Wireless Electrode for Electrocardiogram (ECG) Signal

By

LEUNG Sze-wing

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Abstract

A novel scheme of ECG telemetric monitoring with a single electrode assembly via *concentric electrodes* was investigated. It is called the *"Wireless Electrode"*. Digitization with a kind of oversampling converter, the Sigma-Delta converter, was under study especially for its wireless application. Prototypes for telemetry application applying this technique with the concentric electrode were implemented. Simulation and Experimental results were obtained.

Heart Diseases are prevalent nowadays. This is especially true in the developed countries. Easy and prompt diagnosing and detecting heart diseases are essential. Electrocardiogram (ECG) monitoring is a usual diagnostic tool for this purpose. Two or more electrodes with linking wires are usually required to acquire the signal. With telemetric monitoring, amount of wires has been reduced. In order to reduce further the amount of nuisance from the electrodes and wires, a novel scheme of applying a single electrode assembly with concentric electrode and radio telemetry is devised.

Signals were picked up from concentric electrode in this scheme. Therefore, a single electrode assembly in electrode size can be achieved. Radio telemetry was applied for wirelessly monitoring of the ECG signal. No interconnecting wires are then required for monitoring. Digital transmission was implemented with a kind of oversampling converter. The kind of converter is named as *Sigma-Delta Converter*. This kind of converter is simple in analogue circuitry. The circuit simplicity is essential in telemetry device that can reduce the size of the patient-worn transmitter. In this work, a first-order Sigma-Delta converter was investigated and it was built with simple operational amplifier (opamp) and digital circuits.

The converter has basically one-bit binary output. Signals are reconstructed by either

analogue or digital filtering from the binary stream.

The 1-bit binary stream was sent via telemetry in this work. *Bit Errors* were generated in the communication process. The situation was simulated. AWGN (Additive White Gaussian Noise) was applied simulating the occurrence of bit errors. It was observed that the performance of the first-order Sigma-Delta converter could be better than an ideal 8-Bit converter in some cases under this situation. Clear ECG signals received using this scheme were observed in the experimental results.

Therefore, the application of a "*Wireless Electrode*" scheme in ECG monitoring is feasible and the digitization with the simple Sigma-Delta converter can be a useful component in the digital transmission of ECG signal in the telemetric application.

摘要：

本論文探討一名為〝無線電極〞的創新無線心電訊號監護工具。這工具是通過同心電極而達成的。此外，我們也探討了一種名為 *Sigma-Delta* 的 *Oversampling* 模-數 (A-D) 轉換器在心電訊號模-數轉換上的應用。我們在其中製作了利用以上技術加上同心電極在無線監護上應用的雛形線路。并且，當中我們也取得了實驗及計算機模擬的結果。

心臟病在現今的社會是一個十分普遍的。這情況在已發展國家尤甚。一種對心臟病方便、及時的診斷工具是必須的。心電圖便是其中一個常用的診斷工具。一般而言，量度心電圖時須用兩個或以上的電極。其中也須用上不少連接電線。若在無線監護的情況下，電線的數量已有所減低。為了更加減低電極及其中連接線數量，一個利用單一封裝電極加上無線傳輸的創新的方案因而產生。

心電訊號在這方案中是由一同心電極取得的。一電極大小、單一封裝的監護工具因此能達成。再加上採用了無線傳輸的技術，監護過程中是不須任何連接電線的。另外，我們在數字傳輸方面採用了 *Sigma-Delta* 的模-數轉換方法。這方法的好處在於其在模擬電路上的簡單性。一電路簡單的無線監護器件是有利的。因為這樣便能讓病人身掛的監護無線發射器微形化。在這個研究中，我們探討了一階的 Sigma-Delta 模-數轉換器 (First-order Sigma-Delta Converter), 并且利用了簡單的運算放大器及數字電路來實現此模-數轉換器。此模-數轉換器的輸出是單位元的。其數-模 (D-A) 轉換可透過模擬或數字濾波器達成的。

模-數轉換器的單位元輸出在這研究中是利用無線方式傳播出去的。在這個傳輸過程中，位元的誤差 *(Bit Errors)* 是會產生的。我們利用了計算機來模擬這過程。其中我們應用了 *AWGN (Additive White Gaussian Noise)* 來模擬 Bit Errors 的產生的情況。從中我們發現在這種應用環境下在某些條件下一階的 Sigma-Delta 模-數轉換器的表現能較一理想的八位元模-數轉換器為佳。此外，我們亦能在實驗結果中得到清晰接收得來的心電訊號。

總括而言，〝無線電極〞在心電監護的應用上是可行的。而簡單的 Sigma-Delta 模-數轉換器能成為心電訊號數字無線傳輸的一實用的組成部份。

Contents

Chapter 1 Introduction

1.1 Objectives

In this research, we would like to investigate the application of a "Wireless Electrode" with only single electrode assembly for easy and prompt monitoring of patients' Electrocardiogram (ECG). In the mean time, the Sigma-Delta converter is investigated for its application to digitizing ECG signal due to its simplicity in analogue circuitry that promotes the miniaturization of Telemetry devices.

1.2 Prevalence of Heart Diseases

In Hong Kong, heart diseases ranked the second killer in the ten leading causes of death in the past 30 years [1][2]. In 1996, 17% and 12% of total deaths in urban and rural areas of Mainland China were reported to be due to heart trouble [3]. Heart disease belongs to the class of circulatory system disease group. In the whole world about 30% (15.3 million) were due to circulatory system. Most deaths from circulatory diseases were coronary heart disease (7.2 million), cerebrovascular disease (4.6 million), other heart diseases (3 million) [4][5].

While deaths due to circulatory diseases declined from 51% to 46% of total deaths in the developed world during the period 1985-1997, they increased from 16% to 24% of total deaths in the developing world [5]. From these facts, we can see that the importance of prompt and easy diagnosis and detection of heart diseases in order to ease the situation of high death rate due to heart problems.

1.3 Importance of ECG Monitoring

One of the useful diagnostic tools for heart disease is the Electrocardiogram (ECG). Analyses of them are common diagnostic procedures in modern healthcare and monitoring of the ECG and heat rate in intensive care is providing additional information [6]. Originally, ECG is monitored with bulky wires running between patient and machines. With advance of wireless technologies, the wires can be eliminated and this wireless monitoring method is called the ECG telemetry which offer various advantages over the original wired version. Details on Telemetry will be given in Chapter 2.

1.4 Wireless Electrode

Two or more electrodes are usually required in performing ECG telemetry, with wires connecting the electrodes to the transmitter transmitting the ECG signal to the air. Special assemblies of the electrodes have been made eliminating the interconnecting wires [7]-[10]. Although the interconnecting wires are removed, two or more disposable electrodes are still needed to acquire the ECG signals. In order to further reduce the complexity of measurement setup, we would like to ask a question:

(1) Is it possible that by using a single electrode assembly, ECG signal can be picked up for diagnosis and detection of heart diseases?

(2) And is it possible to apply this scheme in telemetry application making it a single "Wireless Electrode"?

In this research, we would like to investigate on the above questions in more detail.

1.5 Analogue-to-Digital Converters

Digital transmission, nowadays, is usually used in telemetry devices. With digital transmissions, Analogue-to-Digital Converters (A/D converters) are required for transforming the analogue signal into binary form. There are different kinds of A/D converters available, each has its own strengths and weaknesses. Most often, the sampling rate is about 2 times the signal bandwidth and the *Successive Approximation converter* is used for ECG telemetry. Another type of A/D converters operates with a much higher sampling rate that is called the *Oversampling* converters. One example is the Sigma-Delta converter. It gives 1-bit binary output and it is an attractive converter since it is composed of simple and robust analogue circuitry that is especially beneficial to IC fabrication process. It is also renown for its capability of offering high-resolution A/D conversions. To achieve high resolution, complex Digital Signal Processing (DSP) units should be incorporated. It can be illustrated in Figure 1.1.

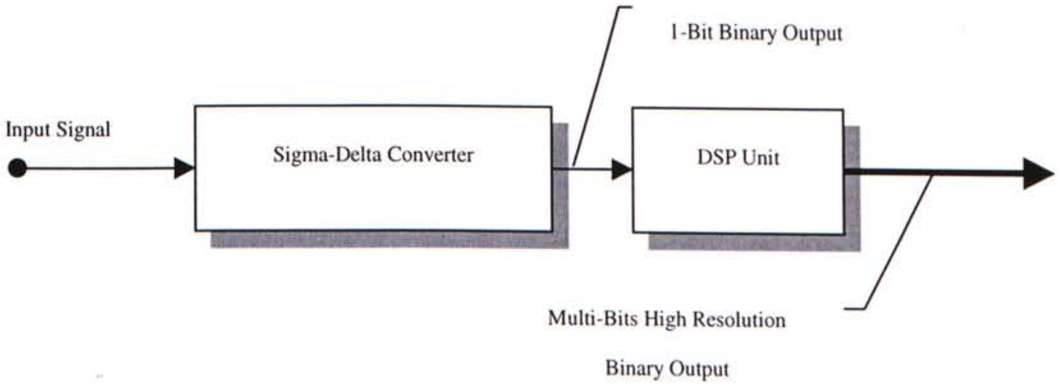


Figure 1.1 Sigma-Delta Converter Block Diagram

Usually, these DSP units are fabricated within a single chip assembly. In this research, we would to investigate whether it is possible to separate the two parts in a telemetry application. The first part, the simple Sigma-Delta converter with 1-bit output, is placed in the transmitter, while another part, the DSP unit, is replaced by a computer in the remote monitoring station. It is depicted in Figure 1.2.

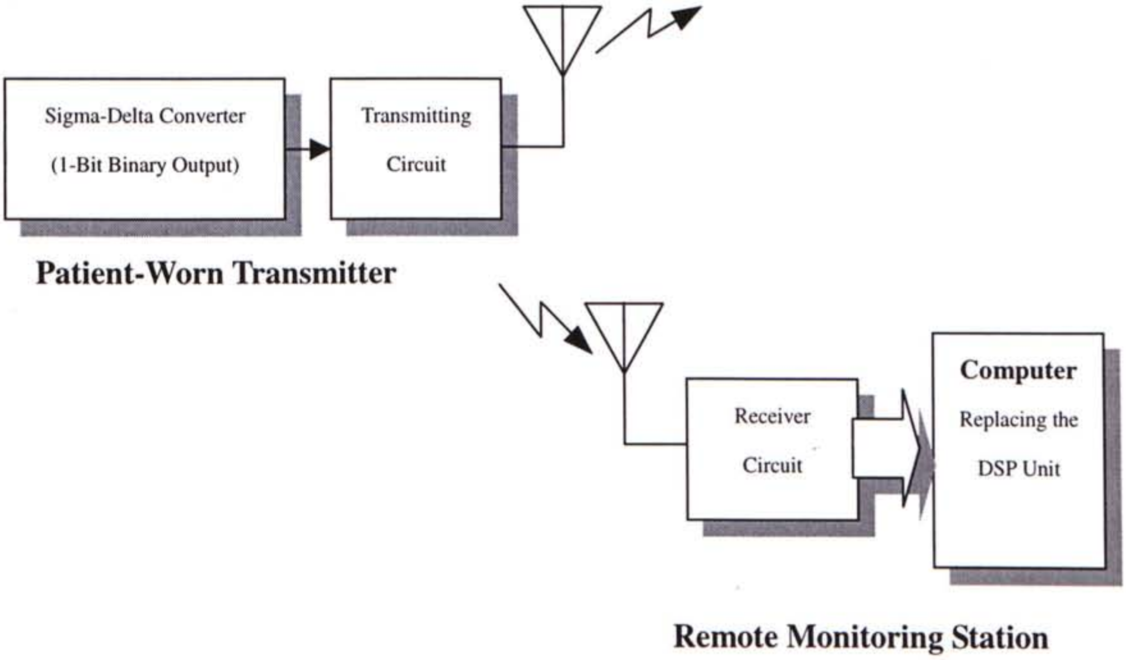


Figure 1.2 Sigma-Delta Converter with Computer replacing the DSP unit

Is this scheme feasible? Is there any degradation of performance of the Sigma-Delta converter? These questions will be taken into account in this research as well.

1.6 Organization of Thesis

This chapter forms an introductory part of thesis. Main objectives and themes are illustrated in this chapter. In Chapter 2, literature review on several main topics will be given. The main topics are *Telemetry, and Sigma-Delta converter*. In Chapter 3, 4, the implementation of the wireless electrode and the application of Sigma-Delta converter in digitizing ECG signal will be discussed respectively. Conclusions, with future research work discussed, will be presented in Chapter 5, the last chapter. Bibliography and a brief list of abbreviations will be given lastly.

Chapter 2 Literature Review

In Chapter 1, we have seen that heart diseases are prevalent in the world nowadays. Early detection of heart diseases is important and ECG (Electrocardiogram) is one useful diagnostic tool in modern health care. Patients under ECG monitoring will have wires running between them and the ECG machines. These wires cause nuisance to the patients making them staying still during the monitoring period. Telemetry technique is therefore applied to ease this situation. With ECG telemetry, patients can be mobile and this offers advantages over the "wired" version of ECG monitoring. In this chapter, literature review on several topics will be presented that are closely related to Telemetry. The first one will be on the topic of Telemetry itself, its definition, history and components. Second, since telemetry nowadays is usually digital in nature, digitization or analogue-to-digital conversion is a common process. In Chapter 1, we have introduced the Sigma-Delta converter. It is one of the digitization methods. There are also other types like Single-Slope, Dual-Slope, and Successive-Approximation converters. These converters, along with the Sigma-Delta type will be discussed in this chapter.

2.1 Telemetry

In this section, the topic "Telemetry" will be reviewed. Definitions, Advantages, and Compositions of Telemetry will be presented hereafter.

2.1.1 Definitions of "Telemetry"

"Biotelemetry or obtaining biologic information from afar has made incredible advances over the past 50 years" by Harold Sandler, "Biotelemetry: Its First 50 Years", Proceedings of the 3rd International Symposium on Biotelemetry, pp1, 1976.

By the above quote, it was shown that biotelemetry can be equivalent to "obtaining biologic information from afar. And in [17], another author, Kimmich gave a thorough account on the definitions of "biotelemetry". He stated that the main criterion for the definition of "Telemetry" is "assessment of control of biological variables from patients, subjects, or animals, with relatively little restraint of the patient/animal leading to undisturbed and distortion-free measurement of the physiological variables. Therefore, the distance may not be definitive element for the definition of "Telemetry" Telemetry is a broad term and can be equivalent to various alternatives like ambulatory monitoring, wireless monitoring, radiotracking, telediagnosis [17, pp85]. It can be applied on human or animals. When it is utilized on humans, it is sometimes called the medical telemetry, [20, pp185].

It was suggested in [18] that the goals of biotelemetry include the capability for monitoring humans and animals with minimum restraint and to provide faithful reproduction of the transmitted data. By adopting this meaning of "Biotelemetry", even wired application like transtelephonic transmission of ECG signals is also considered to be one kind of Biotelemetry.

In view of these broad definitions of "Telemetry" therefore, in this thesis, we would like to restrict the definition of "Telemetry" to radiotelemetry or Wireless Telemetry, where the information is transmitted wirelessly in between the patients (human) and the monitoring stations for display or further processing, [21, p113].

2.1.2 Advantages of Telemetry

Though the broad meanings of "Telemetry", it is advantageous of applying telemetry. Optimal interference reduction and freedom of movement of the patient are retained [50][32]. This enables patient to move around a wider area while still being monitored, the need for lead wires between patient and monitor eliminated [51]. Patient is totally isolated electrically and has ambulatory freedom, which allows continuous, uninterrupted monitoring of physiological parameters [20]. Kuiper [21] added that the application telemetry also leads to the reduction of psychological effects on the patient.

