A Comparative Review of Wireless Sensor Network Mote Technologies

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***Abstract*—In the past 10 years, wireless sensor networks have grown from a theoretical concept to a burgeoning modern technology. In this paper, we present a comparative review of several wireless sensor network motes. We analyze these WSN devices under a number of different parameters and criteria, including processing ability, expected lifetime and measurement capabilities. We compare and contrast the selected WSN motes under these different headings, highlighting the individual mote's performance under each category.**

I. Introduction

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices which use sensors to cooperatively monitor physical and/or environmental conditions (e.g. temperature, sound, vibration, pressure, motion or pollutants) at different locations. Practical WSN nodes, or "motes", currently range in size from disc-shaped boards having diameters less than 1cm to enclosed systems with typical dimensions less than 5cm square. The term "mote" was coined by researchers in the Berkeley NEST (now WEBS [1]) and CENS [2] projects) to refer to these sensor nodes. Each sensor node is composed of a microcontroller, transceiver, memory, power source and one or more sensors, either internal or external to the sensor board. The motes function within the network and typically fulfil one of two purposes: - either data-logging, processing (and/or transmitting) sensor information from the environment, or acting as a gateway in the adhoc wireless network formed by all the sensors to pass data back to a (usually unique) collection point. In this paper, we present a review of several current WSN motes, compared and contrasted under a number of different parameters. These parameters range from physical characteristics such as size, weight and battery life to electrical specifications for the microprocessor and radio transceiver employed in the respective mote architectures. The paper is organized as follows: - Section II lists the parameters used in the comparison and the individual mote platforms being reviewed in this paper. Section III presents the actual review of the mote platforms. Finally, Section IV summarizes the findings of our review in the conclusions section.

II. Scope of the comparative study

We have divided the review into 5 separate categories: - general parameters, processor and memory, communications capabilities, sensor support and power consumption. For the purposes of this paper, we will be limiting ourselves to 6 of the currently available mote platforms. The following motes will be discussed: -

TelosB/Tmote Sky: - Wireless sensor modules developed from research carried out at UC Berkeley and currently available in similar form factors from both Sentilla and CrossBow Technology.

Mica2/MicaZ: - second and third generation wireless sensor networking mote family from CrossBow Technology.

SHIMMER: - SHIMMER (Sensing Health with Intelligence, Modularity, Mobility, and Experimental Reusability) is a wireless sensor platform designed to support wearable applications. Currently available from RealTime Ltd.

IRIS: - latest wireless sensor network module from Crossbow Technologies. Includes several improvements over the Mica2 / MicaZ family of products. Improvements include increased transmission range.

Sun SPOT: - the Sun "Small Programmable Object Technology" (SPOT) is a wireless sensor network mote from Sun Microsystems. Unlike many of the other offerings considered here, both the hardware and software are open-source.

EZ430-RF2480/2500: - the EZ430-RF2480 and EZ430-RF2500 wireless networking solutions from Texas Instruments incorporate the MSP430 microprocessor and CC2480/2500 radio transceiver on each board. These kits are the most inexpensive mote solution reviewed in this paper.

III. Comparative Review

A. General Parameters

In this section, the motes being considered are contrasted based on characteristics such as physical dimensions, weight, size and costing. The first physical parameter which may dictate mote selection for a given application is physical size. Table I provides an overall comparison of the physical dimensions of all the motes in this review. Crossbow and other suppliers optionally offer smaller form-factor implementations for design-in solutions. Table I also lists the motes' weight, which can be a decisive factor when choosing a certain WSN, especially in applications where the motes are components of a mobile unit or are integrated into wearable health monitoring solutions [3]. The final factor to be considered in this section is cost. For the 6 sensor motes reviewed, current pricing

TABLE I
PHYSICAL CHARACTERISTICS

Mote Platform	WxLxH [inches]	Weight No batt [g].	Weight Batt [g]
TelosB	1.26 x 2.58 x 0.26	14.93	63.05
MicaZ/Mica2	1.25 x 2.25 x 0.25	15.70	63.82
SHIMMER	0.8 x 1.75 x 0.5	4.87	10.36
IRIS	1.25 x 2.25 x 0.25	21.29	69.40
Sun SPOT	2.5 x 1.5 x 1	33.49	58.08
EZ430-RF2500 (USB)	1.16 x 3.17 x 0.43	1.80	30.89
EZ430-RF2480 (Batt)	1.02 x 3.72 x 0.55	1.80	30.89

NOTE: - All sizes are for mote assemblies i.e.PCB,batteries,enclosures,etc.

information as of Jan 2009 for each mote is as shown in table II.

