suisMOTE A novel Ultra Low Power ARM based sensor for IEEE 802.15.4 Wireless Sensor Networks

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***Abstract*—The improvement of low power microcontrollers, sensors and RF transceivers gives the possibility to implement compact and low cost solutions for a wide range of applications.**

This paper proposes a new ultra low power ARM-based sensor (suisMOTE) for Wireless Sensor Networks (WSNs).

An IEEE 802.15.4 transceiver Integrated Circuit (IC) provides the wireless connectivity, additionally a USB interface is also implemented to communicate the system with a computer.

Moreover, since the platform is designed for low power applications it incorporates adaptive power modes in the microcontroller's peripherals and low power states in the radio to save energy. The management of these peripherals and radio was implemented to handle different energy saving levels (including shut-down).

The results of the experimental measurements show the impact of the use of the power modes on the power consumption.

Keywords. *WSN mote, IEEE 802.15.4, Low Power, PCB prototyping, ARM Cortex-M3*

I. Introduction

The emerging technologies require more computing power to allow the collection and computation of data from various sensors.

Wireless sensor networks consist of small and low cost platforms which are being more and more embedded in the environment. This WSNs nodes provide an autonomy which can go from some Months to many Years. In most of the cases the nodes are supplied only with a small coin cell battery, forcing the applications to be energy management oriented.

In this paper we introduce suisMOTE a novel wireless sensor node designed to be low power, small size, focused in data storage. suisMOTE provides an expansion slot that allows the connection of external sensors and make available the peripherals of the microcontroller.

The use of the most recent hardware technology guarantees a low power design. In addition to the hardware used, a good energy management firmware design makes suisMOTE a reliable low power wireless node.

II. Popular WSN motes

The market offers lots of wireless sensors nodes based on Berkeley designs. The most commons are clones of Telos and Mica2 motes[1]. These motes are using ATmega128 or MSP430 microcontrollers. The power is supplied from two AA batteries which define the size of the board. There are also reduced size versions.

When Telos was released MSP430 processor was the most efficient microcontroller at the time[2], nowadays we can find emerging rivals using different processor architectures and silicon technologies.

It is also common that custom nodes are designed for dedicated applications where the specifications ask for more and more smaller sizes, less consumption, and cheaper solutions.

III. Hardware design

The need of portable devices push the design to the use of low power consumption processors. While traditional processor architecture manufacturers are introducing in the market low power versions of their processors like eXtreme Low Power PIC from Microchip, MSP430 from Texas Instruments, and picoPower from ATMEL, ARM processors are becoming more and more popular in the industry due to its scalability and acceptance of developers.

ARM-Cortex-M3 and ARM-Cortex-M4 cores have shown a good trade-off between power consumption and performance. This explains why these processor's architecture are being widely integrated alongside with peripherals in embedded microcontrollers. The Harvard bus architecture and the ARMv7 Architecture with the Thumbs-2 instruction set, makes the Cortex-Mx family the most suited for new portable embedded designs.

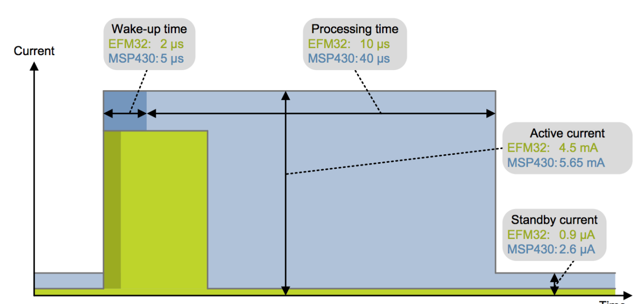

Fig. 1. EnergyMicro ARM processors, reduced Processing Time(Courtesy of Silicon Labs)

TABLE I. TELOS, MICA2, AND SUISMOTE COMPARISON

Microcontroller	ATmega128	TI MSP430	EFM32GG840F1024
Platform	Mica 2	Telos	suisMOTE
Program memory (KB)	128	48	1024
RAM (KB)	4	10	128
Active Power (mW)	33	3	1.6
Sleep Power (uW)	75	15	1.2
Wakeup Time (us)	180	6	2

While Texas Instruments is claiming that the MSP microcontroller families are the lowest power consumption processors[3] available in the market, EFM32 ARM processors manufactured by Silicon Labs (previously EnergyMicro) demonstrate that EFM32 processors are more energy efficient [4], this is illustrated in Figure 1.

