The comparative performance of mobile telemedical systems based on the IS-54 and GSM cellular telephone standards

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Summary

The performance of mobile telemedical communications links based on the IS-54 and GSM cellular telephone standards (the most widely used commercial systems in North America and Europe, respectively) was studied by computer simulations. A photoplethysmography signal was used to investigate the transmission of medical data over simulated mobile phone channels. Various conditions were simulated in the communications path between a mobile transmitter and receiver, from perfect to distorted conditions. The results showed successful transmission, with bit error rates of better than 10^{-7} at the receiver for the IS-54 standard. The performance of the IS-54 standard was superior to that of GSM in terms of minimum path delay variations, especially in built-up (urban) areas.

Introduction

There has been extensive research in telemedicine in the last decade[1], using various forms of telecommunication, including the public telephone network and ISDN. These have been used for the transmission of medical data, including video images, in order to provide medical consultation services[2,3]. However, such applications have been mainly for communications between fixed stations and not for ambulant patients.

In recent years, there has been a rapidly growing market for digital mobile telephones, which operate to various cellular standards, such as GSM (Global System for Mobile communications), PCD (Japanese Personal Digital Cellular) and CDMA (Code Division Multiple Access for US). Wireless and mobile telecommunications are having a major effect on the way that health-care organizations deliver health care to their customers. Cellular digital networks, in-building wireless and portable information systems have extended the reach, range and manoeuvrability of applications and content[4]. The main work in mobile telemedicine to date has concerned the transmission of medical data in mobile environments[5–8]. Recently, experiments have begun concerning the transmission of video pictures at low frame rates from ambulances[9]. However, there have been few, if any, studies of the design and modelling issues relevant to mobile telemedical systems which use commercial cellular telephones.

We have modelled a mobile telemedical system using two different digital mobile telephone standards, namely IS-54 (TDMA for US) and GSM. The transmission of a photoplethysmography (PPG) signal was simulated in order to study the relevant communication design issues. The aim of the study was to investigate the feasibility of using a mobile telemedical system to monitor patients who are not necessarily bed-bound, for example people at home or at work, in ambulatory conditions and possibly somewhere remote from a specialist centre.

Performance indices

Before overviews of the GSM and IS-54 standards, a brief definition of the performance indices used in the simulation process is given here for completeness. The detailed design and digital communications concepts have been described in several recent texts[10–12].

The bit error rate (BER) is a measure of the number of bit errors occurring in a transmitted data sequence.

Additive white Gaussian noise (AWGN) is a noise signal which has flat power spectral density with

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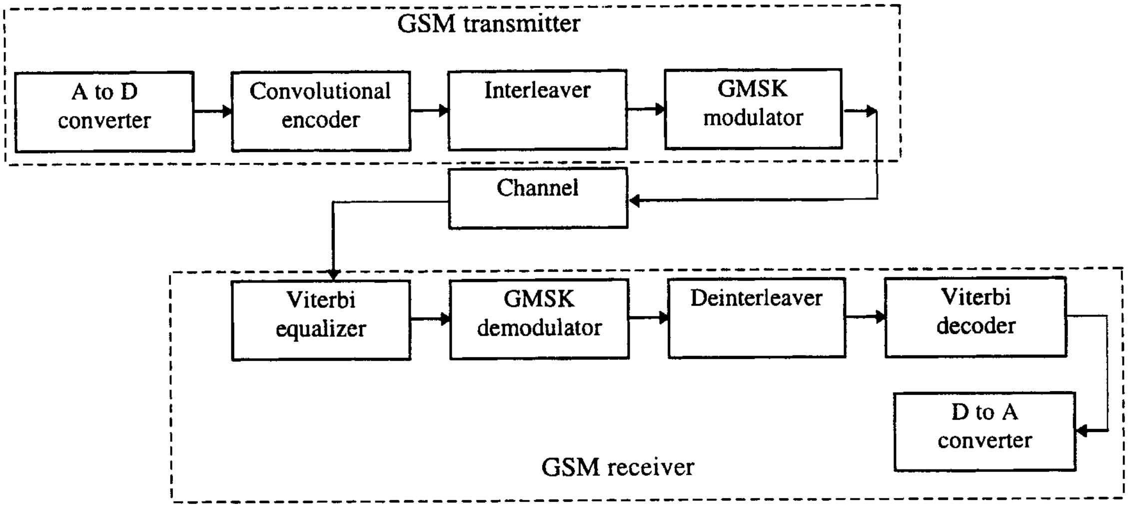

