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Design of Multi-Channel Wireless Sensor Networks Based On Compressive Sensing Theory and Spectrum Sensing Theory

Naji Ma [1, 2], Ming Diao [1], Xiao Hu [3], Jian Sun [2] and Anchang Ma [2]

[1] College of Information & Communication, Harbin Engineering University, No.145, Nantong Avenue, Harbin 150001, China
[2] Information &Network Center, Heilongjiang University of Science &Technology, No.2468, Puyuan Avenue, Harbin 150022, China
[3] Institute of Electronics, Chinese Academy Sciences, No.19, Beisihuan Avenue, Beijing 100190, China)
5203datashare@163.com

Abstract

The single-channel wireless sensor networks (WSNs) exists the problem of low efficiency of monitoring data transmission, however the multi-channel WSNs exists the problem of communication collision caused by the sensor node's wireless channel competition. The paper at first introduces the causes of the above problems and selects a reasonable wireless channel resources allocation method of the multi-channel WSNs. Then to solve these questions, the theory of compressive sensing and spectrum sensing are adopted to improve the existing multi-channel WSNs. Finally, a new sensor node of the multi-channel WSNs is designed based on the above improvement. By analyzing the monitoring data of the field test, the improved multi-channel WSNs could complete monitoring mission efficiently and accurately, meanwhile it reduced power consumption of the WSNs effectively.

Keywords: *WSNs, monitoring, sensor node design, multi-channel*

1. Introduction

Wireless sensor networks (WSNs) owes to the mutual development of sensor technology, micro-electro-mechanical systems, modern network and wireless communication technology [1]. It consists of a mass of micro sensor nodes (SNs) which are deployed in the monitored field randomly. These SNs are formed a multi-hop network system by the way of wireless communication [2]. The WSNs monitors the needed physical quantity data, and all the monitoring data are transmitted up to the monitoring center or Internet. Therefore, the management and control of monitored target can be performed easily [3]. Currently, WSNs is widely used in industry, agriculture and many other fields [4].

Traditional single channel model is used in WSNs widely. The communication model uses a fixed communication frequency to transmit monitoring data. The single channel communication model enjoys the advantages of simple and convenient networking, easy-to-find SNs in the network and easy-to-fulfill multi-node information broadcast and so on [5]. However, with the increasing of scope, standard and item categories which the WSNs monitored, the number of SN in the network also grows. Single channel model leads to intensifying wireless channel competition and mutual interference between adjacent SNs, which cause transmission error or fail. Therefore, single channel communication cannot meet modern monitoring demand and communication standard for it cannot provide a kind of efficient and reliable wireless sensor networks. As for multi-channel

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communication model, SN could use several channels to communicate which increases available communication resources enormously. The numbers of SN in the WSNs can be dispersed at different channels to reduce communication competition and to improve throughput of network communication. When a channel was disturbed, SN can use other channels to communication, improving the anti-jamming capability of the WSNs.

Therefore, in this paper a multi-channel WSNs with high communication efficiency was designed. From the point of practical application， the paper describes the network structure and multiple channel resource allocation method of the multi-channel WSNs which was designed. Aiming at the issues of wireless channel competition and reduced power consumption, by improving the existing SN, a low-power SN for the multi-channel WSNs was designed. The SN used of compressive sensing and spectrum sensing algorithms. Through the field test, it effectively reduced power consumption and probability of communication collision.

2. Channel Resources Allocation Method Design of Multi-Channel Wireless Sensor Networks

The network model of multi-channel WSNs is the same as single-channel WSNs's, which includes five layers from the bottom to the top: physical layer, data link layer, network layer, transmission layer, application layer, as is shown in Figure 1.

