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Design of low energy consumption multi-channel wireless senor networks for monitoring mechanical vibration signals

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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]. Currently, WSNs is widely used in industry, agriculture and many other fields [2].

Traditional single channel model is used in WSNs widely. The communication model uses a fixed communication frequency to transmit monitoring data. 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.

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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.

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 [3], 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 is 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.

3 Algorithm designs 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. 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.

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. [4]

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 a 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 [5]. 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 [6]. 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. Therefore, in the design the spectrum sensing algorithm of cognitive radio is invited into the WSNs so as to solve issue of lack of channel resources [7].

Currently, there are mainly two kinds of wireless communication channels: common channel and authorized channel. 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. Once other idle channel was searched, the wireless module of the SN adjusts frequency parameter to accessing the channel.

The 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 [8]. Energy detection algorithm is a detection algorithm for noncoherent 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:

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

(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:

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

(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:

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

(11)

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

(12)

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

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

(13)

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

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

(14)

4 Design of the sensor node of the multi-channel WSNs

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 Fig. 1.

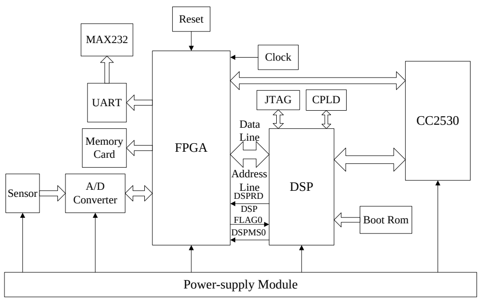

Fig .1. The hardware schematic diagram of the SN

The figure 1 shows that the SN is mainly composed of monitoring data acquisition sensors, analog to digital converter, digital signal processor (DSP), low-power field-programmable gate array (FPGA), and 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.

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.

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 [9]. 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 [10].

5 Field testing and testing data analysis of the multi-channel WSNs

In this field test, the power plant of ship is selected as the monitoring target. 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 [11].

The monitoring process for the multi-channels WSNs is: The SNs to start the initialization after power up the WSNs is set up accordance with the development of multi-channel wireless network transport protocol. After the wireless sensor network set up was completed, monitoring orders are issued by the monitoring center to each SN, began to collect vibration data by the ADXL001-70; the collected vibration data were processed with amplification, filtering, and AD conversion to obtain noise-free digital signals; by using compressive sensing algorithm, the digital signals were compressed; these work processes were controlled by the FPGA of the control and data processing module. In addition the FPGA also controls the process of energy detection of the channels; the DSP computes energy value of signals in the channel which was received by the CC2530 by using the energy detection algorithm; comparing the calculation result and the threshold value to determine whether the channel is idle; when judging the channel is idle, the CC2530 adjusts frequency parameters to the channel used for transmitting the compressed vibration data to the monitoring center.

In order to test the wireless sensor networks for monitoring accuracy, we compare and analyze two sets of monitoring data which were collected respectively by the WSNs and the high precision data acquisition card (HPDAC) in the same monitored area and the same time period.

The digital signals obtained by sampling the collected vibration data; the sampling frequency is 5120 Hz; and the sampling points to 2048 points. The spectrum of signals obtained by using the FFT is shown as Fig. 2.

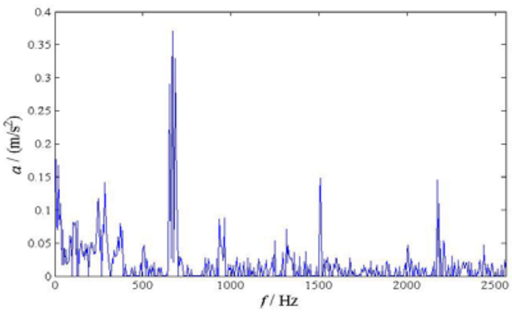

Fig .2. The spectrum of the monitoring data collected by the WSNs

The spectrum of the vibration data collected by the HPDAC after the same processing is shown in Fig.3.

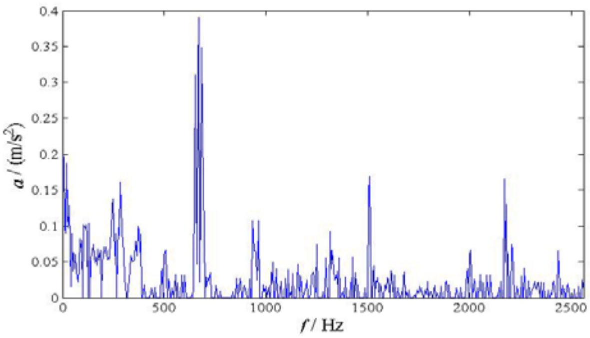

Fig .3. The spectrum of the monitoring data collected by the HPDAC

By comparing the Fig. 2 and Fig. 3, 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

5 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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