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Potential and challenges of Body Area Networks for personal health

Julien Penders, Jef van de Molengraft, Lindsay Brown, Bernard Grundlehner, Bert Gyselinckx and Chris Van Hoof

Abstract—**This paper illustrates how body area network technology may enable new personal health concepts. A BAN technology platform is presented, which integrates technology building blocks from the Human++ research program on autonomous wireless sensors. Technology evaluation for the case of wireless sleep staging and real-time arousal monitoring is reported. Key technology challenges are discussed. The ultimate target is the development of miniaturized body sensor nodes powered by body-energy, anticipating the needs of emerging personal health applications.**

I. Introduction

It is predicted that healthcare systems will change in response to new demographic factors including an aging society, increasing number of chronic diseases and a growing concern of individuals in managing their own health. Key trends of future health systems include the evolution from disease centric to patient centric care, the delocalization of care from hospitals to home, and a focus on prevention rather than cure [1]. This paradigm shift calls for new technologies to enable ubiquitous personal health.

Body Area Networks will play an important role in enabling this change, by providing people with personal health solutions for medical, lifestyle, assisted living, sports and entertainment applications [2]. Early market adopters of body area network technology illustrate its potentials for use in the field of entertainment (emotive, Neurosky, Nintendo) and sports (Nike, Adidas, Polar). On the other hand, the scientific community has seen the multiplication of body sensor network platforms. For instance, Shimmer Research has developed a wearable, miniaturized sensor platform for real-time kinematic motion and physiological sensing [3]. Quasar has developed a wireless sensor platform for monitoring physiological and cognitive state [4]. The advantage of this platform comes from a proprietary non-invasive biosensor technology, enabling dry measurement of bio-potential signals. Recently, Toumaz introduced Sensium™, a low power sensor interface and transceiver platform, enabling long-term continuous monitoring of vital signs [5]. Many more examples have been reported in literature [6]. Overall, these sensor nodes differ by their form-factor, their autonomy, the inherent building-blocks (micro-controller, radio, sensors) and their portability. However, they are all facing the same technological challenges including: autonomy, functionality, intelligence, miniaturization and manufacturing cost.

Early research achievements in these areas enable the development of prototypes of new wireless health concepts, and their deployment in different application environments. Technology evaluation for these applications is in turn translated into new challenges that will need to be solved in order to enable widespread acceptance of the technology in every day life. In this paper we present a few emerging applications relying on body area network technology. In particular, the cases of wireless sleep monitoring and emotion monitoring are reported. Technology challenges emerging from early technology deployment in these applications are discussed.

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Julien Penders, Jef van de Molengraft, Lindsay Brown, Bernard Grundlehner, Bert Gyselinckx and Chris Van Hoof are with Holst Centre / IMEC-NL, High Tech Campus 31, 5656 AE Eindhoven, The Netherlands.

Corresponding author is Julien Penders, phone: +31.40.277.4000, e-mail: Julien.Penders@imec-nl.nl.

II. Body Area Network technology platform

The Human++ research program addresses key technology challenges associated to micro-power generation and storage, ultra-low-power radios, ultra-low-power DSPs, sensors and actuators and advanced electronic integration. Recent research achievements in these areas were recently reported [7]. In the area of bio-medical sensors, a set of ultra-low-power front-ends for the read-out of bio-potential signals have been developed. In particular, a single-channel read-out front-end has been designed with a variable gain amplifier allowing to electronically adjust the gain of the readout for varying application needs [8]. Similarly, high cut-off frequency of the readout channel can be electronically adjusted via bandwidth select switches. These features make this single-channel bio-potential read-out ASIC particularly suitable for a wide range of biomedical applications, as its characteristics can be adapted depending on the bio-potential of interest: ECG, EEG, EMG or EOG. Furthermore, its low-power consumption (21µA at 3V) allows to dramatically reduce the size of the battery, hence of the entire monitoring system.

