Hybrid wireless sensor network for homecare monitoring of chronic patients

Radu Dobrescu, Dan Popescu, Maximilian Nicolae, and Stefan Mocanu

***Abstract*—** The paper presents a hybrid wireless sensor network which contains both mobile and fixed nodes, which enables the monitoring of chronic patients and their home environment via normal or, if necessary, emergency communication with long-distance transmitting system like Internet. Each patient and his/her home compose a hybrid node, i.e. a sensor node pair, one for patient (mobile) and one for his/her environment (mobile or fixed). The hybrid node is integrated in a real-time homecare monitoring system able to monitor and diagnose patients outside hospital and also to control the home/car ambiance. If the patient is transported by specially equipped car, the hybrid node becomes fully mobile. Because the number of assisted patients is time-dependent, we can consider that the hybrid node belongs to a scalable ad-hoc wireless sensor network (WSN). This WSN covers an administrative delimited area and contains a central fixed node which monitors the patients and emergency communication and also makes decision for the entire network. One can say that the network has three levels: basic (hybrid nodes for chronic patients), medium (general practitioner and ambulances), and high level (specific physicians at hospital and city hall services).

Both nodes, mobile and fixed are presented as same as the design stages which drove to respective hardware architecture. From the software architecture it is described the communication engine because of the particularity in its implementation. Several critical tests were made for reliability of the architecture and some of the results are presented.

***Keywords*—** hybrid wireless sensor network, homecare system, remote sensing and diagnosis, digital signal processing, communication technologies.

I. Introduction

INFORMATION and communication technologies have many new application in the medical field, such as diagnosis and expert systems, cognitive systems, telemedicine, *eHealth* concept [17], fast medical signal processing algorithms [14] and so on. Willmer [16] points out that the increasing use of ICT by patients and medical practitioners alike improves the quality of health care delivery.

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There were several projects that focus on this E-Health topic. One very similar example is the AMON system [11]. Already tested for two and a half years, this EU IST sponsored project proved the efficiency of the tele-monitoring system including a portable telemedical monitor, a wearable medical monitoring and alert system targeting high-risk cardiac/respiratory patients. The system includes continuous collection and evaluation of multiple vital signs, intelligent multiparameter medical emergency detection, and a cellular connection to a medical center. Technically, the system described in this paper offers the same medical facilities with a supplementary advantages assured by an evolved processing and communication technology. By integrating the whole system in a safe and reliable enclosure and applying low-power design techniques, continuous long-term monitoring can be performed without interfering with the patients' everyday activities and without restricting their mobility.

A "Vital signs data monitoring via GPS navigation system" was proposed in [12] and it was tested by specific physician at Maharaj hospital, Chiang Mai, Thailand. The patient home unit consisted of four components: ECG detector and transmitter, body temperature monitor, heart rate monitor, and a PDA (personal digital assistant) monitor. The patient position was reported by GPS aid.

Another home care medical application was presented in [13]. The proposed monitoring system named "Intelligent Reminder System of Having Medicine for Chronic Patients" had dynamic monitoring screens, auto-oral notifying system, alarm system, timing and procedure management for having medicine, and auto tracing patient system by GSM system to deal with all kinds of patients without punctually having medicine.

Progress of the medical ICT application is presented in [14]. The prototype of the "Multifunctional health information system for the comprehensive management of a sleep clinics franchise chain" should facilitate the decision-making process and the clinical management for the diagnosis and treatment of sleep disorders and related diseases.

Progress in wireless sensor networking and internet facilities have opened up new opportunities in home automation for healthcare. Portable medical devices were designed and used in recent years. For example, chronic patients are currently using personal digital assistant (PDA) to collect and send critical medical data to a follow-up center [12]. These smart systems allow the chronically ill people, elderly and disabled people to stay in their homes, instead of moving to a costly health care facility. In addition to causing medical stress, it also cost much society medical resource.

The rate of collection of data at basic level should be higher in this type of network than in many environmental applications. Efficient communication and processing are essential. Event ordering, time-stamping, synchronization and quick response in emergency situations are also required.

Sensors and other devices must operate in real-time, with enough reliability to yield high-confidence data suitable for diagnosis and treatment. Since the network will not be maintained in a controlled environment, devices must be robust [1]. The integration of different types of sensors, RFID tags, and back-channel long-haul networks may necessitate new and modular node architectures [2].

Patient tracking can be considered at three levels: symbolic (e.g., a room or house number), geographical (e.g., GPS coordinates of a patient on an assisted living area) and relational (e.g., a pager or SMS connection) [3].