Fig 1 Block diagram of a mobile telemedical system using the GSM standard.

frequency—that is, all noise frequencies are represented equally. For convenience, most digital communications texts and indeed practising engineers assume that noise (from natural sources, for example atmospheric noise, thermal, shot noise and so on) falls predominantly into this class.

Intersymbol interference, caused by radio noise and signal boundary reflections, represents one of the most difficult challenges for a wireless telecommunications designer. This means that the received signal is not an exact replica of the transmitted signal because of mobile channel noise and multipath effects. These can give rise to a problem called 'delay spread', in which signal reflections from buildings and other terrain features and the addition of the direct path transmissions to the reflected data result in the received data becoming 'smeared out' in time. This error is compounded by the motion of a mobile transmitter, because Doppler shift occurs, which is relevant in cases such as transmission from a moving ambulance.

The GSM standard

The GSM standard is the most popular mobile telephone standard in Europe and the rest of the world, apart from North America. If current trends continue, GSM will become the dominant cellular telephone standard worldwide[13]. The GSM standard is different from the IS-54 standard (see below) in terms of its transmitter and receiver subsystems. Both are designed for the digital transmission of analogue speech signals with a typical bandwidth of 4 kHz.

The block diagram for a GSM-based mobile telemedical system is shown in Fig 1. It comprises:

(1) a data channel encoder;
(2) a transmitter;
(3) a transmission channel;
(4) a receiver;
(5) a data channel decoder;
(6) an error counter.

A brief description of the important functional blocks of the GSM telemedical system is given next.

Analogue-digital (A-D) conversion. The most appropriate method of A-D conversion for the PPG data was considered to be a linear 16-bit converter, where each sample of the analogue signal was converted to a corresponding binary value of 16 bits. This is not necessarily required for all types of medical data and in some cases 8-12-bit resolution would suffice.

Data formatting and encoding. In this stage, forward error-correction techniques are employed. These are represented by convolutional encoding and interleaving steps. The resultant data are then formatted in a normal burst format suitable for mobile transmission. This process is basically for accurate timing reference for each mobile transmitter handset. The GSM frame format is such that eight users are assigned to the same transmission frequency, and hence eight time slots are provided for each frame, which are repeated regularly in subsequent frames. Each user must transmit information at a rate of 270 kbit/s within the 200 kHz bandwidth allowed, even though the individual user's data rate from the voice coder is only 13 kbit/s. This is a useful facility for transmitting medical data of different bandwidths because the medical data can be stored and processed 'at leisure' over the seven remaining time slots as well as during the arrival time slot. An interleaver is included in the transmitter and a deinterleaver in the receiver, so as to disperse burst errors that occur when the receiver signal is fading[11,12].

Modulation. The modulation in GSM is Gaussian minimum shift keying (GMSK) at an intermediate frequency of 900 MHz. The GMSK modulator performs Gaussian low-pass filtered MSK modulation (a digital frequency-modulated or continuous-phase frequency shift keying modulation technique, having a modulation index of 0.5). In cases where there is multipath fading, the best technique is the Viterbi maximum likelihood sequence estimation (MLSE) method, which obviates the need for a separate GMSK demodulator at the receiver. This method relies on knowledge of a finite set of possible signal shapes received during the 1-bit period[11,12]. The modulated output is a complex envelope signal. Parameters that define this block are the carrier frequency, the 3 dB bandwidth, tap length, sampling frequency and baud rate.

Demodulation. The demodulation technique used in a GSM system is the non-linear MLSE equalization method.

Data parsing and GSM error correction. This is the inverse process of data formatting, where redundancy is removed, errors which have occurred during transmission are corrected and the digital stream is restored. The data are decoded using a Viterbi decoder and deinterleaved. The normal data frame format is removed and the user data stream is recovered. The GSM error-correction mechanism calculates the errors between the transmitted signal and the received signal.

