Politechnika Świętokrzyska
Kielce University of Technology

TI university program

Texas Instruments Innovation Challenge: Europe Analog Design Contest 2014
Project Report

Wireless Personal Monitor

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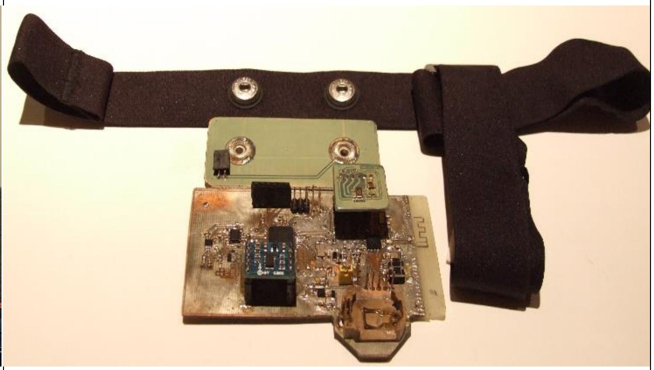
University:	Kielce University of Technology, Poland
Date:	31.07.2014

Qty.	TI Part Number & URL	Qty.	TI Part Number & URL
1	TM4C123GH6PMI	1	INA321
1	CC2541	1	OPA2336
1	TPS61025	1	TL4051
1	TPS62730		



Project abstract: The report presents a brief description of the wireless patient monitoring system. The monitoring system consists of a device placed on a patient body and receiving station in the form of a smartphone with HMI application. The device gives the ability to monitor user selected parameters such as heart rate, body position, temperature, barometric pressure, altitude above sea level or warnings detected by the device such as free fall or absence of breathing. Bluetooth Low Energy was used for communication between devices. The monitoring device provides the possibility to select modules and adjust configuration according to user needs and budget. Interchangeable elements are sensors that user can easily put on a plate without use of tools. This concept allows to use the device in a variety of applications, which makes it a versatile, low cost personal monitor.

1. Motivation for project

The motivation for this project was to solve the problem of health monitoring of patients, elderly, lonely and people working in conditions which constitute a threat to their lives. Knowledge about the state of the monitored person and any irregularities can increase the safety of life and health of monitored person. The immediate response in the event of irregularities may help to avoid unpleasant consequences.

From the analysis of the available devices on the consumer market, results that none of them provides the possibility of monitoring user state in wide range, and gives ability of adding extensions. In addition none of the facilities currently available does not monitor the position of the user's body nor provides information about the possible events as the fall of patient, lack of movement or absence of his breathing during sleep. In our opinion, such information’s are important and gives broader picture of the user state. Equipment available on the market are quite expensive and have imposed functionality. That is why we decided to create a device with a modular concept, allowing the user to choose the functionality by his own will. In addition, we assume that the device should be a cheaper alternative to those currently available and provide wider capabilities.

2. Introduction

User state should be understood as a physical state of person which consist of vital functions like: electrical activity of heart, breath and blood flow. Physical state of user also can be considered as a movement of person (eg. posture, operations performed etc.). All mentioned components of user state carry important information which can be used for diagnosing or monitoring of user state.

Rapid lifestyle causes that many people do not have time to take care of the elderly people and provide them constant control. This is a very important issue that has recently intensified because society lives longer. For this reason, there is a need for devices that can help in the process of monitoring state of this group of needy. Presented in this report device can be used not only by the people residing permanently at home with health problems. An important potential group of buyers could be employees, working in life threatening conditions such as miners, steelworkers or mountain rescuers. Workers who are under constant control of their body are better protected and can receive immediate assistance when it's needed. Detection of threats (user state irregularities) such as syncope in case of an employee working on heavy equipment such as crane or digger, increases safety of the rest of employees residing in the area of working machine. Wireless communication allows for a comfortable use of device no matter where the user is located. Wireless Personal Monitor (WPM) depending on the installed sensors can transmit desired information and can be used in a variety of situations

Main functions of WPM are:

- Monitoring of user body position (lying, staying)
- Detection of user fall, his immobility, and chest movement during sleep
- Measurement of ambient :temperature, altitude and pressure
- Measuring Heart Rate of user
- Assistance button
- Informing about irregularities

Block diagram of the Wireless Personal Monitor is shown on figure 1. Full system consist of parts like: **main device board**, **PCB sensor modules, small PCB** with connectors to **chest belt** and **smartphone** with Android. On main board are placed all analog and digital components.

