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Development of Special Smartphone-Based Body Area Network: Energy Requirements

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***Abstract*—In recent years, smart-devices became very popular among people of all ages around the world. Very important is especially their usage in health applications. Special Body Area Network (BAN) for the stress monitoring is currently being developed within the authors' department. Android-based smartphone is employed as the main control unit of the sensor network built on the star architecture. Since the power consumption of the smart-phone as well as of the single sensor node is one of the key limitations of the network, special attention has to be given on it. In this article, energy requirements necessary for the data transmission among the network is analysed in detail. For this purpose, communication solution based on 2.4 GHz proprietary RF transceiver is implemented.**

I. INTRODUCTION

THESE fast moving, hurried times we live in bring along different health risks to the people's lives. In particular, the growing number of people suffering from stress, which induces high numbers of severe diseases such as cardiovascular disease, impaired immune system, asthma, peptic ulcer disease, indigestion, headaches, migraines and depression, is one of the typical problems of nowadays. Many people do not realize soon enough that their current stress level is harmful for their health. Therefore, it is necessary to have the stress issue under control and manage it somehow. For this reason, this paper presents the proposed system for monitoring the vital signs of a human body that are related to the stress issues. The system is based on the networking principles of Body Area Network (BAN). The sensor nodes around a human body that communicate in a coordinated fashion create BAN [1]. BAN requirements include low energy specifications and this fact is preferred for various applications including the field of e-Health [1], [2], [3]. Wearable sensor components enable monitoring anywhere, anytime and during wide range of activities (at home, at work, indoors, outdoors, during sports, etc.). Mostly, a comprehensive health image is obtained in comparison with the traditional diagnosing methods [3]. In addition, prompt disease identification typically leads to successful treatment even in case of serious illness [4]. Mostly, a central and most powerful network node is the coordinator of the network [1], [3]. The network coordinator for this application has been chosen to be a smartphone. The reason for this comes from smartphone features - embedded microprocessor, touch screen, capabilities to perform calls (emergency calls), send short text messages and connect to the internet [2].

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Various such systems, using the smartphone assets, have been already introduced. In [6], a special body monitoring system for detection of the human body temperature by thermopile sensor, electrical activity of brainwaves by electrocardiogram and electrical activity of the heart by electroencephalogram have been introduced. Smartphone had been in this case used as the communication gateway interfacing the sensors' data with the remote monitoring server, in spite of its management and local-storage functions.

In [7], more complex telemedical system measuring ECG, heart rate, heart rate variability, pulse oximetry, plethysmography and fall detection was presented for the purpose of the patients' physiological parameters outside the clinical environment monitoring and recording. The smartphone was except the common features used for the data visualization and patient's localization matters in order to the emergency communication with a clinical server will be guaranteed on a certain level of quality.

An agent-based approach was presented in [8]. A multi-agent architecture for mobile health monitoring interacting doctor and patient beyond the episodes of visits is presented, involving a team of Java-based intelligent agents that collate patient's data through Bluetooth compliant monitoring device and recommend actions to patients and medical staff in a mobile environment. Agents at the smartphones are also able to monitor the patient's environment through an integrated VGA camera to track patient actions and relay images back to medical staff.

System in [9] is devoted to the monitoring of the athletes during their training process providing them information about the body response to fatigue. Different sensors are utilized within the system, including the photoplethysmographic (PPG) sensor for the heart beat-variability monitoring that is used for the arrhythmias or arterial stenosis and occlusions detection, and the earlobe sensor for the tissue impedance measurement that defining an amount of physical effort due to the ions' concentration analysis. Whilst the smartphone was employed as the main control unit for the data collection and analysis, the system provide non-invasive method for the athletes monitoring without interfering their training.

Energy optimization through scheduled communication, Bluetooth parameter tuning and protocol optimization was stressed within the system in [10]. There was developed a Bluetooth-based body sensor network consisted of one smartphone as the network coordinator, multiple sensor nodes for the human body monitoring, and a wristwatch as the user interface. Since the Bluetooth is characterized by large power overhead, its duty cycle was minimised. The developed platform was supplied with a set of APIs for applications on the phone to manage the network, collect data from the sensors, and interact with users via the watch. Data from sensors, which had been most time in a sleep mode, were on account of the measurement request reported to the Internet server or to the phone which could perform its own analysis displayed afterwards through the wristwatch.