Digital–analogue (D–A) conversion. The digital bit stream is finally converted to an analogue signal using a 16-bit converter (in the present case) to retrieve the original data with acceptable quality.

The GSM digital cellular standard is an example of a system based on time division multiple access (TDMA—basically a method of combining multiple users on a given channel bandwidth using unique time segments) that has been designed to cope with the problems of the wireless environment. The following features were incorporated to improve the efficiency of the mobile communication link[11,12]:

(1) A reference word is contained in each frame for channel equalization and to overcome the multipath delay problems discussed earlier.
(2) Time-slot advance features are used to measure the time delay for the information to be sent, for accurate timing reference of the transmitted signals from each mobile cellular handset (see above). This relates to the fact that the GSM system carries data in TDMA frames that are composed of eight bursts. In the present work it was appropriate to use the advance mode, in which one user (e.g. patient or ambulance) occupies one burst per TDMA frame and the remaining seven are not significant—after the completion of a burst the system skips to the next within-TDMA frame.
(3) Frequency hopping (also called the frequency reuse technique) involves changing the frequency of the transmitted signal to that which imposes least degradation on the signal. The operating frequency is changed every TDMA frame.

These are important design issues that can facilitate mobile data transmission with the relevant confidentiality and security requirements for telemedicine.

The IS-54 standard

The IS-54 standard[14] has been upgraded recently to the IS-136 (which incorporates TDMA). The latter has the same generic structures of the IS-54 but defines in more detail the digital control and air interface traffic specifications for transmission of user data and related control information[14]. The main communication design elements remain and the basic advantage of this upgrade is that the two specifications provide the information necessary for the development of IS-136-compliant products in future[14]. These are designed to achieve a compromise between high mobile performance and low cost, and to make maximum use of customized digital signal processors (DSP).

The generic block diagram of a telemedical system based on this standard is shown in Fig 2 and a detailed description of the relevant design blocks can be found elsewhere[15,16]. A brief summary of the main blocks is given here for completeness.

In the transmitter subsystem, the converted and formatted PPG medical data are encoded and modulated using 16-bit convolutional pulse code modulation (PCM) and quaternary phase shift keying (QPSK) techniques. The data are then passed to a pulse shaping (raised cosine) filter to minimize intersymbol interference at the receiver.

In the receiver subsystem, the received signal is shaped and filtered using a matched (raised cosine) filter and a Viterbi MLSE equalizer to minimize intersymbol interference and channel distortion. The resultant signal is retrieved using a QPSK demodulator and Viterbi decoder, then converted to an analogue signal using a 16-bit D–A converter to retrieve the original signal.

Simulation

To test the performance of the mobile telemedical system the PPG data were transmitted using different simulated path delays and noise conditions in the mobile telephone channel. The aim was to study the