2.1.3 History of Telemetry

Telemetry or Biotelemetry has been widely used since the invention of the transistors in the 1950's, [20, pp185]. Jeutter [18] also dated the history of biotelemetry back to the 1950's Sandler, [23, pp2], on the other hand, suggest an even earlier birthday of biotelemetry by the 1920's which began with the transmission of heart sounds and a marine radio link in 1921 by Winters. This event was also reported by Mackay, [22, pp11]. From then on, physiological parameters from either animals or humans are transmitted via biotelemetry [23][19].

The physiological parameters of interest are usually the Electrocardiogram (ECG), Electroencephalogram (EEG), Electromyogram (EMG), Acidity (pH), temperature and pressure [18]. These signals vary greatly in terms of amplitude and frequency spectrum. For instance, the ECG signals basically range from 0.1 to about 100 Hz while for temperature, from 0 to 1 Hz. Amplitudes can be small in order of μV as in the case of EEG [21, pp112].

A biotelemetry system includes the sensor, transmitter, transmission medium, receiver and a recipient [23, pp4] which can be a displaying device or a recorder or a PC [21, pp113]. This configuration constitutes a one-way communication or a simplex communication. This configuration is defined in [21, pp114] as the feature of medical telemetry. However, other researchers [20, pp187][24] suggested and demonstrated duplex alternatives of telemetry system respectively.

The first part is the Sensor, it is consisted of a transducer and amplifiers. The transducer is to bridge the gap between the physiological variable of interest and electric circuits for picking the signals. Amplifiers are usually required to make minute signal large and meanwhile enhance the signal quality (like increase S/N ratio). Different configurations and features of amplifying circuitry existed due to the differences in the physiological variables being measured.

Sensors for ECG telemetry are simple, it consisted of electrodes, and amplifiers. For ECG measurements, various combinations of electrodes can be applied to give different useful information on patient's heart activity. Each electrode combination is called a "Lead". Basically, each lead consists of a pair of electrodes. For instance, in standard 12-lead wired ECG measurements, Lead I is the electrode-pair of right and left upper limbs.

For a single lead ECG telemetry system, which is the simplest one, at least requires two electrodes. However, as stated Chapter 1, we have investigated the feasibility of single electrode assembly measurements for ECG telemetry and this will be accounted for in later section of this chapter. As for multi-lead ECG telemetry [24], more electrodes are required and more amplifiers may be required for amplifying each lead signal.

Following the amplifiers, signals may undergo further processing such as modulation before being transmitted wirelessly. Modulation serves two main purposes: 1. for multiplexing more than one signal; 2. for enhancing the signal quality when delivered wirelessly. Firstly, for the sake of multiplexing, signals should be modulated somehow before transmission. Two categories of modulation or multiplexing schemes exist. They are the Frequency Division Multiplex (FDM), and the Time Division Multiplex (TDM) [26, pp279][18, pp17-24]. For FDM, signals are separated by frequencies of modulating oscillators. They are called the Subcarrier Oscillators (SCO's). Examples can be found in [7][27] On the other hand, signals are separated in time intervals. It involves sampling signals at designated time intervals [19, pp18] and Pulse Modulation Methods are used in coding the sampled signals before transmission. Jeutter [19, pp18-19] listed 5 of them: PAM (Pulse Amplitude Modulation), PDM (Pulse Duration Modulation), PPM (Pulse Position Modulation), PFM (Pulse Frequency Modulation), and PCM (Pulse Code Modulation). Details of these modulation methods can be found in [28]. Examples with TDM or Pulse Modulation can be found in [25][29][30]. PCM, being one of the key elements of digital communication is usually used for telemetry system for its higher performance among the other types of pulse modulation [19, pp21][28, pp444]. Examples with PCM can be found in [25][29][31][32]. It can also be viewed in the commercial product information in [33][34].

One of the methods of producing PCM of analog signals is the Sigma-Delta Modulation, which is one of the main investigations of this research as stated in Chapter 1. More details on PCM will be given in the following section on Sigma-Delta Modulation.

For carrier modulation methods, usually FM (Frequency Modulation) and AM (Amplitude Modulation) will be employed. On the other hand, with PCM, digital modulation schemes can be incorporated. Common techniques like ASK (Amplitude Shift Keying), FSK (Frequency Shift Keying), and PSK (Phase Shift Keying).

On the receiver side, signals are demodulated and recovered. Display devices or recording devices are used as the final output. With availability of computers (PC's or workstations), display and recording functions can be provided at the same time. With network capabilities of computers nowadays, signals can be transmitted to very distant places. An example of a world-wide network ECG monitoring system is illustrated in [35]. In this system, patients can acquire their ECG's at home through PC-based acquisition units and data can be sent through the worldwide web for display and record. Fueled by the advance and accessible network technologies, the networked recipients of telemetry system are getting more and more common.

2.1.4 Special Considerations on Telemetry System

Special considerations should be paid on designing a biotelemetry system. In [23, p5], 11 categories or dimensions within a biotelemetry are listed and some of them are given below:

1. Size

2. Range

3. Operating Frequency

Firstly, the size of transmitters of telemetry devices can be varied a lot, they can range from pocket size to those which can be swallowed [22, pp11] or implanted inside subjects' bodies. Mackay [22] gave an example of miniature telemetry system which can be used on cockroaches. Other examples of small telemetry devices for implantation can be viewed in [36]. The sizes of the telemetry devices are always striking and no one would anticipate a big telemetry device that violates the main element of being telemetry: reducing restrains on subjects, as stated in section 2.11. Jeutter [18, pp11] said that miniature is one the cornerstones of modern biotelemetry design and construction which shows us that how important to design miniature telemetry devices rather than some bulky devices.

Considering the range of operation of telemetry device, Scanlon [20, pp186] divided the ranges of telemetry system into 3 categories as shown in Table 2.1.

Range	Transmission Aspects	Application
Less than 30cm	Weak Inductive Coupling	To interrogate instrumentation circuits worn by bed-bound or ambulatory patients.
Less than 3m	Transmitted power in μW order; Simple RF circuits; Direct Modulation	Situations requiring unattended monitoring by bedside Controllers
More than 30m	1-5mW transmission power may be need to secure signal quality; more complex RF circuits	Useful in hospital wards and in the home.

Table 2.1 Categories of Telemetry Devices according to their ranges

Not only the ranges fall into different categories, the operating frequencies also can be divided into several usual bands. Scanlon [20, pp186-187] listed 4 main bands: LF (300-500kHz), VHF (174-216 MHz), UHF (418-470 MHz, 902-928 MHz, 2.4-2.48 GHz). Kuiper [21] also listed out some bands for telemetry at that time. Examples in the UHF band are like [7][37][38]. Example operating at even higher frequencies at 2.4GHz is by Grumley *et al.* [24]. Examples of lower operation frequencies in the VHF band are [29][30][38][39][40]. Size and Operating Frequency are interconnected as higher operating frequency can employ smaller antenna and thus reducing the size of the telemetry device as increasing the operating frequencies making compact radiators become more efficient [20, pp187].

2.2 Sigma-Delta Converter

In previous section, we have taken in account various aspects of Telemetry system. PCM, being one of the pulse modulation methods used in telemetry, is receiving more concern in nowadays telemetry. In PCM, signal samples are represented by a set of binary numbers. Each sample will be assigned to one of 2^R amplitude levels, where R is the number of binary digits used to represent each sample. This assigning process is called quantization. The whole process comprising Sampling and Quantization can be called "Digitization". There are various methods in achieving digitization and corresponding circuitry is called the Analogue-to-Digital (A/D) Converter. These methods will be discussed in the following sections.

2.2.1 Conventional Digitizing Circuitry

Conventional digitizing circuitry is usually Nyquist-rate converters. In sampling an bandlimited analogue signal, the frequency of taking samples, by Nyquist Sampling Theorem, should be at least 2 times the bandwidth. If an A/D converter sampled signals with just 2 times the signal bandwidth (Nyquist Rate), it is named as Nyquist-rate converters. In contrast, there are converters that operated with sampling rate in much excess of the Nyquist rate and they are called the Oversampling Converters.

Quantization process actually adds noise to the original signal since each signal sample is represented by a limited set of binary numbers. This quantization noise power is known that decreases by 6dB/bit [41, pp126] assuming the noise is white and with a uniform probability density function (pdf). This noise power also relate to the sampling frequency, it is found that doubling of the sampling frequency decreases the total *in-band noise* by 3dB, increasing resolution by only 0.5 bit [42, pp5].

In following 2.211 to 2.213 sections, some common Nyquist converter techniques will be presented. The Sigma-Delta Modulation, being one member of Oversampling techniques, will be presented in section 2.22.

2.2.2 Single, Dual-Slope A/D Converters

Single-Slope A/D Converter

The single-slope converter works with the principle of finding how long for a ramp to equal an input signal at a comparator [43]. The situation can be depicted by the following figure[1]:

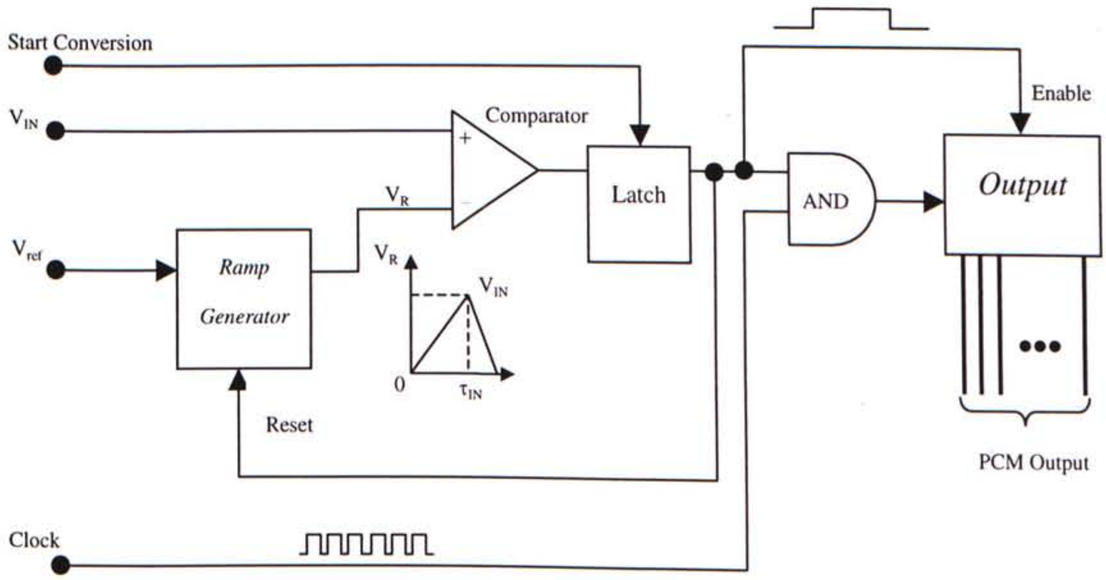


Figure 2.1 Block Diagram of a Single-Slope A/D Converter

A conversion is started by asserting the Start Conversion Signal, the latch will be enabled and set to high until the comparator outputs a "HIGH" resetting it. The comparator output normally is "LOW" until the ramp signal V_R gets just higher than the input signal V_{IN}. The time interval τ_{IN} will be counter by the Output Counter with reference to the Clock applied. If this converter is to have N-bit resolution, it can take

[1] Figure modified from [44, pp649, Figure 8.3-6] and [45, pp625, Figure 9.54].

maximum $2^N T$ period of time for the conversion where T is the clock period. The advantages of Single-Slope converter is its simplicity but it is subject to error in the ramp generator and it is unipolar [44]. In [45], it is stated that it is not suitable for high accuracy application due to the severe requirements on the stability and accuracy of the capacitor (inside the ramp generator) and comparator required. Another shortcoming is that it requires, in worst case, long conversion time of $2^N T$ [44]. We can see that this maximum conversion time rises exponentially with the number of bits N provided by the converter. Thus, it also limits the signal bandwidth to be lower [43, pp103][44, pp651]. Since the conversion time $2^N T$ should be at least less than 2 times the reciprocal of the signal bandwidth BW. That is, it can be written as

$$2^N T \geq \frac{1}{2BW} \tag{2.2.1}$$

With T equal to 1μs, Table 2.2 illustrates the relationship of N and BW_{MAX} (Maximum Bandwidth Supported).

N/ bits	BW_{MAX}/ Hz
1	250000
2	125000
3	62500
4	31250
5	15625
6	7812.5
7	3906.3
8	1953.1
9	976.6
10	488.3
11	244.1

Table 2.2 Maximum Signal Bandwidth (BW_{MAX}) versus Number of bits (N) With Clock Period (T) equal to 1μs

From (2.2.1), we can observe that the BW_{MAX} decreases with the increase in number of bits, the resolution, provided by the converter. Therefore, there exists trade-off between resolution N and the maximum Signal Bandwidth allowed BW_{MAX} provided that the clock period T kept the same.

Dual-Slope Converter

The Dual-Slope converter elimination of the dependence of the conversion process on the linearity and accuracy of the ramp generator. A dual-slope A/D converter integrates the input signal V_{IN} for a fixed period of time as determined by a clock-stepped counter and the resulting integral is returned to zero by integrating a reference signal of polarity opposite that of V_{IN} [46]. V_{IN} is therefore restricted to be positive [44, pp650]. In [44], the analysis on the converter also takes into account the threshold of the comparator. The voltage of the integrator in the conversion process is depicted in Figure 2.2. In phase I of conversion, where V_{IN} is integrated for a fixed period of time, the integrator voltage $V_{int}(t)$ given by [44].

$$V_{\text{int}}(t) = KV_{IN}t + V_{th} \qquad (t_0 < t \le N_{ref}T) \qquad (2.2.2)$$

$$V_{\text{int}}(t)\Big|_{t=N_{ref}T} = KN_{ref}TV_{IN} + V_{th} \qquad (2.2.3)$$

and the time $N_{out}T$ taken by the opposite reference signal to discharge the integrator voltage back to V_{th} is given by [44].

$$N_{out} = N_{ref}\left(\frac{V_{IN}}{V_{ref}}\right) \qquad (2.2.4)$$

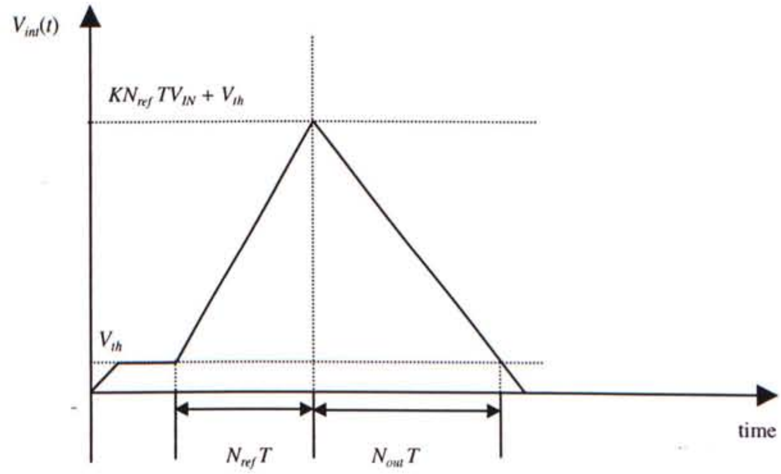


Figure 2.2 Integrator Voltage $V_{int}(t)$ versus Time of a Dual-Slope Converter

From (2.2.4), it can be observed the merit of the Dual-Slope Converter of which N_{out} is not a function of the threshold of the comparator, slope of integrator, or the clock rate [44] rendering it an accurate conversion method. In [45], it is reported that the dual-slope conversion can achieve very good accuracy without putting extreme requirements on component stability. The capacitor inside the integrator need not to be particularly stable and drifts or scale errors in the comparator can be cancelled out by beginning and ending each conversion cycle at the same voltage or same slope. In addition, it is mentioned that there is high tolerance in clock frequency stability problem. Though it is a very accurate method of conversion, it requires relatively long conversion time, $2(2^N)\,T$, in the worse case [44].

