UTD Mote System (UTMOST): Improving Functionalities in Wireless Sensor Nodes

Gustavo Litovsky, Marco Tacca, and Andrea Fumagalli

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Gustavo Litovsky, Marco Tacca, and Andrea Fumagalli
The Open Networking Advanced Research (OpNeAR) Lab
Erik Jonsson School of Engineering and Computer Science
The University of Texas at Dallas, Richardson, TX 75080, USA
Email:{ggl052000, mtacca, andreaf}@utdallas.edu

***Abstract*—The UTD mote system (UTMOST) is a low power all purpose platform for wireless sensor nodes (WSN) based on off-the-shelf components. UTMOST offers a number of improved functionalities over previously designed platforms, e.g., energy consumption, wireless reprogramming, processing frequency, and storage capability. This paper details how hardware components are selected and integrated to enable such improvements. Experimental measurements demonstrate, among other things, a reduction of 37% in sleep current compared to previous platforms. The proposed design enables extended remote programming and lower maintenance, longer lifetime, and the support of more computational intensive applications.**

I. Introduction

Past research into WSN design has centered primarily around reduction in energy consumption and improvement in the storage and communication capabilities because of their significance. Consistently with these goals, each generation progressivly enhanced motes with new devices or customized them for specific applications. For example, the choice of batteries has a profound effect on the performance of the WSNs, including energy consumption and functionality. Alkaline batteries have been commonly selected for many platforms, including UTMOST, for several reasons, e.g., they are inexpensive, widely avaialble, and provide a good capacity. Some other key issues, which are critical to a WSN's operation, have not however been fully addressed. For example, the progressive decline in battery voltage slowly cripples the microcontroller, transceiver, storage, and other devices either partially or completely. Many new applications require more storage and communications capability than what is currently available, and energy consumption remains an aspect that must be further reduced if possible so that the sensor node network will survive longer. The off-the-shelf component design of the UTMOST WSN, presented in this paper, accounts for a number of these issues and delivers a system that provides consistent functionalities over the lifetime of the mote and improved performance in many aspects. The selection of components with low supply voltage and low energy consumption allows for a wider range of operation as well as significant savings in total system consumption, respectively. An innovative DC-DC booster, the Dynamic Voltage Booster (DVB) provides 3.6 V on demand, consuming little energy when not used, and operating efficiently when it is required. This system allows the microcontroller to operate at any of the frequencies in its range, which enables bursts processing to reduce latency at many levels and enable faster processing of data from multiple sensors. Wireless reprogramming, previously limited to only an initial fraction of the WSN lifetime, is now possible at any time since the necessary voltage can be provided when needed by the dynamic voltage booster. A communication link that offers higher transmission capacity at longer distances compared to previous mote systems can now be established by the transceiver. Storage capacity and data transfer speed have also been increased by a new storage device. All these improvements combined enable the realization of demanding applications previously difficult to realize, such as voice [1] or storage dependant data collection [2]. Before describing the UTMOST, previous work done in the area is discussed in the next section.

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II. Related Work

As noted earlier, there are currently several WSN platforms. Table I presents the most significant parameters of some of these platforms as they relate to the topics presented in this paper, along with the UTMOST platform values. It is important to note that the voltages presented refer to the minimum voltage required of the battery, not of the component, and can therefore change from datasheet specifications if the system provides power management such as a DC-DC converter. The importance of this choice will be seen later when each system's capabilities are analyzed. The reader can refer to [3] for a more detailed comparison about Telos and previous generations of WSNs.

