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Investigation of Wireless Protocols for Remote Condition Monitoring

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ABSTRACT

Condition monitoring (CM) is an effective strategy to maintain the performances of modern industrial machines. Currently, wired online condition monitoring has been successfully employed in large industrial machines. However, the high cost of these systems have restricted their wide applications, among which, the installation and maintenance cost of the communication cables are one of the major factors. With the quick development of the wireless and electronics technology, communication cables could be replaced by wireless transmission, which brings several inherent advantages, such as low cost, convenience of installation and easy to replace or upgrade. One key issue of implementing wireless communications in CM system is the selection of suitable wireless protocols. In this paper, the current popular wireless protocols and their applications in CM are investigated. IEEE802.15.4 is proved to be the most suitable protocol to establish wireless CM systems because of its low power consumption, low cost and its capability of setting up large scale networks. In the meantime, its bandwidth limitation can be overcome by a scheme of embedding more local processing. To evaluate the scheme, a prototype wireless CM system is developed to embed the algorithm of envelope analysis into the node for rolling bearing monitoring. The results show that the amount of data communication over the wireless network can be reduced by 95% while it upholds the performance to monitor the simulated bearing fault in real-time.

Keywords: Condition monitoring, IEEE802.15.4, ZigBee, Envelope analysis, Local processing

INTRODUCTION

Condition monitoring (CM) is an effective strategy to maintain the performance of modern industrial machines. It provides the optimal maintenance actions according to the actual conditions of the machinery to prevent the unexpected catastrophic faults and thus improve the system’s reliability. As the industrial machines are getting increasingly complicated, the maintenance cost has been snowballing. It is estimated that approximately half of operating costs in most processing and manufacturing operations can be attributed to maintenance [1]. Currently, wired online CM systems have been successfully employed in industrial fields. However, their applications have been restricted to large industrial machines and the testing points are quite limited due to the high cost, which results the testing system cannot cover the entire detection area and some important signals may be lost.

The installation and maintenance cost of the communication cables is one of the major costs of the wired online CM systems. Sometimes, the installation cost may be even higher than the cost of the sensor, particularly for remote monitoring [2]. Fortunately, with the quick development of wireless and electronics technology, communication cables could be replaced by wireless transmission. This brings many inherent advantages, such as relatively low cost, convenience of installation, and easy to upgrade. These merits make a low-cost CM system possible. One key issue in applying wireless communications in CM systems is the selection of suitable wireless protocols. In the past few years, wireless networks have gained enormous developments and a variety of wireless protocols have sprung out, such as 2G/3G/4G mobile communication, Wi-Fi, Bluetooth, UWB, ZigBee, etc. They are replacing the traditional wired communication methods in their own specific areas, and have brought great benefits to our routine work and daily lives, as well as the industrial fields.

These wireless protocols are designed for different kinds of applications; therefore, the specifications such as signal range, transmission speed, cost and power consumption, etc. are quite different. This paper investigates kinds of popular wireless protocols and their potential applications in the industrial CM area, based on which, IEEE802.15.4 is considered to be the most suitable. Three protocols based on IEEE802.15.4 are further reviewed in section III and the state-of-the-art wireless network chips are listed and compared. In order to testify the local implementation of envelope analysis for rolling bearing fault diagnosis, an improved wireless node is proposed and tested in section IV. Finally, section V presents the conclusions.

Overview of Wireless Protocols and Their Applications for CM

Wireless network standards can be divided into four specific groups according to their application area and signal range [3]: wireless wide area network (WWAN), wireless metropolitan area network (WMAN), wireless local area network (WLAN) and wireless personal area network (WPAN), as shown in Figure 1. For the selection of applying wireless protocols in CM systems, the data transmission speed, cost, power consumption, security and the ability to establish large scale networks are the main factors need to be considered. The preferred wireless protocol should be able to setup large scale networks with relatively high transmission speed, low cost, low power consumption and high security.