Among all the available EFM32 ARM-Cortex-M3 microcontrollers; Gecko, Leopard, and Giant, the Giant family is the most appropriate choice for our application. The reason is because this microcontroller is a trade-off between cost and features offered like flash memory of 1024Kb, RAM of 128Kb and dedicated low power peripherals. Figure 2 illustrates the block diagram of EFM32GG980F1024.

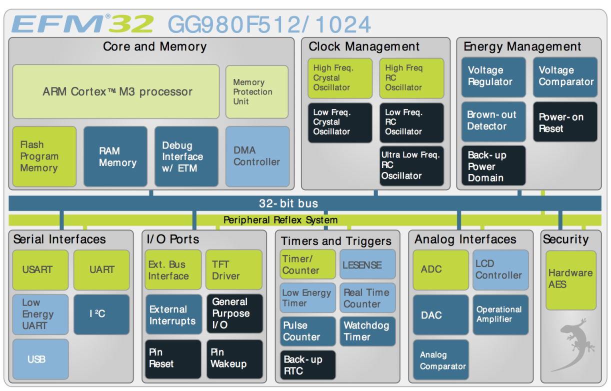

Fig. 2. EFM32GG980F1024 block diagram (Courtesy of Silicon Labs)

Table I depicts the comparison between the processors used in Telos, Mica2 and suisMOTE. As we can see the EFM32GG is less power hungry.

The radio selected for the IEEE 802.15.4 communication is the Texas Instruments (TI) CC2520 radio module. The CC2520 is TI's second generation ZigBee / IEEE 802.15.4 RF transceiver for the 2.4GHz unlicensed ISM band with encryption capabilities. This version of the radio overcomes power consumption issues encountered in the previous radio ICs tested at SUPSI's lab.

The microcontroller communicates with CC2520 radio through an SPI interface and GPIOs. The microcontroller will send instructions to CC2520 and it is the responsibility of the instruction decoder to execute the instructions or pass them on to other modules[5].

Below is shown a list of some transceiver features[5]:

- DSSS transceiver (2394-2507MHz)
- 250kbps data rate, 2 MChip/s chip rate
- O-QPSK with half sine pulse shaping modulation
- RX (receiving frame, -50 dBm): 18.5 mA RX (waiting for frame): 22.3 mA
- TX (+5 dBm output power): 33.6 mA
- TX (0 dBm output power): 25.8 mA
- Three flexible power modes for reduced power consumption
- Sensitivity (-98dBm)
- High adjacent channel rejection (49 dB)
- High alternate channel rejection (54 dB)
- On chip VCO, LNA, PA and filters.
- Low supply voltage (1.8 - 3.8 V)
- Programmable output power up to +5 dBm
- I/Q direct conversion transceiver

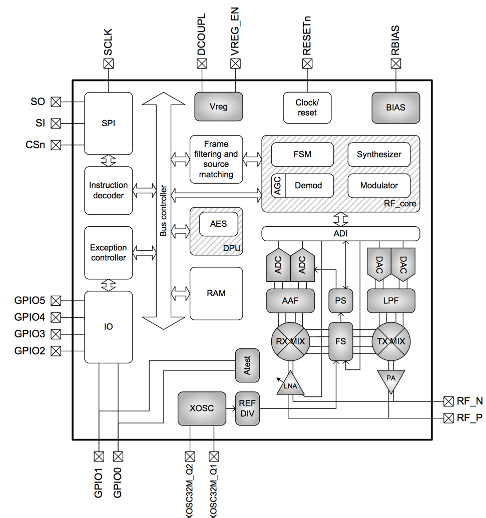

Fig. 3. CC2520 Block Diagram (Courtesy of TI)

The CC2520 radio also includes IEEE 802.15.4 MAC Hardware Support for a better and low power design.