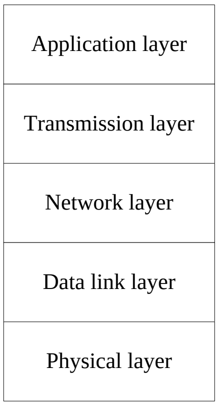

Figure 1. Model of the Multi-Channel WSNs Communication Protocol Stack

Medium access control protocol, which belongs to data link layer of the WSNs to build information transmission link among the SNs. MAC layer protocol of the multi-channel WSNs needs to distribute all wireless channel resources reasonably among the SNs to improve communication efficiency of the WSNs and to reduce power consumption of the SN effectively [6].

The channel resources allocation methods of multi-channel WSNs are mainly divided into centralized allocation and distributed allocation. Centralized allocation has the advantage of global optimum of the wireless network's channel resources allocation [5], which sets a resource manager knowing the topology of whole the WSNs to distribute channel resources rationally to every SN according to the setted rules. However, the WSNs are a dynamic network. The topology of the WSNs changes frequently due to SNs join or exit continuously. When the allocation method was applied, channel resources manager has to readjust allocation plan each time that topology changed. The allocation method reduced transmission efficiency and restricted expansibility of network. With changeable characteristics of network topology for the WSNs, the distributed channel allocation method is used in the design. This allocation method is characterized by none of resources manager of the WSNs so that each SN can select the channel resources freely.

Although the multi-channel mode is adopted in the design, but the number of SN is much more than that of wireless channels. Therefore, the wireless channel competition happens inevitably, a further project of wireless channel resources allocation on times domain is needed. There are mainly two solutions for the wireless channel competition currently. One is to divide communication time into several independent time frames according to the number of SN, and then these time frames are distributed to each SN by predefined rules. SN can be exclusive to the channel in the time frame which was assigned, thus avoiding wireless channel contention. The other is called the carrier sense multiple access model. The model requires the SN to sense each channel, and search for an idle one. Once the idle channel is perceived, the SN switches to the channel sending the monitoring data immediately. Therefore, in the paper the McMAC protocol is used as MAC protocol in the WSNs to distribute wireless channel resources [7]. The McMAC protocol is a multi-channel MAC protocol of distributed allocation model. It takes CSMA channel access pattern; dynamic channel resources hold model and parallel channel consultation schema.

3. Algorithm Design of Improving Communication Efficiency and Reducing Power Consumption in Multi-Channel WSNs

Experiment shows that most power consumption in the WSNs occurs to the SN transmitting monitoring data. Communication collision will lead to transmission failure during the SNs sending monitoring data by used the same channel, which needs the SN resends the data when the wireless channel idle again. This process wastes a lot of energy. The sensing access channel model will cause channel competition and communication collision unavoidably, when there are too many SNs in the WSNs. There are mainly two solutions to reduce channel competition and communication collision: One is to shorten each monitoring data length; the other is to increase the number of available wireless channel. Both solutions are adopted in the design. Compressive sensing algorithm is used to reduce the sampling number of monitoring data (signals) so as to shorten data length. Spectrum sensing algorithm is used to increase the number of wireless channel so as to improve data transmission efficiency. Each algorithm will be listed as following.

3.1. Compressive Sensing Algorithm of Monitor Signal

Compressive sensing (CS) algorithm is also named as compressive sampling or sparse sampling, which is a method to seek the sparse solution of the underdetermined linear system brought forward by David Donoho, Emmanuel Candes, Terence Tao, J. Romberg etc. in 2004. Compressive Sensing algorithm could reduce the data sampling frequency and shorten monitoring data transmission time without decreasing sampling accuracy. The original monitoring data can be reconstructed completely by compressive data at the monitoring center.