TABLE II
COST PER NODE

Mote Platform	Price	Comments
TelosB	US$99 / US$139	no sensors / with sensors
MicaZ/Mica2	US$99	Mica2 no longer available
SHIMMER	EUR199	base SHIMMER SDK with 2 boards, several sensor boards and software available for EUR1,900
IRIS	US$115	
Sun SPOT	US$750	3 base boards and 2 sensors boards
EZ-RF2480	US$99	3 nodes, one is a USB interface
EZ-RF2500	US$49	2 nodes

B. Processor and Memory

Table III reviews the microprocessors specifications (bus width and processor clock speed) for each of the respective motes reviewed[4]. Table IV provides information on available on-board memory for each mote platform. There is a wide variation here in available memory sizes and types for the different motes, possibly a reflection of their different application spaces. In addition to these on-board memory capabilities, some sensor nodes now also allow the option of saving data to additional external non-volatile memory. In this paper, the majority of the motes considered are programmed via the TinyOS operating system [5]. Typical programs for these distributed motes are written in nesC, a derivative of the C programming language. The TI EZ430-RF2XXX motes do not at present support TinyOS. Another exception to the TinyOS programming interface are the Sun SPOT motes. Sun SPOT uses a small J2ME [6] which runs directly on the processor without an OS. Both the Squawk VM and the Sun SPOT code are open source [7]. Standard Java IDEs (e.g. NetBeans) can be used to create SunSPOT applications. The latest revision of the Sentilla Tmote sky also includes a Java Virtual Machine, allowing Java code to be run on this mote as well.

TABLE III
MICROPROCESSOR SPECIFICATIONS

Mote Platform	uProcessor	Bus	Clock
TelosB/Tmote Sky	TI MSP430F1611	16-bit	4-8MHz
MicaZ/Mica2	Atmel Atmega 128L	8-bit	8MHz
SHIMMER	TI MSP430F1611	16-bit	4-8MHz
IRIS	Atmel ATmega 1281	8-bit	8MHz
Sun SPOT	Atmel AT91RM9200	32-bit	180MHz
EZ-RF2480/2500	TI MSP430F2274	16-bit	16MHz

C. Communications Capabilities

The TelosB/Tmote Sky, MicaZ, SHIMMER and Sun Spot motes employ the 802.15.4 [8] compatible CC2420 radio chip from Texas Instruments [9]. The Iris mote also uses an 802.15.4 compatible chip, namely Atmel's AT86RF230 [10]. These two radios are packet level radios, with a maximum packet length of 127 bytes.

The MicaZ mote uses the Texas Instruments CC1000 [11], the EZ430-RF2500 uses the Texas Instruments CC2500 [12] while the EZ430-RF2480 uses the CC2480 [13], once again from Texas Instruments. The CC1000 and CC2500 are both bit level radios and the CC2480 is a Zigbee [14] compatible packet level radio which contains a Zigbee coprocessor. In addition to the CC2420 the SHIMMER also contains a second radio, a class 2 Bluetooth radio compatible with the Mitsumi WML-C46 series [15]. Table V lists the operating specifications of the six radios and Table VI gives the power consumption of each radio in sleep mode/switched off, idle/recieve mode and when transmitting at the specified power level. Specific points of interest or features worth noting for each radio are as follows:

CC1000: - As shown in Table V the CC1000 is capable of operating anywhere between 300 and 1000 MHz, with the frequency being programmable in 250 Hz steps, thus allowing frequency hopping if required. Normally this radio operates in the Industrial, Scientific and Medical (ISM) radio bands[16]. The power values given in Table VI are for a CC1000 operating at 433 MHz. In general the higher the frequency the higher the power consumption. The CC1000 is the oldest of the radio chips in this list and as a result it lacks some features and configurability of the other radios. Its successor, the CC1100 [17] is already available with these

TABLE IV
MEMORY SPECIFICATIONS

Mote Platform	RAM	Flash	EEPROM
TelosB	10K	48K	1M
MicaZ/Mica2	4K	128K	512K
SHIMMER	10K	48K[1]	none
IRIS	8K	640K	4K
Sun SPOT	512K	4M	none
EZ-RF2480/2500	1K	32K	none

NOTE: - All sizes in bytes
[1] NOTE: - In addition, SHIMMER's MicroSD Expansion Card Type is also Flash Memory

