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Safety and Health Monitoring of Bridge Construction Based on Wireless Sensor Network

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Abstract

The existing safety and health monitoring methods for bridge construction are mainly manual monitoring and wired monitoring with many disadvantages, such as low efficiency, poor accuracy, great implementation difficulty, short bridge age, etc. To solve such problems, the paper provides a design scheme for the bridge construction safety and health monitoring System based on wireless sensor networks. In the system, various sensors are mainly used to collect data about the wind, temperature, traffic load, humidity, static position, static displacement and external load response, and then send to the host by route and gateway nodes. After data analysis and processing, the safety of the bridge is evaluated to help the personnel make correct bridge safety precautions. With such advantages as low power demand, wireless transmission of monitoring data, etc., the system is suitable for large range of promotion.

Keywords: *bridge safety monitoring, wireless sensor network, sensor, gateway node*

1. Introduction

In operation, the damages to the bridge are unavoidable, which decreases the safety of the bridge and takes a lot to drop the bearing capacity of the bridge construction. Data about the national census on road bridges displays that a lot of bridges have been damaged to various degrees. In Jiangsu Province, there were more than 1,307 bridges in danger. On the basis of the statistical data in the Statistical Yearbook of the Jiangsu Province in 2003, the tube raise of it belonged to the road management. A series of bridges collapse accidents at home and abroad in recent years, such as the accident of south gate bridge of Yibin in Sichuan province, remain us that more and more attention should be paid to the safety monitoring and assessment of bridges.

The existing safety and health monitoring system adopted for bridge construction is mainly the distributed one, which means that in the monitoring system, the wired connection is adopted between each monitoring points and the central control station. Due to the depressiveness of the geographic location of the monitoring points, safety monitoring system with traditional wired connection have many disadvantages, such as high cost, too much interference, large construction load, inconvenient monitoring points adjustment, and vulnerable to lightning impulse bridge. 70% of the wired systems installed are paralyzed or semi-paralyzed. There are also nearly or above 80% of reservoirs are still in the state of manual testing due to high system

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cost. Compared with traditional monitoring method, wireless sensor network has the following apparent advantages: (1) the self-organizing dynamic network makes it is possible to network automatically without manual intervention and is applicable for long term work demands. The sensor can be connected to or disconnected from the network, which is helpful for changing the position of monitoring point; (2) With large quantity of sensor nodes and high distribution density, the monitoring accuracy and stability of the system is significantly increased because of high accuracy and large network data collection quantity; (3) Capable of wireless communication, the sensor node can support multi jumping technology, which may realize remote health monitoring and reduce the wiring load. And the sensor can be moved flexibly; (4) the objects of health monitoring are different and the sensor nodes are of good flexibility; thus, various sensors can be adapted for different monitoring purposes. Therefore, it has been the general trend to develop the bridge construction safety and health monitoring system based on the wireless information transmission mode [1].

In this paper, a bridge construction safety and health monitoring system based on wireless sensor network is studied and analyzed [2]. It is a wireless bridge safety monitoring system with IEEE 802.15.4 protocol, which consists of wireless sensor, wireless router and wireless network management. The whole system is used by full wireless mode, with each powered by battery, which significantly reduces the complexity of system installation. The low-power mode has made the design optimized, so that the average replacement cycle of the node battery is 5 years and maintenance workload in the future can be also greatly reduced. After on-site installation, the system has been used for a few years in normal operation. After testing, the system complies with the design standards.

2. The Bridge Construction Safety and Health Monitoring System

Assuming that 4 piezometer tubes are evenly distributed along the bridge direction with 3 sampling points on each column and there are piezometer tubes with 3 different depths in each sampling point, it can be calculated that the total number of the piezometer tube is 36, as the bridge is generally several kilometers long.

2.1. Overall Scheme of the System

According to the distribution of the piezometer tube, the network topology of the system [3-6] is shown in Figure 1 by taking the scalability of the system into account.

