Performance Analysis of Interoperability Protocols and Algorithms in Networks-on-Chip for the Next Generation Biomedical Sensor-Networks:

A Study on Human Heart ECG Monitoring and Analysis via Nano-Multiprocessor-Networks

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Abstract—**We present a nano-interconnect platform utilizing biomedical sensor networks and the network-on-chip technology for human heart electrocardiogram (ECG) real-time monitoring and analysis. We analyze the performance of the platform interoperability protocol by setting the medical-application-specific figures-of-merit. These figures of merit are: the analysis-time required to converge to an alarm signal in very short rescue intervals due to life-critical medical situations, and power consumption in rechargeable biomedical sensors (lasting for a maximum of 24 hours). In this paper, we focus on the figure-of-merit of analysis-time for a power-rechargeable system-on-chip every 24 hours. This is an industry-relevant bio-medical application, with a huge potential market, that is still in the research and development phase. Hence it is an ideal target for an application-specific network implementation. We investigate the ECG network as a multi-processor architecture based on commercial VLIW DSPs that process, in real-time, 12-lead ECG signals. This architecture improves upon state-of-the-art designs for ECG analysis in its ability to analyze all the 12 leads in real-time, even with high sampling frequencies, and ability to detect heart malfunction. We explore the design for the wearable platform and consider the need for inter-communications protocol/algorithmss.**

Keywords-component; performance; interoperability; network-on-chip; biomedical, sensor networks: electrocardiogram, nano-multiprocessors

I. INTRODUCTION

The innovation and advancement in the multi-core processing field and embedded systems architecture make possible the development of nano-single-chip solutions for computationally-intensive bio-medical applications with significant medical benefits. The biomedical application we focus on, in this paper, is the real-time analysis and remote monitoring of analyzed data for human heart activity. Heart analysis is a challenging problem for biomedical scientists and engineers. Cardiovascular Disease (CVD) and stroke are the heart disorders constituting the primary cause of death in the globe. CVD and stroke are not related to ethnicity nor are they different between men and women. In 2003, CVD alone was responsible for around thirty percent of the total deaths in the world as reported by the United Nations World Health Organization (UNWHO), and this percentage is on a yearly rise [1]. More than half of CVD and stroke deaths can be saved by reliable monitoring and accurate analysis [1]. To analyze heart activity, electrical recordings from sensors connected to the human body are a basic step. The most commonly used recording is known as the electrocardiogram (ECG) signal, which can readily reveal a number of heart malfunctions [2][3][4]. Up till now, the most reliable ECG technique is the 12-lead ECG. It requires the reading and analysis of 12 signals from an interconnection of 9 biomedical body-sensors (Figure 1) [5]. The main challenge is the very high number of computations needed to analyze very large amounts of ECG recorded (and filtered) data in parallel. Another challenge is that this processing must be done within hard time deadlines to meet the real-time analysis requirement. A third challenge is that sensors nowadays can offer relatively high sampling frequencies, hence there is a mismatch between the sensor sampling frequency and the analysis techniques and products. All these challenges are intensified with a need for high accuracy, correct alarms, and fail-safe system needs due to the application commodity of being life-critical [6]. More demands become evident when the monitored patient is mobile as in the case of homecare [7]. State-of-the-art biomedical solutions/products for heart monitoring lack the ability to provide high computational real-time analysis at the point of need (location of the patient). Therefore the transmission of life-critical medical data in large number of bytes to a cluster of computing devices at a remote location becomes an essential need [3]. This imposes the availability of an always functional, always connected wireless link, because life-critical application data must not be lost. To overcome these challenges, our proposed solution is to parallel-process the large biomedical computations of the 12-lead ECG on a wearable nano-multi-processor network-on-chip (NoC). The biochip only transmits

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The joint work on the biomedical network-on-chip system and platform for ECG monitoring of Heart patients and of Space astronauts is co-sponsored by iITC^{TM} the Swedish IT company in Stockholm, and the San Marco Project Research Center (CRPSM), Rome, Italy.

secure alarm signals and reports on the results of the analysis, unless full raw ECG data was requested (remotely) by the healthcare center. Reports on results are in the range of a few bytes, while the ECG data is in the range of MB. Consequently, if the transmission of results fails, these reports can be re-transmitted until a secure acknowledgement packet is transmitted from the healthcare center to the biochip. Result reports are saved on an off-chip memory for every analyzed ECG data chunk. The data chunks we use are for 4 seconds of heart recordings, which is a biomedical requirement. The understanding of these objectives reveals a requirement for more than one biochip (each chip is an NoCs), which can interact to converge to an alarm and solution within the hard time deadline. Hence, there is a need for the design of special-purpose interoperability algorithms and an inter-NoC communications protocol, featuring increased energy efficiency while providing high computation capabilities. In this paper we introduce a novel architecture for ECG analysis which improves upon state-of-the-art mostly for its capability to perform a number of real-time analyses of input data with high sampling frequencies. With this architecture, we address usability, security, and safety of the patients in emergency situations, long-term treatments, and homecare. Comparison between our design and previous work shows the advantages of our design from a System-on-Chip performance point of view and from an application point of view.

