Telecommun Syst (2014) 55:115–124
DOI 10.1007/s11235-013-9756-4

An efficient and low cost Windows Mobile BSN monitoring system based on TinyOS

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Published online: 11 September 2013

Abstract Monitoring methods for human body parameters are used over years to identify health conditions and biofeedback. For example, the core-body temperature is correlated with women fertility and ovulation periods. Mobile devices offer an extraordinary solution for health monitoring with mobility and continuous monitoring. This paper presents a Windows Mobile based system for body parameters monitoring. The proposed system comprises a SHIMMER-based body sensor network used to measure and collect body parameters, and a mobile application for personal monitoring. The communication between the sensor and the mobile device is performed over a Bluetooth connection. This system provides a low cost, reliable and robust mobile solution platform with full mobility support for active people that should be under continuous monitoring. The system was evaluated and validated, and it is ready for use.

Keywords Body sensor networks · Healthcare applications · Mobile health · Mobile monitoring · e-Health

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1 Introduction

Health monitoring is based on acquiring, processing, and presentation of human biological and physiological parameters. The construction and creation of systems to perform these tasks in autonomous way could improve the healthcare conditions to patients that need continuous monitoring procedures. Even today, medical staff performs most of these procedures or by patients themselves, which has to collect these parameters handling appropriated equipment at regular periods. For example, to monitor body temperature the regular procedure is to measure this parameter hourly. The use of standalone systems based on body sensor networks (BSNs) supported by wireless networks could suppress the human interaction to collect these parameters [1–3]. Although, these systems improve the quality of the collected values because they are less prone to bad handling of the equipment that could lead to wrong measures. In this context, mobile devices become a natural personnel information system, due to its specific characteristics and massive use by the general population. The connection of these devices to BSNs and it sensors allows the data transfer and its graphical representation to the user [4]. Thus, becomes easier to control and analyze the monitored parameters by the user itself.

This paper proposes an integrated system for long-term acquisition, processing and analysis of data collected from body sensors. The system is comprised of three modules.

- First module is the *sensor* itself. Body sensors include a temperature sensor, electrocardiogram (ECG) sensor, electroencephalography (EEG) sensor, electromyography (EMG) sensor, pressure sensor, and motion sensor, among others.
- The second module is the *processor unit* responsible for the acquisition and long-term collection of the measured values.
- Finally, the third module is a *Windows Mobile device*, used for collection, representation and control of the measured values.

Then, this paper proposes a Windows Mobile based system for body parameters monitoring. It comprises a SHIMMER-based body sensor network used to measure and collect body parameters under monitoring, and a mobile application for personal monitoring of these parameters.

The scientific contributions of this research work are summarized as follows:

1. An integrated system for health monitoring of patients in their regular daily life;
2. A Windows Mobile based for graphical representation of data collected by body sensors placed in a patient;
3. Bluetooth's communication mechanisms for Windows Mobile to access the data collected by body sensors in a BSN;
4. Secure Bluetooth connection through the implementation of some encryption algorithms;
5. Real time monitoring and presentation of data gathered from the BSN interface.

The remainder of the paper is organized as follows. Next section describes research projects for human body monitoring. Section 3 presents the body sensor used in this project to measure and collect human parameters. As an example, it is presented a temperature sensor to collect women's core body temperature. Section 4 describes the developed sensor's firmware while the Windows Mobile application is presented in Sect. 5, focusing on its architecture, Bluetooth communication with the sensor, and data representation. Next, the user interface, deployment and system validation are described in Sect. 6 while discussion is addressed in Sect. 7. Finally, Sect. 8 concludes the paper and proposes some future works.

2 Related work

Health monitoring is the key for controlling several diseases. Nowadays, mobile systems are applied in several situations for patient's personal and remote monitoring. The use of these devices allows improving patient's healthcare providing continuous biofeedback of controlled parameters.