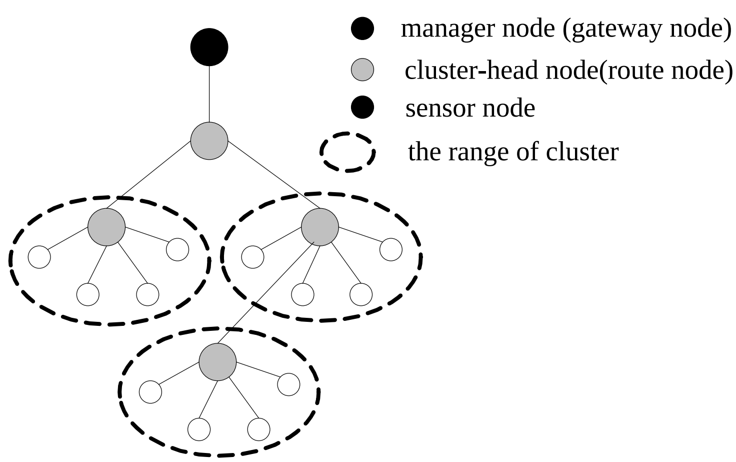

Figure 1. The Network Topologic Structure Diagram of the System

As shown in Figure 1, the system is divided into two-level structures. According to geographic location or close degree of the network connection, the sensor node is divided into a number of regions with each known as a “cluster”. Each cluster is provided with a route in the tree structure and is a sub-network as the star structure. The combined structure of this tree and star network can effectively extend the coverage of network, enhance the signal strength of network and reduce data loss, which can be used for monitoring larger region. When the region monitored is small, the communication radius of the node can be completely covered and the network structure can be simplified as the two-level star network.

There are three nodes in the whole network, *i.e.* the management node, cluster-head node and sensor node. The management node is responsible for the data exchange between the sensor network and the internet. The acquisition task released by the host is forwarded to the sensor network, or the data collected by the sensors is forwarded to the host, sometimes also referred to as gateway.

In the system, two gateways are designed, *i.e.*, the conversion gateway for the sensor network to the USB and for the sensor network to the CDMA network, which are applicable to the data transmission of the short-distance and the ultra long-distance respectively.

The cluster-head node has two functions: managing the cluster sensor nodes and routing forwarding backbone network data. The management of cluster sensor nodes mainly includes the clock synchronization of nodes, releasing acquisition command, receiving collection data and data fusion, etc. Each sensor node is connected to a pressure measurement water level sensor to collect water level information.

The position of each node is relatively fixed, as the system will generally not be changed after installation; thus, the network structure is essentially unchanged. Corresponding network protocols can be designed based on the characteristics, which can significantly improve the transmission efficiency while have certain scalability.

2.2. Design of System Nodes

According to the characteristics of the wireless sensor network and some special requirements of the bridge monitoring system, the design of node shall comply with the following: ultra-low power consumption, good moistureproof performance, low cost, safety and reliability, strong communication ability and calculation ability. Typically, various indices are related with each other, and the performance of one index will be reduced, if the performance of the other is improved. Thus, considering various indicators, it is more important to choose the appropriate combination point.

2.1.1. Design of cluster head node: The third-order headings, as in this paragraph, are discouraged. However, if you must use them, it must be of 11-point Times New Roman, boldface, initially capitalized and flush left, and shall be preceded by one blank line, followed by a colon and your text shall be on the same line. The circuit diagram of the cluster head node [7-10] is shown in Figure 2.