The Compressive Sensing technology predominantly includes three steps: 1. Data sparse decomposition; 2. linear measurement of sparse data; 3. sparse data reconstruction from a small number of measurements. [8]

1. Monitoring Data Sparse Decomposition

Suppose the value discrete signal (monitoring data, with the length is N) is x, acquired by the SN(i) (the x can be regarded as a N dimensional vector) and suppose there is a basis in N-dimension linear space, $W = [w_1, w_2, w_3, \cdots, w_N]$ and it is satisfied that $W \cdot W^T = W^T \cdot W = I$ (I represent unitary matrix). The basis of the monitoring data can be expressed as follows:

$$x = \sum_i s_i \cdot w_i \tag{1}$$

In the formula, the s_i is the inner product of the vector x and the vector w_i, the monitoring data x can be represented as:

$$x = W \cdot S \tag{2}$$

There into, $S = [s_1, s_2, s_3, \ldots, s_N]$, it is called the sparse coefficient. The sparse feature shows that most elements in the S are zeros or similar to zeros (this is because the engineering design also needs to go through zero processing). Suppose there are k non-zero elements in S $(k \ll N)$, we name it the sparseness of S.

2. Linear Measurement of Sparse Signals

The perception matrix is the subject of CS as an algorithm to acquire the compressed monitoring data. Suppose there is a matrix A, $A \in R^{M \times N}$. Linear compressed signals y ($y \in R^M$) can be obtained by means of linear projection of the monitoring data x from N-dimensional linear space to the M-dimensional space $(N \succ M)$ with the help of matrix A. The y could be expressed as follows:

$$y = A \cdot x \tag{3}$$

Now the y includes all the information about the original monitoring data x. In the formula, the A is named as sensing matrix. In addition when choosing a sensing matrix, should also ensure that the sensing matrix A and the sparse matrix W are not relevant or two matrices have a lower relevance [9]. Since the Gaussian random matrix is uncorrelated with most matrixes composed of orthogonal bases, the Gaussian random matrix is used as sensing matrix in the design.

3. Reconstruction of Sparse Signals

The signal y is reconstructed at the monitoring center, that is to say, to thoroughly renew the monitoring data x (N-dimensional) from the received signal y (M-dimensional). However, the formula (3) tells that the reconstruction is a process to find the solution of equations comprising N variables and M equations. Since $N \succ M$, the equations have infinite solutions unable to be calculated. Nevertheless, in a particular circumstance, since vector (signal) x only has k nonzero elements corresponding with vector S in the transform domain, it is sparse. When the number of samples is large enough, the value of k nonzero elements can be accurately reconstructed by means of the value of vector y [10]. Next we will determine the number of samples, namely the value of M. The theory of compressive sensing reveals that, when the number of samples M satisfies the following formula, high-precision reconstruction can be achieved.

$$M \geq \delta \cdot k \cdot \log(N / k) \tag{4}$$

There into, the δ is the positive constant, the N is the length of the signal x and k is the sparseness. As is proved, when the number of the value of the acquired monitoring signals in Gaussian independent and identical distribution satisfies Formula (4), the solutions to the equations can be precisely reconstructed through finding the optimal l_0 norm solutions, that is:

$$\min \|S\|_0 \quad s.t. \quad y = \theta S \tag{5}$$

There into, $\|s\|_0$ is the l_0 norm, $\theta = A \cdot W$, $\theta \in R^{M \times N}$. However it is also disastrously difficult to find the solution in the approach of the minimum l_0 norm. David Donoho has proved that in the case of sparse signals, the optimal solutions of the l_0 norm and the l_1 norm in the target function in the constrained space border on each other. So the l_1 norm can be applied for reconstruction and optimization in engineering application, that is:

$$\min \|S\|_1 \quad s.t. \quad y = \theta S \tag{6}$$

It can thus be seen that signal CS and reconstruction aim to solve convex constrained optimization problems so as to reconstruct the original monitoring data x acquired by the SN:

$$x = w^{-1} \cdot S \tag{7}$$

3.2. Spectrum Sensing Algorithm of Sensor Node

Generally, the WSNs uses common wireless channel to transmit monitoring data. However, the number of common wireless channel is very limited. For instance, there are sixteen channels of 2.5GHz frequency band in 802.15.4 protocol. In order to avoid disturbance between adjacent SNs when sending monitoring data, only eight channels are selected [11]. Therefore in the design, the spectrum sensing algorithm of cognitive radio theory is invited into the WSNs so as to solve the issue of lack of channel resources [12].

