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ZigBee Based Underground Cable Monitoring System

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Abstract: This study mostly discusses about the monitoring of power transmission cables. In densely populated cities overhead transmission has a limit. More over faults are more in overhead transmission due to damage in conductors, birds, temperature, wind and so on. These drawbacks can be avoided to a large extend through underground cables. If it is monitored real time its power transmission capability and reliability can also be increased. Even though this is a costliest type of transmission cables are adopted in cities. In addition to the underground cables, power cables are used in industry to carry the power from control station to the site. Cable trenches and cable trays are used for this.

Key words: Birds, temperature, wind, underground cables, transmission cables

INTRODUCTION

Power transmission is tedious task. Generating stations are far located from cities. The generating voltage in India (standard 11 kV) cannot be transmitted as it is. It has to be stepped up for long distance transmission. The factor which is considered are voltage and distance during transmission. Current is a factor since by Joules law Eq. 1:

$$H = RT \quad (1)$$

Where:
H = The heat produced
I = The current through the conductor, Resistance of the conductor
T = The time taken through which power is transmitted

By analyzing the law Eq. 1 heat loss is directly proportional to the square of the current. So, current cannot be increased. By the Eq. 2 power to be transmitted can be increased by increasing the voltage:

$$P = 3VI \text{ (for three phase)} \quad (2)$$

Where:
P = The power
V = The voltage
I = The current and is the power factor of the alternating current system

This power can be increased with more reliability through power transmission cables. The 3 core and 3 and half core are more common. SF6 filled cable is also one type of cable used in India. Its different parameters can be measured using the techniques. The measured parameters (using power transducers) can be transmitted using GPRS techniques. These are interfaced to a personal computer for monitoring.

At present robots are under development for monitoring underground systems. The disadvantage lies in their elaborate structure. Maintenance is needed and it involves working crews (Kobayashi *et al*., 1991; Jiang and Mamishev, 2004; Jiang *et al*., 2005. The remote operated robotic system for live line maintenance work are semi-autonomous, human-coperativerobot technology (Nio and Maruyama, 1993). This study presents a novel real time autonomous underground cable monitoring system.

PARAMETER MEASUREMENTS

The different parameters can be measured using sensor technology. Figure 1 shows the block diagram of monitoring parameters of power cable.

Current measurements: Current is an important parameter. Each cable is designed for a specific current. This current will raise beyond a limit when fault occurs. The high current produces heat in cable and sometimes damages the insulation.

Insulation resistance measurement is discussed in the study. Siemens high current sensors can be used to measure the current. These types of sensors can measure from 10 A to around 1000 A (CS 500, 1000). The characteristics of Siemens sensors are:

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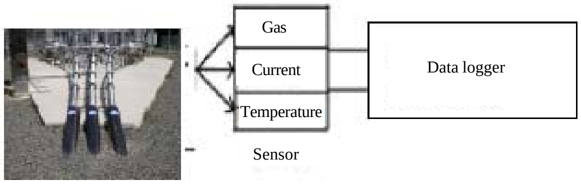

Fig. 1: Block diagram of monitoring parameters of power cable

- A model of reliability
- A perfect efficiency in every environment
- Excellent measuring accuracy
- High reliability
- High overload capacity
- Small size: 124 (L)×100 (W)×44 or 81 (H) mm

Temperature measurement: Temperature is a parameter which limits the transmission capacity of cables. So, temperature has to be measured. In hot countries underground cable and cable in the tray get affected by temperature. Different cable have different temperature withstanding capacity based on insulation (XLPE, EPR, etc.). If the temperature exceeds the limit prescribed the FT series infrared sensor will detect it and send via ZigBee. When the temperature is sensed by the sensor it produce an electrical signal.

Insulator fault monitoring: At load centers the cable has to be terminated and are stepped up or stepped down according to the customer needs. The insulator has infinite resistance. But during flash over insulation break down. This can not be identified unless and under system fails. The breakdown occurred in its internal. The insulator flashover discharge between iron cap and iron pin ceramic, the trace cannot be seen but the insulation has been lost and it may be completely destroyed due to arcing. For breakdown, the discharge traces of iron legs and burnt situation should be paid great attention. Transmission line insulator flashover in operation can cause blackout accidents, to affect seriously the power grid stability and reliability. All insulators are affected to some extent by impact, thermal and mechanical cycling, ablation from weathering and electro-thermal causes, flexure and torsion. Current sensor (CT-BASED) can be used here. The increase temperature causes the insulation to break down. This produce leakage current which is sensed using sensor module. The insulation resistance can be formulated as follows. The cable has a sheath of inside radius R:

$$R_{ins} = \frac{\rho}{2\pi l} \ln \frac{R}{r} \text{ohms} \quad (3)$$

Where:

R = The insulation resistance of the cable, resistivity of the insulating material of the cable
l = Length of cable
r = Radius of the conductor

Average value of or impregnated paper varies from 5-8 X Ωm at 15. This sensor embedded in sensor module transmits the data through ZigBee network.

