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Research on Low Power Methods for Wireless Devices in Intelligent Industrial Communication Systems

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Abstract

Industrial communication devices achieve low power consumption and high efficiency in WirelessHART networks through hardware and software optimization. Hardware advancements include advanced manufacturing processes, highly integrated chips, low-power components, dynamic power management, energy harvesting, and intelligent sensor technologies. On the software side, the network manager optimizes routing schedules, the data link layer adopts TDMA technology, and the protocol stack is tailored for specific scenarios. These measures ensure the network's efficient operation. Furthermore, the integration of smart devices enhances monitoring, control, and energy-saving capabilities, enabling real-time data analysis and decision-making. This fosters innovation and sustainability in industrial automation, paving the way for advanced analytics and seamless connectivity among different devices and systems in industrial environments.

Keywords

WirelessHART Networks; Smart Device Integration; Low Power High Efficiency.

1. Introduction

1.1. Overview and Future Trends of Low-Power Communication Systems

With the rapid advancement of wireless communication technology, low-power wireless communication technology has emerged as a pivotal research focus in the field of mobile communications. The widespread adoption of the Internet of Things (IoT) and sensor networks has further heightened the urgent need for optimizing device energy consumption and ensuring long-term stability. Against this backdrop, the design objectives of wireless low-power communication systems are clearly defined: to effectively extend the operating endurance of devices limited by battery capacity, significantly reduce energy consumption, and comprehensively enhance system energy efficiency, ensuring that devices can continue to operate stably with limited power supply.

This thesis aims to provide an overview of the current design status of wireless low-power communication systems and to foresee future development trends. Firstly, it will review existing achievements in low-power sensor technology, communication protocols, and energy-saving optimization algorithms. Secondly, it will delve into the challenges faced by these systems, such as energy constraints, transmission distance, data reliability, and network capacity. Lastly, it will propose forward-looking research directions and countermeasures to address the ever-increasing demand for low-power communication.

1.2. Comprehensive Analysis of Low-Power Communication Systems

This study integrates theoretical research findings with practical application cases to conduct an in-depth analysis of the design principles, key technologies, and application scenarios of wireless low-power communication systems. The aim is to provide a comprehensive perspective for both academia and industry, fostering innovation and advancements in low-power communication technology.

2. Introduction of Wireless Networks in Industrial Intelligence Systems

2.1. Background

In industrial production environments, numerous sensors are often deployed to monitor and report data on equipment operations within factories. However, in current measurement systems, many sensors are typically wired, posing numerous constraints during system layout. For instance, when temporary measurement points are added or the locations of existing points are adjusted, it necessitates the installation of additional cables, incurring significant costs and extra workload, while also placing greater strain on the system's carrying capacity. In recent years, advancements in information and communication technology and sensor technology have accelerated the development of the Internet of Things (IoT), which has now entered a new phase and is widely used in various fields such as industry, daily life, and urban construction.

Compared to wired transmission, wireless transmission operates without the protection of cables or other media, often leading to issues such as attenuation, interruption, and various defects during transmission, including frequency dispersion, multi-path delay interference, frequency-dependent attenuation, as well as problems related to node sleep mode, node concealment, and security. However, these factors that affect wireless transmission quality can be overcome or mitigated by adopting appropriate mechanisms at various layers of the communication layer model [1]. It is important to note that not all mechanisms are compatible with others or may negatively impact key performance attributes and properties. Therefore, communication systems must optimize the combination of mechanisms adopted at each layer according to their specific application environments to achieve the best overall communication performance. In recent years, there has been an increasingly strong demand for wireless connectivity for devices, including mobile devices, leading to exponential growth in wireless systems, indicating that wireless communication has substantially entered the realm of industrial control.

2.2. Wireless Network Protocols Suitable for Smart Industrial Environments

In smart industrial settings, the choice of network protocols is crucial, prioritizing high security and real-time performance, followed by transmission speed. Wireless communication technologies, categorized by transmission distance, include WAN, MAN, LAN, and PAN. Among them, wireless PANs, especially short-range wireless communications like Bluetooth and infrared, play a vital role in industrial monitoring and control.

IEEE 802.15.4, tailored for low-rate wireless PANs, emphasizes low power consumption, cost, and data rates, suitable for connecting devices within personal or home environments. Aligned with wireless sensor network characteristics, it's widely adopted as their communication standard. The ZigBee Alliance built a comprehensive wireless solution based on this standard, with new versions enhancing security and performance. Meanwhile, IEEE 802.15.4 is also utilized by the ISA100.11a standard, providing reliable and secure low-data-rate wireless connectivity for industrial monitoring and control applications.