For evaluation in various application scenarios, the bio-potential ASIC has been integrated in a ExG sensor board. A generic wireless node has also been developed to provide embedded processing and wireless transmission functionality. Commercial off-the-shelf elements are used for this generic node, including the TI MSP430f1611 micro-controller and Nordic nRF24L01 radio chip-set, selected for their low-power performances. Customized power management circuitry has been developed to optimize power performances of the sensor node, and a Li-ion battery of 160mAh capacity is connected to the system. Power consumption of the ExG sensor board is 25µA at 3V. The average power consumption of the generic wireless node ranges from 28mA (max current consumption) to less than 1mA for customized applications, at 3V. Low-power firmware, TDMA-MAC protocol and communication protocol have been implemented to enable several sensor nodes to work within a star-topology network. For a network configuration of three nodes, with 2 data channels per node, and packet retransmission enabled, the average power consumption of the generic wireless node is 2.4mA at 3V. Average packet losses have been experimentally measured to be less than 1ppm in static conditions, and shown to stay below 1% in most dynamic environments.

In addition to bio-potential, other sensor boards have been designed and developed to meet the requirements from various health monitoring applications. In the current state of the Human++ BAN technology platform, sensor boards are available for measurement of bio-potentials, motion (accelerometer and gyroscopes), respiration (based on piezo-electric sensor), skin temperature and skin conductance. This set provides a generic BAN platform from which specific sensor boards can be collected depending on application requirements.

III. Emerging Applications

A. *Enhancing sleep monitoring*

Sleep disorders are known to affect a significant part of the population, up to 10% of the American population and 4% of the European population. Typical diagnosis of sleep disorders is performed through polysomnography tests at the point-of-care. Ambulatory sleep monitoring devices have been introduced for home monitoring and pre-screening. They however suffer from important burdens such as their weight (mainly due to the battery) and the high-density of wires going from the head to the data acquisition box (often located around the belt). Centers for sleep disorders would already benefit from a miniaturized, wire-free, sleep-staging system, targeting the monitoring of the patient's hypnogram—that is, the sequence of sleep stages overnight.

Wireless sleep staging was selected as an application case for technology evaluation. A prototype body area network for wireless sleep staging was developed based on the generic platform reported in previous section, and relying on the ultra-low-power single-channel bio-potential ASIC. The integrated system, illustrated on *Fig. 1*, consists in a body sensor network composed of three wireless sensor nodes, collecting data at 200Hz from 2-channel EEG, 2-channel EOG and 1-channel EMG, and sending it wirelessly to a receiver located in the patient's room. These particular signals were selected as per the Rechtschaffen and Kales standards for sleep staging. Thanks to their small size and light weight, the three sensor nodes can easily be integrated in a headband, hence increasing patient comfort and acceptance.

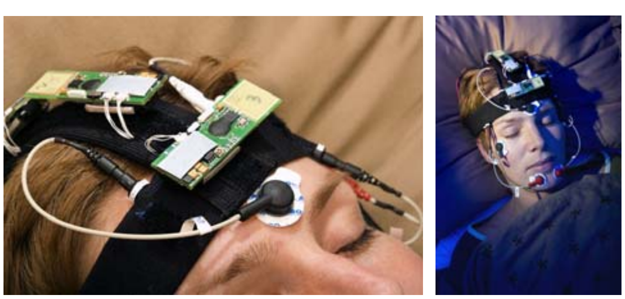

Fig. 1. Prototype wireless body area network for sleep staging

The system has been benchmarked against commercial off-the-shelf portable PSG systems, in collaboration with the Sleep Laboratory of the Vésale Hospital in Charleroi, Belgium. 12 healthy volunteers participated in the study, from which 9 are used for the benchmarking analysis. Each volunteer is monitored for a complete night, during which the 5 physiological signals (2ch-EEG, 2ch-EOG and 1ch-EMG) are recorded using the wireless BAN prototype and a reference system. The two systems are set-up in parallel, and all electrodes are duplicated. Once all subjects have been recorded, the recordings are manually and blindly analyzed by a sleep expert to obtain the hypnograms for both systems. The two systems are compared using two criteria: hypnogram similarity analysis and hypnogram feature correlation analysis. Hypnogram similarity is quantified as the percentage of time for which the two hypnograms – inferred from the wireless and reference systems – are similar, and is computed individually for each stage. A set of features can be extracted from each hypnogram, namely: time spent in each stage, number of stage changes, number of micro-awakenings (or arousals) and sleep efficiency. Hypnogram feature correlation is quantified using correlation coefficient, slope and confidence interval.