Lightning arrester monitoring: Transformer is important equipment in power transmission system. It is also the costliest ac machines. It is very sensitive to lightning. So, it has to be protected. Also, the cables exposed in cable trenches in various industries are subjected to lightning. In country like China and Bangladesh it is severe. Thyrite lightning arresters are mostly used in India. The lightning arresters act as insulators for normal current but act as conducting material during surges. When severe lightning occurs it breakdown and does not work effectively. During this time it conducts for normal current also. The current sensor (CT-based) implemented can also measure this value. The measured values are send to the wireless sensor network ZigBee gateway.

Power cable visual monitoring: Substation and control station are located away from the site equipments. When insulation failed the conductor may get in touch with cable trench/tray. This will cause damage to the whole system and system gets tripped. The spliced cables also cause problems if not connected properly. So, high sensitive CCD camera (SAA71, FPGA Series) are installed. The digital signal is digitized and sends through GPRS technology to the control station. Designed gateway has provisions to support GPRS and ZigBee stacks.

PARAMETER TRANSMISSION

Smart system for the meteorological monitoring of transmission line based on ZigBee and General Packet Radio Service (GPRS) technology was developed in order to overcome the shortcomings of the present system such as the totally dependence on the limited coverage of communication network, the single monitoring parameters and the poor extensibility, etc. CT integrates the sensing element and signal processing circuit in a micro-circuit board. It has output of standardized digitalsignal, small size and low power consumption. The system in this study has the advantages of low power consumption, low node cost, large network capacity, long cycle life and strong extensibility. The block diagram of sensor module is given (Fig. 2).

RS-232 are interfaced with the GPRS module and use wireless communication technology. The standard provides the Physical layer (PHY) and Network Layer (NWK) for the wireless communication. RS-232 layer has seven layers as OSI Reference Model. ZigBee working on the topper performs as the Network layer (NWK) and Application Layer (APL). The PHY, MAC and NWK layers handle the data transmission and the APL layer handles the tasks of each device. CC2430 made by TI (Texas Instruments) was used as MCU and RF module. The chip is chosen to implement the chip system on embedded ZigBee applications.

UNDERGROUND TUNNEL MONITORING SYSTEM

Underground tunnel is made to connect a power transmission line with power tower when tower can not be built through the downtown area. In this case, unlike wire which is used for tower, insulated cable is used. Because of transportability, cable length is limited about 300 m. So, both cables are connected every 300 m and this point is called joint section.

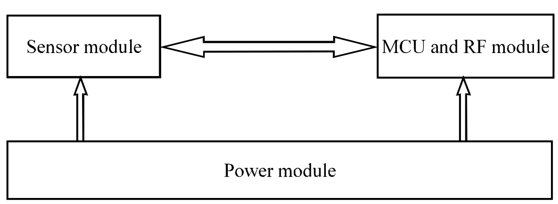

Fig. 2: Block diagram of sensor module

Joint section is a most sensitive facility in underground tunnel. Temperature of joint section is increased along with power consumption. Therefore, temperature monitoring of joint section is important to monitor overload of power transmission line. The underground tunnel has a problem of air circulation because it is sealed in underground. So, it needs to inspect amount of gas to prevent the accident by poisonous gas. Diagram of underground tunnel sensor network is shown in Fig. 3.

The underground tunnel monitoring system is developed in this research. Researchers place thermal sensors about 25~50 m apart in 600 m tunnel. These nodes are called router node which charge the role of a relay node and sensor node of airtemperature. Researchers arrange the router node in linear order following the tunnel because of the environment characteristic of underground tunnel. Researchers design a static routing algorithm. It uses a 16 bit short address instead of 64 bit IEEE addresses to reduce the packet size. A node communicates with another one by one which is predefined in static routing table. Nodes receive a packet

