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A Distributed Computation Platform for Wireless Embedded Sensing

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Abstract

We present a low cost wireless microsensor node architecture for distributed computation and sensing in massively distributed embedded systems. Our design focuses on the development of a versatile, low power device to facilitate experimentation and initial deployment of wireless microsensor nodes in deeply embedded systems. This paper provides the details of our architecture and introduces fine-grained node localization as an example application of distributed computation and wireless embedded sensing.

1. Introduction

The rapid advancements in embedded wireless devices have enabled a new set of interesting and diverse applications. One class of applications is wireless microsensor networks where small devices embedded in the environment coordinate with each other to perform unsupervised sensing and actuation. Typical tasks include condition-based maintenance in factories, monitoring remote ecosystems, endangered species, forest fires and disaster sites [9]. To complete their sensing tasks, in tiny wirelessly connected sensor nodes are required to form an ad-hoc network that can sense events, interpret the sensor readings and report the results to a remote control center. This paradigm creates a set of new multidisciplinary challenges that need to be addressed. First, new lightweight and energy efficient methods are required to enable nodes to self-organize and construct a network on the fly are required. Second, the different sensing modalities need to be well understood. Third, new mechanisms for the in-network processing of sensor data need to be developed to improve system latencies and help to conserve power by reducing communication.

In our efforts to develop robust wireless sensor networks that can operate without human supervision, we study the operation of sensor nodes under realistic deployment conditions by constructing a deeply embedded wireless microsensor system. As a vehicle to the exploration of such systems, we have developed the Medusa MK-2 node (Figure 1), a versatile, low cost, low power wireless sensing device. The goal of this device is to enable experimentation with different sensing technologies, assist with the development of new sensor network protocols and applications and to accommodate the first deployment phase of a deeply embedded sensing environment, the Smart Kindergarten [3]. In the context of our research, the Medusa MK-2 node is used to provide fine-grained node localization services in the Smart Kindergarten environment for studying group interaction problems, but can also provide a flexible platform for the study of a wide variety of applications.

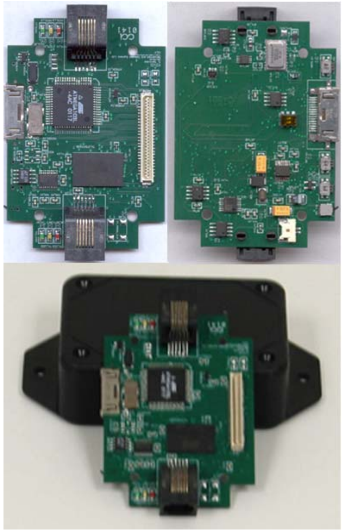


Figure 1 The Medusa MK-2 node

This paper presents the details of the Medusa MK-2 design. While our design focuses on producing a low cost low power distributed computation platform for wireless embedded sensing, great care is taken to attain the maximum flexibility for experimentation. The remainder of this paper is organized as follows. The next section provides an overview of some general sensor node requirements and introduces the MK-2 architecture. Section 3 provides a detailed description of the node subsystems. Section 4 discusses node localization as an example application, section 5 presents the related work and section 6 concludes the paper.

2. Sensor Node Requirements

In typical sensor network scenarios, large numbers sensor nodes are expected to be deployed an ad-hoc manner to monitor a set of events [9]. The design of such sensor nodes is driven by the following factors:

- **Size –** In order to be unobtrusive to their environment these nodes should have a small form factor.
- **Cost –** These devices are expected to be deployed in large number and be disposable. This implies that they should be manufactured with very low cost.
- **Power Efficiency –** Since these devices are expected to be small, they should be able to operate over small batteries for prolonged time periods. To do so sensor nodes should use low power components and also try to make optimal use of the available energy resources.
- **Flexibility –** To facilitate experimentation these devices should be very flexible in programmability and should have a rich set of hardware and software sensor interfaces to accommodate different sensing technologies.

Figure 2 depicts a typical sensor node architecture. The node consists of a power supply subsystem that contains a battery and a DC-DC converter, a processing unit which is usually made up of a low cost, low power microcontroller, some memory, a set of sensors and a low power radio for communicating with other nodes. To optimize the operation of a sensor network made of such nodes all components attributing to the operation of the sensor node need to be closely studied and understood.