- Automatic preamble generator
- Synchronisation word insertion and detection
- CRC-16 computation and verification over the MAC payload
- Frame filtering
- Automatic ACK and setting of the pending-bit
- Clear Channel Assessment (CCA)
- Energy detection / RSSI
- Link Quality Indication (LQI)
- Fully automatic MAC security (CTR, CBC-MAC, CCM)

A. *suisMOTE features*

suiMOTE includes the following hardware blocks:

- ARM Cortex-M3 EFM32GG980F1024 microcontroller
- CC2520 IEEE 802.15.4/ZigBee radio
- L3G4200D gyroscope
- LIS3DH 3-axis accelerometer
- LTC3559 Battery charger
- Micro SD card slot
- Micro USB connector
- FT2232 Serial to USB converter
- Expansion connectors

- External 48MHz XTAL
- External 32.768 kHz XTAL
- Coin cell battery holder

Although all the peripherals are included not all of them are used due to the power consumption. For example is the case of the gyroscope included for test pourposes only. Same case with the FTDI232R that is used for debugging issues.

Figure 3 illustrates a simplified diagram of the involved components and peripherals used for suisMOTE.

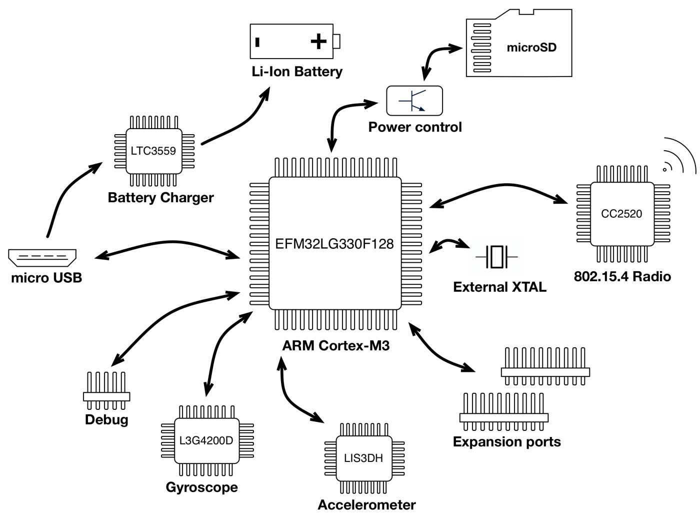

Fig. 4. suisMOTE elements

Due to the fact that the microSD card has a high constant nominal power consumption as shown in Table II, a HW power management circuit was added. It allows to turn on/off the SD's power supply to reduce significantly the power consumption of the whole system.

Because of the need to incorporate a real time clock and USB capabilities, suisMOTE includes two external oscillators, 32.678KHz and 48MHz XTALs.

B. PCB DESIGN

suisMOTE is a six layer PCB assembled on both sides designed using Altium designer CAD tool. The components used are SMD and have reduced size, e.g. ICs with small packages (QFN) or resistors with dimensions of 1 x 0.5 mm (0402).

The dimension of the board is 29x69mm, 1mm height and has a special shape designed to fit in the *Bopla BOS-Streamline* plastic box. The radio antenna of the CC2520 is a standard Small Size PCB printed antenna [6]. The overall cost of the PCB is around 2.4 Euro in smaller quantities (up to 50pcs). The designed hardware is illustrated in Figure 5

The microcontroller has three SPI peripherals, one of them is dedicated to the microSD card, the other two are used for the 3-axis accelerometer and gyroscope. If external SPI devices are needed a re-configurable resistor array layout allows to switch between internal to external sensors, this has to be done during the assembling phase of the board.

Fig. 5. suisMOTE module manufactured

IV. Firmware design and custom API

Silicon Labs provide free tools like the *Simplicity Studio* suite that simplify firmware development. This suite includes a code generator to configure the peripherals and also some C-code examples. The compiler used for the EFM32GG980F1024 ARM Cortex-M3 microcontroller is *IAR-Embedded Workbench*, a professional licensed tool. Other compilers like Atollic, Keil, crossworks are also available. The programming of suisMOTE is done using the J-Link interface included in every EFM32 evaluation kit. This allows also to debug the firmware.

