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Study and Modelling of Selected Energy Consumption Factors for Embedded ECG Devices

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ABSTRACT

Heart attack is a life threatening cardiac disease. Although advances in information and communication technologies have brought us tiny embedded electrocardiogram (ECG) devices and efficient algorithms to continuously monitor and analyse ECG signals, energy consumption of the system is a critical concern for practical usage. However, there have been not many studies focusing on energy consumption of mobile ECG monitoring, especially lacking guidelines in selecting proper data communication strategies and computational algorithms. In this paper,three possible modes of data transmissions for energy consumptionare examined. A generic energy consumption model and a simulated environment were developed to examine the influence of different communication strategies and ventricular fibrillation detection methods in terms of computational efficiency and power consumption.

I. INTRODUCTION

This proposed system shows that the total ratio of energy saving between mode transmitting all data and theproposed event transmission is up to 84.67% with the dramatic increase in healthcare costs and aging world population, research in embedded healthcare monitoring systems has recently received much attentions [1]-[5].It has potential to monitor a patient's health status continuously with quick response. To meet this requirement, numerous embedded devices or sensor nodes for real time monitoring and detection have been developed [6]. These devices were properly placed in body for checking different attributes such as temperature, blood pressure, heart beat rate, respiration, motion, and so on. Among the devices, ECG sensing devices have been widely used as a fundamental tool to detect cardiac attack as well as check health condition, because they can capture a lot of information such as heart rate, rhythm, whether there may be coronary artery disease, and whether the heart muscle has become abnormally thickened, and also are simple to perform, risk-free and inexpensive [7]-[9]. In fact, heart attack is a life threatening disease around the world [10].A pervasive health monitoring system such as ECG often consist of several sensor nodes for capturing and transmitting data from human body to a master node (mobile phone) for gathering and processing data [11]. Most of the early studies focus on examining the functions and effectiveness of capturing ECG signal and transmitting all the data back to mobile device or center computer for processing and detection, and not much on their power consumption.

1.1 Identified Gaps:

A pervasive health monitoring system such as ECG often consists of several sensor nodes for capturing and transmitting data from human body to a master node (mobile phone) for gathering and processing data. Most of the early studies focus on examining the functions and effectiveness of capturing ECG signal and transmitting all the data back to mobile device or center computer for processing and detection, and not much on their power consumption. There are four main factors that may impact the power/energy consumption during the design and use of embedded devices: (1) sensors / embedded hardware module (typical hardware configuration), including sensor such as TI's MSP 430, analog to digital (A/D) converter, and radio frequency (RF) transceiver chip such as CC2500 (2) data communications methods and wireless network protocol, (3) data processing module, including data filtering algorithms such as high pass filter (HPF), low pass filter (LPF) and Kalman filter and the detection algorithms and (4) environmental factors such as weather or skin temperature. Previous methods couldn't concentrated on the power consumption factors.

Previous power consumption researches have been focused on two main streams: energy consumption models of wireless sensor network (WSN) and instructional level.

II.RESEARCH DESIGN AND METHODOLOGY

2.1 Energy Consumption Model:

The integrated VF detection device prototype used in this research consists of three modules: front-end (acquisition, filtering, and amplifying raw ECG), microcontroller (ADC and processing data), and data communications. Thus, the total energy consumption of the integrated VF detection system, *EI*, can be expressed as

$$EI= EF+EM+EC \quad \ldots\ldots\ldots\ldots (1)$$

Where, EF, EM and EC are the energy consumption of the front end device, microcontroller and the communication module respectively. Among these factors, EF is not considered, as the energy consumption of the front-end device is dependent on hardware used for applications. It is proposed to focus on the energy consumption of microcontroller and data communications. The basic units of power consumptions are determined by experimental values and used in this model.

