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Wireless Sensor Node Design for Heterogeneous Networks

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Abstract: *Two complementary wireless sensor nodes for building two-tiered heterogeneous networks are presented. A larger node with a 25 mm by 25 mm size acts as the backbone of the network, and can handle complex data processing. A smaller, cheaper node with a 10 mm by 10 mm size can perform simpler sensor-interfacing tasks. The 25mm node is based on previous work that has been done in the Tyndall National Institute that created a modular wireless sensor node. In this work, a new 25mm module is developed operating in the 433/868 MHz frequency bands, with a range of 3.8 km. The 10mm node is highly miniaturised, while retaining a high level of modularity. It has been designed to support very energy efficient operation for applications with low duty cycles, with a sleep current of 3.3 μA. Both nodes use commercially available components and have low manufacturing costs to allow the construction of large networks. In addition, interface boards for communicating with nodes have been developed for both the 25mm and 10mm nodes. These interface boards provide a USB connection, and support recharging of a Li-ion battery from the USB power supply. This paper discusses the design goals, the design methods, and the resulting implementation.*

1. INTRODUCTION

Advances in the development of electronics and sensors have made it possible to build miniaturised, low-cost, and energy efficient wireless sensors. A Wireless Sensor Network (WSN) is made from a number of these wireless sensors that cooperate to form a network. The sensor readings can be obtained through a gateway that is part of the WSN and also connected to an external database. As a sensor network can have a large number of nodes, it can provide data with a high temporal and spatial resolution, and is resistant to failures of a single node. A wireless sensor network can be useful for many applications such as environmental sensing [1], or industrial monitoring [2].

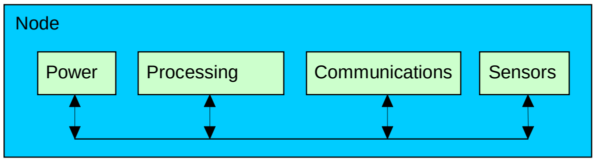

Fig. 1. Sensor node components

1.1. Sensor Node Components

Each node in a WSN is made from a number of hardware components, shown in Fig. 1. The node is built by combining these components. The selection of components depends very much on the application. For sensors, MEMS (Micro-Electro-Mechanical Systems) based sensors are common due to their small size, low energy usage and low cost. The processing capability of a node is usually provided by a low-power microcontroller, which has integrated memory and ADC capabilities. There is also the potential to use DSP chips, FPGAs, or ASICs if there is a demand for sophisticated processing greater than can be provided by a microcontroller, for example encryption or digital signal processing. Wireless communication is usually through a low-power transceiver operating in one of the license free ISM (Industry, Scientific, and Medical) bands, e.g. 433 MHz or 2.45 GHz. Typically, these transceivers are highly integrated and require very few external components. The power source for a wireless sensor node is often from batteries with a high energy density, such as a lithium coin cells or lithium-ion rechargeable batteries. Energy can also be generated in the field using solar cells or by converting kinetic energy into electrical energy [3]. The generated energy can be stored in rechargeable batteries or in super capacitors, which do not have limited recharge cycles [4].

1.2. Heterogeneous Networks

Each application presents different requirements and constraints on the WSN. For some applications, it can be advantageous to have many different types of nodes with different functions that together create a heterogeneous network. This can be because nodes have different components depending on what type of sensors are being used. Another reason is that, to keep costs to a minimum, each node should only have the minimum hardware required to perform its task. For example, if a node is required to only take a reading every 10 seconds and then transmit it, a very low-powered processor is sufficient. Conversely, if a node is required to do relatively complex tasks such as data compression, forward error correction, or routing in large networks, a more powerful processor is required. These tasks would not be possible on a very low-powered microcontroller. In this paper, two nodes are developed that can construct a two-tiered heterogeneous network as in Fig. 2. One node is smaller with less capability and can be used for sensor interfacing. A cluster of these small nodes can be supported by a larger node. These larger nodes provide the backbone of the network, and are capable of more complicated tasks.