Due to the heterogeneity present in the network, communication between devices may occupy multiple bands and use different protocols. In order to avoid interference in the increasingly crowded unlicensed ISM band, biomedical devices may use the WMTS band (wireless medical telemetry services, at 608 MHz) [4]. The homecare network must provide middleware interoperability between devices and support unique relationships among devices such as implants and their outside controllers [5]. In-building operation has more multi-path interference due to walls and other obstructions, breaking down the correlation between distance and connectivity even further. Unwanted emissions are likely to be rigorously restricted and even monitored due to safety concerns, particularly around traditional life-critical medical equipment.

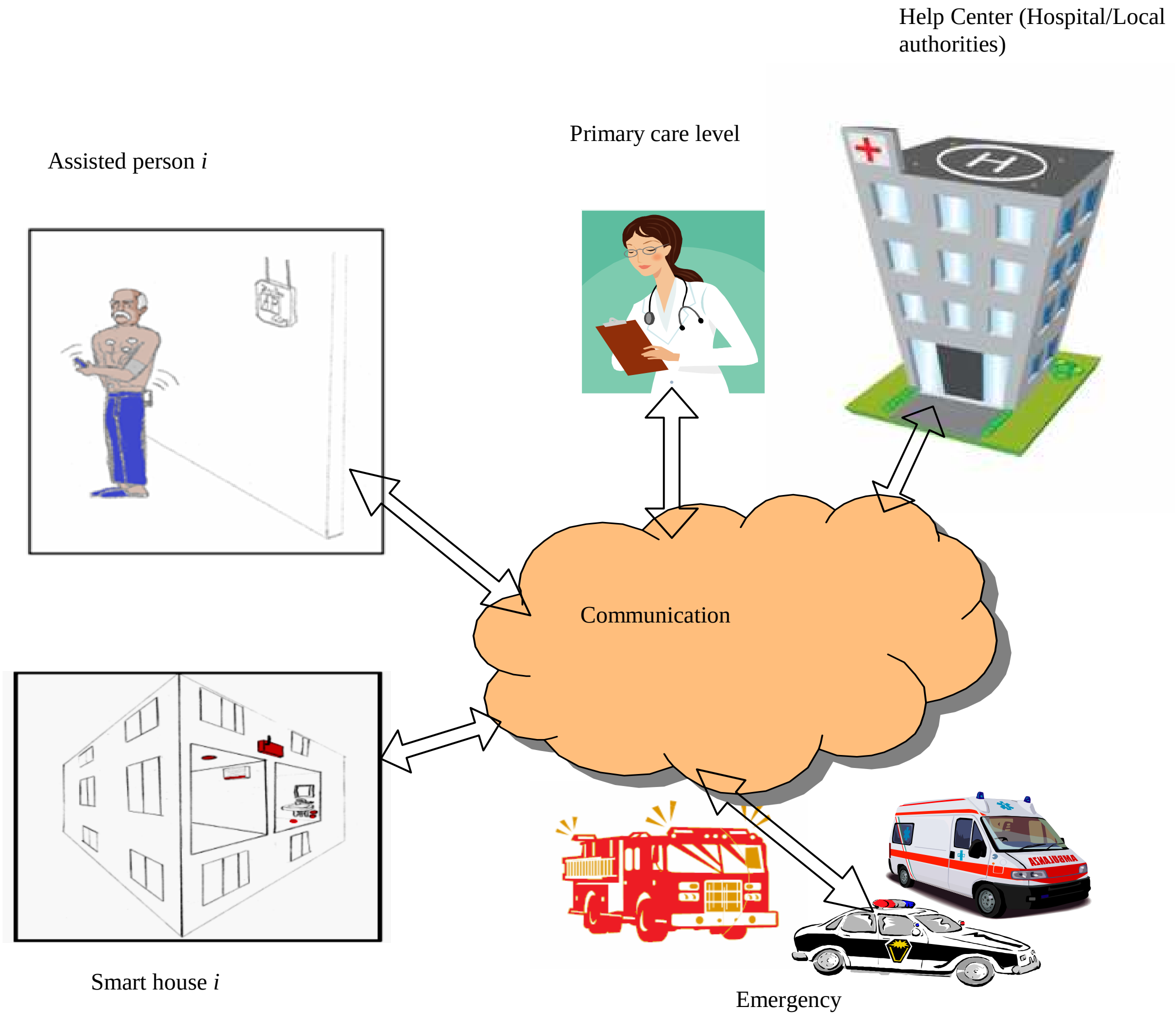

Fig. 1 WSN configuration for homecare monitoring

Data may be aggregated and mined at multiple levels, from simple on-body filtering to cross-correlation and history compression in network storage nodes [6]. Limited computational and radio communication capabilities require collaborative algorithms with energy-aware communication. Richly varied data will need to be correlated, mined and altered.