Multiple-Slope converters, also exist which employ more than two ramp measurements for each input signal [43]. One example is the quad-slope integration method introduced by *Analog Devices, Inc.* [43].

2.2.3 Successive Approximation (SAR)

An *N*-bit successive approximation converter converts an analogue input in *N* clock cycles [44]. Therefore, the conversion time is equal to $N\ T$, instead of $2^N\ T$ as in the case of Single-Slope Converters. Figure 2.3[2] illustrates the building blocks of a successive approximation converter.

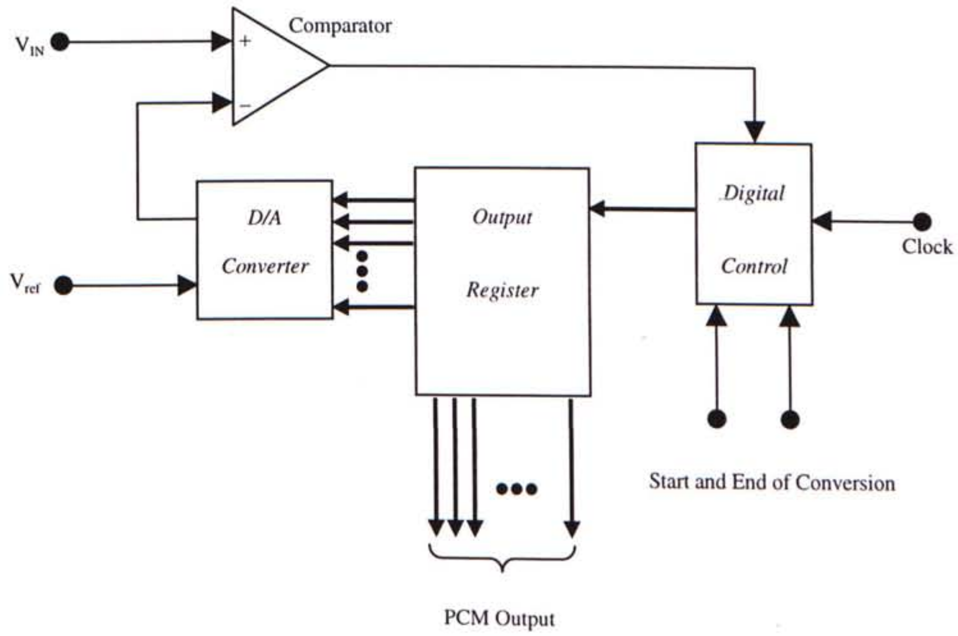


Figure 2.3 Building Blocks of a Successive Approximation Converter

The converter operates with successively testing each bit of resolution from the Most Significant Bit (MSB) to the Least Significant Bit (LSB). The operation is illustrated in [44]. It operates with all bits inside the register being set to "LOW" initially. Starting with the MSB bit, each bit in turn will be set provisionally to "HIGH". This tentative bit pattern will be converted to its analogue voltage via the D/A converter inside. If the D/A output is lower than the input signal V_{IN}, that bit will be set to "LOW", otherwise, its value kept. After *N* such steps, the whole length of PCM output (*N* bits long) will

[2] Figure 2.3 is modified from [44, pp652, figure 8.3-9] with slight modification.

have been tested against V_{IN} and this final register output will be A/D converted value for V_{IN}. The Successive Approximation Converters are relatively accurate and fast, with typical conversion time ranging from 1μs to 50μs, at 8 to 12 bits of resolution [45]. As N increases, the requirement of the comparator to distinguish between almost identical signals from the D/A converter output and V_{IN} must increase [44].

2.2.4 Flash Converters

Flash A/D converter or Parallel A/D converter is the fastest method of A/D conversion. For an N-bit converter, it operates with 2^N-1 comparators each fed with V_{IN} and with a specific fraction of the reference voltage. For an N-bit Flash Converter, the ith comparator output value c_I will be given, for instance, by

$$c_i = \begin{cases} \text{logic}\,1 & \text{if } V_{IN} > i(\frac{V_{ref}}{2^N}) \\ \text{logic}\,0 & \text{otherwise} \end{cases} \qquad (i \in [1, 2^N - 1]) \qquad (2.2.5)$$

These comparator outputs c_i's are then inputted to an encoder with produce the PCM output. The advantage of Flash Converters is certainly their high conversion speed (10^6 to 500×10^6 conversions per second). However, they require vast number of comparators (2^N-1) with consume chip area much.

2.2.5 Sigma-Delta Converter

The Sigma-Delta Converters is one of the examples of the oversampling converters. They operate with sampling frequency much higher than the Nyquist rate. This is a distinct difference from the previous converters that usually operated around the Nyquist rate. The basic structure of Sigma-Delta Converter is given in Figure 2.4.

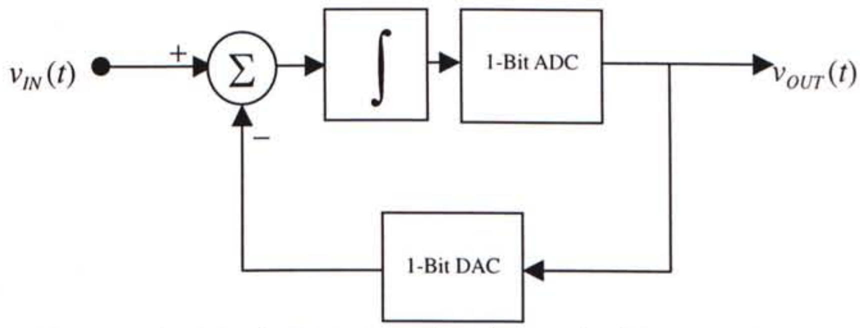


Figure 2.4 A Basic Structure of a first-order Sigma-Delta Converter

Usually a simplified linear model [47, pp42, Fig. 10] is used for analyzing the converter and it is shown in Figure 2.5.

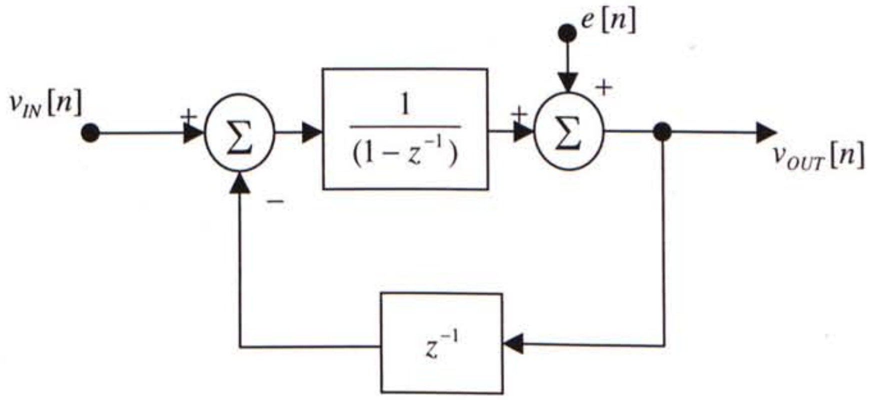


Figure 2.5 Simplified Linear Model of Sigma-Delta Converter

The 1-bit ADC (Analogue-to-Digital Converter) in Figure 2.4 has been modeled as a linear adder with the integrator output and quantization noise $e[n]$ as inputs in Figure 2.5. The relationship among $v_{IN}[n]$, $v_{OUT}[n]$, and $e[n]$ in the Z-domain is given by

$$V_{OUT}(z) = V_{IN}(z) + (1 - z^{-1})E(z) \qquad (2.2.6)$$

where $V_{IN}(z), V_{OUT}(z), E(z)$ are the Z - transform of $v_{IN}[n], v_{OUT}[n]$, and $e[n]$ respectively

With the assumption that $e[n]$ is white with a uniform pdf within the interval $[-\Delta/2, +\Delta/2]$ and the theoretical Signal-to-Noise Ratio (SNR) is calculated and given in [48] as

$$SNR = \frac{3\pi}{2} A_x^2 (3)(\frac{R}{\pi})^3 \text{ with input signal } S = \frac{1}{2} A_x^2 \left(\frac{\Delta}{2}\right)^2 \qquad (2.2.7)$$

where $R = f_S/(2 \cdot f_O)$, f_O is the bandwidth of S. From (2.2.7), the SNR increase in R^3. Therefore, the SNR will be improved by approximately 9dB when the sampling frequency is increased two times. Compared to the case of an N-Bit PCM Analogue-to Digital Converter, the SNR will be improved by 6dB when number of bits provided is increased by 1. Or in other words, for a first-order Sigma-Delta converter, for every double of the sampling frequency, there will be an effective increase of bit resolution of 1.5 bits.

2.3 Conclusion

In this chapter, the topics on telemetry and analogue-to-digital converters are reviewed. The main theme of this research, the *Wireless Electrode*, is based on telemetry and the application of Sigma-Delta Converter. The details of the Wireless Electrode will be presented in the following chapters.

Chapter 3 Wireless Electrode

3.1 "Single Electrode" Measurement

"Single Electrode", it is meant for one single electrode assembly for picking ECG signal. It can be a concentric electrode or any other measurement that involve two contact points on the body surface. However, they are packaged as a single entity that looks as if a single electrode. We may refer them as a **VSE (Virtual Single Electrode)**. ECG telemetry with *VSE* is investigated and this wireless application as a whole is called the **WE (Wireless Electrode)**. In the following sections, the above topics will be discussed in more detail. Section 3.2 will be on the VSE and 3.3 on the WE.

3.2 VSE (Virtual Single Electrode)

Concentric Electrode

Lu [14] reported that Fattorusso is the first one using the concentric ring electrodes for recording bioelectric activity in 1949. It is consisted of a ring conductor and a center dot with the aim of studying myocardial infarcts and arrhythmias related to bundle branch blocks. This concentric ring sensor consisting of a ring conductor and a center dot constitutes a bipolar sensor as depicted by Figure 3.1. Such bipolar measurement provides more localized information [14]. This configuration is also used by He [15] and Manning [16]. Lu himself suggested the *Tripolar Concentric Ring Sensor*, which consists of two concentric rings and a dot at the center [14] as illustrated in Figure 3.2.

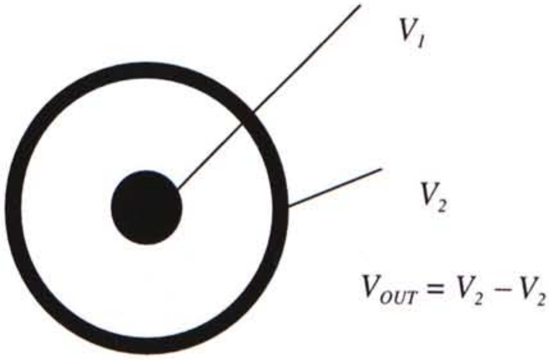


Figure 3.1 A Bipolar Sensor

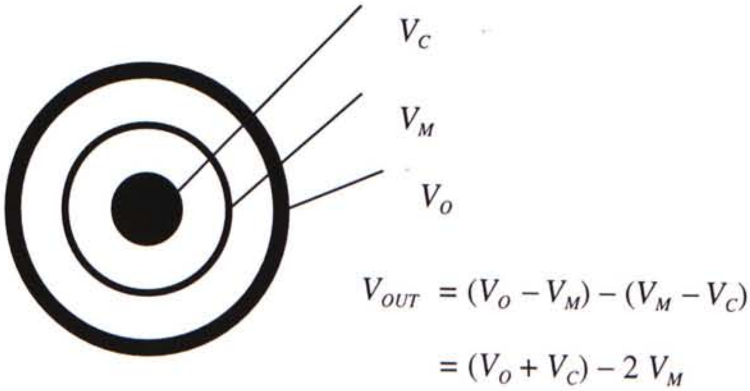


Figure 3.2 A Tripolar Sensor

By using these concentric electrode configurations, VSE's can be constructed.

In [15] and [56], the concentric electrode is fabricated with conductive AgCl. In our laboratory, previous researchers have made some concentric electrodes with some kind of conductive rubber or fabric (Figure 3.3). We have tried using them to pick up ECG signal (Figure 3.4). This excerpt of ECG signal was picked up by placing the concentric electrode on the left lower ribs of a subject. The noise with higher frequency is mainly 50 Hz interference. This may be attributed to the finite and relatively big resistance of the conductive rubber of about 50 to 100 ohms. Electrode impedance imbalance can be easily generated that enhance the 50 Hz interference. In addition, the conductive rubber seemed to generate strong DC voltages when placed with an electrolyte. We have placed two stripes of the conductive rubber over a sponge soaked with tape water simulating the body fluid. Relatively strong DC offsets of several tens of milli-volts to a hundred milli-volts can be measured from a digital voltmeter. Therefore, ECG preamplifiers can be easily saturated.

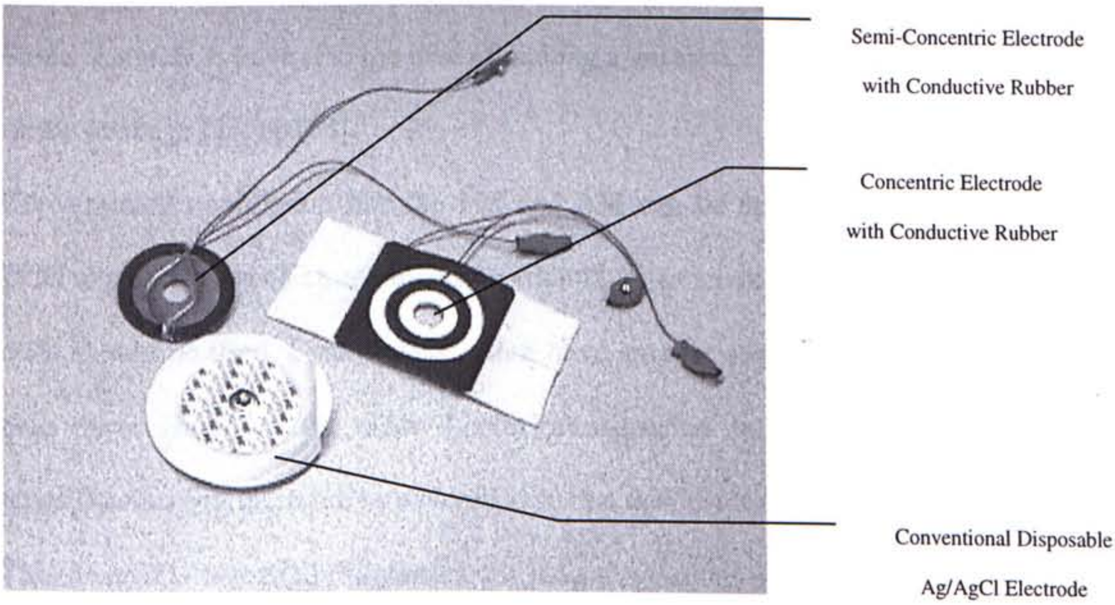


Figure 3.3 Concentric Electrodes with Conductive Rubber and Conventional Disposable Ag/AgCl Electrodes

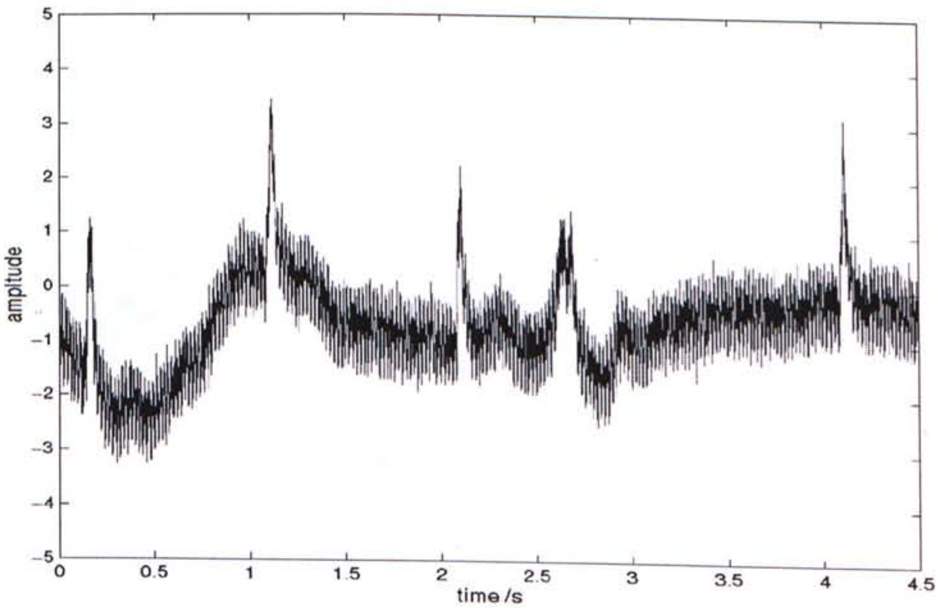


Figure 3.4 ECG Signal Picked Up by Concentric Electrode

3.3 WE (Wireless Electrode)

The application of radio telemetry to the VSE is called the WE (Wireless Electrode). Some researchers have also the idea of making a wireless ECG monitoring device in a single package [57, pp198].

