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MRM: Wireless Sensor Network for Online Milling Roller Monitoring in Harsh Industrial Environment

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Abstract: Roller is a key component of milling machine in iron and steel industry, with the development of industrial wireless technology. The online predictive maintenance of the roller plays an important role in effective production. But the harsh working environment – spray of cooling liquid, moving, high temperature and heavy shelter – cause low quality of wireless communication and need high reliability. The paper proposed a novel roller monitoring system based on star/mesh topology, which use 2.4 GHz in mesh subnet and 433 MHz in star subnet to avoid interference between nodes in large scale networks. The paper designed a self-organized multi-channel link layer protocol optimized network flexibility and power consumption under high reliability. The system was deployed in the real iron and steel plant to monitor support roller of strip mill with one years, which shown a high reliability and low power consumption, and improved the efficiency of the roller maintenance. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor network, Milling roller monitoring, MAC protocol, Predictive maintenance.

1. Introduction

Wireless sensor networks has been deployed in many areas [1], especially, industrial wireless sensor networks have been rapid developed in recent years [2-4]. Because of the harsh industrial environments and the blocking led by the layout of the factory, communication is easily interfered. Reliability has been the first requirement in industrial wireless application like equipment monitoring, feedback control etc. In process industrial like steel or chemical production, which equipped with expensive equipment and the quality control has big relationship with the working condition of those equipment. The monitoring, maintenance and repair cost huge investments each year. Compared with artificial point inspection, wireless equipment monitoring is an accurate, real-time and low cost way to ensure the safety of the machinery and equipment, improve product quality, and reduce labor working intensity, especially for the moving, rotating points of the production line. Strip mill is the key equipment in the cold rolling production. A typical six high cold mill has six rollers including two support rollers. The temperature of the bearings will go high when there are faults occurred on rollers. On-line temperature monitoring of the bearings is an efficient way to monitor the working condition of the rollers, guide the maintenance and prevent major accidents. Industrial wireless sensor network provides a low-cost, flexible and scalable industrial automation technology, which can eliminate wires, save the time of installation, and provide convenience for maintenance.

The challenge of the roller monitoring in strip mill include:

1) The worst environment of the factory wireless communication. The whole strip mill is covered by steel wall and rollers are under spray of the cooling liquid. Thus, the application scenario needs a low complex but high reliable communication protocol.

2) Mobility of rollers. Since rollers need to be changed periodically, sensor nodes need a self-organized protocol to form topology as soon as possible.

The remainder of this paper is organized as follows. Section II describes the related work. Section III presents the design requirement of the application. Section IV shows the system architecture and the protocol design. Section V, we introduced a real field deployment of the system. We conclude our work in Section VI and future work is also discussed.

2. Related Work

There are increasing deployments in industrial wireless sensor networks especially in equipment pre-maintenance [5]. Suratsavdee Korkua [6] proposed a health monitoring system of electric machine based on wireless sensor network using ZigBee, to obtain higher accuracy in diagnostic for the predictive maintenance of induction motors by vibration detection. Faria SPS [7] proposed a predictive maintenance industrial system to monitor rotating machinery, which integrated two temperature and vibration sensors and two kind networks: a wireless ZigBee network and a wired Controller Area Network (CAN). Paper [8] introduced wireless sensor network to the area of monitoring and protection of oil and gas operations. In addition, the paper proposed a model to provide new tools for research in predictive maintenance and condition-based monitoring of factory machinery. Paper [9] studied MEMS accelerometer based monitoring of machine tool vibrations which shown the relationship of the faults and vibration data, and proposed a MEMS-accelerometer based WSN platform. Paper [10] introduced predictive or condition-based maintenance results on selected rotating equipment at High Flux Isotope Reactor (HFIR), which demonstrated that wireless sensors offer an effective method for monitoring key process conditions continuously and remotely. Albe CLF [11] proposed an IEEE 802.15.4 based WSN to monitor the torque and efficiency in induction motors, which acquires electrical signals from the motor in a noninvasive manner, and then performs local processing for torque and efficiency estimation. Pedro Cheong [12] developed a ZigBee based wireless sensor network node for the ultraviolet (UV) detection of flame. The sensor node was verified when the luminous flame was imaged onto the sensor node with different angles ranging from -30° to 30° and distances of 0.1, 0.2, and 0.3 m enabling effective fire safety applications.