The rest of this paper first looks at related work in developing wireless sensor nodes, then the design and construction of the two new nodes is discussed. Results from the characterisation of these nodes are then presented followed by the direction of future work in this area.

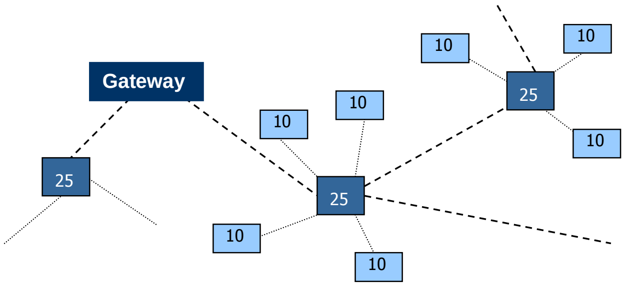

Fig. 2. Two-tiered heterogeneous network

2. RELATED WORK

Many different wireless sensor nodes, also called motes, have been developed in recent years, by both academic research groups and commercial companies.

One of the most popular nodes is the Mica family of motes [5], which were developed at University of California, Berkeley. The mica family has a number of different motes. The Mica2 uses an Atmel ATmega128 microcontroller with a Chipcon CC1000 radio transceiver. It is 58 mm by 32 mm in size and is powered by two AA batteries. The MicaZ is similar to the Mica2 but it has a Chipcon CC2420 transceiver. This transceiver is compatible with the IEEE802.15.4 and ZigBee standards.

The Telos [6] mote (also known as Tmote Sky) follows on from the mica motes. It also uses the CC2420 radio but replaces the ATmega128 with a Texas Instruments MSP430 microcontroller. The MSP430 has faster start-up times, which allows for more energy efficient low duty cycle applications. Another advantage of the Telos motes is the use of a USB connection, which replaces the previous UART and programming hardware needed for the Mica motes.

A commercial node is the Intel Shimmer mote [7]. Similar to the Telos mote, Shimmer uses a MSP430 microcontroller and CC2420 transceiver. In addition to this, it also has a Bluetooth compatible radio. This can be used for easy communications between a node, and a mobile phone, or portable computer. The Shimmer mote is 50 mm by 25 mm.

Previous work has been done in constructing heterogeneous WSNs. The Tenet system [8] is made from a two-tiered network. One of the key differences between our system and Tenet is the type of nodes used. The less powerful node in the Tenet system is comparable in functionality to our bigger node. The bigger node in the Tenet system is an Intel Stargate platform, which has a 32 bit, 400 MHz processor, and 32 MB of program memory. This node is several orders of magnitude more expensive than our nodes.

3. DESIGN

To create a heterogeneous network, we have designed two nodes, one with a size of 25 mm by

25 mm and a smaller node with a size of 10 mm by 10 mm.

3.1. 25mm node

The 25mm node is based on previous work that has been done in developing the Tyndall 25mm node [9] at the Tyndall National Institute. This is a highly modular system, using a number of stackable layers (shown in Fig. 3) that are connected together build a complete wireless node. Different layers can be swapped in and out to allow the node to function in a wide variety of situations. An essential layer is the transceiver layer which has a microcontroller and radio. A number of these have been developed, but they all have an Atmel ATmega128 microcontroller. Radios used on these layers include the Nordic nRF2401, and Ember EM2420, which is compatible with the IEEE802.15.4 standard. Other layers include an FPGA layer, many different sensor layers, and battery layers. The Tyndall node has a very high number of inter connects with 120 pins in total, compared to 51-way for the Mica motes. The orthogonal position of the connectors also gives a high level of mechanical stability.

For this work, a new transceiver layer has been developed. It uses an Atmega128 microcontroller and a Nordic nRF905 transceiver. This transceiver operates in the 433 MHz, 868 MHz, and 915 MHz frequency bands, which allows greater range than transceivers in the 2.45 Ghz band. This also suffers no interference from Wi-Fi, Bluetooth etc., which can be a problem with devices that use the 2.45 GHz band. The drawback is that bandwidth is limited to 50 kbps, compared to 250 kbps for the CC2420.