2.1 Medusa MK-2 Overview

To facilitate our research and experimentation in sensor networks we have developed the Medusa MK-2 wireless sensor node. Although the primary driver for the development of this node is the study of node localization problems, Medusa MK-2 is also a versatile device for testing different sensing solutions and for exploring a wide variety of new protocols and applications in sensor networks.

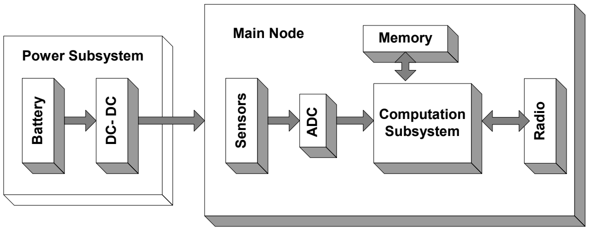


Figure 2 Typical sensor node architecture

Figure 2 depicts the Medusa MK-2 architecture. The computation subsystem of the node consists of two microcontroller. The first one is an 8-bit 4MHz ATMega128L MCU [1] from Atmel. This has 32KB of flash and 4KB of RAM and it is used as an interface to the sensors and for radio baseband processing. The second one is a 16/32-bit AT91FR4081 ARM THUMB processor [2] also from Atmel. This is a more powerful processor based on an ARM7TDMI core running at 40MHz. It has 136KB of RAM and 1MB of on-chip FLASH memory and comes in a compact 120-ball BGA package. The communication subsystem is made up of a TR1000 low power radio from RF Monolithics [7] and an RS-485 serial bus transceiver for wireline communication. The sensing subsystem is made up of a MEMs accelerometer (ADXL202E from Analog Devices) and a temperature sensor. The node also has a rich set of interfaces: 8 10-bit ADC inputs, serial ports (I^2C, RS-232, RS-485, SPI) and numerous general purpose I/O (GPIO) ports. An accessory board implements an ultrasonic ranging subsystem uses a set of 40KHz ultrasonic transducers (both transmitters and receivers). These are used in coordination with RF transmissions to measure inter-node distances for node localization. In addition to the sensors, the node also has two pushbuttons that serve as a user interface. These are used to trigger events and to execute different tests during experimentation. The node has two external connectors (see Figure 3). The first one has all the necessary connections for communicating with a PC to download and debug software. The wiring required for connecting the node to an external GPS module is also provided on this connector. The second connector has a set of ADC, GPIO and communication lines and it serves as an expansion slot for attaching add-on boards carrying different sensors. The description of each of the node subsystems is provided in the next section.

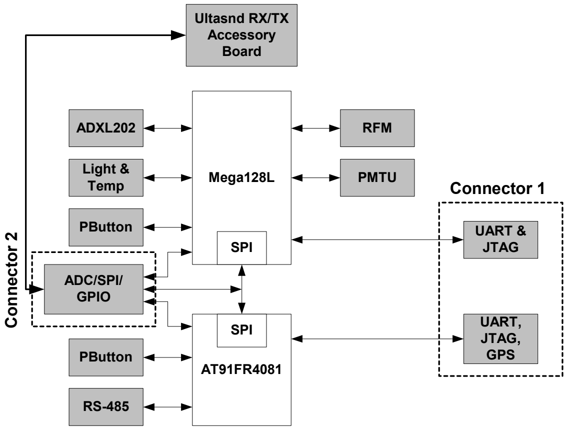


Figure 3 The Medusa MK-2 architecture

3. Medusa MK-2 Components

3.1 The Computation Subsystem

To design the computation subsystem, we classified the node computation tasks into two broad categories; low demand and high demand low frequency, according to their computation needs. The fist class contains the periodic tasks that the sensor node has to make such as the base band processing for the radio while listening for new packets, sensor sampling, handling of sensor events and power management. Although these tasks require a high degree of concurrency, they are not particularly demanding in terms of computation and can be easily handled an 8-bit microcontroller. The TinyOS [4] development effort at UC Berkeley has shown how such a task set can be supported by with a low power AVR microcontroller. The Medusa MK-2 architecture follows the same approach by dedicating an AVRMega128L microcontroller to handle these less computation demanding but highly concurrent tasks that a sensor node has to fulfill.