Industrial researches formed three standards: WirelessHART [13], ISA SP100.11a [14] and WIA-PA [15]. WirelessHART is the first wireless standard for industrial applications released by the HART Communication Foundation in 2007, as an extension of HART bus [16]. It uses TDMA schedule in MAC layer based on IEEE802.15.4 and supports mesh topology, which targets the process monitoring and control applications. And WirelessHart has been voted to be the IEC standards in 2011. ISA-100.11a was started by ISA in 2007, which targets for one wireless standards supporting different industrial field bus, not only the HART bus. WIA-PA is the second IEC standards published in 2011. It uses mesh/star topology and two layers network management. All of those standards use TDMA schedule and central network management by Network Manager and support security communication.

Zigbee Protocol used in many literatures is not suite for industrial application because of its low reliability and low guarantee of delay. The industrial standards, which have high reliability and security technologies, are too complex for the application in harsh cool strip mill environment. For the special requirements of the roller monitoring in cool strip mill, we proposed a simple but reliable protocol using two frequency bands and two layer network architecture, which achieves the low power consumption, mobility of the roller and the reliability requirements.

3. System Design

3.1. Design Goals

The roller of the cold strip mill works in relative harsh environment. Steel walls cover the whole strip mill and rollers work under high temperature and spray of the cooling liquid. Sensor nodes are fixed on the end shield of the support rollers, so that the wireless communications of sensor nodes are weak and easy interfered. Sensor node cannot be artificial maintained when the strip mill is working. The support roller will be replaced periodically, which causes online and offline automatically switching of the sensor nodes. According to the environmental characteristics and application requirements, the design goals are as follows:

1) High reliability.

Reliability is the first requirement in industrial applications. Because of the harsh environment of the cold strip mill, the monitoring system needs higher reliability than common industrial wireless applications. Also, it is impossible to maintain the sensor nodes when the sensor nodes are working online. Additional, to quick trace the temperature variation, when the temperature of a sensor node beyond its alarm temperature, it should automatically short the sample period and alarm the manager by sound, light and SMS.

2) Self-organization.

Support roller works in two states: online working and offline maintenance. Sensor nodes mounted on rollers will leave the original network and join the new network when the roller changes its states. Online sensors form a monitoring network, and offline sensors form a maintenance network with a slow communication period to avoid searching network. When a roller goes online, the sensors mounted on this roller will change to online monitoring network quickly. And also, the online sensor nodes maybe change its router to another for the bad communication caused by the dynamic harsh environment. Therefore, compared with general quasi-static network in industrial applications, cold strip mill roller monitoring network has more dynamic changes and needs self-organization protocol.

3) Low power consumption.

Because of the hard replacement and maintenance of the sensor node, the system need low power consumption to reach a long battery life. Typical work life is 12 months under 1 minute sampling period, or 20 months under 5-minute sampling period, or 30 months under 10-minute sampling period.

4) Controllability and reconfiguration.

Different from the common sensor networks, industrial sensor networks, have a special demand for the network controllability and reconfiguration, which make the network management easily. In the application of support roller monitoring, sample period should be adjusted, in a range of 1 minute to 20 minutes with the minimum step of 1 minute. And also, the alarm level of the sensor node should be configured by the network manager. For the system management, information such as battery capacity, communication quality and work states of each node should be displayed in real-time.

3.2. System Architecture

Based on the above requirements, the architecture of the network is designed as shown in Fig. 1.

As shown in Fig. 1, the system is consisted by two parts: mesh subnet and star subnet. Mesh subnet includes cluster heads and sink node, responsible for transferring data form sensor to sink. Star subnet is consisted by sensor nodes and cluster head, which is responsible for the sensor data collection. Mesh and star using different frequency bands and protocols. Mesh subnet uses 2.4 GHz IEEE 802.15.4 [17] compacted device and DJmesh [18] protocol. Star subnet uses 433 MHz ISM frequency band and a new designed simple TDMA MAC protocol. The mesh/star topology divided the network into small area, which is flexible for control and expansion, and avoids the disturbing between sensor nodes and cluster heads by using two separated frequency band.