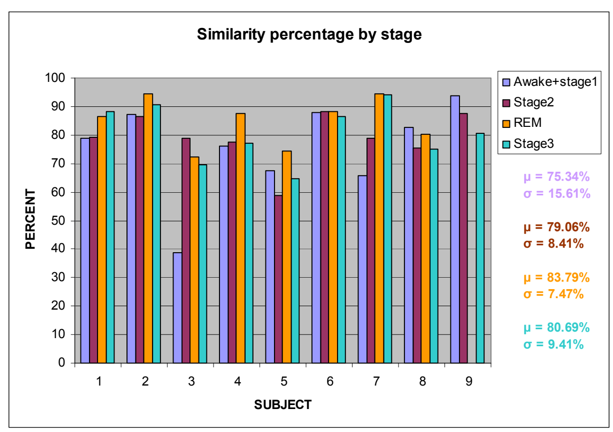

Fig. 2. Benchmark of wireless sleep staging system: hypnogram similarity per sleep stage, for the 9 volunteers included in the study

TABLE 1
Hypnogram Feature Correlation

Feature	Correlation coefficient	Confidence interval	Slope
Time in stage 1	0.41	[-0.36;0.85]	0.48
Time in stage 2	0.89	[0.53;0.98]	0.75
Time in stage ¾	0.95	[0.76;0.99]	1
REM	0.98	[0.90;0.99]	0.77
# state changes	0.92	[0.66;0.98]	1
Sleep efficiency	1.00	[0.99;1.00]	1.19
Arousals	0.72	[0.10;0.94]	0.55

The hypnogram similarity analysis leads to an average similarity across all stages and patients of 80% (standard deviation of 7.85%). This is comparable to inter-rater similarity—that is, the similarity between hypnograms scored by two different medical experts based on the same set of signals, typically included between 80 and 90 % for healthy subjects. *FIG. 2* illustrates the percentage of similarity per stage, in which Stage 1 and awake are grouped. It is worth noting that REM sleep and stage 3/4, very important in sleep disorder diagnosis, both have a similarity percentage over 80%. Finally, the feature correlation analysis shows that the features extracted from the hypnograms inferred from the WBAN system correlate with those inferred from the reference system. *TABLE 1* summarizes the correlation coefficients, slopes and confidence intervals for each feature.

B. Enabling ubiquitous emotion monitoring

The previous case illustrated how Body Area Network technology benefits some existing applications, reducing the monitoring burden and enhancing patient comfort. On another hand, BAN has also the potential to enable applications that were not yet possible before the introduction of the technology. Monitoring of emotions or mental health has received a special interest in the last few years. Emotion is usually defined as a mental and physiological state associated with a wide variety of feelings, thoughts, and behaviors. Monitoring emotions using non-intrusive measurements would enable new ways of interaction with our environment, new perspectives in assistance to mentally disabled people and a whole new range of applications in the domains of (mental) health management, safety, entertainment and ambient intelligence.

There have been several attempts to classify emotions based on bio-signal measurements, differing by the type of signals and extracted features, by the data analysis and classification methods, and by the achieved performances [9][10]. As a starting point to evaluate technology opportunities and challenges for body area networks when applied to wireless emotion monitoring, we selected the case of monitoring physiological responses from the Autonomic Nervous System. The generic BAN platform has been customized to achieve a low-power body area network prototype for monitoring ECG, respiration, skin conductance and skin temperature [9], known to be regulated by the Autonomic Nervous System. The resulting system is illustrated on *FIG. 3*, and consists of two miniaturized body sensor nodes located on the wrist and on the chest [9].

FIG. 3. Integrated body area network for ambulatory monitoring of physiological responses from the Autonomic Nervous System

The system was evaluated for real-time monitoring of arousal in a controlled environment [10]. 20 healthy volunteers are involved in the experiment. A movie extract is chosen as the arousal stimulus, characterized by a calm beginning followed by a building-up phase culminating to a frightening event. Volunteers are asked to watch the movie while their physiological signals are monitored using the wireless system. All tests have been performed in a controlled laboratory environment, in order to minimize the sources of distraction that may eventually lead to unexpected and uncontrolled increases in arousal. A set of features is extracted from the ECG and skin conductance signals, found to be the most responsive parameters to the tests. In a second step, these features are combined in an optimal arousal estimator using linear regression against a target arousal level. The outcome of the regression analysis is a set of coefficients, characterizing the importance of each individual feature in the final estimation of arousal. All algorithms were implemented in the Matlab computing environment. All algorithms are real-time, such that the process of feature extraction and arousal estimation can be applied in real-time on incoming signals measured using the BAN system [10].