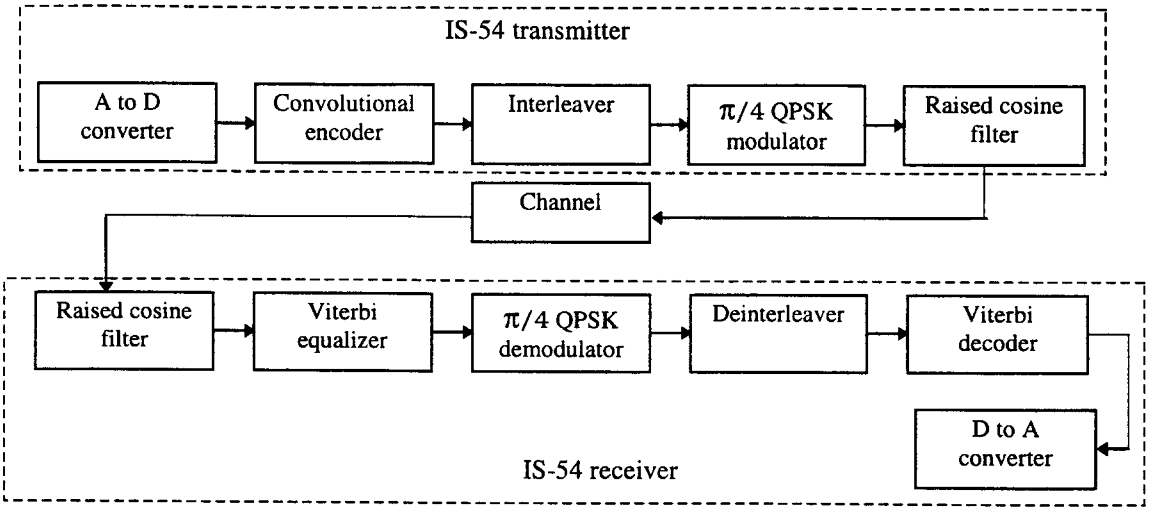

Fig 2 Block diagram of a mobile telemedical system using the IS-54 standard.

number of bit errors occurring in the transmitted medical data sequence and their effect on the received signal. The other measure was the path delay, which can quantify the performance of the system under conditions of multipath fading—the distortion of the received signal transmission as would be caused by signal reflection from buildings, vehicles and other terrain. Depending on the lengths of the different paths, the reflected signals may partially cancel out the main signal[5].

Methods

The model incorporated the TCH/F9.6 data traffic channel (9.6 kbit/s). The cellular channel was modelled in terms of Rayleigh fading with Doppler shift to simulate the effects of relative motion between the transmitter and receiver. The full channel model included several sub-models of multiple faders, co-channel or adjacent channel interferers, and noise elements to provide realistic modelling of the performance of the mobile communication channel in different conditions. This also enabled a test of the effects on the systems' performance of variations of relevant design parameters, such as Doppler frequency, mobile speed, frequency hopping and power delay profile.

Using the chosen test signal, simulations were carried out for a range of noise conditions in the transmission path between transmitter and receiver for the two mobile telephone standards. The two parameters chosen were the noise variance and the path delay. In each case the minimum values corresponded to ideal conditions and the maximum values were typical of bad conditions (Table 1).

Table 1. Simulation parameters for the communications path between transmitter and receiver

Parameter	Minimum	Maximum
Noise variance	0	0.5
Path delay	1	10

The minimum values represent perfect conditions and the maximum values represent typical bad conditions.

The simulations were carried out using the Signal Processing Work (SPW) system and its relevant design libraries (Cadence Design Systems/Alta Business Unit, Bracknell, Berkshire, UK; http://www.cadence.com/alta) running on a UNIX computer. The SPW supports special blocks to simulate different digital communication systems with different levels of complexity and to monitor the output of the system interactively, according to the specified design parameters. This allowed the effect of these parameters on the performance of the mobile telemedical model to be tested.

The PPG signal used as test data was acquired using a PPG system developed at Loughborough University[6]; it had minimum sensitivity to motion artefacts and allowed patients freedom of movement. The PPG signal was sampled at a rate of 1 kHz using 16-bit A–D conversion to provide appropriate resolution. Fig 3 shows a typical digitized PPG signal.

The communication details of the design models of both IS-54 and GSM standards have been described elsewhere[5,6,11,12]. The SPW design steps of the telemedical modelling and simulation steps for both standards were based on the block diagrams shown in Figs 1 and 2.

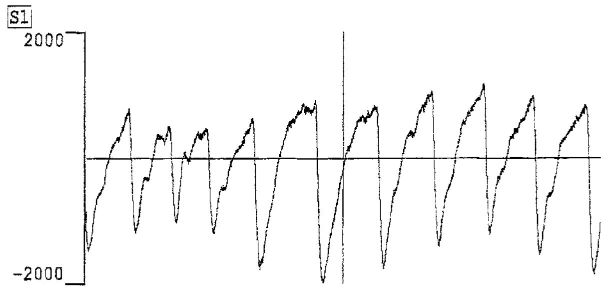

Fig 3 Typical PPG data signal used in the design and simulations.

