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Miniature Wireless Measurement Node for ECG Signal Transmission in Home Area Network

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Abstract— **A miniature wireless node for ECG measurements is presented. The ECG node is designed to be used in various applications including measurement of heart rate during physical exercise and continuous long term measurement of ECG for people assumed having, or being recovering from a cardiac disease. The ECG node is wirelessly connected to a computer using IEEE 802.15.4 based radio protocol. The device sends the measured ECG signal together with additional measurement parameters including battery voltage to the computer, where the ECG signal can be analyzed on-line. The ECG node can operate alone or it can be used as a part of an overall system being designed for monitoring people that are transferred from hospital to home treatment.**

I. Introduction

ECG is clinically the most important bioelectrical signal. Many cardiac diseases are diagnosed through ECG. For people recovering from severe cardiac decease or being assumed having one, continuous measurement and analyzing of ECG signal would bring safety into their lives. Continuous monitoring of ECG for following the influence of certain cardiac drugs is also desired. Research and development of such continuously operating measurement equipment has been in interest of many research groups already since last decade [1]-[3] and some solutions have already came to the market [4], [5].

Today, long term cardiac monitoring for finding e.g. arrhythmia or conduction dysfunctions is done using 24-hour Holter ECG recorders. Usually Holter recorders have three bipolar measurement channels and possibly an additional electrode for right leg driving. For long term measurement it is, however, important that the measurement equipment is comfortable to wear and small enough not to disturb the patient. Most of the cardiac dysfunctions that are searched for with Holter, e.g. arrhythmia, can also be detected by using only one recording channel.

We are introducing a prototype of a miniature sized and light weight measurement device for long term ECG recordings. The measurement unit does not store the measured data but sends it to a computer. This way the data can be processed automatically on-line and sent to a data storage or to a doctor for manual inspection. Schematic diagram of the system is seen in Fig. 1.

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II. Description

A. Hardware

The measurement system consists of an ECG node and a coordinator connected to a computer. The ECG node has one ECG channel with fixed gain of 490 ($\approx$ 54 dB). Measurement resolution of the A/D-converter is 10 bits. Sampling frequency can be chosen from several alternatives between 125–500 Hz. The ECG node also measures three other channels but with smaller sample rate. The sample rate of the additional channels depends on the ECG sample rate being 2.6 Hz and 10.4 Hz when the ECG is measured at 125 Hz and 500 Hz, respectively. One of the extra channels measures device's battery voltage. Other channels can be used to measure for example user's activity with accelerometers but they are not currently in use. The ECG node was made as small as possible without using any sophisticated miniaturization techniques.

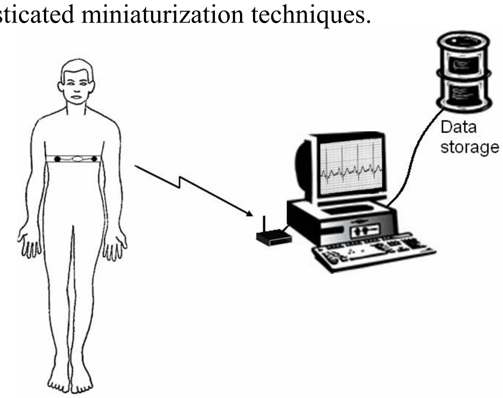

Fig.1. Schematic diagram of the measurement system.

1) Amplifier

The amplifier uses three electrode topology; two electrodes for bipolar measurement and a ground electrode offering a bias current path and a correct offset voltage for the measurement electrodes. The ground electrode is not necessarily needed because the measurement electrodes also have bias resistors in their inputs but if it is not used, 50 Hz power line interference is induced to the signal and the signal needs to be digitally filtered at the computer.

The first amplifier stage uses an instrumentation amplifier and the second one is realized with a non-inverting operational amplifier connection. Between the two stages are low pass and high pass filters, both being passive and of first order. The cut off frequency of the high-pass filter is 0.14 Hz and low pass, anti-aliasing filter 180 Hz.

2) Power source

We have used two different power sources with the device: a rechargeable nickel metal hydride (NiMH) battery and a lithium ion (Li-ion) polymer battery.

