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Wireless Sensor Network Technology for Vibration Condition Monitoring of Mechanical Equipment

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ABSTRACT

The application of wireless sensor networks in mechanical equipment condition monitoring is proposed to make up for the limitations of wired mechanical equipment condition monitoring systems. To record vibration signals from mechanical equipment, it is essential to design a dual-processor wireless sensor network node. Researching the self-organizing network, wireless transmission protocol, and on-chip processing function is also important to develop a full wireless sensor network mechanical vibration monitoring system. The clustering network topology, which is advantageous for applying distributed algorithms, has good scalability, can quickly adapt to system changes, and is appropriate for large-scale networks. Through the design of high-performance vibration measurement nodes, the problem of limited acquisition and storage capacity when a wireless sensor network is applied to mechanical vibration signal acquisition is preliminarily solved. The experimental results show that the time domain signal collected by the node is small, and the corresponding amplitude will be small, but the on-chip processing results of the node correspond to the processing results of the host computer, and the amplitude difference is small, and the maximum error is 8.18%, indicating that the node performance can meet the requirements of on-chip processing. The feasibility of the design scheme is verified by experiments.

Index Terms—Mechanical vibration monitoring system, on-chip processing, synchronous acquisition, vibration signal, wireless sensor network node

I. INTRODUCTION

With the rapid development of industrial production and science and technology, the requirements for the precision, complexity, and automation of mechanical equipment are higher and higher, and the problems of equipment reliability, maintainability, and safety are becoming more and more prominent. More and more people began to study the vibration monitoring technology of mechanical equipment and successively launched a variety of mechanical vibration monitoring systems, which ensured the safe and stable operation of mechanical equipment to a certain extent [1]. At present, the more mature mechanical equipment condition monitoring systems, whether centralized or distributed, mostly adopt wired monitoring technology. They all need to transmit the vibration signals provided by various sensors to the data processing center through corresponding wired cables to realize the analysis, processing, and diagnosis of vibration signals. However, this mechanical vibration monitoring system based on the wired connection has some shortcomings, which affect the quality of vibration monitoring and fault diagnosis of mechanical equipment. For example, the deployment cost is high, a large number of cables and corresponding hardware are required, the maintainability is poor, and the system lacks flexibility. Once the system is deployed, it is not allowed to add or delete monitoring points or change the layout [2]. Especially in some special and extreme cases, wired connection is difficult to realize, such as vibration monitoring of equipment transmission parts in some sealed environment and mechanical rotation environment, and vibration, deformation, and crack fault monitoring of some key components in heavy machinery and other equipment, There are also intelligent machining equipment vibration signal monitoring for cutting quality control and tool life prediction in the machining process. In these cases, wired monitoring is very difficult to achieve [3, 4].

The application of wireless sensor networks to mechanical vibration monitoring presents a number of challenges. This paper examines these challenges, develops a wireless sensor network node that is suitable for mechanical vibration monitoring, and addresses the challenges of challenging mechanical vibration signal pickup, low sampling frequency, and limited data storage space. Vibration signals can be analyzed and processed to help pinpoint the origin of faults. The most efficient way to fix mechanical flaws in mechanical equipment is to monitor any part of the machinery using the vibration signal analysis method. Additionally, it can assess the severity of a fault without disassembling mechanical components and even change the system used for routine maintenance. The research shows that these sensor nodes are not suitable for mechanical vibration signal acquisition for two reasons: (1) The sampling frequency required in mechanical testing is usually in the range of 1–10 kHz. High-frequency sampling will produce a large amount of vibration data. The existing node storage capacity is very small, which is only suitable for slow variable acquisition and temporary storage. (2) Mechanical vibration signals require high-precision acquisition in order to analyze and find weak fault signals, while most of the existing sensor nodes use processor on-chip A/D converter to collect analog signals [5]. The on-chip A/D of the processor generally has low precision, is easy to be disturbed by the digital circuit of the processor, and has a low signal-to-noise ratio and low sampling rate. It is generally used to collect slow-changing signals with low precision requirements such as temperature and illumination. Facing the above problems of mechanical vibration wired monitoring system, an alternative solution is to use the emerging wireless sensor network monitoring mode to build a wireless and distributed vibration monitoring system [6]. The wireless sensor network is a new information acquisition and processing technology, which can work under the condition of long-term unattended and can monitor, perceive, and collect the information of various environments or monitoring objects in real time. It has great application value and potential application prospects in the fields of military, industry, medical treatment, environmental monitoring, traffic management, and disaster relief, as shown in Fig. 1. The paper is organized into five sections, initially, Section I presents Introduction; Section II presents Literature Review; Section III presents Research Method; Section IV presents Results;

Section V represents Discussion; and Section VI presents the major conclusion.

