Wireless sensor nodes: potential and challenges

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Abstract - *Highly miniaturized and autonomous sensor systems or in short wireless sensor nodes can serve many application domains in an ambient intelligent future such as health and comfort, industrial processes, automotive etc. Ultra-low power consumption and energy scavenging from the environment are essential for their commercial success. This paper reviews the technologies necessary to develop these systems, with focus on micropower generation and low-power design. The potential of wireless sensor nodes and the challenges related to their development are illustrated by a test case on body area network technology.*

I. CONCEPT AND APPLICATION AREAS OF WIRELESS SENSOR NODES

Our future is evolving towards a world where compact and inexpensive microsystems will add intelligence to almost every object that surrounds us. Sensing and actuating functionalities will be 'hidden' in the environment. They will be aware of the context and be able to interact wirelessly with people and with each other. These miniaturized sensor systems are configured into a wireless network and work autonomously, based on their low power consumption and energy scavenging from the environment. Hence they are referred to as highly miniaturized and autonomous sensor systems or, in short, wireless sensor nodes. Each node can be imagined as a small computer, extremely basic in terms of interfaces and components. They usually consist of sensors, a radio unit for wireless communication, a logic circuit for basic calculations and a power supply unit. Size and cost constraints result in corresponding constraints on resources such as energy, memory, computational speed and bandwidth.

These wireless sensor nodes are being developed for integration in all possible objects, hence serving applications in a large number of domains. For instance, a variety of state-of-the-art devices for sport, comfort and entertainment applications (such as gaming) will make use of sensors and actuator systems in and around the body. They will be developed to be worn as easily as a digital wristwatch. Equally, wireless sensor nodes will be used to scan, sense and interpret data from the human body, enabling people to better control their healthcare and potentially reduce medical costs. Ultimately, the technology will lead to the development of a personal body area network (BAN) which provides medical, sports or entertainment functions to the user. But also in automotive electronics, the demand for wireless sensor nodes is growing rapidly. They will be used to scan the car and its exterior environment, sense relevant information, collect it, interpret it, record it and communicate it so the driver can respond accordingly. Networks of distributed sensor nodes will as well be used to enhance industrial process control, or to assist farmers in efficiently cultivating large crops. Construction workers and engineers will rely on the data that are collected by miniaturized pressure sensors built into buildings, roads, bridges and railways. It's almost easier to come up with examples than to find areas of our civilization that will not be affected.

In the next section, we will illustrate what today's technology is capable of in the area of healthcare. Ambulatory multiparameter monitoring as an example of a BAN was chosen as a driving application. The features of the first demonstrators have been translated into challenges that need to be solved in order to enable a widespread deployment of BANs. In the remainder of the paper, we will show how advances in generic technologies, with focus on micropower generation and low-power design, can enable such systems in the near future.

II. TEST CASE ON HEALTHCARE: AMBULATORY MULTIPARAMETER MONITORING

A. Body area networks, a component of e-Health technology

It is a common trend - especially in wealthier nations - that people spend increasingly more money on healthcare. Statistics show that the cost lowering effect of technology and automation is more than offset by the impact of an ageing society, consumerism, biotechnology and medical breakthroughs. This results in an overall increase in cost between 2-3% per year. As a result, alternative ways to increase efficiency, productivity and usability while controlling cost are being sought. One strategy consists of offloading healthcare institutions by shifting the health management outside the expensive formal medical institutions. E.g., in the field of chronic diseases, the provision of real-time data from and to the patient anywhere and at any time may hold significant potential for cost reduction. In all this, the supporting role of an adequate technology platform such as an 'e-Health technology platform' is critical. E-Health refers to the use in the health sector of digital data transmitted, stored and retrieved electronically for clinical, educational and administrative purposes, both at the local site and at a distance. Driven by demographics (the ageing society), an increased incidence of chronic diseases and the ever rising patient expectations e-Health technology is increasingly coined as the revolutionizing enabler for the next decades to come.

However, whether and how it will enhance healthcare system efficiency and resolve the associated cost burden remains to be seen, and is currently subject of many investigations worldwide.

Here, we will analyze one component of e-Health, namely the BAN. BAN technology will enable people to carry their personal body area network that provides medical, sports or entertainment functions for the user (see figure 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 and 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.

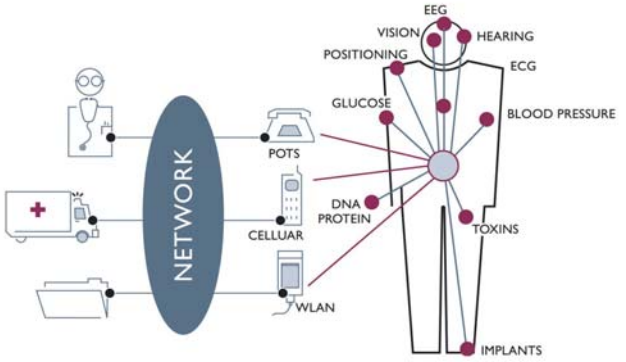

Figure 1: The technology vision for the year 2010: people will carry their personal body area network and be connected with service providers regarding medical, sports and entertainment functions.

