Research on the Application Value of Wireless Mesh Network in Power Equipment of the UPIOT

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Abstract. In this paper, an advanced wireless network called WMN was researched for the construction of UPIOT, especially from the perspective of power equipment. By introducing the fundamentals and analyzing the advantages of WMN, it proved that the WMN should have great application value in the communication system in Power Equipment of the UPIOT. By comparing ZigBee mesh and BLE mesh, it indicated that the WMN can be built by different technologies in relative application scenarios. By proposing a design of architecture with the application of WMN, it provided an innovative idea to construct the Power Equipment of the UPIOT and some theoretical supports for the subsequent research of the Ubiquitous Power Internet of Things.

1. Introduction

Ubiquitous power Internet of things (UPIOT), proposed by State Grid Corporation in 2019, aims to realize the interconnections of all the components in power industry [1]. In an effective way of sharing data, UPIOT will open up a new road to guarantee the security of power grid. Especially for the power equipment, UPIOT could replace the traditional methods of inspection and maintenance.

At present, the live detection usually with portable testing equipment is the dominant method applied in the inspection of power equipment. This method can judge the conditions of power equipment by executing on-site detection for them in running state without cutting off the electricity. However, it cannot totally prevent the crash of equipment due to the detection only lasting a short period of time [2]. Therefore, continuous online monitoring in long term should have been an alternative more reliable to the power equipment. Unfortunately, its development is still encountering some limitations such as the short lifespan of monitoring devices and the heavy load of real-time data transmission and operation [3]. Instead, the Power Equipment of UPIOT could perfectly overcome these difficulties by truly achieving the overall perception and data sharing, it will thus change the above current situation of power equipment inspection and maintenance [4].

In order to possess the above advantages, the architecture of Power Equipment of UPIOT can be divided into four levels: perceptual layer, network layer, platform layer and application layer [5]. The perceptual layer is on the side of power equipment, composed of different sensors, edge computing devices and local communication network, which is used to collect and process the information of equipment state. The network layer is the bridge to link the perceptual layer and the platform layer. The platform layer is responsible for the efficient processing of ultra-large-scale data and unified management of cloud information, which enables the real-time feedback of power equipment status to the application layer based on some warning devices on the side of users. In such architecture, the
communication network plays an important role in data transmission because it performs not only as a part of perceptual layer but also as the core connection to the network layer.

There exist various structures in both local and remote communication network. This paper introduces a multi-hop network structure called Wireless Mesh Network (WMN), compares the performances of ZigBee mesh or BLE (Bluetooth Low Energy) mesh technologies, analyses the practicability of two technologies in different scenarios according to the detailed demands, and finally proposes a design approach of wireless communication system in Power Equipment of UPIOT.

2. Wireless Mesh Network

2.1 Topology structure and fundamental

![Basic mesh topology](image)

![WMN structure](image)

Figure 1. Topology structure of WMN

Figure 1(b) shows the topology structure of WMN. Different from the traditional network mainly adopting star structure, ring structure, bus structure, distributed structure or tree structure which belongs to point-to-point or point-to-multipoint topology, WMN adopts multi-point to multi-point network topology structure shown as figure 1(a). In a WMN, all nodes are interconnected in a wireless multi-hop manner [6]. Each node can serve as an AP (access point), and can also have routing and information forwarding functions [7], so each node can communicate directly with one or more peer nodes. This feature provides not only extremely high degrees of freedom for constructing the network but also multiple redundant communication paths from source to destination. Consequently, even if a path stops working due to hardware failure or interference, the WMN will automatically seek an alternate path to enable the packets to reach the destination.
2.2 Advantages

WMN has been already applied in the mine emergency rescue communication system [8], logistics information transmission platform [9] and the real-time monitoring system in construction site [10] because of its large amount of advantages over traditional Wireless Local Area Networks (WLANs). Inspired by these applications, it is reasonable to consider that WMN should also satisfy the particular demands of Power Equipment of UPIOT thanks to the following features.