In [11], the design and implementation considerations of a smartphone-centred platform for low-cost continuous health monitoring based on commercial-off-the-shelf wireless wearable biosensors were introduced. The platform approach was implemented utilizing PPG biosensors and different smartphones to measure heart rate, breathing rate, oxygen saturation, and estimate obstructive sleep apnea.

The first part of the article describes radio frequency solutions and their comparison in order to better evaluate their power consumption requirements. Smartphone connectivity is investigated in the following part. The next section discusses the mere composition of the network, as well as the principles of communication and timing in the network. Efforts to reduce energy requirements are described in the last part. The proposed sensors are able to capture the temperature, humidity and heart-rate characteristics. Such, values are able to detect if a human is under the stress. Thus, by the analysis of these parameters, the level of human's stress can be found out.

II. Radio Frequency Solutions

An important task of the system design is to select the proper communication mean for the BAN. If one considers a selection of wireless connectivity for a smartphone, two major technologies come to mind. The first is IEEE 802.11.4 (WiFi), which is very powerful, but it is able to drain out the battery in a quite short time. The second option for smartphone wireless connection is IEEE 802.15.1 (Bluetooth). On the subject of the energy consumption, both standards require significant amount of energy and considerably reduce the smartphone's lifetime [12].

Except mentioned technologies, there are also other possibilities which are much more suitable for the BAN purposes, especially in the frame of power consumption. In [7], IEEE 802.15.4 ZigBee platform was implemented within the developed BAN due to the energy-saving reasons. However, though is ZigBee primarily appointed for the low-power, low-cost, multihop networks, it does not exactly meet demands of IEEE 802.15.6 standard for wireless communications supporting ultra-low power devices operating in or around the human body. Therefore, proprietary radio functioning on 2.4GHz ISM was chosen for the BAN purposes. This choice allows definition of the unique low-energy-consuming communication protocol which can be further modified according to the latest release of the BAN standard. Several embedded solutions are available on the market nowadays. The Table I briefly compares the current consumption of the selected transceivers for 2.4 GHz ISM band.

TABLE I
BAN Compliant Transceivers' Current Consumption Comparison in Different Power Modes for Proprietary 2.4GHz ISM Band Radio Modules

Power mode	**Quasar RFM 70 [13]**	**Microchip MRF24J40MA [14]**	**Nordic NRF24E2 [15]**	**Microchip MRF89XAM9A [16]**
RX mode	17.50 mA	19.00 mA	22.00 mA	3.00 mA
TX mode	14.57 mA	23.00 mA	27.00 mA	25.00 mA
Power down	3.00 μA	2.00 μA	-	1.05 μA
Standby	50.00 μA	-	30.00 μA	-

TABLE II
TI System-on-chip Current Consumption Comparison in Different Power Modes

Power mode	**CC2511 [17]**	**CC2530 [18]**	**CC2543 [19]**	**CC2545 [20]**
Active mode	3.97 mA	6.27 mA	4.50 mA	4.50 mA
RX mode	19.12 mA	24,80 mA	21.20 mA	20.80 mA
TX mode	21.50 mA	33,93 mA	27.70 mA	28.25 mA
Power mode 0	4.28 mA	-	3.80 mA	3.75 mA
Power mode 1	0.22 mA	0.25 mA	0.24 mA	0.24 mA
Power mode 2	0.75μA	1.50 μA	0.90 μA	0.90 μA
Power mode 3	0.65 μA	0.70 μA	0.40 μA	0.40 μA

Transceiver solution requires a microcontroller (MCU) to process the measured data and to initialize wireless communication. Furthermore, additional space on the PCB (printed circuit board) is required when taking advantage of the standalone transceiver interconnected with MCU via some interface. As the sensors ought to be as small as possible we decided to investigate system-on-chip (SoC) 2.4 GHz RF solutions as well. Whilst Texas Instruments (TI) is probably the best producer of such solutions in the sense of current consumption, selected SoC representatives from TI family were chosen for comparison in Table II.

Common features of these SoCs and transceivers include low-cost 2.4 GHz radio solution, ultra-low power requirements, suitability for portable applications and several advanced low-power operating modes in order to save the power. Since ultra-low power requirements are necessary for proposed application the power requirements parameter was key part of the communication subsystem selection. All values in the Table II are average values of the current consumption based on the datasheet information.

