

IcyHeart: Highly integrated ultra-low-power SoC solution for unobtrusive and energy efficient wireless cardiac monitoring

Research project for the benefit of specific groups (FP7, Capacities)

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Abstract—The objective of the IcyHeart project is to investigate and demonstrate a highly integrated and power-efficient microelectronic solution for remote monitoring of a subject's electrocardiogram (ECG) signals. A complete System-on-a-Chip (SoC) is being developed that embarks on a single chip an ultra-low-power signal acquisition front-end with analogue-to-digital converter (ADC) for ECG, a low-power digital signal processor (DSP) and a low-energy radio frequency (RF) transceiver. These features, for the first time, coexist on a single die. Energy efficient signal processing algorithms targeting ECG, and expandable to other bio-signals, are embedded and run on the on-chip DSP. The final IcyHeart product will consist of a tiny PCB embarking IcyHeart SoC and all the necessary discrete components and powering circuit. The outcome of the project is expected to generate high market value for the European SMEs developing novel cardio-monitoring products in home and professional environments, and to create high societal impact for several categories of European citizens requiring miniature, comfortable and easy-to-use wireless tele-healthcare solutions.

Keywords-component; ECG, SoC, DSP, ADC, RF

I. INTRODUCTION

The wide acceptance and recent advances in Wireless Technologies and Mobile ICT Solutions, as well as a series of major challenges that the healthcare sector is now facing, such as an aging population and increase of chronic illnesses, have pushed healthcare organisations and governments to gradually start embedding these technologies into an increasing number of medical procedures, applications and devices enabling them

to provide tele-healthcare services to patients around the world. In general, tele-healthcare concerns the remotely delivery of health-related services. In this way, it enables monitoring of patients in their homes increasing their mobility and comfort and allowing their discharging from hospitals resulting in substantial limitation of the overall medical sector budget. Wireless Electrocardiogram (ECG) monitoring constitutes one of the main tele-healthcare services where very-small-size and long autonomy are among the basic requirements that every solution to this area must meet. More specifically the focus is on ultra-low-power wireless and sensing micro-components for long autonomy and unobtrusive body-worn cardiac remote monitoring. Towards this aim, the IcyHeart project is developing a miniature and highly integrated microelectronics System-On-a-Chip (SoC) associated with an intelligent embedded signal processing suite enabling truly low-power wireless electrocardiogram (ECG) monitoring in tele-healthcare. The IcyHeart technology will generate high market value for the European SMEs developing novel cardio-monitoring products in home and professional environments, and create high societal impact for several categories of European citizens requiring miniature, comfortable and easy-to-use wireless tele-healthcare solutions.

II. TELE-HEALTHCARE AND CARDIAC MONITORING: MARKET OPPORTUNITY FOR WIRELESS TECHNOLOGIES

Tele-healthcare enables monitoring of patients in their homes

or when they are mobile, and capturing vital parameters [1]. It concerns the delivery of health-related services and information via telecommunications technologies, and encompasses preventive and curative aspects [2].

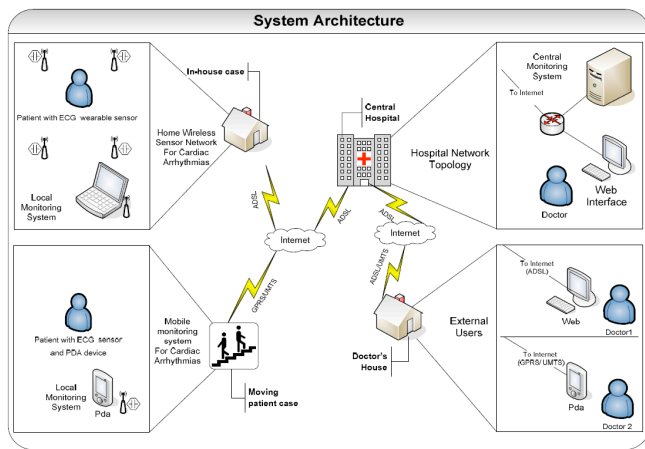


Figure 1. Tele-healthcare architecture in the context of cardiac signal monitoring @IEEE 2007