The Mica platform [4] was a major innovator in the field of WSNs and remains widely used in research concerning applications and networking of WSNs. It significantly reduces energy consumption compared to previous motes and provides much more functionality. Mica incorporates the MAX1678, a voltage booster which provides a stable voltage for all the components, but consumes too much quiescent current since the booster is required to operate constantly [3]. The flash storage provides 512 kB for logging and storage, while the TR1000 radio allows a data rate of up to 40 kbps. Mica2 and subsequent motes have discarded the voltage booster, resulting

TABLE I
COMPARISON OF WIRELSS SENSOR NODE PLATFORMS

Parameter	Platform				
	Telos [3]	Mica [4]	Mica2 [3]	TinyNode [5]	UTMOST
Microcontroller	MSP430F1611	Atmega128L	Atmega128L	MSP430F1611	MSP430F1611
Maximum Frequency	8 MHz	8 MHz	8 MHz	8 MHz	8 MHz
Min Operation Voltage	1.8 V	2.7 V	2.7 V	1.8 V	1.8 V
Min. Programming Voltage	2.7 V	2.7 V	2.7 V	2.7 V	1.8 V
Transceiver	CC2420	TR1000	CC1000	XE1205	CC1101
Data Rate	250 kbps	40 kbps	38.4 kbps	76.8 kbps	500 kbps
Max Output Power	0 dBm	1.5 dBm	10 dBm	15 dBm	10 dBm
Operating Frequency	2.4 GHz	916.5 MHz	868/916 MHz	869 MHz	779-928 MHz
Min Operation Voltage	2.1 V	2.2 V	2.1 V	2.4 V	1.8 V
Tx Current (0dBm)	17.4 mA	N/A 12 mA @ 1.5 dBm	16.5 mA	N/A 33 mA @ 5 dBm	16.8 mA
Storage	ST M25P80	AT45DB041B	AT45DB041B	AT45DB041B	NAND512R3A2BZA6E
Capacity	8 Mb	4 Mb	4 Mb	4 Mb	512 Mb
Interface	SPI	SPI	SPI	SPI	Parallel
Minimum Voltage	2.7 V	2.7 V	2.7 V	2.7 V	1.8 V
Sleep current	1 μA	2 μA	2 μA	2 μA	0.5 μA

in lower and more acceptable energy consumption. The Mica2 mote improves on previous platforms by incorporating a different radio: Chipcon's CC2420, a 2.4GHz IEEE 802.15.4 compliant transceiver capable of a maximum of 250 kbps, a data rate much higher than any previously available on a WSN platform.

Telos [3], a highly popular mote, was designed to further reduce consumption while providing USB connectivity, more storage, and better integration. It too utilizes the CC2420 , because of its advantages, but changes the Atmel microcontroller with TI's MSP430F1611. The latter microcontroller greatly enhances performance while helping reduce power consumption because of its 16-bit architecture and other attributes. The MSP430F1611 is capable of operating down to a voltage of 1.8 V, which results in better extraction of battery energy. The 8 Mb ST M25P80 flash memory in the platform doubles the amount provided by the Mica family, thereby providing better logging and data storage capability. The intergrated USB connectivity is one of the major improvements in Telos, as it makes programming of the mote simple and cost effective.

A similar platform to Telos is deployed in various places in Europe. TinyNode [5] utilizes the same MSP430F1611 microcontroller but includes the XE1205 transceiver from Semtech. This radio is characterized by a 15 dBm maximum output power, which can enable communications between motes that are more distant at a higher energy cost. As with the Mica family, the AT45DB041B Flash storage is also used by TinyNode.

III. THE UTMOST PLATFORM

Figure 1 shows the mote and Figure 2 shows the key blocks and their arrangement. All the components are placed on a 2 layer PCB with no components on the reverse, both done to reduce the cost of multiple layers. The USB connectivity provides JTAG debugging, Bootstrap Loader (BSL), and data

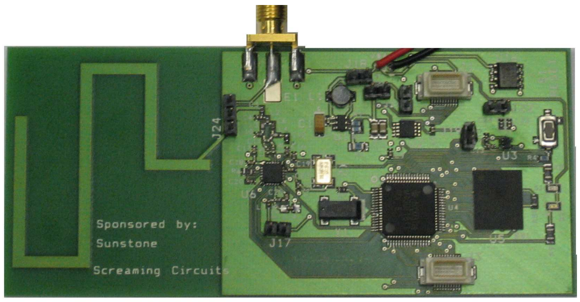

Fig. 1. UTMOST Wireless Senosr Node

transfer capabilities using the USB controller's two channels, and thus does not require any other hardware. Also, the USB programming circuitry is not a part of the UTMOST's main board and none of its components are included on the UTMOST. This reduction of components results in a lower cost of motes since one USB programmer/debugger can be used with with multiple motes. The energy consumed by components which prevent backward current flow into components and the battery from the voltage provided by the USB is also eliminated. Next, a detailed analysis of blocks which are part of the UTMOST's design are described.