Along with the table, it is possible to conclude that the best power consumption requirements had the first SoC solution TI

CC2511. Therefore, the main MCU that is connected directly to the smartphone via USB, functioning as the communication gateway for the BAN, has been chosen the mentioned CC2511. This chip was, however, unsuitable for the sensor nodes since it lacks the most important communication interfaces - SPI and I^2C [17]. Thus, it was necessary to select another SoC solution that comprises these peripherals. The second best solution provided in the Table II was TI CC2545 that had all desired peripherals and features satisfying the sensors' claims [20].

Fig. 1. Central unit - smartphone connection

III. Smartphone USB Connectivity Constraints

Universal Serial Bus (USB) was employed as the main communication interface as well as the power source for the communication gateway board - control node (Fig. 1 and Fig. 2) - since it provides bus-power. That is one of the key advantages, because the device obtains power from the bus and no extra cables are required. In the following subsections, the necessary basics of the USB interconnectivity management will be summarized.

A. USB Device Types

The device specifies its power consumption in 100 mA load units in the configuration descriptor [21]. The device cannot increase its power consumption above the declared amount of load units. Three classes of USB devices exist [22]:

- *Low-power bus powered devices (LPBPDs)* - draw all necessary power from the bus and cannot draw more than one load unit. This class of devices has to be designed to work in 4.40 V up to a maximum 5.25 V voltage range. Therefore, many devices require LDO regulators;
- *High-power bus powered devices (HPBPDs)* - all necessary power is drawn from the bus and cannot draw more than one unit load until it has been configured. After the configuration, the device may drain up to five load units (max. 500 mA) provided in the configuration descriptor. Such devices have to operate in 4.40 V - 5.25 V voltage range. When operating at a full unit load, the minimal voltage level is 4.75 V. Once again, a LDO regulator is needed for many devices;
- *Self-powered devices (SPDs)* - may draw up to one load unit from the bus and the rest of the necessary power may derive from an external source. One load unit allows reliable detection and enumeration of the devices without main/secondary power applied;

No USB device, whether bus powered or self-powered can drive the bus (in sense of the power). If the power is lost, the device has 10 seconds to remove power from the pull-up resistors on the USB data pins that are used for speed identification. Another very important consideration for implementation is the inrush current that has to be limited. The inrush current contributes to the capacitance of the device between the USB power and the USB ground [22]. The maximum decoupling capacitance stated in USB specifications is 10 μF. When the device disconnects, a large voltage peak may occur. Therefore, at least 1 μF decoupling capacitance has to be implemented for safe USB operation [21].

B. USB Suspend Mode

Support for suspend mode is mandatory for all devices. During this mode, additional constrains apply. The maximum suspend current is proportional to the load unit. For one load unit the maximum suspend current is 500 μA [21]. This includes current from the pull-up resistors on the bus. Another consideration for many devices is the 3.3 V regulator. Regular voltage regulator has average quiescent currents around 600 μA [22]. For one unit load it is necessary to implement more efficient and sophisticated voltage regulators. In most cases, microcontroller clock has to be stopped or slowed down to fall within the 500 μA limit [22].

A USB device will enter suspend when there is no activity on the bus for greater than 3.0 ms. Then, the device has another 7 ms to shut down and draw no more than the designated suspend current [21]. In order to maintain connected, the device has to provide power to its pull up speed selection resistors also during suspend mode.

USB specification determines frame packet start as well as periodical sending of keepalive packets. This prevents an idle bus from entering suspend mode during the data absence. High speed bus has micro-frames sent every 125.0 μs, full speed bus sends frames each 1.0 ms and low speed bus sends the keepalive frames every 1 ms only in the absence of any low speed data [21].

IV. Characteristic of the Proposed BAN

Proposed network for the vital function monitoring senses three characteristics of human body, assuming that the stress can be determined with change of sweating, heart-rate and body temperature. Due to the reasons of energy-saving, temperature and humidity was being monitored each time period on temperature/humidity module (TH module), with the time period set to $1s$. If a significant change from the normal value was spotted, the control node/central unit (CU) sent the information to oximeter module (O module) for the need of heart rate measurement. In case that the stress was indicated also from heart rate, signal is sent to the smartphone and according to the stress rate, the smartphone application will choose form available methods and will offer suitable activity for stress dismantle.