EU and worldwide governments and healthcare organizations have been considering tele-healthcare as a major technological and societal solution for solving the major challenges that the healthcare sector is facing today [3]:

- **Aging population:** The population above the age of 65 is increasing at a higher rate as compared to the working population (15-65 years). Europe had nearly 71 million people above 65 years in 2007 and is expected to reach 80 million by 2014, with major impact on hospitalization costs.
- **Increase of the incidence of chronic illnesses:** More than two-thirds of the population who is above the age of 65 has at least two chronic illnesses. Circulatory and cardiac diseases accounted for 42% of all deaths. Prevention and early intervention are thus acknowledged as essential by the governments.
- **Scarcity of resources:** The cost of healthcare is rising exponentially in Europe, whereas governments tend to reduce the funding towards hospitals. Hence hospitals are encouraging discharge of patients by reducing the number of beds, while promoting significant investments in tele-healthcare.

The typical tele-healthcare architecture is depicted in Fig 1. Tele-healthcare results in the elimination of wired connections and increases the mobility and comfort of patients. Supported by the advances in wireless technologies and the worldwide deployment of mobile ICT, healthcare organizations and industries have started **embedding wireless technologies** into an increasing number of medical applications and devices.

A typical tele-healthcare scenario concerns the patients discharged from hospitals or belonging to specific risk categories, and whose vital signs are remotely monitored. When a specific event is detected based on the evolution of

vital signals, **the concerned medical/healthcare services are remotely informed** and specific actions may be taken to improve health either on a **preventive or a curative basis**. This healthcare model allows hospitalizing ill or at risk patients only when necessary. In all cases, the comfort of the patient is increased because he/she stays at home, and the costs are limited because the number of hospitalisation days is minimised.

III. ICYHEART VISION FOR CARDIAC TELE-HEALTHCARE: PROGRESS BEYOND THE STATE OF THE ART

The IcyHeart project is developing a miniature and highly integrated microelectronics System-On-a-Chip (SoC), measuring only 5x6mm. Its associated embedded signal processing suite enables truly low-power wireless electrocardiogram (ECG) monitoring in tele-healthcare.

The focus is on ultra-low-power wireless and sensing micro-components for long autonomy and unobtrusive body-worn cardiac remote monitoring, in order to enable novel products that will be leveraged in home-centric patient care environments (upper and lower left areas of the architectural representation in Fig 1). A conceptual overview of the IcyHeart platform is illustrated in Fig. 2.

Today's wireless solutions do not meet all of these requirements together, and the major challenge of IcyHeart is to improve the personal remote ECG sensing through the following objectives:

- The development of the IcyHeart original equipment manufacturer (OEM) module, which is a tiny PCB including all the hardware and software components to enable novel ECG-based tele-healthcare products. The major differentiators are the **tiny stamp-size module** targeting less than 15mm x 15mm area, and the **low-power operation** with tiny low-voltage coin-cell batteries yielding a **supply as low as 1V** (e.g. single cell Zinc-air or Alkaline type of battery).
- The development of the IcyHeart SoC in 0.18um CMOS, which is the first time realisation on a single chip of all the required functions for ECG processing: the analogue ECG signal acquisition chain, the ADC, a low-power icyflex [10] DSP with the required memory, and the short-range 868-915MHz low-power radio. **Embedding signal acquisition, digital signal processing and wireless transmission on a single chip has a clear impact on minimizing power consumption, while at the same time reducing the physical size of the node and, ultimately, the discomfort for the patient.**
- The development of an optimized, flexible and **ultra low-power ADC-based sensor interface** silicon IP targeting ECG signals primarily with nominal 12-bit resolution, but studied for enabling flexibility of its configuration (various resolutions up to 16-bit, flexible bandwidth configuration up to a few 100Hz). Such flexibility of configuration eventually allows addressing other physiological signals. Scalability of

the performance of ADC-based sensor interface is crucial for guaranteeing lowest power consumption for 24/7 ECG sensing with tiny battery operation.

