Human++: Autonomous Wireless Sensors for Body Area Networks

Bert Gyselinckx, Chris Van Hoof, Julien Ryckaert, Refet Firat Yazicioglu, Paolo Fiorini, Vladimir Leonov
IMEC
Kapeldreef 75
B-3000 Leuven
Belgium

***Abstract* - This paper gives an overview of the results of IMEC's Human++ research program [1]. This program aims to achieve highly miniaturized and autonomous sensor systems that enable people to carry their personal body area network. The body area network will provide medical, lifestyle, assisted living, sports or entertainment functions. It combines expertise in wireless ultra-low power communications, packaging, 3D integration technologies, MEMS energy scavenging techniques and low-power design techniques.**

INTRODUCTION

It is anticipated that microsystem technology will increase the functionality of lifestyle and healthcare devices to gradually match the needs of society. It is expected that by the year 2010, technology will enable people to carry their personal body area network (BAN) [2] that provides medical, lifestyle, assisted living, sports or entertainment functions for the user (Fig. 1). This network comprises a series of miniature sensor/actuator nodes each of which has its own energy supply, consisting of storage and energy scavenging devices. Each node has enough intelligence to carry out its task. Each node is able to communicate with other sensor nodes or with a central node worn on the body. The central node communicates with the outside world using a standard telecommunication infrastructure such as a wireless local area or cellular phone network. The network can deliver services to the person using the BAN. These services can include the management of chronic disease, medical diagnostic, home monitoring, biometrics, and sports and fitness tracking.

The successful realization of this vision requires innovative solutions to remove the critical technological obstacles. First, the overall size should be compatible with the required formfactor. This requires new integration and packaging technologies. Second, the energy autonomy of current battery-powered devices is limited and must be extended.

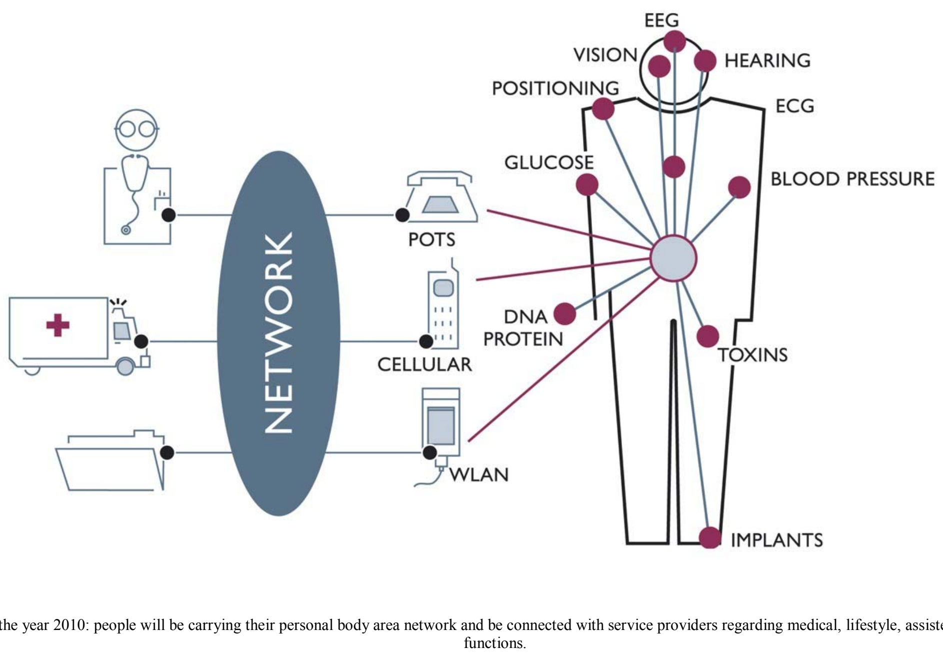

Fig. 1. The technology vision for the year 2010: people will be carrying their personal body area network and be connected with service providers regarding medical, lifestyle, assisted living, sports and entertainment functions.

Further, interaction between sensors and actuators should be enlarged to enable new applications such as multi-parameter biometrics or closed loop disease management systems. Intelligence should be added to the device so that it can store, process and transfer data. The energy consumption of all building blocks needs to be drastically reduced to allow energy autonomy.