Conventional modulation like the FM and AM can be applied for transmitting the ECG signal. As the electrode assembly should be as small as possible, small battery cells should be used. Smaller cells often have smaller capacity. Coin-sized Lithium cells have about a 100 mAh. Lower transmission power and efficient power amplification will therefore be welcomed so that the device can be used for longer time. This benefit is essentially important for long-term monitoring that frequency battery replacement is not desirable. A prototype with FM is shown in Figure 3.5. There was a Single-Transistor Crystal Oscillator and RF power was transmitted from the loop antenna. It can be built even smaller if surface mount components were used. The transmission power can be adjusted by the biasing circuit of the oscillator and the efficiency of the antenna system.

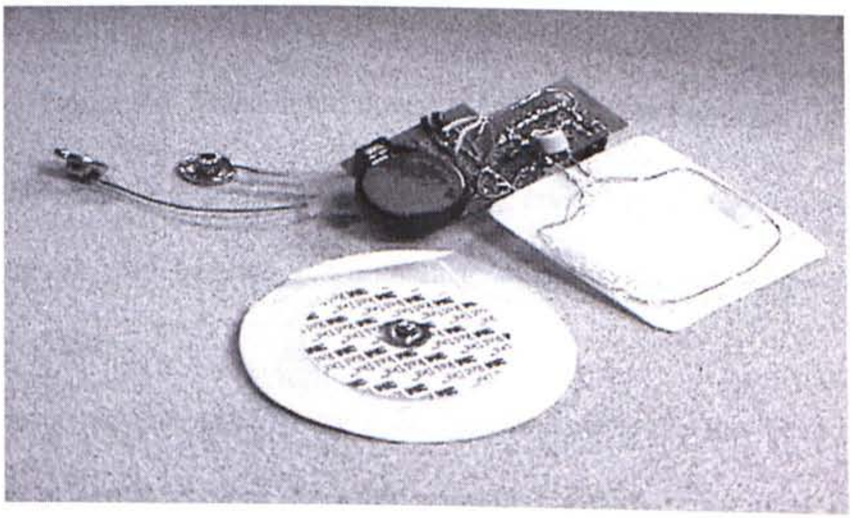


Figure 3.5 A Prototype of Wireless Electrode

The transmitted power at about 61 MHz can easily fallen down to about –100 dBm when the current drain was about several milli-amperes. A typical transmitted power measured by a spectrum analyzer is shown in Figure 3.6. By using a crystal oscillator, the carrier frequency can be very stable and accurate. LC oscillator, on the contrary, drifts greatly with the changes in the external environment such as placing the oscillator to the vicinity of the human torso.

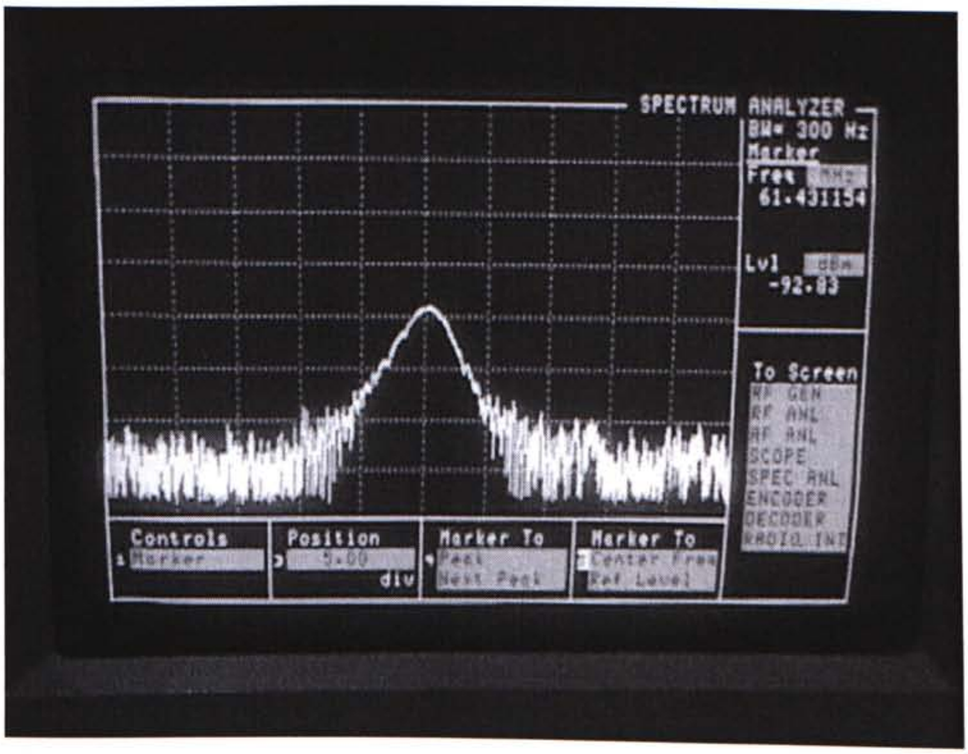


Figure 3.6 Transmitted Power Spectrum by the Prototype

However, the frequency deviation allowed by a crystal oscillator is quite limited. Multiplier stages may be used for both increasing the carrier frequency and the frequency deviation.

With this prototype, analogue FM was used. As discussed in previous chapters, digital transmission of signal is more favorable nowadays. Another prototype with digital transmission was applied. Digitization is performed by a first-order Sigma-Delta converter that will be further discussed in the next chapter. It is operated with ± 3V draining less than 10mA from supplies. The maximum transmission power was measured to be about –60dBm that is safe with operation with other medical equipment and also to the human body. Two photographs of the received signal of this prototype with concentric electrode are shown in Figure 3.7. The two signals were picked up at slightly different location on a subject mid-ribs. Ectopics can be noted in both excerpts of signal.

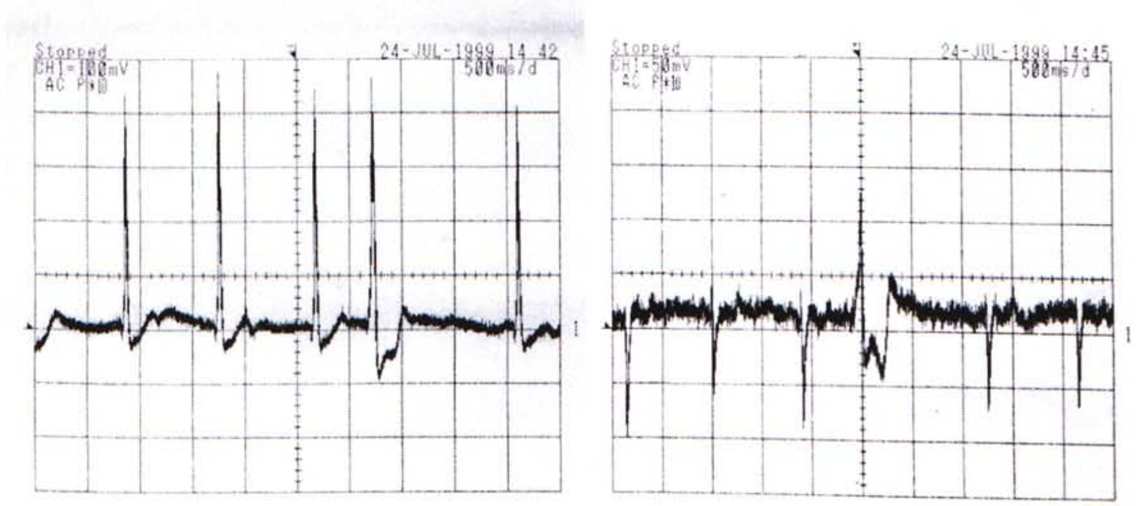


Figure 3.7 ECG Signals Picked Up from a Wireless Electrode Prototype with Sigma-Delta Converter and Concentric Electrode

From the received signals shown above, we can see clear signals obtained. Since the main purpose obtaining the signals is for monitoring purpose, we only concerned with whether signals are existed or not rather than the waveforms of the signals. Important parameters like the heart rate, heart rate variability can be obtained. From these parameters, the patient heart conditions can be detected, whether the heart is beating too fast, or too low, or beating in an uncontrolled manner. For instance, from the above received signals, we can notice that the subject has occasional ectopic and by counting the frequency of the occurrence, the subject heart condition can be evaluated and monitored. Another sets of experiment were done where the original signal and reconstructed signal were shown together. The original signal was the input signal to the Sigma-Delta Converter. Two reconstructed signals were presented. One of them was the reconstructed signal without going through the wireless link; the other one was the one with the wireless link. In Figure 3.8, the original signals were obtained from a signal generator with Sinewave output. The signal frequencies were 17, 6, 2, and 0.14 Hz as shown in Figure 3.8a, 3.8b, 3.8c and 3.8d respectively. The uppermost traces, labeled β, were the reconstructed signals without wireless link. The middle were the original signals, labeled α. The lowest ones were the reconstructed signals with the wireless link, labeled γ.

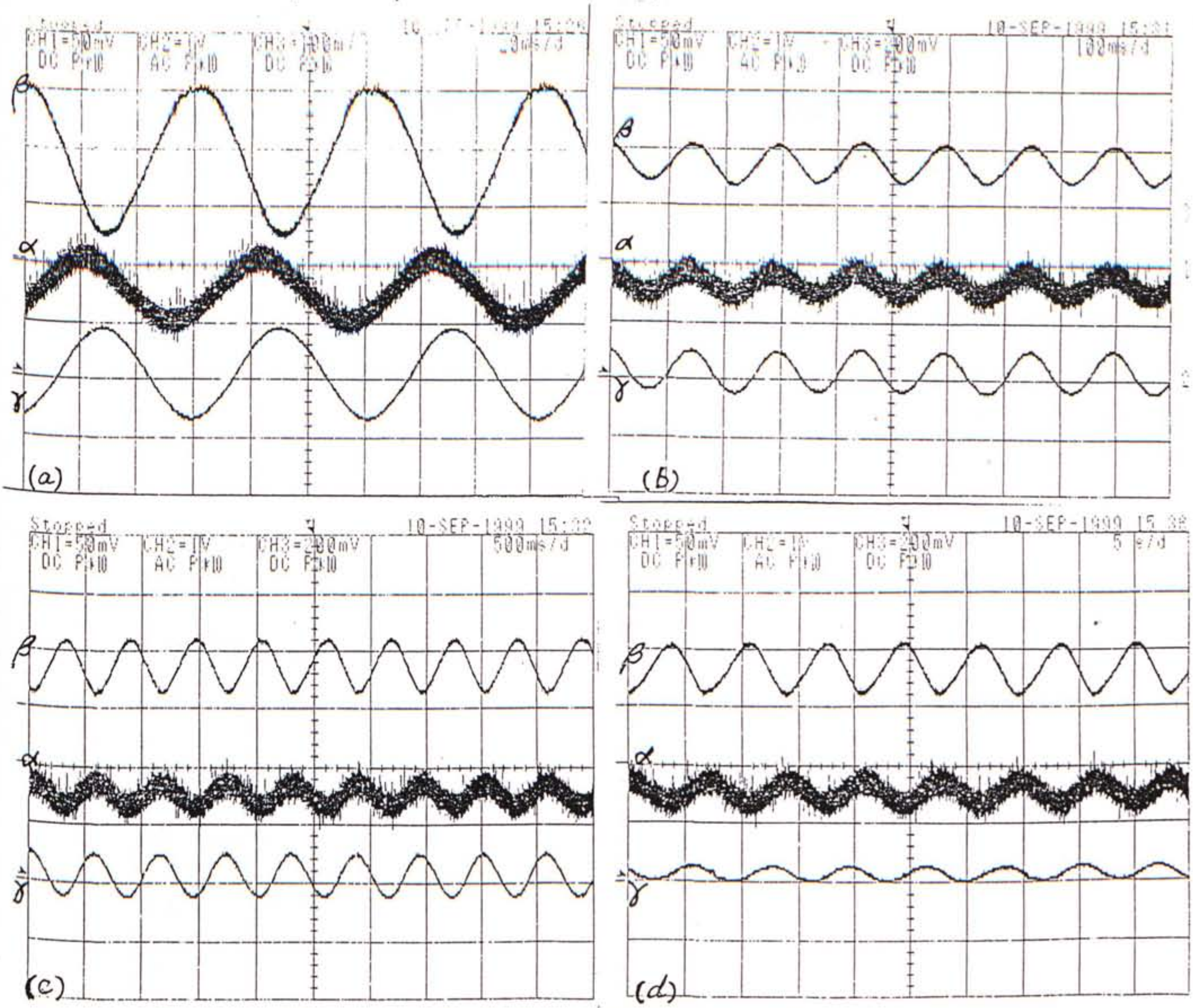


Figure 3.8 Reconstructed and Original Signals for the Sigma-Delta Converter with Sine Input (a-d)

For Figure 3.9, the input signal was from an Arbitrary Waveform Generator (*YOKOGAWA* AG 1200). It was an ECG waveform and used as a test for the system. Like Figure 3.8, the uppermost one was the reconstructed signal without wireless link (β); middle the original (α); lowest one the reconstructed signal with wireless link (γ).