Currently, there are mainly two kinds of wireless communication channels: common channel and authorized channel. Authorized channel refers to give authority of one frequency band to a authorized customer who enjoys free communication in the authorized channel. However, the FFC's investigation shows that in practical application, many authorized frequency bands stays idle state because of the customer rarely used resulting in waste of wireless channel resources [13]. The theory allows secondary user accessing to idle authorized channel to communicate without disturbing primary user's communication normally. When primary user needs to use the authorized channel, the secondary user will exit immediately; meanwhile it begins to search other idle authorized channels by spectrum sensing algorithm. Once other idle channel was searched, the wireless module of the SN adjusts frequency parameter to accessing the channel. On the following page will expound how the SN uses spectrum sensing algorithm to access to authorized channel.

Among the several spectrum sensing algorithms, energy detection algorithm is the most widely used [14]. Energy detection algorithm refers to calculate energy value of the signals which were acquired by the SN in the channel, and then channel state is judged through comparing calculation result with predefined threshold [15]. Channel is considered idle when the acquisition signal's energy value is smaller than threshold; on the contrary, the channel is being used by primary user [16, 17]. Energy detection algorithm is a detection algorithm for no coherent signals based on binary hypothetical model whose mathematical model can be shown as:

$$\begin{cases} H_0 : y(k) = n(k) \\ H_1 : y(k) = h \cdot p(k) + n(k) \end{cases} \quad k = 1, 2, 3, 4, \cdots, N \tag{8}$$

In the formula, the $y(k)$ stands for acquisition signals of the channel acquired by the wireless module; the $p(k)$ stands for acquired primary user's signals; the $n(k)$ stands for noise signals in the channel; Here, assuming the noise signals are additive white Gaussian noise signals which subject to mean 0 and variance δ_n^2; the h stands for gain of the wireless channel. The H_0 and the H_1 respectively stands for channel idle and channel occupied. The statistical value Y in the energy detection algorithm can be shown as:

$$Y = \frac{1}{N}\sum_{i=1}^{N}\left|y_i(k)\right|^2 \tag{9}$$

In formula (9), the N stands for the number of sampling point. As we know, when the value of N is large, the Y follows normal distribution approximately by the central limit theorems. Here we have:

$$Y \sim \begin{cases} N\left(\delta_n^2, \frac{2\delta_n^4}{N}\right) \text{---------}\rightarrow H_0 \\ N\left(\left(\delta_n^2+\delta_p^2\right), \frac{2\left(\delta_n^2+\delta_p^2\right)^2}{N}\right) \rightarrow H_1 \end{cases} \tag{10}$$

There into, the δ_p^2 stands for signal power of the primary user. Therefore, the detection probability P_d and the false alarm probability P_f can be obtained:

$$P_d = Q\left(\sqrt{\frac{2}{N}}\frac{\lambda-\left(\delta_n^2+\delta_p^2\right)}{\delta_n^2+\delta_p^2}\right) \tag{11}$$

$$P_f = Q\left(\sqrt{\frac{2}{N}}\frac{\lambda-\delta_n^2}{\delta_n^2}\right) \tag{12}$$

In the formula, the λ stands for energy detection threshold; the $Q(\cdot)$ stands for Generalized Qom function, which can be shown as:

$$Q(t) = \frac{1}{\sqrt{2\pi}}\int_t^{+\infty} e^{-\frac{\tau^2}{2}} d\tau \tag{13}$$

When the false alarm probability P_f is given, the energy detection threshold the λ can be obtained:

$$\lambda = \left(\sqrt{\frac{1}{N}}\cdot Q^{-1}\left(P_f\right)+1\right)\cdot\delta_n^2 \tag{14}$$

4. Design of the Sensor Node of the Multi-Channel WSNs

Due to the complexity of the working environment and diversity of the monitoring physical quantities for the WSNs, the SN requires high stability, noise immunity, lower power consumption and higher measurement accuracy. Therefore the SN in the design should be focus on the power consumption, scalability, monitoring data transmission efficiency and data sampling accuracy.