The contribution of the present study is given below:

- A wireless sensor network node that is appropriate for mechanical vibration monitoring is developed in this research.
- Overcomes the difficulties of low sampling frequency, difficult mechanical vibration signal pickup, and restricted data storage space.
- Analysis and processing of vibration data can be used to identify the source of defects.
- The study demonstrates that these sensor nodes are unsuitable for acquiring mechanical vibration signals.

II. LITERATURE REVIEW

Wireless sensor network technology has been fully affirmed and demonstrated in the military field, fine agriculture, safety monitoring, environmental protection monitoring, smart home, and industrial monitoring. Arce et al. proposed that mechanical vibration signal is an important signal source to judge whether mechanical equipment operates normally. Through the detection and diagnosis of equipment vibration signals, the health state of mechanical equipment can be predicted in advance [7]. Vibration signals can be obtained using a novel method called wireless sensor network monitoring mode. In order to compensate for the shortcomings of the conventional wired monitoring system in some particular cases, a wireless data transmission mode is constructed using a large number of distributed sensor nodes self-organizing method. Time synchronization issues, communication gaps between sensor nodes, and a lack of real-world protocols that can be implemented in wireless sensor network (WSN) are some of the other drawbacks of the technology [8, 9]. Zhang and Liu believe that the problems of reliability, availability, maintainability, and safety of large rotating equipment are becoming increasingly prominent, and machine vibration monitoring technology is particularly important [10]. Guimarães et al. proposed that sensor nodes are the most basic components of wireless sensor networks, and node performance determines the application field of wireless sensor networks. At present, there are many general wireless sensor network nodes on the market. Most of these nodes
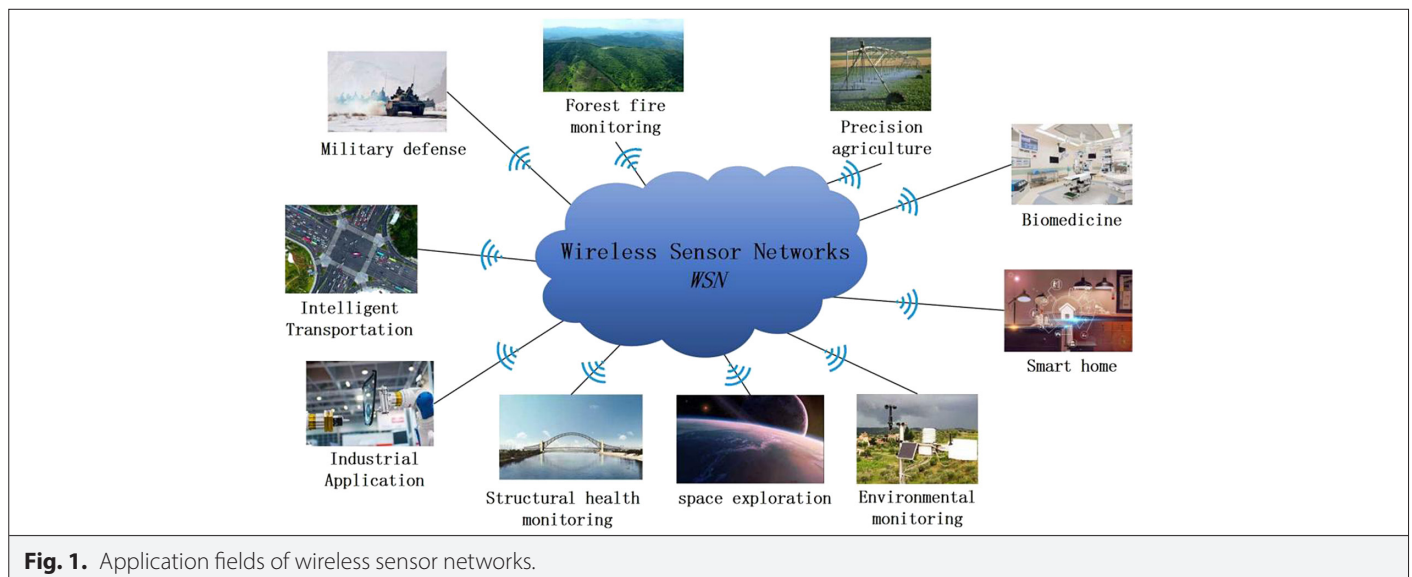