2.2.1. Large coverage. In the traditional network, only the central node connecting to the AP can send data, and the data transmission is effective only within the coverage of central node. However, each node of WMN can send and receive data [6], which indicates an expansion of the network coverage to some extent. In theory, the more nodes join the network, the larger the network coverage is, and the longer the distance from which the data can be transmitted.

Based on this feature, WMN has great application value in the wireless communication system of the Power Equipment of UPIOT because it enables the distributed sensors in a large area to transmit collected data to the edge computing devices or data processing platform in the distance.

2.2.2. Flexible structure. As any two nodes interconnect in a wireless manner [7], WMN has a flexible structure which provides large freedom to constructing the network. Besides, thanks to the wireless transmission, most devices only need one power cord without any network cable and AP connection. It thus facilitates the installation of new devices and reorganization of network after a new node is added into the previous network.

For the Power Equipment of UPIOT, the dynamic feature of WMN makes it easy to install new sensors at the ageing parts of power equipment without disturbing the original network.

2.2.3. Low power consumption. As a multi-hop network, WMN realizes the data transmission by a series of short hops instead of a single long hop. The power consumed by the short hop is much lower, and some nodes can be in sleep mode at most of time, which saves the energy needed by the devices to a great extent [7].

This characteristic of WMN helps prolonging the lifespan of the devices, which promotes an online monitoring on the power equipment for the period of time much longer in UPIOT.

2.2.4. Reliability of data transmission. The WMN provides greater redundancy and communication load balancing mechanism [6]. Each device has multiple available transmission paths, and the network can dynamically allocate routes according to the communication load condition of each node, thereby effectively avoiding communication congestion and the interferences caused by long-distance transmission as well as guaranteeing the success of transmitting data to the destination even facing a breakdown of some device.

There is a fact that the signals collected by sensors are easily disturbed by many factors such as the on-site environment [3]. For example, the GIS ultrasonic partial discharge signals may be affected by the corona interference and magneto-noise outside the equipment. If the signals are further being lost or influenced by the communication network, it will become no longer valid to extract the features indicating the power equipment status, thus losing the analysis value. As a result, WMN that has a considerable reliability of data transmission should appeal to the Power Equipment of UPIOT.

3. Specific technologies for building the WMN

3.1 ZigBee mesh network

ZigBee is a technology based on the universal IEEE 802.15.4 standard, aiming to address the need for a cost-effective and standards-based wireless networking solution that supports low data-rates, low-power consumption, security, and reliability. ZigBee network could be formed with the star structure,
tree structure and mesh structure [11]. This paper discusses ZigBee mesh network through which each module can communicate with each other.

A typical ZigBee mesh network consists of a coordinator and multiple routers and end device nodes [11], as shown in figure 2. The three logical device types play the different roles in the network, which are introduced as below:

1) Coordinator: As the unique centre device indispensable to a ZigBee mesh network, the coordinator is responsible for creating the network and managing security of the network. However, the coordinator can only start the network and allow other devices to join the network, but without network joining capabilities.

2) Router: The routers perform as the bridges assisting its child end devices with communication by multi-hop routing. In general, routers are expected to be active all the time and thus have to be mains-powered.

3) End device: An end device has no specific responsibility for maintaining the network infrastructure. As the device directly related to the sensors for the power equipment, its installation is more dependent on the actual needs of application scenario. Therefore, the end device can be a battery-powered node which can sleep and wake up as it chooses.

![Figure 2. Structure of typical ZigBee mesh network](image)

3.2 BLE mesh network

The traditional Bluetooth technology mainly adopts the star structure, only supporting one-to-one or one-to-many data transmission by pairing or broadcasting, as shown in (a) and (b) of figure 3. One master can only be connected to eight slaves at most [12]. However, Bluetooth SIG (Special Interest Group) announced in 2017 that Bluetooth fully supports the mesh network and built the specific BLE mesh protocol which is compatible with the BLE 4.0 stack and the upper version. Consequently, the new technology, BLE mesh, also supports many-to-many data transmission, thus improving the network coverage.
In the typical structure of BLE mesh network, as shown in figure 3(c), there are four main types of nodes usually used, which are introduced as below:

1) **End node:** The end node is similar to the end device at the edge of the network, without the relay function.