- The investigation and development of energy-efficient ECG signal processing algorithms, which is implemented on the embedded icyflex DSP within the IcyHeart SoC. Research is carried out to leverage innovative and light-weight algorithms (i.e. based on the discrete-wavelet transform and morphological filtering) that can achieve the best trade-off between accuracy and energy consumption. Through the extraction of the relevant signal features to be wirelessly transferred to the hand-held monitor, **energy-efficient embedded signal processing is crucial to reduce wireless streaming of raw ECG data over the power-hungry radio link**

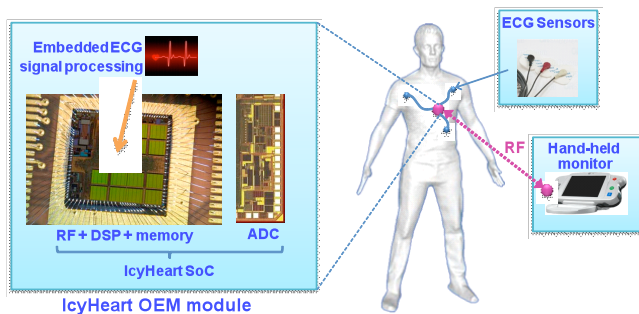


Figure 2. Conceptual View of the IcyHeart Platform

IcyHeart will provide innovations through a top-to-bottom system approach taking into account the key requirements for the targeted ECG & physiological signals monitoring applications. The main goal in the IcyHeart project is therefore to provide a compact wireless sensor platform with high degree of integration and to make it directly exploitable in tele-healthcare contexts.

The primary research areas, where the IcyHeart technology pushed beyond the state of the art, are summarized below:

- **Analogue low-power integrated sensor interface with ADC:** To enable long term continuous monitoring of ECG signals, it is mandatory to achieve an ultra-low power consumption of the analogue front-end (signal conditioning and ADC). The IcyHeart SoC includes a 12-bit ADC targeting a power consumption of 30uW under 1V power supply. This crucial part of the IC leverages the previous experience of partners (CSEM and Dolphin Integration) in designing $\Sigma\Delta$ -ADCs[6]. The main enhancement from previous ADC architecture is the design of the amplifier, for enabling this low supply voltage capability. Embedding the ADC in the same die as the DSP and the RF module allows a reduction in power consumption and Bill of Materials, thanks to increased locality and the introduction of a centralized energy management policy.
- **Energy-efficient embedded multi-lead ECG signal processing algorithms:** advanced multi-lead

delineation and digital filtering techniques are being investigated and will be embedded on the node. In detail, IcyHeart will apply morphological filtering to remove both high- and low-frequency noise (the former being induced mainly by respiration, the latter by muscular contractions). Delineation of the characteristic waves of an ECG will be performed using a wavelet-based technique.

- **868/915MHz radio:** In IcyHeart, the 868/915MHz operating frequency is chosen over 2.45GHz and UWB to achieve better propagation characteristics, lower power consumption and higher receiver sensitivity. The dual frequency approach enables worldwide coverage, with a radio front-end that is compliant both with the European 868MHz license-free band, and with the US 915MHz license-free band. The radio will achieve max 113dBm link budget (10dB to 20dB better than existing PAN solutions) and a factor 2x to 10x better DSP performance (vs. the computing power and current consumption of available solutions), while only 3.5mW in receive mode from a 1V supply (x10 better than ULP Bluetooth or Zigbee).
- **SoC with analogue-to-digital sensor interface, DSP and RF on single-chip:** First time integration of a complete SoC with the entire set of critical functions for sensing and analogue processing close to the sensors, digital DSP core, and low power radio connectivity on a single die.
- **Novel market opportunities:** On top of the technology development, the end-user SMEs will creatively and significantly extend their products functionalities by adding embedded intelligence and wireless connectivity to their ECG sensors.