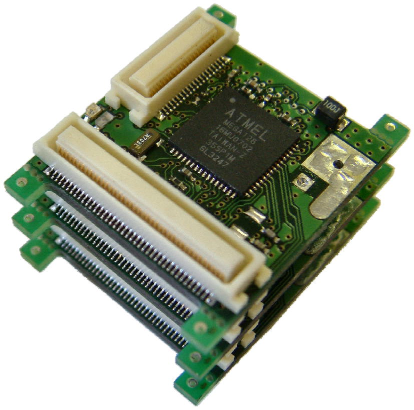

Fig. 3. Tyndall 25mm modular sensor node

The node can accept a DC power supply with a voltage range of 3 V to 6 V, due to the use of a voltage regulator. Switching regulators are usually used in low-power battery powered devices as they have a higher efficiency. However, in the low duty cycle application that this node is designed for, the quiescent current used by the regulator is very important. This current can be lower in linear regulators [10]. For this reason, a Torex XC6215 linear regulator was used, which has a quiescent current of 0.8 μA [11].

3.2. 10mm node

The 10mm node was not directly based on previous work. However the design process began by looking at the advantages and disadvantages of existing nodes [12]. From this, a number of objectives were identified and they are discussed here.

Modularity was seen to be important, due to the success of the Tyndall 25mm node, and it was decided that a similar modular stacking system would be used. This requires a connector with a high pin count to allow the widest possible range of future sensors or actuators. A size of 10 mm by 10 mm was the target size for a transceiver layer, with a microcontroller included. The node is powered by a small battery with limited capacity. Therefore, to have a long lifetime, the system must use as little power as possible. This was considered in the choice of each component. In WSNs, the nodes spends most of their time in a very low-power state, waking up periodically to take readings and transmit them. In many applications the sleep current of components will dominate the overall power consumption, and is therefore especially critical.

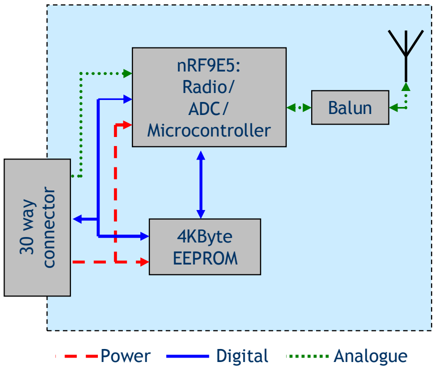

Fig. 4. 10mm Transceiver Layer schematic

After the objectives had been decided, the components were selected, and the schematic and board layout were created. In order to meet the desired size of 10 mm by 10 mm, a single chip transceiver/microcontroller was used, the Nordic nRF9E5 [13].

The radio is the same as in the nRF905 so it can communicate with the 25 mm node. The chip has an 8051 microcontroller with 4 kB program memory. An external EEPROM is needed for non-volatile storage of the program code. The nRF9E5 has a low sleep current of 2.5 μA. This current is used to keep an internal RC oscillator running, so that the node can be woken on regular intervals. A 12-bit ADC is also included in the chip. Fig. 4 shows a simplified schematic of the transceiver layer. The 30-way connector provides 5 analogue lines that are connected to the ADC, and 12 digital I/O lines. The other lines are for power and ground, with three lines left unconnected. In future these can be used to communicate between other layers without using the microcontroller. The size of 10 mm by 10 mm does not include an antenna. One solution is that a flexible quarter-wavelength (8.63 cm at 868 MHz) antenna can be integrated into an application, for example in clothing, whereas size is a more important issue when integrating a rigid PCB board.

3.3. USB interface boards

In addition to the transceiver layers, USB interface boards have been developed for both nodes, the 25mm and the 10mm. These interface boards make the nodes easy to use both in the end deployment and in the software development phase. For the developer it allows programming through a common interface, and for the user, it enables communications with many devices, e.g. PDAs or PCs.

The interface boards provide three functions to the transceiver and sensor layers: power, programming, and wired communication to allow a node to act as a base-station. These are all provided through a single USB connection. A USB device is capable of drawing up to 500 mA from the host, which is more than enough for this application. This current is used to power the interface and transceiver layers, and is also used to recharge a Li-ion battery, which will then provide the power when the device is not connected to a USB host.

