meto[1] - A Versatile and Modular 32 bit Low-power Sensor Node Prototyping Platform for the IoT

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Abstract

This paper introduces the *meto*[1] sensor node, a versatile low-power computing platform for prototyping in the Internet of Things (IoT). Based on the MSP432 microcontroller from Texas Instruments (TI), featuring a 32 bit ARM Cortex-M4F core, this mote combines energy efficiency and processing power for real-time computations and signal processing. An onboard, IEEE 802.15.4g-compliant, sub-1 GHz radio transceiver and various serial communication interfaces ensure both accessibility to wireless networks and expandability and customizability at the same time. The mote features a flexible power supply system, supporting input voltage ranges from 1.8 V to 3.6 V and 4.3 V to 38 V. Still, a generic and compact design (80 mm × 80 mm) was achieved, making the *meto*[1] a modular and reconfigurable prototyping platform for a wide area of applications in Wireless Sensor Networks (WSN), Cyber Physical Systems (CPS), and the IoT.

Categories and Subject Descriptors

B.0 [**Hardware**]: General; C.3 [**Computer Systems Organization**]: Special-Purpose and Applicatuion-Based Systems—*Real-time and embedded systems*

General Terms

Design

Keywords

32 bit microcontroller, internet of things, low-power, modular sensor node, prototyping platform

1 Introduction

Existing sensor node designs are still based on either 8 bit or 16 bit microcontroller architectures [11]. 32 bit architectures are hardly used, with few exceptions, like the aceMote [14]. However, superior performance does not inevitably mean higher power consumption. In fact, [14] showed a better performance-to-power ratio for a 32 bit microcontroller compared to 8 bit and 16 bit designs, and encourages their use in low-power designs.

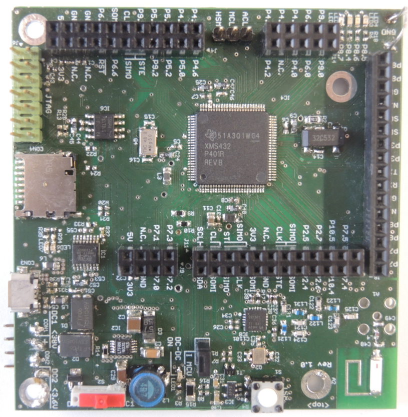

Figure 1. The *meto*[1] sensor node platform with a compact PCB size of 80 mm × 80 mm.

A survey on motes used in Wireless Sensor Networks [11] states that most of the available platforms are not developed for specific applications, but for general use. However, essential hardware features for efficient prototyping, for example supply current monitoring, are not implemented. Moreover, their expandability is often limited by hardware and layout restrictions, for example missing extension ports.

We propose a more generic design as potential improvement. The combination of a 32 bit microcontroller unit (MCU) and low-power components results in a next generation mote, the *meto*[1], as shown in Figure 1.

This platform is an advancement of the SNoW[5] sensor node [7], used in various projects [8]. Hands-on experience gathered with this mote influenced the design choices made for the *meto*[1] platform. Features that proved successful were borrowed and re-designed with up-to-date hardware, features that were lacking were added. The most significant update is the transition from a 16 bit to a 32 bit microcontroller architecture, also resulting in the first general purpose sensor node featuring the MSP432 microcontroller from TI.

Chapter 2 compares today's most popular low-power mote architectures with the *meto*[1] platform. Its hardware components and features are described in Chapter 3. Chapter 4 concludes the paper.

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Table 1. Overview of today's most common sensor node architectures and their hardware components.

Sensor Node	**SNoW**^{5} [7]	**Telos** [12]	**BTnode** [3]	**aceMote** [14]	***meto***^{1}
Developer	Univ. of Wuerzburg	UC Berkeley	ETH Zuerich	TU IASI	TU GRAZ
Year	2005	2005	2006	2014	2016
MCU	MSP430F1611		ATmega 128L	EFM32TG222	MSP432P401R
Architecture (bit)	16		8	32, Cortex-M3	32, Cortex-M4
Clock Frequency (MHz)	8		8	32	48
ROM / RAM (kByte)	48 / 10		128 / 4	32 / 4	256 / 64
Active Current (μA/MHz)	500		1500	157	95
Sleep Current (μA)	2.6		12	1	0.85
Wake-up Time (μs)	6		180	2	7.5
Radio Transceiver	CC1100	CC2420	CC1000	MRF24J40	CC1101
Data Rate (kbits/s)	500	250	500	250	600
Base Frequency (MHz)	315 – 915	2400	315 – 915	2400	315 – 915
Rx Current (mA)	14.4	18.8	9.6	19	14.6
Tx Current (mA)	16.9	17.4	16.5	17.4	17.2
Sleep Current (μA)	0.9	0.02	0.2	2	0.5
On-Board Memory	AT45DB161B	ST M25P80	62S2048U	25AA256	AT45DB161E
Type	Flash	Flash	SRAM	EEPROM	Flash
Size (kByte)	2048	1024	240	32	2048
additional SD Card	no	no	no	no	yes
Power Consumption					
Minimum Operation (V)	1.8	1.8	0.5	0.65	1.8
Total Active Power (mW)	-	-	102.3	-	137.94