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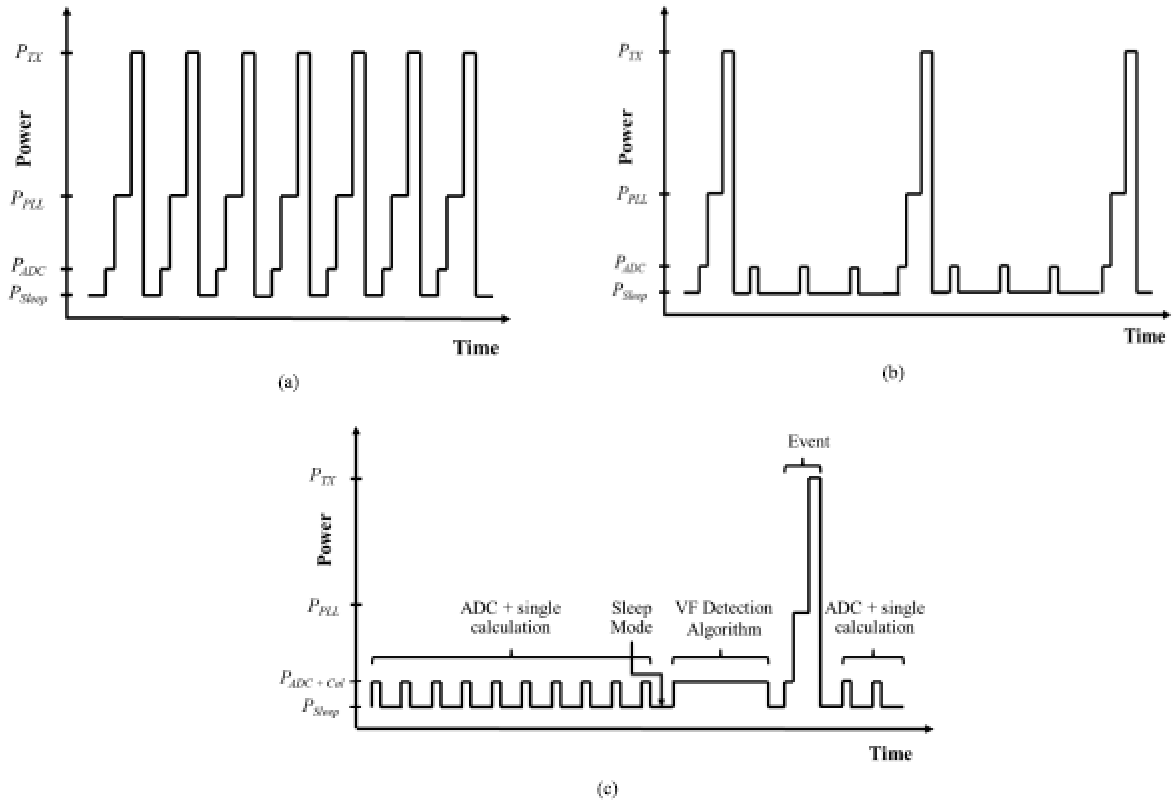

Fig .1. The conceptual graphs basecon the state transition for the three types of operations

2.2 The Design of Testing Environment:

It is proposed todevelop an integrated sensing module as the prototype tested, based upon which to test the energy consumption of the communication methods and the VF detection algorithms. Figure 2.1 depicts the specific block diagram of the tested system. The centralized computer 1 includes the virtual patients (the annotated databases – CU, MIT and AHA), the evaluation model and power consumption analyser. The virtual patients' digital data is converted into analog signals using a digital-to-analog (D/A) converter via a RS-232 in the signal generator. The sensing device with the microcontroller receives analog ECG signal passing through three hardware filters. The software pre-processing in the microcontroller consists of three steps: high pass filter (HPF, cut-off frequency of 1*Hz*), low pass filter (LPF, cut-off frequency of 30*Hz*), and Kalmanfilter (baseline tracking). After analysing ECG signal, the VF detection events are sent back to the centralized computer 1 or center mobile device through RF-communication chip (CC2500) for evaluation. The total energy consumption is recorded by a power observer, and the stored data (over 60000 of ADC values) is sent to centralized computer 2 for assessing the overall power consumption. Figure 2.1(b) shows the actual pin connections of the test framework. In a test environment, the results from the integrated mobile through wireless communication device are stored in the evaluation model and compared with the annotated database. In a real world environment, this module will be carried by a patient and running independently. The power consumption is measured by the other MSP-430 microcontroller and the 10 times amplifier. We add a 5 _ resister between the power supply and the system to measure the power consumption. Since the current values at a 5_ resister are too small to be measured by the embedded ADC, we add 10 times amplifier to the automatic measurement. The module for measuring the power consumption is used to measure the voltage of the 5_ resister [9] at every 166*us*. Based on the Ohm's law, the measured voltage value is 5 times bigger than the current consumption. That is,

$V = I \times R(R = 5\_)$.

