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# Wireless Sensor Networks: A Survey

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**Abstract:** *Wireless Sensor Networks (WSN), an element of pervasive computing, are presently being used on a large scale to monitor real-time environmental status. However these sensors operate under extreme energy constraints and are designed by keeping an application in mind. Designing a new wireless sensor node is extremely challenging task and involves assessing a number of different parameters required by the target application, which includes range, antenna type, target technology, components, memory, storage, power, life time, security, computational capability, communication technology, power, size, programming interface and applications. This paper analyses commercially (and research prototypes) available wireless sensor nodes based on these parameters and outlines research directions in this area.*

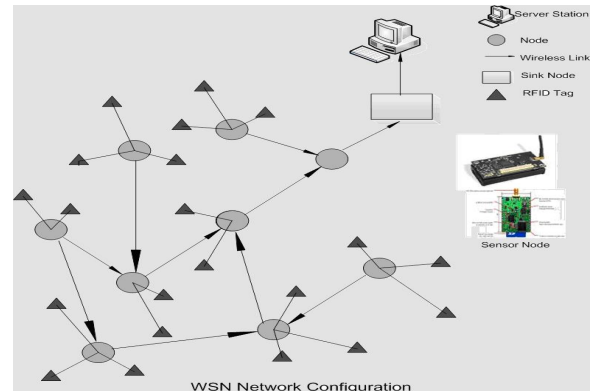
**Keywords:** Wireless Sensor Network (WSN), FPGA, sensor node, Active Node, CCU.

## 1. Introduction

In the last few years wireless sensor networks (WSNs) have drawn the attention of the research community, driven by a wealth of theoretical and practical challenges [1]. This progressive research in WSNs explored various new applications enabled by larger scale networks of sensor nodes capable of sensing information from the environment, process the sensed data and transmits it to the remote location [2-4]. WSNs are mostly used in, low bandwidth and delay tolerant, applications ranging from civil and military to environmental and healthcare monitoring.

WSNs as shown in Fig.1 generally consist of one or more sinks (or base stations) and perhaps tens or thousands of sensor nodes scattered in a physical space. With integration of information sensing, computation, and wireless communication, the sensor nodes can sense physical information, process crude information, and report them to the sink. The sink in turn queries the sensor nodes for information. WSNs have several distinctive features like:

- a) *Unique network topology*
- b) *Diverse applications*
- c) *Unique traffic characteristics, and*
- d) *Severe resource constraints*



**Fig. 1 WSN Network**

WSN node is comprised of low-power sensing devices, embedded processor, communication channel and power module. The embedded processor is generally used for collecting and processing the signal data taken from the sensors. Sensor element produces a measurable response to a change in the physical condition like temperature, humidity, particulate matter (e.g. CO<sub>2</sub>) etc.

The wireless communication channel provides a medium to transfer the information extracted from the sensor node to the exterior world which may be a computer network and inter-node communication [5]. However, WSN using IEEE 802.15.4 Wireless Personal Area Network protocol (WPAN) or Bluetooth is complicated and costly [10, 18]. Using RFID to implement wireless communication is relatively simple and cheap [6]. Zigbee protocol can also be used for communication; alternatively the RS232 standard for wireless transmission of data can be adopted because the data rate of RFID and that of RS232 is same in terms of bits per second (bps).

The rest of the paper is organized as follow. Section 2 defines the system requirements. Section 3 compares different WSN nodes that can be used in variety of WSN configuration targeting different applications. Section 4, evaluates these nodes based upon size, range, technology they have used, storage capacity, communication technology, power, security etc. And finally Section 5 concluded this paper and suggested future work.

## 2. System Requirements

Here we discuss some of the characteristic requirements of a system comprising wireless sensor nodes. The system should be:

**1. Fault tolerant:** the system should be robust against node failure (running out of energy, physical destruction, H/W, S/W issues etc). Some beep mechanism should be incorporated to indicate that the node is not functioning properly.

**2. Scalable:** The system should support large number of sensor nodes to cater for different applications.

**3. Long life:** The node's life-time entirely defines the network's life-time and it should be high enough. The sensor node should be power efficient against the limited power resource that it has since it is difficult to replace or recharge thousands of nodes. The node's communication, computing, sensing and actuating operations should be energy efficient too.

