A basic platform for the study of a wireless health telemonitoring system

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Abstract

A simple hardware configuration of a health telemonitoring system consisting of an instrumentation amplifier including a signal conditioning circuit, a laptop computer, and a GPRS/EDGE air-card is set up at one location to communicate with a computer at another location in the Wi-Fi network. The first computer measures the single-lead ECG data using the built-in soundcard as an analog-to-digital converter, followed by downsampling, filtering, and displaying before sending out to the communication network. The data is then received by the remotely located second computer to display and record in real-time. The whole system is set up to investigate various issues that underline the operating functions of the remote real-time monitoring and displaying of this type of data. The implementation of the front-end subsystem is elaborated here and the performance of a flexible Java-coded digital signal processing is demonstrated. In the data transmission section, without the option to negotiate the QoS as required, low channel bandwidth is always the main cause of data congestion. However, the system output may still be regulated by dynamically adjusting the window size of the received data and by a suitably chosen overall delay time, as explained vividly by a diagram. It is expected that this set-up system can be effectively used as an economical prototype for future study of remote monitoring and real-time continuous data transmission through the heterogeneous network.

Keywords: *ECG signal, telemonitoring, soundcard, internet, GPRS, QoS*

1. Introduction

Health telemonitoring is basically a process of monitoring vital signs of health such as heart rate, blood pressure, blood sugar level, etc., of a patient and transmitting the data over either wireline or wireless communication channels which may be telephone lines, local area networks or a wide area network, to the data recipient who is normally a healthcare officer at a distant hospital. At present there are a number of health monitoring devices either in the form of a stand-alone one (Omron Healthcare Singapore Pte. Ltd., n.d.) or the one that has an integrated wireless personal or body area network (WPAN, WBAN) connectivity (Polar Electro, 2011). With the proliferation of advanced mobile phones and PDAs, it appears that a user-operated health monitoring function is now an available option for such devices (iPhoneNess, 2011). Presently the health checking functions in these devices are basic measurements which can be performed individually and results are not monitored on line by healthcare staff elsewhere. Such a situation could later be changed with the incoming on-line life style and when a higher communication bandwidth is more easily accessible at a lower cost. Among the number of vital signals that can be measured, the recording of the electrical activity of the heart, i.e., electrocardiogram (ECG) is common in healthcare facilities because it is a noninvasive, quick, and effective diagnostic tool. The three lead ECG is the simple standard way of measurement. Although the 5-lead or 12-lead is the clinical norm, the three-lead ECG continues to be used in emergency departments, telemonitoring, and during medical procedure. The interest in measuring the ECG signals as an entry step to the study of biopotentials and medical instruments is widely realized in that there have been many websites describing this type of activity (Kovic, 2008; Physionet, 2011; Vahed, 2005). In this presentation, a front-end system that acts as a user interface for such a device can be shown in a block diagram as in Figure 1.

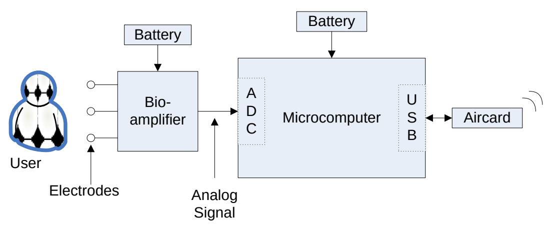

Figure 1 A basic user interface of a biosignal measuring system

Here the block diagram reflects the general approach taken by the project, to be described further, that aims for a portable, simple design, and easily accessible system to be used in the education and research environment. The bioamplifier is a specialized three-stage instrumentation amplifier. The first stage has a high gain and appropriate bandwidth commensurate with the type of input signal, together with high common mode rejection ratio (CMRR), and signal-to-noise ratio (SNR). The second stage is the filter circuit with the additional gain and adjustable DC offset that raises the signal to a suitable level. The third stage provides the galvanic isolation between the user and the system that is connected to the power-line voltage. The output of the bioamplifier is then connected to the input of the analog-to-digital (A/D) converter which is a part of the data acquisition card in the microcomputer system. Logically, the whole circuit from the electrodes touching the human user to the input section of the isolation amplifier is supplied with power from its autonomous batteries. The digitized ECG signal is then processed and displayed on the microcomputer and additionally sent to the remote center via the wireless USB modem (aircard). Further details of the circuit used in the project will be given in section 2.1.

