A review of micro-nano-scale wireless sensor networks for environmental protection: Prospects and challenges

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Abstract

Wireless sensor networks (WSN) play a significant role in environmental pollution control, for example, air pollution control. To become widely acceptable and commercially viable, miniaturization of WSN should be investigated. For this reason, CMOS implementation of sensors and their integration into WSN have drawn much research attention in recent times. In this paper, the suitability of WSN to be employed in environmental monitoring, protection and control has been judged especially from the viewpoint of available communication system standards and CMOS level architecture of sensors. The CMOS implementation of WSN for the two available competitive WSN technologies named ZigBee and Bluetooth has been mainly addressed. Finally, the prospects and challenges for Ultra Wideband (UWB) radios to be used in WSN and the contribution of recent developments of nanotechnology to WSN have been briefly discussed and are given more importance for probable exploitation in environment monitoring and pollution control.

Keywords: Wireless sensor networks; Sensor; Environmental protection

1. Introduction

Wireless sensor networks (WSN) have become very important in the field of protection and control of natural and man-made environment, providing vast arrays of real-time, remote interaction with the physical world. Smart, wirelessly networked sensors can collect and process a vast amount of data, from monitoring and control of air quality, traffic conditions, to weather conditions and tidal flows. A sensor network monitors not only just a few isolated sensors, but also literally tens of thousands of intelligent sensor nodes providing local measurements as well as overall patterns of change. The promising technology of wireless sensor networks helps to run factories, optimize widely spread processes, monitor the weather, detect the spread of toxic gases in chemical industries and even provide precious extra time in advance of tornados and earthquakes. Widespread use of wireless sensor networks (WSN) powered with the concept of distributed sensing and computing of indoor and outdoor environment promises to revolutionize the present state of environmental protection and control. Rather than transmitting large amounts of raw data, the sensor nodes can perform signal analysis, communicating only the modes of vibration or detected anomalies. Sensor nodes can monitor control networks to establish an activity when a sample is taken or even to determine when to sample. Because reducing the cost of obtaining and processing data reduces overall cost, increasing the timeliness of analysis can improve system performance. In this paper, the present state of research of micro-nano wireless sensor networks has been reviewed especially with respect to their performance and contribution to environmental protection and control issues for the available wireless communications standards. CMOS level architectures of sensors with three competitive technologies, ZigBee, Bluetooth and Ultra Wideband (UWB), have also been discussed and compared for ensuring the best performance. In relation to this discussion, reference has also been made to the sensor network applications potentially related to IEEE 802.15.4 WG recommended low-rate, low-power wireless networks. It has also been shown that UWB radio has more advantages in overcoming the drawbacks of ZigBee and Bluetooth and it holds a bright
prospect for being used as a candidate for future WSN technology. The paper is organized as follows: Section 2 provides a brief description of the concept of wireless sensor networks and the sensor. The discussion is followed by Section 3 providing the complete description of presently available WSN technologies of ZigBee and Bluetooth. The prospect of Ultra Wideband (UWB) radio in a Wireless Sensor Network has been discussed in Section 4 followed by Section 5 providing a brief discussion of contribution of recent developments of nanotechnology to WSN. Finally, Section 6 concludes the paper.

2. The wireless sensor network and the environment

Sensor networks are dense wireless networks of small, low-cost unattended micro-sensors that collect and disseminate environmental data. These microsensors are equipped with a sensor module (e.g. acoustic, light, temperature, magnetic, image sensor) capable of sensing a parameter or a quantity regarding the environment, a digital processor for processing the signals from the sensors and for performing operating system applications and network functions, a radio module for communication and finally a battery to provide energy for operation [1]. Each sensor senses the environment and sends sensed data to a distant basestation, through which an end-user can access the information. Fig. 1 shows a typical wireless sensor network consisting of a number of wirelessly connected sensors. The abundance of available technologies makes even the selection of components difficult, let alone the design of a consistent, reliable, robust overall WSN system.