The fulfillment of this vision clearly holds some general technological challenges: the energy autonomy of current battery-powered devices must be extended; intelligence should be added to the device so that it can store, process and transfer data; energy consumption of all building blocks needs to be drastically reduced to allow energy autonomy. But there are also severe constraints on their overall size and eventually, new applications such as multi-parameter biometrics should be enabled.

B. A state-of-the-art system for ambulatory multi-parameter monitoring

An ambulatory multi-parameter monitoring system aims to acquire, process, store and visualize a number of physiological parameters in an unobtrusive way. In this case, the simultaneous acquisition of electroencephalography (EEG), electrocardiography (ECG) and electromyography (EMG) biopotential signals (all µV to mV-range signals) is envisaged. The targeted sensor systems should be small, cheap, power efficient and have ample intelligence to make decisions. They should combine the real-time features of a clinical system with the benefits of ambulatory monitoring.

Figure 2 shows the BAN set up, consisting of EEG, ECG and EMG sensor nodes that are wirelessly connected to a PC or PDA. The latter acts as a base station that collects the information from the 3 sensors through a USB interface. The base station also acts as a master for the network, which makes use of a time division multiple access (TDMA) scheme. The sensors have very similar functionality: incoming signals are amplified and filtered; resulting signals are sampled at 1024Hz with a 12-bit resolution and finally, the digital signals are transmitted over a wireless link operating in the 2.4GHz industrial, scientific and medical (ISM) band (figure 3). The sensors can be realized with the same programmable hardware.

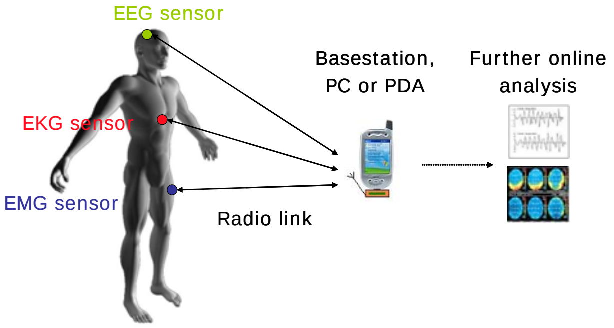

Figure 2: Schematic overview of the BAN set up, consisting of EEG/ECG/EMG sensors wirelessly connected to a PC or PDA.

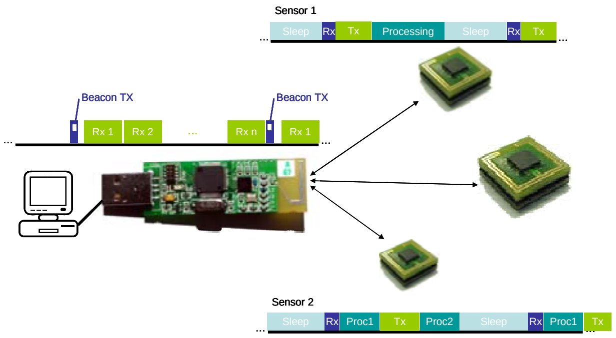

Figure 3: Base station with 3 integrated sensors, sharing the radio interface via a TDMA scheme. The base station sends out a periodic beacon. The sensors synchronize themselves to this beacon and send their data back in the timeslots allocated to them.

The power of the sensor nodes is a key design criterion as it directly determines the size and operational lifetime of the system. The sensors are found to alternate between four different modes of operation: listen (parameters are received from the base station); processing (biopotential signals are monitored and preprocessed); transmit (data are sent to the base station) and sleep (power save mode). Each of these modes has its own power consumption. E.g., the current consumption in listen and transmit mode is much higher than in processing or sleep mode. This is a direct consequence of the radio which is switched on in these modes and which consumes about 90% of the power when active. An analysis of the total average power consumption has shown that with the current system, consisting mainly of off the shelf components, a prototype can be designed that consumes less than 1mW of power if the measurement interval is longer than 1s. If two conventional AA batteries with a capacity of 2500mAh are used, the battery lifetime becomes approximately 3 months. The price of such a system is estimated around 100€ for low volumes and lowering as volumes pick up.