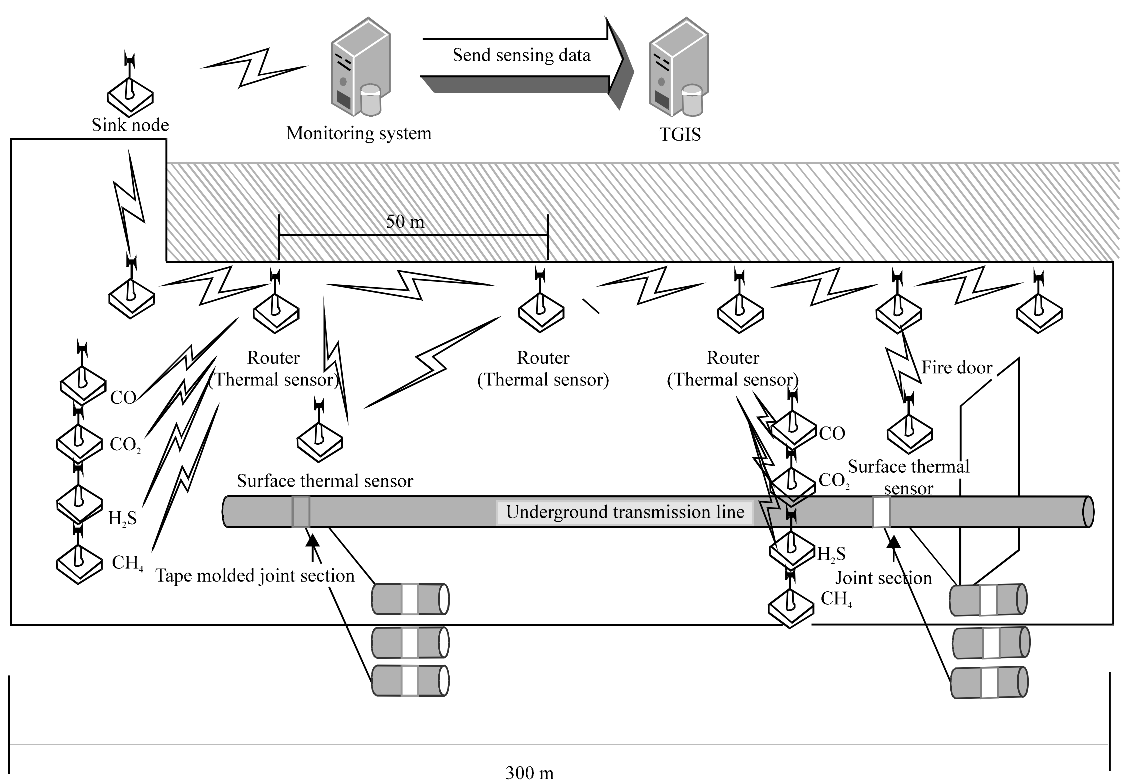

Fig. 3: Underground tunnel sensor network

from a successor and send a packet to a predecessor. This method is similar with clustered tree of ZigBee network which has only one child node.

SYSTEM HARDWARE DESIGN

The system can be divided into two parts: the sensor nodes and the coordinator node. Hardware design should consider carefully several factors such as reliability, energy and cost. The specific designs are in detail as follows:

Sensor node: Underground gas sensor consists of electrical bridge, signal conditioning circuit and alarm circuit. Block diagram of mine gas sensor hardware architecture is shown in the Fig. 4. The CC2430 is a true system on chip (soc) solution specifically tailored for IEEE 802.15.4 fully compatible with the hardware layer and physical layer. And ZigBee application produced by TI company. The CC2430 combines the excellent performance of the leading CC2420 RF transceiver with an industry-standard enhanced 8051MCU. Combined with

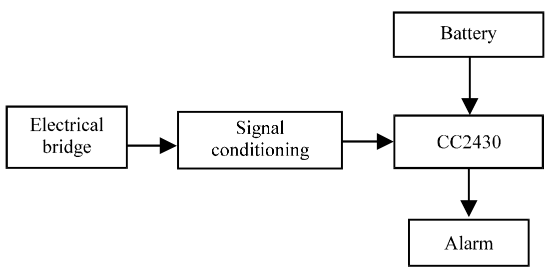

Fig. 4: Block diagram of mine gas sensor hardware architecture

the industry leading ZigBee protocol stack. The mine gas sensor is very important of detecting the mine gas concentration. Researchers choose MJC4/3.0J sensor with supporter catalyst filled element which can detect underground methane with 3 V power supply and can change physical quantity to electrical quantity. The collecting and conditioning circuit can be shown in Fig. 5. The measure bridge consists of D2 (black component also called catalytic component), D1 (white component also called compensation component), resistors R1 and R2. The variable resistor RW can be adjusted to ensure the bridge is in a state of equilibrium. When the gas is zero, the voltage outputs zero. When there is gas, the electrical bridge breaks the balance to produce a differential output signal which is proportional to gas concentration. Differential output signal is relatively weak, so researchers can constitute a differential input toamplify the signal by LM324 operational amplifier, direct be linked to voltage differential input. RW is the zero potentiometer which can realize zero point correction. The different amplification factor can be attained by adjusting R. The CC2430 has an internal 10 bit A/D converter, voltage output signal directly connect to the CC2430 pin to execute internal A/D conversion which can fully meet the precision requirements.

Coordinator node: The coordinator use ATmega128L as the controller. Atmega128L is a low-power CMOS based on the AVRenhanced RISC architecture 8 bit micro controller. The block diagram of hardware structure can be shown in the Fig. 6.

CC2420 module: The CC2420 is a true single chip 2.4 GHz IEEE802.15.4 compliant RF transceiver with baseband