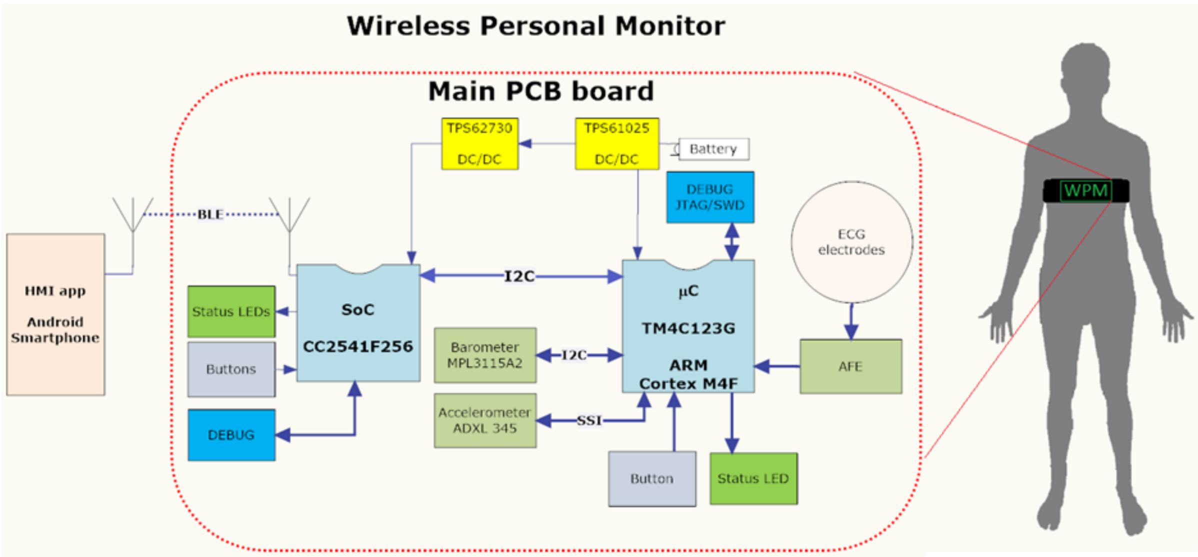


Fig. 1 - Wireless Personal Monitor Block diagram

3. Theoretical background

Electrocardiography is common method used for monitoring electrical activity of heart. Signals of heart are collected thanks to electrodes attached to patient body. Recorded data of heart activity are known as electrocardiogram which consist of PQRST wave (figure 2). Thanks to development of technology, it was possible to adapt electrocardiography and use it in consumer devices such as heart rate monitors. Heart rate monitors allows to measure heart beat in real time. Amplitude of ECG signal is typically between 0.5 mV to 5 mV at frequency between 0.05 Hz up to 250 Hz. Its small amplitude, cause that ECG waveform must be further amplified. Heart rate monitors

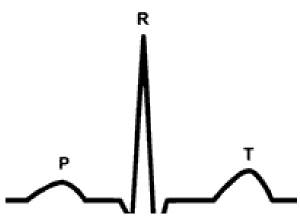


Fig. 2 – PQRST wave

are attached to chest belt with electrodes, and are worn by user on chest close to heart. Because the distance form device to heart is short, the heart signal is strong and muscle artifact interference is low. Also thanks to this, device's circuit are less vulnerable to common-mode interference and there is no need to apply driven electrode to feedback inverted common-mode noise to cancel it form signal. Heart rate monitors use only QRS complex to count how fast heart works.

The force of gravity is the force exerted by the gravitational field of a massive object on any body within the vicinity of its surface. Accelerometer is a main tool used for measuring gravity force. Nowadays MEMS type (Micro Electro-Mechanical Systems) 3 axis accelerometers are relatively cheap and very popular. Thanks to them it's possible to describe position in space. The use of accelerometer allows to sense falls by measuring g-force applied on all axis of accelerometer.

