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Wireless Sensor Network Design For Wildfire Monitoring ‡

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***Abstract* – This paper describes a system design approach for wireless sensor network based wildfire monitoring, including the system architecture, hardware and software framework. Effectiveness of the solution is evaluated in terms of reactivity, reliability, robustness and network lifetime. The main contribution of the paper is the design of a sensor network that can meets the goal of reactivity and reliability, and that demonstrates satisfactory robustness and relatively longer network lifetime.**

***Index Terms* –wireless sensor network, wildfire monitoring, reactivity, reliability, robustness, network Lifetime.**

I. INTRODUCTION

Wildfires are expensive disasters in term of both property loss and life safety. Wildfires often occur in environmental sensitive regions such as forest park, grassland area, or along the urban-wildland interface. Environmental monitoring in such terrains must be environmentally appropriate, which requires easy installation, low maintenance and relatively inexpensive instrumentation. One way to monitor wildfires and impending unattainable areas is to use wireless sensor network (WSN) consisting of miniature sensor nodes to collect environmental data such as temperature, relative humidity and barometric pressure, and deliver high quality information to fire-fighters or remote monitors.

Considerable advances have been made in recent years in hardware [1] and software [2] for building wireless sensor networks. However, to ensure effective data gathering by sensor networks for monitoring remote outdoor environments especially the harsh wildfire environment, the following problems remain:

- **Reactivity:** the ability of the network to react to its environment, and provide only relevant data to users;
- **Reliability:** the ability of the network to provide effective data delivery, high link quality and reliable routing;
- **Robustness:** the ability of sensor nodes to function correctly and be fault tolerant in harsh environments;
- **Network lifetime:** maximizing the length of time the network is able to deliver data before nodes' batteries are exhausted.

The main contribution of this paper is the design of a WSN that can meets the goal of reactivity and reliability, and that demonstrates satisfactory robustness and network lifetime. Testing the performance of the network is the subject of ongoing work. The long term aim of our research is to develop components for sensor networks that can be simply combined to create reactive, long lived networks for a variety of environmental monitoring applications including soil moisture monitoring, dry-land salinity management and flood or environmental pollution forecast.

The rest of our paper is organized as follows. In Section 2, we discuss the related work. In Section 3, a design of the network for wildfire monitoring is described. In Section 4, the approach to achieve reactiveness, reliability, robustness and longevity is explained in detail and some discussions are made to present remaining problems. Finally Section 5 presents our concluding remarks and future work.

II. REALATED WORK

Traditional technology for fire detection using GIS, GPS and GPS remain problems of expensive cost, inaccuracy and non-real-time response. Failure or misjudgment of fire detection happens frequently.

Using wireless sensor networks for monitoring has several advantages over traditional approach:

- The nodes are easy to deploy and use;
- Individual node is relatively inexpensive, allowing more data to be collected per unit cost;
- Motes work collaboratively and provide abundant data for processing to improve accuracy;
- Standardized, freely available and modular software components reduce cost of developing, modifying and maintaining the system;
- The deployed system allows near real-time response to events such as rapid temperature rise reported by deployed sensors.

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The first generation of sensor networks tested in field trials is the habitat monitoring on Great Duck Island [3], to monitor the behaviour of storm petrel. They used periodic monitoring with a pre-set sensing regime of readings taken at regular intervals and relay through a fixed networking tree to base station. For wildfire monitoring sensor network, few test was implemented. In [4], it proposed a design for fire monitoring incorporating wireless sensors, and report results from field testing during prescribed test burns. However, improving reactivity and robustness reliability was not considered. In [5], it described a system design approach for a WSN based application that is used to measure temperature and humidity as well as being fitted with a smoke detector. A simulation was done to show how data rotated from one node to the other.

III. DESIGN OF WIRELESS SENSOR NETWORK FOR FIRE MONITORING

A. *Monitoring Objectives*

The main objective is to study and test a WSN system for wildfire detection and alarm signalling. This system should be able to detect a small fire (about tens of meters in size) and determine its position with accuracy sufficient to make possible a fast intervention and fire spread limitation. The detection cells will be connected via a wireless data transmission system with a central control or data collection point connected to the warning system of the emergency service. In this way, the immediate response fire alarm is realized.

B. *Network Architecture*

The fire monitoring WSN is based on Mica2 motes and MTS400 sensor boards [1]. It uses the following components:

- Temperature, humidity, barometric pressure and light intensity sampling nodes,
- Routing nodes for transporting relative readings from the sampling nodes to the base station,
- Base-station connected to web sever,
- Web server connected to a MySQL database, which is queried by a browser-based client,
- Client providing data browsing, GPS information and fire alarm, sending to fire-fighters to response to the fire.