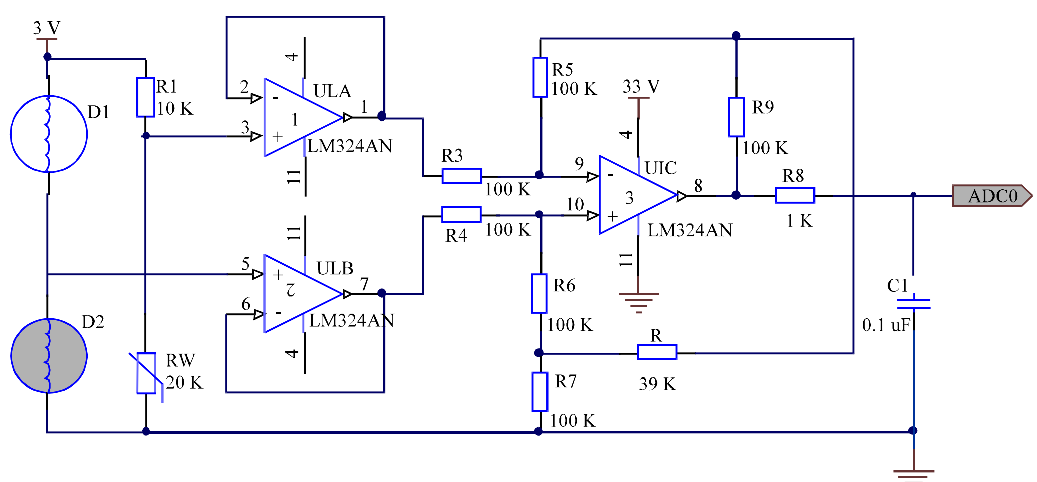

Fig. 5: Collecting and conditioning circuit

modem and MAC support designed for low-power and low voltage wireless application produced by Ti company which is suitable for both RFD and FFD (Montambault *et al*., 2000). CC2420 is configured via a simple 4-wire SPI compatible interface (pins SI, SO, SCLK and CSN) which is used to read, write buffered data and read back status information. CC2420 is connected with the Atmega128L with SFD, FIFO, FIFOP and CCA pins which can indicate state ofsending or receive data. RESET pin can make CC2420 reset, VREG_EN pin can start up voltage comparator of CC2420 and generate 1.8 V voltage so as to put it into proper condition (Fig. 7).

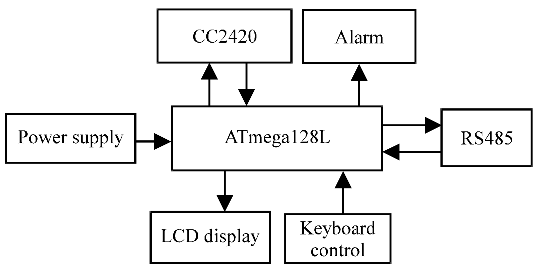

Fig. 6: Block diagram of hardware structure of ATmega128L

Power supply: Power supply voltage of Atmega128L is 3.3 V and researchers can convert 5-3.3 V by LM1117 which is a low dropout voltage regulators features with 3.3 V voltage output. It is shown in Fig. 8.

LCD display: LCD display is the interactive platform between theuser and the coordinator which can display functionmenu by the key-press option. OCM12864-9 is a 128×64 dot-matrix liquid crystal display modules withcontroller by ST7565P produced by Gold Palm Electronics Co., Ltd. which can show the current terminal node parameters from data collection terminal such asdevice type, network ID. LED+ connecting to ATmega128L can control shading value of OCM1284-9 by connecting with 9015. The LCD display module can be shown in Fig. 9.