Hardware structure of the SN is also different from traditional SN, because of compressive sensing algorithm and spectrum sensing algorithm were used in the design. Its hardware schematic diagram is shown in Figure 2.

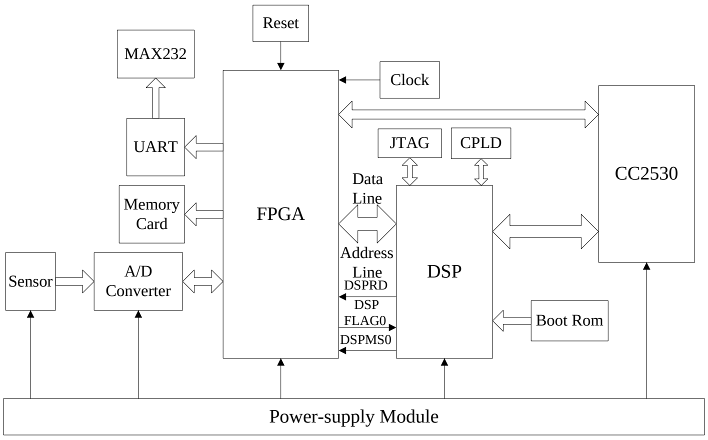

Figure 2. The Hardware Schematic Diagram of the SN

The figure 2 shows that the SN is mainly composed of the monitoring data acquisition sensors, the analog to digital converter, the digital signal processor (DSP), the low-power field-programmable gate array (FPGA), and the wireless communication module.

The main function of the SN includes: monitoring data acquisition, data processing, data compression, communicate with the monitoring center and other SNs, etc. According to the functions it could be achieved, the sensor node is divided into four functional modules include: a data acquisition module, the control and data processing module, a wireless communication module and a power supply device [2, 18]. Next, the specific design of each module will be individually discussed in detail, including its hardware structure, work processes, works principles and linkages between modules, etc. Schematic diagram of function of the SN is shown as figure 3.

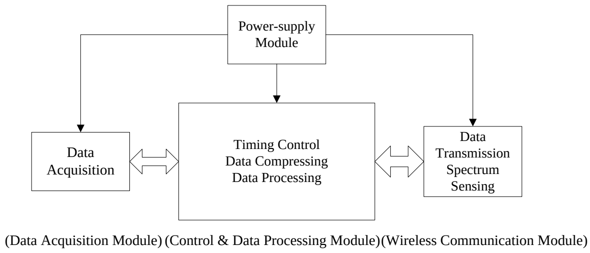

Figure 3. Schematic Diagram of Function of the SN

The data acquisition module includes: monitoring data acquisition sensors, signal conditioning circuits, programmable amplifiers, A/D converters. The module is responsible for acquiring the needed data from the monitored target, then the data will be amplified, A / D conversion, noise filtering and other processing in order to meet the requirements of the data processing and communication.

The control and data processing module including: DSP, FPGA, UART, and their peripheral circuits. The module as the control SN is responsible for the management of the SN, to provide sequential control for data collection, data sampling, spectrum sensing, communications and other operations. In addition it also acts as a processing core responsible for calculations of energy value of signal in the channel and monitoring information extraction.

Wireless communication module is responsible for communicating with monitoring center and other SNs, and the mission of spectrum sensing. The module uses ZigBee, a kind of short-range, low-power wireless communication technology, based on the IEEE802.15.4 transfer protocol [19]. ZigBee's power consumption is very low and most of the time in a dormant state, so it is very suitable for WSNs. Because of its communication distance is limited, multi-hop communication model is selected in the design. The model has the advantage of easy to expand and strong anti-interference ability. The CC2530 was chosen as ZigBee chips in the wireless communication module. The chip has the functions of energy detection of signal can be applied to spectrum sensing algorithm and it is very easy to use and effective [20].