The second class of computation runs a set of algorithms that process acquired sensor data to produce a result or conclusion about what is being sensed. An example of such computation can be drawn from the fine-grained localization problem described in [5]. In this situation, a sensor node is expected to compute an estimate of its location by using a set of distance measurements to known landmarks or beacons. To solve this least squares estimation problem a node is required to perform a set of high precision matrix operations. This type of computation consumes between 3-4 MIPS [5] and has high accuracy requirements and it is more suitable for a higher end processor. Performing this computation on an 8-bit processor, would incur high latencies and less precision in the calculation due to round off errors. Instead the 32-bit instruction set and datapath provided by the 40MHz ARM THUMB processor is a more suitable environment for this type of computation. Furthermore, the THUMB microcontroller has sufficient resources to run some off the shelf embedded operating systems such as Red Hat eCos and uCLinux. This adds the additional advantage of allowing some of the existing applications and a rich set of libraries to run on the nodes.

This distribution of computation is also favorable from a power/latency perspective. The THUMB processor executes instructions at a rate of 0.9MIPS per MHz at 40MHz while drawing 25mA with a 3V supply. This gives a performance of 480 MIPS/Watt. The ATMega128L on the other hand operates at 4MHz and draws 5mA at a 3V supply thus provides 242 MIPS/Watt. Table 1 shows the microcontroller parameters which result in this power/latency tradeoff.

Table 1 MCU Comparison

	AT91FR4081	ATMega128L
Datapath	**16/32 Bit**	**8 bit**
Clock Speed (MHz)	**40**	**4**
MIPS/MHz	**(ARM 0.9), (THUMB 0.7)**	**1**
Power @ 3V(mW)	**75**	**15**
MIPS/W	**480**	**242**

The two processors communicate with each other with a pair of interrupt lines, one for each microcontroller, and an SPI bus. The microcontrollers use the interrupts as a mechanism for waking up each other from sleep mode when information exchange needs to take place. Information exchange takes place over SPI. The SPI interface was selected because of its high-speed capabilities (above 1Mbps). The SPI bus is included on connector 2 (see figure 3) so it can also support additional processors added to the node such as DSP processors or additional microcontrollers that are part of additional sensor boards.

3.2 The Communication Subsystem

The communication subsystem consists of both a wired and a wireless link. The wireless link is implemented with a low power TR1000 radio from RF Monolithics. This radio has a 0.75mW maximum transmit power and has an approximate transmission range of 20 meters. Additionally the radio supports two different modulation schemes, On-Off Keying (OOK) and Amplitude Shift Keying (ASK). The selection of a modulation scheme can be done in software according to the application specification. The radio supports multiple data rates ranging from 2.4kbps to 115kbps. On the Medusa MK-2 node, the base band processing for the radio is done by the ATMega128L microcontroller. This configuration allows running a lightweight medium access control (MAC) protocol on the ATMega128L processor. The S-MAC protocol presented in [12] is a low power MAC protocol for sensor networks that is well suited for this purpose.

In addition to the wireless front end, the Medusa MK-2 node is also equipped with an RS-485 serial bus interface for wireline communication. A low power RS-485 transceiver is attached to one of the RS-232 ports of the THUMB processor and allows the connecting the nodes to an RS-485 network using an RJ-11 connector and regular telephone wire. A single RS-485 network can have up to 32 nodes that can span over a total wire length distance of 1000 feet. Besides providing a wireless networking alternative in places with high interference where radios cannot function adequately this configuration allows a wide variety of node configurations such as:

- **Array formations** – several nodes, each one equipped with different sensors can be daisy chained to form node arrays.
- **Gateway functions –** nodes can act as gateways, connecting other wireless nodes to the wired infrastructure. With the use of RS-485 several gateways can be attached to the same workstation.
- **Out-of-band data collection** – during experiments where the data is processed on the nodes and communicated over wireless links, the raw data can also be collected using the wired infrastructure for offline analysis later on.