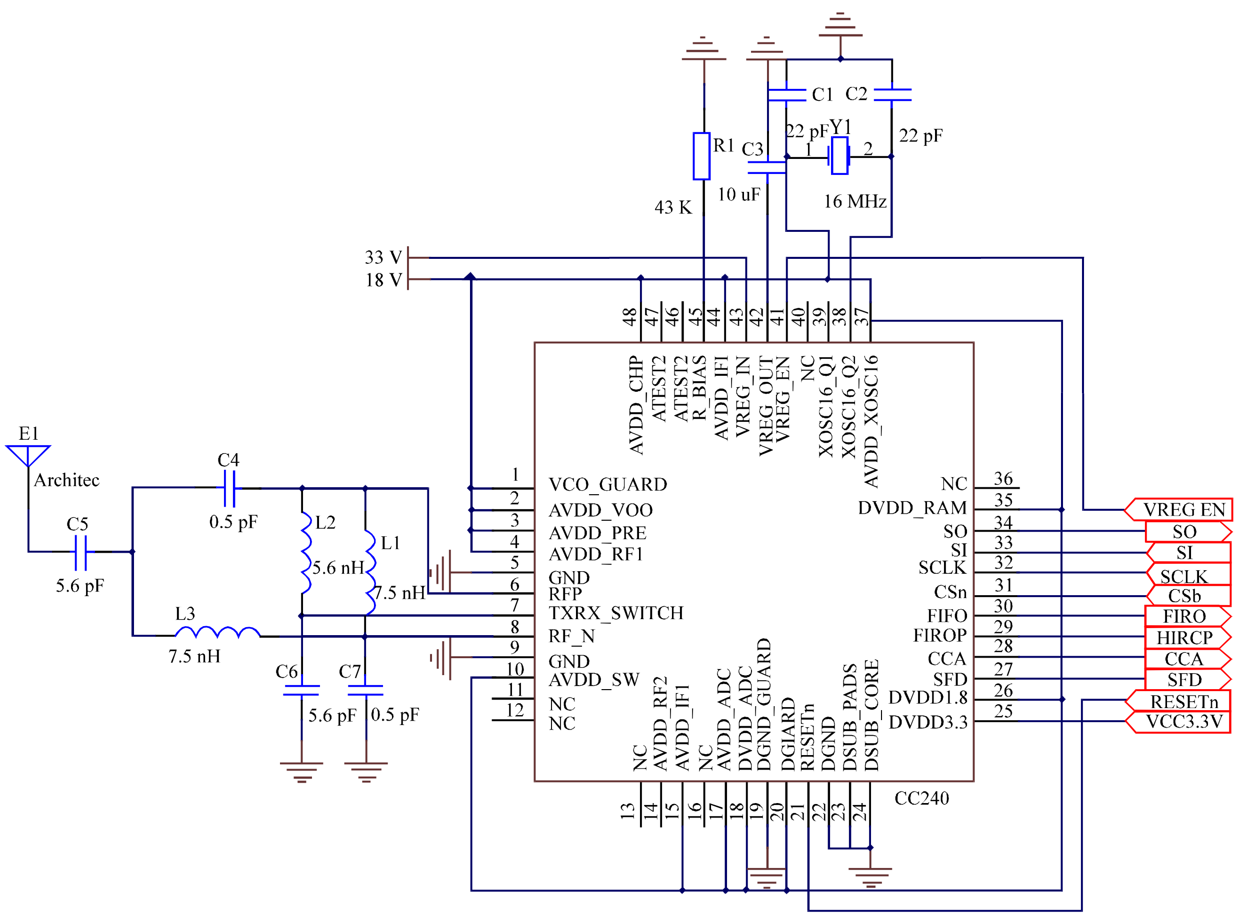

Fig. 7: Pin diagram of coordinator hardware architecture

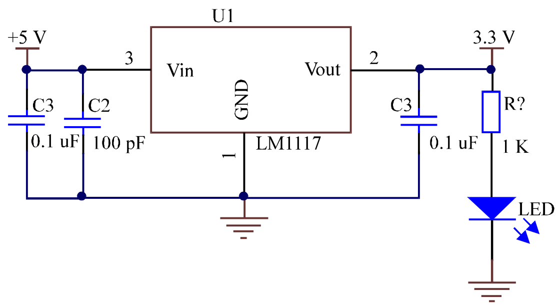

Fig. 8: PIN diagram of power supply unit

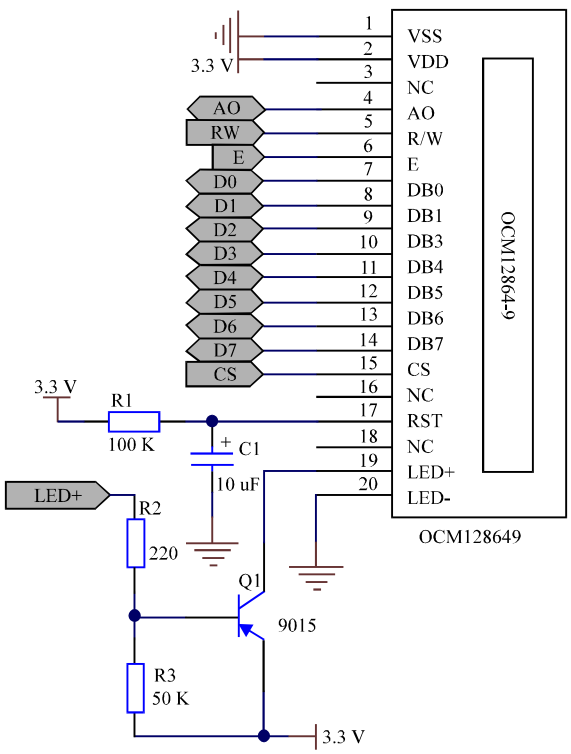

Fig. 9: LCD display module

SOFTWARE DESIGN

Software of system uses IAR Embedded Workbench (EW) for MCS-51 produced by IAR System Company which is a set of high sophisticated and easy to use development tools for programming embedded application. Software System use ZigBee 2007/PRO stack-2.0.0 of TI Company which can be managed byadding the Operating System (OS).

The OS Abstraction Layer (OSAL) API allows the software components in the Z-stack to be written independently of the specifics of the operating system, kernel or tasking environment. OSAL is independent of ZigBee stack. But it whole stack can run based on

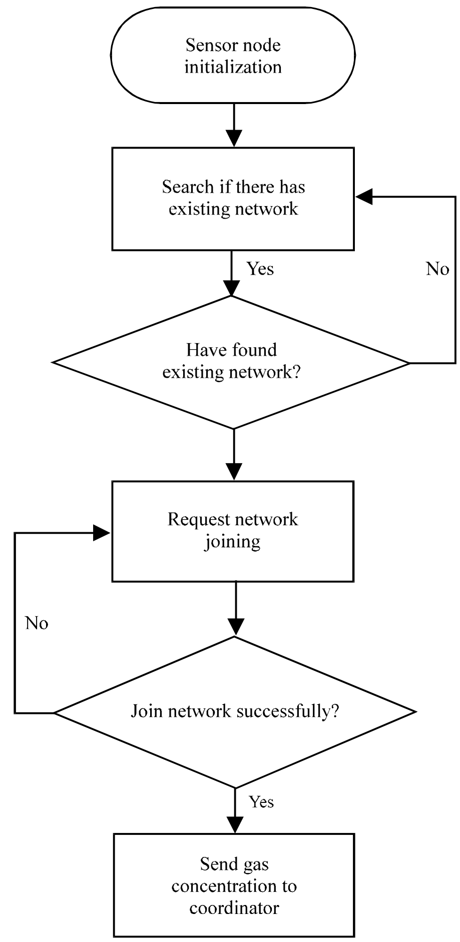

Fig. 10: Flow chart of sensor node software design

OSAL System build a task and allocate task ID and functions. Software design consists of sensor node and coordinator node. The specific design is in detail as follows.