1.1 Constrainting factors in healthcare telemonitoring

A simple model of remote healthcare monitoring systems can be as shown in Figure 2 in which the hardware parts are indicated on the left side and the software parts are on the right side. In the model, the ECG is indicated as a major signal to be measured, but other vital signals are also included as an integrated part. At a more elaborate service level, features of a videoconference system may be included. Further consideration can reveal that the implementation will be affected by various factors in a varying degree. One major problem in real time applications is the intermittent data reception due to non-uniform network delay. The others are data privacy and security issues, and the limited computing power of the mobile devices. These issues are further discussed below.

1.1.1 Intermittent data received

At one location, monitoring health-sign data may involve a variety of medical sensors that deliver various signals at different bandwidths, and the sampling data rate may vary from as low as once per hour to millions per second. Such data when considered in aggregate will constitute a large volume of data that, if it is to be transmitted over a wide-area network and appears as an isochronous data stream, will impose a demand on channel bandwidth that may not always be economically available. In general, a network link may get congested at certain times and there can be long and intermittent delays at the receiver side. As a result of the delay the data packets will therefore arrive asynchronously, and the information delivered may not be acceptable in the real time where a stream may have a certain event that requests immediate attention. The possibility of such a problem arising will be greater in the case of a distributed telemonitoring system in which data are from various sources, each located geographically far apart. The role of the transmitting side here is to find an efficient means to alert the receiving side and the latter must employ intelligent resource management (e.g., scheduling) and graceful degradation strategies (e.g., load shedding) during periods of high load. The implementation of a telemonitoring system may therefore be cast in the framework of a data stream management system (DSMS) (Brettlecker, Schuldt, & Schatz, 2004; Carney, et al, 2002).

1.1.2 Data privacy and security

Medical data records are considered personal information which only two parties, who are basically the patient and healthcare provider, should have access to. Similarly, this data should not be tampered with by any third party in the line of communications between the two involved parties. Although a lack of measures to safeguard the privacy of this data may not result in a great loss in ordinary cases, it can be a bad practice that may lead to some legal issues in others. So the communication links that rely on public telecommunication infrastructure must also provide some optional data security and authentication mechanisms. These features are already available in the existing VPN (Virtual Private Network) technologies. A virtual private network (VPN) is a computer network that uses a public telecommunication infrastructure, such as the Internet, to provide remote offices or individual users with secure access to their organization's network. Secure VPN networks use a tunneling protocol when one network protocol (the delivery protocol) encapsulates a different payload protocol. By using this tunneling technique one can carry a payload over an incompatible delivery-network, or provide a secure path through an untrusted network.