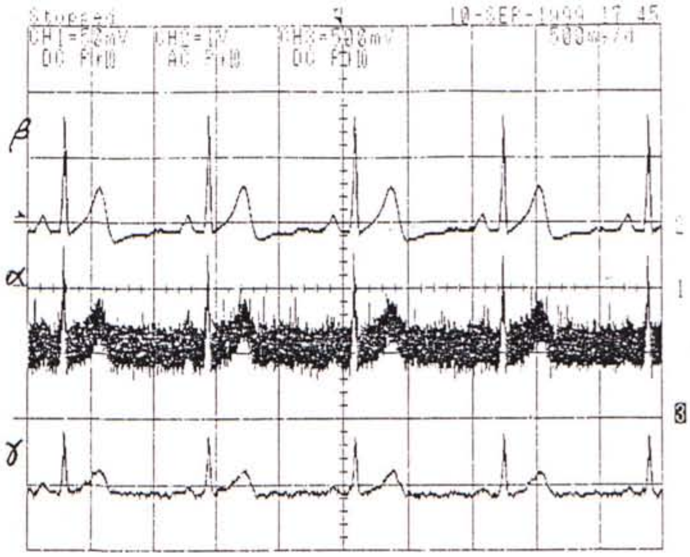
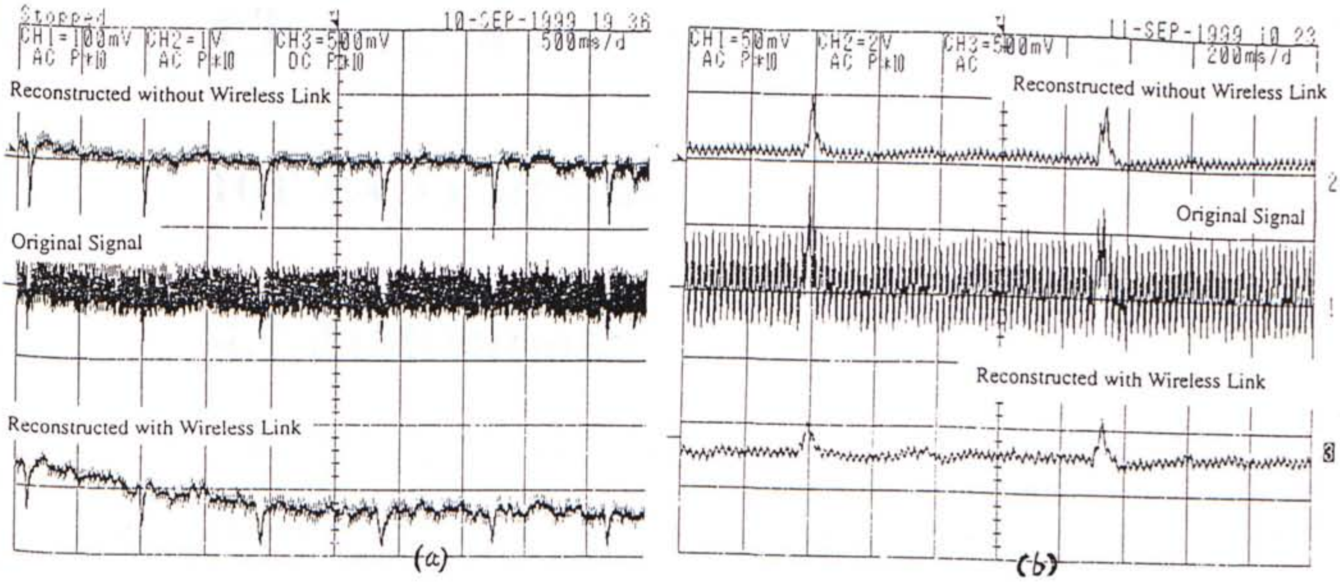


Figure 3.9 Reconstructed (traces β and γ) and Original Signals (trace α) for the Sigma-Delta Converter with Generated ECG Input

Lastly, the signal picked up from a real subject with a single electrode assembly is presented in Figure 3.10a and 3.10b. For 3.10a, The single electrode assembly was built with one of the concentric electrode shown in Figure 3.3. It was composed of two separate conductors half-rings. For 3.10b, another single electrode assembly with two full rings was used. From these figures, it can be observed that the reconstructed signals resemble the original one.



With Two Half Rings Transducer With Two Full Rings Transducer

Figure 3.10 Reconstructed and Original Signals for the Sigma-Delta Converter with Real Subject's ECG Input (with Two Half Rings Transducer (a); with Two Full Rings Transducer (b))

3.4 Discussion

The motivation of Wireless Electrode (WE) with a "Single Electrode" is reducing the complexity of setup in ECG monitoring. Easy and prompt monitoring capability can be provided. More local information can be provided by the concentric electrode assembly [14] and radio telemetry renders patients with ambulatory freedom. With Sigma-Delta Converter, which has simple analogue circuit complexity, digital signal transmission can be achieved. More widespread application of the WE can be anticipated due to its simplicity and robustness.

Chapter 4 Sigma-Delta Converter for ECG signals

4.1 Motivations

Among various Analogue-to-Digital conversion methods, Sigma-Delta converter is superior in terms of circuit simplicity and component tolerance in expense of higher sampling frequency and more complex DSP (Digital Signal Processing). Sigma-Delta converter is consisted of very simple analogue circuitry. An analogue low-pass filter can recover the analogue signal. Complex DSP unit is applied for better performance. The DSP unit is usually fabricated with the simple analogue circuitry, which increase the circuit complexity. It would be beneficial to have simple circuitry in patient-worn transmitter. In this research, we would like to investigate the separation of the DSP unit and the analogue part of the *first-order* Sigma-Delta converter (Figure 2.4). The simple analogue part is included in the patient-worn transmitter while a monitoring computer provides the DSP function. Noise will be induced in the wireless link and errors in the bit pattern are anticipated. AWGN (Additive White Gaussian Noise) is used for simulating the situation and simulations are performed.

This following text will be divided into two main sections. In section 4.2, baseband application of the Sigma-Delta converter will be presented. Simulated data will be presented with comparison to ideal N-bit converters. Experimental data for a self-made Sigma-Delta converter will also be included. In section 4.3, wireless application will be discussed. Similar to section 4.2, simulation and experimental results will be presented.

4.2 Baseband Application

4.2.1 Simulation Results

4.2.1.1 Simulation Results with a 17Hz Sinewave

A zero mean, pure sine tone of 17Hz of about 48000 points is used for simulation. It is chosen to be 17Hz since most of the spectral energy of a QRS complex of an ECG signal is located around 17Hz [53]. The simulation programme for Sigma-Delta converter is modified from [52]. The sampling frequencies for the converter is chosen to be *8000, 4000, 2000, 1000, 500* and *250*, assuming that the maximum frequency of interest is 100 Hz. The input signal of different sampling period is obtained by decimation. Different amplitudes of the sine tone are tried also. They are *0.1, 0.5, 0.8* and *1*. Two figures of merit are used for evaluation, namely the MSE(Mean Square Error) and the SNR(Signal-to-Noise Ratio). They are defined as:

$$MSE = \frac{\sum_{n=1}^{M}(x[n]-\tilde{x}[n])^2}{M} \qquad (4.2.1)$$

where $x[n]$, $\tilde{x}[n]$ are the original and recovered signals respectively.

$$SNR = \frac{\left(\frac{A^2}{2}\right)}{MSE} \qquad (4.2.2)$$

where A is the amplitude of input signal.

And the same signal is applied to two ideal *N*-bit ADC (Analogue-to-Digital Converters) for simulation. They are of seven and eight bits resolution respectively. Same figures of merit are applied to them as well.

For obtaining $\tilde{x}[n]$ in the case of Sigma-Delta converter, a fifth-order digital

Butterworth low-pass filter is used. The binary bit pattern is applied as input to the filter (Figure 4.1) and the output will be $\tilde{x}[n]$. However, as there is delay (Figure 4.2) between the original and recovered signals. Certain amount of shifts is incorporated for compensation.

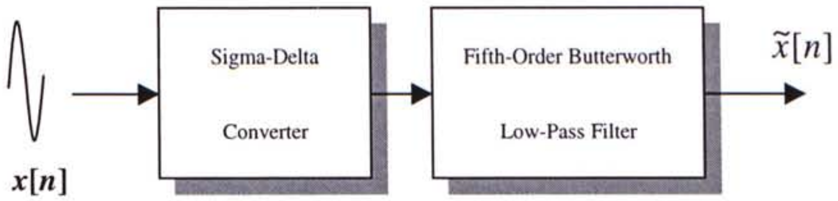


Figure 4.1 Simulation Block Diagram for Sigma-Delta Converter

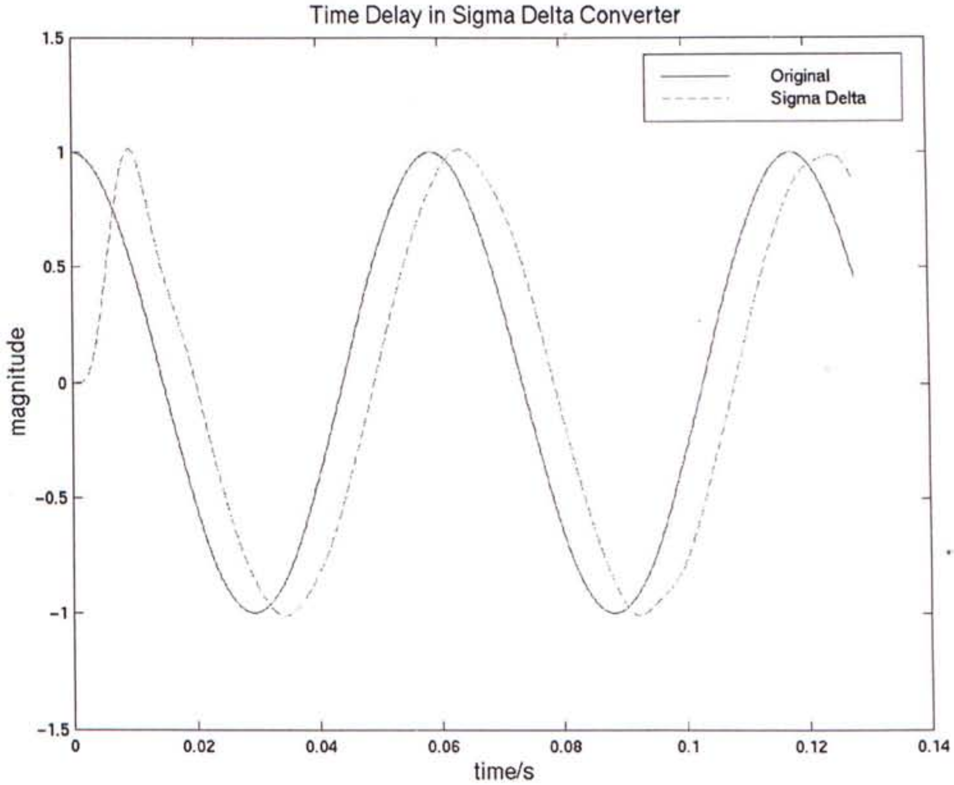


Figure 4.2 Delay in Sigma Delta Converter Recovered Signal

The results are given in Figure 4.3 to 4.8. Figures 4.3 to 4.5 are on the MSE (Mean Square Error) measure for Sigma-Delta Converter, 7 and 8-Bit Converters. Figures 4.6

to 4.8 are on the SNR (Signal-to-Noise Ratio). Subscripts in legends (proceeds with '_') denotes the amplitudes of the sine tone. For instance, "SD_0.1" stands for the case of Sigma-Delta Converter with input sine tone of amplitude 0.1.

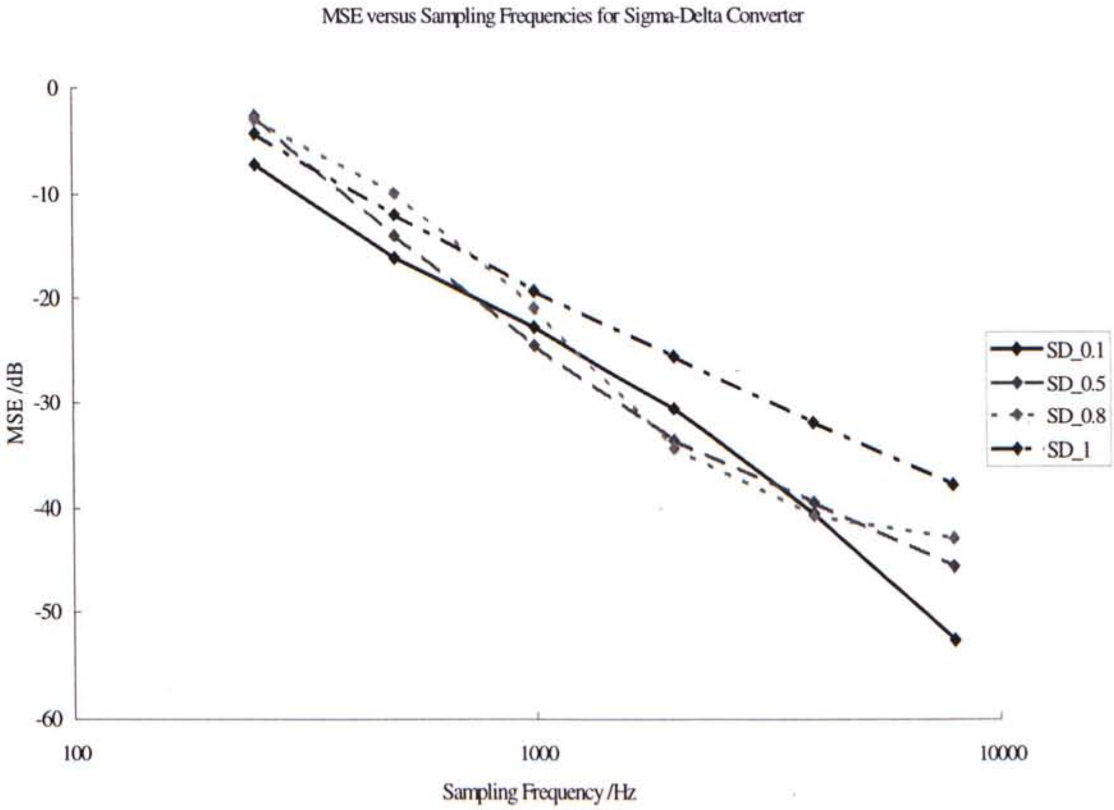


Figure 4.3 MSE for the First-Order Sigma-Delta Converter

(SD stands for Sigma-Delta)