3.3 The Power Subsystem

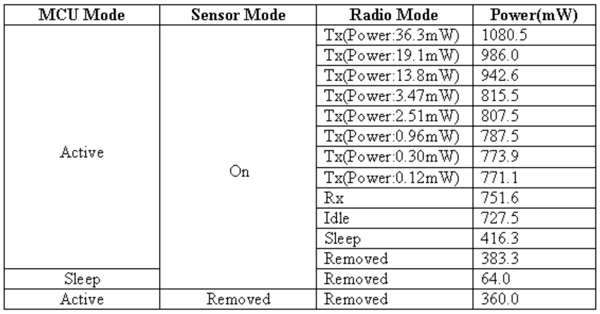
The power subsystem consists of 2 main units: the power supply and the Power Management and Tracking Unit PMTU [10]. The power supply consists of a 540mAh lithium-ion rechargeable battery and an up-down DC-DC converter that has a 3.3V output and can source up to 300mA of current from the battery. Although with no sensors attached, the node requires less than 50mA, the power supply designed to source up to 300mA currents to provide power-additional sensors than can be attached to the node as accessory boards. Table 2 shows the average current drawn by the main node components[1] during active and sleep node. According to the table, the maximum power consumption of the node is less than 150mW. During normal operation, the node consumes less power by putting the unused components in sleep mode. In a typical sensor network setting, the ARM THUMB processor together with the RS-485 and RS-232 transceivers are in sleep mode most of the time resulting up to an 80% reduction of the overall node power consumption.

Table 2 Current drawn by node components

Component	Active(mA)	Sleep(mA)
ATMega128L	5.5	1
RFM	2.9	5
AT91FR4081	25	10
RS-485	3	1
RS-232	3	10
Total	39.4	27

To get an indication of how the Medusa MK-2 power consumption relates to other sensor nodes, we compared its power consumption to the power consumption of a higher end node, the WINS node [8] developed at the Rockwell Science Center. This node is equipped with a more powerful StrongARM SA-1100 microprocessor from Intel, a 100-meter range 100Kbps radio from Connexant and several sensors. The results of the power characterization of the WINS node at different operational modes are shown in table 3. Table 4 shows the same characterization for the Medusa MK-2 node. Based on this comparison, the power consumption of the Medusa MK-2 node when all subsystems are active is approximately 10 times less than the power consumption of the WINS node. Furthermore, by shutting down the THUMB processor on the Medusa MK-2 node when not in use can result in 44 times less power consumption than the WINS node.

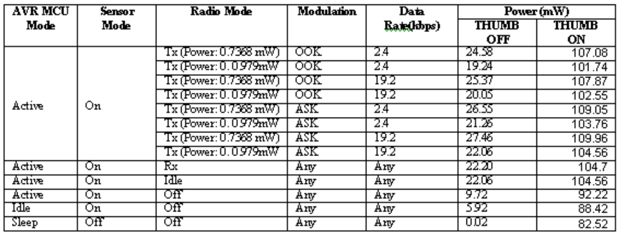
Table 3 Power Characterization of WINS node



MCU Mode	Sensor Mode	Radio Mode	Power(mW)
Active	On	Tx(Power:36.3mW)	1080.5
		Tx(Power:19.1mW)	986.0
		Tx(Power:13.8mW)	942.6
		Tx(Power:3.47mW)	815.5
		Tx(Power:2.51mW)	807.5
		Tx(Power:0.96mW)	787.5
		Tx(Power:0.30mW)	773.9
		Tx(Power:0.12mW)	771.1
		Rx	751.6
		Idle	727.5
		Sleep	416.3
		Removed	383.3
Sleep		Removed	64.0
Active	Removed	Removed	360.0

Another interesting observation noted in the power measurements is that the power consumption of the radio is almost the same regardless whether the radio is in receive transmit or idle mode. This implies that no power is conserved when the radio is in idle state, so it is better to develop protocols that completely shutoff the radio when not in use, hence a media access control protocol like S-MAC is highly desirable.