A dedicated library was written for suisMOTE as well as a custom API to use dedicated peripherals of the microcontroller. Even though a standard API is available for the microcontroller we need more flexibility when using peripherals. To provide more flexibility some functions of the existent API were modified and included in the custom API.

TI provides CC2520 libraries only for MSP430 processors. Since an ARM processor was used the porting and implementation of new functions were done to exploit all the advantageous features of the CC2520 radio.

The custom API developed for this application implements the MAC for the IEEE802.15.4 radio. To maximise power savings it is possible to configure the radio in two different wake-up system modes:

- wake-up the system when packets are received
- wake-up the system when a specific defined packet is received

Moreover the API implements the control of the following peripherals: USART, UART, LEUART (low energy peripheral), SPI, external Interrupts, GPIO, LEDs, SD card enabler, File system for SD card storage, USB as Virtual COM Port.

The following is an example of the custom functions used when the microcontroller is initialised.

Listing 1. suisMOTE initialization functions

```
init_pinout();
init_leds();
init_spi();
init_fileSysFAT32();
init_microSD();
init_radio();
init_irqHandler();
init_accelerometer();
init_gyroscope();
```

TABLE II. POWER CONSUMPTION OF MAIN COMPONENTS

			Power consumption								
Manufacturer	**Part Number**	**Description**	**TX**	**RX**	**Active**	**IDLE**	**Sleep**	**Deep Sleep**	**Power Off (RTC)**	**Power Off**	
			-	-	*32 MHz*	-	*1 MHz*	*32.768 kHz*	*32.768 kHz*		
Silicon Lab	EFM32GG980F1024		-	-	6.4	-	0.05	0.0011	0.0009	0.00002	mA
			-	-	21.12	-	0.165	0.00363	0.00297	0.000066	mW
ST	L3G4200D	Gyroscope	-	-	6.1	-	1.5	-	-	0.005	mA
			-	-	20.13	-	4.95	-	-	0.0165	mW
ST	LIS3DH	Acceloremter	-	-	0.11	-	0.06	-	-	0.0005	mA
			-	-	0.363	-	0.198	-	-	0.00165	mW
Texas Instruments	CC2520		25.8	18.5	1.6	0.2	0.005	-	-	0	mA
			85.14	61.05	5.28	0.66	0.0165	-	-	0	mW
Linear Technologies	LTC3559	Bat. charger	-	-	0.0035	-	-	-	-	-	mA
			-	-	0.01155	-	-	-	-	-	mW
ATP Electronics	AF1GUDI-OEM	microSD Card	-	-	50	0.2	-	-	-	0	mA
			-	-	165	0.66	-	-	-	0	mW

As part of the API are the functions that control the USB peripheral as a Virtual COM Port (VCP). This functions allow the user to modify defined parameters of the EFM32 microcontroller and CC2520 radio. Some of these parameters that can be modified are the sleep-time of the microcontroller, create, read and write files in the microSD card, the Tx power, the radio channel, the IEEE802.15.4 frame's PAN, destination address, source address and payload size.

One of the features that guarantee a low power design is the use of the Clock Management Unit (CMU). The CMU allows, at run time, to configure the clock prescaler and change between clock sources. It is also possible to use different clock sources for different peripherals. The appropriate use of the right clock source and frequency allow the designer to reduce the energy consumption.

The filesystem allows to use standard linux commands to access the files in the SD card. An example of these commands are *cat, ls, mkdir*, etc.

V. SAVING ENERGY USING ENERGY PROFILES

EFM32 microcontrollers provide up to five Energy Modes (EM0-EM4). With this EMs is possible to manage the activity levels of the microcontroller. For example we can keep the configuration of some peripheral registers, or we can enter in a deep sleep state but losing register configuration. All of the EMs are well described in [7].

