Comparative analysis of Wireless Sensor Network Motes

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***Abstract*— Wireless Sensor Network (WSN) applications range from simple data gathering to hard to imagine fields like Internet of Things. For all the applications the physical design space consists of sensors extended with storage, power supply, computation and communication capabilities, the so-called motes. These motes run the network protocol programs that most of the time sleep, and occasionally collect, process, store and communicate the data to Base Station (BS). The number of protocol proposals has increased but unfortunately the number of mote studies has not. This paper discusses the essential sub-systems of motes, surveys and does a comparative analysis of well-known motes. The motes are selected based on a number of criteria including popularity, published results, interesting characteristics and features. The motes are analyzed using a number of different parameters and criteria, including processor used, lifetime, cost, software support, size, their strengths and weaknesses. Simulation of LEACH protocol using motes discussed in the paper is carried out and a comparative analysis of network lifetime, data transmitted and energy consumption of network is presented. The goal of work is to aid WSN application developers to select appropriate mote for their network or determine features that should be included on a custom built sensor node platform.**

Keywords—WSN motes; review; LEACH simulations;analysis

I. INTRODUCTION

WSN networks have diverse applications including human health monitoring, rescue operations, HVAC control, environmental monitoring, civil infrastructure monitoring, precision agriculture, animal tracking, supply chain management, Internet of Things [1]. To cater the design needs of versatile applications of WSN a number of commercial nodes are available in the market. Each node consists of following hardware sub-systems: power source; computational logic; storage; radio modules and sensor transducer(s). The software sub-systems consist of: operating system microcode (or middleware) to shield the software from the machine-level functionality; sensor drivers to shield the application programs from machine-level functionality of the sensor; communication drivers to manage the minutia of the radio. The size of the node is required to be very small such that they are called “smart dust” or “motes” (a small particle, term coined by researchers in the Berkeley [2]). This paper presents a comparative analysis of commercially available motes with comparison parameters like (i) physical characteristics such as size, weight, battery life (ii) electrical specifications for microprocessor and radio transceiver used in the mote design (ii) computing, communication, power and sensing subsystems. The rest of the paper is organized as follows: Section II presents the scope of comparative study and individual motes being reviewed in the paper. Section III presents actual comparative analysis of the motes. Section IV presents results of simulation of LEACH protocol using the motes. Finally, Section IV summarizes the findings of our review in the conclusions section.

II. SCOPE OF THE COMPARATIVE STUDY

The comparative analysis is divided in following categories: qualitative parameters, computational and storage logic, software support, radio modules, on board sensor support and power source.

- *Mica2/Micaz* are the second and third generation mote technologies from CrossBow Technology [3].
- *TelosB/Tmote Sky* are developed by University of California, Berkeley and currently available from MEMSIC Inc [4].
- *SHIMMER,* the Sensing Health with Intelligence, Modularity, Mobility, and Experimental Reusability designed by Real-time Technologies [5] for wearable health sensing in both connected and wireless environments.
- *IRIS* are the latest motes from Crossbow Technologies.
- *Sun SPOT* are small Programmable Object Technology from Sun Microsystems [6].
- *EZ430-RF2480/F2500T* are wireless networking solutions from Texas Instruments [7]-[8].
- *Waspmotes* are open source hardware and software sensor platform from Libelium Comunications [9].

III. COMPARATIVE ANALYSIS OF THE MOTE PLATFORMS

A. Qualitative Parameters

The qualitative parameters used for comparative analysis of motes are: physical dimensions, weight, size, operating temperature range, battery capacity, year in which they are introduced, manufacturing company and costing. Depending on application requirements size of a single mote may vary from size of a brick to a dust particle. Varying size result in varying limits on energy, processing, storage and communication resources. Table I provides an overall comparison of above mentioned qualitative parameters of motes. Weight and size become an important factor when selecting motes for human health monitoring or tracking applications where motes move along with the objects [10]-[11]. The cost factor becomes crucial for applications where motes are to be deployed in huge numbers in a hostile environment [12][13]. The pricing information of the motes is as of October 2013.