C. Towards an improved BAN system

The above clearly shows that with today’s technology, first realistic demonstrators with a reasonable lifetime can be manufactured. However, a couple of major challenges still have to be solved in order to come to a widespread deployment of BANs:

- Run on smaller batteries: AA batteries are good for demonstration, a coin or planar type of battery is finally envisaged. These batteries have roughly 100 times less capacity than the AA cells. To keep the same battery lifetime the power of the electronics has to be reduced by a factor 100. Alternatively, one can scavenge energy from the environment during the operation of the system. If the average scavenged energy is larger than the average consumed energy, the system can run eternally with the battery or a super capacitor acting only as a temporary energy buffer.
- Longer maintenance free operation: the system we demonstrated can run for months. However, to come to a truly autonomous system it should operate over its full lifetime without maintenance. The lifetime of electronic systems is often a few years; compared to the few months we need another 10x power improvement.
- Providing more functionality: today’s sensor system can provide limited autonomy. Most of the devices act as simple gateways, passing on the information to a central hub where the data is converted into actionable information. By adding intelligence to the sensors, they can take decisions locally and the signaling overhead in terms of data and latencies can be reduced.
- Become manufacturable at low cost: today’s systems cost between 10 to a 100€. A major reason for this is the low volume of the market so far, but another more technical reason is that there are no commercially available packaging technologies that can efficiently integrate such heterogeneous components as batteries, MEMS, processors, and radios in a single package.
- Integration of novel sensor and actuator concepts: the quality of the information resulting from a BAN is only as good as what you measure. Today, only simple physical properties such as bio-potentials, temperature and movement are measured. Sensors that can measure these parameters in an ambulatory setting are in high demand. Motion artifacts are often a major source of data corruption. However, in a next step also biochemical measurements will be required in order to interact with the biochemical reactions that drive our daily life.

Hence, in order to become an enabler for e-Health technology, wireless sensor nodes such as these need to be 1000x more power efficient, have ample intelligence to make decisions and cost less than 1€. In the remainder of this paper it is shown how recent advances in micropower generation, ultra-low power radio technology, and ultra-low digital signal processing can enable such systems in the near future. To offer a complete overview of enabling technologies, the progress made in sensors and actuators and in integration technology is discussed as well, however to a minor extent. It should be emphasized that the next session discusses generic technologies that can be tuned to other wireless autonomous system applications.

III. TECHNOLOGICAL CHALLENGES TO DEVELOP FUTURE WIRELESS SENSOR NODES

A. Micropower generation

Today, the batteries needed to power wireless sensor nodes seriously limit the possibilities of this emerging technology. Either large batteries are used that give a longer autonomy but make the system bigger, or small batteries are used that make the system less autonomous. For this reason, a worldwide effort is ongoing to replace batteries with more efficient, miniaturized power sources. A promising strategy is to scavenge or harvest waste energy (thermal, mechanical or solar) from the environment and convert it into electrical energy, stored in a micro battery.

The choice of the scavenging principle depends on the applications and the environment in which it is used. Solar cells seem an obvious first solution in view of their efficiency and the maturity of photovoltaic technology. Moreover, solar-cell manufacturing is largely compatible with standard IC processing steps. However, for indoor and embedded conditions, sufficient access to solar energy is seldom guaranteed. In view of this constraint, scavenging of thermal and vibration energy are more flexible options.

To scavenge mechanical energy from vibrations and convert it to electrical power, the most common approach is to use an inertial system. This can be schematized as a spring connected to the vibrating frame and a mass. The motion of the mass with respect to the frame causes the movement of the different parts of an electromechanical generator, which delivers power to an external load. Three types of generators can be used: electromagnetic, electrostatic and piezoelectric. The latter two are under development at IMEC. In an electrostatic conversion (see figure 4), the polarization voltage determines the charge on the two capacitors. The capacitance changes due to the external vibrations cause a redistribution of the charge and hence a current flows through the load. Key factors controlling the performance characteristics of the scavengers are the polarization voltage and the change in capacitance per unit displacement of the moveable electrode. [1]

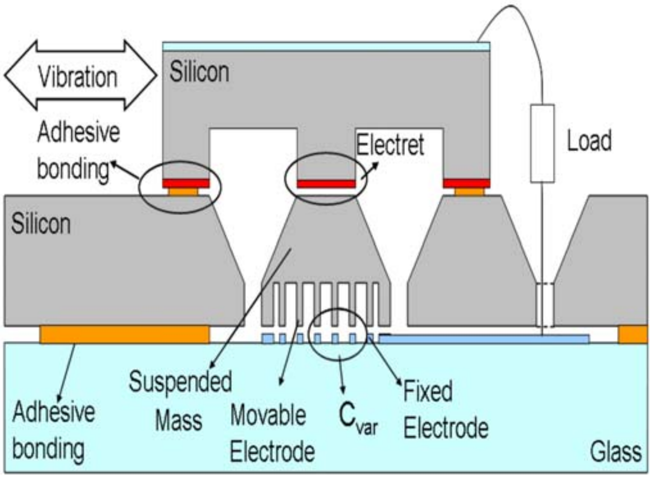

Figure 4: Schematic drawing of a MEMS-based electrostatic vibration scavenger.