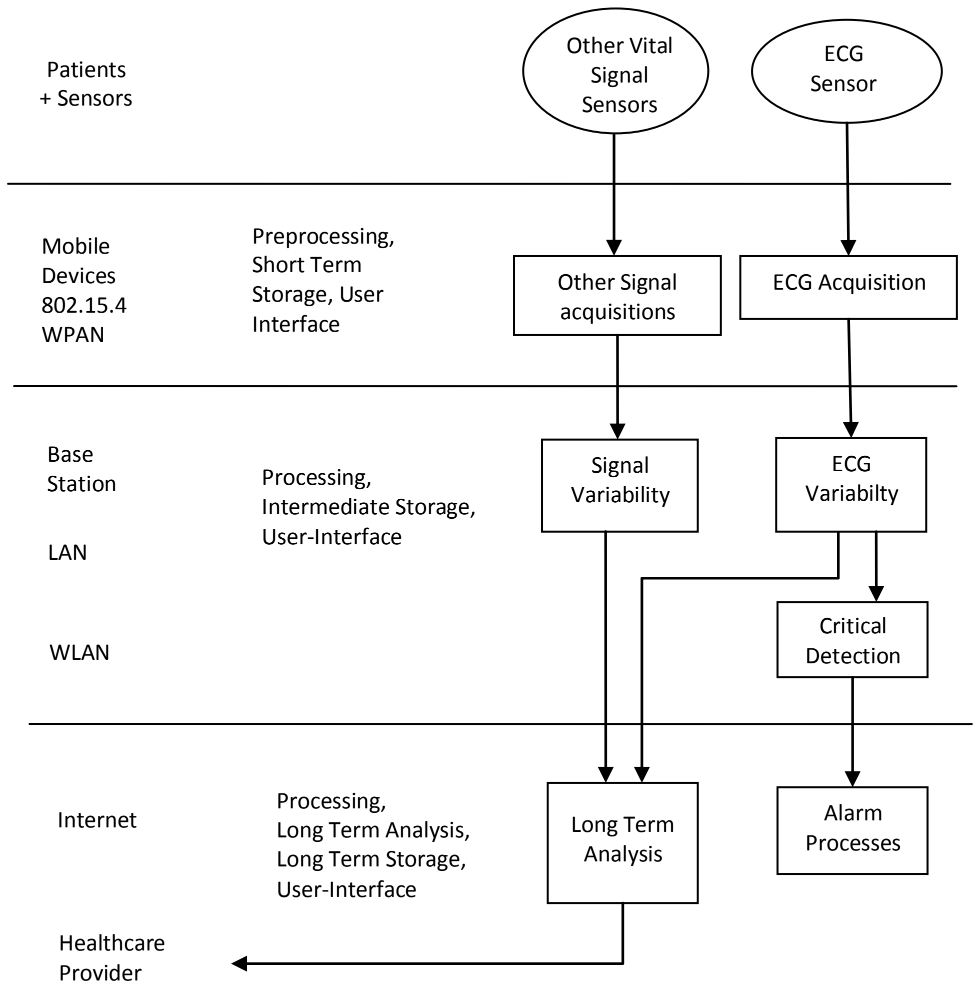

Figure 2 A simple model of a telemonitoring and information processing system for health care applications

1.1.3 Limited computing power of mobile devices

Apart from the limited bandwidth of the telecommunication infrastructure to be shared with the public, the limitations of the computational resources of the mobile computing devices, and finally, the implementation cost are important deciding factors.

To investigate these constraints and introduce some possible solutions, a project that attempted to implement the concept of medical telemonitoring is reported in this paper. The contributions of this paper are as follows:

- Presenting a report on configuring a prototype model of telemonitoring system for the electrocardiogram (ECG) signal.
- Identifying the alternatives to the time-consuming construction of expensive hardware and software and giving test results.
- Elucidating relevant technical problems and identifying possible solutions for further investigation.

As an academic component in the College of Engineering, main resources are primarily available for undergraduate teaching activities. So one objective of this paper is to report on a project that attempts in implementing the concept of medical telemonitoring by configuring a prototype model of the ECG signal telemonitoring system using readily available components and equipment that can lower the cost and expedite the process. Since the interest of students will evolve with the changing technology and interest in the outside world, the focus of the project will have to be adaptable while the main technical objectives are still relevant. These are factors considered before the final approach was eventually taken. A noteworthy project (Boquete et al, 2005) that was carried out for teaching and training in the academic environment is similar to the one present here in its objective, but differs considerably in the sophistication of hardware and software. This is particularly due to the inclusion of a sound card in the circuit and the digital filter implemented here. Furthermore, the delay in the communication network is directly discussed and its remedy is elaborated here.

2. Implementation of various sub-systems

2.1 The electrocardiogram (ECG) signal monitoring

As in most cases, the ECG signal is selected as the crucial vital signal to be measured here. The three-lead ECG measurement (Lead I, Lead II, and Lead III) is the basic one that requires the electrodes to be placed at three locations based on the Einthoven's triangle (Bowbrick & Borg 2006). Lead I measures the differential potential between the right arm (RA) and left arm (LA), Lead II between the right arm and left leg (LL), and Lead III between the left arm and left leg. By measuring any two lead voltages using the analog front end, the remaining lead voltage can be calculated. Here the Lead I voltage is chosen as a test signal and measured using an in-house assembled circuit with an INA114P instrumentation amplifier as a main component. This instrumentation amplifier has a typical three op-amp configuration with the gain given by