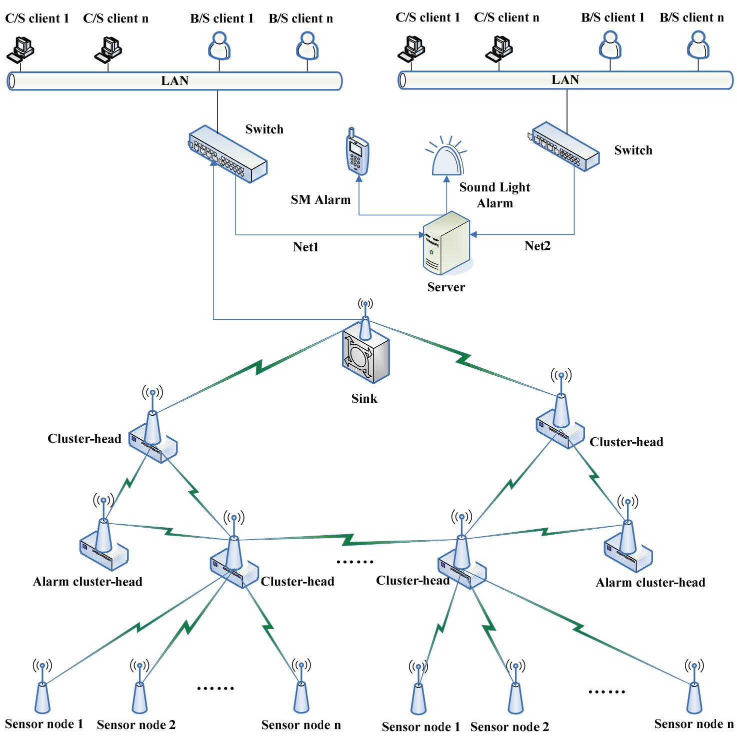


Fig. 1. Architecture of the roller-monitoring network.

Network is consisted by three different kind devices. Sensor node is responsible for the period temperature sampling and forwarding data to the cluster head. When the sampled temperature exceeds the alarm level, it will speed up the sampling period. Sensor node also takes star network transmission performance statistics and responses for parameter configuration commands from cluster head. Cluster head is responsible for the maintenance of the star network, which has two RF transceivers. It will collect sensor data of the whole cluster and performance statistic results of star subnet, and forward the data to sink through mesh subnet. Sink node is connected to a PC server and transfer data of wireless sensor network to Ethernet.

3.3. Hardware Design

Sensor node uses Atmega64 MCU and CC1100 RF transceiver with a PA of 15dbm output. DS18B20 digital sensor is used for temperature sampling. Sensor node is packed in an IP68 protect case to prevent from the spray of the cooling liquid. Cluster head uses ATmega128L MCU and has two RF modules. The CC1100 RF is used for star subnet and the Xbee module is connect to MCU through UART bus. Xbee module uses DJmesh protocol for multi-hop transmitting data between clusters. Sensor node and cluster head are shown in Fig. 2.

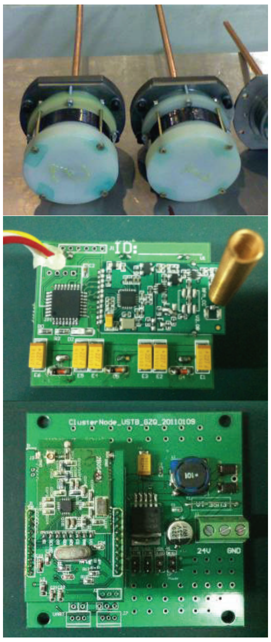


Fig. 2. Architecture of sensor node and cluster head.