B. Computational and storage logic

The computational logic is responsible to handle onboard data processing and manipulation, temporary storage, data encryption, forward error correction, digital modulation, and digital transmission. Depending on the application the computational requirements may range from an 8-bit microcontroller to a 64-bit microprocessor with storage from 0.01 to 2 gigabytes (GB). The faster and powerful processors have high energy consumption and cost. Processors with high code density, different operational modes like active, idle, nap and sleep modes to preserve energy are required. The storage logic of the mote consists of flash memory for program code and RAM for sensed information and other data needed for computations. Shimmer and Waspmotes has a built in micro SD card interface allowing up to 2 gigabytes of data storage. However writing to SD card is power hungry process and at par to sending the same amount of data over a low power Radio. Table II provides a detailed comparison of computational and storage logic of the motes.

C. Software support

The coding for all the motes except Sun SPOT and Waspmotes is done using the TinyOS operating system platform [14]. TinyOS programs are written in nesC, a dialect of the C programming language. The programs for TI EZ430-RF2XXX motes are written in C using Integrated Development Environments (IDE) like IAR workbench [15] or Code Composer Studio [16]. Sun SPOT motes are programmed using J2ME [17] which runs directly on the processor without an OS. Standard Java IDEs like NetBeans [18] can be used to create SunSPOT applications. The latest revision of Tmote sky also includes a Java Virtual Machine, allowing Java code to be run on the mote. Waspmotes programs are written in C++ using open source IDE from Waspmote [19]. Table II shows the software support by the motes.

D. Radio modules

Radio modules are required to enable motes to communicate with each other and to the BS. The major options for transmission medias are: infrared, optical, short range radio, ultrasound and inductive fields. Infrared is comparatively cheap among all and offers low power consumption. But both infrared and optical require a line of sight between sender and receiver which is difficult in WSN applications. Ultrasound is usually ruled out because the network coordinator requires high energy and the size of the equipment increases. Inductive field communication again requires high energy and has a very low transmission range. Hence short range radio links with unlicensed bands are ideal for motes because it is not limited by line of sight and low-power radio transceivers with desired data-rates and scalable transmission ranges are available. Most of the governments around the globe have identified unlicensed bands, known as Industrial, Scientific and Medical (ISM) bands, which can be freely used provided the device follows the rules that control the band. Use of free band for communication decreases the cost of WSN. However the unlicensed bands change from country to country and the wireless local area networks, home appliances like microwave ovens and some of the medical equipments operate in ISM band causing interference. IEEE 802.15.4 (Zigbee) [20] and IEEE 802.15.1 (Bluetooth) [21] are the major wireless standards used by the radios. Zigbee has an advantage of lower memory requirements, lower power consumption and high scalability. On the other hand, Bluetooth allows easy interoperability with a variety of existing devices including mobile phones and laptops without the need for additional hardware or software setup. The TelosB/Tmote Sky, MicaZ, SHIMMER and Sun Spot motes embed the 802.15.4 compatible CC2420 radio chip from Texas Instruments [22]. The IRIS mote uses Atmel's AT86RF230 which is again 802.15.4 compatible chip [23]. The MicaZ mote uses the Texas Instruments CC1000 [24], EZ430-RFF2500T uses the Texas Instruments CC2500 [25] while the EZ430-RF2480 uses the Texas Instruments CC2480 [26]. Along with the CC2420, SHIMMER has a second radio, a class 2 Bluetooth radio compatible with the Mitsumi WML-C46 series [27]. Table III lists the operating specifications, power consumption and other specifications of all the radios.

CC1000 is one of oldest radio chip capable of operating in 300 to 1000 MHz, and the frequency being programmable in steps of 250 Hz, thus allowing frequency hopping if required. The CC2420 is the first IEEE 802.15.4 radio chip with support for encryption using AES 128 [28]. This reduces the power and latency required for securing communications. The CC2500 operates in ISM band, but does not conform to any wireless standard allowing greater design flexibility and higher data rate compared to other radios. It incorporates very low power hardware wake up radio function to permit automatic receiver polling. Thus the microprocessor can go to deep sleep mode for most of the time, resulting in significant energy savings. CC2480 embeds a processor for running a ZigBee protocol stack. Thus processor requires only the application to be run. The WML-C46 is a class 2 Bluetooth radio stack with a range of approximately ten metres. Since Bluetooth was originally designed for personal area networks it is not suitable for WSN but it offers ubiquity through interoperability with existing devices and hence SHIMMER uses WML-C46 as a second radio.