**4. Programmable:** the reprogramming of sensor nodes in the field might be necessary to improve flexibility.

**5. Secure:** the node should support the following

- Access Control:* to prevent unauthorized attempts to access the node.
- Message Integrity:* to detect and prevent unauthorized changes to the message.
- Confidentiality:* to assure that sensor node should encrypt messages so only those nodes would listen who have the secret key.
- Replay Protection:* to assure that sensor node should provide protection against adversary reusing an authentic packet for gaining confidence/network access, man in the middle attack can be prevented by time stamped data packets.

**6. Affordable:** the system should use low cost devices since the network comprises of thousand of sensor nodes, tags and apparatus. Installation and maintenance of system elements should also be significantly low to make its deployment realistic.

## 3. Related Work

Sensor networks are becoming more popular in applications related to environment monitoring to structural health monitoring [15,7] and today a number of research teams are developing efficient nodes for such smart networks capable of processing data at node end before transmitting to base station, having compact size, reduced power consumption, low cost and most important minimum human

intervention. In this section we outline some of this related work.

One of the prime examples of such sensor network is a project named "**Smart-Dust**" carried out by University of California at Berkeley, USA [8]. The main objective of the project was to develop a compact size node that includes sensor, capability to compute the sensor data onboard, low cost, minimal power consumption and having bidirectional wireless communication capability.

Another interesting research testbed was the **Spec platform** [11], which integrated the functionality of Mica onto a single 5 mm<sup>2</sup> chip. Spec was built with a micro-radio, an analog-to-digital converter, and a temperature sensor on a single chip, which lead to a 30-fold reduction in total power consumption. This single-chip integration also opened the path to low cost sensor nodes. The integrated RAM and cache memory architecture greatly simplified the design of the mote family. However, the tiny footprint also requires a specialized operating system, which was developed by UC Berkeley, called TinyOS. TinyOS features component based architecture and event driven model that are suitable for programming with small embedded devices, such as motes. The combination of Motes and TinyOS is gradually becoming a popular experimental platform for many research efforts in the field of WSNs.

The **Medusa MK-2** [12] sensor node was developed by the Center for Embedded Networked Sensing (CENS) at UCLA in 2002 to target both high and low-end processing applications. It integrates two microcontrollers, the first one; ATmega128 was dedicated to less computationally demanding tasks, including radio base band processing and sensor sampling. The second one, AT91FR4081, was a more powerful microcontroller (40 MHz, 1 MB flash, 136 KB RAM) that was designed to handle more sophisticated, but less frequent signal processing tasks (e.g., the Kalman filter). The combination of these two microcontrollers provided more flexibility in WSN development and deployment, especially for applications that require both high computation capabilities and long lifetime.

In 2002 the Berkeley Wireless Research Center (BWRC) developed System on Chip (SoC) based sensor node, named **PicoNode II** [16]. It was built using two ASIC chips that implemented the entire node functionality. In the following year, the same team developed a first radio transmitter (that used power less than 400  $\mu$ W), **PicoBeacon** was purely powered by solar and vibrational energy sources.

Another ASIC based approach was taken by the  $\mu$ AMPS group from MIT. Following their first testbed,  **$\mu$ AMPS-I** [13], the team then tried to build a

highly integrated sensor node comprised of a digital and an analog/RF ASIC,  $\mu$ AMPS-II. The interesting feature of  $\mu$ AMPS-II was the node's capability to operate in several modes. It can operate either as low-end stand-alone guarding node, a fully functional node for middle-end sensor networks or as a companion component in a more powerful high-end sensor system. Thus, it favored a network with heterogeneous sensor nodes for a more efficient utilization of resources.

The Free2move wireless sensor node [14] is based on a transceiver operating in the 2.4 GHz ISM band. The node was initially thought of as an active RFID tag for monitoring temperature in goods. However, it has been shown that it is also possible to use it as a wireless sensor network node. The node is equipped with an extremely low power microcontroller (Microchip PIC16F87), for executing communication protocols and sensor functionality. The memory and processing resources are very limited to keep the price and energy consumption as low as possible. The node is also equipped with a temperature sensor.

Overall we can see that most of the research is focused on developing smart sensing nodes for WSN. Hence we studied the most important nodes in the current literature to see which application can be practical. The next section evaluates these nodes.