Wireless sensor networks facilitate monitoring and controlling of a variety of inhospitable physical environments from remote locations with better accuracy. They have applications in a variety of fields such as home security, machine-failure diagnosis, chemical or biological detection, medical and wild habitat monitoring as well as secure military purposes. Sensor nodes have various energy and computational constraints because of their inexpensive nature and ad hoc method of deployment. WSN applications require reliable, accurate, fault-proof and possibly real-time monitoring. Meanwhile, the low energy and processing capacities of the nodes require efficient and energy-aware operation. The basic selection criteria and design requirements of a typical WSN have been shown in Table 1 [2,3]. It can be understood from this table that battery life and low circuit complexity are the key requirements that differ from those of traditional wireless systems where the data rate is considered as a key requirement. However, due to the large number of nodes, a suitable multiple access scheme is also required to coordinate the transmissions so that multiple user interference can be minimized.

The improvement for currently available wireless sensor networks (WSN) is apparently quite important for utilizing WSN for sense and report applications especially in environmental applications. In wireless networks, there are two different types of networks: Data Communication Networks (DCN) and Wireless Sensor Networks (WSN), which are used in communicating with pieces of information among wireless nodes. Data communication networks traditionally carry the majority of information on the downlink, while, on the other hand, wireless sensor networks would be required to transmit sensor information on the uplink when requested to do so on the downlink from the basestation. This, therefore, places the capacity demand on the uplink [2].

3. Present WSN technologies: A comparative study

Presently there are two available technologies for WSN: ZigBee and Bluetooth. ZigBee is a wireless network used for monitoring and control systems originally defined by Motorola and conforming to the IEEE 802.15.4 standard for low data rate networks. More specifically, this is a standard for short-distance, low-data-rate communications using the frequencies and physical and data layers of the IEEE 802.15.4 PHY specification. ZigBee networks provide transmission speeds of 20, 40 and 250 Kb/s over a range of 10–100 m and can be configured in star, mesh or peer-to-peer topologies. ZigBee networks use considerably less power

![Fig. 1. A typical wireless sensor network.](image-url)
than Wi-Fi or Bluetooth and thus are designed for industrial automation, building automation and home control. Such applications require simple control networks that periodically send small packets from sensors and switches to regulate and turn devices on and off. The 802.15.4 standard defines two node types: reduced function devices (RFDs) are simple nodes that contain less electronics, while on the other hand, full function devices (FFDs) are more complex. RFDs can only communicate with full function devices (FFDs), but FFDs can communicate with both RFDs and FFDs. ZigBee based products can access up to 16 separate, 5 MHz channels in the 2.4 GHz band, several of which do not overlap with US and European versions of IEEE 802.11 or Wi-Fi™. ZigBee incorporates an IEEE 802.15.4 defined CSMA-CA protocol that reduces the probability of interfering with other users and automatic retransmission of data ensures robustness. The duty cycle of a ZigBee-compliant device is usually extremely low, meaning relatively very few packet data units are transmitted, reducing the likelihood of an unsuccessful transmission.

Some recent research has investigated the performance of currently available candidate technologies of ZigBee and Bluetooth. A comparison between the two competitive technologies, ZigBee and Bluetooth, is shown in Table 2 [2,4]. The main disadvantage with Bluetooth is the low battery life resulting from the processing and protocol management overhead required for ad hoc networking. On the other hand, ZigBee can provide a peak information rate of 120 Kbps only, which does not meet the required peak information rate of a typical sensor network as specified in Table 1. Also, neither of the technologies can provide location estimation with the accuracy required in Table 1 and the addition of such a facility would require a considerable increase in circuit complexity and an associated reduction of battery life.