2 Related Work

Today, the most commonly used sensor node platforms are the Telos [12] and the BTnode [3]. Table 1 summarizes their hardware components in comparison with the SNoW^5, the aceMote, and the *meto*^{1}. Obviously, TI's 16 bit MSP430 and Atmel's 8 bit ATmega 128 MCU series are still mostly used for low-power embedded applications. However, compared to the 32 bit MSP432, those architectures lack processing power, energy efficiency, and on-chip memory.

For wireless communication, the industrial, scientific and medical (ISM) frequency band is used, ranging between 300 MHz and 2.5 GHz. However, propagation characteristics below 1 GHz are better than at 2.4 GHz, resulting in higher range and power efficiency [2], especially in vehicular networks [5] and in the context of factory automation with significant interference. Being able to communicate with SNoW^5 and BTnode nodes was another decisive reason for choosing a compatible sub-1 GHz radio transceiver.

3 The *meto*^{1} Hardware and Features

Figure 2 provides an overview of the hardware components and features of the *meto*^{1} sensor node. The original printed circuit board (PCB) has a compact size of 80 mm × 80 mm, but can be reduced in size by removing certain features (see Table 2) in application-specific designs. Therefore, all onboard features are grouped into individual building blocks, and their components were chosen in order to minimize power consumption while maximizing flexibility.

3.1 Microcontroller Unit

The *meto*^{1} platform is based on the TI MSP432P401R MCU [17] [18]. The core, a 32 bit Cortex-M4F, provides sufficient computing power for advanced real-time sensor data fusion and processing. It is supported by an integrated single-precision floating-point unit (FPU), featuring a digital signal processing (DSP) engine, that is capable of single-cycle multiply and accumulate operations. The core has a maximum clock frequency of 48 MHz. A low-frequency (32.768 kHz) and a high-frequency (48 MHz), external crystal oscillator circuit are connected to the MCU for adjustable clock system management.

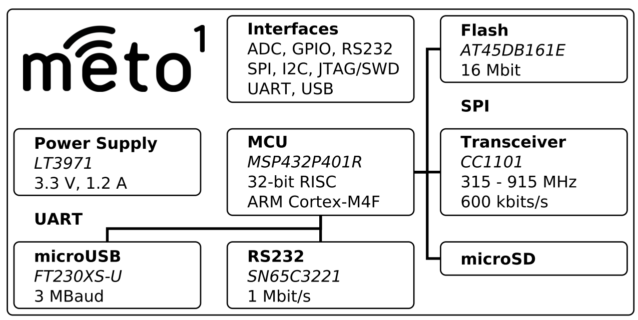

Figure 2. Block diagram of the *meto*^{1} sensor node.

The MCU provides five low-power modes (LPM) which cut down current consumption below 100 nA by disabling all peripherals, clock sources, and the internal voltage regulator. Both, a low-dropout regulator (LDO) and an inductor-based DC-to-DC buck switching regulator (DC-DC) are integrated into the chip. Based on wake-up time and energy consumption, developers can choose the regulation type to further optimize their applications. The current consumption in active mode is 95 μA/MHz using the DC-DC. Low duty cycle applications, for example metering of slowly varying parameters, are supported in LPM3. With a standby current as low as 850 nA, while the real-time clock (RTC) and the watch

Table 2. On-board components of the *meto*[1] platform and their electrical characteristics.