Fig. 2. *System integration roadmap for the coming decade: the development of 3D stacking technology, flex technology, and full wafer-scale 3D integration will lead to 2 orders of magnitude reduction in volume and enable smart unobtrusive autonomous sensor systems.*

AMBULATORY EEG AS TESTCASE

EEG is a monitoring tool used by neurologists to measure the electrical activity of the brain and trace neurological disorders such as epilepsy. In hospitals, it is typically used during several days and involves hospitalization of the patient. Ambulatory monitoring of the brain activity would improve the patient's quality of life to a great extent and therefore, wireless EEG was selected as a testcase. The development started with a prototype using off-the-shelf components, in 2002. This system consists of a portable, battery-powered transmitter with 24 EEG electrode inputs and a personal 'health assistant' receiver that is within short range of the patient. This assistant stores all activity and, if required, streams EEG data to other monitoring equipment. The transmitter, worn on the patient's body, digitizes 24 channels of EEG data at a sample rate of 256Hz with 12-bit resolution. This complies with the industry standard. Digitized data is transmitted over a wireless link at 868MHz. The output power is –10dBm and the data rate over the air is 75kbps. The system has an average power consumption of 145mW. Running on 4AA batteries, an operational lifetime of 3 days is achieved. The system occupies a volume of over 500 cm^3 and is shown in Fig. 3.

In order to improve the convenience of the patient, we used our in-house 3D stack technology to reduce the volume of the system to $1cm^3$ and extend the operational lifetime to one month. Assuming that half of the volume is reserved for a Li-battery with a typical energy density of 200Wh/l, the stored energy is 100mWh. In order to run 30 days on this energy, the average power consumption has to be lower than 140μW.

Fig. 3. *Child carrying the first-generation ambulatory EEG transmitter.*

In the remainder of this paper, we will show how advances in wireless communication, energy scavenging, system integration and sensor technology can enable such systems in the near future.

WIRELESS COMMUNICATION

The radio in the sensor will have to operate at an average power of 50μW. However, low power radios such as Bluetooth and Zigbee [3] cannot meet the stringent Wireless BAN power requirements. If one takes the body environment and the RF properties of the body into consideration, the air interface can be optimized for the WBAN context and the power consumption in the sensor node can be brought down by at least one order of magnitude. Networking and MAC protocols can be optimized for the body-area network context, taking into account the simple network topologies, the relatively small number of nodes and the (e.g. latency) requirements of body monitoring applications. In [4] we showed how an EM-field tends to stick to the skin like a wave creeping from one side to the other. Fig. 4 shows how a TE-field propagates around the human body.

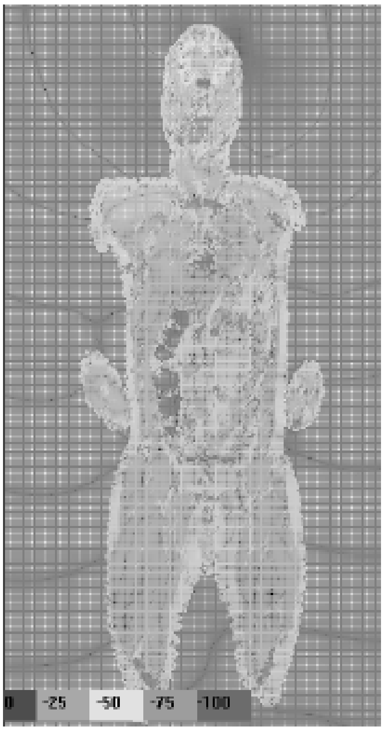

Fig. 4. *TE field propagating along the human body*

Thanks to the low data rate of typical sensors the radio can be operated in burst mode with a minimal duty cycle (e.g. with a burst data rate of a few hundreds of kbps and an average data rate of around 1 kbps, leading to a duty-cycle in the range of 0.1% to 1%).

The power budget in the sensor node and in the master device are very different. The sensor has an extremely tight power budget, whereas the master has a slightly more relaxed power budget. In the air interface definition this asymmetry is exploited by shifting as much complexity as possible to the master device.