4. Implementation

Wireless Personal Monitor was designed to be worn on the chest comfortably. Device is splitted into three PCB's. Main board where microcontroller, Bluetooth chip and AFE is placed. Second and third PCB's are modules with accelerometer and altimeter. This solution makes WPM flexible device which can be easily adjust to user needs or can be fixed quickly. In any time user can plug in or unplug modules from device. The main heart of the system is TIVA TM4C123GH6PMI microcontroller. All calculations, and algorithms are carried out by this MCU because it is efficient 32-bit ARM® Cortex™ M4F processor with clock up to 80 MHz. Wireless communication is handled by CC2541 SoC solution for Bluetooth Low Energy. The CC2541 consist of powerful 8051 MCU with all peripherals needed to build truly functional low-power wireless solution. This project uses software stack available for CC254X devices in combination with modified by us source code from SensorTag kit. The PCB Antenna design was used from Texas Instruments AN043 application note. TM4C123GH6PMI and CC2541 microcontrollers are connected through I2C. In the same manner altimeter is connected. Serial synchronous interface was used to communicate with accelerometer. In first version of device, I2C interface was used to communicate with all IC's. We decided to use SPI form communication with accelerometer. Thanks to it, it's possible to rapidly send warnings and stream data to phone in real time. Device is powered by two CR2016 coin cell batteries, giving a total of 6V DC to input of TPS61025. It is a 96% efficient synchronous boost converter with fixed 3.3V output voltage distributed to all main components on PCB board. This boost converter is well suitable for low power, portable devices because of its small size, output current up to 200 mA and power saving mode. For optimization of power consumption we were using TPS62730 which is a high frequency synchronous step down DC/DC converter optimized for ultra low power wireless applications like our design with CC2541. Figure 3, 4, and 5 presents schematics of device. Figure 9 presents main PCB which is mounted to chest belt. All components was divided into blocks (analog, digital, connectors) in order to separate those, which are sensitive, like AFE from strong interfering blocks like Bluetooth antenna section.