A. Dynamic Voltage Booster

UTMOST relies on 2 Alkaline batteries to supply power. Such power source provides around 3.0 V, dropping down to a cut-off voltage of 1.8 V. Since this is in the voltage range of the MSP430F1611 and other low power microcontrollers, the need for a DC/DC down converter is partially eliminated. However, microcontrollers and other components used in WSNs are supply voltage dependent. The MSP430F1611 has several requirements that can be seen in table I. Specifically, its maximum suggested operating frequency [6] is dependant on

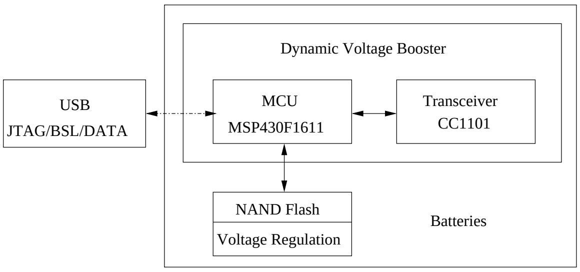

Fig. 2. Block Diagram of UTMOST

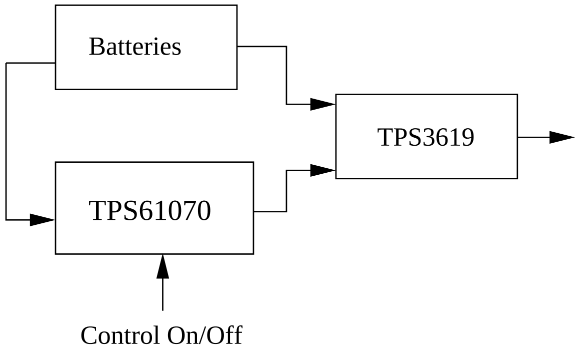

Fig. 3. Dynamic Voltage Booster

the value of the supply voltage, as defined by the following relationship:

$$F_{SYS} = 2.139 V_{SYS} + 0.3 \quad (1)$$

where F_{SYS} and V_{SYS} are the operating frequency measured in MHz and supply voltage measured in Volts, respectively. A system powering the MSP430F1611 using two alkaline batteries is therefore capable of operating at 6.7 MHz in the best case, i.e., when the batteries are fresh. The maximum suggested operating frequency is lowered as the batteries wear out. In order to avoid the problem of changing operating frequency, some platforms fix the operating frequency to the one corresponding to the minimum operating supply voltage, i.e., 4.15 MHz, corresponding to a supply voltage of 1.8 V. Processing capability is thus lowered and latency increased.

Another issue is that flash reprogramming requires 2.7 V on the MSP430F1611. Thus, the decline in the supply voltage will ultimately prevent the microcontroller from being reprogrammed, which can be critical in WSNs that are field deployed[1].

UTMOST's design provides a solution to both of these problems with its Dynamic Voltage Booster (DVB), as shown in Figure 3. This DC/DC booster uses TI's TPS61070 to convert the battery voltage to 3.6 V, allowing the system to operate at the maximum frequency and reprogram the flash even when the batteries are not fresh. The TPS3619 Battery-Backup Supervisor enables switching between the battery and the booster. The system can therefore select the power source and save energy when the higher voltage is not necessary. In such a case, the TPS61070 is shut down and consumes typically only 50 nA [8] and operates at around 85% efficiency. When the TPS3619 is in battery supply mode, i.e., the TPS61070 is not boosting the voltage, it only consumes 100 nA [9]. Thus, the total additional power consumption introduced by the voltage booster in sleep mode is in the order of 150 nA, which can be neglected. The performance of the DVB while operating is addressed in the experimental results section.