To charge the battery a National Semiconductor LM3658 component is used. This was chosen as it is designed to work with a USB power supply, and has a low reverse leakage current of 0.01 μA, when the system is being powered by the battery.

Programming and communications are provided by a USB to serial converter (FTDI FT232R) that converts a UART to USB, and device drivers on the PC provide a virtual UART. This allows bi-directional communication with the target microcontroller. Programming of the Flash/EEPROM containing the program code is also done through the FT232R.

The interface board for the 10mm node uses a simple linear regulator to convert power from the battery (3.7 V) to the transceiver layer (2.7 V for the 10mm, 3.0 V for the 25mm). Because of the larger size of the 25mm interface board, it is possible to have a linear regulator, and a buck-boost switching regulator. At higher current levels, it is better to use a switching regulator, and at lower current levels, the linear regulator is superior. To demonstrate this we can calculate the regulator efficiencies when the node is in a sleep mode (5 μA) and in an active mode (10 mA). The efficiency of the linear regulator can be calculated using the following formula:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{in}(I_{out} + I_{supply})} \qquad (1)$$

When converting from 5 V to 3.3 V, at with an output current of 5 μA, the efficiency will be 57 % for the Torex XC6215. At 10 mA, the efficiency will be 66 %. The switching regulator is a Linear Technologies LTC3531, which has an efficiency of 89 % when converting from 5 V to 3.3 V, with 10 mA output [13]. The efficiency for low output currents is not given in the datasheet, but we can calculate an upper limit of the efficiency by assuming that the only loss is the supply current:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{out} \cdot I_{out} + V_{in} \cdot I_{supply}} \qquad (2)$$

This gives an efficiency of 17 % at 5 μA, showing that it is better to use the linear regulator at this current level.

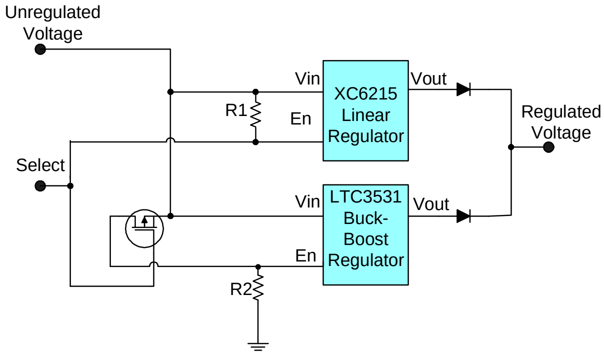

Fig. 5. Schematic of dual regulator system

Fig. 5 shows how the two regulators are connected and controlled by the microcontroller, by the *Select* line. If *Select* is floating or high, then *En* will be high for the linear regulator, and low for the switching regulator. If *Select* is low, then *En* for the switching will be high, and *En* for the linear regulator will be low.

The interface boards also provide support for sensors. It is possible to connect a digital temperature and humidity sensor. There are also pins that can be used for connecting analogue sensors.

4. RESULTS

After the design and layout of the two transceiver layers and interface boards, the boards were manufactured. Low-cost PCB manufacturers were used as the designs had relatively low design constraints of 0.15 mm track-size and gap-size, and 0.3 mm drill size for vias. All of the components are commercially available, to keep costs low, and to have low lead times for manufacturing the boards.

