A Modular 6LoWPAN-based Wireless Sensor Body Area Network for Health-Monitoring Applications

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Abstract— **Reliable, standard-based networking is one of the key enablers for mobile and ubiquitous health monitoring. In particular, multi-hop IPv6-based wireless sensor body area network is one of the most attractive candidates for true internet of things in healthcare. This paper describes a proposal for a modular system comprising 6LoWPAN communication modules, optimized modules for application-specific sensing/digital signal processing, as well as energy harvesting and energy management modules. The connection between the modules is unified, enabling the creation of a wide variety of measurement setups. The unified DSP modules can be used to measure e.g. electrical bio-impedance, ECG, multi-axis acceleration, SpO2, etc. The DSP modules are integrated with low power, small size 6LoWPAN communication controller modules; IEEE 1588-2008/PTP is used for synchronizing the data acquisition nodes.**

I. INTRODUCTION

A. *Motivation*

The past decade has witnessed a tremendous increase in research and development in the field of wireless sensor networks (WSN), which has, in turn, contributed to the birth of the Internet of Things (IoT). These are now at the core of an ever-expanding array of applications including e.g. environmental monitoring, building automation, smart materials, smart cities, and healthcare monitoring.

The latter is of special interest to many developed countries which are facing various health challenges related to population ageing and sedentary lifestyle. The motivation behind our work is to develop WSN-based solutions that help and encourage the population being active and healthy by making health monitoring ubiquitous so as to improve disease prevention and detection, as well as to make disease treatment and management more (cost) efficient.

B. *Modular and scalable 6LoWPAN scenario*

Making health monitoring ubiquitous and (cost) effective can be achieved by fitting the human body with various vital signs, gesture and gait sensors of which the data is either (pre)processed locally or remotely. These data and/or resulting information are then remotely transmitted to medical staff and medical databases/applications for analysis.

In this work, we propose to use a modular and scalable multi-hop 6LoWPAN [1] based wireless sensor body area network to collect the data from the various sensors combined with a gateway that further transmits them to the medical staff or medical database/application (see Fig. 1).

The scenarios targeted in this work include e.g. hospitals where multiple patients can be monitored either individually or in groups (e.g. 10 persons exercising in a gym room), private homes, nursing homes, and outdoor and urban environments. In the first two scenarios, Internet connectivity can be achieved through (W)LAN; in the two other ones, the proposed system can be tethered to e.g. 3G/4G networks.

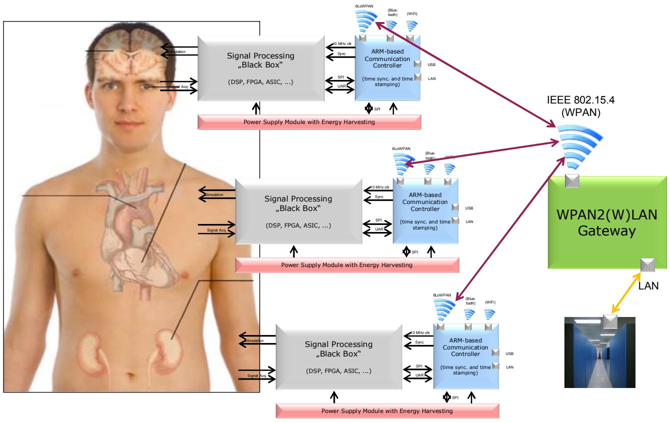

Fig. 1 The proposed modular and scalable 6LoWPAN-based health-monitoring system.

C. *Related work*

A fairly large body of works related to health-monitoring systems based on WSNs has been proposed in the literature; for conciseness we invite the reader to refer to e.g. [2] and [3] for gaining an overview of such works.

This work is conducted in the context of the Centre for Integrated Electronic Systems and Biomedical Engineering (CEBE) and partly funded by the EU Structural Funds via the Archimedes Foundation.

Specific works that are more closely related to our proposal include [4] that supports pulse, ECG, temperature and acceleration sensors that communicate with ‘Silmee’ (now Toshiba Wearable Biological Sensor), a pseudo-system on a chip (P-SOC) over dual-mode Bluetooth. The P-SOC includes the pulse and ECG analog front-ends, the acceleration sensor, the Bluetooth module, as well as an ARM-core. Two limitations of this and similar works are the lack of seamless Internet connectivity and energy autonomy.

A still fairly uncommon example of such seamless internet connectivity is proposed in [5] where 6LoWPAN is implemented on top of IEEE 802.15.4 (on the nodes MCU/OS (MSP430/TinyOS). The gateway (ARM9-based) is responsible, among others, for the IPv6-to-IPv4 address translation needed for transmitting the collected data to the rest of the network.