At lower frequencies radio offers larger range but requires larger antennas which hampers the miniaturization requirements of motes. Waspmote supports eight Radio Technologies. They are long range 3G/GPRS, medium range Zigbee / WiFi and short range RFID / NFC / Bluetooth. Table III shows the radio modules used in the motes with their specifications.

E. On board sensors

Sensors are link between external environment and the mote. Some of the basic sensors are temperature, light, pressure, sound, motion, humidity and magnetic flux. Some of these sensors are built on the motes. Motes also provide ports to attach external sensors for versatility. To attach sensors with analog outputs processors like Atmel ATmega 128L and Texas Instruments' MSP430 contain integrated ADCs. The on board sensor support and their provision for attaching with external environment is discussed next.

• *TelosB/Tmote Sky* provides onboard sensors, namely humidity, temperature and light sensors. Light intensity is measured with a photo-diode, humidity sensor provides digital readings of relative humidity with a typical accuracy of 3% R.H. and temperature sensor connected through SPI link has accuracy of 0.4 degree Celsius. Tmote Sky also provides about 6 ADC inputs, UART and I2C bus and several general purpose ports.

• *Mica2/MicaZ* are equipped with humidity, temperature and light sensors memsic provides an extensive set of sensor boards that connect directly to the mote. They are capable of measuring barometric pressure, acceleration/seismic activity, acoustics, magnetic fields and GPS position. In addition it provides interface for actuators such as relays and buzzers.

• *SHIMMER* are designed for mobile health sensing and incorporates on board 3-axis accelerometer. It also provides expansion boards for connecting other sensors.

• *IRIS* offer on board light sensor support and memsic provides an extensive set of sensor boards. Further external sensors can be connected through a 51 pin expansion connector.

• *Sun SPOT* offers expansion boards with 3-axis accelerometer, temperature sensor and light sensors. Additionally five analogue and five general purpose digital ports are provided to connect custom made sensors.

• *EZ430-RF2480/F2500T* are equipped with on-board temperature, light and humidity sensors in addition to connectors with 10 ADC lines, SPI and an I2C interface.

• *Waspmote* has no on-board sensor support but expansion boards for 60 different sensors including temperature, humidity, CO_2, NO_2, O_2, CO, light, accelerometer, GPS etc. are available from Libelium.

Table III shows on board sensor support for the motes.

F. Power source

An appropriate energy infrastructure or supply is necessary to support mote operation from a few hours to months to years depending on the application. For majority of the applications motes are configured to operate in stand-alone mode and it is difficult or impossible to refill or replace mote's batteries. This demands efficient power sources for the motes.

• *TelosB/Tmote Sky* are to be powered from an external 2 AA batteries battery pack. AA cells may be in the operating range of 2.1 to 3.6V DC. However at the time of programming the flash voltage must be at least 2.7V.

• *Mica2/MicaZ* use the same physical battery configuration as the TelosB or Tmote sky boards.

• *SHIMMER* is typically powered by a 250mAh battery. The battery configurations can be Lithium-Ion/Lithium-Poly cell chemistry/Lithium coin cells/Alkaline batteries.

• *IRIS* uses 2 AA batteries similar to Mica2/MicaZ.

• *Sun SPOT* are powered from an integrated rechargeable onboard battery.

• *EZ-RF2480/F2500T* are equipped with an expansion board with 2 AAA battery pack for powering these motes.

• *Waspmote* gives the option of using Li-Ion rechargeable batteries, Solar Panels or USB charging.

Table I shows power source requirements for the motes.