### 4. Prospect with ultra wideband in wireless sensor network

A recent technology that is now being considered for deployment in WSN applications is Ultra Wideband (UWB) radio [5]. UWB provides a power efficient solution with a location estimation accuracy of less than 1m and is commonly accurate up to 4 cm. UWB radio communicates with baseband pulses of very short duration on the order of tenth of a nanosecond. According to the regulation of the Federal Commission of Communications (FCC), a signal is defined as a UWB signal if it has a $-10$ dB fractional bandwidth, $F_{BW}$ greater than, or equal to, 0.20 or it occupies at least 500 MHz of the spectrum [6], expressed as

$$F_{BW} = \frac{2(f_H - f_L)}{f_H + f_L} \geq 0.20$$

where $f_H$ and $f_L$ correspond to the $-10$ dB high and low frequencies, respectively. Since the allocated 7.5 GHz bandwidth (3.1–10.6 GHz) for UWB signals interferes with many narrow-band systems, FCC has also regulated the spectral shape and maximum power spectral density ($-41.3$ dBm/MHz) of the UWB radiation in order to limit the interference with other communication systems like UMTS or WLAN [7]. For a bandwidth of 7.5 GHz and an average EIRP of $-2.5$ dBm, there is a significant potential to provide coordinated multiple access for a large number of users. According to Shannon’s capacity theorem, $C = B \log_2(1 + SNR)$, for a desired SNR of 6 dB, the calculated channel capacity bound is approximately 17.5 Gb/s. With a peak information rate of 250 Kbps as specified in Table 1, 70,000 nodes could be accommodated, satisfying the requirement of a typical sensor network [2]. In environmental applications with nodes being distributed at the rate of 10 nodes per square meter, an area of 7000 m² equivalent to a square of 84 m×84 m could be covered. However, in order to strengthen the range limitations due to using low power, suitable technologies like directional receive antennas, relaying technologies and diversity gains could be used [2]. The ultra-wide bandwidth of 7.5 GHz would result in the reduction of multiple path effects and thus ultimately help to improve power efficiency and location estimation accuracy. The wide bandwidth also provides high channel capacity, which supports high data rate to a smaller number of users or low data rate to a large number of users. However, since large operating bandwidth is...
shared by other spectrum users, there arises a potential for interference, which can be reduced by a number of available techniques.

As mentioned before, UWB holds a bright promise for providing a location estimation accuracy as fine as 4 cm. Location estimation systems based on conventional radio frequency technology work poorly indoors because the signals reflect off walls, desks, people and equipment, the phenomenon being called multipath distortion, which leads to a significant amount of positioning error in the system. The short duration pulses used in UWB transmissions are easier to filter in order to determine which signals are correct and which are generated from multipath reflections. At the same time, the signal can penetrate easily through walls, equipment and clothing reducing the amount of infrastructure required and eliminating the need to reconfigure the sensor network if the space configuration changes. Three dimensional location estimation can be determined using two different algorithms; Time Differential of Arrival (TDOA), which measures the time difference between a UWB pulse arriving at multiple sensors and Angle of Arrival (AOA). The advantage of using both methods in conjunction is that a location can be determined from just two sensors decreasing the required sensor density compared with systems that just use TDOA. While using UWB for location estimation, sensors support two-way communication using a standard RF channel. Thus the applications for environmental control and protection have bright prospects in the future by using the concept of UWB radio.

5. CMOS implementation of WSN

Nanotechnology has become a key technology in sensor development. Current nanotechnology permits operation on the scale of atoms and molecules. This promises to have a dramatic impact on sensor design and capabilities. Sensors can now exploit novel properties of materials at the nanoscale. Hence nanotechnology is well suited to design of sensors. Initial research in nanotechnology involved miniaturization of the macro techniques. The small size of these sensors leads to reduced weight, low power requirements and greater sensitivity. The existing IC technologies can be used to integrate these nanosensors into integrated circuits. The sensor chips can be used as building blocks to build new, more complex sensors. For protection of environments the WSN used should have to face the following situations in natural environment [8]:

- Huge number of nodes scattered randomly in the environment
- Smallest possible node size
- Low power consumption by the IC and the communication protocols
- Low data rate may also be accepted for WSN
- Communication distance is in the range 0.1–50 m
- Simple communication protocols

