Development of a Wireless Sensor Node for Environmental Monitoring

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***Abstract*—The Wireless Sensor Network (WSN) has emerged as an exciting research field in recent years and has the potential to revolutionize applications such as industrial monitoring and automation, environmental monitoring and biomedical science. Wireless sensor networks achieve these objectives using sophisticated networks of low cost smart sensors that co-operatively monitor and communicate information such as gas concentration, humidity, temperature, etc. One of the shortfalls of the existing wireless sensor network technology is limited coverage area. Environmental monitoring applications such as bushfire detection require vast coverage areas for wireless sensor networks to be economically effective. In this paper, we present the architecture and characteristics of a long range wireless sensor network targeted for environmental monitoring applications. Firstly, the hardware design and software implementation are explained and then the achieved results are evaluated. The developed wireless sensor node can cover several hundreds of kilometers by using a proprietary mesh protocol.**

Keywords-wireless sensor network; DIGIMESH; long range; 9-Xtend

I. INTRODUCTION

Wireless sensor networks have become an important field in wireless technology**.** Wireless sensor networks have certain features that differentiate them from other wireless networks. A typical wireless sensor network has processing and sensing capabilities in addition to the expected communication capabilities. Wireless sensor networks also have very stringent power consumption requirements and have very limited computational and storage capacities. A typical wireless sensor network should be able to function unattended for extended periods of time, usually a number of months off say two AA batteries.

The challenges involved in the design of WSN are how to minimize power consumption and increase the computational efficiency. Most of the power in WSN is consumed during data communication. It is, therefore, very important to implement efficient networking algorithms.

Some of the interesting applications of wireless sensor networks include habitat monitoring [1], environmental monitoring [2], and biomedical applications [3]. The design choice of a wireless sensor network is very application dependant. For example, for environmental monitoring applications we ideally need a wireless sensor network that can cover large geographical areas, whereas in biomedical applications, the wireless sensor network should be tiny and accurate. Nevertheless, the design of the wireless sensor networks should be modular to some extent, in order for the development and manufacturing to be economically viable.

One of the shortfalls of the currently developed sensor nodes is that they can only cover small geographical areas due to their limited transmission range. For applications such as environmental monitoring, the coverage area needs to be at least several kilometers. One example of environmental monitoring application is bushfire detection. A bushfire monitoring system should cover tens of kilometers in order to be effective. Even though the short transmission range of existing wireless sensor networks can be compensated by deploying a mesh topology, it would be economically infeasible to have thousands of densely deployed sensor nodes to monitor bushfire. In fact, one of the advantages of WSN is its low deployment cost.

One possible solution to address the transmission range limitation of the existing sensor nodes is to connect the local wireless sensor network to a larger network, such as the internet, through a gateway node. The weakness of this solution is that it relies on pre-existing infrastructure. For example in a forest-fire detection application, the sensor nodes are scattered in remote areas where there is no other network coverage. In this situation, the nodes must be able to route the messages without relying on any existing network infrastructure.

Another solution is to modify the transceiver hardware of the existing sensor nodes to increases their receiver sensitivity. The JCUMote [4], a sensor node based on the MICAz achieves this through the use of RF power amplifiers. The advantage of this solution is that, it utilizes the already developed technology in the MICAz, but the increased transmission range is still not sufficient for applications such as forest-fire monitoring.

The aim of this paper is to develop a wireless sensor network with vast coverage to be used for environmental monitoring applications. In order to achieve this, we firstly developed the hardware platform. We then developed the node logic or software and integrated a long range transceiver with advanced built-in networking capabilities into the system.

The field tests results are very promising with approximately 22 kilometers of line-of-sight range. The implementation of a mesh network has greatly extended the coverage area and has resulted in enhanced reliability and robustness of the overall network.

II. METHODOLOGY

A. Node Architecture

The hardware of the developed sensor node is composed of two sensors, transceiver, antenna, expansion connectors, external memory and a microcontroller. The developed sensor node interfaces with a PC via a USB connector, and can be reprogrammed using the dedicated on-board programmer. A block diagram of the sensor node architecture is shown in Figure 1.

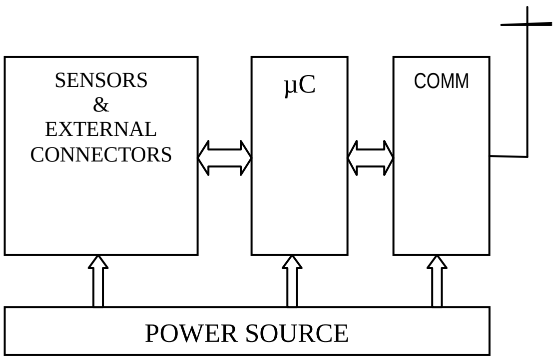

Figure 1. Architecture of the Sensor Node.