$$Gain = 1 + \frac{50k\Omega}{R_G} \quad \text{..................(1)}$$

where R_G is the external gain adjusting resistor. The CMRR of the INA114BP at a gain of 10 is typically 115dB. The circuit details are similar to the one described by Griffiths, Nelo, Peters, Robinson, Spaar, & Vilnai (2002). Two pairs of small signal NPN BC547C and PNP BC557B transistors form an electrostatic discharge (ESD) protection and user current limiter at the input circuit. A right-leg driver circuit (RLD) is used to eliminate the common mode interference noise. The instrumentation amplifier is followed by a bandpass filter with a lower cutoff frequency at 0.1 Hz and a higher cutoff frequency at approximately 250 Hz which covers the highest ECG frequency component of interest. This circuit section will therefore function as a DC blocker and an anti-aliasing filter. The circuit operates on a single 9-V battery and draws the current during measurement at approximately 12.7 mA excluding the isolation amplifier. The total gain of the circuit was adjustable up to 2000 which is sufficient for typical ECG signals which are in the range of 0.5 mV to 5.0 mV (Company-Bosch & Hartmann, 2003), so that the output of the circuit will swing within $\pm$ 2 V around a reference voltage of 2 V. The function block diagram of the implemented circuit is shown in Figure 3 and the completed circuit up to the output of the bandpass filter was electromagnetically shielded in a steel box (Figure 4).

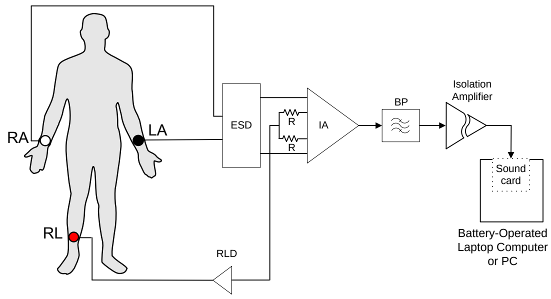

Figure 3 Block diagram showing the implemented user interface

Figure 4 Sensor clips and the instrumentation amplifier with filter in a shielding case.

2.2 Use of sound card as A/D converter

The sound card or the sound module on the main board of a laptop computer can be used as an analog-to-digital (A/D) converter with the input signal taken either from the audio line input or the microphone input (Klaper, 2006). However, since the line input voltage is limited to within the range of $\pm$ 400 mV and the amplified ECG signal may have an amplitude up to approximately 2.0 V, the latter is further attenuated by a shunt variable resistance before being presented to the line input of the sound card. A standard clinical ECG signal bandwidth is between 0.05-100 Hz (Company-Bosch & Hartmann, 2003; Physionet, 2011). The sound card has limitations in that it cannot measure DC voltage due to the fact that its input is AC coupled, and hence its lower cut off frequency may affect the low frequency component of the ECG signal. However, details for diagnostic purposes mainly lie in the higher part of its spectrum. A good-quality sound card for a laptop computer may have an A/D converter resolution of 24 bits, with a maximum sampling rate of 192 kHz, signal-to-noise ratio of 104 dB, total harmonic distortion + noise at 0.006% (at 1 kHz, 2 V rated output), and the frequency response (± 3 dB, 24 bit/ 96 kHz sampling rate input) from 10 Hz to 46 kHz (Wilkins, 2004). For the majority of the 3-lead ECG bandwidth frequency of 100 Hz, the lowest sampling rate of the sound card at 8000 Hz is clearly sufficient. Subsequent signal processing, storing, and display is carried out using a Java program. A biquadratic (two poles and two zeros) infinite impulse response (IIR) filter having the following second order difference equation is implemented:

$$y[n] = a_0 x[n] + a_1 x[n-1] + a_2 x[n-2] - b_1 y[n-1] - b_2 y[n-2] \quad (2)$$

where the coefficients a_0, a_1, a_2, b_1, b_2 can be configured for any of the required response: low-pass, high pass, bandpass, and notch. For a lowpass IIR filter design with the cutoff frequency at 100 Hz the coefficients are given as follows:

$a_0 = 0.17708$, $a_1 = 0.35416$, $a_2 = 0.17708$
$b_1 = -0.31677$, $b_2 = 0.025084$

The magnitude response of this filter is shown in Figure 5. The user interface is shown in Figure 6 which displays the main program window with the original signal plotted at the upper part and the processed signal, after going through the lowpass digital filter as described above, is plotted at the lower part. The time axis is shown in between the two plots. The program also monitors the pulse rate, expressed in beats per minute (BPM) and is

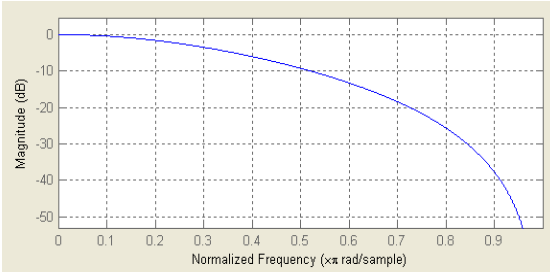

Figure 5 The magnitude response of the biquadratic lowpass filter

displayed by the computer. The pulse rate is calculated from the autocorrelation function of the filtered signal and the pulse itself can optionally be presented as an audio signal. At this stage of development other vital signs are not included in this user interface.