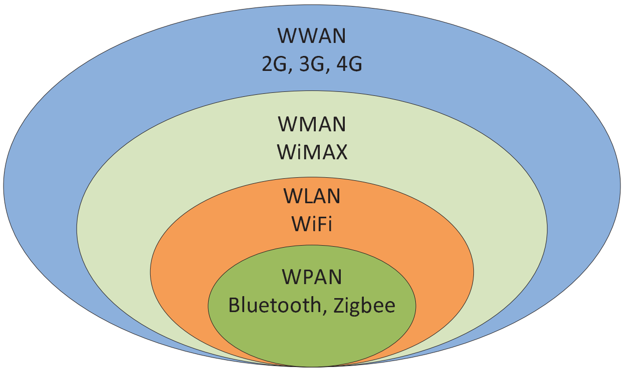

Figure 1 Wireless networks division

A. Wireless Wide Area Network (WWAN)

When talking about wireless network, cellular network is the most familiar one. It is a kind of WWAN that provides the possibility to create wireless connections in a wide geographic area. As the most commercially successful wireless networks, cellular networks have come through four generations in the past several decades. Meanwhile, the transmission speed and quality have increased with the generations. At first, the data services, such as General Packet Radio Service (GPRS) can only offer a maximum upload speed of 20kbps. Nowadays, this figure of third generation (3G) has reached 2 Mbps, and the coming fourth generation (4G) will bring a maximum speed up to 500 Mbps.

The transmission speed of cellular networks is satisfactory for transferring the measured data in CM systems; however, several drawbacks do exist. Firstly, the data traffic is not free, which will bring an ignored cost for transferring the dataset. For the CM system with large scale and great dataset, the service cost may exceed the cost of the system itself. Secondly, the high data rate can only be accessible in major urban areas and the achievable data rate at a particular location, also depends on the number of users, which indicates the data rate may be unstable. Finally, the power consumption is also high due to its long communication distances to the base station.

Considering their popularity in our daily life, the cellular networks can be used to send important warnings, in which case the data amount is not large but could be timely. Hai-Bao Mu, etc. [4] used GPRS to report leakage current analysis results from the remote on-site unit to the expert diagnosis system, in which way, the monitoring no longer subjects to distance restrictions. A wireless sensor was developed in [5] to monitor the load current and transformer oil temperature of the prefabricated substations. In this system, once threshold values exceeded, short message service (SMS) were sent to a cellular phone, thus the operator could be informed in time.

B. Wireless Metropolitan Area Network (WMAN)

WMAN is the official name trademarked by the IEEE 802.16 Working. However, the expression worldwide interoperability for microwave access (WiMAX) is more frequently used. WiMAX is aimed to provide broadband internet connectivity for WLANs and LANs with the wireless access point, therefore, it is often called the technology for the last mile access. The maximum theoretical data rates for WiMAX are 75Mbps, with this number dropping with respect to distance from the base station. Recently, WiMAX has become a part of 4G mobile communication.

C. Wireless Local Area Network (WLAN)

WLAN is created for computer-to-computer connections as an extension or substitution of cabled networks. Comparing to WLAN, the name of Wi-Fi is more popular in the real world. Second only to cellular networks, it is the most commercially successful wireless data network. WLAN was first published in 1997 and has been amended several times since then. Its transmission speed has increased from the initial 11Mbps to the newest 300 Mbps.

This protocol is fast enough for the CM system, which is a significant advantage; however, the high cost and high power consumption have restricted its wide applications in CM systems. In general, Wi-Fi is suitable for continuous CM measurements where a power supply is available. Hongmei Wu and Li Liu [6] proposed a remote monitoring system for mine vehicle, in which system Wi-Fi is used to transfer pressure, velocity, mileage and oil level value data. The system was proved to be helpful in improving the mine vehicles' transportation efficiency and security. One noticeable data acquisition product named WiVib 4/4 Wireless Surveillance Pod [7] is already on the market. It adopts the IEEE802.11b protocol and is capable of processing four channels of vibration with the maximum frequency increments at 20 kHz.

D. Wireless Personal Area Network (WPAN)

WPAN are usually characterized by short-range and low-power. The possibility of ad-hoc mode connection is an advantage of these networks. They have been widely used and gained success in the area of wireless sensor networks (WSNs) which mainly feature on low rate, low cost, restricted energy and short distance transmission. According to IEEE standard, there are mainly three popular protocols in WPAN: IEEE802.15.1 (e.g. Bluetooth), IEEE802.15.3 (e.g. Ultra wide band) and IEEE802.15.4 (e.g. ZigBee, WirelessHART).

Bluetooth

Bluetooth is a proprietary open wireless technology standard for exchanging data over short distances. It is intended for a cordless mouse, keyboard, and hands-free headset. The classic Bluetooth provides a maximum data rate of 3 Mbps within a range of about 10 meters and the high speed version could offer up to 24 Mbps speed over 1 meter range. Bluetooth has been considered as one alternative for WSN implementation, however, the interest toward Bluetooth-based WSN applications has decreased due to its high complexity and inadequate power characteristics for sensors [8]. An extension version named Bluetooth-Low-Energy is an ultralow-power technology addressing devices with very low battery capacity. It allows for data rates of up to 1 Mbps over distances of about 50 m. Nevertheless, Bluetooth network can only contain one master and 7 slave devices, which has limited its application for setting up large scale networks.