With the NiMH battery it is possible to arrange wireless battery charging using inductively coupled coils. This way no wire connectors are necessarily needed and the measurement unit can be totally molded in e.g. polyurethane to protect it from the environment. If disposable electrodes are used, the connectors are at the electrode end and do not hinder molding. With Li-ion polymer batteries, the charging is more precise procedure and a dedicated battery charger should be used for safety reasons to prevent the battery voltage from rising above 4.2 volts.

Both battery options have 150 mAh capacity but physical sizes differ a lot. Weight of the Li-ion polymer battery is 4.2 grams and it is 4 mm thick while the NiMH battery weights 18.7 grams and is 15 mm thick. The ECG node with two different rechargeable batteries is presented in Fig. 2.

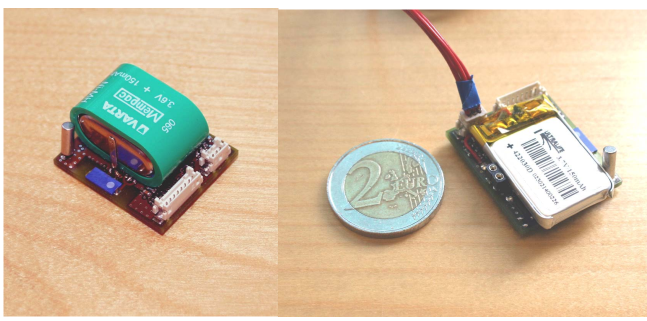

Fig. 2. ECG node with NiMH (left) and Li-ion (right) battery referred to a 2 € coin.

3) Electrodes

We have used both conventional disposable Ag-AgCl ECG electrodes and textile electrodes in our measurements. Textile electrodes, similar as used in [6], are made of silver coated polyester thread. We have used a piece of conducting hydrogel (cross-linked polymer gel containing electrolyte) sheet between the electrode and skin to improve the contact by maintaining moisture on the skin.

4) Physical dimensions

Physical dimensions of the measurement unit with Lithium-ion battery are 31.5 x 22 x 10 mm and it weights 10.0 grams excluding the measurement electrodes and electrode leads. Using the nickel metal hydride battery raises the height to 20 mm and weight to 24.5 grams.

B. Radio communication

1) Communication Protocol

Communication protocol is based on the standardized IEEE 802.15.4 MAC protocol [7] but the standard has not been adopted in its full extent.

When associating the measurement unit with the coordinator, the communication channel is first selected out from the 16 possible channels defined by IEEE standard by scanning through all the channels and selecting the one with least amount of noise, i.e. other radio traffic. We designed the communication so that the network coordinator, which is located next to the control PC is active all the time and replays to the measurement node when it asks if the measurement should be started. This way the power consumption of the ECG node can be kept small and there is no need for a power off switch in the ECG node.

The data is transmitted in packets with size of 121 bits. Even though the measurement resolution is 10 bits, each sample is sent as two byte word for simplicity. Received packets are acknowledged and if a packet is lost, it is sent again

2) Antennas

In the measurement node we are using a ceramic chip antenna [8] which has very small dimensions. In the coordinator we are using an inverted F (IFA) PCB antenna. The IFA design is adapted from Chipcon's reference design [9].

C. PC-software

The user interface software is tailored for each purpose and is used at the PC for controlling the measurement system. It visualizes the measured ECG signal and it has the possibility to set the sample rate used in the measurement. It also saves the measured data as Matlab® struct format if desired on the disk. Front panel of the UI is seen the Fig. 3.

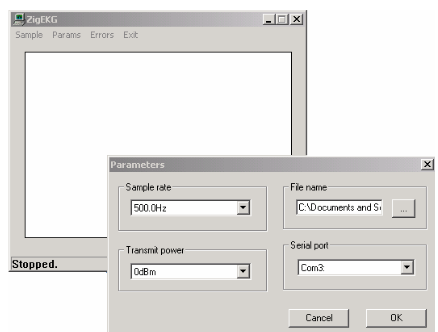

Fig. 3. Front panel of the user interface software.

III. Results

Tested features of the measurement system were signal noise, signal quality, transfer distance, and current consumption.

A. Noise Properties

We measured the rms noise of the measurement device in four ways with different transmit power values. First we measured the noise using disposable ECG electrodes between the electrode leads. Rms noise voltage measured this way in the frequency range 0.14 – 180 Hz with 500 Hz sampling frequency was 8.32 μV as referred to amplifier input, which equals about 9 bit peak-to-peak noise. The rms noise does not significantly depend on the sampling frequency because the amplifier's frequency band is the same for all sampling frequencies. Higher frequency noise components alias to lower frequencies increasing the noise power there when smaller than twice of the cut off frequency of the filter is used in sampling. Noise voltages measured with smaller sampling frequencies e.g. with 125 Hz are practically the same as with higher ones.