Underground cable trunks gas sensor software design: After power up, Mine gas sensor first initialize ZigBee stack including designated device type and network parameter configuration become a beaconless terminal, it can search coordinator of designated channel and request to join, send its network address which is a unique 64 bit extended addresses used for direct communication with the coordinator when joining successfully and is exchanged for a short address allocated by the coordinator. Collect the UG cables trunks gas sensor concentration data every 1 sec. The sensor node can shut offwhen there is no data transmission and go into the sleep mode so as to save the power consumption. The flowchart of its software design can be shown in Fig. 10.

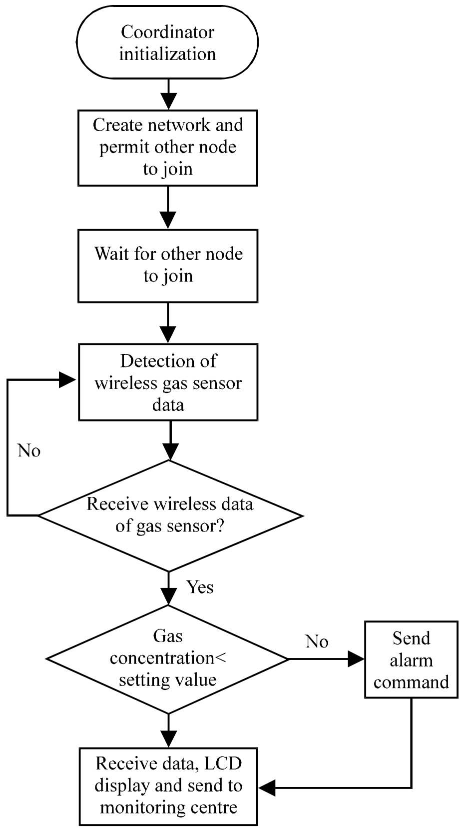

Fig. 11: Flow chart of the coordinator software design

Coordinator software design: The coordinator automatically build network after initialization and allows end devices to join the network. After end devices successfully join the network, it boots binding by key and waits for end device binding request. The key can configure network node and functions such as network joining, address binding, routing, data collection, encryption selection node increasing, decreasing and disconnection from the network. The flow chart of its software design can be shown in Fig. 11.

HARDWARE POC PROTOTYPE

Researchers design a dynamic routing at the first time which changes the routing path dynamically by adding the new node. But it has a power consuming problem. It wastes much power to check the routing status, generate communication packet to establish the new routing path and increase wake up time to synchronize each other. Unlike power tower, in the underground tunnel, it is important to conserve the battery life because recharging technology like solar cell is not available. Researchers need a simple wireless network in tunnel. So, we use a static routing to conserve a battery life (Fig. 12). The surface thermal sensor node that measures surface temperature of joint section has three thermal sensors andmeasures center and both end of joint section. In case temperature differences of three points over five degrees, it alarms a warning of over heating of the joint section. Additionally, researchers place various gas sensors (temperature, carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), hydrogen sulfide (H_2S) and methane gas (CH_4)) in joint section which is placed at intervals of 300 m.

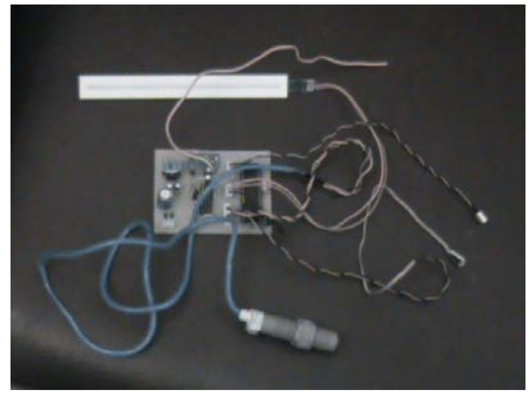

Fig. 12: Sensored node for UG-cable-monitoring prototype (liquid level-mostly H_2O, oil derivatives, T/H-jointing strain detections, proximity levels detections)

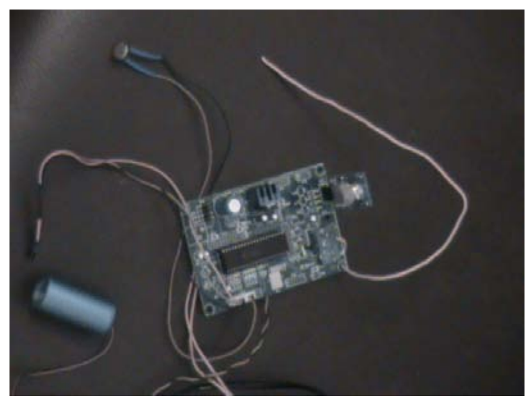

Fig. 13: Gas sensor (CH_4, H_2S, CO, derivatives) and additional sensors for monitoring underground cables