[1]Although the next generation MSP4302XXX microcontrollers lower the required programming NAND flash voltage to 2.2 V, this value is still higher than the minimum voltage supplied by Alkaline batteries, and the frequency voltage dependency still exists [7]

B. NAND Flash

The benefits of using Parallel NAND flash memory instead of Serial and non NAND based flash memory are studied in [10]. The authors demonstrate that the use of a parallel NAND flash device results in a lower energy per byte consumption compared to NOR Flash or SD cards used in the past, although it means a higher I/O use. UTMOST uses the ST NAND512R3A2BZA6E Parallel NAND flash [11], which provides 512 Mb of storage capacity and requires a supply voltage of 1.8 V. This amount of available memory enables more demanding applications not previously possible, e.g., voice transmision, which may require a larger amount of storage at the node. The NAND flash IC selected is unique in that it operates at 1.8 V, compared to 2.7 V or 3.3 V required by other devices, which permits data storage during all of the node's lifetime in which the voltage decays. The 1.8 V is provided using a low dropout (LDO) regulator that is controlled by an external MOSFET switch, This guarantees low current consumption during sleep mode. The sleep mode of the NAND flash is typically 10 μA [11]. Since NAND flash retains data even while not being powered, power can be disconnected by the MOSFET switch and the current can be reduced further. The IC is provided in a very fine ball grid array (VFBGA) package, which reduces size, although this type of package presents a challenge to the PCB design because of the fine pitch. To avoid the use of a four layer PCB which is normally used to lower the cost, the signals were routed using Non Connect (NC) pins, which are unused by the IC.

C. Transceiver

The transceiver adopted by the UTMOST platform is the CC1101 manufactured by Texas Instruments. This is an upgraded version of the CC1100 transceiver which improves spourious response and allows operation in an extended frequency range. It is still pin to pin and software compatible with the CC1100 [12]. It requires 1.8V to operate and therefore can take full advantage of the alkaline batteries. The CC1101 is capable of transmission rates up to 500 kbps, which allows applications that need to transmit a large amount of data in an efficient way. It is also capable of Frequency Hopping Spread Spectrum (FHSS), which can be used to reduce interference and add a measure of security. According to [13], sensor networks are vulnerable to the interference from the future IEEE 802.11n high-data rate WLAN deployments and current IEEE 802.11g networks. An energy constrained wireless sensor node that encounters such interference can not be expected to last, and the use of a different frequency band helps combat these problems. For this reason, the UTMOST tranceiver is configured to operate in the 779-928 MHz range, enabling great flexibility in frequency selection and helping avoid interference from these networks. The DVB system can also be cascaded with the CC1101 to provide the 3.6 V it can use to provide the maximum output power, which is affected somewhat with the transceiver's supply voltage. Therefore, it is possible to realize communication links between distant nodes during times when communications are affected, i.e, an essential routing node has stopped functioning. The UTMOST incorporates both a PCB Antenna and an SMA connector, selectable via a jumper to enable a lower cost alternative. The SMA connector holds on the board's edge and is therefore more rugged than other designs, which depend only on the strength of the solder paste's bonding.

IV. Performance Evaluation

Table II compares the results obtained for UTMOST compared to other motes. The operating current when the MSP430F1611 is put in the LPM3 sleep mode, the lowest capable of being interrupted by internal 32 kHz clock, is 37% less for UTMOST compared to the others. This enables a lifetime longer than 4 years at 1% duty cycle. A longer lifetime can be achieved by leveraging the NAND Flash and its lower energy needs, shown in rows 8 and 9. It is important to note that although the current for the NAND512R3A is higher than the others, it operates with a parallel interface that provides faster data transfer that reduces the time and therefore the energy consumption while operating. The transceiver wakeup time for UTMOST, shown in row 11, is also significantly lower than it counterparts, allowing a quick return to the sleep state to conserve energy. The characteristics of the DVB are also presented in the table. It can operate from as little as 0.9 V, and it uses 0.15 mA when providing the MSP430 with 3.6 V.