#### 4. Evaluation

Wireless sensing technology comprising self-reliant, battery-powered nodes is pushing sensing to the extreme. Sensor modules, motes, and ICs all have had a huge impact on the industry as parts of wide-ranging wireless sensor networks. In this section we compare the design of WSN sensor nodes proposed by a number of research groups. The comparison is broadly based on following technical features

1. Design Range
2. Antenna design
3. Target Technology
4. Components
5. Non Volatile Storage
6. Communication technology
7. Power
8. Security measure
9. Size
10. Programming and Sensor Interface
11. Applications

##### 4.1 Target Technology

In this section evaluate the motes based on the following technical features i.e. design range, antenna, components, non-volatile storage, and power.

From Table 1 it is clear that effective range of motes is entirely defined by the antenna design. The average range is in between 100ft (30.48 meters) to 250ft (76.2 meters) however, there are few motes like Mica2 and Iris that would offer 1000ft addressable range capability and this would be good for a larger coverage area but on the other hand larger the coverage area the lesser will be the average life time of the WSN node [9, 17] so trade-off between the node life time and coverage area should be taken into account during the selection of WSN nodes while planning a WSN network.

Next if we look at the microcontroller it includes not only memory and processor but also non-volatile memory and interfaces such as Analog to Digital Converters (ADC's), Serial Peripheral Interface (SPI), Universal Asynchronous Receiver Transmitter (UART), counters etc. Every mote also uses non-volatile storage element for storing useful information and the sizes vary in the range of 32KB to 4MB depending upon the nature of application.

Other than the non-volatile memory most of the motes use Microcontrollers (like AT90LS8535, ATmega163, ATmega103L, ATmega128, TI MSP430 and XM2110CA) as a central processing unit having clock frequency in the range of 4 MHz to 8 MHz. The effectiveness in terms of energy consumption of a microcontroller or microprocessor is governed from the energy it consumes per instruction execution (measured in nJ/instruction).

The AT90LS8535 (WeC, Rene 1999) is an 8-bit microcontroller consumes 15 mW (consumes 3.75 nJ/instruction) power in active mode and 45  $\mu$ W power in sleep mode and have 1msec wakeup time.

ATmega163 (Rene 2000, Dot 2000) is an 8-bit microcontroller consumes the same power as AT90LS8535 both in active (consumes 1.875 nJ/instruction) and sleep mode but it has 36 $\mu$ sec wakeup time so it is fast to respond changes.

Mica uses ATmega103L microcontroller (4 MHz) with 128 KB program memory and 4 KB RAM. It consumes 16.5 mW power (4.125 nJ/instruction) during active mode and draws less than 1 $\mu$ A during sleep mode. The major drawback of ATmega103L is that it is not self-programmable so we do need some support of co-processors.

ATmega128 (Mica2, Mica2Dot: most widely used microcontroller because of its Tiny OS support in addition to MSP430 alone) is an 8-bit microcontroller with 128 KB in-system programmable flash. It consumes 8mW (Mica2Dot, consumes 1.08 nJ/instruction) and 33mW (Mica2, consumes 4.459 nJ/instruction) during active mode and 75  $\mu$ W in sleep mode (Mica2, Mica2Dot) and have 180 $\mu$ sec wakeup time. It has large space for

programming memory and RAM as compared to AT90LS8535, ATmega163 and ATmega103L.

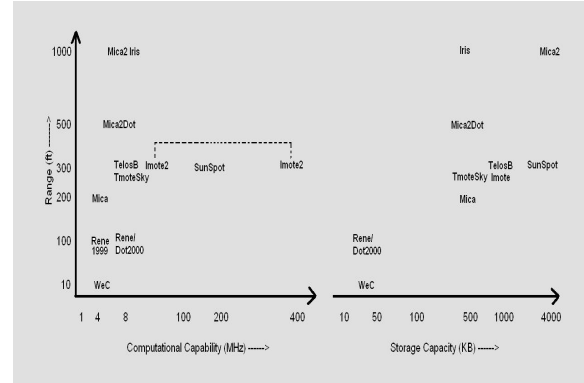
The TIMSP430 (TmoteSky, TelosB) is an ultra low power microcontroller ideally suited for WSN application. It consumes 3mW power (TmoteSky, consumes 0.375 nJ/instruction) and 3.24 mW power (TelosB, consumes 0.405 nJ/instruction) in active mode and 6  $\mu$ W power (TmoteSky) and 15  $\mu$ W (TelosB) in sleep mode and has 6  $\mu$ sec wakeup time. Although it consumes less power but it does not have more program memory and RAM as compared to ATmega128.