As a result, the main requirements for wireless homecare monitoring networks are [7]: real-time data acquisition and analysis, reliability, robustness, patient tracking, object detection and recognition, interoperability, communication amid obstructions and interference, multi-modal collaboration, multi-tiered data management, and energy conservation.

We propose wireless sensor network (WSN) architecture for smart homecare that possesses the essential elements of each of the future medical applications, namely:

- Integration with existing medical practices and technology,
- Real-time, long-term, remote monitoring,
- Miniature, wearable sensors, and
- Assistance to the elderly and chronic patients.

Solutions integrate intelligent sensors into portable devices coupled with appropriate data acquisition modules and medical high- quality services. The research aims for disease management, rehabilitation and treatment at the point of need.

Because the patients (assisted persons) have chronic diseases, sometimes with mobility or memory problems, their environment (home) monitoring is also necessary. If the patient is transported by car, this car becomes his/her new “environment” and must be also monitored. Thus, the wireless sensor network is hybrid, containing both patient nodes and environment node nodes. Also, the wireless nodes can be mobile or fixed (Fig. 1).

Each patient has a corresponding hybrid node i ($i = 1,2,\dots,n$) named basic node, with two sections: one for patient monitoring (mobile, attached on the body) and other for environment monitoring (fixed, room or house of patient). Other mobile nodes are the emergency nodes: ambulances, police cars, and fire trucks.

Besides smart homes, other fixed nodes are: primary care nodes (general practitioner) and Help Center (specific physicians at hospital and local authorities). In terms of functionality, the nodes are on three levels:

► Basic level contains nodes for data acquisition from monitored patients and their homes (inside and outside smart home).

► Intermediate level contains primary care nodes and emergency nodes.

► High level contains an expert center named Help Center (Hospital and Local authority).

The paper presents the architecture of the hybrid node which enables the integration of these basic nodes in a smart homecare monitoring systems, WSN based. The hybrid nodes have two main functions: data acquisition and data communication. The requirements are different for the two mentioned sections: patient and environment.

II. Acquisition Module of the Hybrid Node

The devices attached to an assisted person should be treated as a mobile sensor node called patient node (PWN). The requirements for PWN are the following: portability, lightweight, high supply autonomy, easy operated interface, capability of sensing medical signals and wireless communication support. PWN is fixed on the patient and acquires standard medical signals like electrocardiogram ECG, blood oxygen saturation SpO_2, heart rate HR, blood pressure BP and body temperature BT.

As it can be seen in Fig. 2, in order to carry out the above requirements we used an evaluation module for low power wireless monitoring from Texas Instruments, named eZ430-RF2500. The eZ430-RF2500 uses the MSP430F22x4 which combines 16-MIPS performance with a 200-ksps 10-bit ADC and 2 op-amps and is paired with the CC2500 multi-channel RF transceiver designed for low-power wireless applications as ZigBee. To this module it could be easily interface special body sensor as same as actuators like speaker for audible warning or dosing devices.

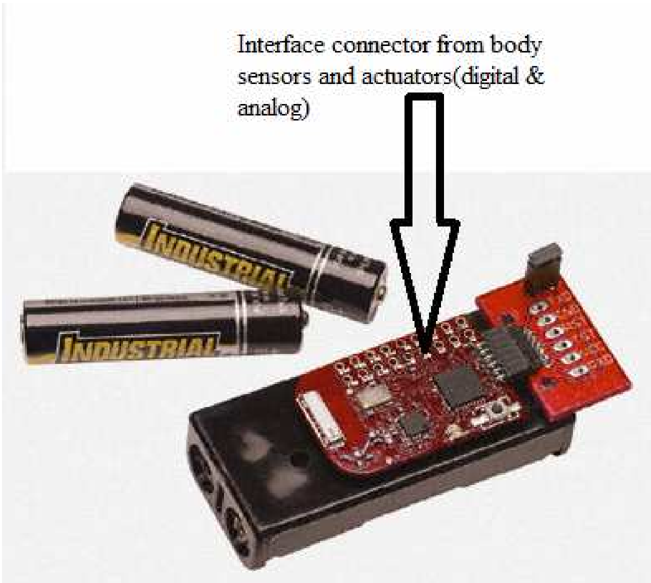

Fig. 2 PWN evaluation module eZ430-RF2500

For remote healthcare applications, small size and weight of PWN sensors are sine-qua-non conditions. Installing large or heavy sensors on the human body is impossible. On the other hand the PWN sensors must be produced in great numbers and with a cost as low as possible. This makes the task of installing such sensors on patient much easier.

Some examples of envisioned missions where the WSNs can quickly make an impact are the following [7]:

- *Sleep apnea*. Every night, network alerts provider and patient if oxygenation falls below a threshold. Monitoring can continue while treatment efficacy is assessed.