A. LED Consumption

The issue of LEDs in wireless sensor nodes has received no attention in the design of motes. Although they provide little benefit during deployment and are used mainly for testing and debugging, LEDs have a profound effect on the energy consumption of low power systems, as shown by our measurements in Table II. The LEDs sensitivity to light results in the variation of the terminal resistance when they are exposed to it, which allows more current to flow. LEDs are usually connected in a configuration as to make the microcontroller the current sink rather than the source. This is a result of a limitation on the maximum current output of all the I/Os together. Although this current is negligible in most systems, it is significant for wireless sensor nodes, especially when they are in the sleep mode, arguably the period in which they spend most of their time. The UTMOST platform includes a jumper that allows the disconnection of the voltage from the LEDs, therefore completely eliminating the problem during deployment. Since this requires the jumper to be manually disconnected before deployment, a MOSFET or other type of switch could be used to automatically disconnect the LEDs. This step was not undertaken in the current design because of the increased cost of another IC and the extra I/O pin required from the microcontroller, which are both scarce commodities.

V. Summary

UTMOST is a low power WSN, which leverages a dynamic voltage booster to offer improved performance over previously designed WSNs. The dynamic voltage booster enables UTMOST to operate at 3.6V even when the Alkaline battery suppllied voltage is lower than that. By being dynamic, the voltage booster overcomes the unacceptable power consumption penalties observed in earlier WSN designs [3]. Thanks to the dynamic voltage booster, the UTMOST microcontroller can operate at the maximum frequency for an extended amount of time and over an extended range of voltages supplied by the batteries. In addition, wireless reprogramming can be performed even after a substantial battery voltage drop has occurred. In practical terms, the reprogramming lifetime of the WSN is significantly extended. The DVB's functionality can also be extended to support energy harvesting methods such as solar panels, eliminating the need to use another DC-DC converter. It can also provide power source switching between any two input sources. Another feature of UTMOST is its combined transmission data rate (up to 500 kbps) and transmission frequency range (from 779 to 928 MHz). Both the offered frequency diversity and data rate may facilitate the support of bandwdith demanding applications, e.g., voice over WSNs [1]. One last advantage of UTMOST is its improved 512 Mb storage capacity, which may enable special applications, e.g., data MULEs [2].

Acknowledgments

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TABLE II
COMPARISON OF WIRELSS SENSOR NODE PLATFORMS

Parameter	Platform				
	UTMOST	Telos	TinyNode	Mica2	EyesIFX
MCU Sleep + Real Time Clock	3.2 μA	5.1 μA	5.1 μA	19.0 μA	5.1 μA
MCU Idle + DCO	49.9 μA	54.5 μA	N/A	3.2 mA	N/A
MCU Active	1.8 mA	1.8 mA	1.8 mA	8 mA	1.8 mA
MCU + Radio TX	18.2 mA	19.5mA	25 mA	25.4 mA	13.7 mA
MCU + Radio RX	17.4 mA	21.8 mA	15.8 mA	15.1 mA	10.8 mA
MCU + Flash Read	9 mA	4.1 mA	5 mA	9.4mA	5 mA
MCU + Flash Write	9 mA	15.1 mA	16 mA	21.6 mA	16 mA
MCU Wakeup Time	6 μs	6 μs	6 μs	180 μs	6 μs
Radio Wakeup Time	150 μs	580 μs	1500 μs	1800 μs	2200 μs
Min. Flash Storage Voltage	1.8 V	2.7 V	2.4 V	2.7 V	2.7 V
Min. Transceiver Voltage	1.8 V	2.1 V	2.4 V	2.1 V	2.1 V
Dynamic Voltage Booster					
Min. Operation Voltage	0.9 V				
Output Voltage	3.6 V				
Shutdown Current	0.15μA				
Operating current(MCU Active)	0.15 mA				

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