In [5], a mobile system was presented for personal electrocardiogram (ECG) monitoring and transmission using multimedia-messaging service (MMS). This system was proposed to enable transmission of ECG using hardware equipment. This equipment uses Bluetooth connection to transmit data to a smart phone. The smart phone plots the received ECG signal using a Windows Mobile 5 application. The system allows capturing the plot and saved as a bitmap images. Then, these images may be sent as an MMS message. This system only collects images and the hardware equipment as to be always connected to the smart phone. In this case, the proposed system is fully dynamic, once the data collected by the body sensors are presented as a set of values instead of a static image. Furthermore, this solution allows long-term data collection inside body sensors, which suppresses the need of a continuous connection with the mobile device, without data loss.

A biofeedback mobile solution for data acquisition and processing was presented in [6]. The system architecture was based on a three-tier BSN. The system is comprised of smart sensor nodes, a sink node and a presentation device to provide an integrated solution for biofeedback. The sensor nodes are responsible for the acquisition of the patient's parameters. The sink node aggregates all the data collected from the sensors, fault tolerance, and outside communication. Finally, the mobile device processes and presents the data sent by the sink node. Body sensors have the ability to save the collected data. This means that proposed architecture is dispensable the sink node to aggregate all the data collected by all the sensors in a BSN. Besides, in the proposed architecture, the suppression of this component avoids the need of a continuous connection between the sensors and sink to transmit the collected data, increasing that way the lifetime of the sensor's batteries.

In [7] was described a mobile platform used in telemedicine and wellness applications, that can provide connectivity between medical staff and several sensor devices placed in patient's bodies. The mobile platform architecture comprises body sensors that are operated (start and stop measuring) by a personal mobile device using a Bluetooth communication. The mobile device is used to store the data collected by the sensors, then the data could be transmitted over 3rd generation (3G), general packet radio service (GPRS) or wireless local area network (WLAN) to a remote health information system. This architecture presents a new technical approach using a mobile database solution for local storage of the data collected by the sensor devices in the patient's bodies. As above-mentioned, this architecture needs a continuous connection between sensors and the mobile device for data storage, which drastically reducing the lifetime of the sensor's batteries.

The use of mobile systems could help health monitoring in several situations. For example, the control of intra-vaginal temperature allows the detection of several symptomatic situations on women. One of the most well known applications is the occurrence of ovulation and fertility periods. Although this women's parameter could be used in studies of its variations and the evaluation of the effectiveness of gynecological therapeutics, the support to discovery of new contraceptive methods, the prevention of pre-term labor and detection of pregnant contractions. The available solutions to control the women temperature are almost based on coetaneous temperature. These values of body temperature, as presented in [8], are highly dependent on environment temperature. Therefore, the use of women's core-body temperature values could improve the validation of monitoring systems in detection and control of the above mentioned women's health situations. Over the years few systems for continuous control and monitoring of women's core-body temperature was presented. One of these systems was presented in 1994 [9] and 1996 [10]. It consists in an intra-vaginal system for temperature collection. The system needs a permanent radio-frequency connection to a computer. The computer receives all the temperature measures and collects them. The sensor itself could not store the measured values. This limitation imposes the sensor must be near to the personal computer difficult the mobility of the monitored woman. The use of mobile systems frees women to follow their regular day life, always under monitoring. However, if the sensor can collect the temperature measures in long-term way, it is dispensable a permanent connection to any device, which improves the sensor's battery lifetime.

Next, a mobile system is presented based on a Windows Mobile application to monitor a BSN. The following section presents a BSN sensor for temperature collection in long-term way of women's core-body temperature. This sensor should be placed inside vagina [11]. Once the temperature sensor is placed inside women's body it collects core-body temperature instead of coetaneous temperature. This sensor also has the ability to collect long-term intra-vaginal temperature measures. The mobile application could perform a gather operation to get all the temperature measures in the sensor on demand.