- *Journaling support*. Journaling is a technique recommended for patients to help their physicians diagnose ailments like rheumatic diseases. Patients record changes in body functions (range of motion, pain, fatigue, sleep, headache, irritability, etc), and attempt to correlate them with environmental, behavioral, or pharmaceutical changes.

- *Cardiac health*. Cardiac arrhythmia is any change from the normal beating of the heart. Abnormal heart rhythms can cause the heart to be less efficient, and can cause symptoms such as dizziness, fainting, or fatigue. In a homecare setting, wearable EKG sensors can monitor for the condition continuously, over days or weeks, until the event occurs [8]. The recorded data is promptly sent to the physician for analysis. If the event is serious enough, the emergency communication channel may be used to call for help, or it may be dispatched automatically. The module for data acquisition from patient is characterized by energetic efficiency and has a small battery to power supply the mobile node.

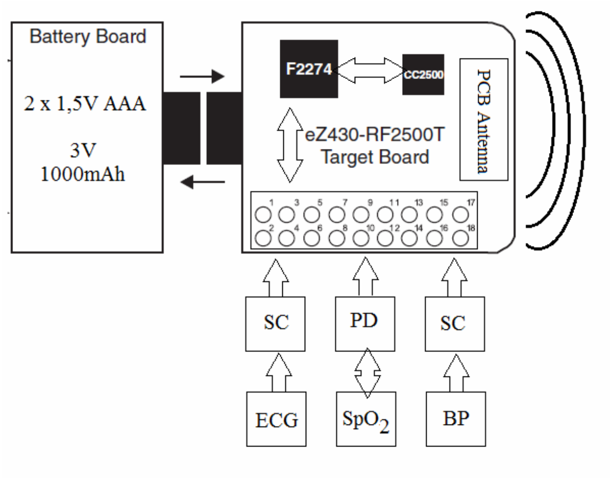

Fig. 3 Bloc scheme of PWN

The signal acquisition module is built around low power consumption, 16 bits microcontroller. In Fig.3 it is presented the bloc diagram of the PWN in a specific configuration, namely for blood and heart parameters' monitoring. The significance of notations in Fig.3 is the following: ECG – Electrocardiography signal, SpO_2 – Oxygen saturation or dissolved oxygen signal, BP – Blood pressure signal, SC – Signal conditioning instrumental amplifier, PD – Photo detection conditioning instrumental amplifier. Both SC and PD can be realized using the internal op-amps of the microcontroller. Alike above measures it can be very easily monitor others parameters such as environmental parameters. The two batteries used are typical capacity batteries found in commerce. Regarding the experimental results presented in the final part of this paper, the module autonomy is of over two weeks.

For the sensor models were used data acquisitioned with Holter equipments from ASPEL [18], as follows: – HoICARD CR-07 for blood pressure and AsPEKT 812 for ECG. The transmission is wireless, using ZigBee. For the measurement of SpO_2 we have utilized a DS-100A sensor with two photodiodes (red and infrared) placed on a finger [19]. The signal from this sensor is demultiplexed, amplified and then separated in *dc* and *ac* components, in order to compute the impulse period and the saturation level of the oxygen in blood.

PWN cooperates with a fixed node, located in the house and called home wireless node (HWN). This node takes the data from PWN and from the sensors of home ambiance monitoring system, produces a primary data processing and communicates with nodes on intermediate level or high level. Another task of HWN is to provide video surveillance of the assisted person in order to signal failures.

HWN structure contains two functional modules: module for acquisition, processing and communication and power module. The first contains four functional blocks: sensory data acquisition, video acquisition, digital processing and communication. As you can see in Fig. 3, this module is developed around a DSP. This is because DSP gives designers the best combination of power, performance, price and flexibility and allows them to quickly deliver their real-time applications to the market [9]. The programmable flexibility of DSP enables developers to implement complex algorithms in software. Not only can a DSP support a video codec like MPEG-2 and easily handle different resolutions with a simple software upgrade, but it can implement emerging codecs and standards as they arise without hardware redesign. It is used the High-Performance, Low-Power, Fixed-Point DSP TMS320VC5509A with 5-ns Instruction Cycle Time, 200 MHz Clock Rate, based on the TMS320C55x DSP generation CPU processor core. The C55x™ DSP architecture achieves high performance and low power through increased parallelism and total focus on reduction in power dissipation.