The biomedical system builds upon some of the most advanced industrial components. The processing cores are commercial VLIW DSPs connected to off-the-shelf biomedical sensors. All system components are connected in a scalable and flexible platform. Therefore, we have ensured the platform reusability for future purposes, especially for applications collecting input data from wired/wireless sensor networks and that require parallel processing of the collected data in real-time.

II. The Medical Application and the Interconnect

State of the art biomedical sensors are characterized by increasing energy efficiency allowing longer lifetimes (up to 24 hours), and higher sampling frequencies (up to 10 kHz for ECG) and oftentimes can run wirelessly [8]. However, there is a mismatch between sensor technologies and state-of-the-art heart analyzers [6]. In our medical application, there are two types of networks to consider: a sensor network on the patient body, and the Network-on-Chip where sensed signals are analyzed. Figure 1 shows how interconnecting the nine sensors gives 12 leads known in biomedical terms as: Lead I, Lead II, Lead III, aVR, aVL, aVF, V1, V2, V3, V4, V5, and V6 (Fig.1-a). The 12-lead ECG produces data in the range of hundreds of MB every hour. Although the data storage requirements are large, physicians still use the 12-lead ECG method, because it allows them to view the heart in its three dimensional form. In other words, it enables the detection of any heart abnormality in any position. Figure 1-b shows real recorded signals from 12 leads, which are printed on the pink eyeballing paper (used nowadays although it is the classical technique used for looking at ECG). The eyeballing paper prints makes the check of the different rhythms (time on the x-axis) and peaks (mV on the y-axis) hard and inaccurate since the check depends on physicians' eyes. Since each lead senses data independently, each of the 12 signals can be assigned to a different nano-technology processor of the multiprocessor NoC. With this in mind, to extend ECG analysis to 15 leads, or more, what can be done is to add more processing elements in the interconnected platform (NoC). By reading data continuously every 4 seconds, we emulate a sensor sending continuous data to an intermediate buffer that holds 4 seconds of data sampled at 1KHz (maximum non-commercial sensor sampling capability is 10KHz). The application program module uses an autocorrelation function (ACF) to calculate the period of the heartbeat. The ACF shows how much the heart signal resembles itself after a certain time lag. The ACF, defined in (1), is periodic for every periodic signal.

$$R_y[k] = \sum_{n=-\infty}^{n=\infty} y[n] \times y[n-k] \qquad (1)$$

where, R_y is the autocorrelation function, y is the signal under study, n is the index of the signal y, and k is the number of lags of the autocorrelation. We run the experiments for n = 1250, 5000 and 50,000 relative to the sampling frequencies of 0.25, 1, and 10KHz, respectively. For the heart period detection, we need at least 4 seconds of ECG data for the ACF to give correct results. Hence, the application time *figure of merit* is 4s.

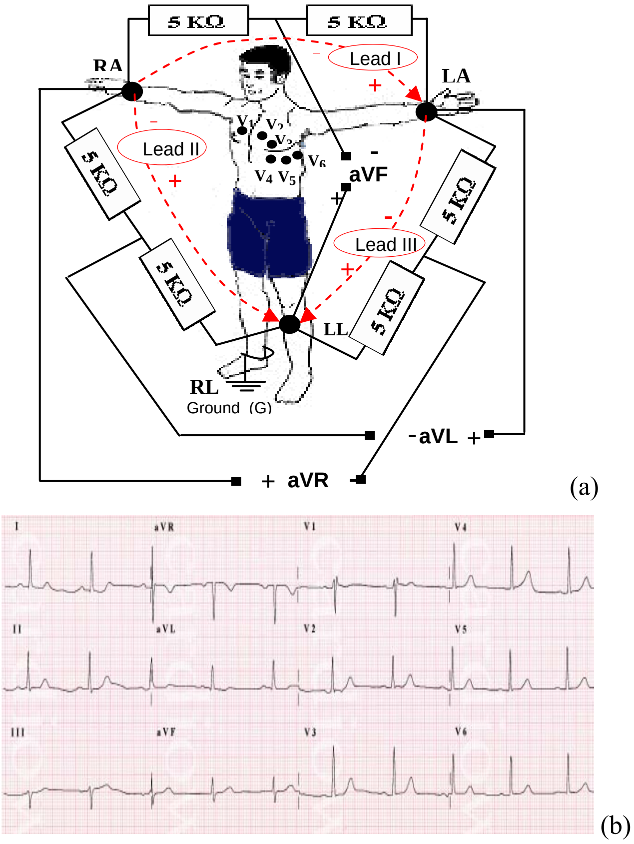

Figure 1. (a) 12-lead ECG interconnected biomedical sensor network with (b) twelve biomedical signals to input to the on-chip nano-multiprocessor-network, which runs the real-time analysis of huge amounts of data in less that 4 seconds (i.e. respecting real-time constraints).