Table 4 Power characterization of Medusa MK-2 node



AVR MCU Mode	Sensor Mode	Radio Mode	Modulation	Data Rate(kbps)	Power (mW)	
					THUMB OFF	THUMB ON
Active	On	Tx (Power: 0.7368 mW)	OOK	2.4	24.58	107.08
		Tx (Power: 0.0979mW	OOK	2.4	19.24	101.74
		Tx (Power: 0.7368 mW)	OOK	19.2	25.37	107.87
		Tx (Power: 0.0979mW	OOK	19.2	20.05	102.55
		Tx (Power: 0.7368 mW)	ASK	2.4	26.55	109.05
		Tx (Power: 0.0979mW	ASK	2.4	21.26	103.76
		Tx (Power: 0.7368 mW)	ASK	19.2	27.46	109.96
		Tx (Power: 0.0979mW	ASK	19.2	22.06	104.56
Active	On	Rx	Any	Any	22.20	104.7
Active	On	Idle	Any	Any	22.06	104.56
Active	On	Off	Any	Any	9.72	92.22
Idle	On	Off	Any	Any	5.92	88.42
Sleep	Off	Off	Any	Any	0.02	82.52

To further reduce power consumption, the Medusa MK-2 node is equipped with a power Management/Tracking Unit (PMTU). This is a set of three DS2438 battery monitors from Dallas Semiconductor that keep track of the power consumed by the different node sub-systems. The first battery monitor keeps track of the power consumed by the AT91FR4081 processor, the second tracks the power consumed by the radio while the third monitors the overall node power consumption. Using the PMTU information, the Medusa MK-2 node can implement power aware algorithms to maximize battery

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[1] Numbers obtained from data sheets

lifetime. By making this power consumption information available to the application level, applications can set up their own power aware policies and decide which parts of the node to shutdown in order to conserve energy while meeting their sensing, computation and communication requirements.

4. An example application: Node Localization

To illustrate the use of the Medusa MK-2 node as a distributed computation and sensing platform we use an instantiation of the multihop node localization problem described in [5]. In this problem, nodes with unknown locations (white nodes in Figure 4) are expected to estimate their locations by setting up and solving a global non-linear optimization problem. To solve this problem, nodes first "sense" their separation to their neighbors using the node's ultrasonic ranging subsystem. When all the required measurements are made, the nodes with unknown positions combine these measurements with known location information of landmark nodes (black nodes in Figure 4) to estimate their locations using *distributed collaborative multilateration*.

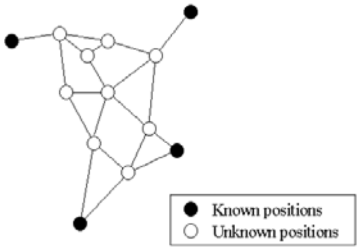

Figure 4 Solving for node positions in a multihop network

In this type of setup, the optimal position estimate is the one computed from a global vantage point that considers all the physical topology constraints. This however is a large non-linear optimization problem that computation and memory-constrained nodes cannot solve individually. With distributed collaborative multilateration nodes with unknown locations in setups similar to the one in figure 4 are able to estimate their locations locally while taking global constraints into consideration. As it was shown in [5], using this fully distributed computation model, resource constrained MK-2 nodes with unknown position can collaborate with each other to estimate their physical positions, a task that none of the nodes can perform individually.

5. Related Work

Research efforts in the last few years have produced a wide variety of sensor nodes ranging from tiny sensor nodes promised by the Smart Dust project [6] to fully-fledged nodes such as the WINS nodes [11] produced by Sensoria Corporation. The Smart Dust nodes still in development promise cubic millimeter scale form factor and a few cents per node manufacturing cost. The WINS nodes are already in use by the research community. They feature a Hitachi SH4 floating-point processor running linux and a long-range frequency hopping radio. Although these nodes are very powerful for some applications they are still large and power hungry and fairly expensive for some indoor applications and building large experimental networks in a lab setting.

UC Berkeley's MICA nodes [13] are an example of lower cost nodes that is currently widely used within the research community. The MK-2 node shares many similarities with this node. It uses the same AVR microcontroller and radio, it can support similar sensors and it is interoperable with the Mica modes. MK-2 differs from the Mica motes in that it has additional processing power, larger power supply and a set of customized features and sensor interfaces geared towards experimentation, especially for node localization problems.

8. Conclusions

We have presented the Medusa MK-2 node, a wireless node for distributed computation and sensing. The main focus of our development is to produce a simple, low cost design that is easy to program and provides great flexibility for experimentation in many different settings. We believe that this node will provide an affordable solution for constructing reasonable sized testbeds that would help in the development and validation of new protocols and concepts in this new era of wireless embedded sensing.

Acknowledgements

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