Fig. 1. Application fields of wireless sensor networks.

have low hardware performance and can only be used for structural health monitoring, animal living habits monitoring, and crop growth environment monitoring to collect temperature, humidity, light, and low-frequency vibration signals [11]. Halakarnimath et al. transmit the perceived information to the user terminal by multi-hop relay through random ad hoc wireless communication network, truly realizing the concept of "ubiquitous computing." Wang et al. used wireless sensor networks to turn the traditional serial processing and centralized processing system into distributed processing to solve the problem [12]. Tan et al. proposed the application research of pervasive structural health monitoring technology of wireless acceleration sensor networks based on micro-electro-mechanical systems (MEMS) technology. It is feasible to apply WSN to mechanical equipment vibration monitoring [13]. Kang et al. believe that wireless sensor network is a new research field integrating modern sensor technology, MEMS technology, communication technology, embedded technology, and distributed information processing technology [14]. Manikandan and Chinnadurai proposed a new industrial wireless sensor network for mechanical condition monitoring and fault diagnosis by using wireless sensor network module for specific objects, by collecting the current signal and acceleration signal output by the rotor. Then, the signal feature extraction and neural network are used for fault classification, and then the fault fusion is carried out at the routing node to obtain the operation state of mechanical equipment [15]. The development node of the high-performance structural health monitoring system studied by Yuvaraju and Pranesh adopts the high-performance single-chip microcomputer to control the 24-bit high-precision converter for data acquisition. The main control unit is the ARM9 processor running the Linux operating system, uses the wireless module to realize high-precision synchronous acquisition, and transmits a large amount of data through Wi-Fi [16]. The creation of a trustworthy transport protocol for wireless sensor networks is crucial for the adoption of new applications. Depending on the application, each sensor node can be necessary to carry out some local computations [17, 18] and data aggregation [19]. Due to its three-way handshake processes and large packet header size, transmission control protocol (TCP) is expensive to use in wireless sensor networks. Despite the fact that user datagram protocol (UDP) was created to enable unstable data delivery, it is seen to be more suitable for sensors.

To sum up, this paper studies the problem that the existing sensor networks are not competent for mechanical equipment vibration monitoring. It is very important to design a dual-processor wireless sensor network node to realize the pickup of mechanical equipment vibration signals. It is also necessary to study the self-organizing network, wireless transmission protocol and on-chip processing function of wireless sensor networks, so as to form a complete set of wireless sensor network mechanical vibration monitoring system.

III. RESEARCH METHODS

A. Establishment of Wireless Sensor Networks

1) Although wireless sensor networks have made great progress in some aspects, most of them stay in the theoretical stage in mechanical vibration monitoring, and there are still many problems to be solved. For example, the reliable data transmission rate should exceed 95%; there are many types of wireless networks such as Bluetooth in the factory environment, which have serious interference with each other; the multipath effect caused by the reflection and scattering of signals by various large instruments and metal pipes in the plant, as well as the electromagnetic noise generated during the operation of motors and instruments, will interfere with the correct reception of wireless signals; there are also high requirements for real-time. For industrial closed-loop control applications, the data transmission delay should be less than 1.5 times the sensor sampling time [20].

2) In view of these problems mentioned earlier, this paper adopts the clustering network topology, which is conducive to the application of distributed algorithms, can quickly respond to system changes, has good scalability, and is suitable for large-scale networks. The cluster head reduces data traffic and saves network energy through data fusion. It is of great significance to apply it to the condition monitoring system of mechanical equipment. A clustering routing protocol is mainly composed of three parts: cluster head selection, network formation, and data transmission.