Design of the power supply device: Because of the SN used of chips are mostly low-power chips or working in low-power mode in the design, so use the battery as the power supply of the sensor nodes can meet their work requirements. This design could greatly enhance the flexibility of SN deployment.

5. Field Testing and Testing Data Analysis of the Multi-Channel WSNs

In order to test the design of wireless sensor networks for monitoring performance, we conducted field tests. In this field test, the power plant of the ship is selected as the monitoring target, monitors vibration information generated by the rolling bearing in the power plant rotating at the time of acceleration. We collect vibration signals by ADXL001-70 rotational acceleration sensor. To improve the monitoring accuracy we amplified the monitoring data by the programming gain amplifier after AD conversion. PGA113 chip is chosen as programmable gain amplifier in the design [21]. Its hardware schematic diagram is shown in Figure 4

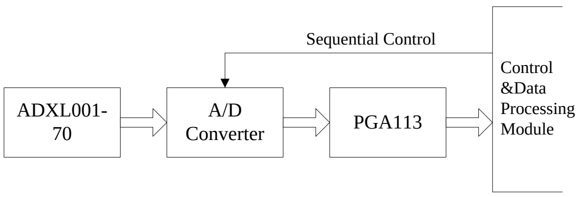

Figure 4. Hardware Schematic Diagram of Data Acquisition Module

The monitoring process for the multi-channel WSNs is that the SNs start the initialization after power up, then the WSNs is built up according to the developed multi-channel wireless network transport protocol. After the WSNs were set up, the monitoring command is issued to each SN by the monitoring center. Based on that orders, the ADXL001-70 begins to collect vibration data. Experiencing the process of amplification, filtering and AD conversion, and the collected vibration data can be converted into the noise-free digital signals. Furthermore, the digital signals are compressed by using the compressive sensing algorithm. All previously mentioned work was finished under the control of the FPGA. In addition the FPGA controls the process of energy detection of the channels. Firstly, the energy value of signals in the channel which received by the CC2530 is calculated by DSP based on the energy detection algorithm. Then, DSP compares the calculated value with the threshold value to determine whether the channel is idle. If the channel is idle, the CC2530 adjusts frequency parameters according to the channel, and transmits the compressed vibration data to the monitoring center.

In order to test the monitoring accuracy of the WSNs, two sets of monitoring data are compared and analyzed. One is collected by any SN in the WSNs and the other is obtained from the high precision data acquisition card (HPDAC) in the same monitored area and the same time period. The time-domain graph of the vibration data collected by the WSNs is shown in Figure 5.

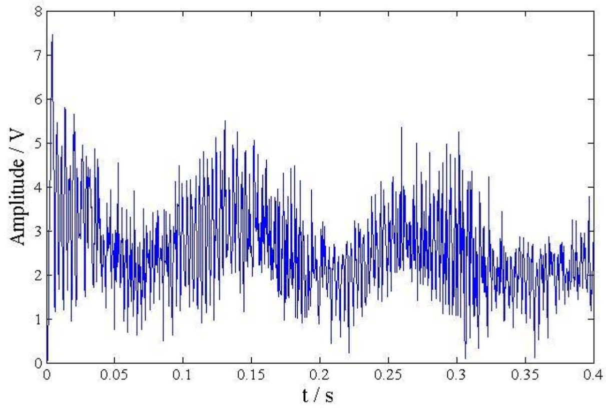

Figure 5. The Time-Domain Graph of Vibration Data

For the digital signals obtained by sampling the collected vibration data, the sampling frequency is 5120Hz, and the numbers of sampling points are 2048. The spectrum of the vibration signals collected by the multi-channel WSNs after FFT is shown in Figure 6.