Imote2 uses Intel's processor (Intel PXA271 having operating frequency of 400 MHz have 32MB program memory and RAM) and SunSpot uses ARM920T (having clock frequency of 180MHz and have 4MB program memory and 512 KB RAM) and supports Zigbee/CC2420. So Imote2 and SunSpot are ideally suitable for applications requiring intensive processing power like the case of visual information processing (monitoring the surroundings e.g. surveillance) or for an application that keeps long history of the recorded information (e.g. CO<sub>2</sub> emission track). Imote2 also support separate interface for the camera as well. These two motes also support high program memory and RAM as compared to the rest of motes and again is true for the above mentioned applications. Once the sensing and processing of information is complete, the next most important factor that determines the quality of a node is its communication technology. We now evaluate these modes based upon the communication technology they implement.

#### 4.2 Communication Technology

While designing a WSN the designer must pay key attention to the life time of the entire network because one of the main objective of WSN is to have minimum human intervention. Other than processing the communication part is considered to be the second largest energy consuming element of the node. The RF transceiver consumes most of the energy during the active state. Network lifetime can be increased by having nodes only operate their radios for brief periods of time.

The CC1000 is a very low power CMOS RF Transceiver (Mica2Dot, Mica2) support data rate up to 76.8 Kbps using frequency shift keying (FSK). It has an internal bit synchronizer that simplifies the design of a high speed radio link with the Central Control Unit (CCU). It consumes 29 mW in Rx mode, 42 mW in TX mode and draws 0.2  $\mu$ A in power in down mode. Its advantage over TR1000 is that it can easily be programmed for operation at other frequencies between 300 MHz to 1000 MHz.



**Fig. 3 Classification of WSN motes based on storage capacity & computational capacity**

The CC2420 (Tmote Sky, Telos B, Imote2, SunSpot, Iris) is a true single-chip 2.4 GHz IEEE 802.15.4/ Zigbee [19] RF Transceiver with MAC supported transceiver designed for low-power and low voltage wireless applications. It includes a digital direct sequence spread spectrum base band modem providing a spreading gain of 9dB and an effective data rate of 250 Kbps using Offset quadrature phase-shift keying (O-QPSK). It provides extensive hardware support for packet handling, data buffering, burst transmissions, data encryption (Hardware MAC encryption AES-128), data authentication, clear channel assessment, link quality indication and packet timing information. It consumes 19.7 mA in Rx mode of operation and 17.4 mA in TX mode. In-addition to hardware support it also performs all communication related processing on-chip, thus leaving the processor free to do other processing. The high data rate in terms of bps is generally required in high-end application like surveillance, high speed sensor data, vibration measurement etc. The two former RF transceivers (TR1000 and CC1000) have no Zigbee support.

Also RF transceivers are most sensitive to power variations but CC2420 has in built power regulator. Another major development in RF transceiver technology was shown by Chipcon CC2431 [22] which include a microcontroller with a radio that supports ZigBee/IEEE 802.15.4 standard. It also implements a unique on-chip feature called "location engine" to estimate relative location of sensor nodes with 0.5m resolution.

Fig.3 & Fig. 4 classifies computational capability and storage capacity of various motes against the mote's addressable range. From this it would be obvious that all mote's are broadly classified into nine different groups based on the effective addressable range (AR), computational capability (CC) and storage capacity (SC) as shown in Table 2.

**Table 2** Comparison of different mote's against their addressable range, computational capability, storage capacity

	AR	CC	SC
WeC	Short	Low	Low
Rene 1999	Med-Short	Low	Low
Rene/Dot 2000	Med-Short	Med	Low
Mica	Med	Low	Med-High
TmoteSky, TelosB, Imote2	Med	Med	Med-High
Imote2	Med	High	Med-High
SunSpot	Med	High	High
Mica2Dot, Iris	Large	Med	Med-High
Mica2	Large	Med	High

This concludes the evaluation of the motes based on its key technical design parameters.

