ORIGINAL ARTICLE

Convex Optimization for Energy Efficiency of a Bluetooth Based Wearable Continuous Cardiac Monitoring Node

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Abstract

Real time cardiac monitoring is an important component of body sensor networks. Due to its typical bandwidth requirements, Bluetooth is often the protocol of choice for wireless transmission from the cardiac monitoring nodes. In order to make the node small and wearable, improving energy efficiency is desirable as otherwise we end up either making the battery too big or changing it too often. In this paper we focus on optimizing energy consumption in cardiac data transmission while providing low latency. We show that this problem can be posed as a geometric program, which belongs to class of convex optimization problems. We analyse the issue based on data bandwidth requirements and latency constraints. The results are mapped to different data type specifications in Bluetooth and recommendations are drawn accordingly.

Keywords— cardiac monitoring, convex optimisation, Bluetooth, energy consumption

الملخص

تعتبر مراقبة القلب لحظيا من العناصر الهامة في شبكات الاستشعار للجسم. و نظرا لما تحتويه تقنية البلوتوث من عرض نطاق ترددي نموذجي فانها غالبا ما تكون هي البروتوكول الأمثل للنقل اللاسلكي لمراقبة القلب من عقد المراقبة . من أجل جعل عقد المراقبة صغيرة ومن السهولة ارتداؤها، لا بد من تحسين كفاءة استخدام الطاقة بها والا ستكون البطارية كبيرة جدا أو تحتاج للتغيير كثيرا . في هذه الورقة ركزنا على تحسين استهلاك الطاقة في نقل البيانات من القلب مع توفير كمون منخفض. وقد وضحنا أن هذه المشكلة يمكن طرحها كبرنامج هندسي و الذي ينتمي إلى فئة من المشاكل المحدبة النموذجية. نحن نحلل هذه المشكلة بناء على متطلبات عرض النطاق الترددي واشكالات الكمون. تم تعيين النتائج حسب أنواع البلوتوث المختلفة ، ويتم رسمها التوصيات وفقا لذلك.

I. Introduction

Real time cardiac monitoring is indicated in several healthcare scenarios. Single or multiple channel monitoring is performed in most post-operative cases. The Gold standard for this monitoring is the use of wired monitors by the patient bedside. But wired monitoring hinders free movements of the patient and thereby, slows down the patient's recovery process also. So, a large number of researchers

have worked on / developed wireless body sensor networks (BSNs) with continuous cardiac monitoring capabilities for various scenarios [1][2][3]. These BSNs enable greater patient convenience and quicker recoveries. Apart from cardiac monitoring, wireless body sensor networks have been used for monitoring various other physiological parameters including heart rate, SpO2 levels etc. for various purposes including post-operative monitoring. Several body sensor networks and their implementations are described in the literature.[2][4][5] The applications of body sensor networks may vary widely, but continuous cardiac monitoring, remains a popular and an integral part of them.

The protocols used for wireless communications in wireless body sensor networks include Bluetooth, Bluetooth low energy, zigbee, ANT, ANT+ etc. [6]. Most of the physiological parameters like HR, PR, SpO2, RR, temperature, motion, etc. require transmission of few bytes in several seconds and thus require very little bandwidth. The parameters like ECG, EEG or EMG whenever monitored require comparatively much larger bandwidth. In such networks, often Bluetooth is the protocol of choice. [7,8,9] Bluetooth is an open standard wireless communication protocol using the 2.4GHz ISM band. It allows up to 8 connections with the master within a range of about 10-30m. The data throughput is good enough to transmit real time multichannel ECG. Recently, Bluetooth version 4.0 (referred to as Bluetooth low energy) was released as an open and license free standard branded as ultra-low power communication.

While Bluetooth is very convenient and has suitable bandwidth for wireless cardiac monitoring, the major challenge in practical use of Bluetooth for continuous cardiac monitoring remains its energy efficiency.[10] The relatively larger data bandwidth capabilities of Bluetooth make it poorly optimized for continuous cardiac monitoring purposes. This demands use of larger battery packs which decreases the unobtrusiveness of the sensors. On the other hand, battery change / recharging is always a concern. In this paper we present a simple model of energy consumption in a wireless body sensor network and derive a cost function based on energy and latency of the data. The function is shown to belong to convex optimization problem. The simulations are then worked on the function and results are presented. The results are then discussed in the light of practical limits of bluetooth communication protocol.