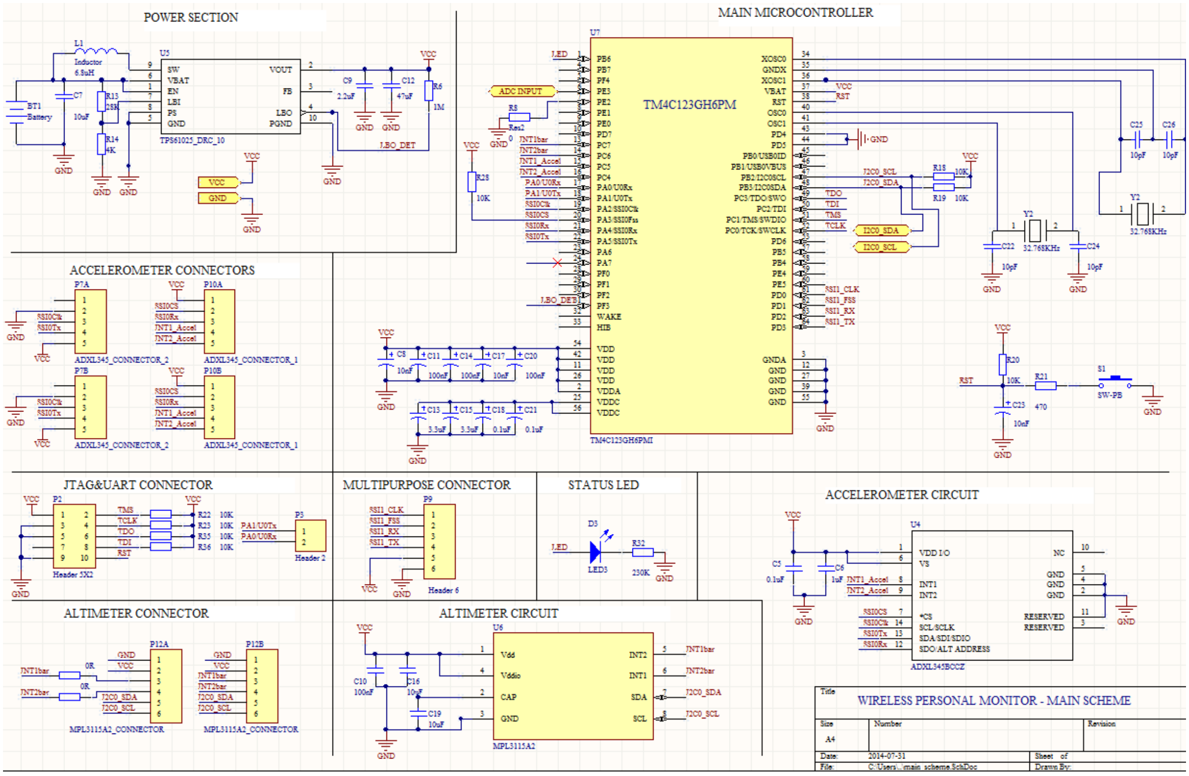


Fig. 3 - schematics of microcontroller, power and sensors

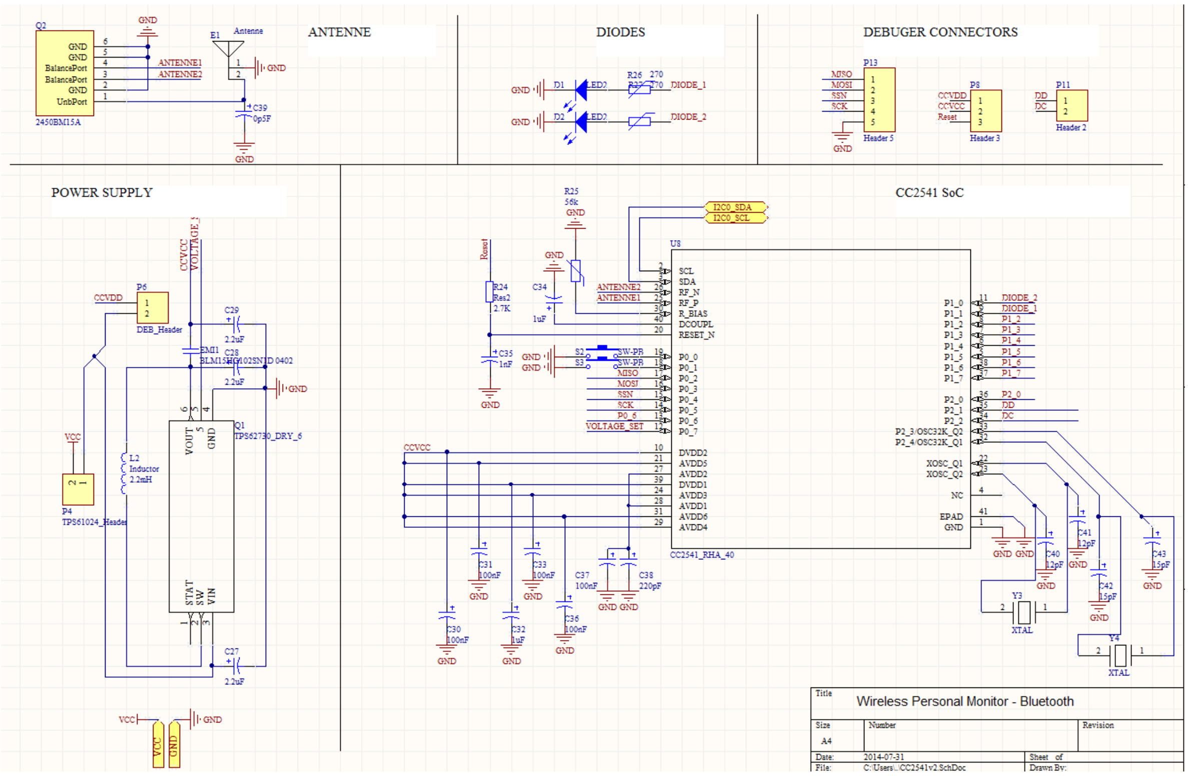


Fig. 4 - schematic of CC2541

- **Heart rate**

Common way to find heart rate is to measure time interval between next heart beats. For measuring ECG waveform to find time interval in portable device, AFE circuit in WPM, was based on low power elements that can be supplied from battery. The choice fell on INA321 instrumentation amplifier, double operational amplifier OPA2336 and TL4051A12 voltage reference. INA321 and OPA2336 are micro-power single supply instrumentation and operational amplifiers with RAIL-TO-RAIL technology. Low bias current, good CMR ratio, and low power consumption of used parts, makes it ideal to build AFE circuit that is perfect for portable devices. AFE ECG circuit of Wireless Personal Monitor is presented on figure 5. Electrical signal of heart is collected by electrodes mounted in chest belt. Its amplified by instrumentation amplifier U1 and then by operational amplifier U2B. Summary input signal is amplified 500 times. U2B operational amplifier also acts as antialiasing filter with about 220 Hz cutoff frequency. Q1 TL4051A12 is used to provide fixed 1.2V reference voltage level for AFE circuit. To manage with baseline wandering of ECG signal which can be caused by the change of skin to electrode resistance (eg. poorly adhering electrodes), op amp integrator circuit U2A have been used. U2A amplifier integrates output signal form INA321 and passed back to reference pin of INA321 amplifier, so output signal remains on constant level. Output signal from AFE is collected by A/C converter of microcontroller. Figure 6 presents heart activity signal and it's spectrum, registered with Wireless Personal Monitor. Signal was sent to computer using UART, and then analized in MATLAB. In figure 6, it can be seen that input signal contains noise (50Hz) that comes from power network and it must be filtered, to increase usability of ECG signal. Because our main assumption was that, the Wireless Personal Monitor must work properly in electromagnetic environment to not increase the total cost of device, we decided to use digital filtration of signal instead analog filters. To remove noise from input signal lowpass, 29 tap FIR filter with 35 Hz cutoff frequency was implemented. Next QRS complex was separated, by using 23 TAP highpass filter with 15 Hz corner