Advances in nano-manufacturing have been both from the top-down approach and bottom-up approach. In conventional micro-electronics, the current line widths in chips are just below 100 nm (0.1 μm) level [9]. Manufacturing from the bottom-up approach is also possible using individual atoms and molecules to build useful structures. MEMS and NEMS hold a very bright prospect to yield small, low cost, low power sensors. Small size would allow sensors to be scattered around unobtrusively to measure environmental parameters. Being of low power they could be operated on small batteries and could even be solar-powered [10]. Low cost can help the number required to be enormously large. Although several industries are already producing ultra low-power small-sized smart sensors which are yielding good results in a variety of applications, reducing the size is still in its infancy. That is why integrated sensors and silicon technology are in good position to yield microscopic components that can be scattered around. The size of smart sensors has been decreasing with time. The use of MEMS has made possible the dream of having ubiquitous sensing and in particular small ‘smart’ sensing. MEMS devices are manufactured using VLSI and can embody both mechanical and electrical functions. MEMS can be used in an environment to both sense and actuate. The main advantage brought by nanotechnology applications is miniaturization. MEMS features are typically on the scale of microns (10^{-6} m). MEMS devices can be found in a wide range of applications from accelerometers for airbag deployment to electronic particle detectors that aid nuclear, biological and chemical inspection. Using CMOS enables implementation of true single chip solutions called System-on-Chip (SoC). The SoC advantages include lower system cost, simpler assembly, simpler testing, increased reliability, less susceptibility to external stray noise pickup, smaller footprint and integrated development environment [8]. However, sub-micron CMOS technology offers some disadvantages like reduced supply voltage that provides more difficulty in designing RF analog modules and noise level versus dynamic range issues. Sub-micron CMOS also results in leakage current increases and requires expensive mask sets [8].

6. Conclusions

In this paper micro-nano-scale wireless sensor networks have been reviewed and the prospects and corresponding challenges have been outlined. Possible usage of wireless sensor networks in environment protection and control has been indicated. If nanotechnology-based WSN is to be successful in environment applications it is inevitable that wireless communication of sensor data must be as good as that of a wired communication, maintain high data security
and integrity as well as minimize end user cost of ownership. For example, in an industry it is always desired to have gas composition analyzers of reduced size, low cost, less maintenance and less analysis time and at the same time of increased sensitivity. Moreover, the received power of wireless sensor network must be strong enough to combat multiple-user interference (MUI). Reliable RF communication in the presence of environmental interference and interference from other RF systems must be ensured. This is because monitoring and control of environmental parameters should be performed on the basis of sensed data by the sensor nodes. A comparison of the currently existing WSN technologies, ZigBee and Bluetooth, has also been made in this paper. The prospect of the recently focussed ultra wideband (UWB) radio technology has also been discussed to indicate its possible potential to be used in wireless sensor networks. More importantly, the specific UWB features of low power emission and accurate location estimation could help the currently available wireless sensor networks to become more suitable for environmental applications. On the other hand, products for wireless applications are generally extremely price sensitive and impose stringent demands of low power dissipation to extend battery life. Smaller physical size is also important and all these requirements together increase the focus on highly integrated RF-IC implementations. Traditionally, RF-ICs rely on bipolar, BiCMOS or GaAs technologies. However, modern fine-line CMOS technologies also provide high RF performance. As CMOS is generally a low cost technology compared to other RF-IC technologies, there is a huge push towards developing CMOS RF-ICs [11]. Highly integrated radio frequency architectures combined with sub-micron CMOS technology are considered to be the key to the development of low cost and low power RF-ICs. With CMOS it is also possible to embed analogue radio modules together with complex digital modules on a single chip, thus enabling real System-on-Chip (SoC) solutions. The number of commercially available CMOS RF-ICs is increasing, and this is why CMOS RF-ICs will, perhaps, be the dominating technology for a large number of applications, especially for Wireless Personal Area Networks (WPAN), remote metering, environmental monitoring and environmental pollution control.

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