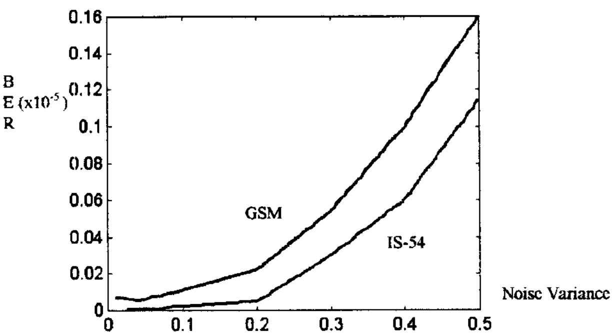

Fig 4 Comparison of the BER as a function of noise variance for the two cellular systems.

Results

The performance of the two systems (in terms of the BER) as a function of the AWGN with a path delay equivalent to one transmitted symbol is shown in Fig 4. It is well known that the level of noise in the channel will impose an upper limit on the number of different unique transmitted symbols (medical data samples in the present case) that can be correctly decoded at the receiver end. This is reflected in Fig 4. In this ideal case, with no multipath effects, the IS-54 system performed better than the GSM system over the range of noise levels tested.

In more realistic environments there will be severe multipaths within the mobile link. Fig 5 shows the BER variation as a function of path delay at a fixed noise level for both standards. It is clear that the IS-54 system performed better than the GSM system over the range of path delays tested. The BER was near zero for path delay variations up to 5 for the IS-54 system—this corresponds to actual delays of up to 78 μs in the fading mobile channel.

For the GSM case, the BER tends to zero for relative path delays of up to about 3, corresponding to actual delays of up to 46.875 μs for a bit rate of 16 kbit/s. For both standards, the AWGN was assumed to be of a minimum value of 10^{-3}, calculated from the earlier

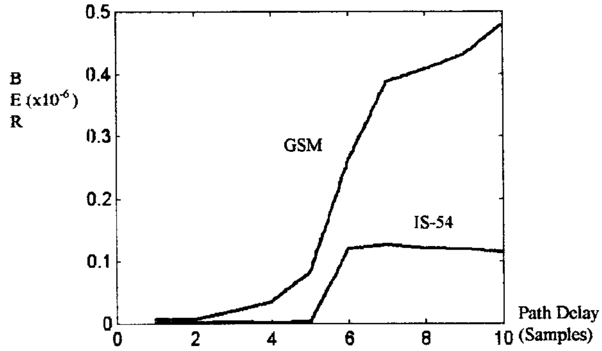

Fig 5 Comparison of the BER as a function of path delay for the two cellular systems.

result. Table 2 summarizes the comparative simulated mobile multipath levels and the corresponding values in time and distance for the IS-54 mobile telemedical model.

It can be seen from these results that the system using the IS-54 standard performed better than the GSM standard for the same values of path delay. This means that the IS-54-based model performed better in more built-up (urban) areas for the specified mobile-channel design parameters than the GSM-based system under the simulated mobile conditions.

The original PPG signal and the output of the mobile telemedical system for the IS-54 standard is shown in Fig 6, after transmission through a channel with a noise variance of 10^{-3} and a path delay of one (the ideal case, with no boundary reflections). The input and output data samples are identical, with minimum output distortion. Fig 7 shows the original analogue PPG signal and the output from the GSM model after transmission through the mobile channel with a noise variance of 10^{-3} and a path delay of three transmitted symbols. This represents the noise variance (AGWN) and the channel path delays in a mobile environment, such as in high-speed ambulances, where the path lengths vary with time and so the relative phases between the signals also vary with the vehicle's position. This

Table 2 Results from the IS-54 simulation: multipath levels and the corresponding values in time and distance

Multipath delay (samples)	Multipath delay (μs)	Multipath delay (km)
1	15.63	4.69
2	31.25	9.38
3	46.87	14.06
4	62.5	18.75
5	78.13	23.44
6	93.75	28.13
7	109.38	32.81
8	125.00	37.50
9	140.63	42.19
10	156.25	46.88

The encoding frequency was 16 kbit/s.