Ultra wide band (UWB)

UWB is a short-range wireless communication technology oriented to setup high-bandwidth within a few meters [9]. One of the most exciting characteristics of UWB is its high bandwidth up to 480Mbps, which can satisfy most of the multimedia applications such as audio and video delivery in home networking and can also act as a wireless cable replacement of high speed serial bus such as USB 2.0 and IEEE 1394. Moreover, it has excellent security characteristics due to its unique mode of operation. However, the communication range is rather limited and the cost is also high for setting up a large scale CM network [10].

IEEE802.15.4

IEEE 802.15.4 standard can trace back to the low-rate wireless personal area networks (LR-WPAN) standard, which was fuelled by the need to enable inexpensive WSNs for remote monitoring and control of noncritical functions in the residential, commercial, and industrial applications. It is designed to provide simple wireless communications with relatively short range, limited power, relaxed data throughput, low cost, and small size. Table 1 gives the basic specifications for IEEE802.15.4. The maximum data rate of IEEE802.15.4 is 250kbps, which could satisfy the requirements of remote monitoring system with static parameters, such as temperature, pressure and humidity. However, this speed is too low for the data transmission of dynamic signals like vibration.

Table 1 Basic IEEE 802.15.4 standard details

Frequency band (MHz)	Coverage	Maximum theoretical data rate (kbps)	Channels
868.0-868.6	Europe	20	1
902-928	Americas	40	10
2400-2483.5	Worldwide	250	16

Fortunately, the idea of local processing has brought an alternative solution, in which way, the raw data are processed on the sensor and only the processing results are sent through the network. Therefore, the load of the network could be relaxed. Hou and Bergmann [2] successfully used the ZigBee network to monitor the operating conditions of a motor. In this system, 512 points fast Fourier transform (FFT) were performed on the vibration signal and 12 most frequently occurring frequency components were extracted in the frequency domain as the fault feature for data transmission. Combined with data fusion methods, the payload transmission data were reduced by more than 99%.

Based on the discussions above, IEEE802.15.4 is proved to be the most suitable protocol to setup large scale CM networks and will be further discussed in the next section.

Further Investigation on IEEE802.15.4

IEEE 802.15.4 only specifies the physical layer and media access control (MAC) layer. Several protocols have extended the standard by developing the upper layers that are not defined in IEEE802.15.4. Among them, ZigBee, WirelessHART, and ISA100.11a are the most popular protocols. ZigBee has achieved wide acceptance and success in building automation, home automation, embedded sensing, and energy system automation. The good characteristics of ZigBee include extremely low energy consumption and support for several different topologies, which makes it a good candidate for several sensor network applications [8]. GST [11] has announced wireless vibration data acquisition device based on ZigBee. WirelessHART and ISA100.11a are two competing protocols separately designed to address the critical industrial requirements for reliable, robust and secure wireless communication. Currently, ABB [12] and Emerson [13] have published wireless data acquisition products based on WirelessHART while GE [14] and Honeywell's [15] products have adopted ISA100.11a.

In comparison, WirelessHART and ISA100.11a are able to communicate simultaneously with current wired protocols and can be easily integrated with other wired protocols while ZigBee does not support wired protocols. Radmand, etc.[16] indicated that WirelessHART and ISA100.11a are more suitable for industrial applications because they behave better than ZigBee in the respect of reliability and latency determinisms. However, implementing these two protocols are quite challenging and the stable modules integrating these two protocols are still limited.

Attracted by the great potential markets, semiconductor manufacturers have provided system on chip (SOC) wireless chips, which include both the microcontroller and the RF components. Due to the necessity for processing data with high sampling rate, chips with high performance and large memory are preferred in CM systems. Table 2 lists the state-of-the-art high performance SOC wireless chips from leading IC companies. As it shows, various CPU structures have been adopted, from the earliest 8 bit 8051 core to the latest Cortex-M4 architecture. For high computing capability and low power considerations, the latest Cortex-M3 or Cortex-M4 core tend to be adopted. Among these chips, KW20 from Freescale has the highest performance, which adopts the latest Cortex-M4 core running at the maximum speed of up to 50MHz. Data memory is another important factor that influences the computing capability and JN5148, MC13226, LTC5800 and KW20 outstand themselves in this aspect. From the view of protocol supporting, most of these chips provide solutions for ZigBee or 6LoWPAN and only LTC5800 has provided the solution for WirelessHART.