Component	Operating Voltage (V)	Active Current (mA)	Active Power @ 3.3 V (mW)	Sleep Current (µA)	Sleep Power @ 3.3 V (µW)
MSP432P401R [17]	1.62 - 3.7	4.6	15.18	0.85	2.8
CC1101 [16]	1.8 - 3.6	17.2	56.76	0.5	1.65
LT3971 [9]	4.3 - 38	-	-	2.8	9.24
AT45DB161E [1]	2.5 - 3.6	12	39.6	0.4	1.32
FT230XS-U [4]	2.97 - 5.5	8	26.4	125	412.5
SN65C3221 [15]	3 - 5.5	-	-	1	3.3
Total Consumption		41.8	137.94	130.55	430.81

dog timer (WDT) modules are active, long lasting battery life can be expected. Apart, a 14 bit successive approximation (SAR) analog-to-digital converter (ADC) is integrated for signal conditioning. Analog sensor data can be sampled simultaneously on 24 channels with up to 1 MSample/s.

The MSP432P401R offers 256 kBytes of flash main memory and 64 kBytes of static random-access memory (SRAM). In addition, a 16 MBit flash memory [1] was added to the sensor node as an alternative to the limited and valuable on-chip memory. Even larger amount of data can be stored on a microSD card. The numerous storage options assure sufficient memory space for sensor data logging and node specific data or software images, even between long transmission breaks and offline operation. Within the MCU, eight direct memory access (DMA) channels and the two bank flash memory allow simultaneous read and write operations optimizing memory operation and speed.

The MCU has eight Enhanced Universal Serial Communication Interface (eUSCI) modules integrated, providing SPI, I2C, UART and IrDA to the *meto*[1] extension headers. Data can be transmitted at a maximum data rate of 3 MBytes/s.

As the *meto*[1] platform is designed for WSN, CPS, and IoT prototyping, the transmission of sensitive data is very likely and can be protected by an on-chip cryptographic module, that supports the Advanced Encryption Standard (AES) in hardware with a key length of up to 256 bit. RAM and ROM memory is protected against unauthorized access by a memory protection unit (MPU).

3.2 Wired and Wireless Communication

To further increase the expandability of the *meto*[1] sensor node, additional communication interfaces are implemented. A bidirectional TTL/CMOS to RS232 voltage level translator [15] with a maximum data speed of 1 Mbit /s and an UART to USB converter [4] with a baud rate up to 3 MBauds can be found on-board. The USB connection accomplishes two core tasks simultaneously: power supply and communication with computers.

Wireless network connections can be established with the TI CC1101 radio transceiver [16]. The device is compliant with the ISM frequency band at 315 MHz, 433 MHz, 868 MHz and 915 MHz. The data rate is programmable from 0.6 up to 600 kbits/s. A wide range of of amplitude (ASK and OOK), frequency (2-FSK, 4-FSK and GFSK), and phase shift modulation (MSK) formats are supported. The transmission power is programmable up to 12 dBm, and sensitivity is as low as −116 dBm at 0.6 kBaud. The typical rx (receive) current consumption is 17.6 mA (500 kBauds) and the typical tx (transmit) current consumption is 30.7 mA at 10 dBm output power. The CC1101 is compliant with the IEEE 802.15.4g standard, thus protocols such as 6LoWPAN (IPv6 over low-power wireless area networks) [6] are supported, enabling the mode to participate in the IoT.

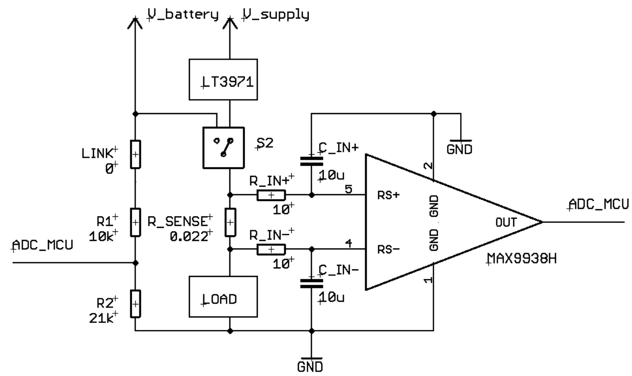

Figure 3. Automatic measurement system for supply current monitoring and battery voltage monitoring.

The on-board ceramic chip antenna is optimized for 868 MHz, but is easily adjustable for other frequencies. Alternatively, a 50 Ω SMC connector can be used to connect external antennas.