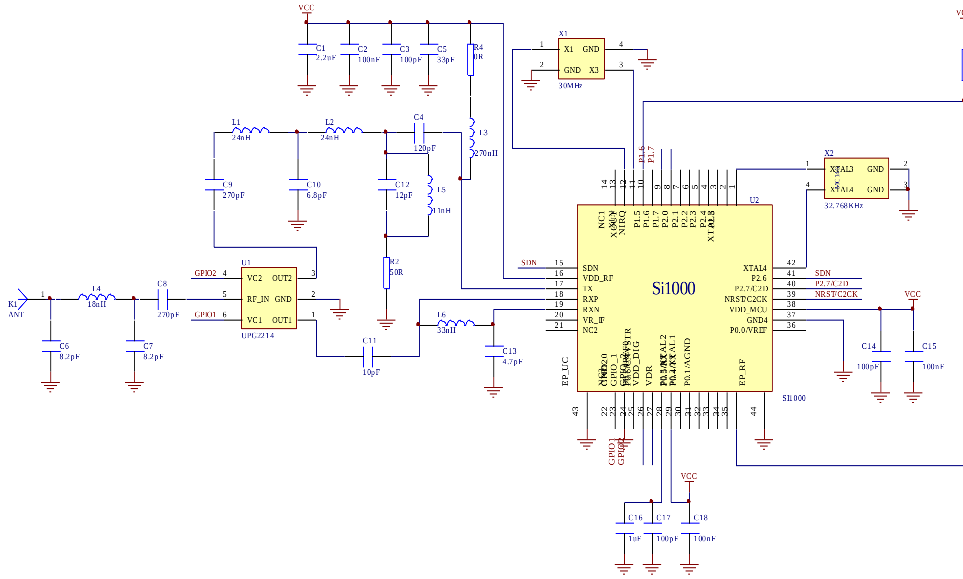

Figure 2. The Circuit Diagram of The Cluster Head node

UPG2214 is an antenna switch with its Pin 1 connected to the receiver circuit and Pin 3 connected to the transmitter circuit. Pin 4 and Pin 6 are two input control logics of the antenna switch, and connected to the corresponding output pins of Si1000. When Pin 4 is inputted high level and Pin 6 inputted low, Pin 5 is connected to Pin 1, conversely, connected to Pin 3. The benefit of using the antenna switch is that the antenna can be either used as a transmission or a receiving antenna. Thus, the volume of sensor nodes can be saved, as two antennas cannot be used at the same time. C11, C13, and L6 constitute a reception circuit, and L6 is connected to two differential inputs RXP and RXN of the Si1000 by bridge connection. Because the Si1000 A low noise amplifier (LNA), the differential receiver, is adopted for Si 1000, it is better to input a differential signal between the RXP and RXN pins with the differential signal phase difference of . C11-L6-C13 combination can provide a signal to the Si1000, the phase difference of the signal is approximately 180 degrees. In the part of RF power supply of the Si1000, C1, C2, C3 or C5 is used as a filter capacitor to reduce the ripple of the power supply. L1, C9 and L2, C10 etc. compose PA matching. The microstrip line between C6 and the antenna should achieve the impedance matching of 50 ohms. The impedance matching is one of the important indicators affecting the RF performance, and can be calculated by microstrip line model calculation tool. In addition, 30MHz crystal oscillator in the circuit is used to provide a reference frequency to the RF part, and 32.768 KHz crystal oscillator to the RTC (real-time clock) in the chip.

2.2.2. Circuit design of the temperature sensor: In order to avoid the analog signal from being interfered during long-range transmission, the temperature sensor circuit is designed by using the front-end digitized mode, the specific circuit [11-16] is shown in Figure 3.