The design of piezoelectric devices is similar to the classical design of accelerometers: a bending structure is connected to a vibrating frame. The beam supports a piezoelectric capacitor and a mass. The vibration of the frame induces a vibration of the mass and a bending of the cantilever. The strained piezoelectric layer generates charges that flow in the external circuit.

For both types of generators, the progress made in semiconductor and micro-electromechanical systems (MEMS) processing can be exploited to obtain the desired cost and efficiency goals. Possible sources of mechanical energy can be both men and machine, but also buildings, roads, bridges and railways with a lot of passing traffic. For human-body applications, reaching the target of 100µW will be very hard. For industrial applications, however, power up to 1mW/cm^3 is within reach. [1]

Thermal energy scavengers are thermoelectric generators (TEGs) that exploit the Seebeck effect[1] to transform a temperature gradient into electricity. A TEG is made of thermopiles sandwiched between a hot and a cold plate. Thermopiles are in turn made of a large number of thermocouples connected thermally in parallel and electrically in series. These types of scavengers can be used in a variety of applications, covering industry, medical, consumer or telecommunication areas, security systems and fire alarms, whenever natural thermal gradients or industrial heat flows are available for utilization. When miniaturized and cost-effective, TEGs are of particular interest for applications of wearable electronics, where wasted body heat can be used to provide power autonomy to wireless sensor nodes.

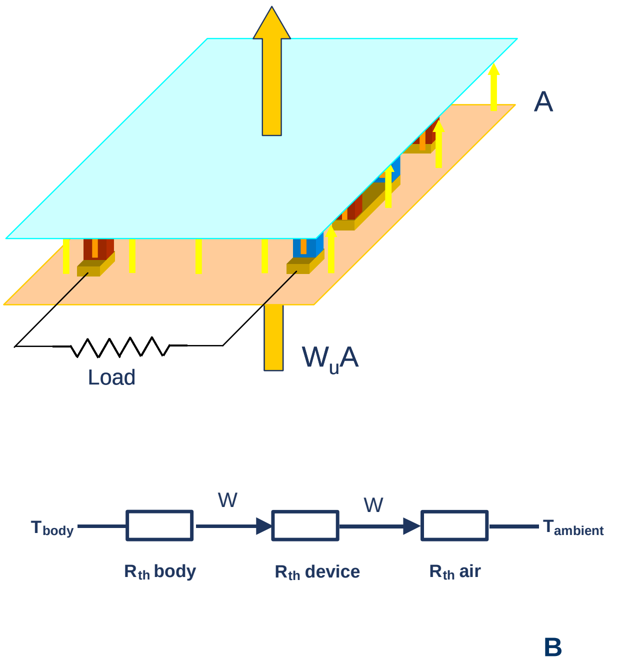

Figure 5: a) Schematic of a thermoelectric generator; b) the schematic thermal circuit representing the generator and its environment.

Figure 5a shows a schematic of a TEG. The red and blue pillars represent the two types of thermoelectric materials, the metal interconnects are drawn in gold. The pink and blue plates are respectively the cold and hot sides of the device. The maximum electrical power is generated when the load is matched to the electrical resistance of the generator and when the thermal conductance of the thermocouples equals the one of the air between the plates. Under this condition, power increases when increasing the height of the pillars. In commercially available thermopiles, typically based on Bi_2Te_3, the pillars have a lateral size of 0.3 – 1µm and a height of 1 – 3µm.

In operating conditions, the generator is inserted in a thermal circuit which includes the thermal resistance of the body and the equivalent thermal resistance of the air. The thermal resistance of the body largely depends on the place of attaching the device to the body. E.g., the presence of arteries is responsible for a significant variation of the body properties from place to place. Investigations showed that the radial artery on the wrist is the most appropriate place for attaching the TEG. However, the air and body resistance should not be too low as this would result in a too large heat flow from the body and in a discomfort for the user (feeling of cold). In an optimized prototype using commercial thermopiles, the power generated by the device is in excess of 0.1mW, the output voltage is above 1V. This power is enough to charge a small battery and to transmit a signal each 1 – 2s to a nearby receiving station. The power conditioning electronics, together with a low power radio transmitted, is mounted on a flexible substrate and glued to the wrist strap.

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[1] In 1823, the German physicist Seebeck discovered that a voltage was developed in a loop containing two dissimilar metals, provided that the two junctions are exposed to different temperatures.