3.3 Power Supply

The flexible power supply system is designed to work at voltages from 1.8 V to 3.6 V and 4.3 V to 38 V. With the voltage regulator deactivated, and thus without power loss, a dedicated battery input (`V_battery`) is directly connected to the main power supply trace, supporting an input voltage range from 1.8 V to 3.6 V. According to Table 2, not all onboard devices support low-voltage operation. Both, the microUSB port's 5 V supply trace and the external voltage input (`V_supply`) are connected to the LT3971EMSE-3.3 [9], a DC-DC converter (0.8 MHz switching frequency), regulating the system-voltage level to 3.3 V. Input voltages from 4.3 V to 38 V are supported, making *meto*[1] also a suitable prototyping platform for automotive and power line applications. A maximum output current of 1.2 A is capable of delivering a maximum electric power of 3.96 W.

The resulting total current consumption of the sensor node in sleep mode is 130.55 µA, in active mode[1] 41.8 mA. Considering other motes with even less performance, both values are still comparably low. Assuming a work load of 20 %, the mote can be deployed for four years when powered by two standard AA Lithium-Iron batteries (6000 mA h).

[1] The MCU clock at 48 MHz, the transceiver in tx mode.

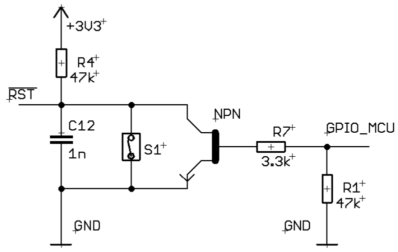

Figure 4. A reset of the *meto*[1] platform can be initiated by pressing button S1 or by the MCU controlled transistor.

3.4 Prototyping, Debugging, and Evaluation

Energy consumption is a crucial design issue for battery-powered portable devices. Thus, besides selecting low-power components for this sensor node, an automatic current measurement system for supply current monitoring was integrated as well (see Figure 3). The MAX9938H [10] amplifies the voltage drop across `R_SENSE`, a linear projection of the load current, which is then quantized by the MCU's ADC. The current demand of the whole platform, except for the voltage regulator, can then be calculated in software. Due to the monitoring of the battery input voltage with the MCU's ADC (see Figure 3), a conclusion can be drawn about the state of charge of the battery, as battery voltage levels decline while discharging [13].

For simplified programming and debugging, processor registers and memory contents are accessible through JTAG and a 2-pin Serial Wire Debug (SWD) port. Other debug options are the microUSB port and four MCU controlled LEDs, that provide visual feedback.

Figure 4 shows the dedicated reset circuit of the *meto*[1]. A reset can be initiated either physically, by pressing the on-board reset button (`S1`), or by software. Therefore, a transistor is connected to a digital output (`GPIO_MCU`) of the microcontroller, and supports a software controlled remote reset of the entire node and its components.

Extension headers are provided to stack daughter boards, that can be easily designed with an EAGLE template, in order to expand the mote's capabilities and to customize the platform for specific applications. Figure 5 gives an idea of the modular and reconfigurable design of the *meto*[1] platform. 18 ADC inputs and 52 general purpose digital I/Os (input/output) are available on the extension headers for sensor data acquisition and control. Data can also be exchanged with the extension boards via one RS232, four SPI, two I2C and three UART interfaces. An extension board could feature for example a CAN (Controller Area Network) controller with a SPI interface for integration into an automotive environment, or various sensors for monitoring environmental parameters.

4 Conclusion

This paper introduced the *meto*[1], the first general purpose sensor node based on TI's 32 bit MSP432 microcontroller. A generic design in combination with an automatic current monitoring system and low-power components provide a next generation prototyping platform for further research in WSN, CPS, and IoT applications. Furthermore the *meto*[1] is

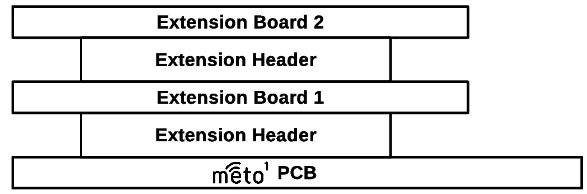

Figure 5. Modular and reconfigurable design of the *meto*[1] platform.

superior to existing mote architectures regarding processing power, on-board memory, energy efficiency, and flexibility. Apart, the mote's capabilities can be expanded with modules, that can be stacked onto each other. Therefore, the sensor node can be used in a wide area of application domains, for example vehicular networks, factory and home automation, smart production (Industry 4.0), or advanced robotics.

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