4. MAC Protocol Design

In star subnet, each star is a cluster and we dispatch each cluster different frequency channel to avoid interference from neighbor cluster. And the channel is calculated by cluster ID. In a star subnet, each sensor node has a physic address PA, which is a two byte unique number in the whole network. And each sensor node has a logical address *LA*, *LA* is a one byte number start from 1, and the sink node identifies a node by combine cluster ID and *LA* together. For cluster head, *LA* is zero.

We defined a NPT structure to describe the relationship of *LA* and *PA*. NPT also stores the parameters of each node. A NPT table includes *PA* address, *LA* address and alarm level, link quality etc.

4.1. Network Joining and Leaving

4.1.1. Channel Scanning

The process of the channel scanning is shown in Fig. 3. First, when sensor nodes start to work or waking up from sleep mode, sensor nodes will judgment whether the network state flag *bInNet* is true. If sensor node is already in network, skip scanning process. If *bInNet* is false, node will start a channel scanning from channel 1 to channel n. Sensor node listens beacon packet on each channel for *T_BEACON_LISTEN* seconds. If beacon packets received, set current channel *channel[i]* to 1, and record the information of cluster head contained in beacon, then, change to next channel. If no beacon received in *T_BEACON_LISTEN* seconds, switch to the next channel to continue listen until all the channels are scanned. When sensor node scanned all channels, if no beacon received in any of the channels, in other words, element of array *channel[n]* is zero, sensor node will start sleep algorithm. If at least one beacon is received, sensor node begins cluster head association steps described in the cluster head association.

Sensor sleep algorithm is a periodic detection process to avoid power consumption in the situation of no cluster heads. Sensor node will sleep for *T_SCAN_SLEEP* seconds and then starts a new channel scanning.

4.1.2. Cluster Head Association

As shown in Fig. 4, sensor nodes scan the array *channel[n]* to search available cluster heads, and check the numbers of sensor nodes in each cluster. If the number in cluster using *channel[i]* equals *MAX_NODES*, set *channel[i]* to zero. If no cluster head found, sensor node will start sleep algorithm. If only one cluster head is available, join the network through this cluster head. If more than one cluster head exist, sensor node selects cluster head with high link quality by function *maxLQI()*, and if several cluster heads have same link quality, choose the cluster head with minimum sensor nodes in the cluster by function *minNODE()*.

When sensor node finished cluster head selection, sends a join request command to selected cluster head, start network join process described in network joining.

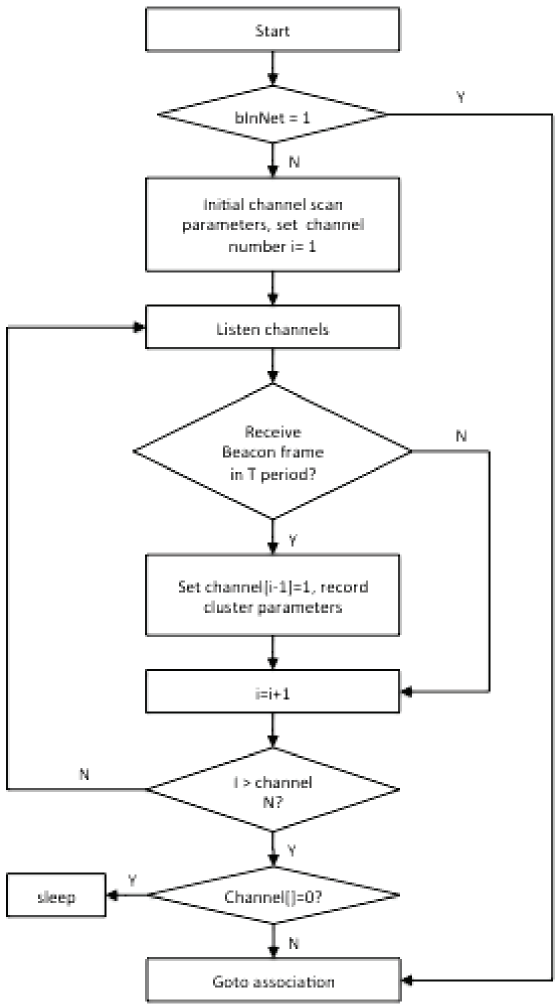


Fig. 3. Process of network scanning.