On the radio side there are three energy modes. The first one, illustrated in Figure 6 part (a), the radio will be turned off after transmission(Tx)/reception(Rx), when waking up all the radio registers need to be re-configured. In the second case, illustrated in Figure 6 part (b), the radio will enter into a sleep mode after every Tx/Rx, when waking up, some registers need to be re-configured. The last case, illustrated in Figure 6 part (c) illustrates the radio in IDLE mode, the registers doesn't need to be re-configured at the expense of a higher energy consumption.

Depending on the number of packets transmitted per second, one of the energy modes previously described could be the most suited solution.

Analysing our use cases with reference to Figure 6 we can define the following relations:

$$\begin{aligned} AvgPower = (TxRx_{energy} + Init_{energy}) \cdot Packet_{freq} \\ + [PowerOff, SleepMode, IDLEMode]_{power} \\ \cdot (1 - \delta) \end{aligned} \tag{1}$$

$$\delta = \frac{t_{TxRx_{energy}} + t_{Init_{energy}}}{T} \tag{2}$$

where T is the period between two transmissions, $\frac{1}{f}$.

Based on Equation 1 and the values from Table II, we can calculate P1, P2 and P3 which represent the Average Power Consumption of our system.

$$P1 = (2.12mJ + 79.2\mu\ J) \cdot f \tag{3}$$

$$P2 = (2.12mJ + 21.12\mu\ J) \cdot f + 16.5\mu\ W \cdot (1 - 29ms \cdot f) \tag{4}$$

$$P3 = (2.12mJ \cdot f + 660\mu\ W \cdot (1 - 25ms \cdot f) \tag{5}$$

Equations 3, 4, 5 are represented in Figure 7. We can conclude that the best working mode for the radio depends on the transmitted/received packet ratio. Up to $f1 = 0.3\frac{Packets}{sec}$ Power-Off mode will be the best choice, between $f1 = 0.3\frac{Packets}{sec}$ and $f2 = 16\frac{Packets}{sec}$ Sleep Mode, and finally over $f2 = 16\frac{Packets}{sec}$ IDLE mode is the most appropriate mode.

We have also defined four states and three components that have impact in the power consumption. Table III describes the involved elements and states to reduce the power consumption of suisMOTE.

TABLE III. ENERGY MODE STATES AND INVOLVED COMPONENTS

State	**MCU**	**Radio**	**SD Card**
Communication	Active	Active	Power Off
Data elaboration	Active	Power Off	Power Off
Idle	Deep Sleep	Power Off	Power Off
Storage	Active	Power Off	Active

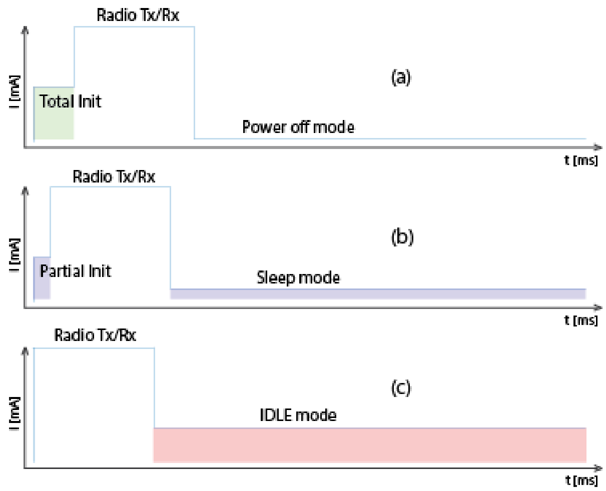

Fig. 6. Radio consumption modes

VI. Software design for a Host computer

The suisMOTE USB interface is used to download the acquired data. The data transfer is done using a Linux-PC. The USB connection is used as a virtual COM port, this choice makes an easier communication with any other embedded device without the needed of dedicated USB drives.

A program to download the data and configure suisMOTE was developed. When suisMOTE is connected to any OS (Linux, MAC OS, Windows) is recognised as a COM port. It is also possible to use a terminal like minicom, Coolterm or Hypertéminal to access to the node.