For these reasons we have chosen to make use of Ultra-Wideband (UWB) modulation. This will allow us to use an ultra-low-power, lowest-complexity transmitter and shift as much as possible the complexity to the receiver in the master. We have developed the first silicon of a pulser, which is key building block for a UWB transmitter. The system generates position-modulated pulses that comply with the FCC regulation mask. It operates between 3GHz and 5GHz and the signal bandwidth can be tuned from 500MHz up to 2GHz as shown in Fig. 5.

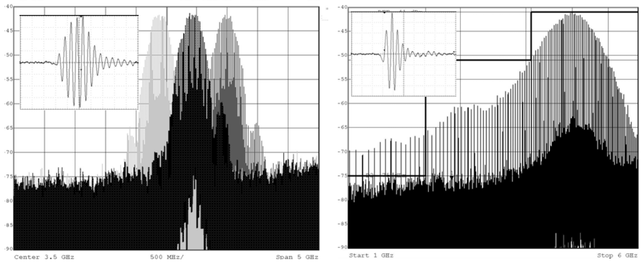

Fig. 5. Measured pulse spectra and time waveform (inset) of pulser ASIC. Left shows 528MHz wide pulses centered at 3.432GHz, 3.960GHz, 4.488GHz. Right shows 2GHz wide pulse.

The system can deliver a pulse rate up to 40MHz. The pulses are modulated in position and the position modulation can be tuned from 4ns to 15ns.

Fig. 6 shows the chip micrograph.

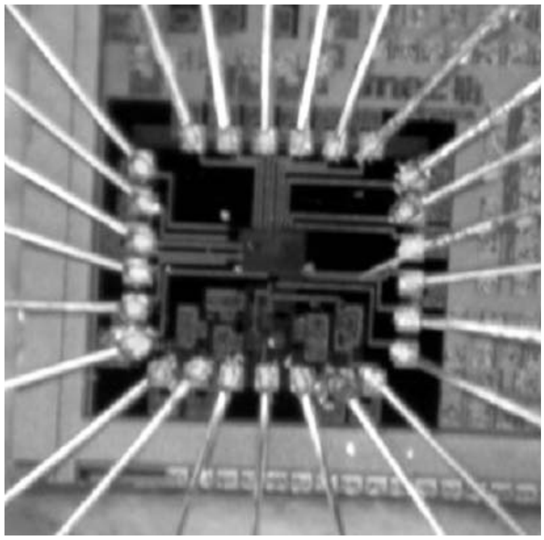

Fig. 6. Pulser die micrograph.

MICROPOWER GENERATION

In order to relax the stringent power consumption requirements of the sensor node, energy scavenging may be an option. Although energy storage (rechargeable battery, super-capacitor) will still be needed in conjunction with the scavenging source, this storage will be smaller than in the case of a primary battery. For body applications, mechanical and especially thermal scavengers are well suited as alternatives or complements to solar energy.

Our thermal generators are conceived for being used in body area networks and the thermal characteristics of human body obtained experimentally are taken into account in device design. (Fig. 7)

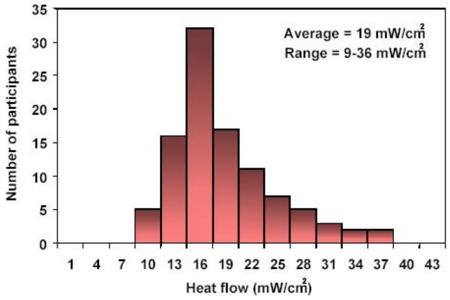

Fig. 7. Heat flow from human body measured at T_{room}(avg)= 22ºC, T_{skin}(avg)= 30ºC, 100 data points in total.

A thermoelectric generator, based on commercial thermopiles has been fabricated and integrated in a sensor node. The node looks like a bracelet (Fig. 9) and has dimensions similar to those of a watch. The device has the following features:

- the device is fixed with its embodiment at one of the most convenient places of the body to scavenge as much body heat as possible;
- the BiTe thermopile generator is thermally matched with the human body and the surrounding air;
- an average power of 100 µW is stored in the battery at an output voltage of 2.4V (the output power generated by the thermal scavenger is much larger, but the efficiency of the power conversion electronics is limiting the amount of energy transferred to the battery);

Performance improvement and volume reduction of the sensor node call for specially designed thermoelectric generators. For this purpose, we are fabricating thermocouples on a deep reactive ion etched rim (Fig. 8). This construction provides thermal isolation between the hot and cold plates.