2) **Relay node:** The relay node is similar to the router. After receiving the data packets sent by other nodes, it determines whether it needs to be forwarded according to the setting conditions of the network.

3) **Low power node:** The low power node periodically queries its friend node for data to arrive instead of always sending or listening to data packets on the broadcast channel, which can save power.

4) **Friend node:** As the proxy node of low power node, the friend node can cache the data, waiting for the low power node to query.

Besides the nodes, the connections also have different types, which are introduced as below:

1) **ADV (Not Relayed):** Two end nodes can send and receive broadcast messages to each other, but because they are not relay nodes, they cannot relay data packets.

2) **ADV (Low power):** This connection is used to send and receive data packets between the low power node and the friend node. The low power node will initiate a request to establish a friendship connection, and query the friend node for its own data.

3) **ADV Bearer:** Broadcast messages can be sent and received between the two nodes based on the advertising bearer, and can be forwarded as a relay.

4) **GATT Bearer:** For nodes without ADV bearer capability, it can also participate in the mesh network by sending and receive proxy PDUs (Protocol Data Units) on the GATT connection with other nodes through a proxy protocol.

3.3 **Contrast and relative application scenario**

3.3.1. **Common Features.** 1) Frequency band: Both ZigBee and BLE mesh networks support the global common frequency band which is 2.4GHz, so there should be no obstacle to the UPIOT in China.

2) Unlimited expansion of transmission distance: The standard distance between each ZigBee network node is from 10m to 75m while the transmission distance of the BLE 5.0 can reach up to 300m which is 4 times that of BLE 4.2. However, both two networks can be joined by up to 65536 nodes in theory, which leads to a theoretically unlimited expansion of the overall transmission distance.
Therefore, the transmission distance is less affected by the technology, but more dependent on the actual coverage of mesh network.

3) Gateway supporting: A mesh gateway is a node that is able to translate messages between the mesh network and another technology [7]. Both ZigBee and BLE mesh networks support the gateway through which their connections to other networks could be realized. Consequently, both two networks can break the bounds of the single sensor layer or network layer by providing the exchange port, thus improving the compatibility of all components in UPIOT.

3.3.2. Different Features. The ZigBee and BLE mesh networks have several typical differences as below:

1) Transmission rate: The low transmission rate is a typical feature of ZigBee technology. It varies from 20kbps to 250kbps with the different frequencies. For the global common band 2.4GHz, the transmission rate is 250kbps. However, BLE mesh has a high transmission rate because it absorbs the advantage of BLE technology. The newest BLE 5.0 stack enhances the maximum of transmission rate from 1Mbps of previous BLE 4.2 to 2Mbps.

2) Latency: According to the test executed by Silicon Laboratories, as shown in Table 1, the latency of both ZigBee and BLE mesh network becomes longer as the number of hops or the payload size increases. However, the increment of BLE mesh is larger than that of ZigBee, and the BLE mesh network has a longer latency than ZigBee mesh network in general for the same payload.

| Table 1. Contrast of latencies for the 4-hops mesh networks |
|-------------------------------------------------------------|
|                  | 10 bytes | 30 bytes | 50 bytes | 100 bytes | 150 bytes |
| **ZigBee mesh**  | ~50ms    | ~70ms    | ~90ms    | ~120ms    | ~150ms    |
| **BLE mesh**     | ~80ms    | ~210ms   | ~350ms   | ~640ms    | ~940ms    |

3) Power consumption: Take two SoCs (System-on-a-chips) representative for ZigBee and BLE mesh technology as the example, the datasheets about the power consumption are listed in Table 2.