## 5. Conclusion

WSN is a promising future technology and presently used in range of application that requires minimum human intervention. In this paper we have surveyed the WSN technology. We have also presented the WSN mode evaluation based on its key technical specifications. Although researchers have already designed a number of network configurations like heterogeneous and single-hop which uses WSN technology but in such configurations most of the processing is carried out at the server end. It would be good if in-network processing capability will be incorporated at node's end. By this way the node pre-processes the data and sends wirelessly the compact form of the extracted information to the sink.

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Module Type	Image	Model	Range	Antenna Design	Frequency	Program. Memory	RAM	Active Power	Sleep Power	Wake-up Time	Components	Non-Volatile Storage	Chip Connection	Size	Radio	Data Rate	Modulation Type	Rx Power/Rx Sensitivity	Tx Power @ 0dBm/FS Sensitivity	Power Source	Min. Operating Volt	Total Active Power	Programming & Sensor Interface	Expansion Communications	Integrated Sensor	Size	Security	Applications
		Iris	1000 ft/304.8 m	Integrated	8 MHz	128 KB	1 KB	1.5 mW	4.5 μW	1000 μsec	MicroCtrl, Storage Memory, on-board light and temperature sensors	Yes 24LC256 12C 32 KB	24.8x24.89x12.95 (mm)	TR1000 10 Kbps OOK 9 mW	36 mW	2.7 V 24 mW	None/51-pin IEEE 1284/RS232	No	Yes 0.98x0.98x0.51 (inches) 24.89x24.89x12.95 (mm)	2.7 V	24 mW	Yes	None/51-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Security is provided	Indoor building monitoring and security, Accoustic, Video, Vibration and other high speed sensor data to the Internet
		Sun Spot	300 ft/91.44 m	Integrated	13-400 MHz	32 MB	10 KB	2.5-90 mW	draw 8 μA	draw 32 μA	MicroPro, Analog I/F, Switches, Sensor Interface, Storage Memory	Yes SPI 4MB	300 ft/91.44 m	TI CC 2420 250 Kbps O-QPSK -101dBm	3 dBm (typ)	Battery 2AA 3.0 V	20-pin USB/RS232/ SPI	Yes	1.357x1.94 (inches) 34.47x49.26 (mm)	2.8 V 86.8 mW	Yes	100+pin USB/RS232/ I C	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Public-key cryptography	Developing new architecture for auto-configuration network and other connectivity to the Internet	
		Imote2	300 ft/91.44 m	Integrated, External	8 MHz	60 KB	2 KB	3 mW	6 μW	6 μsec	MicroCtrl, Sensor Interface, Storage Memory, JTAG	Yes STM24F80 1 C 1MB	300 ft/91.44 m	TI CC 2420 250 Kbps O-QPSK -94dBm	-24 -0 dBm	Battery 3AA 2.8 V 86.8 mW	100+pin USB/RS232/ I C	Yes	1.421 87x.32 (inches) 35.66x7.56x1.12 (mm)	2.8 V 86.8 mW	Yes	100+pin USB/RS232/ I C	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Elliptic Curve Cryptography	Digital Image Processing, Industrial monitoring and analysis, Seismic and Vibration monitoring	
		Telos B	300 ft/91.44 m	Integrated	8 MHz	48 KB	10 KB	3.24 mW	1.5 μW	6 μsec	MicroCtrl, Sensor Interface, Storage Memory, LCD Display	Yes STM24F80 1 C 1MB	300 ft/91.44 m	TI CC 2420 250 Kbps O-QPSK 41.4 mW	35 mW	Battery 2AA 1.8 V 32 mW	16-pin USB/RS232	Yes	2.52x1.24x2.24 (inches) 64.8x31.5x6.1 (mm)	1.8 V 32 mW	Yes	16-pin USB/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Public-key cryptography	Developing new architecture for auto-configuration network and other connectivity to the Internet	