In case of gas sensor, it is not commercialized so par which is specialized in wireless sensor networking and low power consuming. So, researchers use a normal industrial sensor which is not effective in wireless sensor network. This is the main cause of static routing of this system (Fig. 13). Researchers develop a sensor network communicating with sleep and wake up method to synchronize periodically. Sink node having a permanent power, sends a synchronization packet to sensor node to synchronize each other. Sleep time interval can be changed with a monitoring system and propagate from sink node to sensor node with control signal. Generally, sensor node sequentially receives a synchronization packet and control packet after wake up. Then, it sends sensing data to sink node. To activate the sleep and wake up method with all sensor nodes, it is important to make an exact synchronization. Researchers use a various kinds of sensor and they take a different time to sense. The thermal sensor takes several hundred millisecond and gas sensors take several seconds. So, researchers design to wake up not together but respectively depending on the sensing time. The sensor node wakes up earlier amount of required time for sensing before wake up time schedule. It receive synchronization packet after finished sensing (Fig. 14). UG cables being detected for its outage points were identified using the prototype and its mapping view has been showed in Fig. 15-18. Power cable laid in under ground cables can

Fig. 14: ZigBee telemetics box with gateway featured cloud API interface allows to collect, push information from the nodes UG and pushs it to the interface; a) GPS Galelio integrated RFID transceiver; b) Unit based on SS deadreckoning SWAPS GPS Galelio Addon card on top AoDV communication mode; c) Unit upon configured in RFID AoHC mode via tag to tag protocol on enables routing tag information without intermediate reader GW support; d) FE display button panel; e) Backend interface connections (GPS Galelio RFID-IP-HSSDIO-com) and f) Prototype-RFID-GPS Telemetics with WLAN-_IEEE802.11-Interface)

Fig. 15: NEMA data along with mobile RFID transceiver 3G-TAG data relayed through AoDV protocol to the master monitoring station

Fig. 16: Active RFID GPS telemetics unit mounted on the demo car

Fig. 17: Active RFID GPS telemetics unit showing the location embedding Google Earth onto GIS mapping layout (Tail point will rely real time data from that location can show live view of the event)

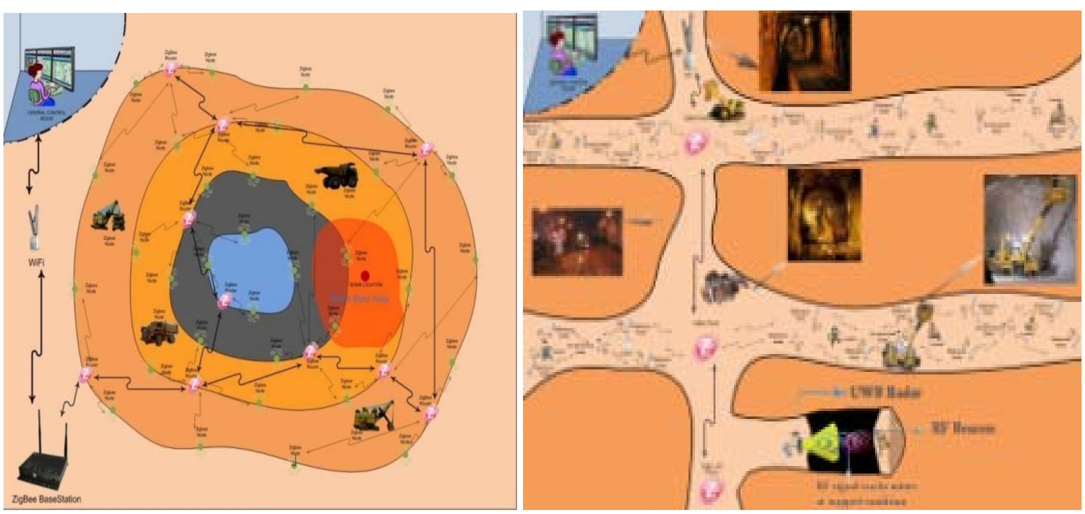

Fig. 18: Underground monitoring of power cable inside mines

be identified using ZigBee nodes which in turn communicate with the ZigBee co-ordinator which will relay the UG cable parameters monitoring like gas intensity levels, strain levels, proximity levels, tilt-levels, temperature, thermal-imaging, etc. the parameters monitoring are endless the application specific target board has parameters monitoring has the ability to handle concurrent events from more than 750+ sensors to the ZigBee station and its data will be parsed in to an XML using an auto server configuration framework will run on the server send.

ENERGY HARVESTING

Electromagnetic wave energy harvesting: Theoretically, an electric field of 1 V m^{-1} yields 0.26 μW/cm^2. However, such electric fields may only be encountered close to powerful transmitters.

Although, smart grid environments are energy rich, sensors must be located further away from high voltage conductorsto function properly. Instead of this, RF energy can be broadcasted to power electronic devices. But this approach is limited by legal limits set by safety and health implications. This approach is already usedin passive Radio Frequency Identification Systems (RFIDs).

Modulated back scattering: Data transmission is one of the major battery-consuming processes insensor nodes. A design technique called Modulated Back scattering (MB) is very promising since byusing this technique, wireless sensor nodes send their data just by switching the impedance of their antennas and reflecting the incident signal coming from an RF source. The source of energy isan RF power source which is AC/DC powered. In this technique, an RF source transmits RF power torun Wireless Passive Sensor Network (WPSN) nodes and transmits and receives information from the nodes simultaneously. Hence, the expected lifetime of WPSNs utilizing MB is longer than WSNs. On the other hand, the RF coverage provided over the field directly affects the communication performance ofWPSNs.

