An integrated biomedical telemetry system for sleep monitoring employing a portable body area network of sensors (SENSATION)

Alexander Astaras, Marina Arvanitidou, Ioanna Chouvarda, Vassilis Kilintzis, Vassilis Koutkias, Eduardo Montón Sánchez, George Stalidis, Andreas Triantafyllidis and Nikolaos Maglaveras

***Abstract*—A flexible, scaleable and cost-effective medical telemetry system is described for monitoring sleep-related disorders in the home environment. The system was designed and built for real-time data acquisition and processing, allowing for additional use in intensive care unit scenarios where rapid medical response in case of emergency is required. It comprises a wearable body area network of Zigbee-compatible wireless sensors worn by the subject, a central database repository residing in the medical centre and thin client workstations located at the subject's home and in the clinician's office. The system supports heterogeneous setup configurations, involving a variety of data acquisition sensors and several targeted application scenarios. All telemetry data is securely transferred and stored to the central database server under the clinicians' ownership and control.**

I. INTRODUCTION

APPROXIMATELY 20% of the population in modern "24 hour" societies suffers from sleep disorders at least mildly or temporarily [2], [3]. As people increasingly tend to exchange sleep and serenity for work or pleasure, sleep loss, stress and inattention are affecting concentration and performance more and more in everyday life. In addition, industrial and traffic accidents have been linked to prolonged inattention or the involuntary transition from wakefulness to sleep.

Project SENSATION is an EC funded research effort aiming at the development and adaptation of biomedical engineering technologies to achieve unobtrusive, cost-effective, real-time monitoring, detection and prediction of human physiological states in order to study wakefulness, fatigue and stress. Part of the project involves biomedical data acquisition from a subject at their home environment in order to study sleep patterns, sleep quality and disorders. It comprises an application scenario which does not explicitly require real-time data monitoring or processing. The same telemetry platform was developed for use within a medical centre intensive care unit (ICU), taking advantage of the system's real-time monitoring capability, enabling rapid emergency medical response.

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Alexander Astaras, Ioanna Chouvarda, Vassilis Kilintzis, Vassilis Koutkias, Andreas Triantafyllidis and Nikolaos Maglaveras are with the Laboratory of Medical Informatics, Medical School, Aristotle University of Thessaloniki, Greece (phone: +30-2310933825; fax: +30-2310933825; e-mail: astaras, ioanna, billyk, bikout@med.auth.gr, atriand@auth.gr, nicmag@med.auth.gr).

Marina Arvanitidou was with the Laboratory of Medical Informatics, Aristotle University of Thessaloniki. She is now with the Communication Systems Group, Technische Universität Berlin, Germany (phone: +49-30 31423835; e-mail: arvanitidou@nue.tu-berlin.de).

Eduardo Montón Sánchez is with the ITACA R&D Institute (phone: +34-96-387-7606; fax: + 34-963877279; e-mail: edmonsan@itaca.upv.es).

George Stalidis was with Pouliadis Associates Corp, Greece and is now with the Dept. of Marketing, Alexandrian Technological Educational Institute of Thessaloniki, Greece (phone:+30-2310791246; e-mail: stalidgi@mkt.teithe.gr).

II. DESIGN AIMS

The data originates at a body area network (BAN) of sensors attached to the subject's body, is wirelessly transmitted in real time to a portable data processing unit (PDPU) and subsequently uploaded to a home-based PC workstation. Upon receiving data from the PDPU and other optional sources, the home workstation integrates it into a single, automated and secure IP transmission for deposition into a centralized online data repository residing in a collaborating medical centre. The data repository database in turn processes incoming data, analyses and securely distributes it to certified medical workstations upon demand.

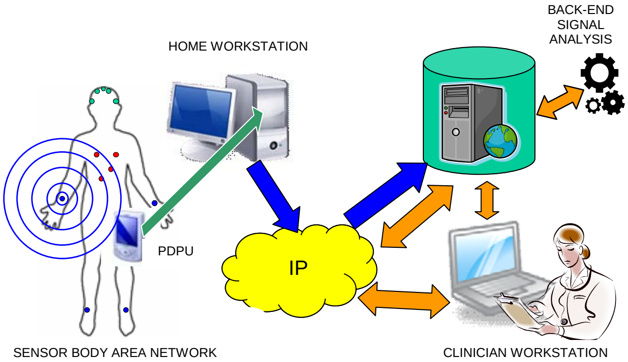

Fig 1: Schematic depiction of the biomedical telemetry system for sleep-related monitoring at home. Data flow is initiated at the BAN of sensors on the left and eventually reaches the clinician's workstation on the right.