Regarding the energy harvesting aspects, [6] presents a 6LoWPAN-based WSN with energy harvesting and energy management capabilities dedicated to structural health-monitoring. Although their proposed solar and wind energy harvesting techniques are not easily transposable to human health-monitoring, the suggested dynamic voltage and frequency scaling (DVFS)-based task algorithm is a suitable candidate for our managing the harvested energy in our proposed system.

In our view, overcoming the individual limitations of existing WSN solutions for health-monitoring requires a system that combines modularity, IPv6 connectivity, and suitable energy-harvesting and energy-management. The design of such a system is discussed in the next section.

II. DESIGN CONSIDERATIONS

This section describes the design of the elements that compose the nodes (see Fig. 2) and the gateway.

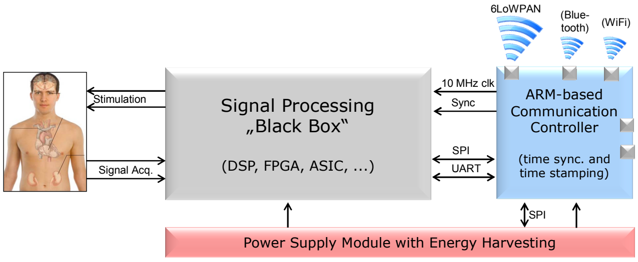

Fig. 2 Details of the proposed node architecture for WSN-based health monitoring.

D. *Sensors and signal processing module*

A large range of sensors (for measuring e.g. electrical bio-impedance, ECG, multi-axis acceleration, SpO2) can be supported. This is made possible thanks to the modularity of the system whereby the “Blackbox” signal processing module (shown in grey in Fig. 2) implements the adequate and optimized signal acquisition, stimulation (if needed) and processing techniques for each sensing technology.

In principle, this module can be implemented on a digital signal processor (DSP), field-programmable gate array (FPGA), or application specific integrated circuit (ASIC). In the current version of the system, a DSP is used (see Section III.A).

E. *Communication controller module*

The signal processing module is connected to a microcontroller-based communication controller module over SPI and UART interfaces. Furthermore, the communication controller module provides the reference clock and synchronization signals to the signal processing module. The communication controller module is also responsible for transmitting the acquired data to the gateway by means of 6LoWPAN over IEEE 802.15.4. The implementation of this module is discussed in Section III.B.

F. *Synchronization*

An important design aspect is the synchronization of the nodes for proper time-stamping of the sensed data. Although not critical in all applications, precise and accurate time-stamping is highly desirable for certain health applications for which meaningful data analysis requires consistency among the data collected from multiple types of sensors; this can be achieved by means of a dynamic clock synchronization mechanism.

In this work we have selected the precision time protocol version 2 (PTP V2) as defined in the IEEE 1588-2008 standard [7]. In PTP, synchronization takes place between one master and one or several slaves by exchanging special messages over two phases: i) correction of a slave’s clock offset and ii) correction of the transmission delay. This is complemented by the best master clock algorithm that builds the clock hierarchy and decides which node/gateway should be the grandmaster clock. Further details about PTP can be found in [7]. The implementation of the synchronization mechanism is discussed in Section III.B.

G. *Energy harvesting and management*

Another critical design issue is that of the energy powering and energy management. Regarding the former, various energy harvesting techniques can be used for supplying power to the modules. In the context of this work, the study presented in [8] indicates that kinetic energy harvesting i.e., collecting energy from common human activities, is a very promising candidate for WSN/IoT applications. Such systems rely on e.g. piezoelectrics, MEMS, or electromagnetic induction to convert the mechanical energy generated by human activities such as walking, running, or even typing/tapping/sliding into electrical energy.

According to [8], energy levels range from less than 1 µW when opening a building door to more than 3000 µW when shaking an object. One major issue though, is the intermittent nature of the harvested energy; according to the above study, as much as 95% of the total energy is collected during 4-7% of a day.

This clearly calls for methods and techniques to store and allocate the energy as efficiently as possible so as to minimize energy losses. Furthermore, for scenarios where the patients are largely immobile and/or to complement kinetic energy harvesting, radio wave energy harvesting may provide an alternative mean for powering the nodes.

III. SYSTEM PROTOTYPING

This section focuses on the prototyping of the nodes and the gateway. Note that this is a work-in-progress, thus not all details are in place yet. Also note that the following specifications apply for a bio-impedance measurement setup; however, as discussed in Section II, the various modules can be adapted for other applications with different constraints:

- Communication range: 10m,
- Sample measurement buffer data-rate: 1.5 Mbits/s every 10 ms,
- Packet size: ~150 Bytes,
- Delay: 2 ms,
- Reference clock: 10 MHz,
- Synchronisation precision: 1 µs.