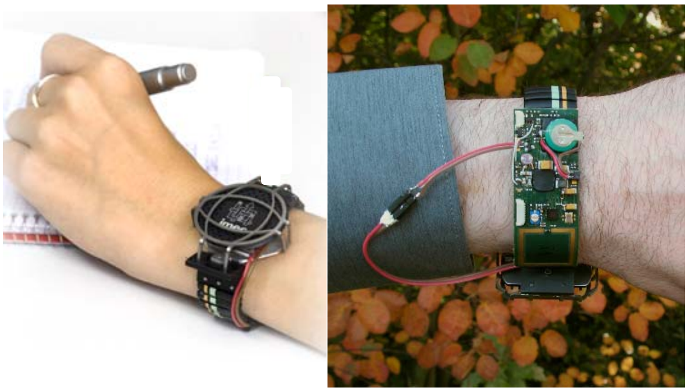

Figure 6: Left, a thermoelectric generator fabricated using commercial thermopiles; right, the power conditioning electronics and a transceiver mounted on the wrist strap.

Commercially available thermopiles for thermal scavenging aren't optimal for two main reasons. First, they do not allow optimizing the power and the voltage at the same time. This would require the number of thermopiles to be increased while at the same time reducing the cross-section. The cross-section of commercial thermopiles however has certain technological limits. Second, they are fairly expensive. A further optimization is enabled by the use of micromachined thermocouples. They offer the potential advantage of reducing the lateral size of the thermocouple. Drawback of this technology is that the height of micromachined thermocouples is limited to a few micrometers. IMEC has come up with an ingenious solution to bypass this restriction. By using a special design, a large thermal resistance, needed for optimal power, can be combined with a large number of thermopiles, needed for optimal voltage. The setup consists of several thousands of thermocouples mounted on a silicon rim. The function of this rim is to decrease the parasitic plate-to-plate conductance of the generator caused by the small height of the thermocouples. Initially, SiGe thermocouples were used because of their compatibility with standard IC processing, resulting in calculated powers of 4.5µW/cm^2 at 1.5V on the human body. Using a better-performing thermoelectric material like Bi_2Te_3 would result in power up to 30µW/cm^2 at over 4V for the same setup. Prototypes are being built to demonstrate the potential of this technology. [1]

B. Ultra-low-power radio communication

A sensor network requires ultra-low-power radio technology to enable wireless communication between the sensors and a central device. Wireless communication is a major power drain in wireless autonomous transducer systems as it consumes up to 70% of the total power budget. Since the sensor nodes can only rely on energy harvested - or scavenged - from the environment, extremely low power consumption is therefore essential. Emerging systems typically make use of Bluetooth or Zigbee chipsets, some use proprietary radio chipsets that operate most often in the ISM bands. Typical chipsets for these radios consume in the order of 10 to 100mW for data rates of 100 to 1000kbps. New communication techniques and devices are required that operate at power levels one order of magnitude below current solutions.

Recently, a solution based on ultra-wideband impulse radio has attracted large attention from the wireless community. This new technique for low-power radios has the potential to better serve sensor-network applications because of its ability to generate a wide range of data rates. In addition, the Federal Communications Commission (FCC) has authorized UWB communications between 3.1GHz and 10.6GHz. Although, the regulations on UWB radiation define a power spectral density (PSD) limit of -41dBm/MHz, there are very few regulations on the definition of the time-domain waveform. The latter can then be tailored for low hardware complexity as well as low system power consumption. In pulse-based UWB, the transmitter only needs to operate during the pulse transmission, producing a strong duty cycle on the radio and the expensive baseline power consumption is minimized. Moreover, since most of the complexity of UWB communication is in the receiver, it allows the realization of an ultra-low power, very simple transmitter and shifts the complexity as much as possible to the receiver in the master. An important constraint however is the subdivision of the entire UWB spectrum in 500MHz sub-bands, posing severe challenges to the pulse generation mechanism.

Short high-frequency UWB signals can be realized by gating an oscillator. The oscillator center frequency is then defined independently from the bandwidth by the gate duration. An interesting solution (figure 7) is to use a triangular pulse generator, confining most of the power in the useful bandwidth, and a ring oscillator that are activated simultaneously. The gating circuit activates the ring oscillator when a pulse must be transmitted, avoiding useless power consumption between the pulses. The triangular signal is multiplied with the carrier created by the oscillator. A measured 0.18µm full CMOS version can deliver a pulse rate up to 40MHz. The measured energy consumption is 50pJ per pulse at a 40MHz pulse repetition rate for a pulse bandwidth of 1GHz. In other words, if ten pulses are used to code one bit, this pulse generator provides an average data rate of 10kbps with an average power consumption as low as 5µW [2].

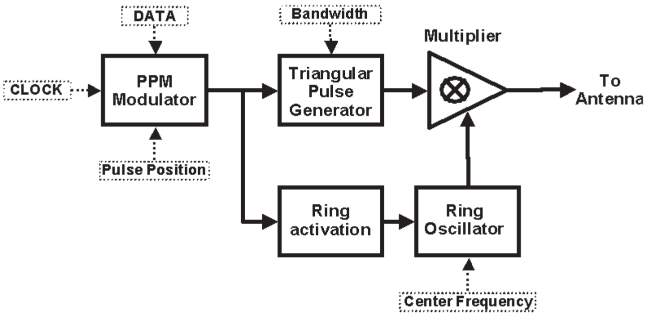

Figure 7: Architecture of the pulse generator.