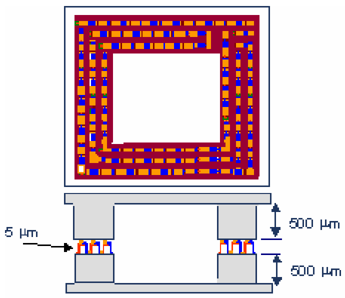

Fig. 8. Concept of the MEMS thermopile chip.

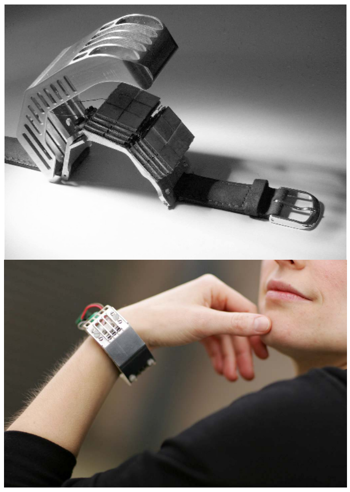

Fig. 9. Thermal micropower generator prototype.

MEMS technology allows fabricating a large number of miniaturized thermocouples on the limited area the rim provides. A prototype of this generator is currently under fabrication using SiGe as thermoelectric material (Fig. 10).

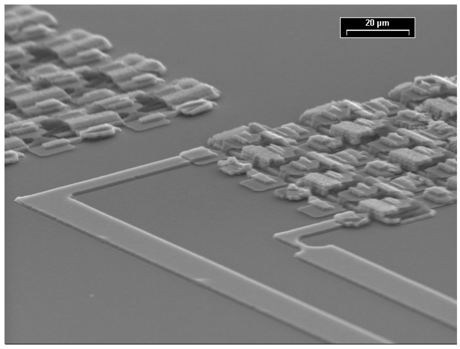

Fig. 10. Thermal micropower generator - detail of partly micromachined module.

We expect the first demonstration thermopile based micro-power generator to have the following specifications (Table 1).

Table 1: thermopile generator specifications

Thermopile chip size, mm^3	4.5×3×0.8
Generator size, cm^3	3×3×1.5
Number of thermocouples	1500-5000
Voltage, V	1.7 – 3.5
Power, µW	4
ΔT on the thermopile, ^oC	5

SENSOR TECHNOLOGY

In the EEG prototype built with discrete components (Fig. 3) the EEG biopotential signal amplification and filtering was a major power sink. For this purpose, we developed a low-power 25 channel biopotential ASIC [13]. The ASIC allows to preprocess typical biopotentials such as ECG and EEG signals. It can be configured in different operational modes thanks to its variable bandwidth and gain settings.

The mixed-signal ASIC consists of 25 channels (Fig. 11). In a typical configuration, 24 channels are configured for EEG measurements and 1 channel is configured as ECG channel. Each channel of the ASIC consists of a high CMRR instrumentation amplifier, followed by a variable gain amplifier. There are 8 different gain modes ranging from 200 to 10000 for the EEG channels and from 20 to 1000 for the ECG channel.