3 Hardware

In order to correctly acquire specific data, a corresponding sensor must be used. To achieve this goal, authors choose the MA100 Thermistor [12], which is a NTC Type MA Biomedical Chip Thermistor developed by GE Industrial Sensing and it is exclusively used for biomedical applications. Its main features fulfill the requirements of our solution. Its sensitivity ranges from 0° C to 50° C and its size is 0.762 × 9.52 mm; moreover it is exclusively created for biomedical applications. To get more accurate temperature

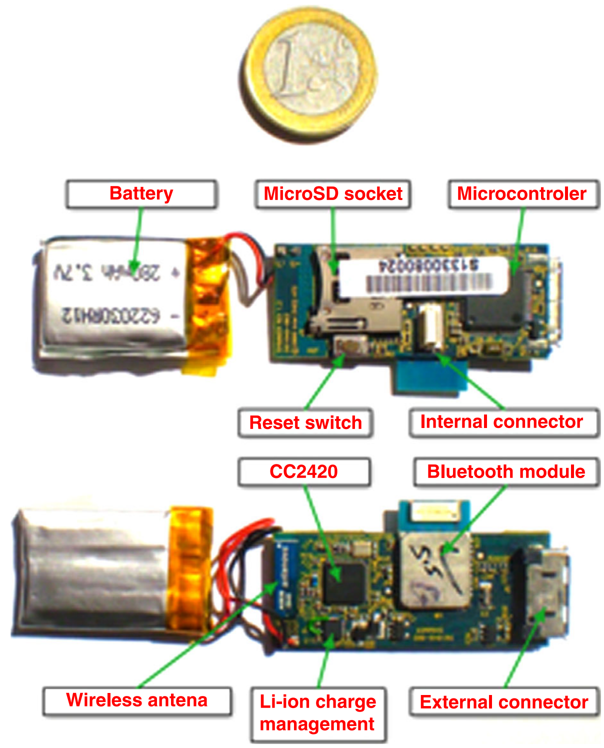

Fig. 1 SHIMMER hardware

readings, the temperature sensor must be placed inside the female cervix that is an ideal thermal source. For this purpose, the MA100 needs to be placed inside the vagina. Although in this example authors use the sensor for intra vaginal sensing, the system can be used with other sensors.

Using this information as reference, authors choose the SHIMMER (Sensing Health with Intelligence Modularity, Mobility and Experimental Reusability) platform as a processor unit for the inherent intra-body system, because its excellent characteristics [13]. It fully supports TinyOS and have the following main components: an 8 MHz Texas Instruments^{TM} MSP430 processor, a Bluetooth$^{®}$ radio communication, a 2.4 GHz IEEE 802.15.4 Chipcon^{TM} wireless transceiver (C2420), a 3-Axis Freescale^{TM} accelerometer, a MicroSD^{TM} slot for up to 2 GBytes, an integrated lithium-ion battery management and some extension boards. Figure 1 shows the SHIMMER hardware platform and its components.

Using a small device as SHIMMER platform allows the user to move freely without having the notion of being on use. Since the sensor placement is on a very sensitive and intimate part of the women the use of a device with characteristics like this permits the women to fell the less intrusive possible.

4 SHIMMER software development

Since medical data has extremely high priority and the security inherent to it is highly important, the authors' objective was to develop innovative and dynamic software. Then, it was needed to create a custom SHIMMER firmware in order to support mobile device connectivity and data transfer.

The custom SHIMMER firmware has several specific characteristics and configurations whose were created specifically for this approach. Since SHIMMER support various digital ports some functions to access the specific digital port and retrieve the raw data from it were created. After the data collection they must be packet for Bluetooth communication. At this point data are transformed and two encryption algorithms are applied. Firstly to the raw data a Rivest, Shamir and Adleman (RSA) algorithm is applied. The public key used to encryption is hard-coded on the SHIMMER device. With the raw data encrypted another secure step is applied. The SHIMMER not only sends the raw data but also some information flags, so, at this time a substitution cipher, the Caesar cipher, is applied. The private key, Caesar dictionary and shift key is hard-coded on the mobile device. Next is explained the behavior and operation mode of the custom firmware.