3) LEACH protocol is the first distributed clustering protocol proposed. It generates a random number between [0,1] for each node. If this number is less than the threshold T (n), the node broadcasts that it is a cluster head to the whole network. The threshold value is calculated as shown in (1):

$$T(n) = \frac{k}{N - k \times \left[r \bmod(n/k) \right]}, n \in G$$

$$T(n) = 0, Another$$ (1)

where N represents the number of sensor nodes in the network, K is the number of nodes of cluster heads in a network, and R is the number of cycles at present; G is the total number of rounds of network lifetime, where a round represents a cycle. It can be seen that cluster heads are randomly selected. Therefore, LEACH protocol cannot guarantee the uniform distribution of cluster heads in the network and the load balance of clusters in practical applications. In order to adapt to the environment of mechanical equipment vibration signal acquisition, an improved cluster head selection algorithm is proposed [21].

First, the base station broadcasts a hello message to inform the whole network that the establishment of a new cluster begins. At this time, the energy-saturated node uses its own energy saturation signals (judged by the threshold) to independently decide to become a cluster head and inform the whole network of the fact that it becomes a cluster head. At this time, the first layer cluster head is established successfully.

Second, the improved LEACH algorithm is used to select the cluster head of the second layer. Fully consider the energy of the second layer cluster head itself. After a period of network operation, the residual energy of the renewable node at the current time is $E_{cur}(n)$, then the energy residual rate is as shown in (2):

$$R(n) = \frac{E_{cur}(n)}{E_{ini}(n)}$$ (2)

where $E_{ini}(n)$ is the initial energy of the node. Then, the improved calculation formula is shown in (3):

$$T(n) = \frac{k}{N - k \times \left[r \bmod(n/k) \right]} \times R(n)$$ (3)

4) Network formation. After the cluster head is generated, the cluster head begins to broadcast the selected message to the surrounding nodes. According to Friis free space equation, the expression of received signal power when the distance between receiver and transmitter is d is given as shown in (4):

$$P_{revd}\left(d\right)=\frac{P_{tx}G_{t}G_{r}\lambda^{2}}{\left(4\pi\right)^{2}d^{2}L} \qquad (4)$$

where P_{tx} is the transmission power, G_{t} and G_{r} are the antenna gains of the transmitter and receiver, respectively, λ is the wavelength of the signal, and $L \geq 1$ represents the loss from the transmission to reception.

According to the above formula, the communication distance should be minimized if allowed. LEACH routing algorithm does not consider the size, number, and load balancing of clusters from the perspective of energy. An improved leach cluster formation scheme is proposed.

The cluster head node broadcasts a message, which includes the flag true, transmission power, cluster head ID, and residual energy to become the cluster head, and notifies other nodes to be selected as the cluster head. If the node can receive messages from many clusters of hair, then it needs to make a series of judgments. The node gives priority to adding the cluster head with the strongest received signal. If the received signal strength sent by several cluster heads is similar, it gives priority to adding the cluster head with the most residual energy. In order to reduce the data forwarding pressure of the cluster head, the size of the cluster should be limited to a limited range [22].

5) Data transmission. For vibration signals, the whole vibration waveform reflects the health status of mechanical equipment. In order to reduce the pressure of the cluster head and the mutual interference during data transmission, time division multiple access (TDMA) will be used to allocate a time gap for each node in the cluster. When the time slice of the node arrives, relevant data will be sent to the cluster head, and the cluster head will fuse the collected data, and then transmit it to the upper cluster or the base station.

1) Characteristics of Wireless Sensor Networks

A good wireless sensor network must have the following characteristics:

(1) Low power consumption. Typical wireless sensor networks require that the average power consumption of network components is much lower than that of existing wireless networks (such as Bluetooth). Sensors used for monitoring and control require that their batteries can be maintained long enough to complete the task. When applied to large-area environmental monitoring, many devices are required, and it is impractical to replace the battery frequently.
(2) Low cost. Cost is very important for wireless sensor networks, especially when there are a large number of nodes in the network.
(3) Wide adaptability.
(4) Network topology. The traditional star network can meet many applications by using one host and several or more slave devices. However, due to the limitation of transmission power of this network device, the network shape should support multi-hop routing.