II. Network model

A wireless body sensor network may consist of several sensor nodes for measuring physiological parameters like ECG, temperature, SpO2, pulse rate, respiration rate, etc. of a subject. The nodes communicate wirelessly to a personal gateway, which could be a mobile phone, or a dedicated hardware. The hardware is often body worn, but could also be a nearby-placed node in certain scenarios. The data from the sensor nodes is continuously transferred to the gateway.

The gateway in turn transfers the data to the required destination using wires or wireless media. As most of the sensor nodes, except ECG, are comparatively less straining on the node computing resources as well as wireless resources; we focus our attention to optimisation of ECG sensing nodes. So, for the purpose of this investigation we consider network consisting of one wireless node for continuous single channel ECG monitoring. The node relays the data to a nearby placed gateway which is assumed to be sufficiently resourceful. The overview of the considered node is shown in fig 1. It has an analog front end and a microcontroller that controls sample and hold circuit, ADC and buffering. The sampling circuit continuously samples ECG signal from the amplifiers and reasonably fast ADC digitises it. The digital data is held in the buffer till the controller takes it, packetizes it and transmits to radio for further wireless transmission. Each of these steps as well as steps like generating clocks and other essential activities of controller and that of analog front end consume energy from the battery.

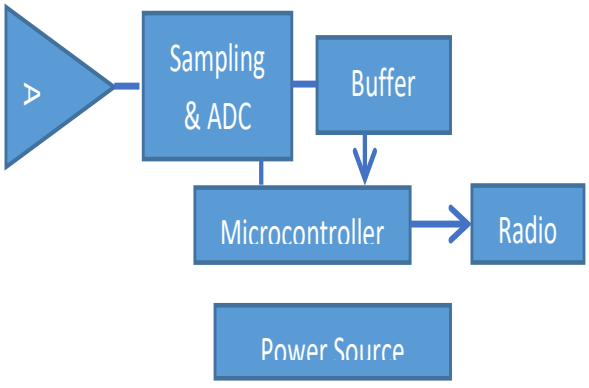


Fig 1. The configuration of ECG Sensor Node

We assume the radios on sensor node and gateway node work as per the Bluetooth protocol in a master - slave configuration. For simple pairing the two radios undergo a series of steps which include – device discovery, connection, security establishment and authentication before the data exchange can take place. Several of these steps can be tuned (like using dedicated bonding instead of general bonding) to improve the latency and instantaneous energy consumption [11]. However, for our purpose of continuous monitoring scenario the contribution of initial pairing and bonding exercise to the overall energy consumption is insignificant. We assume the link once established is maintained uninterrupted and the energies involved during continuous transmission are considered. The sensor node radio behaves as a master and communicates with slave in the gateway. It exchanges data packets based on the clock defined by the master. In accordance with Bluetooth classical standard, [12] each 625 microsecond interval time slot is uniquely identified and packet transmissions can begin at the start of such time interval only. The master transmits in even slots and receives in odd interval slots as shown in fig 2. A packet of transmission consists of three entities, access code, header and payload. The access code and the header have a fixed length of 72 bits and 54 bits respectively. Assuming ideal operating conditions, the payload can be anything from 0 to 2744 (or 343 bytes practically 320 bytes only) bits at the maximum.

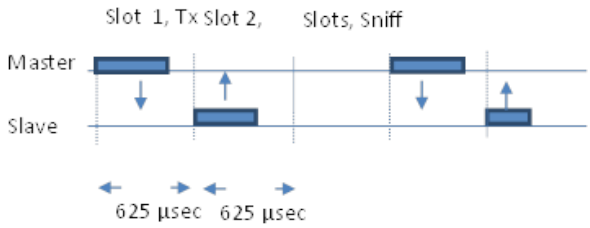


Fig 2. Indicative scheme of timing slots

I. Optimization framework

In this section we address the problem of designing an optimal packet size and map it to convex optimization problem. We consider the case of continuous transmission of ECG data over Bluetooth link. The constraints are based on Bluetooth specifications for the radio, clinical utility of the ECG signal, buffering requirements based on packet size and the signal latency. Noting the tradeoff between energy consumption in different steps and latency, the problem of interest becomes designing optimal intervals for which the data can be buffered and then transmitted for lowest energy and latency values.