The SHIMMER will connect to the mobile device trough Bluetooth and it always waits for commands over the connection. The commands are sent from a mobile device, which in turn, receives data from the SHIMMER. Once a command is received and it is valid then it proceeds accordingly.

The firmware supports various commands, such as, *Start*, *Stop*, and *Acquire*. Each command corresponds to the inherent "Start Communication", "Stop Communication" and "Get SSD values" and results in a different operation. The Start command indicates that SHIMMER must starts data collecting. If a Bluetooth connection is available data are simultaneously sent to the mobile device and stored at the SD card, otherwise it only stores them at the card for further analysis.

That way, SHIMMER prevents any data loss associated to Bluetooth connection and allows future analysis of data. All the data analysis is performed in real time. The Stop command as the name suggests stops the data collection. Finally, the Acquire command performs the transfer of all the storage data on the microSD over Bluetooth communication to the mobile device. Figure 2 presents the SHIMMER firmware diagram and it provides all the above-mentioned features. After the SHIMMER initialization it keeps in standby operation waiting for commands over a Bluetooth connection. At this point it waits for three special input commands. When the command "Start Communication" is received, the SHIMMER enters on a cyclic procedure with the following steps: (i) data collecting from the digital port; (ii) encryption of data; Send data over Bluetooth if available; and (iii) Store data on the SSD card. If the Command "Get SSD values" is received, the SHIMMER will look on the internal SSD card form data, if it has any data it will be sent over Bluetooth connection to the mobile device. Otherwise, if the "End Communication" command is received the SHIMMER will close the Bluetooth port and goes to offline mode.

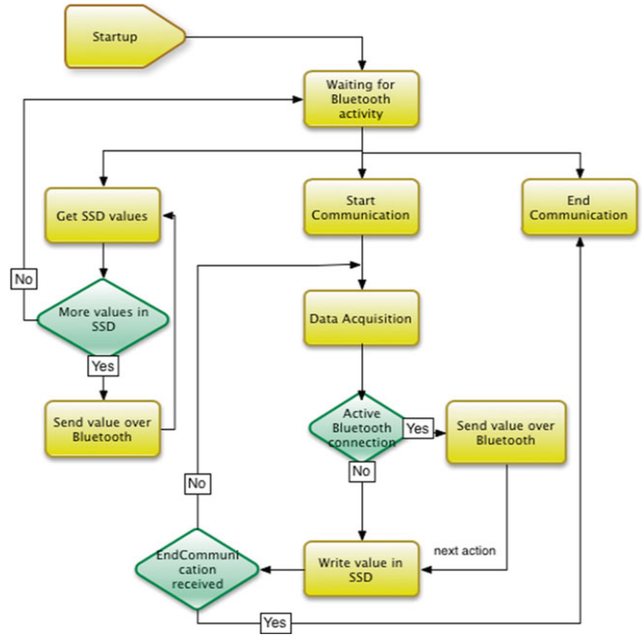

Fig. 2 SHIMMER custom firmware diagram

5 Windows Mobile application

After the construction of the custom firmware, it has the ability to connect and transfer data with a mobile device. Therefore the next goal was to develop the inherent mobile device application. Since Symbian version of this application was already proposed [14], authors assume that a Windows Mobile approach is a must in terms of ease of access to equipment, user friendly and devices price. After Symbian, Windows Mobile devices are the cheapest in the market making an easy access to them by a greater number of the population worldwide. Windows Mobile has a long history and since Microsoft is investing a lot of time, money and energy into the future of Windows Mobile we believe that this platform is a must in terms of technology and development.