(5) Data throughput. Wireless sensor networks do not require high data throughput.
(6) Long information latency. Because it does not support synchronous communication and cannot carry out real-time audio and video transmission, the delay requirements for information are very loose. In some cases, a few minutes delay is acceptable.
(7) Mobility. Wireless sensor networks generally do not need node mobility.
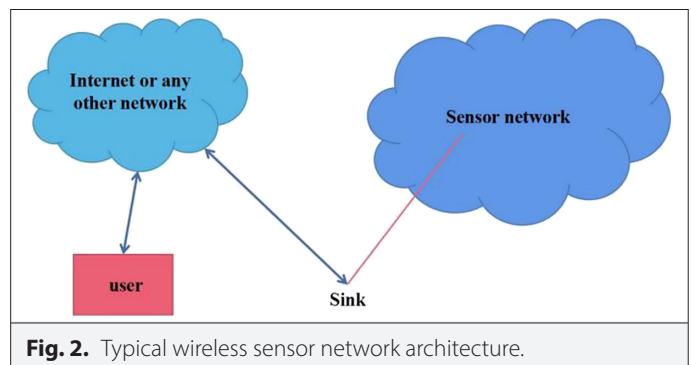
B. Wireless Sensor Network Architecture

In wireless sensor networks, the nodes form a network in the form of self-organization, transmit the monitoring data to the sink node through multi-hop relay, and finally transmit the data in the whole area to the remote center for centralized processing by means of long-distance or temporarily established sink link. A satellite link can be used as a sink link. It is also a way to recover the data on the sink node with the help of unmanned aircraft cruising over the monitoring area. If the network scale is too large, the cluster hierarchical management mode can be adopted. The typical wireless sensor network architecture is shown in Fig. 2.
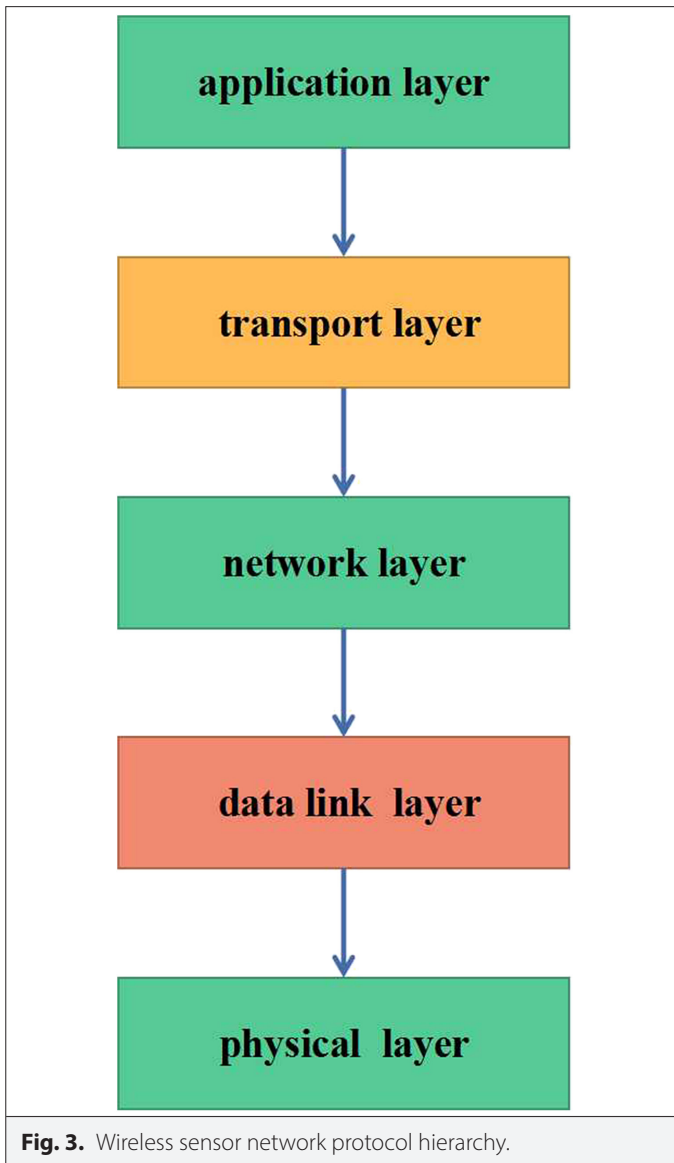
Figure 3 shows the protocol hierarchy of wireless sensor networks. In this structure, each layer of the wireless sensor network is designed to three management: energy management, task management, and mobility management. However, the emphasis of each layer to realize the three management is different. For example, the application layer mainly considers task management and assigns monitoring tasks to each subnet and sensor node. The application layer also considers mobile management, while the energy management is undertaken by the network layer and the data link layer. Mobile management is also implemented in these two layers. The physical layer also has energy management, but mobile management and task management are less considered.