The integrated sleep-monitoring platform therefore has to accommodate home-based data acquisition, storage, analysis and distribution in a secure, flexible and cost-effective fashion, further meeting restrictions imposed by the home environment and the subject's lifestyle, as well as experimental and data-processing requirements defined by clinicians.

III. SYSTEM ARCHITECTURE

The platform design team translated these aims and requirements into several data processing and communication nodes: a portable data acquisition unit to be worn or carried by the subject, a home base station for data collection and transmission, a central data repository server and a clinician workstation for data processing and evaluation (**Error! Reference source not found.**). In order to facilitate system deployment and expansion a choice was made to adopt a thin client architecture (clinician workstation), relying on a back-end signal analysis module attached to the central database to perform on-demand signal processing and data analysis.

A. Sensors and portable data acquisition

The BAN implemented is a specialised wireless sensor network (WSN) adopting star topology [6] interconnections and comprising two main electronic modules, the Sensor Communication Module (SCM) and PDPU (Fig 2). It was built in an open and scalable fashion in order to accommodate various sensors used in the project.

Nine different sensors were used to capture biomedical data from the subject's body during sleep, capable of detecting heart beat, blood pressure, temperature, eye movement, acceleration, electromyographic and encephalographic activity. Most sensors provided an analogue output signal, with two exceptions (ACTIWRIST, FINGERING).

Multiple sensor output is integrated by the SCM which also supplies power through a rechargeable Li-ion battery. It is a small device measuring 3.4 x 4.8cm and capable of accommodating up to 4 analogue or digital output sensors. It incorporates 32Kbytes of on-board FRAM and communicates with the PDPU via an IEEE 802.15.4/Zigbee-compatible wireless communication protocol [1], [9].

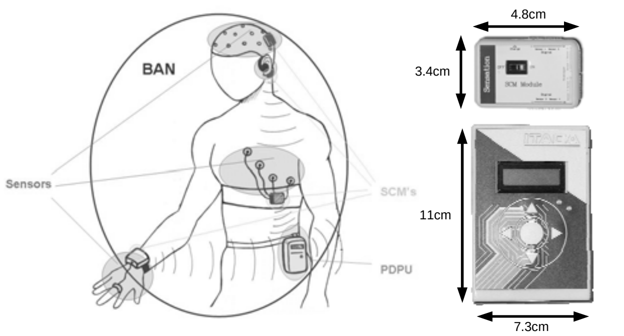

Fig 2: Schematic diagram of the body area network (BAN) and pictures of the sensor communication module (SCM, top right) and portable digital processing unit (PDPU, bottom right) used for sleep data acquisition in the home environment.

The PDPU is the central data acquisition and storage device of the BAN, measuring 7.3 x 11 x 2.5cm (roughly the size of a deck of cards). It coordinates and synchronizes data flow from the SCMs and any stand-alone Zigbee BAN sensors and handles data storage and re-transmission to the home workstation. It has limited data processing capability, though in the present architecture this is not required. Connection to the home workstation is achieved via a USB cable or wireless Wi-Fi link.

B. Home base station

The primary task of the home workstation is to integrate multiple signal transmissions from the PDPU into a European Data Format (EDF) file, bundle it with any supplementary data and securely upload it to the central database repository. It also serves for data entry of personal information and medical questionnaires by the subject, as well as configuration of the PDPU and sensor BAN before a sleep monitoring session (performed by a technician).

Communication with the database repository residing in the medical center is achieved using HTTP post through the DSL connection. More specifically HTTPS (SSL2, SSL3 protocols) is used to ensure the secure transfer of acquired data.

The minimum hardware requirements for the home workstation are relatively small. A 1.5GHz Pentium 4 or equivalent PC with 256MB RAM, a 10GB hard drive and a digital signal line (DSL) connection to the internet is sufficient. Our prototype platform employed such a PC running the MS Windows XP operating system and the SQL server 2005 (Express edition) software package.

C. Medical center database

The central data repository for the data acquired is physically located in the medical centre, ensuring that the ownership and accessibility of subject and patient data is controlled exclusively by medical personnel. It comprises a web server and a back-end processing engine. The former handles secure IP communication with the home and clinician workstations, subject record storage, retrieval and management, while the latter handles ECG and EEG analysis.