A. Energy consumed at the sensor node

Energy consumed at the sensor node consists of energy consumed by the radio for transmission and that consumed by other activities at the node including microcontroller activities.

Based on heath condition or clinical requirements ECG requirements may vary. Let the node sample the ECG at a sampling rate 'S' per second. If the ADC is sufficiently fast, in time time, 't', the controller has 'S.t' digitised samples. To avoid complications, we assume contents of buffer are transmitted in a single packet. We further assume the ADC depth of 8, so that each data sample is efficiently placed in the stream and there is no need of eliminating unwanted zeros or such manipulations anywhere in the entire system.

The radio communication is undertaken in slots of 625 µs, in compliance with Bluetooth protocol. Assuming ideal operating conditions for radio, the master node can take anything from one to five time slots of 625 µs each while one 625 µs slot is taken by the slave to acknowledge. So the radio on the node acting as master listens to slave for 625 µs, consuming 'Ir' current from the battery. It then transmits using 'It' current for one to five slots of 625µs each. It consumes s.625.It charge during the 's' slots of transmission. Let the node go low into energy state for 'Le' time slots of 625 µs where the master radio is temporarily put in sleep mode, consuming only a sleep current of 'Is'. Assuming the complete system works at a voltage v; Energy, E consumed by the system in any time period with n different states each can be given by

$$E = v*(\sum \text{ in} * tn)$$

So, the energy used by radio for one transmit- receive-sleep cycle can be given by

$$Er = v*(625.Ir + s.625.It + Le.\ 625.Is) \quad (1)$$

This corresponds to a time, T

$$T = (1+s+Le)*625 \quad (2)$$

In this time S.(1+s+Le).625 – samples would be available and buffered. So, buffer size equal to packet payload size, P is given as

$$P = S.(1+s+Le)*625 \quad (3)$$

Total energy consumed by different operations in the controller can estimated as sum of energies spent on analog amplification and digital processes including sampling, digitisation and buffering.

$$Ec = E_{analog} + E_{sampling} + E_{ADC} + E_{buffering} \quad (4)$$

As energy for analog amplification for any time is independent of both the sampling rate and transmission packet size, so it is ignored. Energies for sampling and ADC are considered dependent only on sampling frequency, S and do not vary with transmission packet size so, the equation 4 reduces to

$$Ec = [v*S*(Isa)*T] + E_{buffering} \quad (5)$$

where, Isa represents sum of currents consumed for various processes including sampling and digitisation. Using expression for sum of first n natural numbers, current for holding a buffer filling at a constant rate would be,

$$Ib*((Peak\ buffered)*(Peak\ buffered+1))/2$$

where Ib is the current consumed for buffering a sample byte. Thus, Ebuffering comes out to be,

$$E_{buffering} = v*Ib*T((P)*(P+1))/2 \quad (6)$$

B. *Formulation of cost function*

Overall cost function is based on energy consumption and latency as the two metrics of the network performance. Energy consumption of the system is sum of energies consume in different processes of the system. using equations 1, 5 and 6 we get the energy E, consumed at the node as

$$E = Ec + Er = [v*(625.Ir + s.625.It + Le.\ 625.\ Is)] + v*[S*(Isa)*T] + [v*Ib*T((P)*(P+1))/2] \quad (7)$$

Latency is defined on per sample basis as the time interval between collection of the sample and its transfer to the gateway node. Ignoring the ADC conversion time, the maximum delay in reaching of a sample is T. so the average per sample latency can be estimated as

$$L = T/2 = (1+s+Le)*625/2 \quad (8)$$

The overall cost function can be given as cost of energy consumption and cost of latency period.

$$C = E + \lambda . L$$

where, the E is given by equation (7) above and L is given by equation (8) above. The parameter λ can be interpreted as dimension equalizer. It can also be considered as relative importance given to latency with respect to energy. Combining the constraints that s can be between 1 and 5 only and that the energy given by E above is the energy based on T time periods for packet size P. Thus the optimisation problem can be written as

$$Minimise\ [E/P + \lambda. T/2]$$

where E is given by equation (7) above and minimization is over time period T. This is a geometric program solvable in polynomial time and thus a convex in optimisation variable T. [13] .