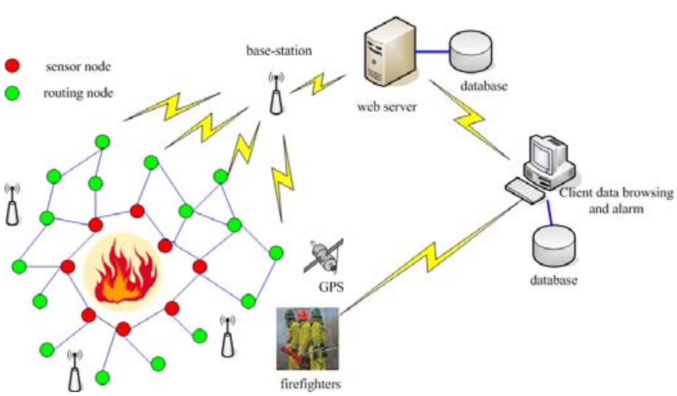

Fig.1 the Architecture of WSN for Wildfire Monitoring

The wildfire monitoring system is designed to be platform independent, simple to deploy and use under extreme stress conditions, and to require minimal training for operating the system after deployment [4]. The architecture of the system is shown in Fig. 1. A novelty of our design is its reactivity to the environment, which will be discussed in IV.A. In usual time, environmental data are collected by a few sensor nodes in a low frequency when it is humid with low fire possibility. When a fire occurs, the nodes surrounded are activated to sample related data such as temperature, humidity and barometric pressure in a relatively high frequency. The collected data are relayed through routing nodes and base-station to be stored into a MySQL database connected to web server, which is queried by a browser-based client. Data information are processed or aggregated in the base-station to reduce the communication cost. Client provides effective information including fire extent and location for fire-fighters to make responsive action. PDAs can also be used by fire-fighters for spot monitoring.

C. *Wireless Sensor Network Hardware*

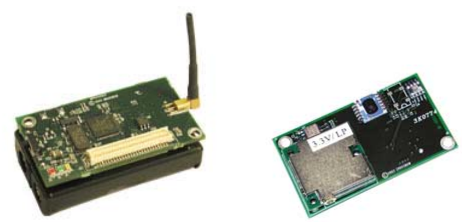

Fig.2 Mica2 Mote and MTS400 Sensor Board

The sensor motes are composed of the mote platform with an independent mounted sensor board. This separation allows hardware and software development of wireless sensor networks to proceed independently. The Mica2 mote, as shown in Fig.2, hosts an Atmel 128L CPU running the Tiny Operating System (TinyOS), executing programs written in the nesC language. The “fireboard” (MTS400 sensor board), as shown in Fig.2, is a separate component from Mica2 mote and connects to the mote using a 52 pin connector. The architecture of the fireboard is derived from the Mica Weatherboard used for Great Duck Island [3] study, and hosts temperature, relative humidity, light intensity, barometric pressure, acceleration and GPS location sensors.

D. *Wireless Sensor Network Software*

The Crossbow Mica2 mote is operated using TinyOS, an operating system specifically developed for programming small devices with embedded microcontrollers. TinyOS is programmed largely in the nesC language, which is designed expressly for efficiently capturing the semantics of programming for small embedded devices.

TinyOS and the nesC language use a modular, interface driven syntax, but there is still a high degree of interaction between components. To program the nodes so that different motes can use different configurations of the same code-base requires effective high-level abstraction of basic behaviour. The abstractions required for our application are [6]:

- Sensing activities
  - Temperature, humidity, barometric pressure and light intensity data,
  - Weather triggered events,
- Timing activities:
  - Clock synchronization,
  - timer setting and triggering,
  - time-stamping,
- Logging activities
  - writing samples to EEPROM as backup,
- Communication activities:
  - all nodes and node-serial port communication
- Localization activities:
  - node localization
  - fire localization
- Power Management

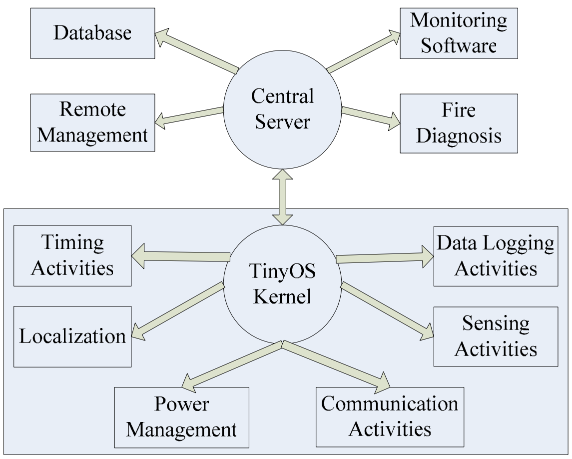

Fig. 3 Software Architecture

Fig.3 shows the software architecture for WSN based fire monitoring. TinyOS kernel implements the activities of sensing, timing, localization, communication, data logging and power management. In central server, it provides the service of database, remote management, monitoring software and fire diagnosis.