2.2.1 Safety considerations

In order to avoid an electrical hazard from electrical shock, the instrumentation amplifier and the notebook computer were operated only on battery during measurements. When a desktop computer is used or when the main power line is connected to the circuit, the isolation amplifier is always included (Webster, 1998).

3. Communication model and VPN implementation

Figure 7 shows the related modules and the communication link between the two sides of the telemonitoring system, each one is located in a separate local area network. The figure illustrates the server-client relationship in which the patient side is the client who seeks the attention of the healthcare giver acting as a server. The communication link between client and server is established using TCP/IP socket protocol. Initially, the server has opened the socket and waits for the incoming data. In the mean time the client initiates a socket with the IP address and port number of the server machine it is connecting to. The client also gets the streams on that socket for reading and writing. It can then read from and write to the socket, and finally closes the socket when it finishes the transaction.

Figure 6 The main program window showing the original signal (above) and the processed signal (below)

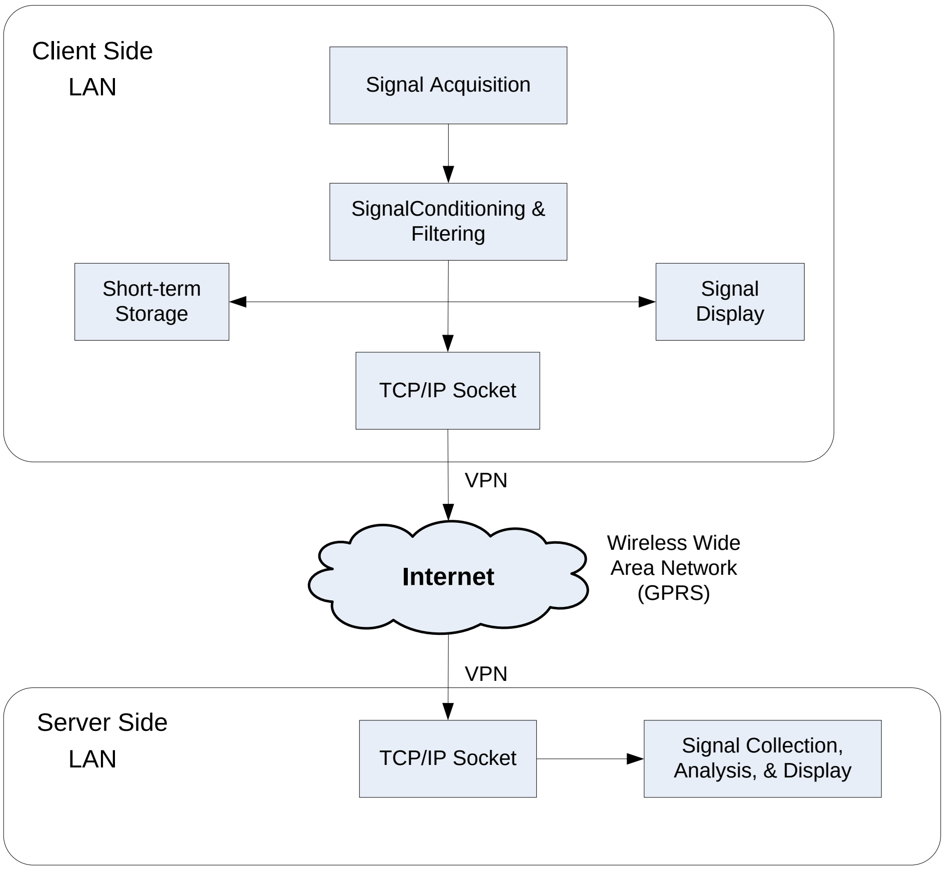

Figure 7 Basic function modules at Server-and-Client sides

In the local network environment, the link can be easily set up by indicating at the client side the private IP address of the server to be connected to, but in the wide area network (WAN) where the communication link is between different LANs, the public IP address is required. This address should be known prior to the communication set up and it can be found easily by using a utility program available in the public domain. Additionally, establishing the communication link between clients and server at geographically different locations also needs a robust and fast set-up time to minimize the delay. It was found that a