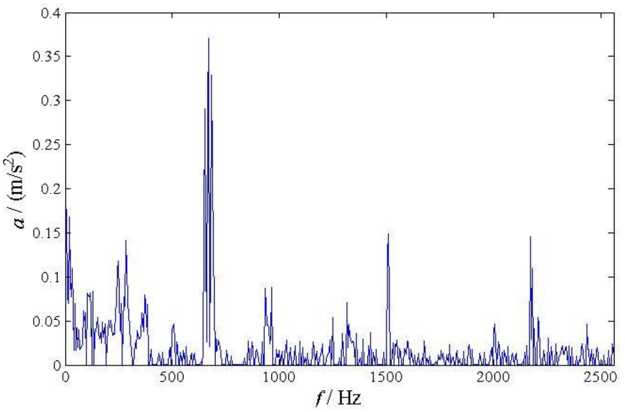

Figure 6. The Spectrum of the Monitoring Data Collected by the WSNs

The spectrum of the vibration data collected by the HPDAC after the same processing is shown in Figure 7.

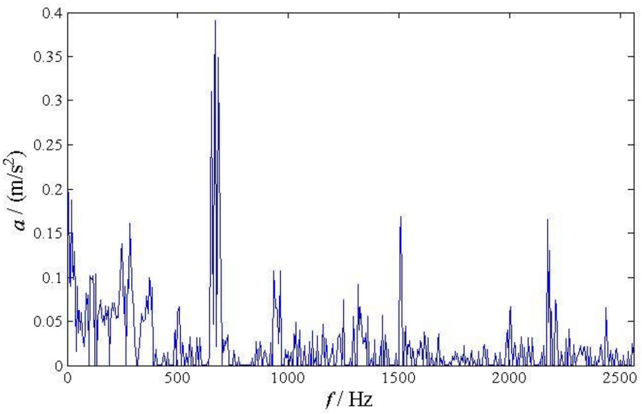

Figure 7. The Spectrum of the Monitoring Data Collected by the HPDAC

By comparing the Figure 6 and Figure 7, it can be seen that the two spectrums of the monitoring data are basically identical. The frequency errors of several key information points are very small with slight difference in the amplitude. The difference was caused by the energy attenuation during the transmission of the monitoring data in the WSNs, and it will not affect the accuracy of the monitoring information. The values of frequency and amplitude of the key information points in the spectrum, as well as their errors are shown in Table 1.

Table 1. Comparison of the Amplitude Value Error & the Frequency Error of Main Information Points of the Spectrum Line

Comparison of the frequency values			Comparison of the amplitude values		
HPDAC/Hz	WSNs/Hz	Error/%	HPDAC/ $m \cdot s^{-2}$	WSNs/ $m \cdot s^{-2}$	Error/%
260.75	260.86	0.42	0.1648	0.1619	1.75
693.97	693.90	0.01	0.3914	0.3840	1.89
985.14	985.20	0.01	0.1189	0.1077	9.31
1507.57	1508.14	0.37	0.1777	0.1741	2.02
2187.10	2187.37	0.02	0.1769	0.1704	3.68

By the results shown in Table 1, it can be illustrated that the multi-channel WSNs could accomplish monitoring tasks with higher accuracy.

6. Conclusion

A novel multi-channel WSNs model was designed in the paper to reduce power consumption and improve communication efficiency. The reasons of high power consumption and low communication efficiency in the traditional WSNs are firstly analyzed. It is found that the communication collision resulted by the wireless channel competition which may led to the failure of data transmission is the main reason. Then several improved methods to reduce the probability of communication collision are proposed. Firstly, selecting a reasonable channel resources allocation protocol is essential. Then the monitoring data transmission time is shortened based on the improved sampling method by using the compressive sensing algorithm, and the amount of the wireless channels are increased by using the spectrum sensing algorithm. According to the above improvement, a new SN model in the multi-channel WSNs is designed, including hardware design and program design. The working principle of each part in the new SN is described clearly in the paper. Finally, the field test of the designed WSNs was completed. By analyzing the time domain and frequency domain characteristics of the obtained data, it is shown that the multi-channel WSNs can implement a higher precision monitoring.

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Author

Ma Naji, (1981) Male, PhD student, research interests: wireless sensor network, reducing network power consumption, monitoring signal processing.