A synthetic overview of the key technological features differentiating the IcyHeart technologies from the state of the art is provided in Table 1.

IV. ICYHEART SOC AND EMBEDDED ADC

A block diagram of the SoC is illustrated on Figure 4. The heart of this SoC is a 32-bit icyflex1 DSP/microcontroller [10] with 96 Kbytes of SRAM for data and program, and 32 Kbytes of ROM memory which holds the boot program and different general purpose routines.

In addition, the sensor interface also incorporates an active ground control to cancel large common variations. It probes the common mode voltage of the three leads through a simple star connected resistors network and feeds back a signal corresponding to the inverted value of the common mode. Finally, the sensor interface also implements lead-off detection by injecting a 1 MHz square signal via the active ground connection and detecting this signal on the 3 ECG leads.

TABLE I. PROGRESS Beyond SOTA WITH THE ICYHEART RESEARCH AND TECHNOLOGIES

TECHNOLOGY	SOTA (state of the art)	Beyond SOTA With IcyHeart
<i>Sensor interface & DSP & RF SoC</i>		
Rx power cons.	>20mW at 2.4GHz	3.5mW at 868/915MHz
SoC complexity	Radio with uC (no DSP) on a single die	Radio & analogue sensor interface with 12-b ADC & DSP on a single CMOS IC
RF link budget	95dB at 2.4GHz	113dB at 868/915MHz
<i>Analogue sensor interface hardware</i>		
ADC	>1.5V supply for >10bit 10-bit, 30uW Not on SoC with on-chip DSP Fixed configuration	1V supply, with 12bit 12-bit, 30uW On SoC jointly with on-chip 32-b DSP Study of circuits for configurability of bandwidth and resolution
<i>ECG signal processing</i>		
Real-time ECG delineation	Single-lead	Multi-lead wavelet-based delineation
Baseline wander removal	Not filtered	Morphological filtering
High-frequency noise reduction	Simple analogue HW filters	Real-time optimized digital filtering

The SoC also contains a 863-915 MHz ultra-low power radio, several digital peripherals (SPI, I2C, GPIO, timers, RTC) and power managements blocks [11] to enable the use of a large range of supply voltage sources ranging from 1 V up to 3.6 V. It is optimized for battery powered systems with low duty cycle, with a stand-by mode (with RTC active) consuming only 1 uA.

V. ICYHEART ECG EMBEDDED PROCESSING

A comprehensive signal-processing suite allows IcyHeart nodes to reject noise and artifacts typically present in ECG acquisitions. To this end, two morphological filtering [8] steps are employed. In a first phase, the iso-electric baseline of the different leads is estimated and subtracted to the acquired signals. The obtained zero-centered acquisitions are then further processed to remove high-frequency noise. By using an optimised implementation to manipulate the sliding windows employed by morphological operators, processing of multiple leads can be performed in real-time on the IcyHeart SoC.

Filtered signal thus obtained can then be either wirelessly transmitted or *delineated*, i.e. analyzed to retrieve the onset, peak and end of heart beats characteristic waves. This information, transmitted with or without the support of the ECG data, is of paramount importance for an early detection of heart conditions. In the IcyHeart platform, delineation is performed by combining signals using a Root-Mean-Square (RMS) operation and delineating the resulting data by decomposing the signal in five wavelet scales [9]. The main heart-beat wave (the QRS complex) is then highlighted at scales from 2^1 to 2^4 , while the P and T waves surrounding it are retrieved at scales 2^4 and 2^5 . In both cases, waves are marked by zero-crossing points in-between pairs of maximum and minimums across scales.

The implementation results in a compact, yet robust application. It is, on one side, able to cope with different signal morphologies and heart-beat aberrations, and on the other it can be executed on a resource-constrained platform such as IcyHeart, occupying only 40KB for data and code and using up less than 50% of the core computational power (with a core frequency of 6 MHz).