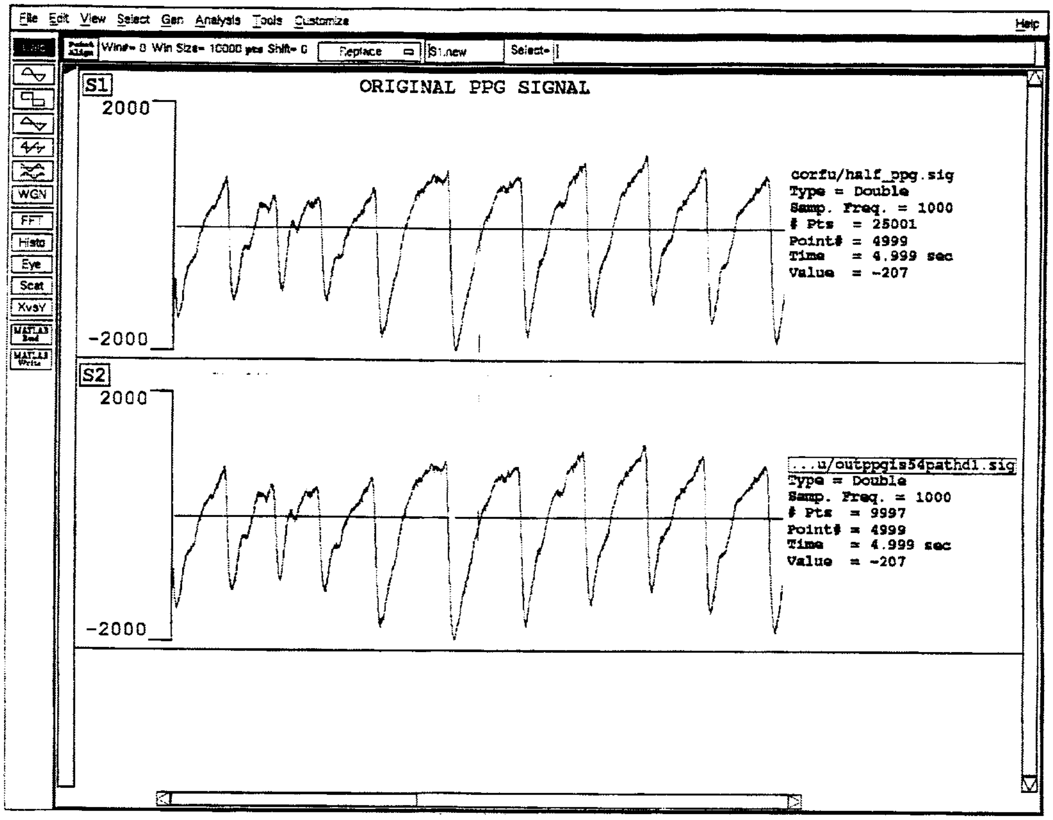

Fig 6 Comparison of the original PPG signal and the output of the IS-54 telemedical system.