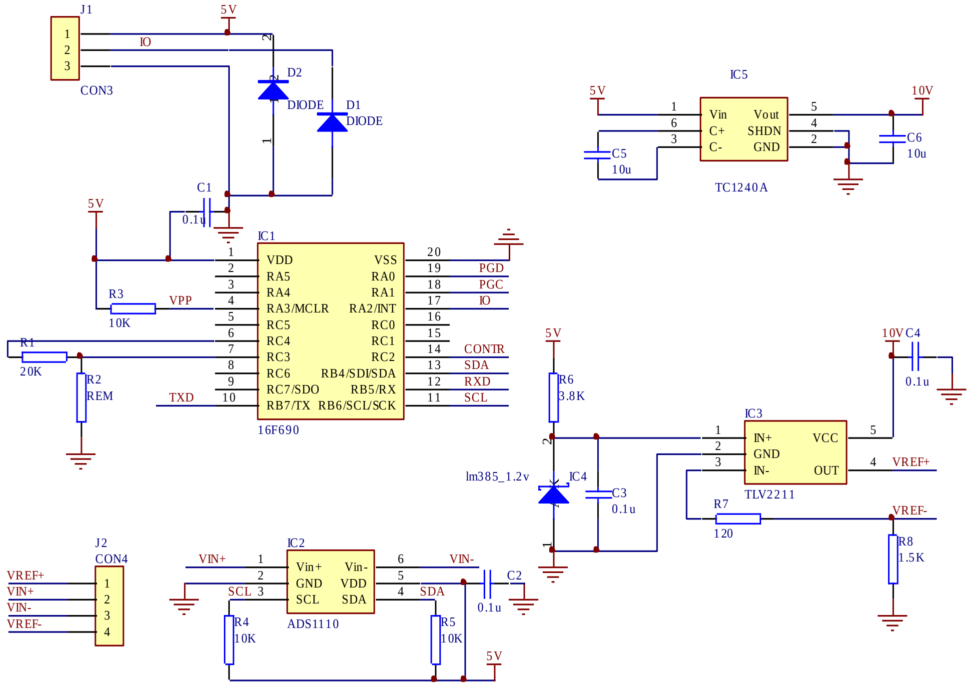

Figure 3. The Circuit of The temperature Sensor

In the graph, the 16F690 is a micro controller of Microchip's PIC16 series, which integrates 10 bit AD converter and I2C bus controller. ADS1110 is a single differential signal 16-bit AD converter chip introduced by AD, which integrates oscillator, internal reference source and programmable gain amplifier. Simply connection will be able to acquire differential signal. The constant current source composed of TC1240 and TLV2211 supplies power to the sensor. The resistor R2 is a thermistor, which is connected to the input terminal of the AD microcontroller to collect temperature information.

The circuit is so designed that the thermistor can collect temperature information, of which the main reason is that the temperature change has a great impact on the output of the sensor when working. According to practical measure, there will be nearly 0.5cm/ ℃ temperature drift even buying a temperature compensation sensor. To ensure measurement accuracy, it is necessary to add temperature acquisition circuit to provide temperature compensation. The sensor in the circuit is a differential pressure / bridge type pressure sensor.

2.2.3. Design of the gateway circuit: USB is used to realize the data transmission and power supply between the gateway node and the PC. But Si1000 only supports UART communication, so Microchip's PIC18F14K50 is used as data conversion intermediary. The data flows into 14K50 from the signal line D+ and D- of USB. After the protocol conversion of 14K50, the standard interface TX and RX of the UART is formed to connect Si1000. 14K50 can be powered directly by USB.

The CDMA module interface terminal has adopted the Huawei EM200 CDMA modules and integrated UART, UIM card, antenna and other rich resource interfaces, which has supported the standard AT command set. The EM200 module is connected with Si1000 through the UART standard interface, which has achieved the data receiving and delivering between them. The circuit diagram of EM200 CDMA is shown in Figure 4.

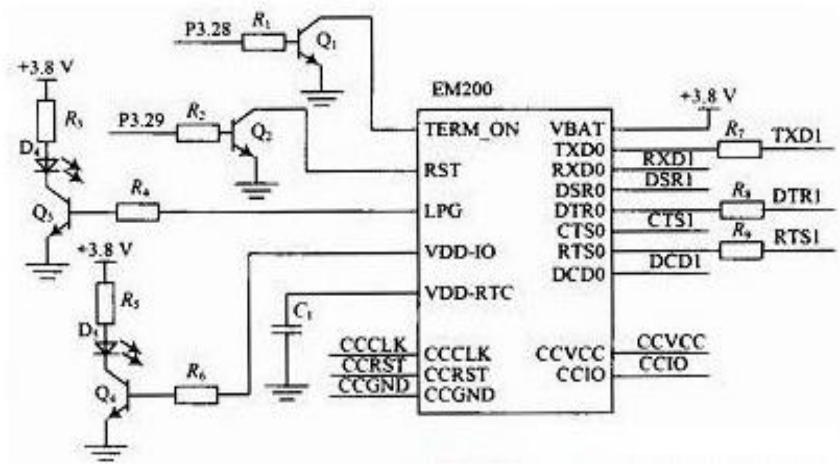

Figure 4. The Circuit Diagram of EM200 CDMA

3. Software Design

Two layers of nodes - the N th layer and the N +1 th layer node – are taken as the example to explain the process of software.

3.1. Detection Scheme for Wireless Sensor Nodes

The flowchart of the N th layer node [17-19] is shown in Figure 5.