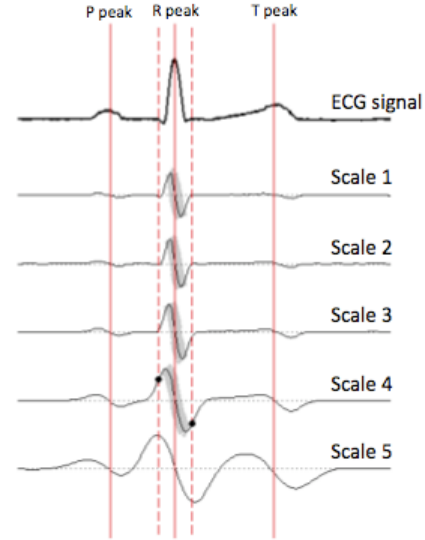


Figure 3. ECG recording of a heart beat and its DWT decomposition

VI. ICYHEART INTEGRATED MODULE

IcyHeart module consists of a tiny PCB which includes all of the associated hardware components. In particular, the PCB embeds the IcyHeart SoC (embarking the 868MH/915MHz radio, icyflex micro-processor and digital peripherals and low-power ADC-based sensor interface for ECG signals and auxiliary signal input), the necessary discrete components (e.g. regulators, crystal oscillators, etc.), the battery holder and the power supply and battery supervision circuit

The architecture of the IcyHeart Integrated module comprising the following blocks and terminals is presented in Fig 4:

- ECG sensors (three leads plus a lead for electrical reference).
- Auxiliary signal input.
- Antenna for RF communication.
- System-on-Chip (SoC), mainly RF transceiver, ECG sensors interface, LED drivers, IcyFlex microprocessor, power management.
- USB interface for wired serial connection and battery charging.
- LED indicators: correct fitted electrodes, transfer or record of data, battery's life, and failure.
- Battery, power management, on/off or reset button

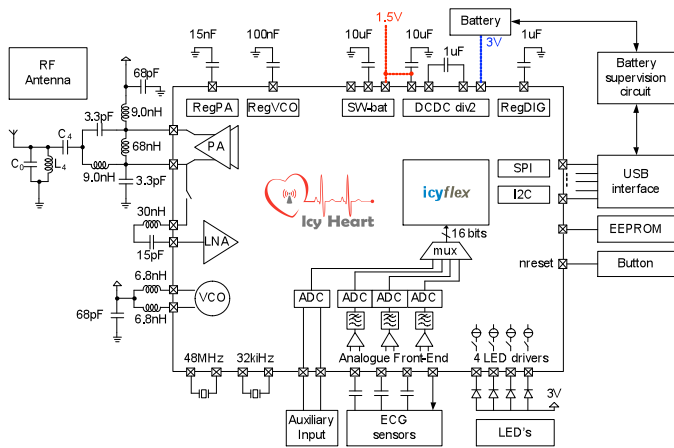


Figure 4. IcyHeart SoC and System Architecture

VII. DISCUSSION AND CONCLUSIONS

The IcyHeart project is developing a miniature and highly integrated microelectronics System-On-a-Chip (SoC), measuring only 5x6mm, and advanced embedded signal processing suite enabling truly low-power wireless electrocardiogram (ECG) monitoring in tele-healthcare.

IcyHeart will provide innovations through a top-to-bottom system approach taking into account the key requirements for the targeted ECG & physiological signals monitoring applications. The main goal in the IcyHeart project is to provide a compact wireless sensor platform with high degree of integration and to make it directly exploitable in tele-healthcare contexts.

The IcyHeart research enables major technological breakthroughs in the areas of highly integrated “sensing-converting-processing-transmitting” solutions in a single chip. The IcyHeart technology will generate high market value for

the European SMEs developing novel cardio-monitoring products in home and professional environments, and create high societal impact for several categories of European citizens requiring miniature, comfortable and easy-to-use wireless tele-healthcare solutions.

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