IV. Simulation of LEACH Protocol

LEACH is a well referred cross layered protocol architecture that combines medium access with routing to collect and deliver data to BS [29]. It uses a hierarchical approach and organizes the network into a set of clusters with a cluster head administering the cluster. The cluster head creates a TDMA-based schedule to assign a time slot to each cluster member for periodic data transmission to cluster head. Cluster head then aggregates the data to remove redundancy among correlated values and transmits it to BS. The function of LEACH is divided into rounds which are further organized in setup phase which consist of cluster head selection and cluster formation followed by steady-state phase. The setup phase starts with the self-election of motes to become cluster heads. The self-election algorithm ensures that CH role rotates among nodes to distribute energy consumption evenly across all nodes. In the cluster formation algorithm every node that has opted to become a cluster heads broadcasts its new role to the network. Each non cluster head node joins the cluster based on received signal strength of cluster head broadcast message. Once the cluster is formed, cluster head creates and distributes a TDMA-based schedule to assign a time slot to each of its cluster members. During the steady state phase, non-cluster head nodes periodically collect sensor data and transmit it to cluster head in their allocated slots and enter the sleep mode otherwise.

• *Simulation and Results*

All the simulations were carried out using Matlab [30] with different motes. Table IV shows the basic simulation settings for all simulations. To reduce the occasionalism, twenty simulations with different seeds were carried out for each scenario and average values were adopted as the results.

TABLE IV SIMULATION SETTINGS FOR ALL SIMULATIONS

Parameter	Description
Protocol	LEACH
Nodes	100
Network size	100m x 100m
BS location	(50,175)
Radio Propagation speed	3×10^8 m/s
Data size	500 bytes
Initial energy	0.5 J
Cross-over distance for Friss and two-ray ground attenuation models	87.7 m
Radio propagation speed	3×10^8 m/s
Processing delay	25 µs
Packet length	6400 bytes
Nodes	TelosB/Tmote Sky; Mica2/MicaZ; SHIMMER; IRIS; Sun SPOT; EZ-RF2480/F2500T; Waspmote

The radio electronics energy, compute energy for performing data aggregation and radio amplifier energy are taken according to the node's specifications. In these simulations, all the 100 nodes begin with an unlimited amount of data to be periodically sent to the BS. The sensors transmit data at the rate of 1MBps. The sum of residual energy of the nodes in the entire network is tracked at an interval of 100 rounds. Figure 1 shows that the sum of residual energy for all the nodes. From among all the nodes, EZ-F2500T is the most energy efficient node. This is because MSP430F1611controller consumes the least amount of power in its active and sleep modes. It has four sleep modes in total. The deepest sleep mode, LPM4, only consumes 0.3 µW, and the controller can be woken up by external interrupts in this mode. In the next higher mode, LPM3, a clock is also still running, which can be used for scheduled wake ups, and still consumes only about 6 µW. During the course of simulation the nodes use up their energy and are finally said to be dead when they can no longer transmit or receive data. Figure 2 shows the total number of nodes that die over the simulation rounds. The number of dead nodes is again least in the case of EZ-F2500T because energy consumption of each mote is minimum. In most of the cases merit of a WSN mote is application-specific measure. But one application independent method of determining merit of the node is to determine the total amount of data packets received at the BS. The analysis of the sensed environment will be more precise if more aggregated data is received at the BS. Figure 3 shows the total number of aggregated data packets received at the BS over the simulation rounds. It shows that EZ-F2500T sends maximum packets to the BS compared to any other mote. This is because the number of nodes dead over the simulation rounds is minimum in case of EZ-F2500T.