Communication structure of the BAN modules was based on the star network architecture, where the central unit interconnecting whole BAN was set to be CU. More about the architecture of BAN was written in [2], [3]. The interfaces

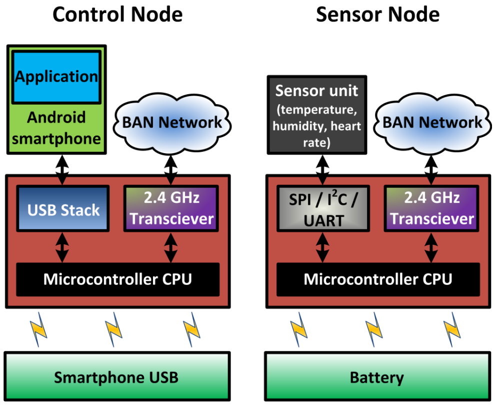

Fig. 2. BAN concept

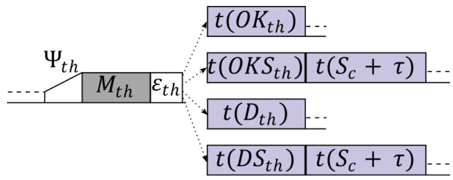

Fig. 3. Time diagram for temperature-humidity module

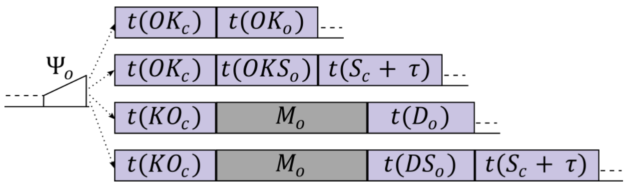

Fig. 4. Time diagram for oximeter module

utilized within the particular nodes are depicted in Fig. 2. The central unit was connected to the smartphone through USB.

For temperature and humidity monitoring, HIH-6131-021-001 sensor is used. The sensor goes into sleep mode when not taking a measurement and consuming only 1 μA of power. In full operation consumes 1 mA and the time of power-on to data ready is 60 ms [23]. Standard way of the pulse oximetry with emitting diode and photodetector is used for the heart-rate measures in a fingertip.

V. Timing and Communication Slots

Aforementioned modules communicate with each other in window slots (TDMA). CU which collects information from sensor modules, is responsible not only for measured data evaluation but also for synchronization of measuring modules.

Because the aim is to decrease the energy requirements, CU is active in communication slots for each module. Then it evaluates data, sends them to smartphone and goes into sleep mode for the next communication period.

In Fig. 3 time diagram for TH module is depicted. The module sleeps and wakes in the time Ψ_{th} [s] before measurement. Ψ_{th} depends on the wake-up-time of the selected core TI CC2545 necessary for getting from power mode 3 to active mode as well as on the assurance constant value. Ψ_{th} was set to $150\,\mu s$. Because the measurement is required before each communication slot, the RX/TX initialization is made at the same time as the measurement is made. Measurement of used temperature/humidity sensor HIH-6131-021-001 is ready after $M_{th} = 60\,ms$. The measurement is sent to core through SPI interface and the data are concerned for sending. Data processing and communication of the core with the sensor last for ε_{th} [s]. If data do not get over the change limit, the data are not sent, only information about good condition of module is sent in packet OK_{th}. Type of communication after data processing is visible in the Fig. 3 with respect to the Table IV. After last communication in corresponding communication period the module returns back to the sleep mode.

Measured data are processed in CU. If the values are in the scope where the stress was not identified, CU sends only OK_c packet to O module in corresponding time slot and the O module does not measure heart rate. Because measuring is energy-demanding, in this way it is assured that energy consumption is suppressed. Time flow of oximeter communication period is depicted in Fig. 4. O module does not measure before each communication slot, but it needs to wake up in the time Ψ_o before the packet arrives from the CU. $\Psi_o = 650\,\mu s$ depends on the ability of module to change from power mode 3 to active mode, on the time necessary for the activation of receiving as well as on the subsumption of the assurance constant.

Because the communication with each module is different, for communication purposes not the same packets are used. Form of the packet is visible in Table III, acceptable types of packet and length of data are mentioned in Table IV.