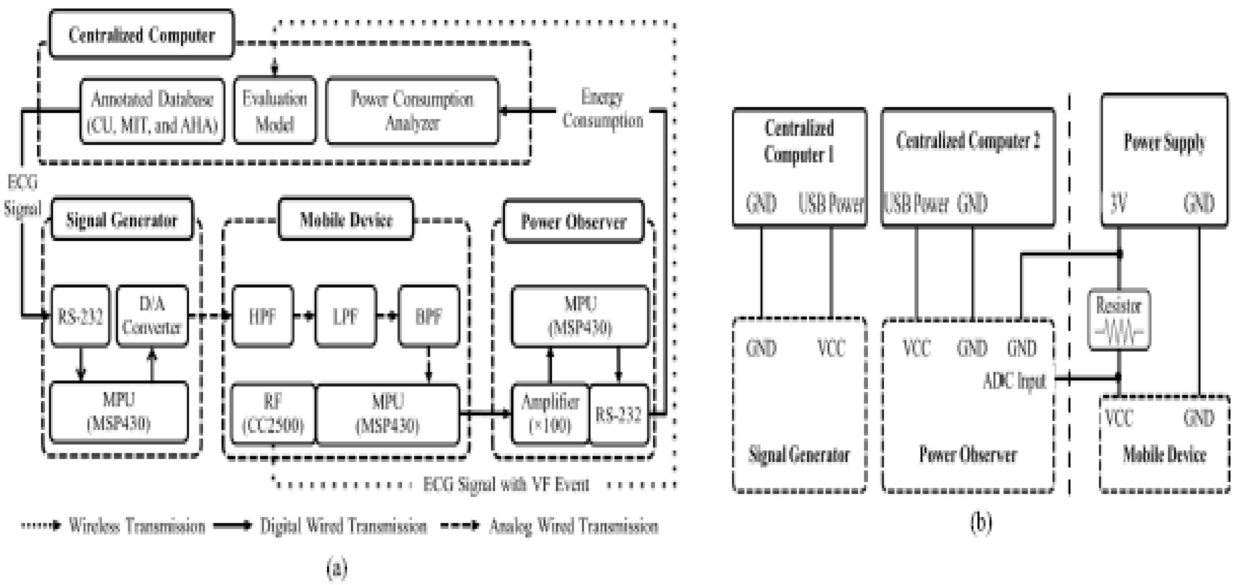

Fig 2. a) Block diagram of testing environment b) pin connection of the integrated sensing devices

III. THE DESIGN OF TESTING ENVIRONMENT

A. The Development of Testing Prototype

We develop an integrated sensing module as the prototype testbed, based upon which to test the energy consumption of the communication methods and the VF detection algorithms. Figure 3 (a) depicts the specific block diagram of the testbed system. The centralized computer 1 includes the virtual patients (the annotated databases – CU, MIT and AHA), the evaluation model and power consumption analyser. The virtual patients' digital data is converted into analog signals using a digital-to-analog (D/A) converter via a RS-232 in the signal generator. The sensing device with the microcontroller receives analog ECG signal passing through three hardware filters. The software preprocessing in the microcontroller consists of three steps: high pass filter (HPF, cut-off frequency of 1Hz), low pass filter (LPF, cutoff frequency of 30Hz), and Kalman filter (baseline tracking). After analyzing ECG signal, the VF detection events are sent back to the centralized computer 1 or center mobile device through RF-communication chip (CC2500) for evaluation. The total energy consumption is recorded by a power observer, and the stored data (over 60000 of ADC values) is sent to centralized computer 2 for assessing the overall power consumption. Figure 3(b) shows the actual pin connections of the test framework. In a test environment, the results from the integrated mobile through wireless communication device are stored in the evaluation model and compared with the annotated database. In a real world environment, this module will be carried by a patient and running independently. The power consumption is measured by the other MSP-430 microcontroller and the 10 times amplifier. We add a 5 resister between the power supply and the system to measure the power consumption. Since the current values at a 5 resister are too small to be measured by the embedded ADC, we add 10 times amplifier to the automatic measurement. The module for measuring the power consumption is used to measure the voltage of the 5 resister [23] at every 166us. Based on the Ohm's law, the measured voltage value I is 5 times bigger than the current consumption. That is, $V = I \times R(R = 5)$.

B. The Actual Test Environment

We deploy our virtual patients and the evaluation system in a laptop computer, to send the data to the integrated module, and evaluate the performance of algorithms using a 4-second window length. We also conduct the energy consumption test using the testing prototype with energy monitoring system and the embedded integrated module. Figure 3 shows the actual test environment deployed for this study.