| Table 2. Contrast of power consumption datasheets |
|--------------------------------------------------|
| SoC                  |  |  |  |  |  |
| **ZigBee mesh**     | CC2652R | 7.5mA | 6.83mA | 0.92μA | 125nA |
| **BLE mesh**        | STM32WB55 | 5.5mA | 3.8mA | 1.8μA | <50nA |

Tx means the power consumption of transmitting data while Rx means that of receiving data. In standby mode, RTC (real time clock) runs while RAM/CPU holds. In shutdown mode, the SoC keeps sleep status and wakes up when an external event occurs. By contrast, the single SoC for BLE mesh has lower power consumption in general. Nevertheless, the power consumption of the whole mesh network will be affected by many other factors.

On one hand, for the ZigBee mesh network, only the end devices can stay in sleep mode while the core nodes, routers, should keep active all the time, thus increasing the power consumption of whole network [11]. On the other hand, BLE mesh is currently based on the flooding protocol rather than routing protocol [12]. The flooding protocol is a relatively primitive mesh network technology which send and forward the data packets in the form of broadcasts. Therefore, a large number of repeatedly transmitted data packets are generated in the network, which also has a negative impact on the overall power consumption of the network. Consequently, the overall power consumption relies on the actual network structure and coverage.

4) Application scenario: The flooding protocol currently adopted by BLE mesh is only suitable for networks with relatively small scales, and is not suitable for application scenarios with a huge quantity of data. When the payload is small, ZigBee and BLE mesh behave similarly in small networks. When the payload increases, ZigBee obviously outperforms BLE mesh. When using short messages, especially for multicast messages, BLE mesh has the best performance. Besides, ZigBee is suitable for the application without strict transmission rate requirements. BLE mesh could be an alternative when
the ZigBee cannot satisfy the specific demand of high transmission rate for some application. Furthermore, compared with BLE mesh, a new technology proposed in 2017, ZigBee is far more mature after a decade of development, which decreases the difficulty of building the network. In actual application, the appropriate technology should be selected in comprehensive consideration of the monitoring needs of the power equipment and the comparison of the above various factors affecting the performances of mesh network.

4. Design of Power Equipment of UPIOT with WMN
After researching the fundamentals and practicability of WMN, this paper designs a construction structure of Power Equipment of UPIOT by using the WMN as the communication system. The architecture is shown in figure 4.

![Figure 4](image)

**Figure 4.** The designed architecture of the Power Equipment of UPIOT

The WMN performs as the communication system which serves the transmission of the data collected by distributed sensors to the edge computing devices and the connection between the perceptual layer and the network layer. By the mesh gateway, WMN can access to other networks such as the Internet and satellite network. As a result, it integrates the on-site monitoring devices for the power equipment and the information management cloud platform at backstage, thus realizing the ubiquitous internet of things. The status of power equipment can be monitored all the time, and the information will pass through sensors, WMN (edge computing devices may be included), other networks, the cloud platform or others, and finally reach the application with the specific service such as alarming the technician to inspect the power equipment when some unhealthy signals are detected.

5. Conclusion
This paper researched the fundamentals and features of the WMN to prove that it has the great application value in Power Equipment of UPIOT. After analysing of the detailed ZigBee and BLE mesh, it can be inferred that the WMN can meet different power equipment monitoring demands by selecting the appropriate technology. It can achieve the overall perception in space by communicating with the large quantity of distributed sensors, and realize the long-term monitoring by the efficient real-time transmission to the edge computing nodes. Consequently, the application of WMN in Power Equipment of UPIOT has the probability to overcome the shortcomings that the current online monitoring usually misses alarming when the problem occurs or alarms by error when the power equipment is in healthy condition. Besides, WMN can easily access to other networks such as the
Internet by the mesh gateway, thus promoting the integration of the components in UPIOT. The architecture proposed in this paper provides a construction idea of Power Equipment of UPIOT by applying the WMN.

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