II. Simulation results and discussion

In order evaluate the minimisation problem we substitute the values of different variables and vary the variables to their limits. First we consider the sampling rate. For ECG monitoring, AAMI guidelines suggest a minimum rate of 300 Hz. So, $300 \leq S$. A higher sampling rate would be preferable, but the simple logic that higher will increase the not only the sampling current but also the data payload and so minimum clinically advisable limit is good enough. So, we set $S = 300$. From the data sheets of Bluetooth module [14] we substitute $Ir = It = 50mA$ and $Is = 20mA$ (for sniff mode or sleep mode). We vary the s from 1 to 5 for different data formats suggested in bluetooth and summarised in table 1.

We observe ACL data type given by DH5 is most versatile and is used for getting the results. We also note that maximum latency at the extreme of DH5 comes to be (794 + 6) slots of 625 µsec. This comes out to be average latency of 0.25 secs, which for most practical purposes is tolerable. We set $\lambda = 0$. The energy curves were observed to be monotonously decreasing. The results at extreme values are tabulated in table 2.

We observe that ACL data type of DH5 is best suited for transmission of ECG signal with reasonable latency. Most Bluetooth modules which are configured for serial port profile of EDR (corresponding to payloads of 81 bytes) are actually not really the best alternative. The DH5 although apparently most suitable requires a tolerance of signal latency upto 500 µsecs. It also demands a buffer size of 150 bytes (=S*latency). Thus if the latency of upto 0.5 secs is allowed DH5 mode with 320 bytes of payload, 5 slots of master transmission and 794 slots of sniff mode is the optimal setting for ECg data

Table 1. ACL Data type [12,14]

ACL Data type	Range of variables		
	Payload (bytes) (P)	Slots of 625µsec used by master (S)	Slots of 625µsec in Sniff or sleep mode (Ts)
DH1	1 - 27	1 only	4 – 70
2-DH1 (EDR)	1-54	1 only	4-142
3-DH1 (EDR)	1-81	1 only	4-216
DH3	1-180	1-3	4-130
DH5	1-320	1-5	4-794

Table 2. Result of simulation at extreme points

Sample payload (bytes)	S Time slots of 625µsec	Le Time slots of 625µsec	Energy metric (mAs)	Average Latency msecs
1	1	4	30.0	1.875
81	1	216	22.1	68.125
320	5	794	20.2	250

transmission. The results can also be interpreted as confirmation of the fact that Bluetooth data packets have a large overhead and it is optimal to have as big payload as possible.

Also it is important to note that we have assumed ideal operating conditions and so have not accounted for ambient noise. Further, it is important to take note of the fact that we have only considered single ECG sensing node. The metrics are going to change drastically if multiple and / or heterogeneous sensors are taken into consideration of wireless body sensor network.

III. Conclusion

We have developed a Framework for optimisation of wireless sensor node for continuous ECG transmission. The model is a geometric program which is a convex optimization problem. It can be solved for optimisation of desired parameters.

The model has been worked for standard Bluetooth data types. From the results, it is clear that making the data available to Bluetooth transmitter from the on-chip ADC is a good idea but the energy metrics are improved further if we buffer the digitised data rather than pass it straight to the radio module. Use of ACL data types DH3 or DH5 marginally improves the energy metrics of ECG sensor nodes provided noise immunity and latency are not critical. Tweaking the data transmission modes with suitable buffering to suit to DH5 can make the sensor node upto about 30% more energy efficient than transmitting signal as it becomes available.

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