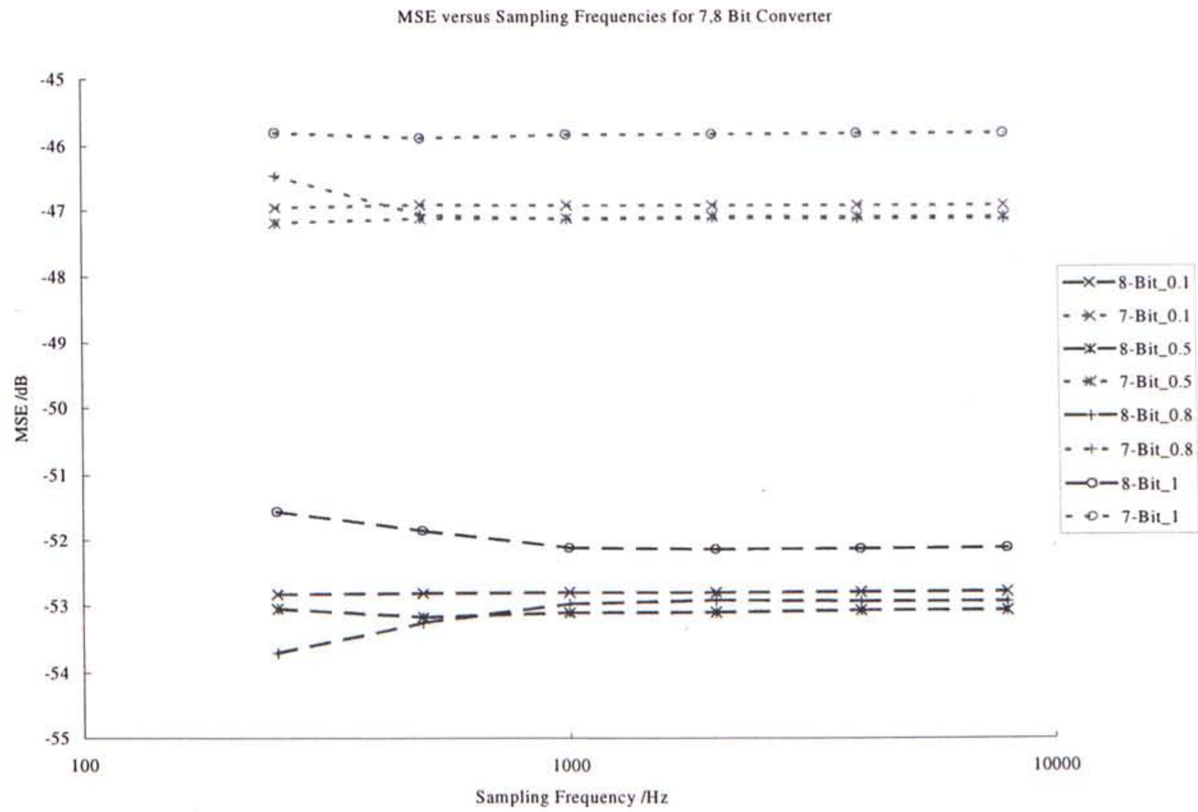


Figure 4.4 MSE for 7, 8-Bit Ideal Converter

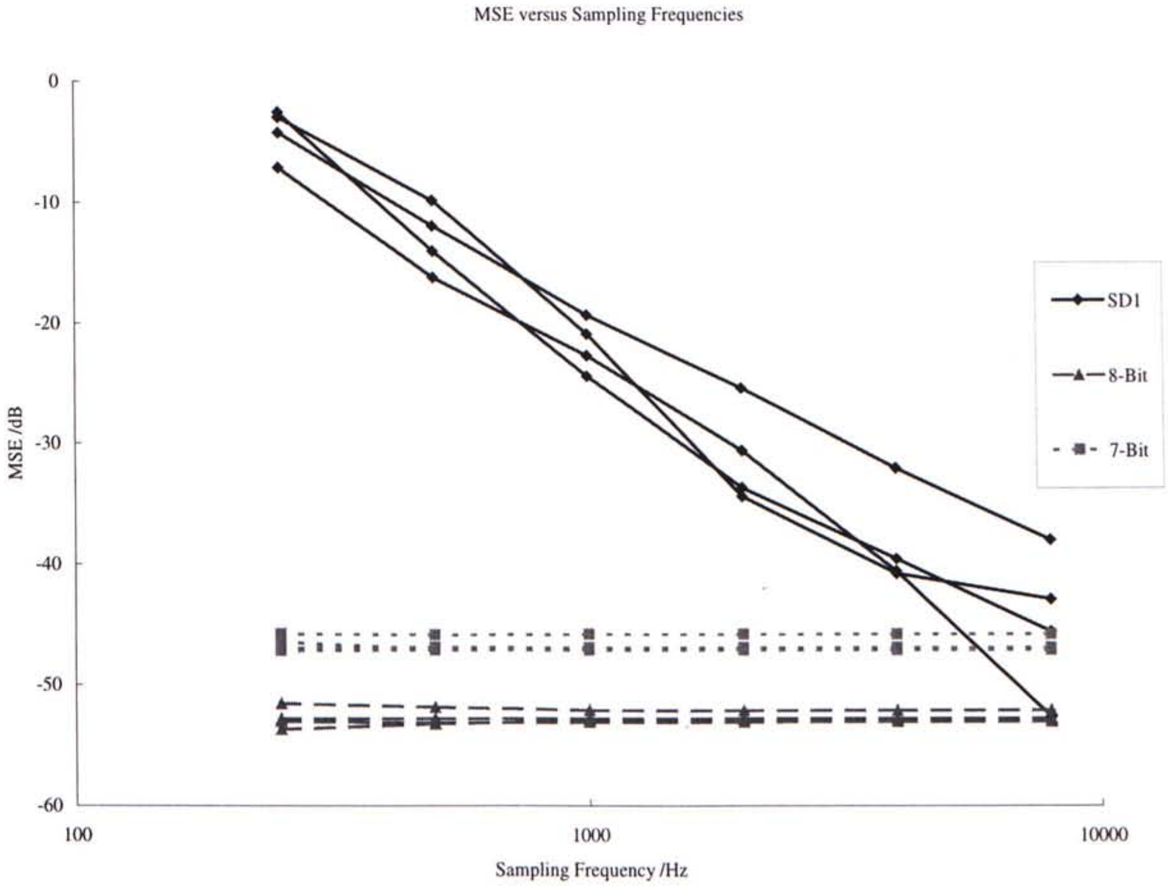


Figure 4.5 MSE versus Sampling Frequency for First-Order Sigma-Delta Converter and 7,8-Bit Converters

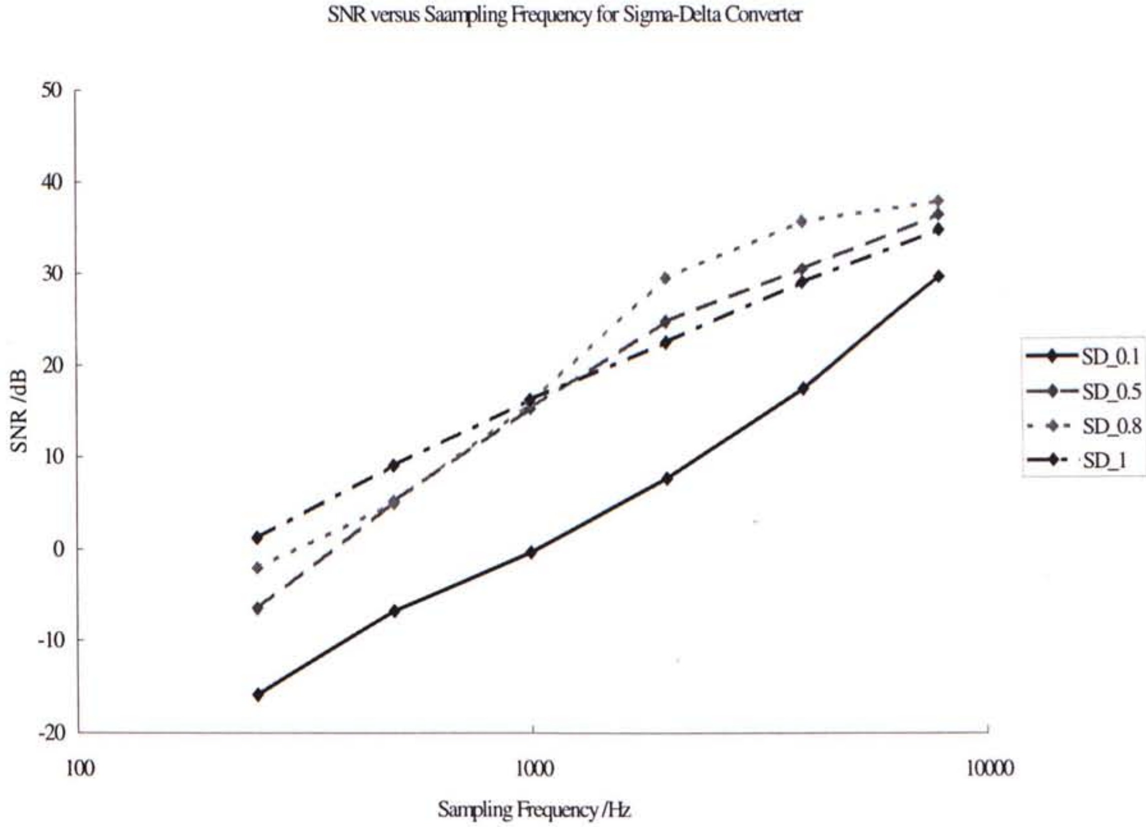


Figure 4.6 SNR versus Sampling Frequency for First-Order Sigma-Delta Converter

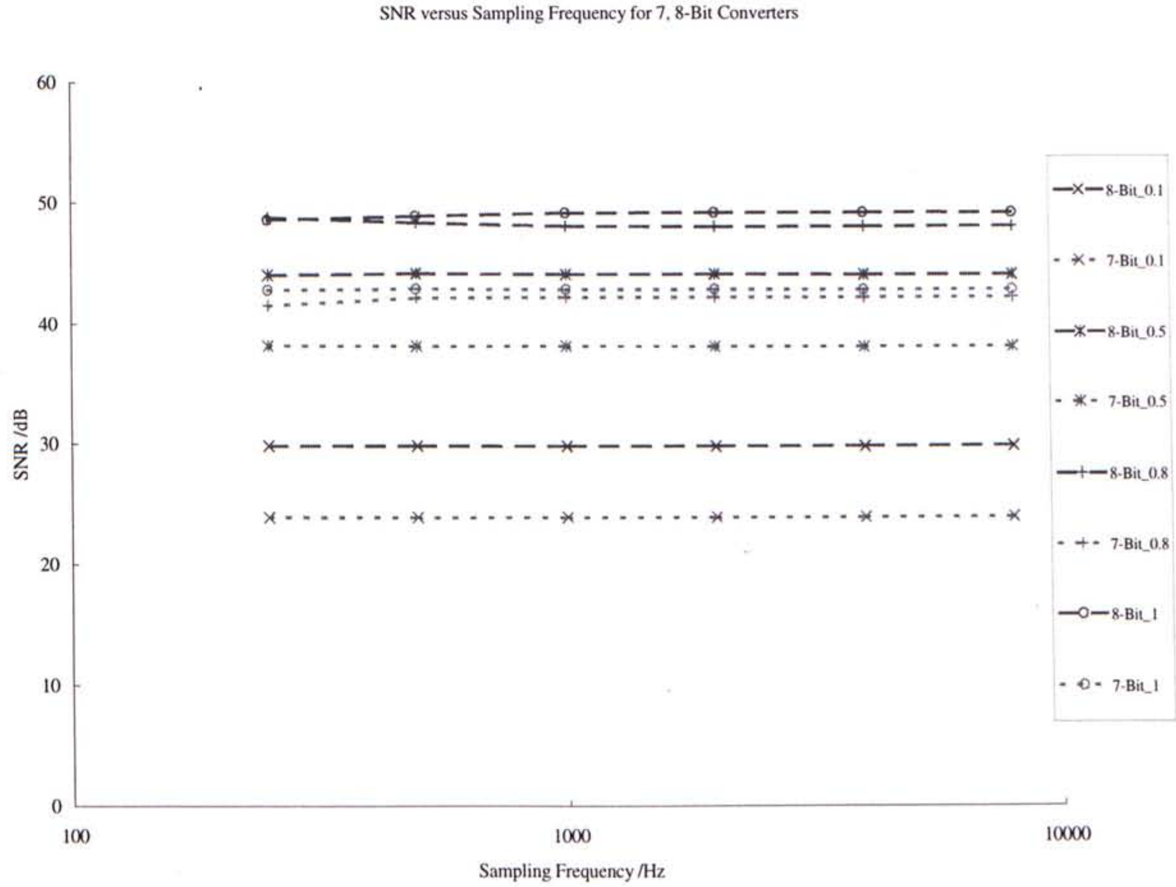


Figure 4.7 SNR versus Sampling Frequency for 7, 8-Bit Converters

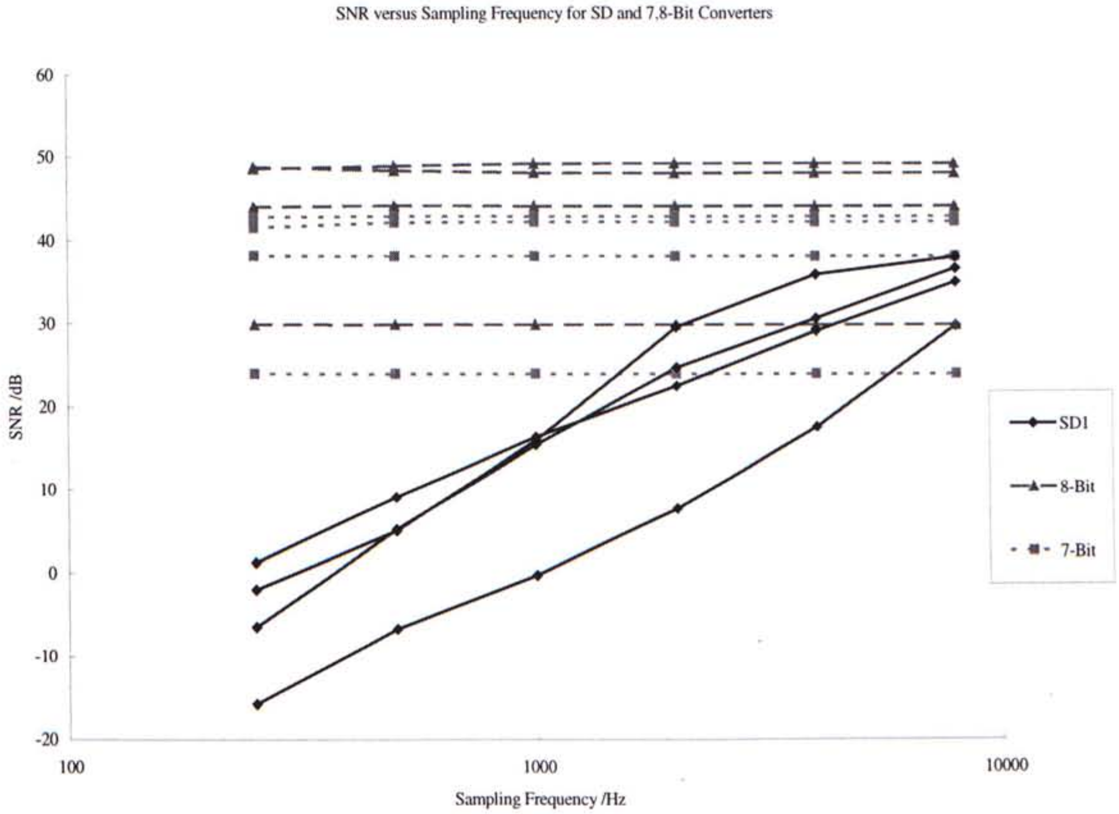


Figure 4.8 SNR versus Sampling Frequency for First-Order Sigma-Delta and 7, 8-Bit Converters

Discussion

From the above figures, the MSE's for seven and eight-bit converters are nearly constant with changes in sampling frequencies and input amplitudes and are around -46 and –53 dB. These are close to the theoretical quantization noise power of $\frac{\Delta^2}{12}$ where Δ is the quantization interval. The above information can be mathematically presented as:

$$x = x_q + q_E \qquad (4.2.3)$$

$$E\left(q_E{}^2\right) = \frac{\Delta^2}{12} \qquad (4.2.4)$$

$$\Delta = \frac{FS}{2^B} \qquad (4.2.5)$$

where x is sample amplitudes of the original signal, x_q is the quantized value of x with

q_E being the quantization error or quantization noise; *FS* is the Full Scale level allowed for conversion and *B* is the number of bits provided by the converter. The SNR's change with the input amplitudes as by definition (4.2.2). It is the ratio of average signal power to the MSE. As MSE's are constant with the sampling frequencies and input amplitudes, the SNR's are linear with the input signal power as shown in Figure 4.7.

In our case, the above parameters can be shown in Table 4.1.

Parameter Name	Numerical Values
FS	2
B	7 and 8
Δ	$\frac{2}{128}$ and $\frac{2}{256}$
$E(q_E^2)$	-46.9154 and -52.9360 dB

Table 4.1 Parameters for Simulations

For the case of the first-order Sigma-Delta converter, the MSE's and SNR's vary with both sampling frequencies and input amplitudes. From Figure 4.5, the performance of the first-order Sigma-Delta converter can be comparable to the seven or eight bit converters in terms of MSE with sampling frequency of *8000* Hz. The performance is improved by about 5 to 12 dB with sampling frequency doubled from the simulation results. Theoretically, the MSE of the first-order Sigma-Delta converter decreases by about 9 dB with sampling frequency rises two times.