Processing wideband analog signals in the digital domain requires an extremely fast sampling ADC with a wide input bandwidth. Such solutions have all flexibility in terms of digital signal processing but are often less attractive due to their required power consumption. In order to minimize the overall sampling rate and total power consumption, analog preprocessing is an interesting alternative. To solve this problem, an analog-based correlation receiver architecture can be used that is well suited for low data-rate impulse-based UWB applications. This receiver architecture has been implemented in 0.18µm CMOS technology. The total current consumption of the chip including the digital baseband is 16mA measured on a 1.8V supply at 20MHz clock rate. This power consumption is substantially higher than that of the pulse generator. However, for use in e.g. BANs, only the transmitter in the sensor has to be extremely low power, while the receiver in the central station has a slightly more relaxed power budget. [3]

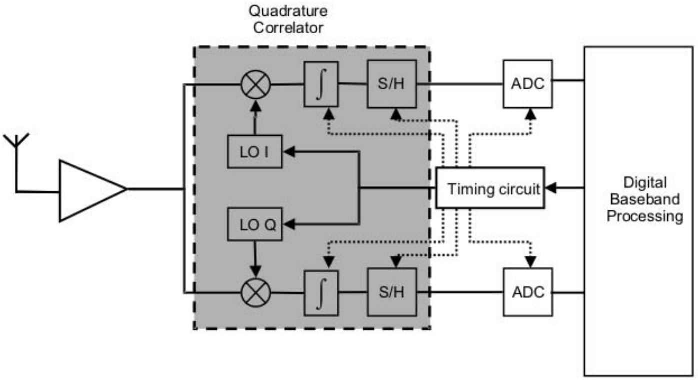

Figure 8: UWB analog receiver.

C. Cross layer optimizations

Building a wireless sensor node solution that is able to deliver the required performance at minimal energy consumption requires a very careful global design where power, performance, cost and size for each building block are carefully considered and traded off. Since wireless sensors can be used in such a large range of possible applications, the number of possible designs is equally broad. Some of the design choices have to be fixed during the design time phase since it is too expensive to allow for multiple options, e.g., the battery size of the micropower generation. Other design choices are fixed early on in the design since they are dominantly optimal or since they have very little impact on the overall power, performance or cost.

In a number of cases however, it can be very useful to maintain some well-chosen flexibility during the run time phase. A first reason for this is to overcome the dynamics inherently present in wireless communications and many applications. Given for instance the pathloss variations encountered in a typical wireless communication setup, it can be very suboptimal to design the communication link for the worst case possible pathloss. Indeed, adapting during the run time phase to the current channel conditions allows to save a lot of energy. A second reason is that, in order to meet the cost constraints per sensor, it is useful to be able to use a single wireless sensor design over a range of possible applications with potentially very different characteristics.

At IMEC, an approach has been designed that allows to globally model the power and performance that is achieved as function of a set of design choices. In figure 9, the DC power versus sensitivity of a receiver for a constant-envelope Gaussian minimum shift keying (GMSK) physical layer is given for a large number of possible design options. First, it is clear that a large number of designs are suboptimal in the dimensions DC power and sensitivity, and should hence not be considered further in the design exercise. Only the points that are on the optimal trade-off curve should be considered when selecting the optimal receiver. It should be clear that the receiver that is finally selected depends also on the transmitter characteristics, the typical pathloss encountered in the target context, the application data rate and asymmetry of the communication link.

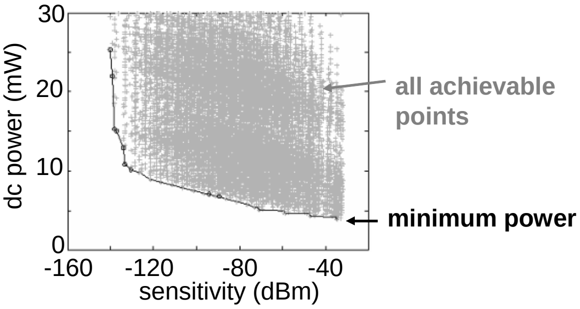

Figure 9: Minimum receiver power as a function of sensitivity with all achievable points in power-sensitivity plane.