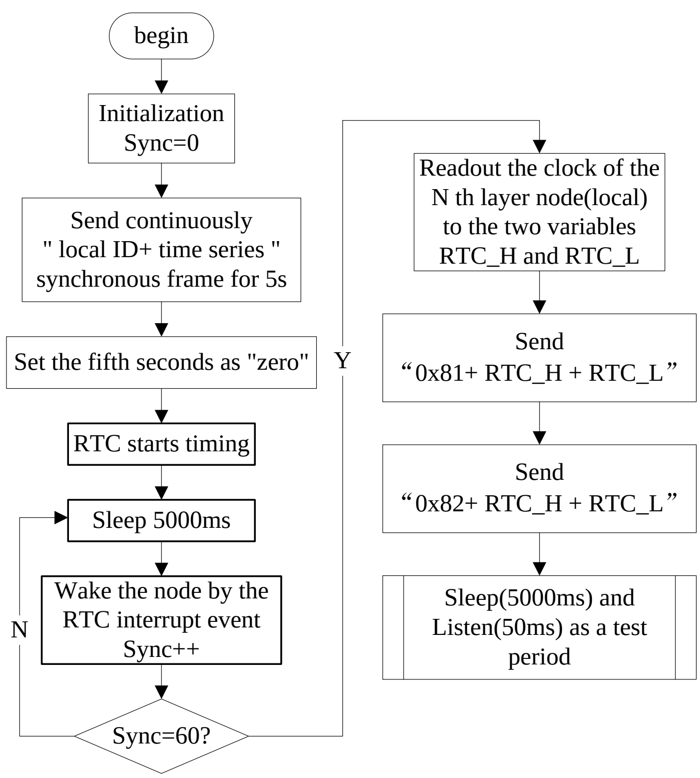

Figure 5. The Flowchart of The N th Layer Node

All nodes are in a low-power mode after being powered up, and the nodes of each layer are not synchronized, so it is required to initialize the first synchronized action. The N th cluster head sends continuously the “local ID + time series” synchronous frame, using the momentary synchronization technology to synchronize the two layers of nodes to "zero".

The Sync is an unsigned char variable, which can track the growth of time. The initial value of the Sync is 0, and every RTC interrupt makes the value of the Sync to plus 1. RTC interrupt event occurs once every 5 seconds, so Sync with the value 60 means 5-minute compensation.

When sending the local clock, to ensure that the N +1 th layer node can reliably receive the time correction signal, it is necessary to send the same content twice. The time information carried by the two transmission frame is identical, and the time difference the physical layer needed to send two signals is 22ms. Header 0x81 and 0x82 are used to help the lower nodes to distinguish the receive time correction signal which one is sent.

The flowchart of the N+1 th layer node [20-21] is shown in Figure 6.