B. Sensors and Expansion Connectors

There are two analog sensors integrated into the developed wireless sensor node, namely, humidity and temperature sensors. These sensors were chosen because of their popularity in many environmental monitoring applications.

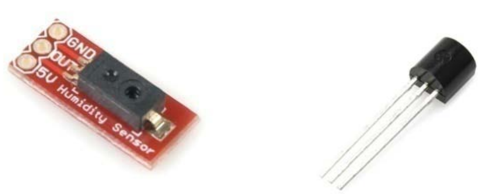

Figure 2. HIH-4030 and LM335 Sensors.

HIH-4030 [5] from Honeywell was chosen as the humidity sensor. HIH-4030 is an analog humidity sensor that can be connected directly to the microcontroller due to its near linear output. The special packaging provides protection against environmental hazards such as condensation, dirt, dust, and other chemicals.

According to the datasheet, output voltage and relative humidity are related according to the following equation.

$$V_{out} = (V_{cc})\ (0.0062(RH) + 0.16 \quad (1)$$

where V_{out} stands for the output voltage of the sensor, RH for relative humidity in percentage and V_{cc} for the supply voltage. The output of the sensor is connected to one of the ADC channels on the microcontroller via a current limiting resistor.

In order to compensate for temperature changes, which affect the precision of the sensor, the following equation is used.

$$\text{True RH} = (\text{Sensor RH}) / (1.0546\text{-}0.00216T) \quad (2)$$

where True RH stands for the compensated relative humidity and T for the temperature in degrees Celsius.

LM335 [6] from National Instruments was chosen as the temperature sensor. LM335 is an analog temperature sensor that operates over a -55 degrees Celsius to 150 degrees Celsius temperature range. It can be directly connected to the microcontroller due to its near linear output response.

According to the datasheet the calibrated output of the sensor and temperature in Celsius are related according to the following equation.

$$T(C) = T_0\ (K)\ (V_{out}/\ V_{outT0}) - 273 \quad (3)$$

where T(C) stands for temperature in degrees Celsius, T_0 (K) for a reference temperature in Kelvin, $V_{outT0}$for the output voltage at the reference temperature and V_{outT} for the output voltage at any temperature. The chosen reference temperature for this sensor was 298 degrees Kelvin and the corresponding output voltage was measured to be 2.94 volts.

The developed sensor node has expansion connectors for two analog sensors, two SPI compatible sensors and three I^2C compatible sensors. I^2C and SPI interfaces were implemented because of their popularity in digital sensors. An external EEPROM is also connected to the microcontroller via I^2C interface.

C. Processor

ATmega168 is the chosen processor for the developed wireless sensor node due to its user friendly interface and author's prior experience in programming Atmega family of microcontrollers. The important factors in choosing the processor were: power consumption, built-in interfaces for UART, SPI, I^2C, speed, and size.

D. Communication and Networking

The transceiver is where the communication and networking take place in the sensor node. The important factors for choosing the transceiver were transmission range, network topology support, power consumption and size. The Xbee-PRO from Digi International, the RMX-232 from Embedded Communication Systems and the 9-Xtend from MaxStream [7], [8], [9] were evaluated. The 9-Xtend RF radio module was the chosen transceiver due to its superior transmission range and support for mesh networking. The transceiver is connected to the microcontroller via UART interface. The following table summarizes the characteristics of the evaluated transceivers.

TABLE I. SUMMARY OF EVALUATED TRANSCEIVERS.

	Xbee-PRO	RMX-232	9-Xtend
Power Consumption	954 mW	630 mW	3650 mW
Dimension (cm)	3.29x2.44x0.546	8.5x6.5x2.5	3.65x6.05x0.5
range	9.6 Km	2 Km	64 Km

DIGIMESH [10], a proprietary mesh network protocol, is the networking protocol used in the developed sensor node. In a mesh network, messages are routed through several nodes in order to reach the final destination. Other than the extended range, DIGIMESH offers a unique set of capabilities that makes it suitable for our sensor node. Some of the important features of DIGIMESH include:

- Self healing
- Flexibility to expand network
- Elimination of expensive gateway routers
- Reliability

Self healing means that during node failures, the network can find an alternative path to the destination. Flexibility to expand the network is due to the fact any node can be added and removed from the network without affecting the functionality of the network as a whole. The homogenous nature of the network results in equal functionality of all the nodes; therefore there is no need for any gateway node with enhanced functionality. This makes the configuration of the network substantially easier. Finally, reliability is achieved through the use of acknowledgments and retransmissions.

The routing algorithm in DIMIMESH is very similar to the AODV (Ad hoc On-demand Distance Vector) [22] algorithm. There is an associative routing table for each node that maps the destination address to its next hop address. Thus messages from the source node will go through possibly several nodes until they reach the destination node. When the source node doesn't have a route for the specified destination, it will initiate a Route Discovery process.