The implementation contains a large amount of memory for an embedded device composed of 32Mx16bits synchronous DRAM (MT48LC32M16A2) and 512Kx16biti Flash memory (AT49BV802DT). The transfer of digital data output of video decoder is perform by the fast DMA included in the DSP. For each data available the video decoder generates an interrupt which is synchronized with a DMA event. The DMA transfer is dependent on the occurrence of this event. Each frame taken at high speed (20 fps) is transferred in the SDRAM. Then, the DSP will analyze some rare frames (2fps) for which, if it will find something "interesting", it will be capable to access the neighbour frames from the memory in order to improve the decision.

The processing power of the HWN helps to eliminate unwanted floods at the remote data centres by being able to decide over the relevance of data and others important events like deviations of signals from their correct pattern. It can also decide over the optimal hours when will download uncritical data that are stocked over a day period.

The proposed homecare node integrate a coherent set of interacting portable and fixed devices, while preserving person mobility and independence and bringing optimum assistance to medical support. This integration includes the following features:

- Automatic detection of falls, considered by professionals as a major risk for elderly and disabled people;
- Automatic monitoring of vital medical physiological parameters such as ECG, SpO_2, HR and BP.

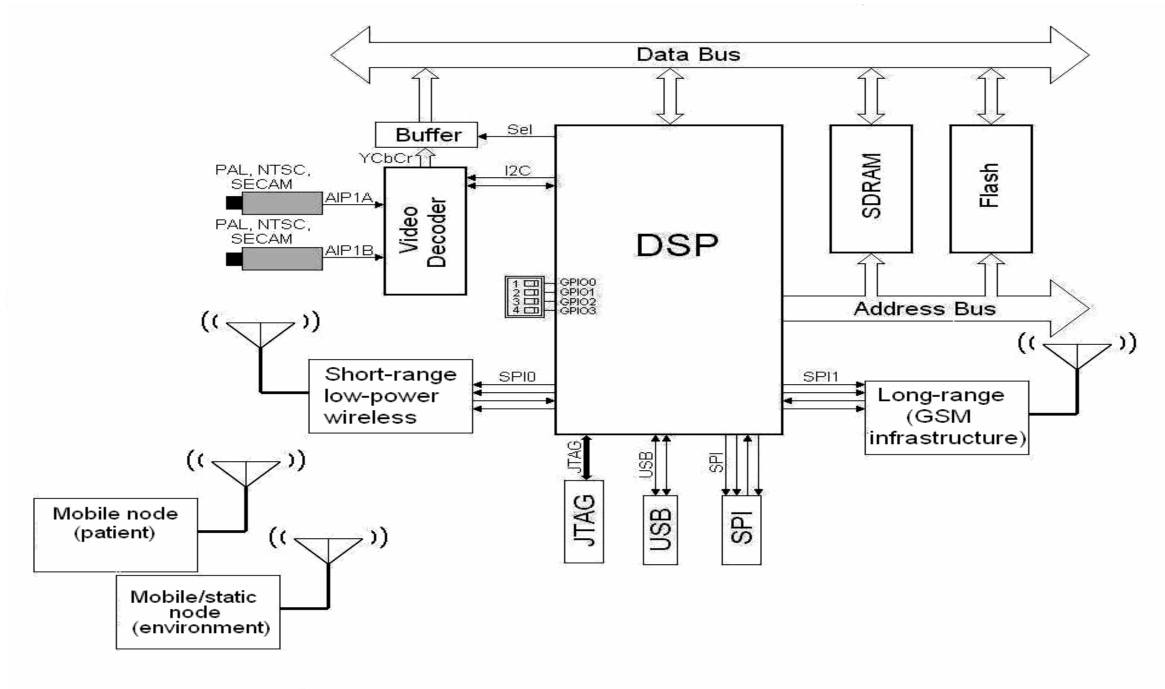

Fig. 3 HWN structure: block diagram of the acquisition, processing and communication module

- Communication of physiological parameters and voice between the user and external intervening parties such as physicians (primary care), social institutions (local authorities).

III. Communication Modules of the Hybrid Nodes

Wireless communication tends to be one of the major trends in medical applications to increase usability and comfort in the long time patient monitoring. Inside the network shown, nodes can communicate with each other. PWN can communicate over short distances with HWN and collection nodes of the car rescue or hospital. This standardization enables integration of WSN-based platforms in an advanced homecare monitoring system. In normal cases, over long distances the communication of PWN with primary care level and help center is provided via correspondent HWN.

The monitored parameters are wireless and transmitted to HWN that is also connected to the public phone network. HSW processes and relays the received parameters and sends alarms to the external people such as socio-medical monitoring centers, neighbors and medical doctors, whoever is best suited to intervene depending on the type of alarm. When the link is established, the user may speak with healthcare professionals.

In order to choose the proper technology for communication infrastructure, in Fig.4 a comparison between available wireless communication technologies was made [10].