5.1 Architecture

This system assumes a three-layer architecture. Through this approach, the architecture has its own responsibilities and allows extraction of system functionalities where each layer

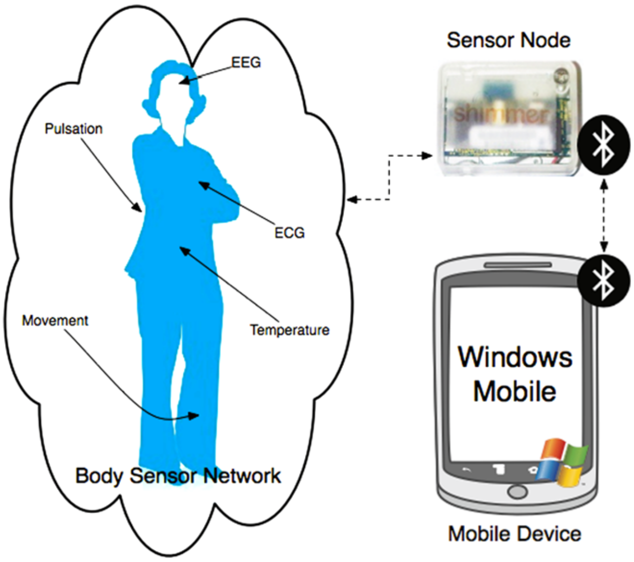

Fig. 3 System architecture

is responsible for an individual task. Sensors are responsible for data collection, sensing health parameters of a given person. The BSN (Body Sensor Network) assumes the data collection and storage, protecting them from the external world and non-authorized accesses. The mobile device assumes data processing and presentation of all received data. Consequently, if the mobile device malfunctions, the connection is broken or is not present; data are not compromised because they will be stored in real time on the SHIMMER node.

In addition, the mobile device is independent from the involved BSN technologies because it may use a wired communication, a 2.4 GHz wireless radio or any other. Current implementation only supports wireless Bluetooth communications. The only thing that really matters for a perfect data gathering, processing, and presentation is the type of connection between both mobile device and BSN node. This proposed system architecture and its construction, testing and validation are easier to accomplish because every module can be worked and tuned as a single part. Figure 3 presents the system architecture.

5.2 Bluetooth connectivity and security

Bluetooth is one of the most widely available wireless technologies and is used by over 2 billion Bluetooth-enabled devices, e.g., cell phones, mobile devices, laptops, gaming consoles and many other devices. It is the predominant wireless personal area networking technology. Therefore, a robust connection and communication mechanism had to be created [15].

The BSN and its nodes are protected from the outside world through a specific connection port and a unique password that is hard coded. Using two or more mobile devices to communicate with the same sensor leads to a priority system. Only one mobile device can communicate with a sensor node at a time. This password is a prerequisite for device pairing and using it correctly will give access the Bluetooth connection, data acquisition, analysis, and presentation. On the development processes the main focus was on system robustness, convenience, and user-friendliness since gathered are critical to human life and behavior.

The Bluetooth connection has its advantages in term of user friendliness but have some faults in terms of security [16]. Since Bluetooth communication does not provide a fully secure connection and data exchange, some additional encryption methods were created to achieve more security, robustness and reliability [17]. In a given scenario where the communication is submitted to a sniffer or any other attack the data is not compromised if detected. Since the detectors do not know the stream structure neither the encryption associated to them, the data acquired is encrypted and not readable. Only an authenticated and paired mobile device running the application can receive, process and present the data correctly.

Since the sink node of this prototype is very small, it offers the possibility for being placed on small places such as patient belt or pocket. Then, it supports a mobile and portable solution for real time data monitoring, processing, and visualization.

5.3 Data presentation algorithms

Data is an extremely important factor of the application because it uses human vital signs, so, the application must perform error tests constantly. It must be the most robust and precise as possible, so all the data received must be precisely analyzed in looking for possible errors. Each time the application receives data from the sensor node, it will perform specific tests in order to guarantee that user really see valid information and not false positives. The application suspects of all received data, since it is received through Bluetooth and data may be corrupted or compromised. If some data was cataloged as corrupted or compromised, the application will notify the user about it immediately.