FOR each element *channel[i]* in array *channel[]*
IF *channel[i]* !=0
cluster_head[j] = cluster head work in *channel[i]*
IF number of sensor nodes of *cluster_head[j]* >= *MAX_NODES_IN_CLUSTER*
channel[i]=0
ELSE
candidate[k]=cluster_head[j], *j*++,*k*++
ENDIF
ENDIF
i++
ENDFOR
IF *k*==0
sleep
ENDIF
IF *k*>1
FOR each element of array *candidate[]*
selected[i]=maxLQI(candidate[]),i++
ENDFOR
IF *i*>1
FOR each element of array *selected[]*
selected_head = minNODE(selected[])
ENDFOR
ELSE
selected_head = maxLQI(candidate[])
ENDIF
ENDIF
join network

Fig. 4. Cluster head association algorithm.

4.1.3. Network Joining Process

The sensor node joining process block diagram is shown in Fig. 5. After finished cluster head selection, sensor node will send a JoinRequestFrame with its physical address *PA* to cluster head using CSMA, if no ACK received, retransmits JoinRequestFrame at max *MAX_SEND_NUM* times. When cluster head received the JoinRequestFrame, it will assign a logic address *LA* and corresponding TDMA slots for the new joining device through an ACK frame. The allocation method is as following:

1) Search NPT table to find a *LA* where *PA* is zero, assign this *LA* to the new sensor node as the logic address, and then, fill *LA* address in ACK frame.

2) Set *accept_flag* in ACK frame to one, if no available *LA* is found, set *accept_flag* to zero to reject the join request of the new sensor node.

3) Transmit the ACK frame to sensor node.

Sensor node will check *accept_flag* when ACK frame is received. The *accept_flag* equal one indicates that join network successfully, and then sensor node will set *LA* in ACK as its logical address and calculate the TDMA slots. Otherwise if *accept_flag* equals zero, join request is reject by cluster head. Sensor node will mark current cluster head invalid (set *channel[i]* to zero) and select a new cluster head using algorithm in cluster head association to join the network.

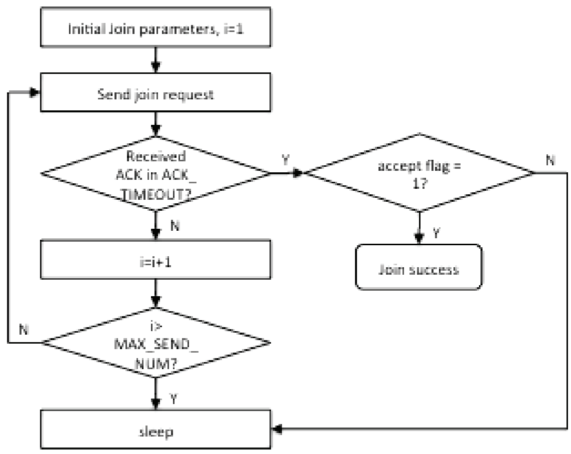


Fig. 5. Sensor node joining process.

Cluster head will send a join notification to sink node after successfully transmitted ACK, join notification packet includes updated NPT table and cluster ID.

4.1.4. Network Leaving

Network leaving happens in two scenarios. The first is communication interruption caused by environment interferences; sensor node cannot communicate with its original cluster head and then rejoin the network. The second is the support roller has been replaced with another roller, which causes moving of the sensor nodes, thus sensor node will change the state of online and offline and search a new cluster to join.

Sensor node must judge whether leaving one cluster in a limited time when it leaved the network. When *bInNet* flag is true, if sensor node continuously lost ACK in *PACKAGE_LOST_MAX* times sample periods, sensor node sets *bInNet* flag to false and starts join process.

Cluster head can detect leaving of sensor node. For cluster head, in each sample period, PRR (packet receive rate) minus one, when sensor data is received, the corresponding parameter PRR in NPT table is set to value *MaxPRR*. If PRR equals zero, corresponding sensor node has left the network, cluster head will set PA of this sensor node to zero. Network leaving process is shown in Fig. 6.