For technology selection, two important features are represented on the axes, namely maximum distance and data rate, both in logarithmic scale. The area of each technology representation figures the level of energy consumption approach in design of the respective technology. A small area represents a standard with energy consumption optimization; instead a wide area represents a technology which was not designed for energy efficient.

Based on requires demanded by the mobile sensor network, this representation can be seen like a guide from which, can be chosen the suitable wireless technology for a communication module. An example of choice of the proper technology is presented in Table I where the eliminatory demand was low power consumption.

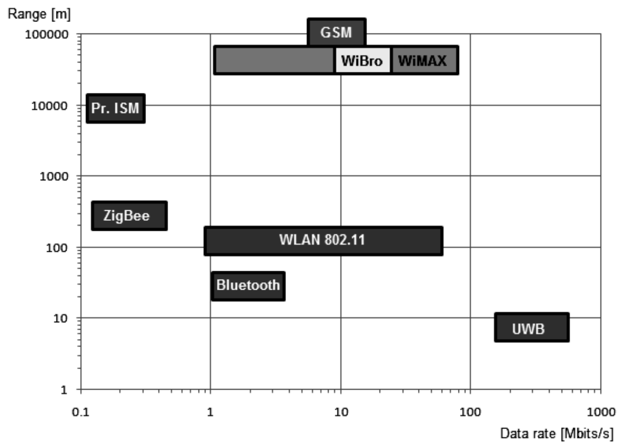

Fig. 4 graphical representation of performances of wireless technologies

Because the UWB technology (Ultra Wide Band) is designed for PANs (Personal Area Network) and has a covering range of 10m, it also loses its viability in the mobile sensor network field. Finally we remain only with two options for communication infrastructure technology, ZigBee (practically it was especially develop for such application as mobile sensor networks), and GSM through its lower cost data transfer services GPRS, EDGE and the newly entered in the cheap communication category, HSDPA.

TABLE I
LOW POWER WIRELESS TECHNOLOGIES

		Range	
		Low	Wide
Data rate	Low	ZigBee	GSM(GPRS)
	High	UWB	WiBro, GSM(HSDPA)

The application requirements and the limitation imposed by building a mobile node for PWN, determined us to use a CC2500 transceiver from Texas Instruments. The technical characteristics of the CC2500 transceiver, which recommended it for our application, are:

- High Performance RF-CMOS 2.4 GHz ISM band Radio Transceiver targeted for low power wireless communication as IEEE 802.15.4 and ZigBee Applications
- Programmable Output Power from -30 dBm up to 0 dBm
- Receiver Sensitivity -101 dBm
- Ultra-Low Power Consumption:, RX- 13.3 mA, TX- 0dBm mA (at max transmit power of 0 dBm)
- Fast registry and buffer access via a SPI interface
- Programmable data rate from 1.2 to 500kbps
- Industrial Temperature Range: -45 ^{o}C to 85 ^{o}C

Its characteristics are consistent with our requirements for a low-power, cheap, modular, reliable, mobile node. Using this transceiver, our platforms are able to communicate acquired information to a management node. This node is capable to transmit date over distances longer then 50m indoor to the HWN.

The IEEE 802.15.4 standard specifies that communication should occur in 5 MHz channels ranging from 2.405 to 2.480 GHz. In the 2.4 GHz band, a maximum over-the-air data rate of 500 kbps is specified, but due to the overhead of the protocol the actual theoretical maximum data rate is approximately half of that. While the standard specifies 5 MHz channels, only approximately 2 MHz of the channel is consumed with the occupied bandwidth. At 2.4 GHz, 802.15.4 specifies the use of Direct Sequence Spread Spectrum and uses an Offset Quadrature Phase Shift Keying (O-QPSK) with half-sine pulse shaping to modulate the RF carrier.

The same transceiver we will also find on the HWN for communication over short distance, but not like in the PWN case where the transceiver is controlled by a ultra low power microcontroller (MSP430 family from TI), it is controlled by the central processing unit of the node, a DSP microprocessor. In order to ensure the modularity of the system, we have chosen our electronic components so that the communication between them is standardised.

The HWN will have also a communication module for long distance. Looking in table I on the wide range column we will find the GSM infrastructure. The WiBro is also presented in table but not in our location so we couldn't test it. Instead we tested the worst case scenario for GSM data transfer technology, GPRS. It was obvious that if this tyoe of connection will succeed (with nominal speed of 48kbps), the faster EDGE (384kbps), actual HSDPA (7.2Mbps) and future HSPA+ (42Mbps) will support even HD video streams without problems. For reliability, some backup solutions for communication are also possible (wired or wireless).