V. CONLUCSION

Some of the other motes not talked about in the paper are BTNode motes [31], Intel IMote [32], Freescale13 evaluation boards [33], Fleck [34], ProSpeckz II [35], Ember RF [36], µAMPS [37] and LOTUS [38]. This paper presents an unbiased review of several well-known generic motes for WSN. In terms of individual observations, it is found that for power and computer hungry applications Sun SPOT motes are the best option. SHIMMER motes are designed for wearable applications such as telemonitoring of human physiological data, human health monitoring etc. The EZ430-RF2XXX motes are the cheapest motes and are best suited for applications envisaging sensor data to be provided from external source(s) and requiring large number of motes. Wapsmote is the latest development in the applications like Internet of Things. It provides a large range of radio modules and models integrating more than sixty sensors. In the arena of node programming programmers new to TinyOS will find a steep learning curve in programming approach unless they know Java which can program Sun SPOT. The review will help application developers to make decisions for selecting the motes for their work and researches and node manufacturers can look for the limitations of the popular motes and overcome them. Some of the general facts about the motes are discussed below: (i) For the majority of WSN applications the choice of node was, is, and will continue to be application dependent (ii) Though there are ample number of motes available in the market the types of microprocessors/ microcontrollers and radio modules therein are limited (iii) Most of the time motes are designed for certain projects which locks its features with respect to the applications for which it is designed. In each case when a hardware design was fixed the software was limited by the choices made in the beginning (iv) Motes have evolved considerably in recent years but there is still no "one size fits all" kind of solution (v) The processors, memory, input/output ports, bus standards of conventional computing systems, such as desktops, mobile phones, etc., are the features researched upon and upgraded exponentially. For node technology it is more required to decrease the energy consumption and the cost. This is because the vision is to have these motes to be actually disposable and this is possible if the price is less than a dollar and lifetime is at least a year.

VI. REFERENCES

[1] S. H. Gajjar, S. N. Pradhan, K.S. Dasgupta, "Wireless Sensor Networks: Application led research perspective", Proc. of IEEE Recent Advances in Intelligent Computational Systems, pp. 025 – 030, 2011.

[2] K. Pister, "Centre for embedded network sensing", http://research.cens.ucla.edu/.

[3] Moog Crossbow Technologies Wireless Sensor Network products [Online]. Available: http://www.xbow.com/.

[4] MEMSIC Inernaltional corporation Wireless Sensor Network products [Online] Available: http://www.memsic.com/.

[5] Realtime Technologies Wireless Sensor Network products [Online] Available: http://www.realtime.ie/.

[6] Project Sun SPOT report [Online] Available: http://www.sunspotworld.com.

[7] User guide eZ430-RF2480 [Online] Available: http://www.ti.com/lit/ug/swru151a /swru151a.

[8] User guide eZ430-RF2500 [Online] Available: http://www.ti.com/tool/ez430-rf2500.

[9] Libelium Communications waspmote catalogue [Online] Available: http://www.libelium.com/products/ waspmote/.

[10] G. Pradhan, B. Prabhakaran, "Storage, Retrieval, and Communication of Body Sensor Network Data", Proc. of ACM Multimedia, pp. 1161-1162, 2008.

[11] P. Castillejo, J. Martinez, J. Molina, A. Cuerva, "Integration of wearable devices in a Wireless Sensor Network for an E-health application", IEEE Wireless Communications, pp.38-49, 2013.

[12] Z. Butler, P. Corke, R. Peterson, D. Rus, "Virtual Fences for Controlling Cows", International Conference on Robotics and Automation, pp. 4429 – 4436, 2004.

[13] T. Wark, P. Corke, P. Sikka, L. Klingbeil, Y. Guo, C. Crossman, P. Valencia, D. Swain, G. B. Hurley, "Transforming Agriculture through Pervasive Wireless Sensor Networks", IEEE Pervasive Computing, vol. 6, no. 2, pp. 50-57, 2007.

[14] TinyOS guide [Online] Available: http://www.tinyos.net/.

[15] IAR Embedded workbench official website [Online] Available: http://www.iar.com/ServiceCenter/Downloads/.

[16] Code composer studio IDE Tools from Texas Instruments [Online] Available: http://www.ti.com/tool/ccstudio.

[17] Lurker's guide to Java Sun SPOT development using Java ME (J2ME) [Online] Available: http://www.blueboard.com/spot/.

[18] Netbeans IDE guide [Online].Available https://netbeans.org/.

[19] Waspmote IDE guide [Online] Available: http://www.libelium.com /development/waspmote/sdk_applications/.

