over long distances to save power. This module is based on the SX1278 chip from Semtech Corporation and operates in the 433MHz frequency band. It provides a reliable communication link, suitable for applications such as IoT, smart cities, agriculture, and environmental monitoring. This module usually includes an integrated antenna and a microcontroller to control the LoRa chip and connect it to other devices such as sensors, microcontrollers, and computers. It can communicate with other LoRa modules or gateways connected to the internet, allowing it to send and receive data over long distances and save power. Figure 7 shows our complete hardware configuration of a mesh LoRa node with compact dimensions of 7cm wide and 12cm long.



(a) Printed Circuit Board layout (b) LoRa node hardward

Figure 7. A complete structure of the mesh LoRa node

3.3 Software Design

Window Form is part of the Microsoft.NET Framework and is used to develop desktop applications on the Windows operating system. Window Form provides a graphical interface that allows users to interact with components on the application interface. With Window Forms, we can design the interface of our application using components such as text boxes, buttons, lists, windows, and other graphical controls. These components can be dragged and dropped on the interface to create easy-to-use sections with an intuitive interface. In addition, Window Form also allows the integration of data from a variety of sources, including databases and web services. Developers can use Window Form components to access and process this data and display the results on the application's interface.

4. Experiment Results

We test the transmission and reception capabilities of the nodes. For each test transmission distance, we send 20 packets at the transmitter and count the number of packets successfully received at the receiver. The performance results are displayed on the Winform interface as shown in Figure 8. The figure shows result of sending packets successfully or failure between multiple mesh LoRa nodes. In particular, in the case of close transmission distance (*e.g.* 10 meters), there are some corrupted packets that cannot be sent due to interference. After performing many tests runs with a number of different terrain cases, we have compiled the results in the Figure 9.

In transmission distances less than 10m, mesh structure does not respond as well as point-to-point because mesh requires many packets to form routing table. This leads to more bandwidth being occupied and interference between nodes close to each other also increases. When the transmission distance is over 20m, mesh architecture has shown advantages over point-to-point. The first advantage is the higher number of successfully transmitted packets and the second is the double transmission distance.

Figure 9 also help readers visually compare the two transmission modes: direct and mesh. We find that, with the help of middle node, the mesh structure increases the transmission distance by 2 times while still ensuring the same number of successful packets as point-to-point.

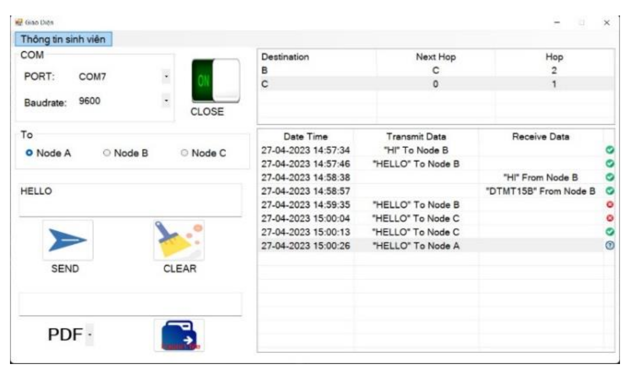


Figure 8. Results of sending packets between mesh LoRa nodes

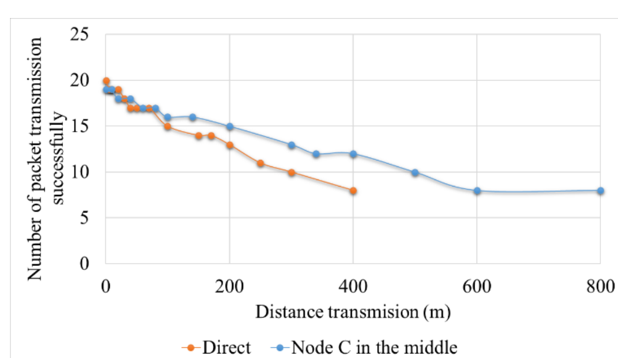


Figure 9. Number of packet transmission successfully vs. distance

5. Conclusions

We have presented our mesh LoRa node hardware embedded by AODV routing protocol with energy-saving capabilities, flexibility in automatically identifying the best communication pathway for data transmission along with enhanced performance and providing low latency, high data transfer speeds. From our results, it is very suitable for applications in IoT models, smart homes, homestay. AODV protocol is used to route data in the IoT network, allowing IoT devices to communicate and exchange data effectively with each other. When there is data to be transmitted, devices use AODV to find the most optimal pathway to transfer data from source to destination node.

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