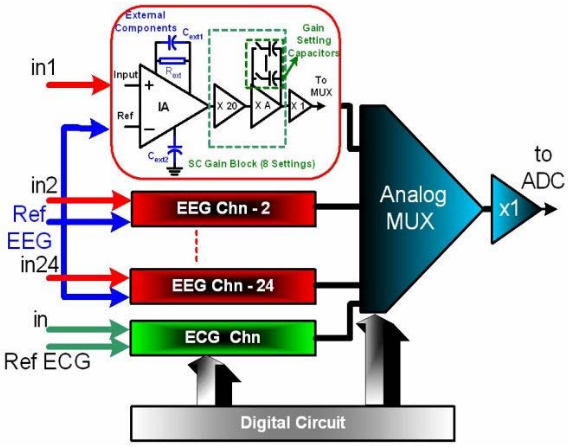

Fig. 11. Biopotential ASIC architecture

The front-end instrumentation amplifier has bandpass filter characteristics, where in-band gain and the cut-off frequencies are settable with external components. With an external capacitor of 1 µF , a bandwidth of 0.5 - 80Hz is selected. The CMRR is larger than 90dB at 50mV electrode offset. The total input referred voltage noise of each channel is less than 1 µVrms in the 0.5 Hz – 80 Hz bandwidth. These features allow to effectively suppress the input common mode voltages coupled to the human body, while amplifying the microvolt level biopotential signals.

The mixed signal ASIC is designed and fabricated in 0.5µm CMOS process. The ASIC can operate from a voltage supply ranging from 2.7 V - 3.3 V while dissipating less than 10.5 mW.

All the channels of the ASIC are multiplexed with a frequency of 1 kHz per channel and buffered at the output. Therefore, a single ADC with a maximum input capacitance of 50 pF can sample all the channels of the ASIC.

In a test setup, two channels of the ASIC are connected to Ag/AgCl electrodes for reading the brain activity at the occipital cortex (backside of the head). A microcontroller with integrated ADC, is directly connected to the ASIC. Operation and gain settings of the ASIC are controlled from the microcontroller. When the patient closes his eyes, the typical alpha rhythm becomes clearly visible at the output (Fig. 12).

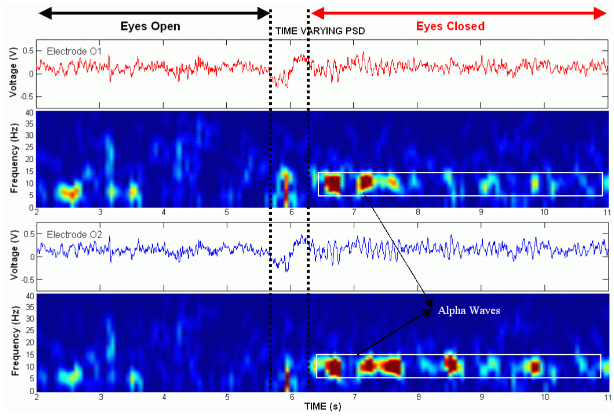

Fig. 12. Alpha activity from the two electrodes at occipital cortex, and their Short-Time Fourier Transform.

We are presently fabricating an alternative instrumentation amplifier architecture with a target power consumption of 15µW per channel while maintaining a CMRR of 110dB. This will represent an additional factor of 20 in power savings.

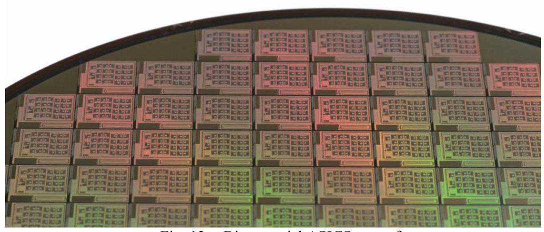

Fig. 13. Biopotential ASICS on wafer

INTEGRATION TECHNOLOGY

One form factor suitable for many applications is a small cubic sensor node. To this end, a prototype wireless sensor node has been integrated in a cubic centimeter (Fig. 14). In this so-called three-dimensional system-in-a- package approach (3D SiP) [5], the different functional components are designed on separate boards and afterwards stacked on top of each other through a dual row of fine pitch solder balls. This system has the following advantages: (i) modules can be tested separately, (ii) functional layers can be added or exchanged depending on the application, (iii) each layer can be developed in the most appropriate technology. The first generation 3D stack offers a complete System-in-a-Package (SiP) solution for low power intelligent wireless communication. The integrated stack includes a commercial low power 8 MIPS microcontroller [6] and 2.4GHz transceiver [7], crystals and all necessary passives, as well as a matched dipole antenna custom-designed on the top layer laminate substrate. The bottom layer has a BGA footprint, allowing standard techniques for module mounting. This sensor module has been integrated with the thermal scavenger presented above and this is the basis for sensor networks [9, 10, 11] which, unlike most of their predecessors, are fully energy autonomous.