ISA100.11a specifies OSI stack and network architecture, suitable for non-critical monitoring and control with execution times up to 100 milliseconds. It ensures robustness in wireless systems, maintains functionality under interference, and interoperates with devices based on IEEE 802.11x, 802.15x, and 802.16x standards, enabling interchangeability.

Named for bees' communication, ZigBee's network standard, set by the IEEE 802.15 committee, suits applications with low data rate and QoS requirements. The ZigBee Alliance oversees high-level applications, testing, and marketing.

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Wireless HART, a wireless mesh communication protocol designed for process automation, is backward-compatible with existing HART devices and applications. The HART Communication Foundation has published the Wireless HART protocol and collaborated with ISA to assess its compatibility as a subset of ISA100.11a, aiming for interoperability between the two to meet industrial needs.

2.3. Overview of the WirelessHART Protocol

WirelessHART is a wireless sensor network protocol specifically designed for industrial automation, building upon the traditional HART protocol and adapting it for wireless communication environments. This protocol supports multi-hop wireless network topologies, utilizing the 2.4GHz ISM frequency band and frequency-hopping spread spectrum (FHSS) technology to ensure reliable data transmission in complex industrial settings. Additionally, WirelessHART offers multi-layered security mechanisms, including 128-bit AES encryption algorithms, to safeguard the confidentiality, integrity, and availability of communications. Its communication protocol supports event-driven and query-response modes, encompassing various communication types such as measurement data transmission, device configuration and management, alarm and fault handling. Furthermore, the protocol incorporates mechanisms for network management, battery life management, and device interoperability, ensuring network reliability, stability, and seamless communication between devices from different manufacturers. Therefore, WirelessHART provides a reliable, secure, and low-power wireless communication solution for the industrial automation field, widely applied in industrial environments such as oil and gas, chemicals, energy, and manufacturing, enabling flexibility and scalability in monitoring, control, and data acquisition. Based on its advantages in the field of industrial automation, WirelessHART boasts five core characteristics:

Multi-hop Wireless Network Topology: WirelessHART supports multi-hop data transmission in complex industrial environments, enabling effective signal routing through relay nodes to ensure reliability and flexibility in data transmission [2].

Efficient Spectrum Utilization: By adopting the 2.4GHz ISM frequency band and FHSS technology, WirelessHART reduces interference in wireless communications, enhancing the system's anti-jamming capabilities and communication stability.

Multi-layered Security Mechanisms: This protocol integrates 128-bit AES encryption, supports authentication and key management, ensuring the security and integrity of data transmission, and providing robust security for industrial automation.

Flexible Communication Protocol: WirelessHART supports event-driven and query-response communication modes, meeting various communication needs, including device configuration, alarm handling, and fault reporting, which improves system response speed and efficiency.

Device Interoperability and Energy Management: Based on open standards, it ensures seamless communication between devices from different manufacturers. Meanwhile, through optimized energy management strategies such as sleep modes and message compression, it extends the battery life of sensor nodes and reduces maintenance costs.

In summary, the WirelessHART protocol offers a reliable, secure, and low-power wireless communication solution, providing more flexible and scalable solutions for monitoring, control, and data acquisition in the field of industrial automation. It is widely used in various industrial environments, such as oil and gas, chemicals, energy, and manufacturing.

3. Hardware Design of Intelligent Industrial Devices

3.1. Selection of MCU

In the field of IoT technology, the principle of "adequate is sufficient" is adopted when selecting processors [3]. Under the condition of meeting functional requirements, the design requirements for low power consumption and miniaturization of the system need to be considered, mainly based on factors such as power consumption, modulation mode, communication distance, and transmission rate. The power consumption of a processor is mainly determined by its operating voltage, clock frequency, and manufacturing process. Therefore, when the system is not in operation, the processor needs to support sleep mode. Experiments have shown that when the processor is in sleep mode, its energy consumption is 3 to 5 orders of magnitude lower than when it is in active mode [4], see Table1.