More specifically, an SQL database is used for data storage and retrieval as well as subject record management. Report requests from client workstations are handled using PHP and Javascript. The back-end design module performs on-request signal analysis using the Matlab software package and transmits the results to the clinician workstation. The full signal data is also available to clinicians for download upon request.

The minimum hardware requirements for the central database server involve a machine with an Intel Pentium IV or equivalent CPU, 512MB or RAM, 2GB of hard disk space and a 10Mbps or faster permanent internet connection with a static IP address (a hardware firewall is recommended for enhanced data security). Any operating system capable of supporting a web server and the Matlab server software package can be used, as the rest of the developed software is cross-platform based. The experimental setup used for project SENSATION was based on an Intel XEON 3.6GHz server board, 2GB of RAM and a 200GB SATAII hard disk, uninterrupted power supply (UPS) support and a 100Mbps static IP connection.

D. *Clinician's workstation*

The clinician uses a thin-client workstation to view subject records, modify clinical information and access acquired signal data from multiple sensors and monitoring sessions. This is performed via a graphical user interface (GUI) which was developed using the Java programming language in order to ensure compatibility across various operating systems.

The clinician may further request signal analysis for any signals stored in the medical center database. This is performed by the analysis module, a web-based application developed using the PHP programming language and made available by the database server. It is accessible via any Javascript-enabled browser and guides the clinician through the process of configuring a signal analysis request form (Fig 3). It subsequently securely relays the request to the database back-end analysis module (Matlab) downloads the results and presents them on screen.

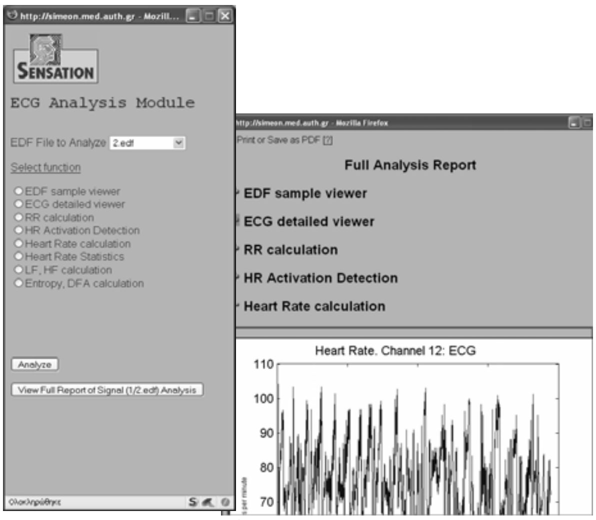

Fig 3: Screenshot capture of the signal analysis and report generation module, a web-based application available through any Javascript-enabled browser. An ECG analysis request form and subsequent results window are depicted.

The thin client architecture of the clinician's workstation ensures low hardware requirements, however a fast DSL connection to the internet is required for reviewing most signal recordings. The transfer of multiple channel EEG signals, in particular requires a fast internet DSL connection. Secure data transfer is achieved using HTTPS post, similar to the home workstation setup.

IV. Application Scenarios

The sleep-related medical applications in project SENSATION cover the areas of medical diagnosis of sleep disorders, medical treatment and monitoring in safety- and emergency-related scenarios. More specifically, four distance-based and three intensive care unit (ICU) based applications were defined, as summarised in Table I.

TABLE I
MEDICAL APPLICATION SCENARIOS

Scenario	Condition	Monitoring needs
Home-based diagnosis	Obstructive Sleep Apnoea Syndrome	single night recording
Home-based diagnosis	Obstructive Sleep Apnoea Syndrome	Home-based diagnosis, single night recording
Home-based treatment	Psychophysiological Insomnia	Home-based treatment follow-up, 24 hours recording for 3 days
Home-based treatment	Insomnia	Home-based treatment follow-up 24 hours recording for 3 days
ICU	Anaesthesia	Emergency, continuous recording during surgery
ICU	Myocardial Infarction	Emergency, continuous recording while in ICU
ICU	Chronic Obstructive Pulmonary Disease	Emergency, continuous recording while in ICU

Summary of the medical application scenarios which were selected to be supported by the SENSATION biomedical telemetry system.