[20] Zigbee specifications [Online] Available: http://www.zigbee.org/ Specifications.aspx.

[21] Bluetooth specifications, [Online] Available: https://www.bluetooth.org/en-us/specification/.

[22] Texas Instruments, CC2420 datashee [Online] Available: http://focus.ti.com/lit/ds/symlink/cc2420.

[23] A. Corporation, AT86RF230 datasheet [Online] Available: http://www.atmel.com/dyn/resources/prod documents/doc8087.

[24] Texas Instruments, CC1000 datasheet [Online] Available: http: //focus.ti.com/lit/ds/symlink/cc1000.

[25] Texas Instruments, CC2500 datasheet [Online] Available: http: //focus.ti.com/lit/ds/symlink/cc2500.

[26] Texas Instruments, CC2480 datasheet [Online] Available: http: //focus.ti.com/lit/ds/symlink/cc2480a1.

[27] M. E. Co., WML-C46 datasheet [Online] Available: http: //www.mitsumi.co.jp/Catalog/pdf/communwmlc46e.

[28] J. Daemen, V. Rijmen, AES Proposal: Rijndael, AES Algorithm [Online] Available: http://www.nist.gov/CryptoToolkit.

[29] W. B. Heinzelman, A. P. Chandrakasan, H. Balakrishnan ", An Application Specific Protocol Architecture for Wireless Microsens Networks", IEEE Transactions on Wireless Communications, vol. 1, no.4, pp. 660-670, 2002.

[30] MATLAB guide [Online].Available: http://www.mathworks.in/.

[31] BTnode plateform guide, [Online] Available: http://www.btnode.ethz.ch.

[32] L. Nachman, R. Kling, R. Adler, J. Huang, "The Intel® mote platform: a Bluetooth-based sensor network for industrial monitoring", Proc. Of 4th International Symposium on Information Processing in Sensor Networks, pp. 437-442, 2005.

[33] Freescale evaluation boards reference manual [Online] Available: http://www.freescale.com/files/rf_if/doc/ref_manual/MC13192EVBR.

[34] Fleck mote series project report, [Online] Available: http://www.snm.ethz.ch/snmwiki/Projects/Fleck.

[35] Guide to ProSpeckzIIK [Online] Available: http://www.inf.ed.ac.uk/ teaching/ courses/slip/ prospekz-QSG.

[36] The EmberNet RF node specification sheet [Online].Available: http://csag.ucsd.edu/teaching/cse291s03/Readings/EmberNet-Node.

[37] µAMPS project report [Online] Available: http://www-mtl.mit.edu/researchgroups/icsystems/uamps/.

[38] LOTUS datasheet [Online] Available: http://www.memsic.com/ userfiles/files/Datasheets/WSN/6020-0705-01_A_LOTUS.