Table 1. Considerations for Selection

Factor	Description	Indicator	Importance Rating
Function Needs	IoT devices	Comparison	High
Low Power	power design	Test Report	Medium
Size & Package	space constraints	Specifications	Medium
Communication	range	Compatibility	High

3.2. Selection and Enhancement of RF Modules

The power consumption of wireless communication modules accounts for a significant portion of the total power consumption in wireless sensor networks [5]. The communication module is only turned off in sleep mode; in standby mode, it also needs to monitor the signal channel to confirm whether there is data being transmitted. The power consumption is highest when the wireless communication module is in transmit mode, while the power consumption in standby mode is basically the same as in receive mode. Therefore, to reduce power consumption, the wireless communication module should be kept in sleep mode as much as possible during unnecessary reception and transmission, reducing unnecessary monitoring, which can lower the power consumption of network nodes. However, simply turning off the wireless communication module can cause data delays and poor real-time performance. The relationship between energy consumption and distance in wireless communication is E=kdn, where typically n=3, meaning energy consumption is proportional to the cube of the distance [6]. Therefore, under the premise of meeting the communication rate, the communication distance should be minimized.

3.3. Dynamic Management of Device Energy

Effective power management design in IoT technology can significantly reduce the power consumption of wireless sensors. On the one hand, component selection should prioritize components that meet usage requirements while also being low-power. On the other hand, in the design of standalone working modes, power management should be precise and intelligent, providing power only to the required functional modules during the necessary time periods. Fully utilize the configuration functions of handheld devices to adjust sensor nodes to switch between different working modes [7]. The main measures for achieving low-power power management include:

During the level conversion between the power supply and the processor, Schottky diodes can be used for level conversion, so that the energy of the power supply is not lost through intermediate devices but is all used to power the processor, maximizing battery endurance [8].

Sensitive components can be powered through the stabilized voltage of the processor's I/O ports, achieving controllable power supply. When sampling and data transmission are not required, the processor enters low-power mode and simultaneously controls the I/O ports to turn off voltage output, cutting off power supply to sensitive components, thereby effectively controlling electric energy consumption. That is, the power supply is disconnected when not in use, serving the purpose of energy conservation.

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Through program control, the processor can switch reasonably between working mode, sleep mode, and low-power operation mode. High current output to the circuit is only required during signal transmission.

4. Software Design

4.1. Routing Scheduling

For the WirelessHART network to function properly, the network manager, as the core device in WirelessHART, is responsible for selecting appropriate routing paths for each device node in the network, arranging and allocating communication time slots and channels, and controlling and optimizing them at any time. In a network, the process of determining the data transmission path from the source node to the destination node is crucial. In a complex network, there may be multiple paths from the source node to the destination node, so routing scheduling needs to consider various factors such as network topology, bandwidth utilization, and latency to select the optimal data transmission path.

4.2. Data Optimization

Additionally, in the WirelessHART protocol, the data link layer employs Time Division Multiple Access (TDMA) technology, where all network communications are based on clock synchronization. In the WirelessHART network, data communication between adjacent nodes is completed in the data link layer using time slots as the basic unit of communication. Selecting the optimal path for superframes within the WirelessHART network can reduce the total power consumption of the devices [9].

4.3. Protocol Stack Optimization

The topology of WirelessHART is a mesh network, where data transmission or retransmission in WirelessHART may follow different paths. Due to the multi-path routing between nodes in a mesh network, the network has strong fault tolerance and robustness. Therefore, the protocol stack can be optimized to reduce wireless power consumption. The main optimization areas include: optimizing these algorithms for specific scenarios and requirements; using various data structures to manage network topology and state information, such as neighbor tables, routing tables, etc. By optimizing the design and implementation of data structures, the performance and efficiency of the protocol can be improved. Additionally, optimizing the code can enhance the performance and efficiency of the protocol stack. For instance, using more efficient algorithms and data structures to replace existing implementations or refining and compressing the code to reduce resource consumption during runtime [10].

5. Conclusion

Industrial communication devices have achieved low power consumption and high efficiency in WirelessHART networks through comprehensive optimization of both hardware and software. On the hardware front, they utilize advanced manufacturing processes, highly integrated chips, and low-power components, combined with dynamic power management techniques, to effectively reduce power consumption. Furthermore, the integration of energy harvesting and intelligent sensor technologies further boosts energy-saving efforts, enhancing the overall efficiency of the network.

On the software side, the network manager optimizes routing schedules to select the optimal data transmission paths, ensuring efficient use of network resources. The data link layer adopts TDMA (Time Division Multiple Access) technology to manage communication among devices, minimizing interference and maximizing throughput. Additionally, the protocol stack is tailored

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with optimized algorithms and data structures for specific scenarios, improving performance and efficiency.

These measures collectively ensure the low power consumption and high-efficiency operation of WirelessHART networks, enabling reliable and efficient communication in industrial environments. They also pave the way for the integration of smart devices and advanced analytics, fostering innovation and sustainability in industrial automation.

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