Table 2 SOC wireless chips

Corporation	RF Module	Processor			
		Architecture	**Flash (KB)**	**Data (KB)**	**Speed (MHz)**
TI	CC2530	8bit, 8051 core	256	8	32
	CC2538	32 bit, Cortex-M3	512	32	32
Freescale	KW20	32 bit, Cortex-M4	512	64	50
	MC13226	32 bit, ARM7	128	96	26
	MC13237	8-bit, HCS08	128	8	32
Silicon Labs	EM357	32bit, Cortex-M3	192	12	24
ST	STM32W108CC	32bit, Cortex-M3	192	16	24
NXP	JN5148	32 bit, RISC	128	128	32
	JN5168	32 bit, RISC	256	32	32
Atmel	ATmega256RFR2	8 bit, AVR	256	32	16
Radio Pulse	MG2470	8 bit, AVR	64	6	16
Linear Technology	LTC5800	32-bit,Cortex-M3	72	512	20

Considering the complexity of realizing wireless protocols and setting up wireless networks, several specialized companies have provided ready-to-use solutions to ease the development process. The Xbee wireless RF module is an outstanding one of these solutions. It provides a variety of wireless solutions, such as ZigBee, IEEE802.15.4, and Wi-Fi communication. By using the X-CTU tool provided by the company, the configuration of the module can be easily achieved. After being properly configured, the modules will set up a network automatically. Moreover, these modules are pin-to-pin compatible with one another, which means the wireless protocol could be easily upgraded by utilizing different kinds of Xbee modules.

Proposed Wireless Sensor Node Design and Test Results

Based on the investigations above, it is proved that IEEE802.15.4 is the most suitable protocol for setting up wireless CM networks and local processing has brought an alternative solution for enlarging its application to dynamic signals collected with high sampling rate. In order to estimate the local implementation of CM algorithms embedded on the wireless sensor, a preliminary wireless CM system for rolling bearing has been setup.

The rolling bearing test rig is shown in Figure 2. A faulty rolling bearing with a scratch on the outer race is put inside the bearing house. When the bearing is running, the scratch will be rolled over periodically, which results in a fault signal modulated by a carrier signal at the resonant frequency of the bearing house [8]. The detection of this bearing defect is to extract the modulating frequency signal. However, this early stage defective signal tends to be masked by machine noises, which makes it difficult to detect the fault by the traditional spectrum analysis alone. Envelope analysis is an effective method to extract this kind of faults [17], therefore it will be implemented on the wireless sensor node.

In order to focus on the algorithm realization, the Xbee module for ZigBee protocol is chosen to setup the wireless network and a LaunchPad board with 32-bit Cortex-M4 processor is adopted to implement the local processing algorithms. The LaunchPad board together with one Xbee module acts as a wireless node and the other Xbee module acts as the sink node. The system works as follows: A piezo-electric (PE) accelerometer mounted horizontally to the bearing house senses the vibration signal. After being conditioned by a charge amplifier, the signal is connected to the on-board analog-to-digital converter (ADC) of the LaunchPad. Then, the envelope analysis algorithm is implemented on the collected data and the processing results are wirelessly transmitted to the sink node. Finally, the data are sent to the personal computer (PC) via a USB-to-TTL. On the PC host, matlab is used to receive and display the data from the sink node.