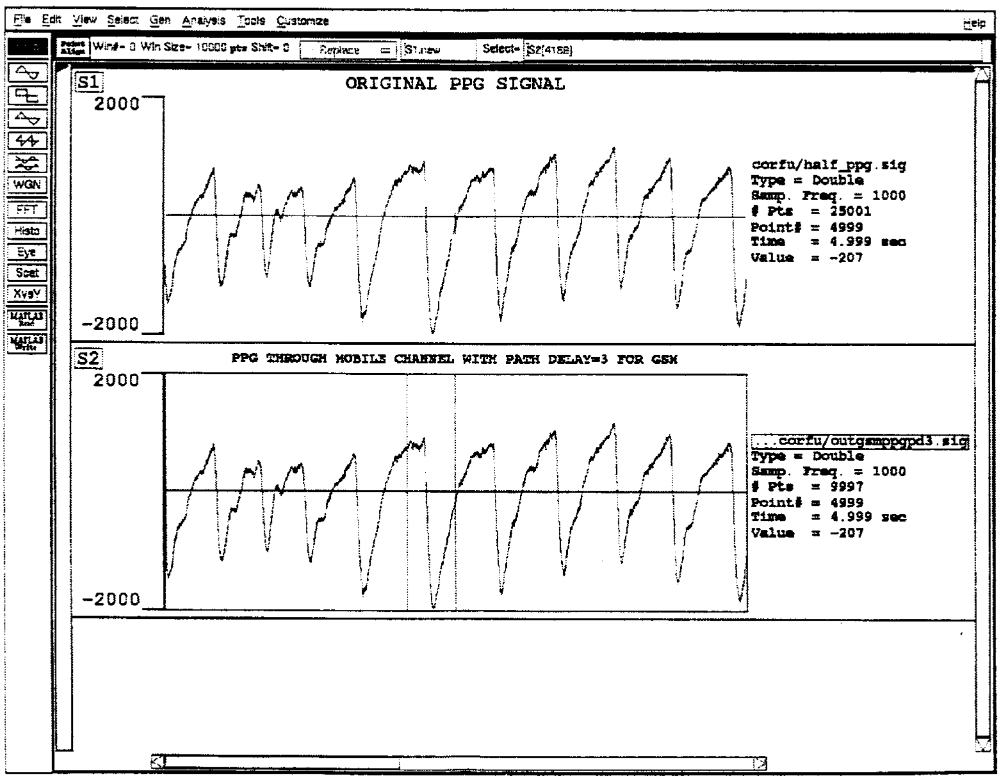

Fig 7 Comparison of the original PPG signal and the output of the GSM telemedical system.

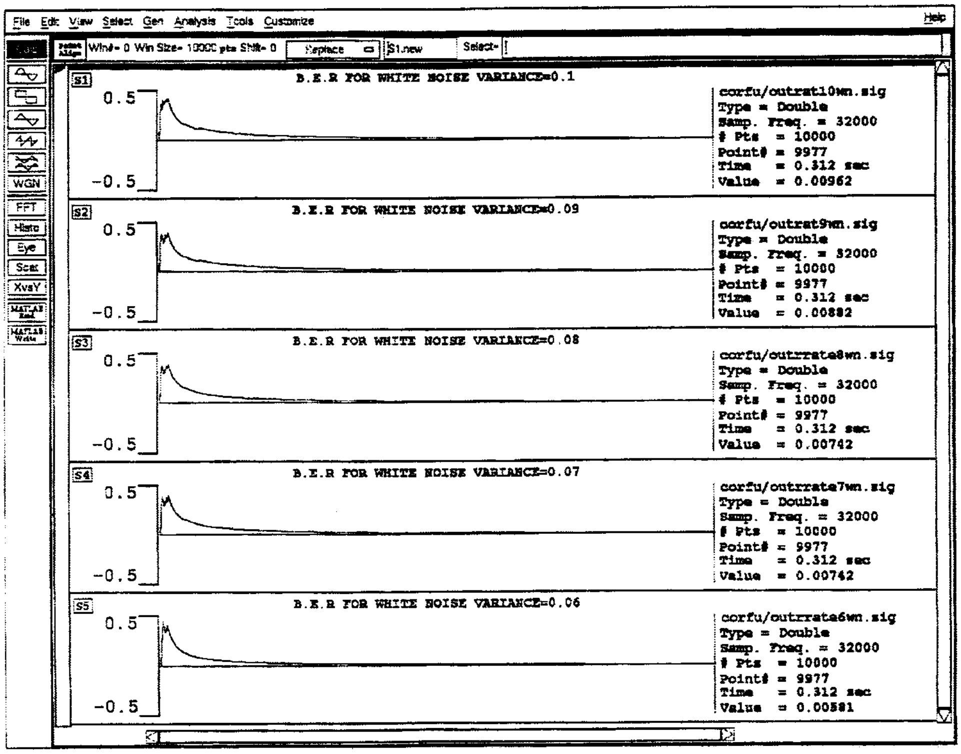

Fig 8 The BER performance of the IS-54 system at different values of noise variance.