Although it may not always be possible to allow a lot of flexibility during the run time phase, it can be useful to adapt, e.g., the receiver sensitivity, to the current pathloss conditions. The approach developed at IMEC also enables to determine during the design time which configuration options, or control knobs, are useful to maintain during the run time phase since they potentially allow to save a lot of energy. For instance, we consider two conflicting energy management approaches that exist in current wireless communication systems: shutdown and scaling [4]. The shutdown approach tries to send data as fast as possible, thereby allowing the system to be in the low power sleep mode as much as possible. The scaling approach however, minimizes the energy consumption by sending the data as slowly as possible, thereby allowing to save transmit power as much as possible. It is clear that both approaches are contradictory. However, it depends on the application scenario to conclude which approach results in the largest energy savings. As a result, we propose to decide only at run time, when the exact application context is known, on the amount of sleeping or scaling to employ. The resulting energy consumption of the proposed approach is shown in figure 10 for a range of application loads. It is clear that, for a low load, shutdown is better, while for a larger load, scaling is better. Our combined cross-layer approach however adapts during the run time and saves maximally.

Key in the proposed cross-layer adaptation strategy is that we only keep the ‘just required’ flexibility during the run time. Also, the optimal configuration (i.e., amount of sleeping or scaling in the above presented example) is pre-stored in a set of scenarios (8 scenarios were considered in the example for figure 10). As a result, the run time adaptation algorithm is very light, hence suitable for sensor networks.

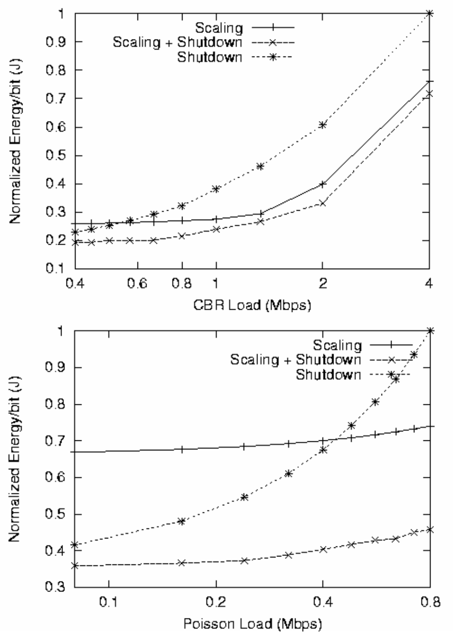

Fig. 10: Normalized energy per bit for a topology of 5 nodes, D=100ms (a) at distance 28m, for a range of constant bit rate (CBR) loads (b) at distance 33m, for a range of Poisson loads.

This approach can also be used to determine the amount of processing to be carried out locally, given the cost of transmitting versus processing that information. Alternatively, we can easily determine if it is better to transmit the sensed data in a single hop to the central PDA or if the use of multiple shorter transmissions around the body are more energy efficient.

D. Other challenges

Existing devices typically make use of bulky macro sensors and actuators that consume several 100mW of power. Moreover, most closed-loop systems focus on physical properties such as light, temperature, pressure, sound, magnetic field, motion dynamics and impedance. Therefore, the development of sensors and transducers with enhanced performance and functionalities and with extremely low power consumption (typically an overall average power budget of 20µW for the sensor and actuator layer) is highly demanded. Microfabrication techniques and new functional materials integration can be exploited for this purpose. The development of a low-power 25 channel biopotential ASIC, allowing to preprocess the ECG and EEG signals, is a good example of sensor and actuator development. In a typical configuration, 24 channels are configured for EEG measurements, and 1 channel is configured as ECG channel. Each channel consists of a high common-mode rejection ration (CMRR) instrumentation amplifier, followed by a variable gain amplifier. 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 0.5Hz – 80Hz bandwidth. These features allow suppressing 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 2.7V - 3.3V while dissipating less than 10.5mW. More recently we have also fabricated an alternative instrumentation amplifier architecture with a power consumption of 20µW per channel while maintaining a CMRR of 110dB. This ASIC provides an additional factor of 20 in power savings per channel compared to the 24 channel version. [6], [7]

Finally, when all building blocks of today's wireless transducer systems (including sensors and actuators, radios and micropower systems) are put together, it results in systems of typically several tens of cm^3 weighing several 100g. Portable applications or environments that cannot tolerate such a form factor demand for new system-in-a-package (SiP) and system-on-chip (SoC) integration techniques that are tuned to the needs of sensor networks. For this purpose, 3D integration technologies, advanced PCB stacking and flexible stretchable substrates are being developed. The final SiPs will be tuned for different applications and manufactured with industrial processes. This will lead to generic modules that can be manufactured in large volume at an affordable cost.

3D sensor cubes that include radio, DSP and sensors have already been demonstrated using a 3D SiP approach (figure 11) [5]. The different functional components are designed on separate boards and afterwards stacked on top of each other through a dual row of solder balls. The sensor layer contained the programmable ECG/EEG/EMG read-out ASIC. Parallel research was started to implement the same technology on a flexible carrier. 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.