The resulting estimator can then been used to monitor the arousal level of individuals wearing the system. The system was further tested for different stimuli, and gradually releasing the constraint of a controlled environment to public places such as scientific fairs. Arousal responses to a Stroop test and to an audio sequence were evaluated. These tests have suggested that the arousal monitor extends to other stimuli than the movie fragment, provided that the particular stimulus generates a startle response in the test subject. Apart from the expected responses, some responses were also observed that do not origin in any of the stimulus events. These false positives can be due to anything that triggers the mind of the subject, such as an arousal triggering thought, or something surprising in the surrounding environment. Further experiments will be required before conclusions can be drawn about the extension of the results to fully uncontrolled environments, such as daily-life situations. The low-power BAN technology platform presented in this paper will certainly facilitate the transition from lab to real-life environments.

IV. DISCUSSION

Previous section has highlighted a few examples in which early technology advances already contribute to enhance existing applications, or to enable new type of personal health applications. Technology evaluation in these environments leads to refined application requirements, and points out to important technology challenges that shall be addressed to eventually enable widespread deployment of body area networks.

Ultra-low-power technologies: when integrated in prototypes of wireless health systems, the best low-power commercial off-the-shelf electronic components lead to typical power consumption ranging from 1 to 10 mA, depending on the application. This paper suggests how the design of ultra-low-power front ends can already enable drastic reduction in power budget. Further research is needed on ultra-low-power analog interfaces, sensors, DSP and radios to meet the target of 100µW per body sensor node.

Autonomous systems: the prototypes presented in this paper can run for a few days at full functionality. Breakthroughs in ultra-low-power technologies will eventually enable months or years of autonomy. To come to a truly autonomous system however, it should be able to operate over its full lifetime without maintenance. Harvesting energy from the environment during the operation of the system will allow the system to run eternally with a battery or a super-capacitor acting only as a temporary energy buffer.

Multi-parameter sensors: both sleep and emotion monitoring are complex problems. Extending the range of functionality to include new sensing modalities will be crucial in fostering research in personal health applications, leading to new discoveries. Novel sensing technologies are needed to reliably measure more complex parameters whilst pursuing ultra-low-power consumption. Continuous measurement of melatonin (resp. cortisol) in saliva would for instance open new perspectives in insomnia (resp. stress) monitoring.

Increasing functionality: most of today's body-worn sensors act as simple gateways, passing on the information to a central hub where the data is converted into actionable information. Sleep or emotion monitoring requires simultaneous monitoring of multiple sensors on the body, and possibly the local extraction of relevant information out of the sensor data. Low-complexity and real-time algorithms are required to enable intelligent autonomous systems. Furthermore, compromises between local processing of the data versus data streaming or data storage exist and need to be investigated. A rational approach to distributed processing will allow achieving optimal performances for minimized power consumption.

Dry electrodes: most of current systems for physiological signal measurement require wet, gel electrodes to be attached to the skin or the scalp. Although they have the major advantage of providing good quality signals, gel electrodes exhibit significant drawbacks with regards to long-term use and ease of use. Dry electrode technology is required to enable simple set-up of the system by the user itself. A few groups have explored the area of dry electrode for physiological monitoring applications [4]. Further research is required to systemically tackle the issues of signal quality, robustness to motion artifact and bio-compatibility.

Integration technology: as body sensor nodes shrink in size and power consumption, end-user acceptance and compliance will eventually be bound to comfort and ease of use. Pioneering research in electronic integration technology has led to first functional prototypes of ultra thin chip packages [11] and stretchable interconnects. Electronic integration in bi-dimensional flexible and stretchable foils will enable disappearing body sensor nodes, integrated in patches, clothes or even fashion accessories.

V. Conclusion

This paper shows how the concept of body area network may enhance existing health monitoring systems, and enable new personal health applications. A Body Area Network technology platform is introduced, which integrates early research achievements from the Human++ research program on autonomous wireless sensors. This platform is evaluated in the context of two application scenarios: wireless sleep monitoring and ambulatory emotion monitoring. Early technology deployment in these application environments leads to the identification of key technology challenges that need to be addressed in terms of ultra-low-power radios, DSPs and analog interfaces, ultra-low-power sensors extending the set of monitored parameters, dry electrode research and 2D flex/stretch electronic integration. The ultimate target is to develop wireless body sensor nodes consuming an average power of 100µW, disappearing in patches or clothing accessories, and anticipating key requirements of future personal health applications.

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