C. Hardware/Software Setting

We use the TI's MSP430-2500, which consists of MSP430f2274 microcontroller with 32KB + 256B of Flash Memory (ROM) and 1KB of RAM, and CC2500 radio chip using 2.4GHz, to deploy our integrated module. We implement all the algorithms on the MSP430f2274 microcontroller platform using the C programming language. The real-time evaluation and energy monitoring programs are coded with C# programming language running in a general laptop running Windows 7 operating systems.

IV. PERFORMANCE EVALUATION

A. Experimental Design

We design two experiments to evaluate the relative energy consumption. In the first experiment, we conduct the experiment to evaluate the three different types of wireless transmission methods in two sampling frequencies, 125Hz and 62.5Hz. The sampling frequency of CU-DB is 250Hz, which is somewhat redundant sampling. Here, we use half frequency (125Hz) and quarter (62.5Hz). In the second experiment, we apply type 1 communication with 62.5Hz frequency to test the energy consumption of the five VF detection algorithms. We also use these experiments to verify the derived energy consumption model and the feasibility, efficiency, and effectiveness of our proposed embedded ECG prototype. The analytic results are compared with the experimental results.

B. **Performance Measures**

The performance is measured by three relevant indexes:

• Algorithm Complexity: We use the O-complexity which is one of the common methods for analyzing the time complexity of algorithms.

• Total Energy consumption (ET) : The amount of energy consumption is the integral power consumption in a total computational time T . The computational time (or execution time) counts each operation with a certain amount of time, which is closely related to algorithm complexity. The computational time of a certain program is obtained by: $T = N \times \tau$, where N is the number of clock cycles and τ is the clock period. The lower value means lower power consumption.

• Energy Saved (Esaved): Total energy saved is the amount of energy that the state transition from the maximum state to the sleep state. In this paper, the maximum state is TX mode with the highest sampling frequency (320Hz). And sleep state is LPM3 of MSP430f2224 and CC2500. The bigger value means lower power consumption.

V. RESULTS AND ANALYSIS

A. Algorithm Complexity

We use the O-complexity, which is one of the common methods for analyzing the time complexity of algorithms, to obtain the approximate complexity of VF detection algorithms. Let η be the time segment of window size, ψ be the sample frequency, and θ be the inner processing factors in VF detection process. For the convenience of analysis we assume that the inner factors of VF filter, TOMP, and TD sampling are represented as θ. Table III shows the algorithms' complexity. As can be seen from the table, TCI algorithm is the most efficient algorithm in terms of time complexity, followed by

SUMMARY OF ENERGY CONSUMPTION FOR DETECTION ALGORITHMS ($T = 508\ ms$, $W_S = 4\ s$, $F_{ADC} = 62.5\ Hz$)

Algorithm	Experiment E_T (mJ)	Relative Value	Experiment E_{saved} (mJ)	Relative Value
TCI	4.06	1.02	73.08	1.000
VFF	**3.97**	**1.00**	**73.11**	**1.000**
TOMP	4.24	1.07	72.96	0.998
TD	4.88	1.23	72.43	0.991
TCSC	4.37	1.10	72.715	0.995

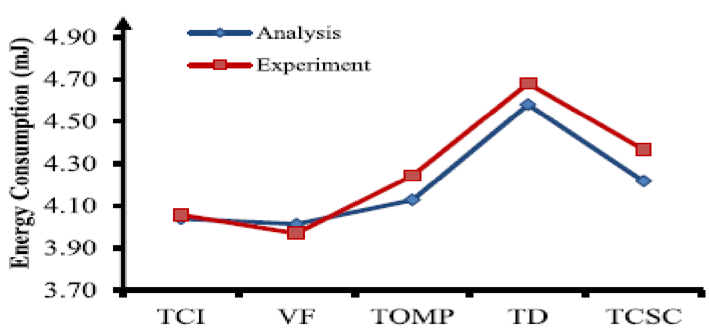

Fig. 3. Energy consumption of VF detection algorithms.

B. Comparison of Detection Algorithms

Table IV summarizes the energy consumption results of VF detection algorithms and Figure 5 depicts the results. The results indicate that the VFF algorithm is the overall best method in term of energy consumption and computational efficiency. The experimental results are consistent with theoretical complexity analysis of Table III, in which VFF and TCI have simpler algorithm complexity than others, and TD has the highest algorithm complexity. The complexity of the detection algorithm has direct impact on energy consumption.