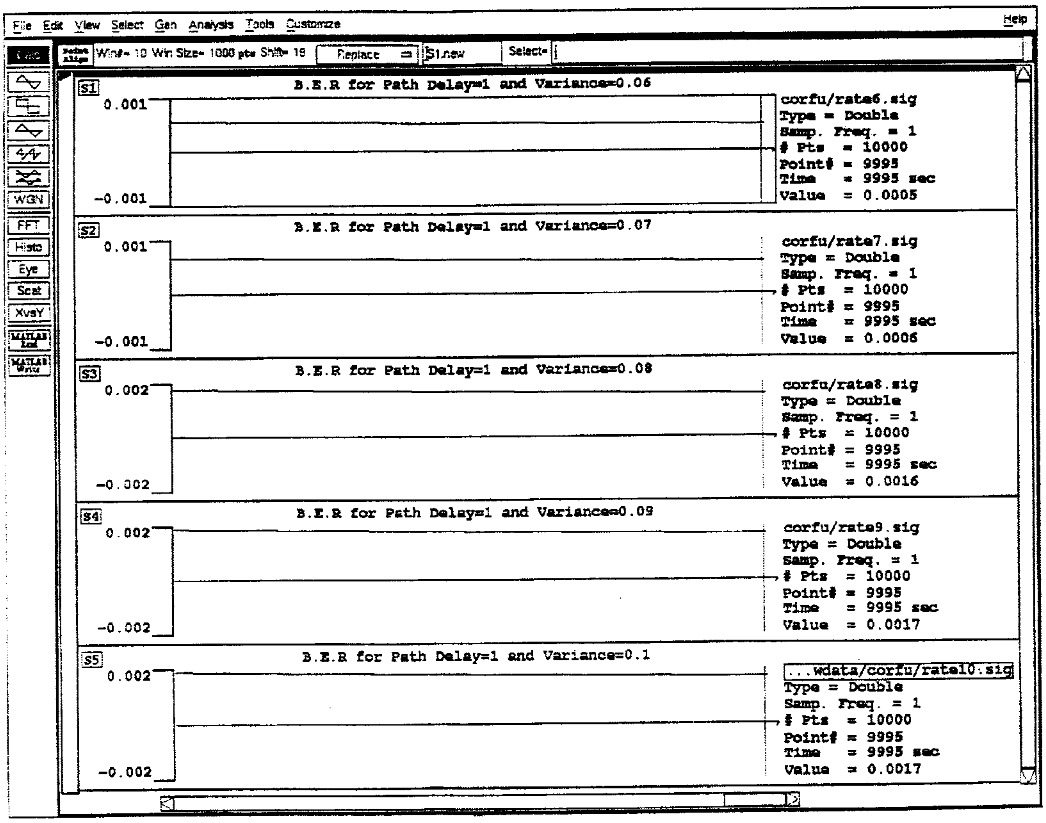

Fig 9 The BER performance of the GSM system at different values of noise variance.

indicates that the noise variance and the channel path delays are important parameters in the design of mobile telemedical systems based on cellular telephones.

The comparative BER performance of the two systems is illustrated in Figs 8 and 9, with the different white noise variance measures. It can be seen that for the IS-54 case the BER fades to near zero with time, whereas for the GSM system the BER remains constant throughout, with the same variations in the noise level. However, the performance of both systems degrades as the path delay increases substantially. This means that in a noisy channel environment, for example in urban areas, where the noise variance has large values, the IS-54 system performs slightly better than the GSM system. The probable reason for the relatively poor performance of the GSM system is the equalizer structure used in the receiver system, which differs from that in the IS-54 system.

Discussion

The IS-54 and the GSM standards represent the most widely used global commercial mobile telephone systems. The simulation results of mobile telemedical systems using both standards using PPG medical data show that successful transmission over cellular channels is possible, subject to certain communications design constraints. The results of the present study lead to the following conclusions:

(1) the modelled IS-54 system performed better than the GSM system in terms of minimum path delay variations;
(2) the modelled GSM system performed better than the IS-54 system in terms of AWGN variations;
(3) in both systems, the equalizer in the receiver did not perform adequately for receiving clinically acceptable medical data under certain mobile conditions, especially in the presence of higher noise levels in the mobile channel.

The results suggest the need for further studies both of the effects of the conventional Viterbi equalization techniques for mobile telemedical data systems, and of the design of improved equalizer structures compatible with different cellular medical data transmissions. Attention should also be paid to the different layers of the GSM structure and their capacity for transmitting clinically acceptable medical data[11]. Further research is required to develop improved digital signal-processing methods for mobile telemedical systems. Work is currently under way to develop the relevant mobile telemedical hardware and signal processing structures using these cellular standards.

The importance of mobile telemedicine is that it will enable the wider use of telemedicine and emergency consultations, such as in developing countries where reliable telephone services are not available, or in under-served and rural areas.

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