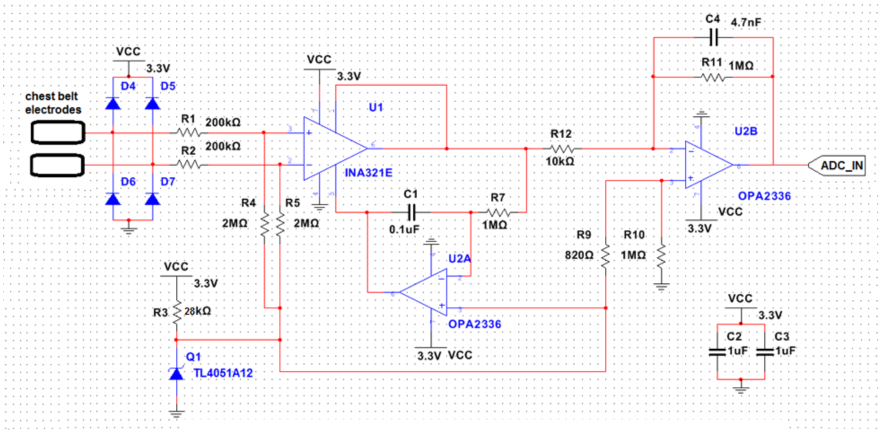


Fig. 5 - AFE of Wireless Personal Monitor

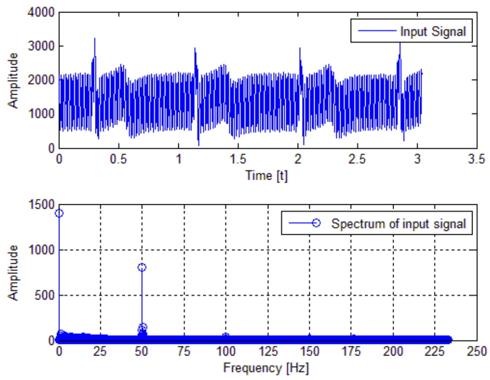


Fig. 6 - Heart activity signal registered by WPM, close to devices powered form network.

frequency. Coefficient of both filters was designed in MATLAB. Figure 7 presents results of filtration made on microcontroller. Thanks to designed application we were able to display data sent from microcontroller to computer through UART interface in real time. Blue waveform on figure 4, presents isolated QRS complex from ECG trace by FIR highpass filter. On last step, isolated QRS complex was integrated using trapezoidal numerical integration method (blue trace on figure 10). All negative values are set to zero. Integrated signal of QRS complex was used to calculate heart rate. We have tested several method, but the most efficient way to accurately measure heart rate it to monitor time interval between next QRS complex.

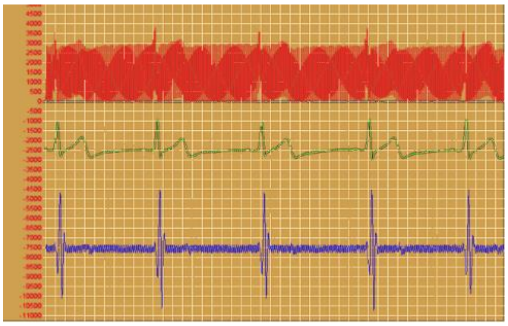


Fig. 7 - filtered data on microcontroller. Input signal (RED), filtered signal – lowpass filter filtration (GREEN), separated QRS complex – highpass filter filtration (BLUE).