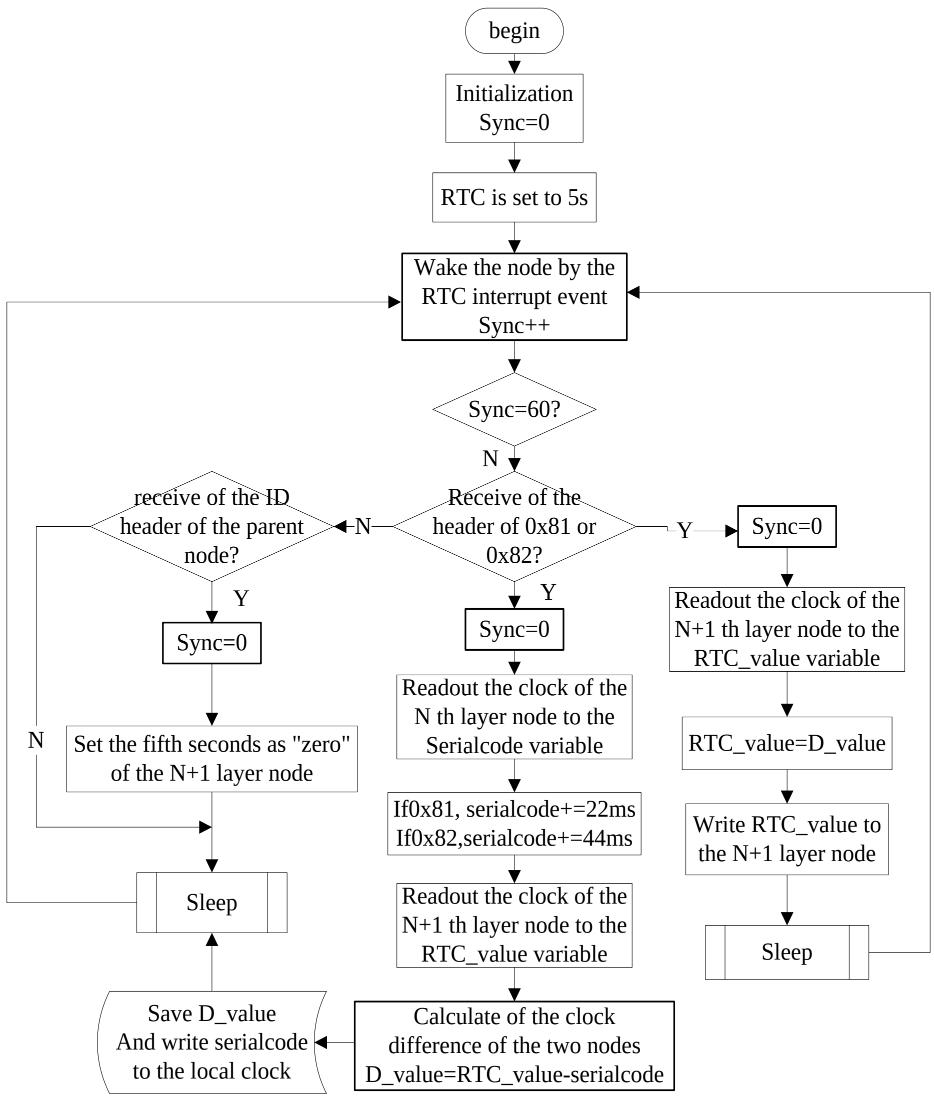

Figure 6. The Flowchart of The N+1 th Layer Node

When receiving the ID header of the parent node, at momentary synchronization mechanism, the node is synchronized initially with the upper layer node at first. When receiving the 0x81 or 0x82 header node, between which the clock is proofread: the difference D_value between the local clock and the upper layer clock is saved, and the reference clock received from the upper layer is write in the CAPTUREn register of the local RTC.

This layer node realizes one crystal offset compensation every 600 seconds: the local clock minus D_value, and is then written to the RTC register to complete proofreading.

Since the listener window of the sensor node is 5ms, if the same 20ppm crystal is used, the clock check is needed in the first minute, otherwise beyond the listener window after calculating.

3.2. CDMA Wireless Network Access Program

The CDMA module can be controlled by terminal through the AT command so as to achieve the wireless network access and the network data transmission. When the system is operated, the CDMA module should be initialized. Then it will be kept in the dial-up waiting state. The terminal will connect with the logon network through the PPP dialup. The user name and the password are of card type. After launching the Internet, it is necessary to send the information of the terminal to the monitoring center through the timing mode.

The AT command with the PPP (point-to-point protocol) connection as well as the return values can be shown as follows:

```
AT%ACCNT= card.card
OK
AT%PPPOPEN
%CORC: #888,1
%PPPOPEN: 0
%PPPSTATUS: 0
OKAT%PPPSTATUS //PPP
%PPPSTATUS: 0
```

3.3. CDMA Wireless Network Communication Program

When the terminal is connected with Internet through the CDMA network, the wireless network communication program will upload the GPS data parsed by terminal to the monitoring center through the Internet. The procedures of the wireless network communication program of the monitoring center can be shown as: 1) the socket () function is used to establish the socket; 2) the bind () function is adopted to use the socket and the local IP address; 3) the listen () function is employed to connect the request; 4) the accept () function is used to send and receive the data; 5) the fork () function is adopted to derive the new child process and the terminal communication.