A dedicated Communication Instruction Set was also defined in the firmware. The API allows the user to mount/unmount the microSD card, download the stored data in the microSD card, configure the node's parameters, restore to the default state, erase files in the microSD, create configuration files, and keep track of the time with a resolution up to 30.5us for real time applications.

Below is listed part of the code of the CIS defined in the Host side (linux, MAC OS, Windows) to comunicate to suisMOTE:

Listing 2. Communication Instruction Set
```
const char SD_MOUNT[]   = "SD_MOUNT";
const char SD_SDREF[]   = "SD_CARD_ cat sdref ";
const char SD_SDEOR[]   = "SD_CARD_ cat eor ";
const char SD_SDLFR[]   = "SD_CARD_ cat lfr ";
const char SD_ENDOR[]   = "SD_ENDOR";
const char SD_LAFIR[]   = "SD_LAFIR";
const char sM_TIMST[]   = "sM_TIMST";
```

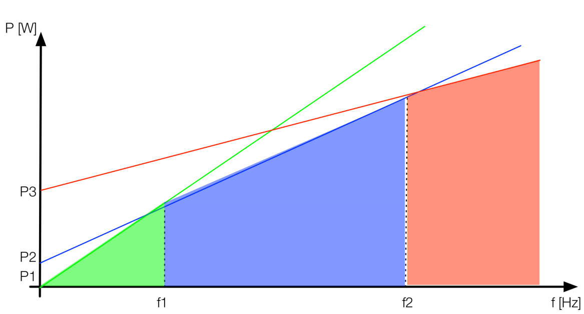

Fig. 7. Average Power Consumption

Keywords (SD_MOUNT, SD_CARD, etc.) were used to identify the action that suisMOTE has to execute.

VII. Test results

To test the performance of the HW and FW implementation we ran the use cases exposed in Figure 7. For the experiments we use a *Li-Ion ICP582930PR-01* battery from Renata.

The measures obtained and illustrated in Figure 8 confirm the result values from equations 3, 4, 5. Figure 8 correspond to the case (a) from Figure 6.

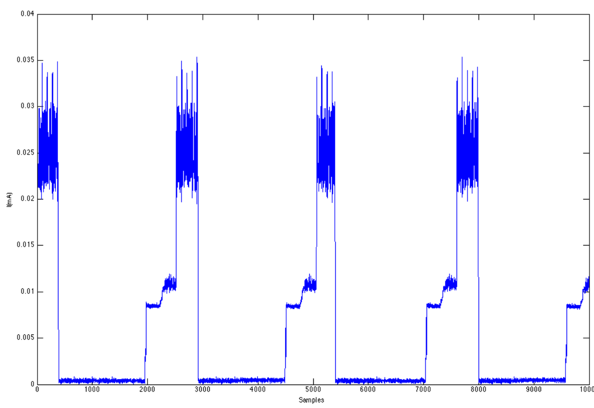

Fig. 8. Measured values corresponding to case (a)

Similar results are applicable to the other two cases (b,c).

VIII. Conclusion and future work

suisMOTE is a hardware that is suitable for very low power applications. With the adopted HW and FW strategies explained in this paper we could take advantage of the microcontroller's Energy Modes all together with the power saving modes of the radio.

The proposed HW can be a good solution for Body Area Network implementations and Wireless Sensor Networks applications that need big storage capabilities due to the integration of an SD card and USB communication for fast data transfer.

As future works, suisMOTE can evolve to higher level protocols like ZigBee, and also include an operating systems like Tiny OS or Contiki as potential options.

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His research is mainly concentrated in Home Automation technologies, trends for Home area Networks, Smart Grids, and health care technologies for impaired people.

Armando Rivero Was born in La Paz - Bolivia in 1985. In 2010 he received the B.Sc degree in Electronics Engineering with a minor in Control Systems and Telecommunications awarded with the highest honours from the Universidad Mayor de San Andres - Bolivia. He gave also the graduation commencement speech of his generation. He received the MAS Master of Advanced Studies Degree in Embedded Systems Design in 2014 from the University of Lugano (USI).

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