- **Position and fall detection**

To monitor physical user state – its location and irregularities, Wireless Personal Monitor uses 3-axis MEMS accelerometer. Accelerometer is mounted the X-axis to the top. It's fixed position relative to the user, allows to determine if user is laying or standing. It's possible by measuring g-forces applied on each axis according to position of user. For detecting falls of user, free fall detection function implemented in accelerometer was used. When accelerometer sense free fall, for example cause by stumble, the accelerometer inform microcontroller about this event. Next microcontrollers monitors if force applied to X,Y,Z exceed threshold to sense fall. To validate fall of user, timer was used to apply time window in which g-forces measured on axis must exceed threshold. If fall was detected, Wireless Personal Monitor sends warning to mobile phone, and monitors activity of user. It Wireless Personal Monitor does not sense movement after fall is detected in next 10 seconds a critical warning is generated. Threshold was experimentally determined by performing several fall tests. After averaging test results, the 2.2g threshold was selected. Figure 8 presents acceleration measured on X,Y,Z axis during fall. After fall, no movement phase can be seen in the end of traces.

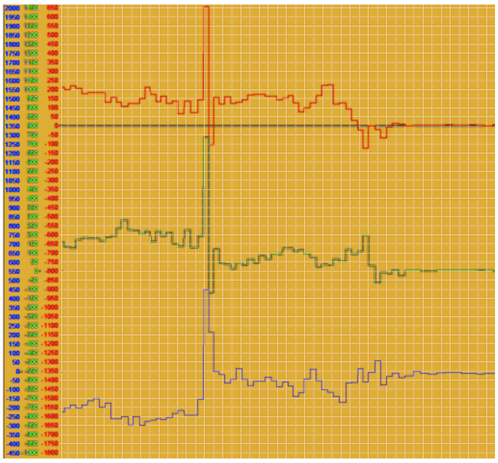


Fig. 8 – acceleration measured on X (RED), Y (GREEN), Z (BLUE) axis during fall.

- **Assistance button and monitoring chest movement during sleep**

Assistance button was implemented in Wireless Personal Monitor to inform others about needed assistance. Button is realized thanks to tap and double tap detection function of accelerometer. What user must do to call help is just double tap into device. Breath monitoring during sleep is also implemented. It's realized by monitoring accelerations on all axis. If there is no move, accelerometer switches to sleep mode, and inform microcontroller about it. Microcontroller then monitor time of no movement state and take proper action.

- **HMI application and warnings**

For our purpose we have modified Bluetooth SensorTag application shared by TI. App is able to connect, display collected data and manage services on remote device. Application is installed on mobile phone with Android System. Also it gives ability to send text message by application, when Wireless Personal Monitor will generate warning (eg. when fall was detected or no movement phase takes too long).

- **Temperature, pressure, altitude**

In the design altimeter sensor is used to measure altitude which user is located. Thanks to the altimeter sensor it's also possible to measure temperature and ambient pressure. This parameters are important especially for mountain rescuers.

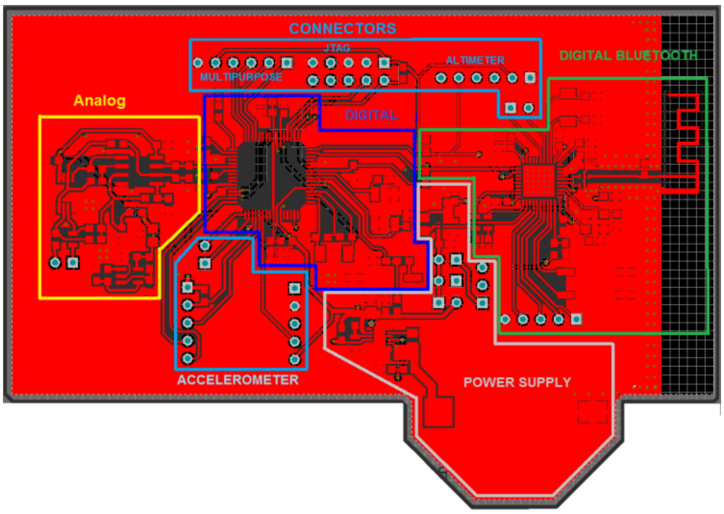


Fig. 9 – PCB view of Wireless Personal Monitor

5. Experimental results

The whole system is operating correctly and data can be received on smartphone. User is not encumbered by device when it is connected to his body and can perform all needed actions. All functions of device has been checked if they are working correctly. Heart rate measurement was verified and compared with commercial sigma sport heart rate monitor. Measurements are similar. Also we were verifying hear rate by observing integrated QRS complex (figure 10). In next step ambient parameters and assistance button operation was verified. Altitude, temperature and pressure was compared to weather station. Reads are similar. Assistance button works correctly, as

HMI application sends SMS to specified number with information "I need help". The verify fall detection several fall test were conducted which confirmed proper operation of device. More test should be conducted to verify proper operation of device in various conditions. Warnings of no movement are working properly. If no movement for a long time was detected, mobile phone send information to specified mobile number "User is not moving". At the end lack of breath during sleep was tested. It was possible to detect apnea when user is lying on his back. In case of other position more precise algorithm is needed.