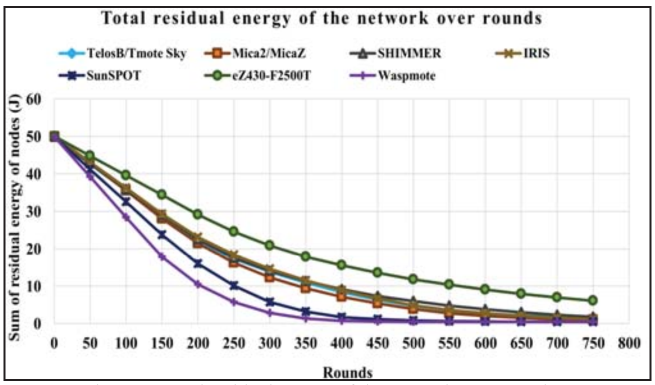

Figure 1: Total residual energy of the network over rounds

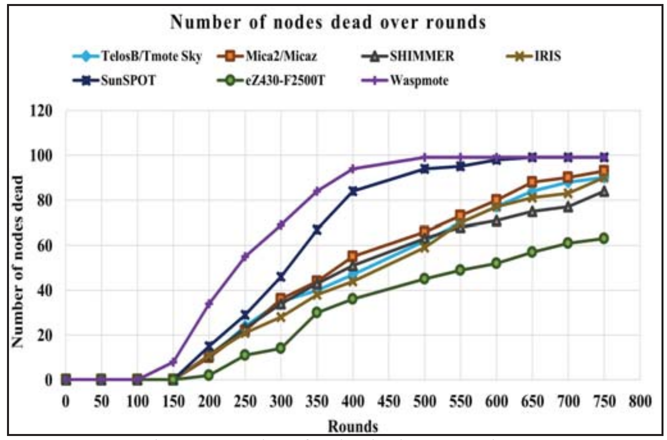

Figure 2: Number of nodes dead over rounds

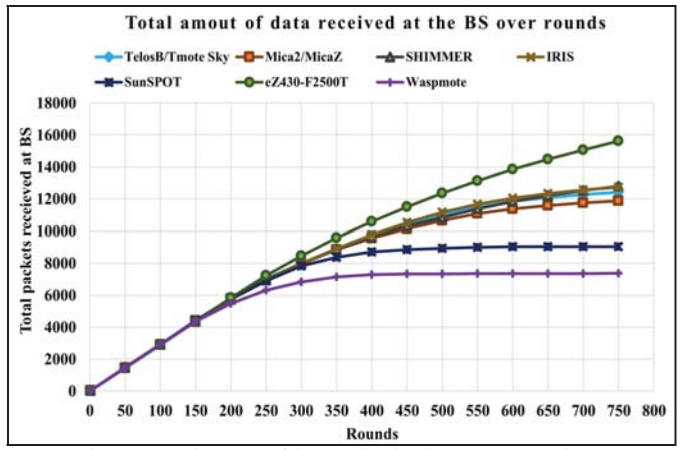

Figure 3: Total amount of data received at the BS over round

TABLE I QUALITATIVE PARAMETERS OF MOTES

Parameter	TelosB/Tmote Sky	MICA2/MICAZ	SHIMMER	IRIS	SunSpot	eZ430-F2500T	Waspmotes
Size (inches)	2.55 x 1.24 x 0.24	2.25 x 1.25 x 0.25	1.75 x .8 x 0.5	2.25 x 1.25 x 0.25	2.5 x 1.5 x 1	1.16 x 3.17 x 0.43	2.9 x 2.01 x 0.51
Weight (gms)	63.05	63.82	10.36	69.40	58.08	30.89	20.00
Battery	2xAA	2xAA	250 mAh Li-Ion	2xAA	750 mAh Li-ion	2xAAA	1150 mAh Li-on
Year	2005	2002/2004	2006	2007	2005	2007	2013
Manufacturer	UC Berkeley	Crossbow	Intel	Crossbow	Sun	Texas Instruments	Libenium
Cost (US$)	99/139	99	269	115	750	58	173.77
Strong Points	• Low power microcontroller and RF module	• Expansion connectors for attaching external sensors	• Supports Bluetooth, Real time capability • For long term wearable use	• 3- times radio range compared to MICA nodes at half the power consumption	• Open source hardware and software support	• Lowest Cost, size	• Solar powering option • Eight types of radio support
Weak Points	• Software optimization ignored in design	• Hardware concentrated	• No battery indicator • Lacks robustness	• Less number of on board sensors	• Expensive	• Works best with SimpliciTI RF protocol	• Complex hardware