C. Key Technologies of Mechanical Equipment Condition Monitoring and Wireless Sensor Network

1) Condition Monitoring of Mechanical Equipment

The vibration characteristics of machinery are unique to special faults. Through the analysis and processing of vibration signals, the cause of faults can be determined. In the maintenance of mechanical equipment, using the vibration signal analysis method to monitor any part of the machinery is the most effective method to eliminate mechanical faults. At the same time, it can also determine the fault degree without dismantling mechanical parts, and even replace the regular maintenance system. It is inevitable for equipment to generate vibration during operation. Generally speaking, vibration is composed of a series of simple harmonic vibration components, other

Fig. 2. Typical wireless sensor network architecture.

Fig. 3. Wireless sensor network protocol hierarchy.

vibration components and random noise. Most of the frequencies of simple harmonic vibration components are related to rotor speed or natural frequency, and irregular vibration mainly comes from nonlinear self-excited vibration [23]. By analyzing the vibration waveform,

observing and inferring the vibration process and change law of the equipment, various characteristics reflecting the operation state and fault of the equipment are obtained. The current and future research hotspots of mechanical fault diagnosis are reflected in the following aspects: multi-sensor data fusion technology; online real-time fault detection algorithm; diagnosis technology of intrinsically nonlinear dynamic system; hybrid intelligent fault diagnosis technology; remote cooperative diagnosis technology based on Internet; and research on fault-tolerant control, monitoring system, and credibility system based on fault detection and separation.

2) Wireless Communication Technology

(1) Wireless communication standard. In today's network and communication technology, wireless communication technology is the most active field. It has multiple standards and has been successfully applied in their respective fields, and new technologies emerge in endlessly. Among many general wireless communication technology standards, wireless sensor networks do not determine a specific standard as the official mainstream communication technology [24]. At present, the popular wireless communication technology standards include Bluetooth, ultra-wideband technology Wi-Fi and 802.15.4/ZigBee. The specific parameters of each standard can be clearly compared in Table I.

(2) Transmission band of WSN. Choosing the appropriate transmission medium is very important for a wireless communication system. Theoretically, the optional carrier media of a wireless sensor network can be infrared, laser, and radio wave. The use of infrared does not need to apply for frequency band, will not be interfered by electromagnetic signal, and the infrared transceiver is cheap. Laser communication has strong confidentiality and high speed. However, a common problem of infrared and laser communication is that the transmitter and receiver are required to be within the visual range, which is difficult to achieve for wireless sensor networks with randomly distributed nodes, so the use is also limited. Thus, radio wave has become the best choice of carrier media in wireless sensor networks. The radio spectrum is non-renewable. The unique space exclusivity of radio communication determines that it must comply with certain specifications in practical application. The frequency band selection of wireless sensor networks should also be implemented according to the provisions of relevant departments [25-27]. At present, the selected frequency bands of wireless sensor networks are industrial, scientific, and medical

TABLE I. COMPARISON OF WIRELESS COMMUNICATION STANDARDS

Name	ZigBee	Bluetooth	UWB	Wi-Fi
Standard	IEEE802.15.4	IEEE802.15.1	IEEE802.15.3	IEEE802.11a,b,g
Rate	20/40/250 Kbps	1–3 Mbps	110 Mbps–l .6 Gbps	10-105 Mbps
Transmission distance	10–300 m	10 m	4–20 m	10–100 m
Power waste	Ultra low	Low	Low	High
Number of nodes	65 535	8	128	32
Application area	Detection and control	Alternate outside line	High-speed wireless access	Wireless access
Technical advantages	Power consumption and cost	Cost and convenience	High rate	Bandwidth, flexibility

TABLE II. ISM FREQUENCY BAND DESCRIPTION

Frequency	
13.553–13.567 MHz	
26.957–27.283 MHz	
40.66–40.70 MHz	
433–464 MHz	European standard
902–928 MHz	American standard
2.4–2.5 GHz	Global WPAN/WLAN
5.725–5.875 GHz	Global WPAN/WLAN

(ISM) frequency bands, namely industrial, scientific, and medical frequency bands. For the protection of wireless band resources, ISM bands in various countries have their own band division. (see Table II).