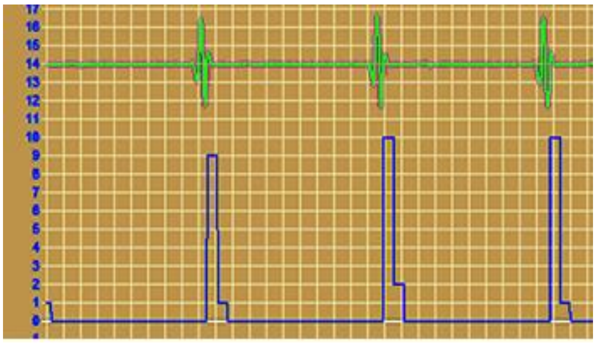


Fig. 10 – integrated QRS complex.

Current consumption of whole developed system in peak equals 50 mA. Consumption on TPS62730 which powers up CC2541 equals 19 mA in transmit mode (with two active LEDs). On TPS61025 when Bluetooth SoC is physically disconnected, the current consumption is about 32 mA.

Range of WPM is very well but depends on environment where it's used. WPM is always able to connect and receive data up to -94 dBm. In free space range is about 50 meters. In buildings WPM is working correctly within 10 meters. Signal easily passes through walls, floor to other rooms. The device works seamlessly in single-family houses. Figure 11 presents Android application when device is active and transmitting data to smartphone. Data requests takes place

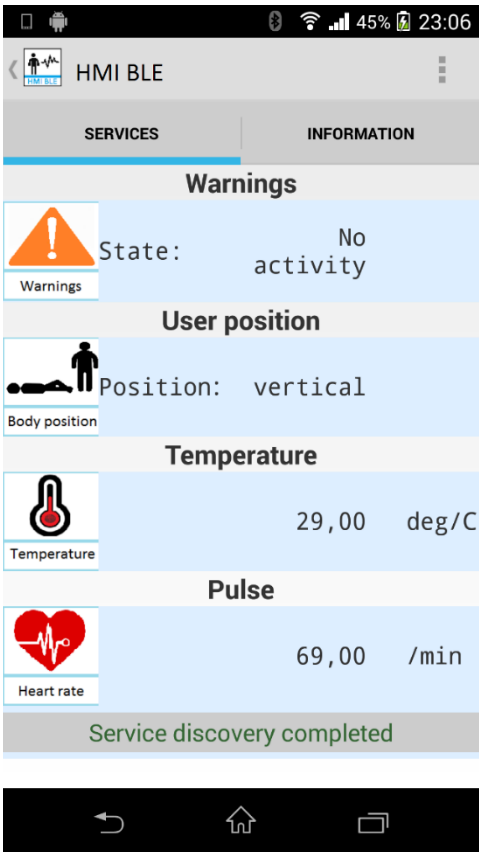


Fig. 11 – working HMI application

Fig. 12 – authors during tests.

every second and continues until application is closed or device is disabled. Figure 12 presents authors during device tests.

6. Conclusions and summary

Thanks to Texas Instruments professional parts, tools, great documentation, reference designs and support community forum we were able to develop, build and test Wireless Personal Monitor in short time. We were using hardware platforms like CC2541DK-MINI, Stellaris EK-LM4F120XL and Tiva EK-TM4C123GXL launchpads. Amps were tested on OPAMPEVM-SOT23 blank circuit board from TI which simplifies evaluation of surface-mount parts. In the project we have pattern AFE on Texas Instruments SLAAA280A application report.

For best performance we were using software from TI such as *Code Composer Studio*, *BTool*, *StellarisWare* and *TivaWare*. There were also other programs used for simulations, programming and debugging like *Matlab*, *IAR Embedded Workbench for 8051*, *NI Multisim* and *Eclipse* with *Android SDK* plugin. PCB was designed in *Altium Designer*.

Total cost of the WPM in case of series manufacture in hundreds of pieces is about 50$, which allows for compete with other devices on the market. PWM met all objectives and can be a fully functional device, which could be used as a medical personal monitor.