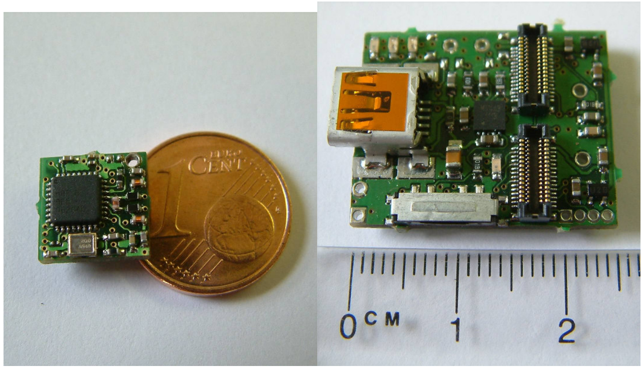

Fig. 6. 10mm transceiver and USB interface layers

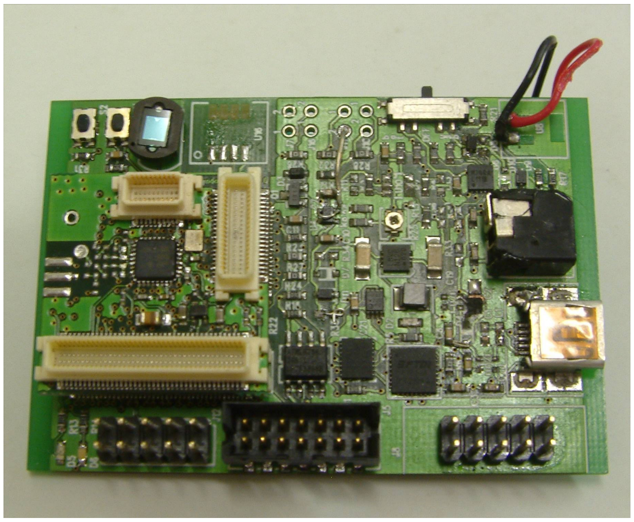

Fig. 7. 25mm USB interface layer with transceiver layer

Fig. 6 shows the assembled 10mm transceiver layer, and the 10mm USB interface layer. Fig. 7 shows the 25mm transceiver layer, with USB interface layer. As the 10mm node is a completely new system it is interesting to characterise its energy usage. This is necessary in order to allow estimations of the lifetime of the node when running from a battery. The current was measured using a digital ammeter connected in series with the battery output. The node was programmed into a number of different modes, with varying MCU (MicroController Unit) clock speeds, radio modes, and sleep modes. The deep sleep mode requires a longer start-up time, 1ms, compared to 7 µs for the moderate sleep mode so it is not always best to use this mode. The results from this are in Tab. 1.

Operation State	**Current**
20MHz MCU	2.57 mA
500kHz MCU	688 µA
500kHz MCU & +10dBm transmission	29.63 mA
500kHz MCU & -10dBm transmission	10.35 mA
500kHz MCU & reception	13.32 mA
Moderate sleep	166 µA
Deep sleep	3.3 µA

Tab. 1. Current consumption of 10mm node

As the deep sleep current can dominate energy usage in low duty cycle applications, it is very important. The 3.3 µA compares favourably with existing nodes. The current used by the MicaZ mote is 27 µA, and the Telos 5.1 µA [6].

Characterisation work has also been carried out on the Nordic nRF905 radio. Operating at 433 MHz it was expected that it would have greater range than nodes operating at 2.45 Ghz. This has proven to be true. When testing in an outdoor line-of-sight environment, at 2.45 Ghz the Tyndall node can achieve 200 m with a transceiver supply current of 17.4 mA. The new transceiver layer can achieve up to 3.8 km with a transceiver supply current of 30 mA.

5. FUTURE WORK AND CONCLUSIONS

Parallel to the development of hardware, work is ongoing on software systems to support the development of heterogeneous networks [15]. This will allow the deployment of a heterogeneous network. Initially a test network will be setup in the Tyndall National Institute. 10mm sensor boards have been developed that can measure, temperature, humidity and light levels. Future work will be able to characterise the operation of the complete heterogeneous network and allow comparison with homogeneous networks, from functionality and performance viewpoints.

This paper presented new nodes for use in developing and deploying heterogeneous wireless sensor networks. Heterogeneous networks minimise the cost of the overall network, and also facilitate non-uniform functionality of each node. The new nodes have a modular design to allow the rapid creation of application specific nodes. They are also energy aware to maximise the lifetime of the nodes from battery sources. The USB interface boards enable communications with many USB host devices for both programming of the nodes and communication with the nodes. Characterisation work has been carried out showing the energy efficiency and long range of the sensor nodes.

6. ACKNOWLEDGEMENTS

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