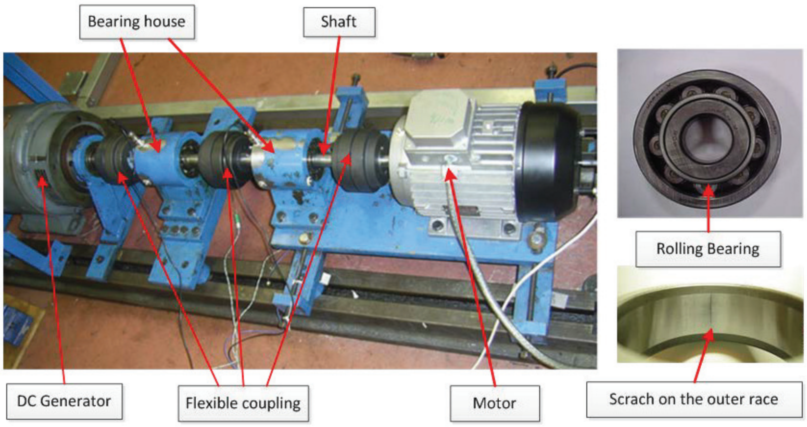

Figure 2 Bearing test rig and the faulty bearing

The generation mechanisms of faults on the inner race, cage and balls are similar to the outer race fault and these fault frequencies can be theoretically calculated [17]. In the experiment, the shaft runs at the speed of 1460 revolutions per minute (rpm). After being calculated, the inner race fault has the highest frequency at about 135.5Hz and the outer race fault has the second highest fault frequency at about 83Hz. Obviously, up to the 3rd harmonics of these four faults are all within 500Hz. Therefore, a band-pass filter with the bandwidth of 1 kHz is applied in the envelope analysis to enhance the signal to noise ratio (SNR). For this bearing rig, the effective band of the envelope spectrum is restricted to lower than 500Hz, so only data in this spectrum band need to be sent through the wireless network for further diagnosis.

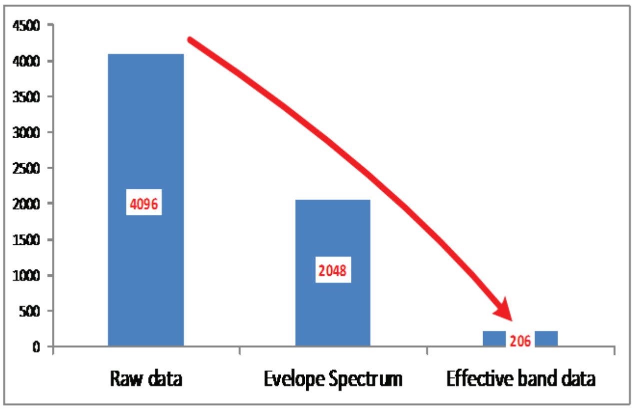

Figure 3 Comparison of the data amount

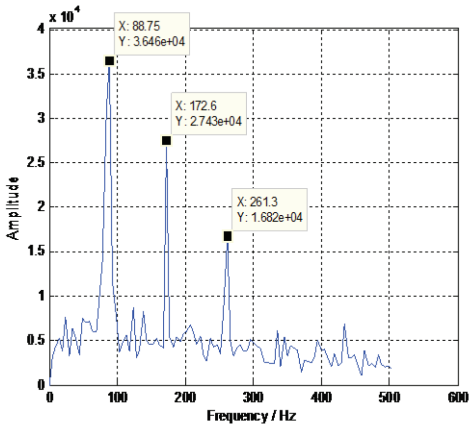

Figure 4 Matlab display results on the PC host

In the test, the sampling rate is set at 10 kHz and 2048 points of data (stored with 16-bit resolution) are processed per frame. Figure 3 shows the data amount in different processing stages. Only 103 points of spectrum data are transmitted over the air, which contributes a significant reduction of nearly 95% and the data output rate is reduced to approximately 8 kbps. Since the bearing's state is relatively stable in a short period, the transmitted results of neighbouring frames contain a host of redundant data. Therefore, averaging in the frequency domain can be employed to further reduce the amount of data for transmission. If the analysis results are averaged by four times, the output rate will be reduced to only 2 kbps. Figure 4 gives the matlab display results on the PC host. It can be seen the three peak frequencies roughly match the fault frequency of the outer race, its 2nd and 3rd harmonic frequencies respectively. In other words, the outer race fault information can be detected based on this wireless CM system.

CONCLUSIONS

Because the low power consumption, low cast and large scale network capability, IEEE802.15.4 is advocated to be the most suitable protocol for developing wireless CM systems. As shown by the preliminary test, the local implementation of the envelope analysis algorithm allows the data transferred in the wireless network to be reduced by 95%. Meanwhile, the outer race fault of the rolling bearing can be successfully detected in real time. Due to the similar fault generation mechanisms, faults on the inner race, cage and balls of the rolling bearing could also be effectively identified using this wireless CM system. Furthermore, local processing on the wireless sensors brings great flexibility on implementing CM algorithms and enlarges the wireless CM applications to dynamic signals collected with high sampling rate. However, the ZigBee protocol adopted in this study may not be the best protocol for industrial applications and hence WirelessHART or ISA100.11a could be attempted for wireless condition monitoring in future works.

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