Another advantage of MB-based WPSNs is that theoretically long-range communication withthe WPSN nodes is achievable without increasing the power consumption of the nodes. An important criterion which affects the design of WPSNs is the number of RF sources required for effectiveMB-based communication.

Magnetic field energy harvesting: The magnetic field near T&D power cables lines can be harvested to power sensor nodes. Most of the magnetic field energy harvesters are based on transformer action which requires a clamp around the conductor for energy harvesting.

EMERGING AMENDMENTS TO IEEE 802.15.4

To promote open standards for smart grid environments and to meet specific national and regional regulations, the IEEE 802.15 Smart Utility Networks (SUN) Task Group reviewed the IEEE 802.15.4 standards and proposed amendments. Initially, the IEEE 802.15.4 standard was designed for low-power wireless PHY and MAC layers which offer low-power consumption with link speeds up to 250 kbps in the 2.4 GHz ISM frequency band. The amendment, IEEE 802.15.4 g, adds new PHY support and also defines some MAC modifications. The PHY supports multiple data rates in bands ranging from 450-2450 MHz in three different modes with data rates of 5-400 kbps and PHY frame sizes up to 1500 octets. With this amendment, the IEEE 802.15.4 radio can now operate in one of the dedicated use or unlicensed bands. The IEEE 802.15 Low Energy Critical Infrastructure (LECIM) Task Group 4k (TG4k) was also formed to provide an amendment to IEEE 802.15.4 to facilitate point to thousandsof points of communications for critical monitoring applications such as network traffic congestion monitoring, fault circuit indicators and perimeter security. The amendment addresses minimal network infrastructure and enables schedule-driven and trigger-driven data collection from a great number of battery-powered end points which are widely dispersed or are in challenging environments such as specific smart grid infrastructures. The amendment supports data rates of up to 40 kbps and minimizes device wake durations and network maintenance traffic to support low energy operation for long battery life. It can also operate in any of the regionally available bands.

LINK RELIABILITY ANALYSIS

In this study, the results of the reliability analysis are given for different smart grid environments including indoor power control room, outdoor 500 kV substation and underground network transformer fault. This analysis is based on experimentally determined log-normal channel parameters obtained in the previous experimental study which was conducted using IEEE 802.15.4 compliant wireless sensor nodes in different power system environments at NTPC. Table 1 shows the path-loss exponent and shadowing deviation in smart grid environments. Experimentally determined log-normal channel parameters for different power system environments in Non-Line of Sight (NLOS) are given in Table 1. In this case study, researchers have modelled the wireless channel by the use of a log-normal shadowing path-loss model through a combination of empirical measurements and analytical techniques. Experimental studies show that modeling the wireless channel using a

Table 1: The path-loss exponent and shadowing deviation in smart grid environments

Propagation environment	Path loss (η)	Shadowing deviation (σ)	Noise floor (pn)
500 kV substation (non line of sight)	3.51	2.95	-93
Underground transformer vault (NLOS)	3.15	3.19	-92
Main power room (NLOS)	2.38	2.25	-88

log-normal shadowing pathloss model provides more accurate multi path channel models compared to the Rayleigh Models. In this model, signal to noise ratio (d) at distance d from the transmitter can be calculated by the following:

$$\gamma(d)_{dB} = P_t\text{-}PL(d_0)\text{-}10\eta\log_{10}\left(\frac{d}{d_0}\right)\text{-}X_\sigma\text{-}P_n$$

Where:

P_t = The transmit power in dBm
$PL(d_0)$ = The path loss at a reference distance d_0
η = The path-loss exponent
X_σ = A zero mean Gaussian random variable with standard deviation σ
P_n = The noise power (noise floor) in dBm

In this study, Packet Reception Rate (PRR), the ratio between the number of successful packets and the total number of transmitted packets is used to evaluate the reliability of wireless links in three different smart grid environments such as outdoor substation, underground transformer vault and indoor main power room.

CONCLUSION

Power transmission is through cables in cities and industries. The sensor technology incorporated with the data logger and GPRS technology provide high reliability of the system. The data received from the module are processed and instant remedial measures can be taken. The most vulnerable fault is the breakdown of insulation resistance.

The early detection cause the system more attractive to electricity boards and industry. Overall, this study explains research challenges resulting from inherent properties of WSNs and smart grid propagation environments. In addition, the experimental studies show that network designers planning to use WSNs for smart grid applications need to consider important sensor node parameters including transmission power, range and channel parameters.

Future research includes the development of cross layer ommunication protocols to address link-quality variations in smart grid environments, QoS provisioning and coordinated network management for different application types of smart grid. In addition, in order to prove the advantages of energy harvesting techniques for WSN-based smart grid applications, a set of experiments will be conducted and statistical evaluations will be done. A group of field tests will be conducted in a main power room and near a substation. In the same locations, another group of field tests will be conducted to examine the relation between link reliability and node lifetime.

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