(3) Spread spectrum communication technology. The technologies used in the physical layer of WLAN can be roughly divided into three categories: narrowband microwave technology, spread spectrum technology, and infrared technology. Each technology has its advantages and disadvantages. At present, spread spectrum technology is becoming the mainstream. Spread spectrum communication is to spread the information data to be transmitted by pseudo-random code and then transmit the signal with extended-spectrum bandwidth on the channel; At the receiving end, the same spread spectrum sequence is used for despreading and demodulation to recover the original information data [28-30]. A typical spread spectrum system is shown in Fig. 4.

IV. RESULTS

In order to test the performance of this node in mechanical vibration monitoring, adxl001 acceleration sensor is selected to obtain the vibration signal through the 16-bit A/D converter on the data acquisition board of the node. In the experiment, the vibration signal is collected at the sampling frequency of 1 kHz and stored on the secure digital (SD) card, and then the vibration data on the SD card is analyzed at the personal computer (PC) end. As shown in Figs. 5 and 6, the time domain waveform and amplitude spectrum of vibration

shock response collected by one node of wireless sensor network are shown. A similar trend has been obtained in the studies of Ohtsu [31] and Holm and Eide [32].

V. DISCUSSION

The time domain signal of the node collected data is small, and the corresponding amplitude will be small, but the on-chip processing result of the node corresponds to the processing result of the host computer, and the amplitude difference is relatively small, with the maximum error of 8.18%. Eliminating the problem that the node collects small time-domain signals can show that the node performance can meet the requirements of on-chip processing. It was observed that traditional mechanical vibration monitoring systems have some shortcomings that affect the quality of vibration monitoring and mechanical equipment fault diagnosis. For example, the deployment cost is high, many cables and corresponding hardware are required, and the system's maintainability is poor. It has been demonstrated that clustering network topology facilitates the use of distributed algorithms and can react quickly to system changes. It scales well and is appropriate for massive networks. The experimental findings indicate that the node's time domain signal collection will result in a small amplitude, but that the node's on-chip processing results will be similar to those of the host computer, with only a small amplitude difference. It is concluded from the proposed method that it can function under long-term unattended condition and that it can monitor, perceive, and gather data on a variety of environments or monitoring objects in real time. It is ideal for large networks and scales well. According to the experimental results, the node's time domain signal collecting will produce a tiny amplitude, but its on-chip processing outcomes will be largely comparable to those of the host computer. According to the proposed approach, it can monitor, perceive, and collect data on a variety of surroundings or monitor objects in real time while operating under a long-term unattended scenario. Various characteristics representing the operating status and fault of the equipment are acquired by analyzing the vibration waveform, monitoring, and deducing the vibration process and change law of the equipment.

VI. CONCLUSION

This paper studies the difficulties faced by the application of a wireless sensor network in mechanical vibration monitoring, develops a
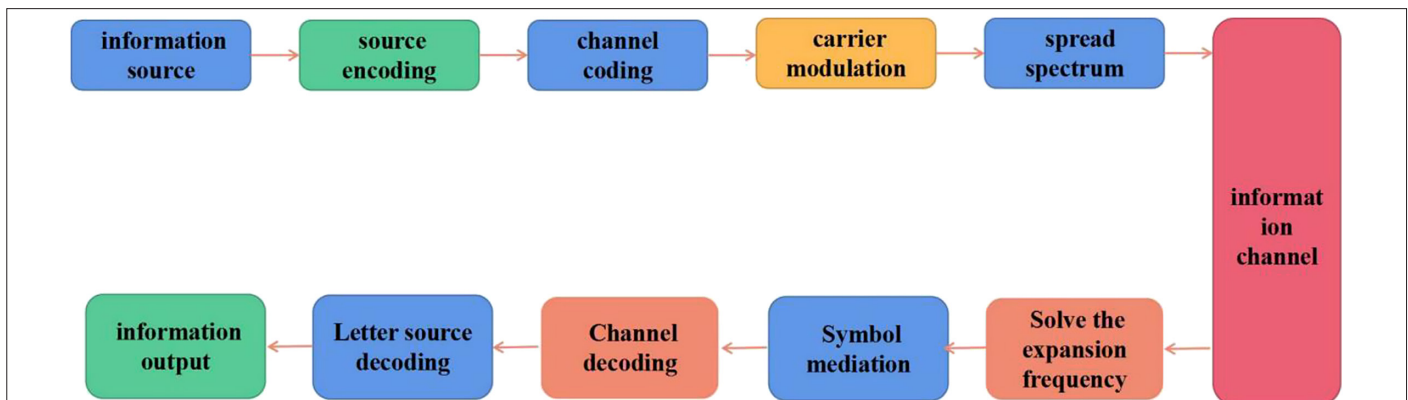