7. Future plans

There are plans to add more sensors and increase the number of services for handling data transfer to mobile application. Considered are sensors, modules and upgrades like: carbon monoxide, methane, GPS, GSM/GPRS, ZigBee, data storage (offline) on microSD card and others. Also there are plans to display ECG in real time in Android application and send it to specialist if it’s needed. Software optimization for increased power savings is also considered. Realization of those objectives will require new PCB designs, better power sources and miniaturization of whole design.

We are currently working on creating mother station which can be installed in area where user (patient or employee) mainly stay. All Wireless Personal Monitors will be connected to this station and send data to it about user state.

No.	Part	Description	Value	Part no.	QTY
1	TI TM4C123GH6PM	IC		U7	1
2	TI CC2541F256RHAT	IC		U8	1
3	TI INA321	IC		U1	1
4	TI OPA2336PA	IC		U2	1
5	TI TL4051B12IDBZT	IC		Q1	1
6	TI TPS61025DRCR	IC		U5	1
7	TI TPS62730DRYT	IC		Q1	1
8	ADXL345BCCZ	IC		U4	1
9	MPL3115A2	IC barometer		U6	1
10	MURATA BLM15HG102SN1D	Ferrite bead		EM1	1
11	JOHANSON TECHNOLOGY 2450BM15A0002E	Balun		Q2	1
12	COILCRAFT PFL2015-222MEB	Inductor	2.2 uH	L2	1
13	ABRACON - ABS10-32.768KHZT	Crystal	32.768 Hz	Y2,Y4	2
14	TXC - 7M-32.000MEEQ-T	Crystal	32 MHz	Y3	1
15	COILCRAFT - PFL2015-682MEB	Inductor	6.8 uH	L1	1
16	7M-16.000MEEQ-T	Crystal	16 MHz	Y1	1
17	MC0603B104K250CT	Capacitor	100 nF	C1,C11,C14,C20,C18,C21,C5,C10,C30,C31,C3,C36,C37	14
18	MC0603X105M6R3CT	Capacitor	1 uF	C6,C34,C32,C2,C3	5
19	GRM21BR61A225KA01L	Capacitor	2.2 uF	C9,C27,C28,C29	4
20	GRM188R61A335KE15D	Capacitor	3.3 uF	C13,C15	2
21	06036D106MAT2A	Capacitor	10 uF	C7,C19	2
22	TACR476M006XTA	Capacitor	47 uF	C12	1
23	MC0603B102K500CT	Capacitor	1 nF	C35	1
24	MC0603B103K500CT	Capacitor	10 nF	C8,C17,C16,C23	4
25	MC0603X474K100CT	Capacitor	4.7 nF	C4	1
26	TACR476M006XTA	Capacitor	0.5 pF	C39	1
27	C1608C0G1H100D080AA	Capacitor	10 pF	C22,C24,C25,C26	4
28	MC0603N120J500CT	Capacitor	12 pF	C40,C41	2
29	MC0603N150J500CT	Capacitor	15 pF	C42,C43	2
30	MC0603B221K500CT	Capacitor	220 pF	C38	1
31	MC0805S8F2700T5E	Resistor	270	R32,R26,R27	3
32	CR0603-FX-4700ELF	Resistor	470	R21	1
33	CRGH0603F820R	Resistor	820	R9	1
34	CRGH0603F2K7	Resistor	2.7 k	R24	1
35	MC0063W0603156K	Resistor	56 k	R25	1
36	RC0603FR-0710KL	Resistor	10 k	R20,R28,R18,R19,R22,R23,R35,R36,R12	9
37	CPF0603B200KE1	Resistor	200 K	R1,R2	2
38	MC0063W0603128K	Resistor	28 K	R13,R3	2
39	TNPW06034K02BEEA	Resistor	4 K	R14	1
40	RK73H1JTTD1004F	Resistor	1 M	R6,R7,R10,R11	4
41	ERJ3GEYJ205V	Resistor	2 M	R4,R5	2
42	TLMO1000-GS08	LED		D1,D3	2
43	150060SS75000	LED		D2	1
44	TL3302BF180QG	Switch		S1,S2,S3	3
45	BAGLC32Z	Battery holder		BAT1	1
46	ZL201-36G PIN:36; THT; 2,54mm	Pin header			2
48	MX-90121-0766 Pin 6, THT	Pin header			2
49	ZL262-5SG, PIN 5; 2,54mm, THT	Header female			3
50	Transil TESDU5V0	ESD diode		D4,D5,D6,D7	4

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