The software of communication module is divided in a communication part and an application part. The link between the communication and application part is the dictionary of objects. The communication part contains the task of communication in network and a real time kernel that includes a task launcher, a Round Robin scheduler, resource sharing flags and handles of interrupts. The application part contains up to seven tasks witch solve all the equipment demands less those in connection with the communication in network.

The link between the communication and application part is the dictionary of objects. In Fig.5 it is showed the software structure.

Each task has a status flag in FLGX byte and a mask flag in MASX byte. Thus the bit 0 of FLGX, called flgx_0 is the status flag of task number 0, task_0, while bit 0 of MSCX, mscx_0 is the mask flag of task_0, bit 1 - flgx_1 and mscx_1 for task_1 and so on. A task is active or inactive if the mask flag of this task is set or not. A task is ready to be launched in execution if the status flag of this task is set and it is cleared after the task was launched.

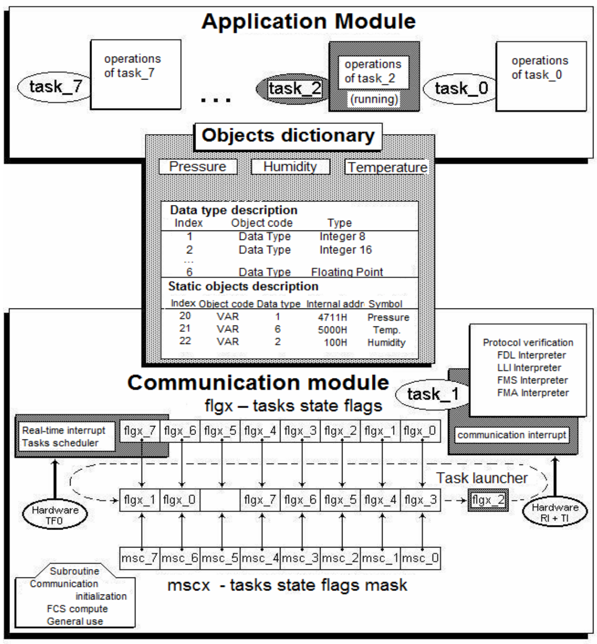

Fig.5 Software architecture of communication module

The launching in execution of a task can be prepared in an interrupt service routine different to the real time interrupt service routine, in other task or in the task scheduler. The real time interrupt service routine includes the task scheduler. It prepares the launching in execution of tasks which should run periodically (base time, multiple of base time, seconds, minutes, etc.). These tasks have one counter of launching and a constant of launching (initial value of counter).

The counters of launching are decremented with one to each interrupt of real time. If the launching counter of one task becomes zero will be set the status flag of this task and the counter will be reinitiate. The task will be launch in execution only if it is active (its mask flag set). The task launcher is the main loop of software and it is included in the real time kernel.

The task number 1, task_1, is allocated for communication in network. This task, together with task launcher, task schedule, real time interrupt service routine, and communication interrupt service routine form the communication part. For an existing network and for participants to communication which occupy the same hierarchical position, the software differences appear only to level of application part and to the dictionary of objects.

IV. Experimental Results

Extensive tests have been made to quantify the efficacy and reliability of this monitoring system with respect to the physiological signals. The results obtained have confirmed the expected performance:

- Reliability and accuracy of parameter acquisition in working conditions conform to accepted medical requirements, specifications and standards.
- Signal processing such as noise reduction, parameter extraction and data fusion give sufficient information for decision making.
- In-house wireless communication is adequately reliable and the transmission range meets the expectations (from 10–200 m according to the application, for example, 20 m in the home, 200 m in the workplace). It complies with electromagnetic regulations. In addition, data security, confidentiality and authenticity are ensured by the communication protocol.
- The overall power consumption that is necessary for the operation of accelerometers, signal processing and sensors in a small portable system has been achieved with the use of a novel power-management systems, which extend battery life to years for smart house environmental monitoring and almost a month for the assisted person.

TABLE II TYPES OF MEASURED SIGNALS

Parameter	Range	Freq Hz	Sensor or method	Bit rate for 10 bits A/D
BP	10 – 400 mmHg	60	Strain gage integrated	1.44 kb/s
Pulmonary arterial BP	0 – 50 mmHg	50	Strain gage integrated	1.2 kb/s
Central venous BP	0 – 50 mmHg	50	Strain gage integrated	1.2 kb/s
Electrode ECG	0.5 - 4 mV	250	Electrodes on skin	18 kb/s
SpO_2	80 – 99%	30	two photodiodes	1.44 kb/s
HR	4 – 25 l/min	20	Thermistor	0.48 kb/s
BT	32 – 40 ^{0}C	0.1	Thermistor, thermocouple	0.0024 b/s

Next we present the results of the monitoring of a patient during 24 hours. The messages were sent from the HWN at an interval of 15 minutes, the amount of transmitted data being about 450 kB. For the transmission, FTP through GPRS was used. Table II presents the measured signals types.