		T mote Sky	250 ft/76.2m	Integrated	8 MHz	60 KB	2 KB	3 mW	6 μW	6 μsec	MicroCtrl, Sensor Interface, GPIO, DMA, Storage Memory	Yes STM24M015 1 C 512 KB	250 ft/76.2m	CC 2420 250 Kbps O-QPSK 38 mW	35 mW	Battery 2AA 1.8 V 32 mW	10-pin USB	Yes	2.52x1.24x2.24 (inches) 65.5x32x6.6 (mm)	1.8 V 32 mW	Yes	10-pin USB	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Encryption + Authentication	Monitoring Applications, Rapid application prototyping	
		Mica2	1000 ft/304.8m	Integrated	7.4 MHz	128 KB	4 KB	33 mW	7.5 μW	180 μsec	MicroCtrl, Storage Memory	Yes AT45D0041B SPI 4MB	1000 ft/304.8m	CC 1000 38.4 Kbps FSK 29 mW	42 mW	Battery 2AA 2.7 V 89 mW	51-pin IEEE 1284/RS232	No	2.25x1.25x1.25 (inches) 57.2x31.8x6.35 (mm)	2.7 V 89 mW	Yes	51-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Elliptic Curve Cryptography	Environmental Monitoring, vibration detection in bridges, monitoring the condition of machinery	
		Mica2Dot	500 ft/152.4 m	Integrated	7.4 MHz	128 KB	4 KB	8 mW	7.5 μW	180 μsec	MicroCtrl, Storage Memory	Yes AT45D0041B SPI 512	500 ft/152.4 m	CC 1000 38.4 Kbps FSK 29 mW	42 mW	Battery 2AA 2.7 V 44 mW	19-pin IEEE 1284/RS232	No	2.25x1.25x1.25 (inches) 57.2x31.8x6.35 (mm)	2.7 V 44 mW	Yes	19-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Elliptic Curve Cryptography	"Smart Dust" and RFID technology for "smart" environmental monitoring, home sensor network, battlefield monitoring	
		Mica	200 ft/60.96 m	Integrated	4 MHz	128 KB	4 KB	16.5 mW	7.5 μW	180 μsec	MicroCtrl, Storage Memory	Yes AT45D0041B SPI 512 KB	200 ft/60.96 m	TR 1000 50 Kbps ASK 12 mW	36 mW	Battery 2AA 2.7 V 27 mW	51-pin IEEE 1284/RS232	No	1.24x2.21 (inches) 31.5x56.13 (mm)	2.7 V 27 mW	Yes	51-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	Elliptic Curve Cryptography	Environmental Monitoring, vibration detection in bridges, monitoring the condition of machinery	
		Dot 2000	100 ft/30.48 m	Integrated	8 MHz	16 KB	1 KB	1.5 mW	4.5 μW	36 μsec	Sensor Interface, MicroCtrl, Storage Memory	Yes 24LC256 12C 32 KB	100 ft/30.48 m	TR 1000 10 Kbps OOK 9 mW	36 mW	Battery 2.7 V 24 mW	None/51-pin IEEE 1284/RS232	Yes	24.8x24.89x12.95 (mm)	2.7 V 24 mW	Yes	None/51-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	limited security	Large federated networks for high-resolution sensing of environment	
		Rene 2000	100 ft/30.48 m	Integrated/External	4 MHz	16 KB	1 KB	1.5 mW	4.5 μW	36 μsec	Storage Memory, MicroCtrl, GPIO, sensor interface	Yes 24LC256 12C 32 KB	100 ft/30.48 m	TR 1000 10 Kbps OOK 9 mW	36 mW	Battery 2.7 V 24 mW	None/51-pin IEEE 1284/RS232	No	24.8x24.89x12.95 (mm)	2.7 V 24 mW	Yes	None/51-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	No Unique ID (UID), limited security	Large federated networks for high-resolution sensing of environment	
		WeC	1.5 ft/4.572 m	Integrated	4 MHz	8 KB	0.5 KB	1.5 mW	4.5 μW	1000 μsec	Storage Memory, on-board light and temperature sensors	Yes 24LC256 12C 32 KB	1.5 ft/4.572 m	TR 1000 10 Kbps OOK 9 mW	36 mW	Battery 2.7 V 24 mW	None/51-pin IEEE 1284/RS232	Yes	24.8x24.89x12.95 (mm)	2.7 V 24 mW	Yes	None/51-pin IEEE 1284/RS232	Yes	51-pin USB/RS232 / I C/GPI	2.25x1.25x1.25 (inches) 34.47x49.26 (mm)	No Unique ID (UID), limited security	Designed for Environmental Monitoring having on-board temperature and light sensors.	

Table 1: WSN Motes Comparison Chart