The data presentation algorithms are divided in two main steps: Decryption and data Transformation. The Decryption algorithms are responsible for converting the encrypted data into raw data for later analysis and transformation. Since two encryption algorithms are applied on SHIMMER, at this point the inverse method must be applied. First, the Caesar cipher is decrypt (using the alphabet and key stored on the device). At this point and if the data is correctly decrypted, the inherent stream flags are available, plus the raw data encrypted. Now, the raw data must be decrypt using the (RSA) private key stored on the device. Now, data are ready for the second part of algorithms. The second step is the transformation of raw data into a meaningful data for the device and the inherent representation on screen.

In this approach, data flows in streams. Each stream has a specific data format. By default, the BSN node captures and sends the streams with a frequency of 1 second. Since the first received data until the final value, it passes through several algorithms (taking for granted that data was correctly decrypted). The goal is to convert the received data, in bytes, to the inherent correct graphical presentation. This step has several algorithms linked together to reach the end result that is the correct point draw on the mobile device monitor.

- The first step is to strip the correct range of bytes from the stream received to post analysis. The stream is composed by the bytes acquired from the BSN and some control flags. This step is essential to security improvement because the received stream have some associated flags. After that, and if the bytes number are correct, we must strip the correct value from the stream. At this point, we have guarantees that we are working with the correct data and we can go to the next step.
- The data stripped it considered raw data and must be converted to an appropriate temperature value, in Celsius degrees. Such conversion should be performed with another algorithm. All the transmitted data is organized in bytes, and then a transformation is needed. The algorithm must convert a 12-byte value, which corresponds to 4096 single values, in the equivalent temperature value. Afterwards, the temperature is striped and ready for display drawing. This step is very robust and has several related activities because all these activities are done in real time and they are used each time that new data is received. These activities will be reproduced on the display by informing the user of the real temperature, maximum and minimum values or even the data frequency.

The graphical representation of the signal is very important to assist and inform the patient in real time. In order to draw the correct points on the graphic, the calculation of the bottom line of the graphic, based on screen resolution and text occupancy was performed. A transformation function is used to map the 4096 values on a zero to one scale. This representation is totally dynamic and will adjust itself to the situation presented adjusting the y-axis according to the temperature value. By default, the graphic will have a range of valid temperatures to display but it will automatically adjust to a new scenario if the data received demands.

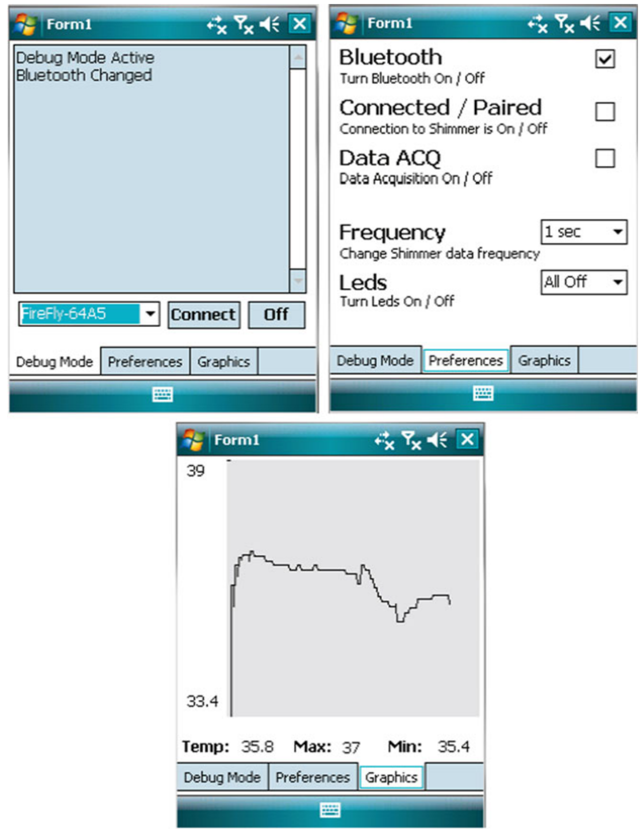

Fig. 4 Windows Mobile 6 emulator

6 User interface, deployment, and validation

6.1 User interface

The designed user interface was created to be clean, simple, and easy to use and show the necessary and useful information in a good meaningful way.