IV. EVALUATION OF THE NETWORK

A. *Reactivity*

Sensitive reactivity to the environment is needed to ensure that most interesting data is gathered, given the resource restrictions of sensor networks. For example, the fire detection WSN needs to react to the weather: frequent temperature and humidity readings should be collected in sunny and dry days when fire could possibly occurs (say, every 5 minutes), but only infrequent readings (say, once an hour) are needed during rain. Reactivity can be achieved by adding a threshold to sensing parameters like humidity and light density. The sensing rate of sampling nodes automatically changes as the parameters get across the threshold. Therefore, the time spent sending, receiving and listening to messages can be minimized during humid days. Making wireless sensor networks more reactive is an important step towards prolonging the lifetime and enabling them to become effective monitors.

B. *Reliability*

An important aspect of network reliability is the loss rate of radio message transmission between neighbouring nodes in the network, because one failure in a sequence of transmission. Besides, the link quality is more disappointing in the outside area than in laboratory with the same hardware and software.

Fig.4 shows how link quality varies over a distance for a collection of many pairs of nodes. For a given power setting there is a distance within which essentially all nodes have good connectivity. The size of this effective region increases with transmit power. There is also a point beyond which essentially all nodes have poor connectivity. However, in this clear region, some distant nodes occasionally do receive messages successfully. Between these two points is the transitional region, where the average link quality is falls off relatively smoothly, but individual pair exhibits high variations. Some relatively close pairs have poor connectivity, while some distant pairs have excellent connectivity. The dynamic and loss behavior is the largest obstacle of achieving reliability in sensor networks.

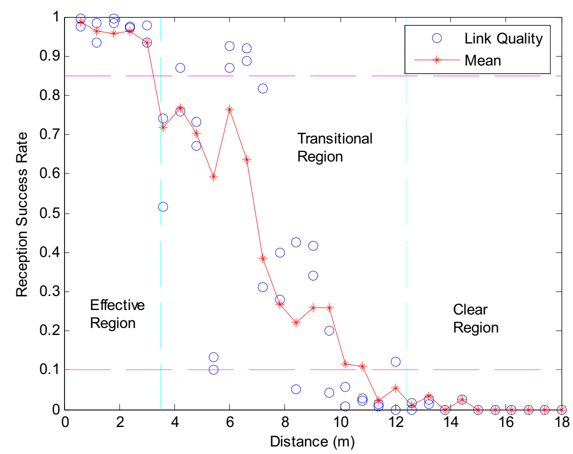

Fig.4 Reception Probability of All Links in a Network, with a Line Topology on an Outdoor Court

In order to reduce the number of message lost because of poor radio connectivity, our routing protocol includes a diagnostic phase for each node when it first turned on in which the node connects to its upstream neighbour and unicast a packet every 30 seconds. We then monitor at the base node and if necessary move and restart the node until good quality reception is achieved.

Another method for improving reliability is to have more than one path between critical pairs of nodes communicating in the network. When a routing node is unable to reach one neighbour it simply resends the message to another. As extension to this method, we adopt a link quality based routing protocol [7], which means only nodes with the best historical link quality will be chosen to route the message. The link quality is acceptable if m out of k consecutive data packet has been successfully transmitted. The link table only records historical k link states and can be updated dynamically with a low computing cost and complexity. Thus the chosen node is the one with the largest value of m. This routing protocol is demonstrated in simulation to be energy and data delivery efficient. However, the initialization of the routing tree needs some time and the test of the protocol in real WSN has not yet been implemented, leaving to future work.

C. Robustness

The robustness of a WSN depends on the following factors: the ability of network protocols to recover from errors, how well the nodes withstand harsh outdoor conditions and misadventure from wildlife or humans, and the accuracy of sensors used for measuring environmental parameters. Our field site is native forest and grasses visited by birds, animals and (rarely) humans. We design and build outdoor housing for the nodes and their batteries using water-and-fire-proof boxes. Nodes and batteries are securely mounted in these boxes on raised platforms to prevent damage if the node box is disturbed by wind, rain, fire or wildlife. Fig.5 shows the newest indoor Mica2 node with housing which is produced by Crossbow Technology, Inc.

Fig.5 New Mica2 Node with Housing

There is the situation that certain nodes are destroyed despite the protective housing. In order not to influence the accuracy of collected environmental parameters, we need to adopt the technology of multi-sensor fusion to do in-network collaborative signal processing [8]. In that case, the temperature or humidity values passed on to the client do not depend on single sensing node, The invalidation of a small number of nodes will not affect the function of the whole system and this kind of network is to some extent fault-tolerant.