Obstructive sleep apnoea syndrome (OSAS) and Insomnia were selected as targets for the home based scenario, given that vital signal monitoring for up to 3 days is required for diagnosis and treatment assessment purposes [4], [5]. The ICU-based applications, focusing on anaesthesia, myocardial infarction, Chronic Obstructive Pulmonary Disease (COPD) and the weaning from electromechanical support process, have a rather emergency form and require continuous recording while in ICU. In the four home-monitoring applications data is transferred to a monitoring centre (central database repository). In the case of the three ICU related scenarios the data is stored, processed and reviewed within the medical centre (point of care).

The resulting biomedical signal data is made available for analysis and medical interpretation via the integrated data acquisition, transmission and management platform described in previous sections. The clinician accesses and evaluates patient and subject records via a set of reports generated by the central database. The reports are requested via a web-based application running on the clinician workstation (Fig 3).

Monitoring procedures in each application scenario involve a variable and heterogeneous set of sensors. Moreover, the requirements for volume of transferred data, the emergency medical response time window, equipment cost considerations and the number of clinician and home workstations attached to the central database vary among application scenarios, which made design goals and overall integration non-trivial tasks.

V. Future Research Directions

The developed telemetry system was a prototype developed primarily in order to facilitate sleep disorder medical research. It takes advantage of recent technological developments, particularly on the data acquisition end. We foresee several improvements and targets for future development on both the hardware and software front.

The most obvious target for future technological development is the fusion of the PDPU and home workstation into a single, portable device. Given recent advances in low-power short range telecommunications (Zigbee, Bluetooth/Wibree [5]) and the increasing amount of processing power available in commercial portable devices, the mobile phone is a strong candidate platform for facilitating this integration.

Based on experience gained developing the SENSATION integrated telemetry platform, we are currently improving on the interoperability, maintainability and extensibility issues that arise in pervasive monitoring systems. In particular, we focus on the intra-BAN communication and data exchange mechanism, towards the construction of a novel wireless sensor network (WSN), the functionality of which will be configurable by medical personnel. With regards to the monitoring application, our focus is on an open architecture extensible with additional sensors [9].

This approach is inspired by the Sensor Web Enablement framework, which envisions web resident sensors which are easily detectable and accessible through the Internet. The framework relies on the SensorML model language [8], which provides a standard XML-based mean for encoding and describing any process of measurement by sensors and the instructions for deriving higher-level information from observations. For each process, all input, output, parameters, methods, as well as relevant metadata are described using SensorML.

As more advanced sensors become available with respect to computational resources, we consider scenarios in which processing capabilities are not residing in a single control unit. Instead, the WSN consists of sensors capable of incorporating appropriate data processing algorithms and sending data to the medical personnel only when required. This reduction in processing burden is indispensable when compared to the communication cost savings, considering an alternative scenario in which all data recorded by each sensor is transmitted.

More specifically, our future development relies on three basic quality attributes: a) *formal sensor description*, i.e. sensors provide standard self-descriptions and processes, so as the entire network can be sufficiently described; b) *openness*, i.e. sensors can be easily added or removed from the network in a plug-and-play mode, provided that the sensor is appropriately self-described; and c) *configurability*, i.e. sensors can be configurable in run-time, in the sense of adapting their operation logic. The abovementioned attributes are released by using SensorML as a means to describe sensors' functionality.

In this context, the dynamic update of BAN behavior becomes possible, according to the requirements specified by the medical personnel, while sensor discovery and interoperability assurance is achieved in the entire WSN. Compared to the implemented architecture presented in Fig.1, in this case the PDPU is equipped with more advanced processing capabilities, enabling this way the application of SensorML-based serialization and de-serialization of data, coordination of network tasks and communication with sensors in an efficient manner. In this context, each sensor processes the recorded data according to the specified parameters and is also equipped with efficient mechanisms for serialization and de-serialization of data.

A major advance of this approach is the embodiment and distribution of intelligence within the entire WSN. Thus, events and actions triggered by events may be described for each sensor leading to different severity levels. From an implementation viewpoint, we currently emulate the PDPU via a personal digital assistant (PDA) and two biosensors, one for heart rate monitoring and the other for blood glucose observations, using J2ME (Java 2 Micro Edition) enabled mobile terminals.

VI. CONCLUSION

We have demonstrated that a flexible, cost-effective medical telemetry system can be successfully developed and operated in both the home and ICU environments, acquiring, securely storing and distributing real-time data. The hardware built is flexible, scaleable, unobtrusive and supports data acquisition from a variety of sensors using popular open communication protocols. The supporting software was developed based on widely available cross-platform programming languages, complemented by commercial signal processing software. The system relies on wireless and secure IP.

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