TABLE VI
RADIO CHIP POWER CONSUMPTION

Radio Module	Sleep	Idle/Rx	Tx (mA)
TI CC1000	0.2 μA	74 μA to 7.4 mA	10.4 (0 dBm)
TI CC2420	0.02 - 426 μA	18.8 mA	17.4 (0 dBm)
TI CC2500	400 nA - 160 μA	13.3 - 19.6 mA	21.2 (0 dBm)
TI CC2480	0.3 - 190 μA	26.7 mA	26.9 (0 dBm)
Atmel AT86RF230	20 nA	15.5 mA	16.5 (3 dBm)
Mitsumi WML-C46	50 μA - 1.4 mA	40 mA	60 (0 dBm)

TABLE V
RADIO CHIP SPECIFICATIONS

Radio Module	Frequency (MHz)	Modulation	Data Rate	Tx Power (dBm)	Rx Sensitivity (dBm)
TI CC1000	300 - 1000	FSK	76.8 kBaud	-20 - 10	-110 (at 2.4 kBaud)
TI CC2420	2400 - 2483.5	OQPSK	250 kbps	-24 - 0	-95
TI CC2500	2400 - 2483.5	OOK, 2-FSK, GFSK, MSK	500 kBaud	-30 - 1	-108 (at 2.4 kBaud)
TI CC2480	2400 - 2483.5	OQPSK	250 kbps	-55.8 - 0	-92
Atmel AT86RF230	2405 - 2480	OQPSK	250 kbps	-17 - 3	-101
Mitsumi WML-C46	2400 - 2483.5	GFSK	721 kbps	-6 - 14	-82

features and improved performance.

CC2420: - The CC2420 is a very popular chip for use on wireless sensor nodes, being used on four of the motes under consideration here. The CC2420 was the first 802.15.4 radio chip to be widely available in the market. 802.15.4 is very suitable for use in WSNs due to its very low power and flexibility. A feature of the CC2420 lacking on the other radios under consideration is its support for encryption using AES 128. This feature can greatly reduce the cost, both in terms of power and latency, of securing WSN communications.

CC2500: - The CC2500 also operates in the 2.4 GHz frequency band, but unlike the CC2420, CC2480 and AT86RF230 does not conform to the 802.15.4 standard. This allows greater flexibility and higher data rate than these other radios. A major feature of the CC2500 not available on any of these other radios is a very low power hardware wake up radio function to allow automatic RX polling. This allows the microprocessor to remain in deep sleep mode for more of the time, potentially providing a significant energy saving.

CC2480: - The aim of the CC2480 is to drastically simplify the integration of wireless communication into embedded solutions by handling the entire communication stack on the radio chip itself. The CC2480 radio chip contains a processor that runs a ZigBee stack (ZigBee certified) which offers standardized and robust mesh networking. As a result only the application itself has to run on the external MCU. The fact that the entire communication stack is handled on the radio chip is reflected in the higher power measurements given in Table VI.

WML-C46: - The WML-C46 is a class 2 Bluetooth radio, with a range of approx 10 metres. As with the CC2480, the WML-C46 handles the entire communication stack. Wireless sensor networks were not considered as a target application for Bluetooth when it was being designed and as a result it is not ideally suited for use in these networks, being overly complex for most WSN applications.However, the ubiquity of Bluetooth allows it to address a current problem faced by 802.15.4/Zigbee, which is interoperability with existing devices. It is mainly for this reason that the SHIMMER mote uses the WML-C46 as a second radio. For many applications a mobile phone can be a very convenient device to use for data aggregation or network querying. Currently this is not easily possible using an 802.15.4 network or with the other radio chips mentioned here. There is work ongoing to achieve this by adding hardware to existing phones, interfacing to the phone using MMC/SD card sockets but this technology is currently in early development stages and is not commercially available [18]. Therefore using Bluetooth allows more powerful devices to take part in a WSN without requiring any modification

A final point to note is the lower the frequency the radio operates at, the greater its potential range. As a result of the radio chips mentioned here the CC1000 or CC1100 have the greatest potential range, up to 70-80 times greater than the other radios. However the lower frequencies also require larger antennas, hampering miniaturization efforts.

D. Sensor Support

This section investigates the measurement capabilities of the respective sensor motes, and their provision for interaction with their environment(s).