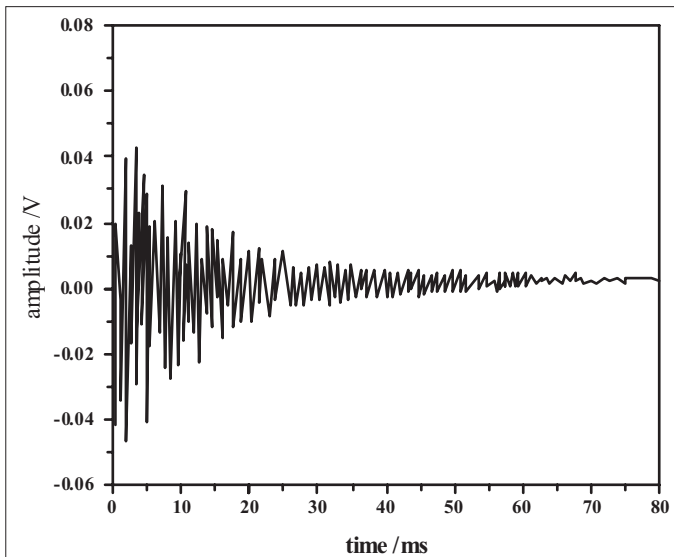**Fig. 4.** Typical spread spectrum transceiver mechanism.

Fig. 5. Time domain waveform of vibration signal.

wireless sensor network node suitable for mechanical vibration monitoring, and preliminarily solves the problems of difficult mechanical vibration signal pickup, low sampling frequency, and small data storage space. Additionally, it investigates these problems, develops a wireless sensor network node appropriate for mechanical vibration monitoring, and deals with the problems of challenging mechanical vibration signal pickup, low sample frequency, and constrained data storage. It is possible to examine and process vibration signals to help identify the origin of defects. The most efficient way to repair mechanical flaws in mechanical equipment is to use vibration signal analysis to monitor any part of the machinery. The on-chip processing algorithm is also used to extract the characteristic parameters of mechanical vibration signal on the node to reduce the amount of data communication, so as to realize the real-time monitoring of mechanical equipment status. Experiments are used
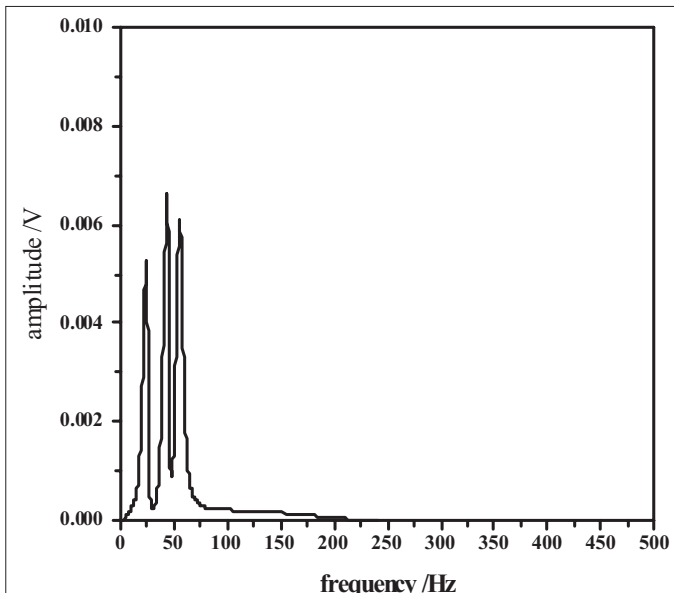

Fig. 6. Amplitude spectrum of vibration signal.

to confirm the design scheme's viability. The development of compact, inexpensive sensor nodes that use very little energy has been made possible by developments in computation and communication technology. They are also very quickly deployable. Moreover, in the coming years, WSNs might be utilized for underwater wireless sensor systems, cognition sensing, and mechanical equipment spectrum management.

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