4.2.1.2 Simulation Results with Real ECG signals

For Normal ECG Lead II Signals

A sampled ECG (with 8000 Samples per second) signal from a subject was used as the input signal. The ECG signal was first low-pass filtered by a second-order digital Butterworth filter with 100Hz cut-off frequency. Since that excerpt of ECG signal contained only one beat, we compiled eight copies of the filtered excerpt into one as the final input signal to the simulation program.

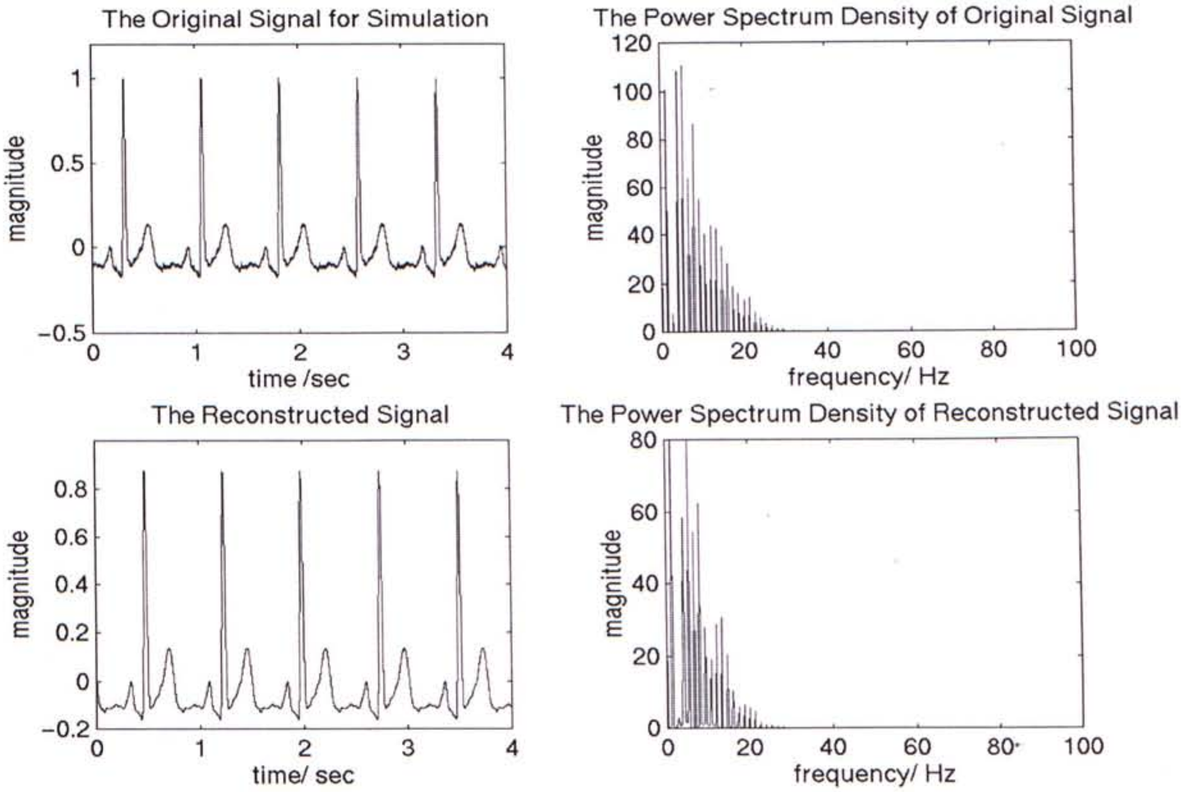


Figure 4.9 The Simulation Results

For convenience, only five out of eight beats of the input signal are shown in Figure 4.9, while the power spectrum density is that of all eight beats. From these results, we can see that the reconstructed signal shown at the lower left corner resembles the original signal. This reconstructed signal is obtained by passing the digital output signal through a digital Butterworth low pass filter.

ECG Signal with a single PVC (Premature Ventricular Contraction)

The original signal for simulation is shown as Figure 4.10.

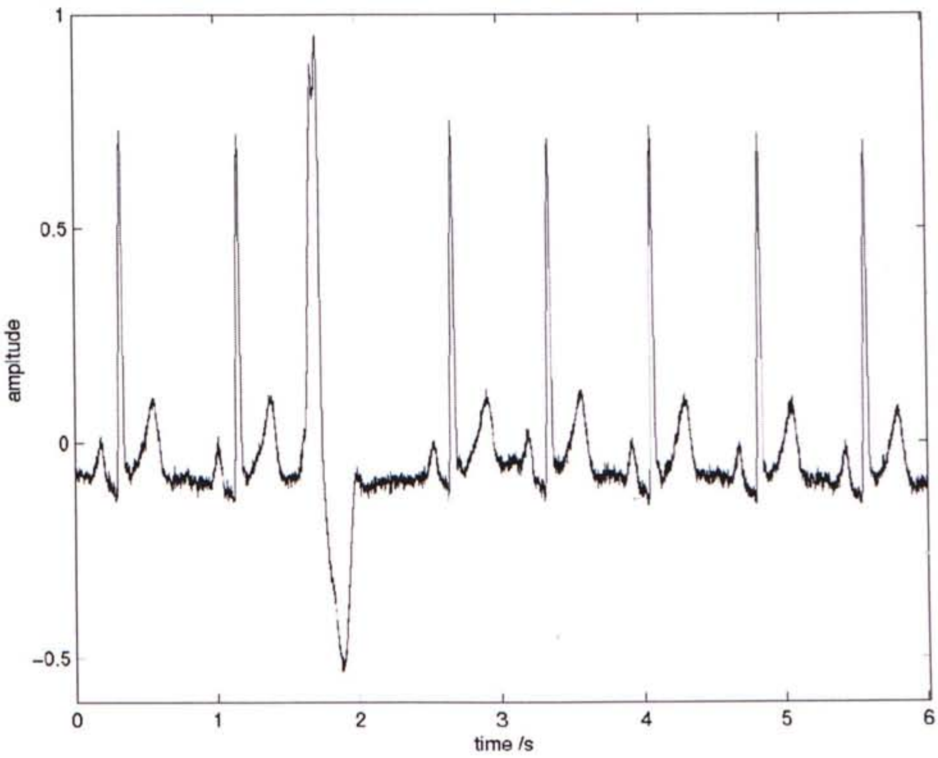


Figure 4.10 Original Signal with a Single PVC (at time ≈ 2s)

From simulation, the MSE (Mean Square Error) for Sigma Delta converter and a 7, 8-bit ADC is obtained as shown in Table 4.2 and Figure 4.11.

Sampling Frequency fs /Hz	MSE (Sigma-Delta) /dB	MSE (7-Bit ADC) /dB	MSE (8-Bit ADC) /dB
8000	-43.2134	-46.8442	-52.9634
4000	-39.4112	-46.8354	-52.9809
2000	-30.8914	-46.8377	-52.9809
1000	-20.4959	-46.8396	-52.9948
500	-15.154	-46.7763	-52.9962
250	-7.653	-46.899	-53.0872

Table 4.2 MSE for Sigma Delta and 7, 8-Bit Converters

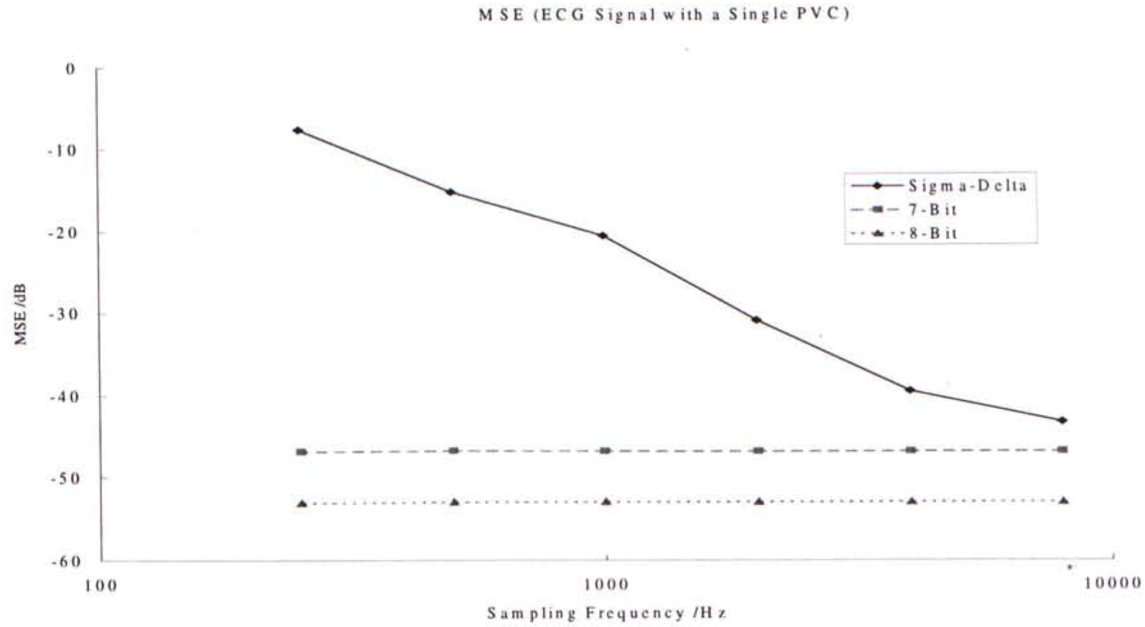


Figure 4.11 MSE for Sigma Delta and N-Bit Converters

ECG Signal with Frequent PVC's

Another excerpt of ECG signal is from the *Samples of Physiologic Signal Databases, MIT-BIH Database*. It is from the data file " *x_119.dat* ". This record contains many PVC (Premature Ventricular Contraction) beats [55]. The data file is generated by digitizing analogue signal with sampling frequency of 360 Hz. 4096 points are extracted from the data file and different sampling frequency simulation is performed by linear interpolation on the original 4096 data points. The original signal is shown in Figure 4.12

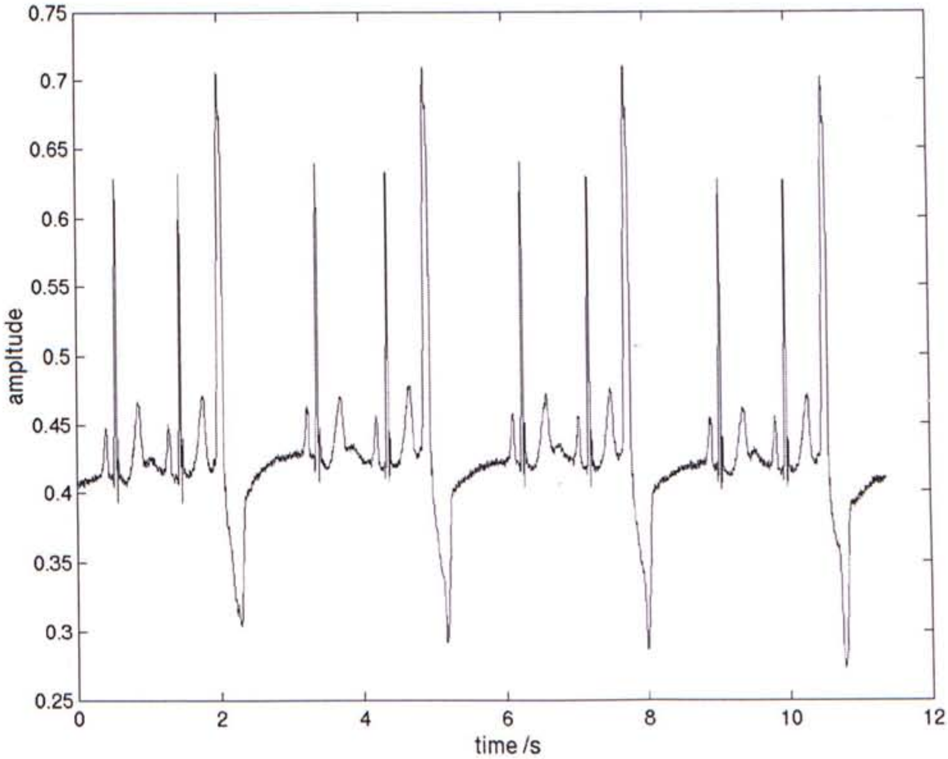


Figure 4.12 ECG Signal from record " *x_119.dat* " (MIT-BIH Samples Database)

Table 4.3 and give the MSE for the first-order Sigma-Delta converter and 7,8-Bit ADC.

Sampling Frequency fs /Hz	MSE (Sigma-Delta) /dB	MSE (7-Bit ADC) /dB	MSE (8-Bit ADC) /dB
11520	-52.6059	-47.2013	-52.8395
5760	-48.4669	-47.2009	-52.8396
2880	-40.3138	-47.2004	-52.8392
1440	-32.0938	-47.1991	-52.846
720	-19.1344	-47.2018	-52.8556
360	-6.732	-47.216	-52.8639

Table 4.3 MSE for Sigma Delta and 7, 8-Bit Converters with " *x_119.dat* "

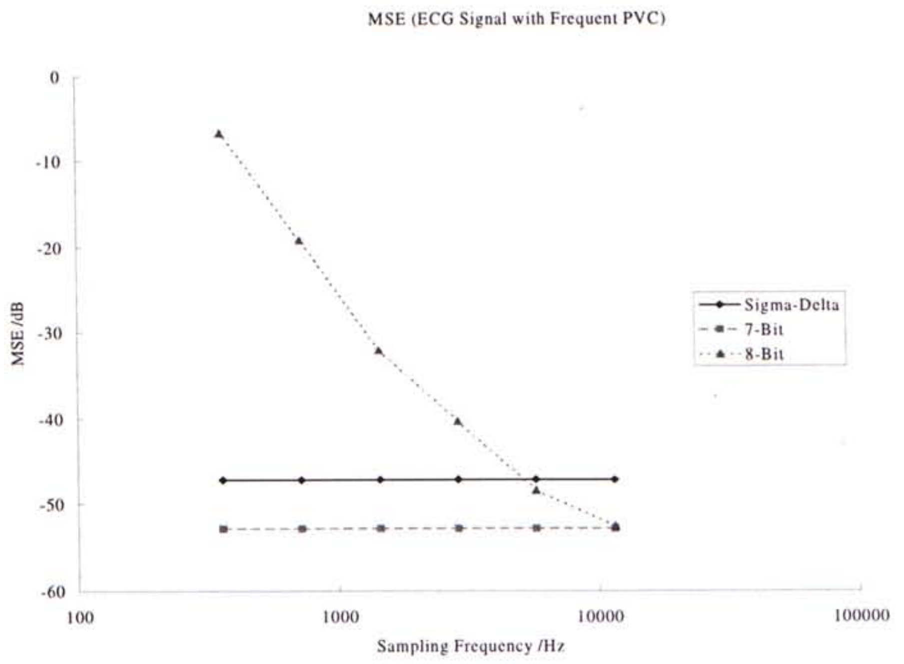


Figure 4.13 MSE for Sigma and 7,8-Bit Converters with " *x_119.dat* "

ECG Signal with Other Ventricular Arrhythmia

Lastly, a data file "*x_418.dat*", also from MIT-BIH sample database, is used for simulation. This is the "*Malignant Ventricular Arrhythmia Database*" that contains ventricular arrhythmia signals. Similar to "*x_119.dat*", 4096 points are extracted for simulation. The sampling rate for this data file is 250 Hz, slightly lower than that in *"x_119.dat"*. The original signal is shown in , the simulation results tabulated in Table 4.4 and graphically shown in Figure 4.15.