A. Signal processing module implementation

The current version of the signal processing module builds upon a TMS320F28069 Piccolo DSP. For the bio-impedance measurement setup, the DSP is programmed for i) generating the multi-frequency excitation waveforms with the help of the onboard PWM block and ii) analyzing the response signal. The first 12-bit channel of the onboard ADC acquires the response signal while the second acquires the generated excitation signal. A complex discrete Fourier transform is performed for every frequency bin in every time window. Fig. 3 shows the current signal processing module.

B. Communication controller implementation

The prototyping setup for the communication controller of both the nodes and the gateway builds upon Dresden Elektronik deRFarm7 25A00 radio module [9] that features an AT91SAM7X512 32-bit ARM7 microcontroller, an AT86RF231 (2.4 GHz) transceiver, and a chip antenna.

As shown in Fig. 3, such radio modules are plugged onto deRFnode [10] and deRFgateway [11] development boards, respectively. For illustrating the modularity and flexibility of the system, we are also developing versions of nodes' communication controller software for the deRFmega256 23M00 modules (8-bit AVR ATmega256RFR2) that can also be plugged onto the same development boards.

Fig. 3 Photography of the first version of the DSP-based signal processing module prototype.

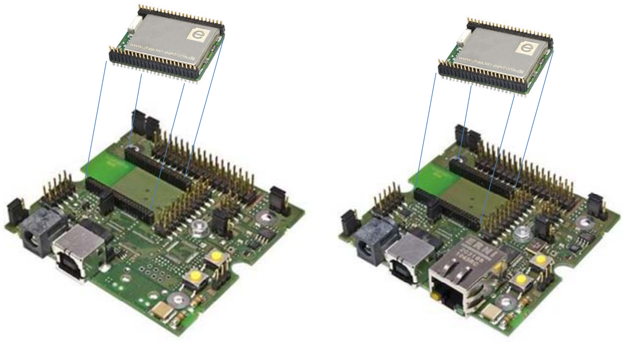

Fig. 4 Photography of the node and gateway prototyping setup. Node: Dresden Elektronik deRFarm7 25A00 (top left) and deRFnode development Board (bottom left). Gateway: 25A00 (top right) and deRFgateway development Board (bottom right).

The communication stack is implemented as follows.

- The AT86RF231 transceiver implements the 802.15.4 MAC hardware layer. In particular it features a hardware accelerator used for e.g. automated acknowledgement, CSMA-CA, retransmission, and automatic address filtering,
- The 802.15.4 software stack consists of a modified version of Atmel's 802.15.4 MAC stack reference design complemented by an add-on provided by Dresden Elektronik [12],
- The 6LoWPAN stack builds upon LwIp and is provided by Dresden Elektronik [13].

On top of the communication stack, we are implementing PTP to ensure proper clock synchronization and data time-stamping. For this, we use PTPd [14] as a reference design. However, for our currently OS-free setup, OS-dependent functions have to be replaced with interrupt-based versions.

The application layer interacts with the other layers by calling functions. In particular, it initializes the PTPd and 6LoWPAN functionalities and initiates the synchronization process. It should be noted that the functions that start PTPd and 6LoWPAN are called periodically.

The PTPd block performs the clock synchronization. The PtpClock structure is declared as ‘extern’ in the application layer and is modified by PTPd and 6LoWPAN. The incoming messages arrive from the network, pass through the MAC and 6LoWPAN layers before being transmitted to the PTPd block where the clock parameters are corrected. Outgoing messages follow the reversed route.

Transmitting messages is handled by means of protocol control blocks (PCBs) and stored inside buffers before being copied into queues. There are two types of queues: event queues that handle event messages only, and general queues that handle all the other types of messages.

The selected hardware platforms do not have specific hardware support for PTP time-stamping. Thus, two solutions can be considered for time-stamping, i.e. pure software or pseudo-hardware. With a purely software implementation, (1 ms precision) can be achieved, whereas the pseudo-hardware solution could achieve (1 μs precision).

However, implementing the pseudo-hardware solution requires various modifications such as:

- Modifying the software part so that it can read the value of a hardware timer/counter on the microcontroller,
- In the MAC layer, some functions have to be added to convert hardware internal sub-second value to PTP nanosecond/microseconds,
- It is also necessary to enable multicast frames and the Internet group management protocol on the interface,
- The UDP packet handling of the 6LowPan layer has to be modified to ensure the proper relaying of the timestamps of the transmitted packets.

IV. CONCLUDING REMARKS

The implementation process is ongoing and we are currently considering various commercial and self-developed solutions for implementing the energy harvesting approaches discussed in Section II.G. Furthermore, gesture recognition capabilities will be added to the proposed system by means of a cooperation effort with team members of the BOWI project [15].

Once the first prototypes are completed, initial tests and improvements will take place, among others in collaboration with North Estonia Medical Centre. The precision, accuracy, synchronicity, autonomy and scalability of the system will be evaluated for various scenarios, including when groups of patients exercise in a single room. This will be followed-up by more thorough real-life clinical testing once the proposed solution is mature enough.

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