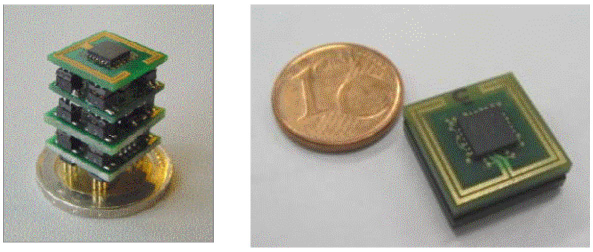

Fig. 14. *Wireless sensor module as miniaturized but conventionally-connectorized module (left) or as integrated 1cm^3 volume 3D stack (right).*

In a next generation, which will appear shortly, the 3D SiP will be further equipped with the biopotential ASIC described above and a solar-cell micro-battery combination. An artist's impression of this configuration is shown in Fig. 15.

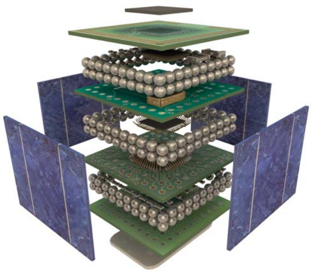

Fig. 15. Artist's impression of 3D SiP

Recently, parallel research was started to implement the same technology on a 2D carrier. The ultimate target is to create a small and smart band-aid containing all the necessary technology for sensing and communication with a base station. It will provide a generic platform for various types of applications (wound healing, UV-radiation, EEG, ECG, EMG…).

The first prototype (Fig. 16) is 10 times smaller than a credit card (12 x 35 mm) and about as thin as a compact disc (1-2 mm). The flexible 25 µm polyimide carrier contains a microprocessor and a wireless communication module (2.4 GHz radio). It enables IMEC to optimize the antenna for its activity on human skin. Current focus lies on adding the necessary sensors and energy equipment (rechargeable battery, energy scavenger and advanced electronics to keep energy consumption as low as possible). IMEC targets an ultimate device thickness of approximately 100 µm.

The biggest challenges in developing this kind of modules are the extreme miniaturization and its effects on the functionality of the used components. Some of the many problems to tackle are the use of naked chips, chip scaling, assembly processes like wire bonding and flip-chip on a flexible substrate, application of thin-film batteries and solar cells and integration of the entire technology in a biocompatible package.

Fig. 16. Prototype sensor in a flexible band aid

BODY AREA SENSOR NETWORK

A network of the above sensors was demonstrated where the sensors share a single communication medium (a radio-channel in the 2.4GHz band). The low-duty cycle, non time-critical measurements typical for a network of low-power sensor modules, allow for a time division multiple access (TDMA) method to share the medium [8]. A sensor module's power consumption profile during a TDMA cycle is shown in Fig. 17. This TDMA cycle returns at a specified measurement interval, with the system returning to a 6µW sleep mode in between.

The resulting average power consumption for 10s measurement intervals and in practical operating conditions is 100µW.

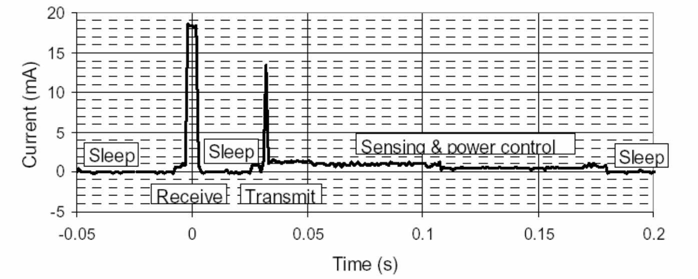

Fig. 17. *Power consumption profile of the wireless sensor module [12].*

CONCLUSIONS

This paper gave an overview of the Human++ research program at IMEC, which is targeted at developing key technologies and components for future wireless body area networks for health monitoring applications. Several working prototypes have been discussed, such as micropower generation devices and a $1cm^3$ low-power wireless sensor node. This modular wireless 3D stack is now used as a platform for the integration of future developments (sensors and actuators, energy scavenging devices, ultra-low-power local computing and transceiver) in order to realize fully integrated, autonomous ultra-low-power sensors nodes for body area networks.

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