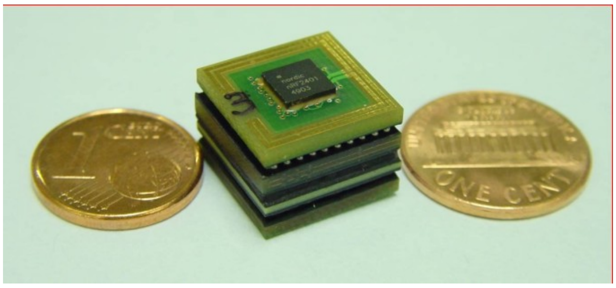

Figure 11: 3D SiP wireless autonomous sensor node.

III. CONCLUSION

From 2010 on, wireless autonomous sensors and actuators on flexible substrates or with sizes of 1cm^3 and below will surround us in an almost invisible way. They will cooperatively monitor our physical and/or environmental conditions. Low cost, energy scavenging from the environment and ultra-low-power consumption of all building blocks are key requirements for their development. This was exemplified by a test case on EEG, ECG and EMG monitoring. Recent advances in low-power communication, including the development of an ultra-wideband pulse radio and a UWB signal processing core, and progress made in micropower generation - solar, thermal and mechanical – are an important step towards the realization of these systems in the near future.

Most of the results reported in this paper have been developed in the frame of IMEC's Human++ Program, which develops generic technologies that can be used in the fabrication of devices that improve the quality of life. The generic technologies being developed within Human++ can be tuned to other wireless autonomous system applications. A number of research programs within Human++ are transferred to the Holst Centre. The Holst research center was initiated by IMEC and TNO in September 2005 to develop generic technologies for future generations of wireless autonomous transducer solutions and systems-in-a-foil.

REFERENCES

[1] R.J.M. Vullers, V. Leonov, T. Stercken, A. Schmitz, 'Energy Scavengers for wireless intelligent Microsystems', OnBoard Technology, June 2006

[2] J. Ryckaert, M. Badaroglu, C. Desset, V. de Heyn, G. Van der Plas, P. Wambacq, B. Van Poucke, and S. Donnay, 'Carrier-based uwb impulse radio: Simplicity, flexibility, and pulser implementation in 0.18μm CMOS', International Conference on Ultrawideband, ICU 2005, 2005.

[3] J. Ryckaert, M. Badaroglu, V. De Heyn, G. Van der Plas, P. Nuzzo, A. Baschirotto, S. D'Amico, C. Desset, H. Suys, M. Libois, B. Van Poucke, P. Wambacq, and B. Gyselinckx, 'A 16mA UWB 3-to-5Ghz 20Mpulses/s quadrature analog correlation receiver in 0.18μm CMOS', In ISSCC Digest of Technical Papers, pages 114–115, February 2006.

[4] S. Pollin, B. Bougard, R. Mangharam, F. Catthoor, I. Moerman, R. Rajkumar, L. Van der Perre, 'Optimizing Transmission and Shutdown for Energy-Efficient Real-time Packet Scheduling in Clustered Ad Hoc Networks', EURASIP JWCN, pp. 698-711, no. 5, December 2005.

[5] S. Stoukatch, M. Ho, K. Vaesen, T. Webers, G. Carchon, W. De Raedt, E. Beyne, J. De Baets, 'Miniaturization using 3-D stack structure for SIP application, Proc. SMTA (Surface Mount Technology Association) International Conference, 21-29 September 2003; Chicago.

[6] R. F. Yazicioglu, P. Merken and C. Van Hoof, 'Integrated Low-Power 24-Channel EEG Front-End', Electronics Letters, Vol. 41, 2005.

[7] Refet Firat Yazicioglu, Patrick Merken, Robert Puers, Chris Van Hoof, 'A 60μW 60 nV/√Hz Readout Front-End for Portable Biopotential Acquisition Systems', ISSCC Digest of Technical Papers, pages TBD, February 2006.

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Bert Gyselinckx is program director for the Wireless Autonomous Transducer Solutions program at the Holst Centre (www.holstcentre.com). This program offers one stop solutions for partners looking for enabling technologies for highly integrated wireless autonomous systems. Envisaged applications are in the domain of healthcare, lifestyle, gaming, education, and industrial process control.

Bert received the M.S. degree in Electrical Engineering from the Ghent University, Belgium, in 1992 and the M.S. degree in Air and Space Electronics from the Ecole Nationale Superieure de l'Aeronautique et de l'Espace, Toulouse, France, in 1993. At this time, he was also a trainee at the Research and Development group of Siemens in Munich, Germany.

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Sofie Pollin obtained the Electrical Engineering Degree in 2002 and the Ph.D. Degree in Electrical Engineering (with honors) in 2006 from the K.U.Leuven, Belgium. Since October 2002, she is a researcher at the Wireless Research group of IMEC working on cross-layer energy and performance optimization of wireless systems. In the summer of 2004, she was a visiting scholar at National Semiconductor, Santa Clara, CA. In the summer of 2005, she was a visitor at UC Berkeley. At this moment, she is a post-doctoral researcher at UC Berkeley working on Cognitive Radio.