D. Maximizing Network Lifetime

The problem of power management has been recognized as crucially important for wireless sensor networks, but it has also proved difficult to achieve a practical solutions. The power management approach designed for Berkeley mote hardware is for motes to alternate between active and sleep states. If we could maximize the percentage of time each mote is asleep, it should be possible to extend a mote's lifetime to many months or even years.

A reactive network can not simply set its sampling nodes to sleep at usual because nodes must be ready to respond frequently as soon as a potential fire occurs. Furthermore, when a sampling node awakes, all the router and gatherer nodes that it relays on to deliver its message must also awake. Clock drift between nodes makes the coordination of waking cycles a difficult task.

SMAC [9][10]is a MAC protocol designed to address the problem of energy efficient, coordinated sleeping, and so is well suited to our application. Nodes synchronize with their neighbours for a cycle of sleeping and waking. In the lowest duty cycle of 1%, nodes sleep for approximately 12 seconds and then awake to for the coordinated transmission and reception of messages by reliable unicast or by broadcast. The SAMC software stack also provides a reliable physical layer implementation with Manchester encoding.

Besides aspects like architecture, communication protocol, algorithm, circuits and sensing must be energy efficient, a Dynamic Power Management (DPM) [11] should be adopted to reduce power consumption and consequently, improve the network lifetime. The DPM is to decide when a sensor node should go to a sleep or idle state and the amount of time to stay there, and even when a transmission task could be done. The sampling rate could be tied to current environmental state: high temperature with low humidity in daytime would increase the sampling rate, the converse decreasing.

We take temperature data monitoring for example. The available temperature data from May to September for our monitoring area can be described as follows:

- Maximum absolute temperature: 35℃;
- Minimum absolute temperature: 8℃ ;
- Maximum average temperature: 25.5℃;
- Minimum average temperature: 15.5℃ ;

Additionally, we assumed the following temperature information about fire detection:

a) The minimum temperature to be considered as fire is 45 ℃ , temperature higher than 45 ℃ is considered a potential fire;
b) Temperature variation below 0.5 ℃ are considered normal and do not need to be reported;
c) Variation above 5 ℃ in a short period of time are considered abnormal and should be analysed as a possible fire, even if the temperature remains below 45℃.

Case b represents the sensor node sleep mode when the radio and the sensing are turned off, case a and case c represent a sensor node with high sensing mode when sensing and communication operating are performed in a high rate. Other situations like the variation is between 0.5℃ to 5℃ or temperature is under 25℃ represent a sensor node with low sensing mode when sensing and communication operating are performed in a low rate. This approach of reducing the overall power consumption can improve the network reactivity as well.

E. Discussion

Besides what we discussed above, the issues of sensor deployment and coverage is also critical to the installation of the whole system [12]. The problem can be described as follows: assuming that each node can monitor a disk (the radius of which is called the sensing range of the sensor node) centred at the node on a two dimensional surface, what is the minimum set of nodes that should be put in the active mode in order to cover the entire area? How should the operational set rotate among all the sensors in order to maximize the operational period? There should be enough nodes to cover the monitoring area yet too many nodes may be wasteful. The balance between the degree of coverage and the cost is what we would consider. Current research of this area remains in the state of theory and simulation, few field testing is implemented.

The location of the fire is of great importance to our fire fighters. To solve the problem, the sensor node should process to gain the knowledge of its physical location in space. Nowadays, with the help of GIS technology, localization is becoming more and more briefly. Nevertheless, GIS is not suitable for WSN while the GIS instrument is costly, giant and energy consuming for wireless sensor nodes but the sensor nodes are smaller, costless and energy considered. On the platform of WSN, the majority of existing localization discovery approaches consists of two basic categories: Range-Based and Range-Free. The former is defined by protocols that use absolute point-to-point distance estimates or angle estimates for calculating location. The major two approaches of this category are TDoA (Time Difference of Arrival) and RSSI (Received Signal Strength Indicator) technologies. The latter makes no assumption about the availability or validity of such information. [13] proposed a RSSI Based Localization scheme, which is easy to implement and do not need extra instrument. However, the accuracy is to be improved.

In most of the sensor networks, the base-station is stationary. We propose a mobile base-station to periodically collect real-time information (e.g. fire conditions) about the environment. Such strategies include local spatiotemporal query (query of spatial neighborhood), global spatiotemporal query (query of all sensors), and border query (query of the border of danger fields). Through in-network processing, the region of the fire can be calculated and we can even roughly predict the spreading trend of the fire.

V. CONCLUSIONS

We have described the design of a novel reactive WSN for monitoring wildfire and evaluated the reactivity, reliability, robustness and longevity of the network. Future work will focus on field testing the system and find the limitation of the current prototype of in reliability, robustness and network longevity, and in guaranteeing network response to events of interest.

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