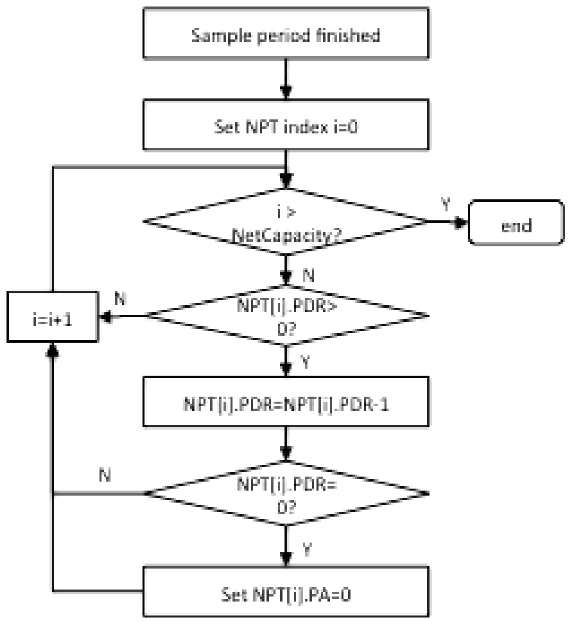


Fig. 6. Sensor node leaving process.

4.1.5. Slot Dispatch

Slot allocation in the MAC protocol using a fixed dispatching method. Because each sensor node has a one byte *LA* address in a cluster, thus, we use *LA* address as the input of the slot allocation algorithm. The whole slots are divided into two parts, the front slots are allocated for sensor node sending data to cluster head and the rest slots are allocated for cluster head send packets to sink. In sensor and cluster communication slots, each sensor node has a base slot, which is the same of its *LA* address number, and the rest slots are for alarm packets transmission. Thus, we do not need a slot request or slot allocation command, which reduced the communication complexity and increased the reliability.

4.2. Network Running

4.2.1. Sensor Running Process

As the flowchart shown in Fig. 7, sensor node samples temperature and battery voltage after it wakes up. If the temperature is higher than the alarm level, set *bIsAlarm* to true and send the data using alarm slots, then change sample period to speed monitoring. Otherwise, when temperature is lower than alarm level, make sure *bIsAlarm* is false and resume normal sample period and transmitting slots.

Sensor node will create a DataFrame filled with temperature, voltage, link RSSI and LQI, and send it to cluster head. When received the ACK, sensor node will compare the parameters (such as alarm level, sample period etc.) in ACK with local parameters to decide whether to modify the parameters. If ACK is not received in *ACK_TIMEOUT* time, go to sleep.

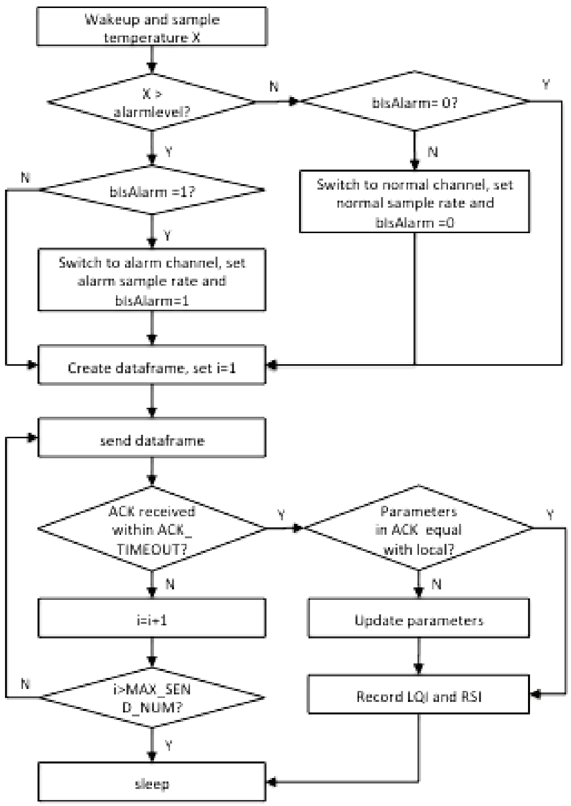


Fig. 7. Sensor running process.