Figure 4 presents a screenshot of the development application running at the Windows Mobile 6 emulator. The interface has three main screens:

1. The first one acts as debug window. It will inform the user about all the information gathered and custom messages for specific events like emergency situations, connectivity problems, corrupted data and others.
2. The second screen owns the configurations and preferences. Here, all the standard configurations are shown and they are the following: Bluetooth connectivity, Connection, Data acquisition, Frequency, LEDs.
3. The last screen is the presentation screen. It is the principal screen and where the user has a visual presentation of the gathered data.

Regarding the emulator, it is important to mention that authors were able to activate and use the Bluetooth on the emulator and used the RFCOMM and SPP (Serial Port Pro-

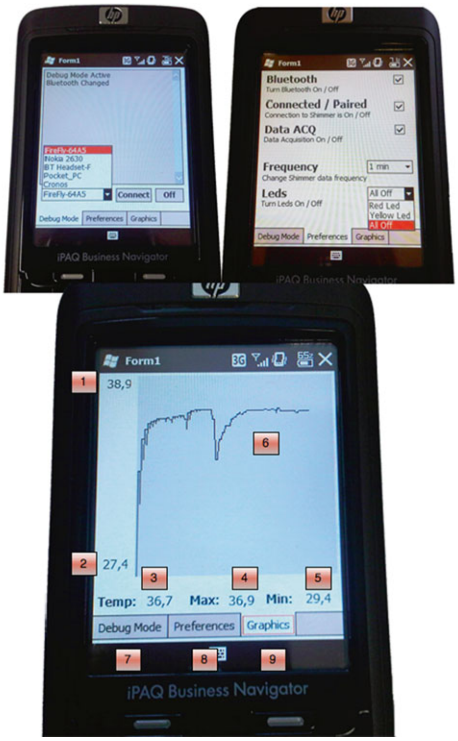

Fig. 5 Windows Mobile graphical presentation

file). By default, it is disabled and some special configurations were needed on the windows default Bluetooth stack to perform it.

Figure 5 presents a screenshot of the instantaneous monitoring signal value. In terms of the mobile application functionalities two areas are presented, (i) a text information, and (ii) a graphical signal representation. In Fig. 5 each label represents the following:

- Label "1" represents the maximum absolute temperature value.
- Label "2" presents the minimum absolute value.
- Label "3" points the instant temperature value.
- Label "4" shows the maximum relative value of the temperature that current session has acquired.
- Label "5" presents the minimum relative temperature value.
- Label "6" shows the graphical representation of data.
- Label "7" depicts the Debug screen,
- Label "8" presents the Preferences screen.

Finally, label "9" indicates the current screen, the Graphics screen.

6.2 Compatibility

The mobile tool was deployed, tested, and evaluated on several different devices, such as the HP iPAQ Business Navigator (Windows Mobile 6.5), the HTC HD (Windows Mobile 6) and the Asus M539W (Windows Mobile 6). The application ran effortlessly on every one without any problems.

Run on background Since those recent mobile devices are primarily used to make phone calls, text messages, calendar events, emails and Web browsing the system was designed to cooperate with them without disturb each other's. When any of these functionalities are under use, the application is prepared to run on background while a person uses the mobile device without issues. On all evaluated devices were performed several tests such as phone calls, text message exchange, Web browsing and, as expected, the data continuously flowed from the Shimmer to the application without any problem.

6.3 Performance evaluation

Some performance tests were made and the results were compared between devices. Series of thirty experiments were performed and results express the average of them.

Table 1 summarizes the results between the evaluated devices in five different approaches.