user-friendly freeware program can be conveniently used for this purpose without knowledge of the public IP address of both parties (Rosenblatt, 2010). The security feature is built-in and the VPN or a virtual LAN connection between computers can also be established as an option by this software. Figure 8 shows the graphical user interface.

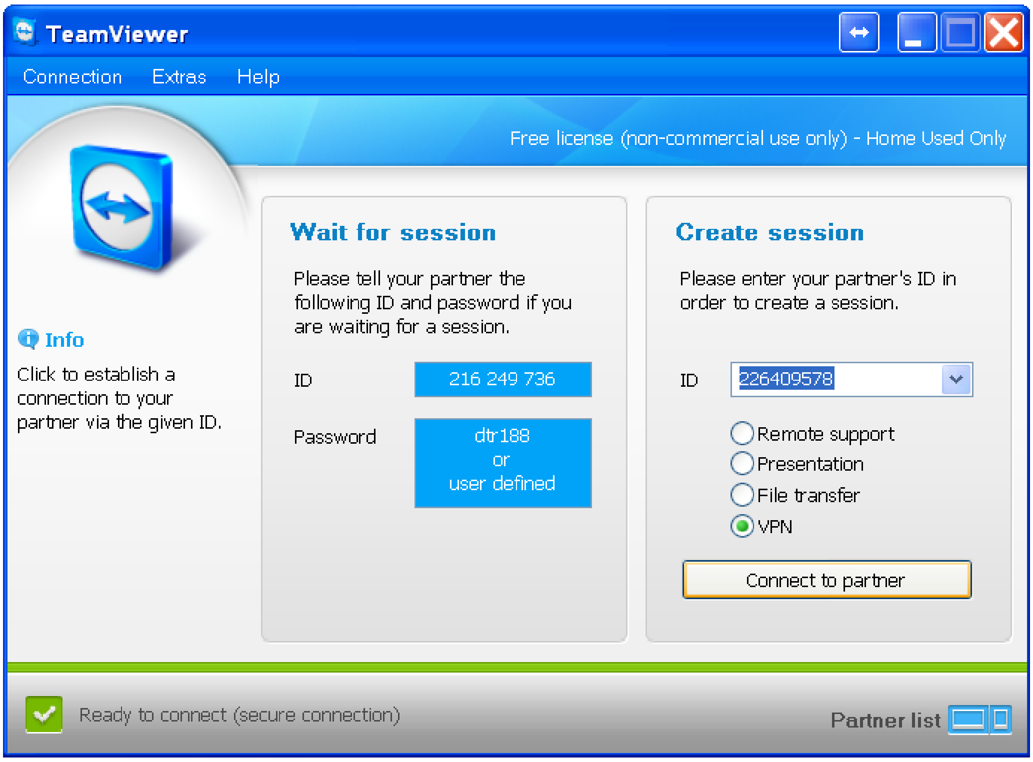

Figure 8 User interface of the communication software

3.1 Data exchange by file sharing

Data exchange between the two parties can be done by file transfer or by file sharing after the secure connection has been established. By right clicking at the folder to be shared in the Windows Explorer, the drop-down menu appears. The sharing and the data security option is chosen together with the setting of various properties. A folder can then be shared between computers and its contents can optionally be compressed or encrypted. After setting up the sharing process, the measurement can be initiated at the client side and data can be stored as a text file. The server computer can subsequently see the saved file and will be able to share the contents in the same manner as file sharing in a single LAN. At the server side the data can be plotted by the same program that is used for live signal measurement, but this time the option to display the stored data is chosen.

4. Transmission characteristics and design methodology

A simple scenario for system usage is as follows: A patient with a heart problem activates the ECG monitor system and looks at the display of the mobile laptop. He then follows a procedure to set up a VPN connection to the hospital emergency department to upload the ECG signal. The physician is informed of the incoming data via

SMS, voice, or email. The physician is then connected to the server via a modem installed in the laptop or PC and runs the program to see the displayed waveform. He then evaluates the situation and communicates with either the emergency department or the patient directly to give his instructions.