In the second measurement method we measured the noise without having the electrodes connected between the amplifier inputs but only 15 cm long leads short circuited at the other end.

In the third method we used 15 cm long leads and connected 10 kΩ resistors between the two measuring inputs and between one measuring input and ground connector, and a 15 kΩ resistor between the other input and ground connector.

In the fourth method we did not use any leads but shorted the amplifier input right at the connector where there is less than 1 cm long way to the inputs. The measurement results are shown in Table I. The values are calculated from the noise signal recorded during a 40 second measurement period.

TABLE I
RMS NOISE AS A FUNCTION OF THE TRANSMIT POWER WITH SEVERAL MEASUREMENT SETUPS

Measurement Setup	0 dBm	-3 dBm	-10dBm	-25 dBm
15 cm leads, electrodes	8.32 µV	8.36 µV	8.34 µV	8.45 µV
15 cm leads, shorted	8.38 µV	8.37 µV	8.37 µV	8.45 µV
15 cm leads, resistors	8.52 µV	8.59 µV	8.59 µV	8.71 µV
No leads, inputs shorted	8.28 µV	8.26 µV	8.26 µV	8.30 µV

Noise measurement results show quite good performance for the measurement device. Practically no difference in the rms noise values over the frequency band is seen depending on the transmit power used, which means that radio interference is not coupled to the measurement signal. Lack of radio interference in the measurement signal is explained with radio noise suppression filters located at the inputs of the amplifier. The rms noise voltage also does not depend much on the measurement configuration. Thus, it can be assumed that the most of the noise comes from the amplifier and sampling circuitry itself.

Quantization step for the 10-bit AD-converter when using a 3.3 V reference voltage and a gain of 490 is 6.58 µV. The rms quantization noise calculated for triangular waveform as reduced to input of the amplifier is 1.9 µV, refer to (1).

$$V_{Nqrms} = \sqrt{\frac{\left(\frac{ADC_{ref}}{\left(2^{ADCbits} * gain\right)}\right)^2}{12}} = \sqrt{\frac{\left(\frac{3.3}{\left(2^{10} * 490\right)}\right)^2}{12}} \approx 1.9\mu V_{rms} \qquad (1)$$

B. Measurement Signal Quality

An example of the measurement signal recorded with a three electrode setup from approximate measurement electrode locations V2 and V4 of the 12-lead system (20 cm electrode separation) using disposable Ag-AgCl electrodes (no skin preparation) is shown in Fig. 4. It shows that the quality of the signal is sufficiently good. Due to fairly short electrode leads, good skin-electrode contact, and a separate ground electrode, very little 50 Hz interference from power lines is seen in the signal.

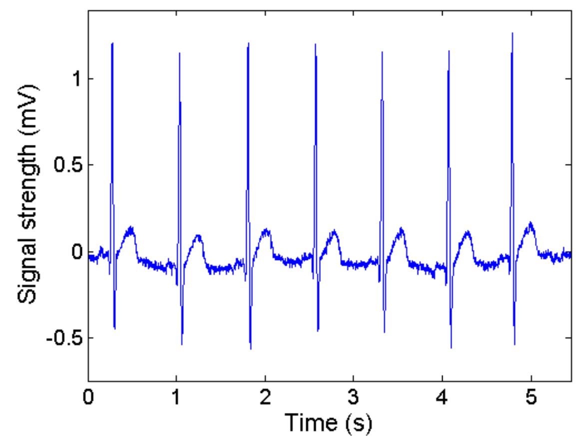

Fig. 4. ECG signal measured with the device.

Fig. 5 shows ECG signal of the same test subject measured from the locations of a regular heart rate belt (horizontally under the pectoral muscles) using textile electrodes having conducting hydrogel . As can be seen in the figure, the signal is much smaller in amplitude than in Fig. 4 and it also contains more interference. The 50 Hz power line noise in the signal is strong, about 40 µV rms as referred to input, because long electrode leads (>50 cm) are used, skin-electrode contact is more poor, and neither driven right leg circuit nor power line interference rejecting notch filter are used. When using shorter or shielded leads, the power line interference decreases substantially.