4.2.2. Cluster Workflow

Cluster head connects the sensor node and sink, which is responsible for two functions: communication with sink and communication with sensor nodes.

Cluster head uses mesh topology and multi-hop DJmesh protocol, when server change a parameter of sensor node, sink will send a command packet to cluster head. When cluster head received the command packet, it will store parameter (such as sample period, alarm period etc.) in a local variable. When cluster head received the data frame from sensor node, it will fill the parameters into ACK frame and send to sensor node. Parameters will be sent with ACK frame in each sample period, so if an accidental disconnection between sensor node and cluster head happened, parameters can be updated in the next several sample periods, thus ensure the reliability of parameter setting.

As the role of sensor nodes management, when received data from sensor node, cluster head firstly searches parameters of sensor node using *LA*, stores temperature and voltage values, and sends an ACK to sensor node. Cluster head will periodically send data fame including temperature and voltage of all sensor nodes in the cluster to sink through mesh network. Also, a link quality frame will be sent to sink including the LQI of uplinks and downlinks.

4.3. Reliability and Power Analysis

This part we will analysis the reliability and power consumption of sensor nodes. For cluster head, we often use active power supply. Consider the situation of intra-cluster communication and assume the packet transmitting successful rate on different channel is *pi* (i =1, 2, ... m), for a sensor node *Si*, if it has at max *r* retransmissions, the transmitting successful rate between sensor and cluster head is:

$$P = P_i(1 + (1 - P_i) + (1 - P_i)^2 + \cdots + (1 - P_i)^{r-1}) = P_i \sum_{x=0}^{x=r} (1 - P_i)^x$$

Low power consumption is one of the targets of the system design, which is high related to hardware. Assume the system transmitting reliability requirement is P, and sensor node has at max r retransmissions, the reliability of the channel is p, then, average retransmission times is: $\alpha = \log_{1-p}(1 - P)$ For sensor nodes, if the sample period is T_{sample} then

$$T_{sample} = \alpha T_{w-fifo} + T_{r-fifo} + T_{sensor} + T_{protocol} = \alpha T_{w-fifo} + T_{r-fifo} + \Delta$$

where sensor data process time T_{sensor} and packet process time $T_{protocol}$ are almost fixed , T_{w-fifo} and T_{r-fifo} are writing packet and reading packet time form RF FIFO, which are related to packet length. The RF working time includes sending, receiving ACK and waiting ACK timeout, as shown in bellowing formula:

$$T_{RF} = \alpha T_{tx} + T_{rx} + (\alpha - 1) T_{ack}$$

In the worst situation, if all transmission are failed, $T_{RF} = r T_{tx} + r T_{ack}$. Thus, in a sample period, sensor nodes power consumption is:

$$\begin{aligned} E_{sensor} &= (\alpha T_{w-fifo} + T_{r-fifo} + \Delta) I_{cpu} + \alpha T_{tx} I_{tx} + (T_{rx} + (\alpha - 1) T_{ack}) I_{rx} + (T_{cycle} - T_{cpu}) I_{sleep} \\ &= (\alpha\sigma L_{tx} + \sigma L_{ack} + \Delta)(I_{cpu} - I_{sleep}) + \alpha\omega L_{tx} I_{tx} + \omega L_{ack} I_{rx} + (\alpha - 1) T_{ack} I_{rx} + T_{cycle} I_{sleep} \end{aligned}$$

where σ is the speed of SPI bus and ω is the RF transmitting rate, L_{tx} and L_{ack} are the length of data frame and ACK frame separately.