Because the communication under the communication rate $v_c = 1\,Mb/s$ is aimed to be accomplished within the system, the time for communication of worst case is when the packet size $PS = 7B$ (according to Table III and IV) is sent. The length of communication slot t_s is set as:

$$t_s = \frac{v_c}{PS} + \lambda \approx 60.5\,\mu s, \tag{1}$$

where λ is assurance constant for resynchronization and was set to $0.5\,\mu s$. λ assures, that also when the crystal inaccuracy

TABLE III
BAN Packet Structure

Byte \ Bit	0	1	2	3	4	5	6	7
0	Synchro bits				ID			
1	Packet length				Type of packet			
2-5	Data[a]							
	CRC[b]							

[a]number of data bytes depends on type of packet
[b]one byte after data block, if is

TABLE IV
BAN PACKET TYPES

Packet type	**Data length**	**Description**
D_{th}	4 B	Data from temperature/humidity module
D_o	1 B	Data from oximeter module
DS_{th}	4 B	Data with synchronization request from temperature/humidity module
DS_o	1 B	Data with synchronization request from oximeter module
OK_c	0 B[a]	Information packet from central unit for oximeter module that there is no need for measurement
KO_c	0 B[a]	Information packet from central unit for oximeter module that there is need for measurement
OK_o	0 B[a]	Acknowledgement from oximeter module about the packet OK_c from central unit
OKS_o	0 B[a]	Acknowledgement about the packet OK_c from central unit and synchronization request from oximeter module
OK_{th}	0 B[a]	Information packet from temperature and humidity module for central unit that everything is all right and the measurement does not change after treshold
OKS_{th}	0 B[a]	Information packet from temperature and humidity module for central unit that everything is all right, measurement does not change after treshold and there is need for synchronization
S_c	4 B	Synchronizing time from central unit

[a]Information packet differs only in packet header. There is no need to transfer data.

will occur, the communication in corresponding time slot will be possible.

Because the communication is performed between the nodes with two different cores CC2511 and CC2545, they oscillators have different crystal frequency (f_{CC2511}, f_{CC2545}) and accuracy (acc_{CC2511}, acc_{CC2545}) . Time of communication period is set to 1s, error of crystal for core CC2511 Δ_{2511} is set to:

$$\begin{aligned} \Delta_{2511} &= \frac{1}{f_{CC2511}} - \frac{1}{f_{CC2511} + acc_{CC2511}} \\ &\approx 1.538x10^{-12}\, s \end{aligned} \tag{2}$$

Error of core CC2545 Δ_{2545} is set to:

$$\begin{aligned} \Delta_{2545} &= \frac{1}{f_{CC2545}} - \frac{1}{f_{CC2545} + acc_{CC2545}} \\ &\approx 1.875x10^{-12}\, s \end{aligned} \tag{3}$$

set for $60.5\,\mu s$ and the number of synchronized periods p_s is set as:

$$\begin{aligned} p_s &= \frac{\frac{\lambda}{2}}{\Delta_{2511} + \Delta_{2545}} \\ &= \frac{0.25x10^{-6}\, s}{3,413x10^{-12}\, s} \\ &\approx 73\,249 \end{aligned} \tag{4}$$

It means that the synchronization is necessary after 73 249 cycles. As was mentioned, cycle for TH measure is long 1 second, so the synchronization is used 2 times a day.

When each of sensing modules need to synchronize, it sends the synchronization packet to CU. The type of synchronization packets are mentioned in Table IV.

VI. ENERGY SAVING IN TH MODULE

Low power consumption is one of major condition in many applications. Amount of required energy is very important in monitoring applications where an effort to achieve long operation time is emphasized. It is not only the problem of applications from BAN area, but also from many other monitoring applications in the field of wireless sensor network [24].

One of the possibility is to use sleep mode as was mentioned in previous part. For TH module, communication period lasts $1s$ and is visible in Fig. 3. TH module is active for time t_a:

$$\begin{aligned} t_a &= \Psi_{th} + M_{th} + \varepsilon_{th} + t_s \\ &\approx 0.066\, s \end{aligned} \tag{5}$$

and sleeps for $t_{sleep} = 0.934\, s$. Concerning the consumptions listed in Table II, average current I_{avg} for TH node was estimated as $2\, mA$. According to used battery CR2450 which capacity is $600\, mAh$, the TH module should operate more than 12 days.

VII. CONCLUSION

This paper presents the smartphone-based Body Area Network for monitoring of human vital signs regarding the stress situation. In particular, energy requirements are discussed. The results showed that the designed BAN is able to last up to 2 weeks without any intervention. On the other hand the smartphone in not capable of such long lifetime. Therefore, until now, the weakest link of the network is the smartphone and the coordinator module attached to it. This application is eligible for eHealth sector as well as general wellness to serve as front-line in cardiovascular disease detection. The future work is focused on implementation of the developed system into different application fields of modern life, primarily into the field of intelligent transportation systems aiming the problematic of the professional drivers' behaviour on the road with the comparison to their actual stress level.

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