Initialization time The first column presents the startup time that the mobile device takes to launch the application.

Connection time The second column has the connection time (in seconds) between the mobile device and the BSN.

Graphical presentation The third column presents the time (in seconds) taken between the initial communication and graphical data presentation.

Smoothness The fourth column informs the smoothness of the application in a range of 1 % up to 100 %, being the 1 % the worst performance value and 100 % the best one. These tests take several parameters in consideration, such as smoothness between menus and graphical interface, temperature signal update, label update, and graphic scaling.

Percentage of corrupted data Finally, the last column indicates the percentage of corrupted or malformed data. Taking into account that on an interval of three hundred seconds an average of six streams are not fully correct let us assume that the overall results are very acceptable.

Since multithread is a software implemented and not a device feature, it is available on all devices, providing the user the capability to make phone calls, text messages, web browsing, email or even play games, while the data is continually acquired.

Table 1 Performance results

Device	Initialization time (in seconds)	Connection (in seconds)	Graphical presentation (in seconds)	Smoothness (percent)	Of computed data (300 s) (%)
HP iPAQ	6 s	2.2 s	1.5 s	75.00 %	2.66 %
HTC HD	3 s	2 s	1 s	90.00 %	1.76 %
Asus M539W	5 s	2.1 s	1.5 s	80.00 %	2.33 %

6.4 Resource consumption

In terms of battery power consumption, the mobile device consumes almost the same when compared to a scenario where a standard Bluetooth connection is used. In several tests carried out the battery drained an average of 4 % to 6 % when using the application.

The application uses 19 KB of persistent storage space, 320 KB of cache memory (for preference settings), 1.87 MB of RAM, and 4 % of CPU usage. To validate and verify the veracity of the results, the same were compared against a similar computer application [18] using the same data source, and the results, as expected, are exactly the same.

Despite the small size and mobility of mobile devices, the application is user friendly, fast and robust in order to be used on every location without data loss. Using mobile applications the user gains mobility and eliminate the personal computer to view the monitored signals.

7 Discussion

Different approaches already exist to gather and present data from BSNs in an easy and meaningful way to the user, although all have some disadvantage comparing to this proposal. This system was managed to meet several conditions of excellence in engineering. With combination of various technologies and methodologies it could offer a real time data acquisition, processing and presentation. Data is transferred through a Bluetooth connection and it is protected from the outside world with several levels of encryption, as above described. The user interface is easy to understand and can be used by a large number and types of people. The mobile device introduces a great mobility and the small size of the BSN offers a new level of portability and small level of intrusion.

8 Conclusions and future work

The use of mobile systems for continuous monitoring provides a big benefit in quality of life to patients. These systems allow patients to continue their normal day life always under monitoring. The combination of body sensor networks and mobile devices provides great personnel monitoring systems.

A Windows Mobile application was presented to monitor, control and analyzes of human parameters collected by an autonomous body sensor. The sensor has the ability to collect long-term human parameters measurements and by demand operation, sends them to mobile device over a Bluetooth connection. As example, it was presented a sensor to measure cervix women's temperature. This system pretends to inform women when the occurrence of ovulation and fertile periods. The data collected by this system also could be used to identify some relations of this parameter with some health situations in women, like effectiveness of gynecological therapeutics, support to discovery of new contraceptive methods, and pre-term labor prevention.

In the future, we are planning the inclusion of new body sensors in the BSN for monitoring other human parameters.

Acknowledgements This work has been partially supported by the Instituto de Telecomunicações, Next Generation Networks and Applications Group (NetGNA), by National Funding from the FCT—Fundação para a Ciência e a Tecnologia through the PEst-OE/EEI/LA0008/2013 Project, by Grant-in-Aid for Scientific Research (S) (2122002) of the Ministry of Education, Culture, Sports, Science and Technology, Japan, and by the AAL4ALL (Ambient Assisted Living for All), project co-funded by COMPETE under FEDER via QREN Programme.

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