During the Route Discovery process, the source node broadcasts a Route Request message. Upon reception of Route Request message, the intermediate nodes rebroadcast the Route Request message if they don’t have a better route back to the source node, otherwise they drop the message. When the destination node eventually receives the Route Request message, it unicasts a Route Reply message back to the source node. Therefore, the source node might receive multiple Route Reply messages. It will choose the one with the best round trip route quality. It should also be noted that the destination address of the source nodes has to match with the source address of the destination node.

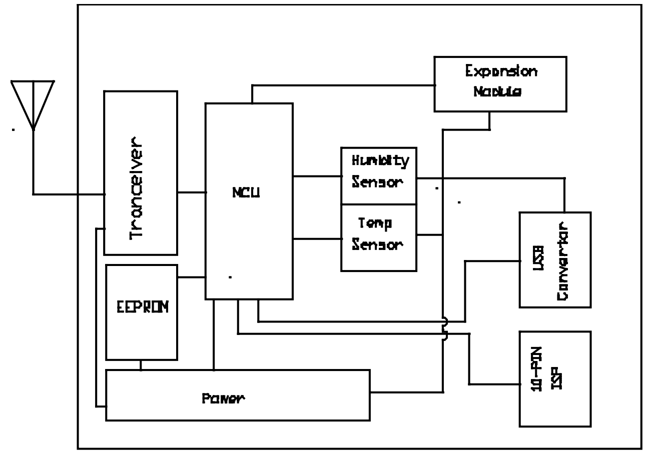

Figure 3. Detailed Block Diagram of the Sensor Node.

E. Power Consumption

There are several wireless sensor nodes already available in the market such as TelosB [11], MicaZ [12], Waspmote [13], etc, all of which have low power consumption, but they have limited transmission range, usually several hundred meters. There are other long range transceivers available, but they are targeted for industrial applications and require constant power supply, and are usually very bulky and expensive.

F. Final Design

A detailed block diagram of the developed sensor node is shown in Figure 3. A PCB for the complete design, including the microcontroller, transceiver, sensors and other peripherals was designed using ExpressPCB [11] manufacturer as shown in Figure 4. The PCB has two copper layers and is 80mm by 70mm in size. A five volt battery is housed underneath the PCB.

Figure 4. Completed Sensor Node.

G. *Node Logic*

The node logic is shown in the following flowchart. In the first step the node is initialized. During node initialization, the ADC, UART, I^2C and SPI modules are configured and the associated registers are initialized. Then, the sensors are sampled including any external sensors attached to the sensor node. The readings from the sensors are digitalized and calibrated. The calibrated results are compared against predefined thresholds and if they exceed, an alarm message is generated and sent to the transceiver via the UART interface. The transceiver then takes care of packetisation and RF transmission of the message to the base-station. After a brief wait, the above procedure is repeated.

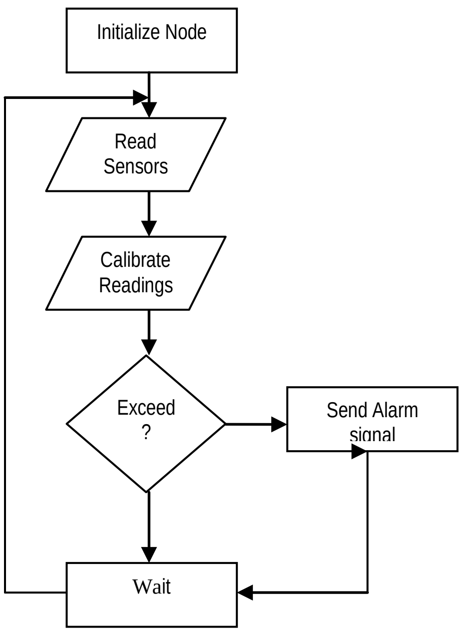

Figure 5. Sensor Node Logic.

III. RESULTS

The modulation technique used in the 9-Xtend RF radio module is BFSK (Binary Frequency Shift Keying) [23]. In BFSK, digital data is carried using discrete variations in the carrier frequency. In other words, we will represent 0s with one frequency and 1s with another frequency. At the same time, the 9-Xtend RF radio module also utilizes Frequency Hopping Spread Spectrum (FHSS) [24]. In FHSS, the carrier frequency is varied within the available bandwidth according to a pseudo-random function. Consequently, the carrier signal will change with time and is no longer fixed. Figures 6 and 7 demonstrate two different snapshots of frequency spectrums measured by portable spectrum analyzer at a close distance from the sensor node.