SUMMARY OF ENERGY CONSUMPTION FOR COMMUNICATION TYPES ($T = 508\ ms$, $W_S = 4\ s$)

	Comm. Type	Experiment E_T (mJ)	Relative Value	Experiment E_{saved} (mJ)	Relative Value
125*Hz*	1	34.31	6.52	42.77	1.00
	2	5.93	1.13	71.15	1.66
	3	**5.26**	**1.00**	**71.82**	**1.68**
62.5*Hz*	1	15.8	3.24	61.28	1.00
	2	5.74	1.18	71.34	1.16
	3	**4.88**	**1.00**	**72.2**	**1.18**

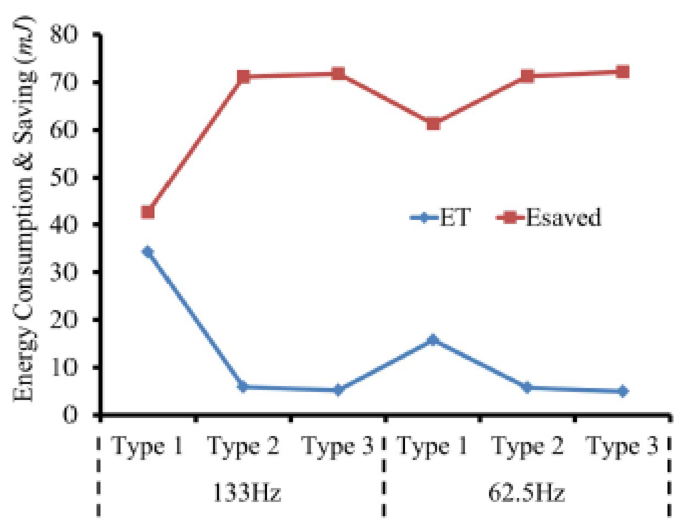

Fig. 4. Energy consumption on three types with two sampling frequencies.

VI. CONCLUSION

Previous research of developing and selecting algorithm for VF detection has been predominately focus on detection accuracy solely. With a trend of moving toward the use of embedded ECG devices for real time detection, energy efficiency and detection response time need to be seriously considered. This study examines different aspects of energy consumption for VF detection. First, we explore the types of data communication modes commonly used in data capture and communications and compare their energy efficiency trade-off. We then compare the energy consumption for five light-weighted algorithms that can be easily adopted for embedded devices. We have also proposed a generic energy consumption model for aiding the above analyses so that it can be used for future prediction needs. In addition, we develop an integrated VF detection environment (similar to the popular medical cyber physical systems used in recent studies), based upon which to test the energy consumption of VF detection methods. Our computational results and analyses indicated that: (1) the conventional way of data communication, which sends all data in real time back to mobile or center computer for processing and detection consume 6.5 times more energy than processing and detecting the data via the embedded microcontroller and only send the detected events back for action. The proposed even-driven approach will also help to shorten the response time, which is important for first aids. The potential side effect of the later approach is that no data was stored for trend analysis. In this case, we suggest the use of an approach that sends all data in batch periodically for processing and detecting via mobile devices (which is what we called type 2); (2) among the five VF detection algorithms we evaluated, VFF is most energy efficient one, but its detection accuracy is also among the worst according to previous studies and our study. As a trade-off, we suggest choosing TD algorithm, which has the best detection capability and suggesting ways of improving its energy efficiency; and (3) experimental results show that the proposed energy consumption model can accurately estimate the energy consumption for our experimental designs within an average error of 4.3 %.; thus, it can be used in the embedded ECG devices we used in this study and may have the potential of being adopted for other applications. To the best of our knowledge, this is the first study comparing data communication types and VF detection algorithms in terms of power consumption. The contributions of this paper are: 1) Generic energy consumption models for three possible modes of data transmissions for VF detection were developed and tested to predict energy consumption, which help save a lot of experimental efforts; 2) We derive the computational complexity of five good VF detection algorithms, evaluate and compare their relative level of energy consumption.

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APPENDIX

ADC_Cal_S: processing state of analog-to-digital conversion and data preprocessing on microcontroller

- *PLL*: state of phase locked loop
- *TX*: state of wireless transmission
- *event*: preparing state for transmission and transmitting

state of VF detection results

- *VF*: processing state of VF detection algorithms
- *T* : total time duration
- *TS*: time duration of each state *S*
- *FS*: frequency of each state *S*
- *ET* : total energy consumption
- *ES*: energy of each state *S*