4. Clock Synchronization of Wireless Sensor Network

For health monitoring of bridge structure, the clock synchronization of each sensor node is crucial for the bridge vibration mode analysis [23]. However, the physical clock of the node various with the change of such external environments as temperature and humidity due to crystal oscillator frequency, which may lead to deviation of clocks between nodes, thus, fail to have common time benchmark [24]. Therefore, it is necessary to use TPSN (timing-sync protocol for sensor networks) algorithm [25] to realize the clock synchronization of wireless sensor network before data collection. Similar with traditional NTP protocol, two-time handshake exchange timestamp is adopted in TPSN to realize clock synchronization.

TPSN can be realized by two stages. Firstly, layer discovery stage. In this stage, it is necessary to firstly determine the root node. The base station node in the monitoring system can be used as the root node of this stage and the level shall be set as 0. Then, the wireless sensor network nodes shall be graded by the root node via broadcast grading data package. The grading data package includes the sending node's sole identification and level. When the closest node of the root node receives the package, it will set its level as 1 and each level 1 node will continue to grade the data package until all nodes in the network are covered. In single hop application, when the node includes the base station node and a layer of wireless sensor network node only, all wireless sensor network nodes will be set as level 1. The second stage is synchronization stage. It is assumed that node A is the base station node with the highest level, and the grading information containing node A and synchronization information package of T1 are sent at T1. The node B is used as the wireless sensor network node in single hop and receives this package at T2. Assuming that t is the time deviation of base station node and senor node, and d is the round-trip time between them:

$T_2 = T_1 + t + d/2$, thus, $T_2 - T_1 = t + d/2$;

$T_4 = T_3 - t + d/2$, thus, $T_3 - T_4 = t - d/2$;

Therefore: $d = (T_4 - T_1) - (T_3 - T_2)$; $t = ((T_2 - T_1) + (T_3 - T_4))/2$

Thus, the clock synchronization of nodes can be completed by adding the clock deviation on the local clock of the nodes to be synchronized. To reduce the time delay error caused by access time, TPSN only marks timestamp after the MAC layer begins to send signal. The test carried out on Mica platform shows that the average clock synchronization deviation of TPSN is 16.9 μs and that of RBS is 29.13 μs, which demonstrates that the clock synchronization of TPSN is more accurate.

5. Energy Management in Wireless Sensor Network

The nodes in the network are in inactivated or activated states. When the nodes are in inactivated state, the wireless communication module is waiting for receiving, and other peripheral devices as CPU are in dormant state. The power consumption of the node is in the minimum level. When the node is activated, the node collects, processes and sends the data. When the node is changed from dormant to activated, it is said that the node is awaken; on the contrary, the node is in dormant state. The node in dormant state will enable the timer with the time as the sample time T_{sample}. The node will be interrupted at the specified time and awake the node; meanwhile, the after the node in dormant state receives the data package, the node can also be awaken. With the data collection interval of the network T_{sample}, it can be divided into the following two parts:

Where, T_{rest} is the sleep time of the network and T_{avtive} is its active time. Thus, in T_{sample}, the average energy consumption of the node can be calculated by formula (1):

$$E_{ave} = (E_{rest}T_{rest} + E_{active}T_{active})/T_{sample} \quad (1)$$

Assuming that $\theta = T_{active}/T_{sample}$

Formula (2) can be obtained by integrating with formula (1):

$$E_{ave} = (1-\theta)E_{rest} + \theta E_{active} \quad (2)$$

According the features of the actual power consumption of the node, $E_{rest} \ll E_{active}$, and formula (3) can be obtained from formula (2):

$$E_{ave} = \theta E_{active} \quad (3)$$

It can be known from formula (3) that, in the life cycle of the node, θ determines the service life of the node to a certain extent. According to the actual requirements, the service time of the network node can be extended by minimizing the θ.

6. Conclusion

By using the technology of wireless sensor network and modern measurement, a network is built to detect and monitor the safety of the bridge. Analyzing the structure of the bridge based on the real-time data of monitoring signal can meet the demand for the health monitoring of the bridge. It is important for the bridge to avoid potential safety hazards, and so, it provides evidence for the management and maintenance. The practice shows that, based on the wireless sensor network technology, this monitoring system is featured by small volume, convenient installation and real-time monitoring.

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