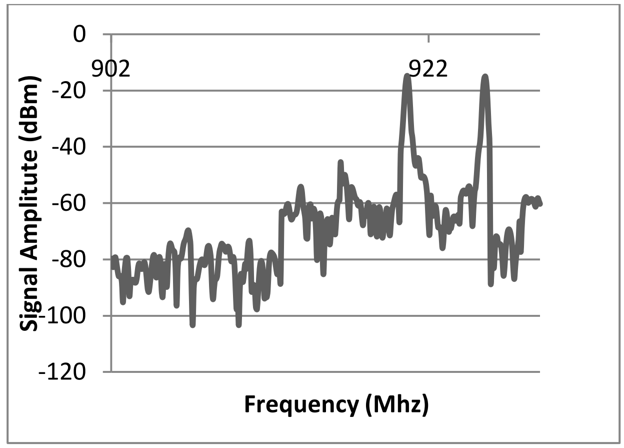

Figure 6. Frequency Spectrum of the Sensor Node at t0.

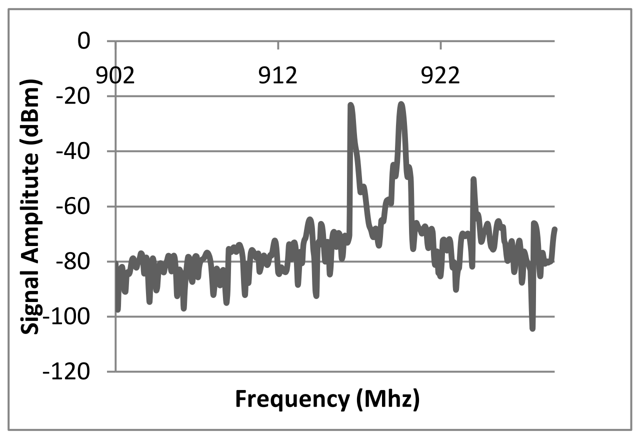

Figure 7. Frequency Spectrum of the Sensor Node at t1.

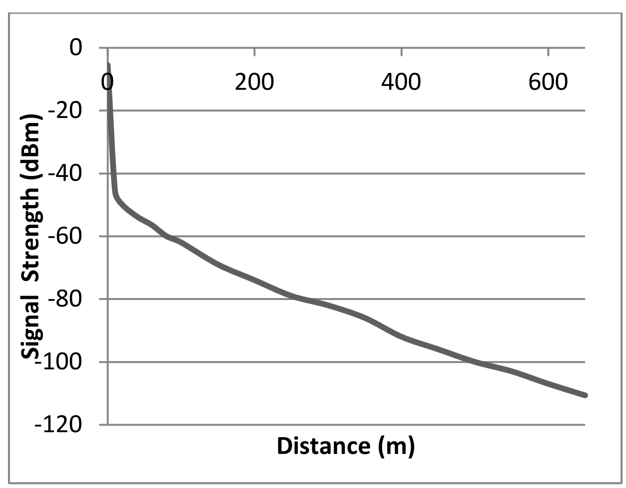

Figure 8. Residential Area.

From figures 6 and 7, it is evident that 0s and 1s are transmitted using two different frequencies (i.e., two peaks around -20 dBm) and the corresponding frequency for 0s and 1s varies with time. These features reduce the amount of interference from other sources and improve the security of the developed sensor node.

The transmission range of the developed sensor node was tested under three different environmental conditions. The maximum line of sight range is almost 22 km. These tests were conducted at 9600 bits per second RF throughput, 1 watt antenna output power and using a dipole antenna with gain of 2.1 dBm. The following graphs demonstrate the signal strength vs. distance at different conditions. The maximum range in vegetated areas is 1100 m

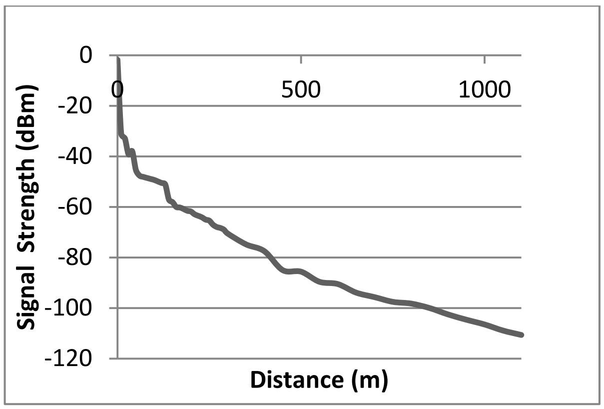

Figure 9. Densely Vegetated Area.

IV. CONCLUSION AND FUTURE WORK

This paper proposed the development of a long range wireless sensor network for environmental monitoring applications. Initially, the hardware of the sensor node was designed and then a long range RF radio was integrated into the system. The developed sensor node was further enhanced by deploying the DIGIMESH protocol to improve range and overall reliability and flexibility of the proposed wireless sensor network. Future works include developing an algorithm for improving power consumption efficiency and incorporating a 2.4GHz radio transmitter so that the node can be used for both long and short range communications.

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