III. THE NETWORKING-ON-CHIP FOR THE 12 LEAD ECG

NoCs have four major characteristics: small size (hence suits aerospace biomedical applications for astronauts), low weight, high computational multiprocessor interconnects, and low power consumption. More than one NoC is needed to analyze the signals and give reports. Hence, there is a need for an efficient set of algorithms and protocols to interconnect many different NoCs. We consider NoC as a *self-governing* system with its private internal policies that are designed and implemented by the manufacturer. We call this system the NoC *Autonomous System* (NAS) [9] as shown in Figure 2.

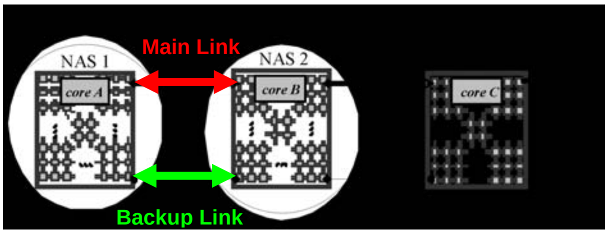

Figure 2. Nano-multiprocessor interconnects. NAS is the NoC Autonomous system, which has to run interoperability protocols on the interconnected multiprocessors. Multiple NASs may also be interconnected to increase the whole platform functionality and increase performance. Each NAS takes a number of input ECG signals (may be 12) and runs the application programs. One NAS may be used for aerospace applications that require millions of instructions per seconds to evaluate space parameters and another one may be used to run the millions of multiplications per second and additions to monitor and analyze the ECG signals of an astronaut.

The main interoperability algorithms and protocols are described in [9]. Each NAS has its own unique address that is defined to be the NoC Hardware Address (NHA$_x$, where *x* is an index reflecting the NAS number). This scheme allows two general types of communications. The first type is when a specific core p, wants to interact with a specific core q. The other scheme is when a core p wants to interact with some application in some NAS. Each of the inter-NoC and intra-NoC mechanisms can have many protocols. A major principle in intra-NoC communications when connecting two NoCs is to physically connect them via two links: Main and Backup (Figure 2). If one of the links fails, then we have another backup link so that inter-NoC communications continue. The Main and Backup links may be wire or wireless connections. We ran simulations for our Inter-operability protocol first version NoC-IOv1 using C++ for three NASs: one for 12 lead ECG, one for aerospace dynamics, and one for choosing best link and the results of the NoC-IOv1 convergence time are shown in Table 1, where the processing core discovering the malfunction changes randomly depending on the medical case. Hence the last column of Table 1 shows in which NAS the malfunction discovery occurred. Power consumption is an important factor in performance analysis, however in this paper we present the rechargeable sensor and NoC scenario, where only the time figure of merit is of interest.

Many challenges face this project from the interconnection to algorithm design, performance metrics, and measurements, which is ongoing work.

IV. CONCLUSION

This paper presents an application-specific nanotechnology multiprocessor network-on-chip and platform for real-time analysis of the human heart. Our solution uses interconnected multi-core chips with generic inter-NoC communication protocols in order to process data for ECG analysis. We use already designed protocols and analyze their performance for the time *figure-of-merit* in order to be able to enhance the protocols. This solution serves healthcare delivery scenarios, homecare, and monitoring of astronauts' hearts for accurate diagnosis and further medical research. We explore some configurations with a simulation of heart failure. Our system is a rechargeable power system for 24 hours, and beyond the 24 hour limit we have another study for the interoperability protocol, which decreases the sampling frequencies so that the protocol can transmits less data.

Table 1. Results of the 2 nano-multiprocessor NAS interoperability protocol. The convergence time to send a warning within the acceptable medical time-interval is in ms. The results are of a simulation of an emergency alarm due to heart malfunction.

Convergence time (ms)	**Information units (# of messages)**	**Node of Alarm signal**
13.69	1220608	NAS1
13.69	1220608	NAS 1
13.53	1220608	NAS 1
7.46	1220608	NAS2
7.46	1220608	NAS2
7.30	1220608	NAS2

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