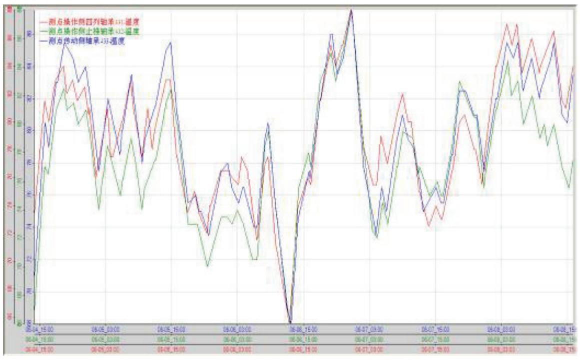
5. Deployment and Validation

We deployed a cold strip mill support roller monitoring system in Ansteel of China in 2010, which works reliably and power efficiently. The cold strip mill has five stands and 6 roller each stand, in which, supporting roller is the biggest roller and with the longest working period. According to the mechanical structure of the supporting rollers, the operating-side of each supporting rollers installed two temperature sensor nodes, and the electrical side installed one node. There are ten supporting rollers for online production, and also ten supporting rollers for offline maintenance, thus the whole network includes 60 sensor nodes. For a reliable communication, we use 5 clusters for online sensor nodes and 2 clusters for offline sensor nodes. The environment of cold strip mill is shown in Fig. 8.

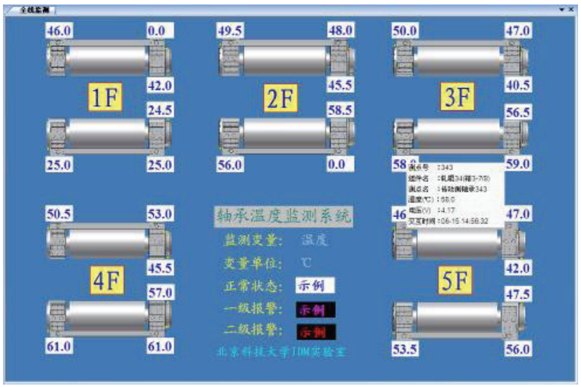
Fig. 8. Cold strip mill application environment.

The monitoring results of the system are shown in Fig. 9(a) and (b). As shown in Fig. 9(a), three sensor nodes on one supporting roller has the same tendency, and we can see form the figure that when a roller offline, the temperature goes down and when changed with a new roller, the temperature goes high. Fig. 9(b) is the display interface for system manager, when temperature beyond the alarm level, the color will be changed from blue to red to notify system manager.

Fig. 10 shows the relationship of temperature and battery voltage. The voltage will go high when temperature goes high which is the characteristic of the battery. Fig. 11 is the variation of the RSS. When the temperature is low, which means roller is not working and store on the maintained ground. In such situation, link reliability is not good as roller working because of the heavy obstacles and long distance between sensor nodes and cluster head.



(a)



(b)

Fig. 9. Temperature monitoring results and system interface.

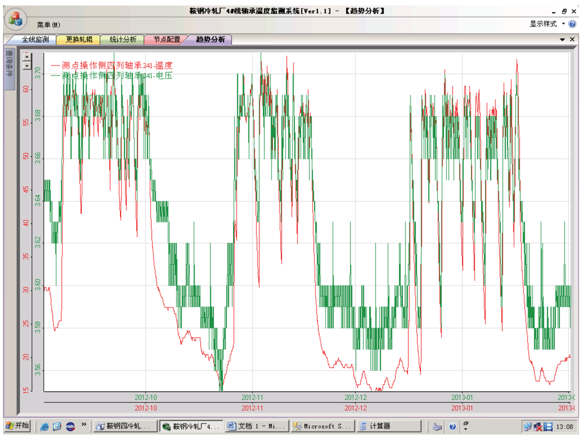


Fig. 10. Voltage variation with temperature.

6. Conclusions

Equipment pre-maintenance is one of the key factors for high quality production in industry. In a cold strip mill factory, the health of the roller direct affect the products, but rollers in mill factory work in a very harsh environment and also impossible for human repair when they are working. The paper proposed a novel wireless system for online roller temperature monitoring. The system uses mesh/star topology and two different frequency bands to avoid the frequency interference. Mesh subnet uses DJmesh protocol and in star subnet, we proposed a simple but reliable TDMA MAC protocol. Each star subnet forms a cluster and uses a unique frequency channel. Sensor node in a cluster will choose the best cluster head to join the network and have a self-organized strategy with low power consumption. The real deployment in factory shows that the protocol has high reliability and low power consumption, which satisfied the requirement in harsh industrial environment.

Fig. 11. RSS variation with roller change.

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