Since the ECG data are sampled at a uniform rate and processed by a fixed algorithm, the output data is continuously available at the source and can be output to the network at a uniform rate. In order to achieve the optimal throughput the packet size and therefore the output buffer size is to be suitably chosen. During transmission the packets may encounter traffic congestion, packet loss, and delay jitter. At the receiving side, the real time ECG data should be displayed smoothly to the viewer similar to what originally appears at the sending side. However the packets usually arrive at nonuniform rate and therefore these packets must first be buffered to reduce the jitter and then played back smoothly after a suitable delay time. The diagram in Figure 9 demonstrates this basic idea.

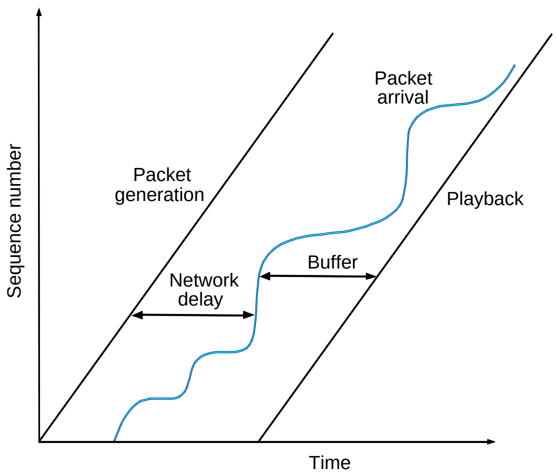

Figure 9 Buffering and smoothing of received data sequence

To deliver the collected data smoothly without loss it can be seen that a combination of ways are necessary, i.e.,

a) increasing the transmission speed, i.e., the channel bandwidth
b) Properly adjusting the payload size and the output/input buffer size.
c) reducing the number of data collected by down sampling or reducing the size of the transmitted data by compression.

In (a) the transmission speed is limited by the infrastructure of the mobile communication GPRS network which is essentially a time variable communication channel dominated by voice services. The load requirement by the latter part leads to a constraint in that existing GPRS or EDGE technologies do not operate at their maximum speeds. Consequently the quality of service (QoS) for non-voice data is limited and cannot be assigned as required (Voskarides et al, 2003). The hopeful solution to this problem is to move into the long-awaited 3G platform ("3G," 2011).

Given the bandwidth assignment from (a) it is then the load that will be put on the line to fill up the capacity. This is the continuous stream of data that is taken out from the buffer to fill in the time slot allocated. The buffer size at the transmitting side therefore plays an important role in keeping the data flow uninterrupted and regulating the data according to the line load condition. This is assumed that the buffer at the receiving side can read and process this data in time without loss. The DSMS is therefore required for (b).

In (c) the amount of data generated from the data source is to be properly regulated as well. However the sampling rate cannot be set too low. Based on the frequency contents in an ECG signal limited to 100 Hz, the Nyquist sampling rate is at 200 Hz which in practice would be set at 500 Hz. By a simple analysis it can be shown that at this sampling rate the network throughput must be greater than 500x2x8 bit/sec. The real bottleneck to the data flow is again the channel bandwidth, and by keeping the data packet small by regulating the data window size together with the data compression, it seems to a certain extent that real-time characteristics can be achieved.

5. Conclusion

We have demonstrated that a cost effective prototype for a health telemonitoring system can be set up and tested to investigate various major existing technical problems. Hopefully these problems have been sufficiently elaborated here and some solutions have been either implemented or proposed. Basically, the problem can be put in the framework of a control system from which the output needs to be regulated properly. The system has time varying with uncontrollable delay elements and very little feedback. We assume that there is no access to the service provider, so the bandwidth is fixed and shared with the public and QoS is not negotiable. The requirement is to have the isochronous data display available at the receiving end within the shortest time without loss. The problem can further be generalized to cover the case of distributed clients connected to one server over a wireless WAN. The differences between this problem and the one with multimedia data streaming in an on-line conference or webinar on the internet should be noted, although there are many similarities that can be learnt from them. We hope that this paper so far has suggested a viable model and some possibilities for further research in this direction.

6. Acknowledgements

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