Tmote Sky: - The Tmote Sky offers a versatile set of on-board sensors, namely humidity, temperature and light sensors. Light intensity is measured with a photo-diode connected to the 12 bit ADC available on the MSP430. Humidity and temperature are measured by Sensirion's SHT11, which provides digital readings of relative humidity (R.H.) with a typical accuracy of 3% R.H. and temperature with a typical accuracy of 0.4°C through a two-line serial link. In addition to the on-board sensors, the Tmote Sky provides access to 6 ADC inputs, a UART and I2C bus and several general purpose ports.

Mica2/MicaZ mote: - The Mica motes do not have on-board sensors. However, Crossbow offers an extensive set of sensor boards that connect directly to the Mica mote, and are capable of measuring light, temperature, relative humidity, barometric pressure, acceleration/seismic activity, acoustics, magnetic fields and GPS position. Additionally, actuators such as relays and buzzers can be attached to the Mica motes.

SHIMMER: - Intel's SHIMMER device was designed for mobile health sensing applications. It incorporates a 3 axis accelerometer and allows connection of other sensors through its expansion board.

IRIS: - With the IRIS mote Crossbow has continued its design philosophy in which the actual mote does not offer any sensor capabilities. However, through the 51 pin expansion connector the existing Crossbow sensor boards (see Mica2/MicaZ section) can be connected to the IRIS mote.

Sun SPOT: - the Sun SPOT offers expansion boards with tri-axial accelerometer, temperature sensor and light sensors. Custom made sensors can be connected via five analogue inputs and five general purpose digital ports. The tri-axial accelerometer has a selectable range of ± 2g or ± 6g.

EZ430-RF2480/2500: - With the EZ430-RF2480 and EZ430-RF2500 Texas Instruments has developed a PCB integrating the MSP430 low-power microprocessor with the CC2480 and CC2500 respectively. No on-board sensors are provided, but a break out connector provides 10 ADC lines (200ksps, 10 bit ADC), an SPI and an I2C interface.

E. Power Specifications

For the 6 separate sensor nodes in this paper, configured to operate in stand-alone mode in a typical deployment setting, power supply options are as follows: -

TelosB/Tmote Sky: - Both the TelosB and Tmote Sky boards are typically powered from an external battery pack containing 2 AA batteries. AA cells may be used in the operating range of 2.1 to 3.6V DC, however the voltage must be at least 2.7V when programming the microcontroller flash or external flash.

Mica2/MicaZ: - the MicaZ and Mica2 sensor nodes use the same physical battery configuration as the TelosB or Tmote sky boards i.e. 2 AA batteries in an attached battery pack.

SHIMMER: - the SHIMMER mote is typically powered by a 250mAh battery. Supported configurations include Lithium-Ion/Lithium-Poly cell chemistry and lithium coin cells or alkaline batteries. The SHIMMER design also includes a Texas Instruments BQ-24080 Smart Li Charger for battery management.

IRIS: - IRIS uses 2 AA batteries similar to Mica2/MicaZ.

Sun SPOT: - Sun SPOT motes are powered from an integrated rechargeable onboard battery. The eSPOT mote PCB typically uses a 3.7V rechargeable 750 mAh lithium-ion battery, nominally operating with a 30 uA deep sleep mode.

EZ-RF2480/2500: - The EZ430-RF2XXX application boards must be externally powered for operation in a standalone environment. An AAA battery pack and expansion board for this purpose are provided with each application/development kit. The expansion pack takes 2 AAA batteries to power the wireless board. Standard supply voltage for the board is 3.6V.

Of the 6 motes considered here, only 2 use rechargeable battery packs, the SHIMMER mote and the Sun SPOT mote. The SHIMMER is supplied with a rechargeable 250mAh battery while the more processor and power-intensive Sun SPOT typically uses a 750mAh Li-Ion battery.

IV. Conclusions

This paper has presented a comparative review of currently available mote technologies. For these different motes, a series of 5 categories have been considered, namely general parameters, processor and memory specifications, communication channels, sensor capabilities and battery operation specifications. In each case, we have presented an unbiased high-level summary of the various mote packages.

In terms of individual observations, we have found that the Sun SPOT motes are the best option if processing power and a high computational overhead are envisaged in the application requirements. SHIMMER motes, with their small form factor and integrated 3-dimensional accelerometer sensors, are best suited for wearable applications such as health monitoring, etc. The EZ430-RF2XXX development kits are the cheapest mote solution reviewed in this paper, and are best suited to application developments where a small form factor is required and sensor data is provided from external source(s). Users new to TinyOS will find a steep learning curve involved with this programming approach; if prior Java expertise is available, a solution such as the Sun SPOT or (Sentilla's) Tmote sky might be preferable.

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