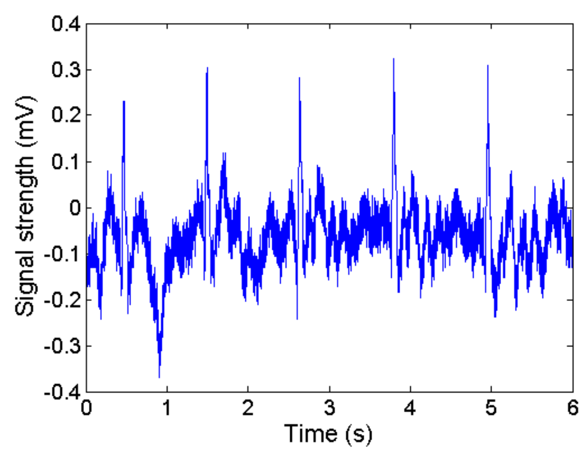

Fig. 5. ECG signal recorded with fabric electrodes having conducting hydrogel sheet between the electrodes and the skin.

The amount of EMG- and movement artifacts in the signal varies a lot between test subjects and electrode locations used. EMG signal is mainly in higher frequencies that ECG

[10] and therefore its influence can be reduced with adequate low pass filtering. Movement artifacts are bigger problem especially when recording with dry textile electrodes while they may saturate the amplifier. When sweat moistens the electrodes or hydrogel is used, the movement artifacts diminish. Also the affect of movement artifacts can be decreased with filtering because those generally are at lower frequencies than the ECG signal.

C. *Transfer Distance*

In an indoor corridor, we measured a transfer distance of more than 35 meters for the device with 0 dBm transmit power and the ceramic chip antenna of the ECG node and IFA antenna of the coordinator. With -3 dBm transmit power at the ECG node, the transfer distance was almost the same which implies that reflections from the corridor's walls, floor, and ceiling extend the distance compared to a free space. At the coordinator, 0 dBm transmit power is always used.

The ceramic antenna does not offer very good transfer distances compared to e.g. an IFA antenna or a quarter wave monopole antenna. Using IFA in both ends was tested earlier in [11] showing transfer distance of more than 70 meters in free space with -10 dBm transmit power at the measurement node. The transfer distance also depends a lot on the amount of 2.4 GHz radio interference present at the testing site.

D. *Current Consumption*

We measured average current consumption with several different transmit power values and data transfer rates. Table II shows the results. As seen in the table, the current consumption does not depend much on the sample frequency or the transmit power used. The main part of the current consumption comes from the CPU.

TABLE II
CURRENT CONSUMPITION AS A FUNCTION SAMPLE FREQUENCY AND TRANSMIT POWER

f_s \ P_{tx}	-25 dBm	-10 dBm	-3dBm	0 dBm
125 Hz	11.9 mA	11.9 mA	12.0 mA	12.0 mA
250 Hz	12.0 mA	12.1 mA	12.2 mA	12.2 mA
500 Hz	12.4 mA	12.5 mA	12.6 mA	12.7 mA

The current consumption when the measurement is stopped and the device is in a waiting mode is 0.37 mA. When the coordinator node is not turned on, the measurement node's current consumption jumps to 2.9 mA since it is looking for the coordinator.

The operation time of the device with 150 mAh rechargeable batteries is 12 hours while continuously measuring. If longer operation times are desired it is possible to either reduce the current consumption by e.g. using smaller frequency crystal at CPU or use batteries with higher capacity. Regular mobile phone batteries have often capacities around 750 mAh which is enough for 2.5 days of continuous operation.

IV. CONCLUSION

A small sized ECG measurement device is presented. The performance of the device's biopotential amplifier is sufficient for the ECG signal measurement. No interference from the radio, located in the immediate vicinity of the amplifier, is seen in the signal.

Maximum transfer distance of more than 35 meters is fairly good. Still, because in a real operation situation the signal can be attenuated due to absorption of structures or more radio noise can be present, attention is going to be paid in future into improving the reliable transfer distance.

Operation time of the device is too short for a 24 hour measurement. It is possible to extend the operation time by using a battery with higher capacity or by reducing measurement node's current consumption. This can be done by decreasing the frequency of the CPU's crystal.

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