Fig 6 shows the download rate during 24 hours of a 450kB file. One can see that this rate was in the range of 27 – 32 kbps, in average about 30 kbps, with only 2 exceptions.

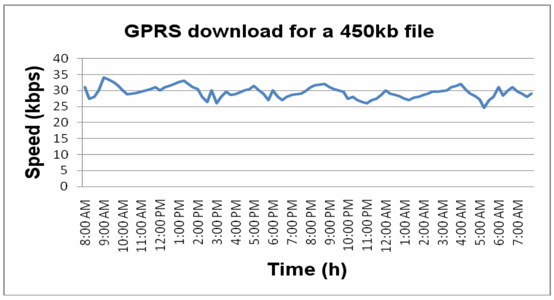

Fig.6 GPRS download speed for 24 hours recorded data

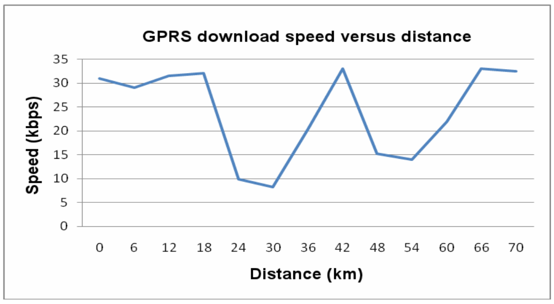

Fig .7 GPRS download speed versus distance

The download rate (Fig.7) is a function of the distance covered by the patient travelling in a car at a speed of 80 km/h during 1h. The measurements and the data transmission frames were made at 5 minutes intervals. The values remain in range of 30 – 32 kbps. The exceptions (values between 8 and 20 kbps) have appeared in condition of bad weather (rain). The file length was 150kB. Also, it was analysed the download speed (Fig.9) and the download duration (Fig.8) for files of variable length (between 1 and 2000kB).

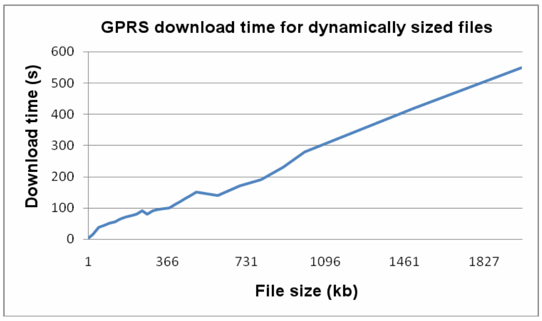

Fig. 8 Download duration according to the file dimension

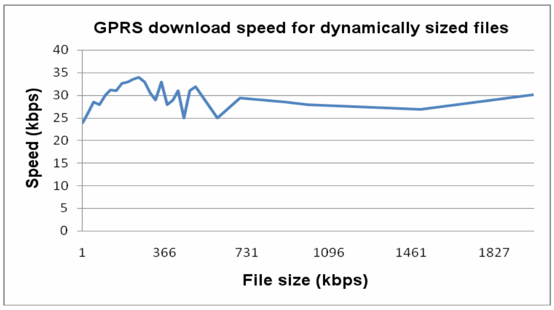

Fig. 9 Download speed according to the file dimension

One can observe that the speed range is between 23.5 and 34 kbps, while the duration growth proportional with the file dimension (about 3 minutes for 450kB).

V. Conclusions

We consider that this approach of using mobile sensor networks for homecare monitoring systems is a fair one in this fast growing domain. Assignment of two nodes: one mobile, for assisted person, and one fixed, for home ambiance, make possible wireless connection of patient node to different network nodes: home node, ambulance node, GP node or hospital node. Further, we concluded that the best available solution for communication system is ZigBee, for short distances, and GPRS (HSDPA where available), for long distances.

Concerning the proper choosing, regarding the complexity of algorithms running on the node, the processing core of HWN node is a DSP. The software architecture is derived from our previous implementation on an 8-bit microcontroller platform. This explains why the software is divided in up to eight tasks: one task, which form the communication part and the remained seven tasks grouped together in the application part. The next step is to extend this architecture on a 32-bit DSP platform and to grow the number of tasks to this value, this way obtaining a more powerful software kernel.

The future of WSN-based health maintenance systems fully depends on development of specific sensors, data transmission, also on embedded systems improvements that take up modern role of our personal guards. Integration of WSN-based platform in homecare monitoring systems enables both reductions of costs for patient in the hospital and increasing the level of the health care in such a way that the critical states of patients just for hospitalization will be found out more quickly.

Acknowledgment

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