TABLE II COMPUTATIONAL, STORAGE LOGIC AND SOFTWARE SUPPORT OF MOTES

Parameter	TelosB/Tmote Sky	MICA2/MICAZ	SHIMMER	IRIS	SunSpot	eZ430-F2500T	Waspmotes
Controller	TI MSP430F1611	AT Atmega128L*	TI MSP430F1611	AT Atmega1281*	AT Atmega91RM 9200*	TI MSP430F2274	AT Atmega1281*
BUS size (Bits)	16	8	16	8	32	16	8
Frequency (MHz)	8	16	8	16	180	16	16
Wake-up time (μs)	6	180	6	4300	Pin change wake up	1	16000
FLASH (Bytes)	48K	128K	48K	640K	4M	32K	128K
RAM (Bytes)	10K	4K	10K	8K	512K	1K	8K
EEPROM (Bytes)	1M	512K	No support	4K	No Support	No support	4K
Serial Communication	UART	UART	UART	UART	UART	UART	UART
Current Active mode (mA)	1.8	8	1.8	8	25	0.270	8
Current Sleep (μA)	5.1	<15	5.1	8	500	0.7/0.1(Standby/off)	8
Operating voltage (V)	1.8 to 3.6	2.7 to 3.3	1.8 to 3.6	2.7 to 3.3	5(±10%)	1.8 to 3.6	2.7 to 3.3
Power consumption active (mW)	3	33	5.94	21.6	92.5	0.594	21.6
Power consumption sleep (μW)	2	30	16.83	21.6	1850	1.54/0.22(Standby/off)	21.6
Timer support	Two 16 bit	Two 8-bit Two 16-bit	Two 16 bit	Two 8-bit Four 16-bit	Two 16 bit	Two 16 bit	Two 8-bit Four 16-bit
Watchdog	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ADC	12-bit SAR	10-bit	12-bit SAR	10-bit	10-bit	10-bit SAR	10-bit
ADC channels	8	8	8	8	8	12	8
Operating temperature range (°C)	-40 to +85	-55 to +125	-40 to +85	-55 to +125	-40 to +85	-40 to +105	-55 to +125
Package	64-pin QFN	64-lead TQFP, 64-Pad QFN/MLF	64-pin QFN	64-pad QFN/MLF, 64-lead TQFP	208- PQFP, 256-ball BGA	38TSSOP, 40VQFN, 49DSBGA	64-Pad QFN/MLF, 64-lead TQFP
OS support	*Contiki, TOS, Mantis OS	*TOS, Mantis OS	*TOS	*Mote Runner, TOS, MoteWorks	Squawk VM (Java)	*TOS	N.A.
Programming and IDE	*TOS, CCS, IAR	*TOS	*TOS	*TOS	J2ME, JDK	*TOS, CCS, IAR	C++, Waspmotes

*TOS=Tiny OS Cross development tools with TOSSIM Simulator, AT=Atmel

TABLE III RADIO MODULES AND ON BOARD SENSOR SUPPORT OF MOTES

Parameter	TelosB/Tmote Sky	MICA2/MICAZ	SHIMMER	IRIS	SunSpot	eZ430-F2500T	Waspmotes
Radio chip	C CC2420	C CC1000/CC2420	C CC2420	AT RF230*	C CC2420	C CC2500	XBee-802.15.4
Data Rate (kbps)	250	38.4/250	250	250	250	250	250
ISM Band (MHz)	2400 - 2483.5	300-1000/2400 - 2483.5	2400 - 2483.5	2400 - 2483.5	2400 - 2483.5	2400 - 2483.5	2400 - 2483.5
Current Receiving (mA)	19.7	18.8	18.8	16	18.8	21.2	50
Current Transmitting (mA)	17.4 (0dBm)	17.4 (0dBm)	17.4 (0dBm)	17(3dBm)	17.4 (0dBm)	16.6(0dBm)	45(0dBm)
Power Consumption receiving (mW)	56.4	56.4	56.4	48	56.4	38.16	148.5
Power Consumption transmitting (mW)	52.2	52.2	52.2	51	52.2	29.88	165
Power Consumption in sleep/idle/power down	1.28mW	1.28mW	1.28mW	60nW	1.28mW	4.5mW	33uW
Modulation Technique	O-QPSK	O-QPSK	O-QPSK	O-QPSK	O-QPSK	OOK, 2-FSK, GFSK	PWM
Sensitivity(dBm)	-95	-95	-95	-101	-95	-108	-92
Transmit power(dBm)	-24	-24	-24	-17	-24	-30	-10
Sensor support	T, H,L*	T, H, L*	A*	L*	2G/6G A, T,L*	T, H, L*	2G/6G/8G A,T*

*T= Temperature, H=Humidity, L=Light, A=3-axis accelerometer, C=Chipcon, AT=Atmel