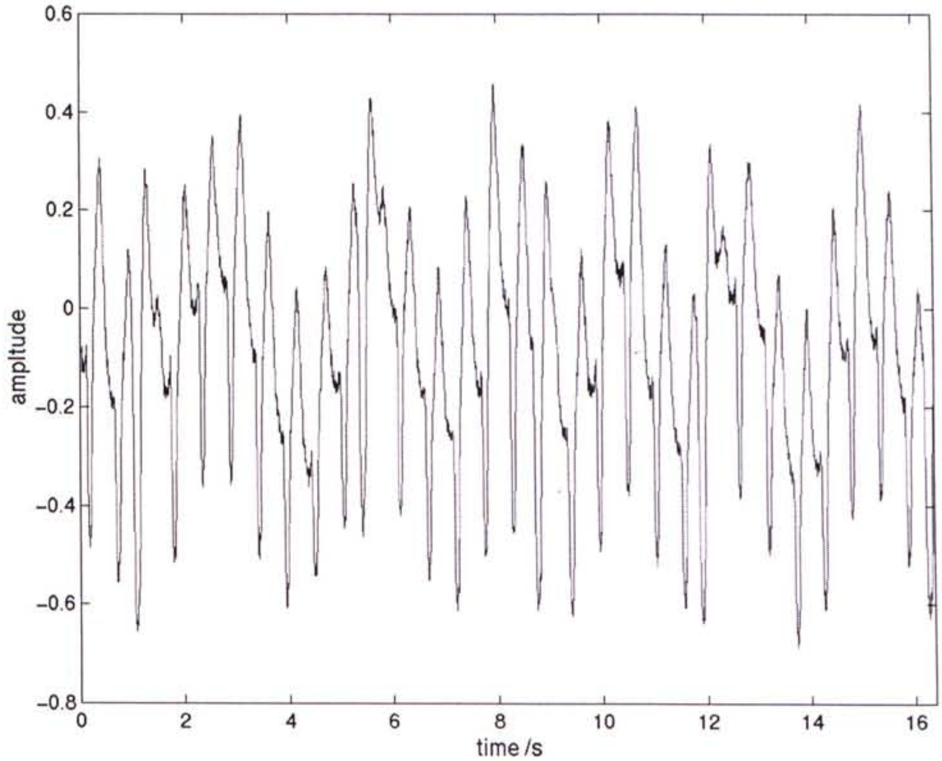


Figure 4.14 ECG Signal from record " *x_418.dat* " (MIT-BIH Samples Database)

Sampling Frequency fs /Hz	MSE (Sigma-Delta) /dB	MSE (7-Bit ADC) /dB	MSE (8-Bit ADC) /dB
8000	-49.1172	-46.8814	-52.994
4000	-40.7259	-46.8813	-52.9969
2000	-32.1542	-46.8837	-52.9977
1000	-23.4893	-46.8935	-53.0268
500	-14.4829	-46.8811	-52.9954
250	-4.0333	-46.8285	-52.9887

Table 4.4 MSE for Sigma Delta and 7, 8-Bit Converters with " *x_418.dat* "

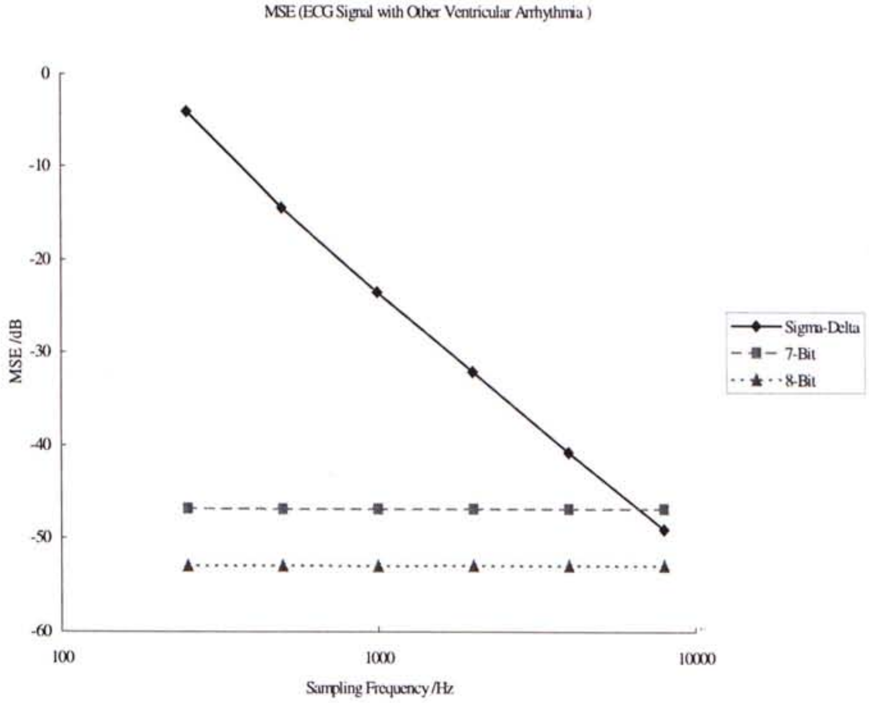


Figure 4.15 MSE for Sigma and 7,8-Bit Converters with " *x_418.dat* "

Discussion

In this subsection, different types of real ECG signals were applied to simulation. Normal and abnormal ECG signals were under study. In the first simulation, normal ECG signal was applied. The MSE for 7,8-Bit ADC is kept to be constant with respect to different sampling frequency) and they are close to the theoretical values. MSE for first-order Sigma-Delta converter decrease with the increase in sampling frequency. With sampling frequency of 8000Hz, it performs similar to an eight-bit resolution ADC for an input sine tone of amplitude *0.1*.

4.2.2 Experimental Results

4.2.2.1 Experiment with Pure Sine Tones

Experimental Setup

A self-built first-order Sigma-Delta converter is used in this experiment. The components for this converter are mainly quad opamp (LM324), D Flip-Flop (CD4013). A relaxation oscillator with NAND gates (CD4011) generates the sampling clock.

Three pure sine tones in-turn are applied to the first-order Sigma-Delta converter. They are of about *0.2, 2* and *20Hz* respectively. The converter is run at about 200 Hz sampling frequency. Input signal and the binary bit stream are digitized by *WINDAQ* and data is further analyzed by *MATLAB*. The sampling rate of *WINDAQ* is 2500Hz for each channel and data consumes about 360 kilobytes disk space each. From the whole excerpt, 131072 (2^{17}) points are extracted and processed to obtain the Power Spectral Density (PSD) with a Hanning Window (131072 points).

Results

The PSD's are shown in Figure 4.16 to Figure 4.20.

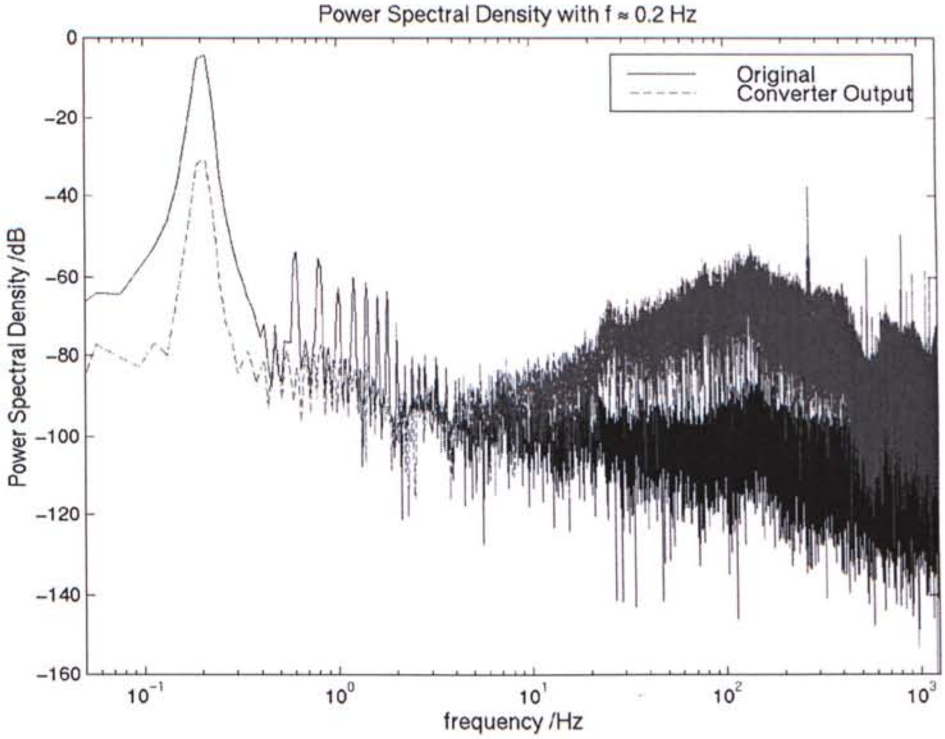


Figure 4.16 PSD of Input Signal and Binary Output with f ≈ 0.2 Hz

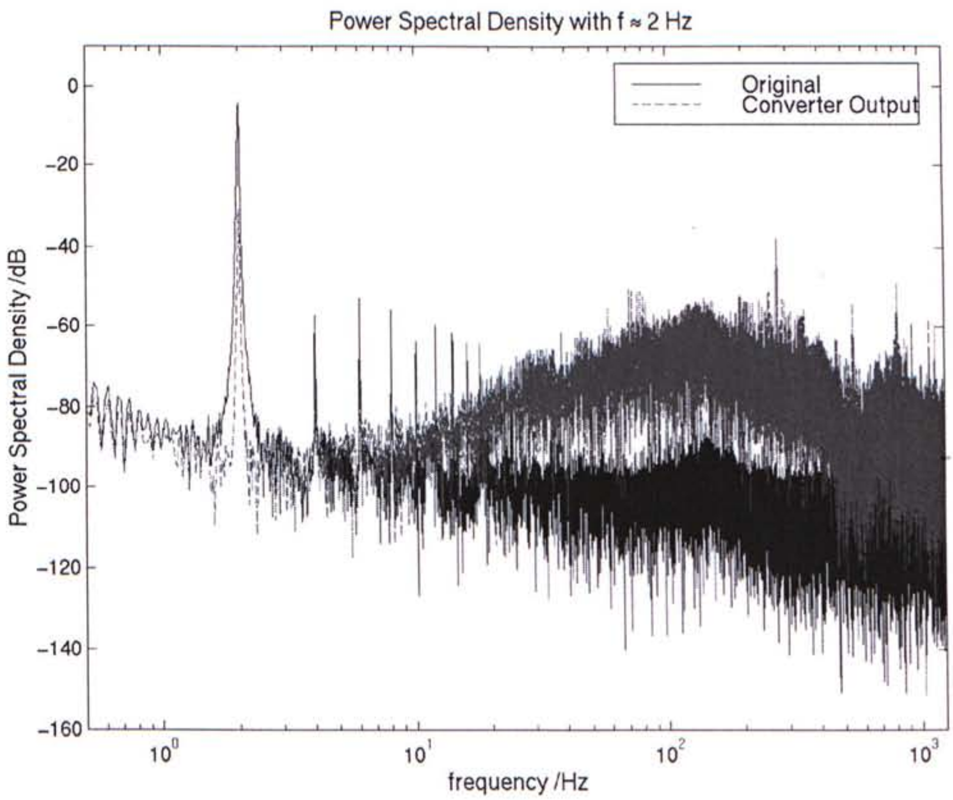


Figure 4.17 PSD of Input Signal and Binary Output with f ≈ 2 Hz

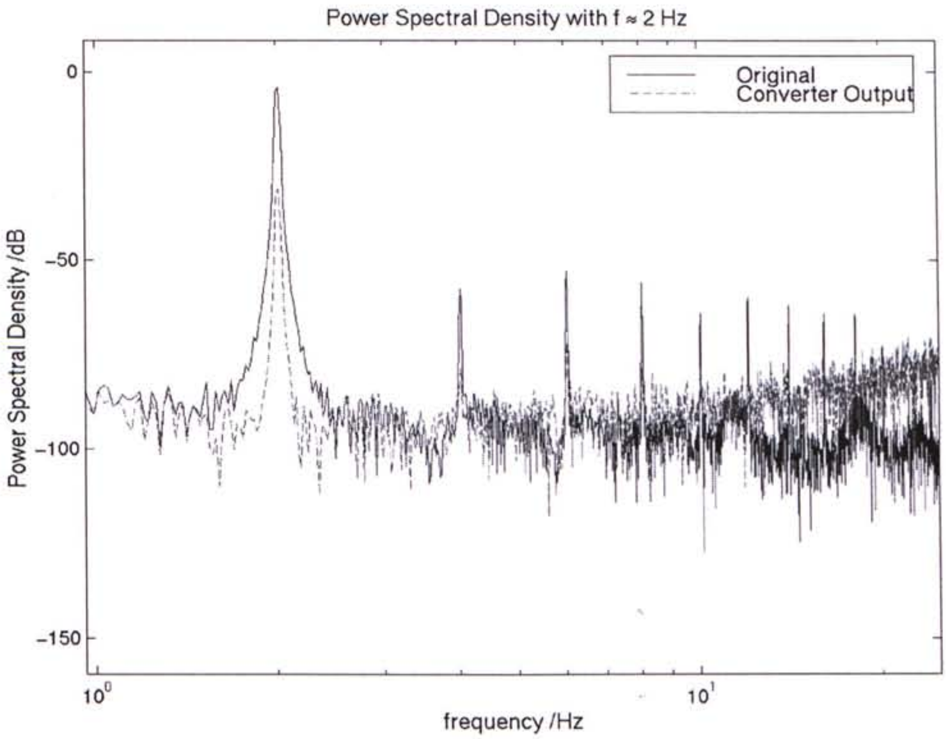


Figure 4.18 Zoomed PSD of Input Signal and Binary Output with f ≈ 2 Hz

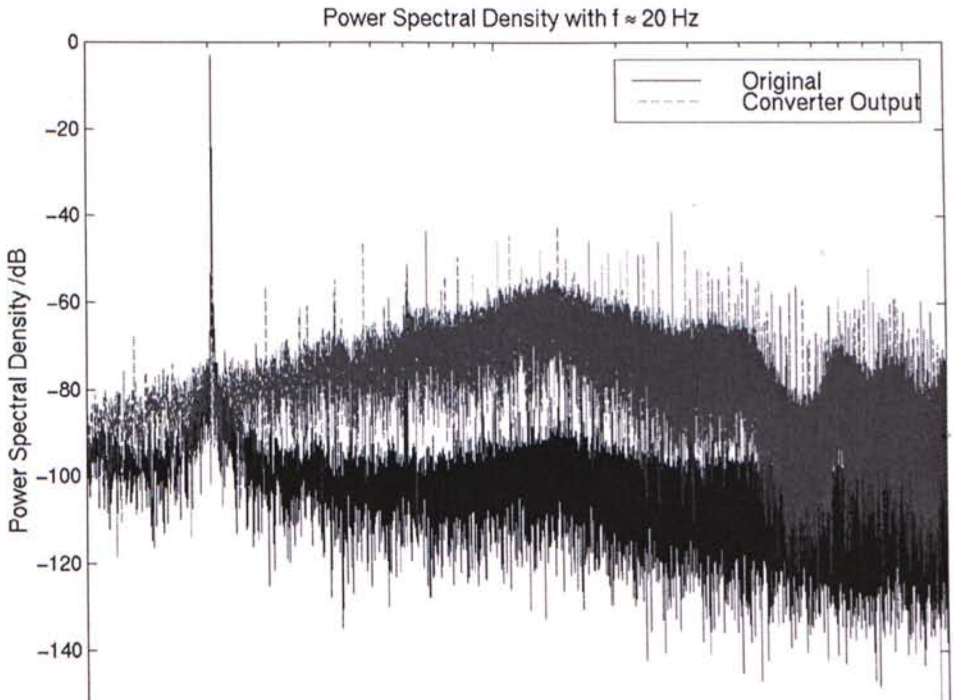


Figure 4.19 PSD of Input Signal and Binary Output with f ≈ 20 Hz

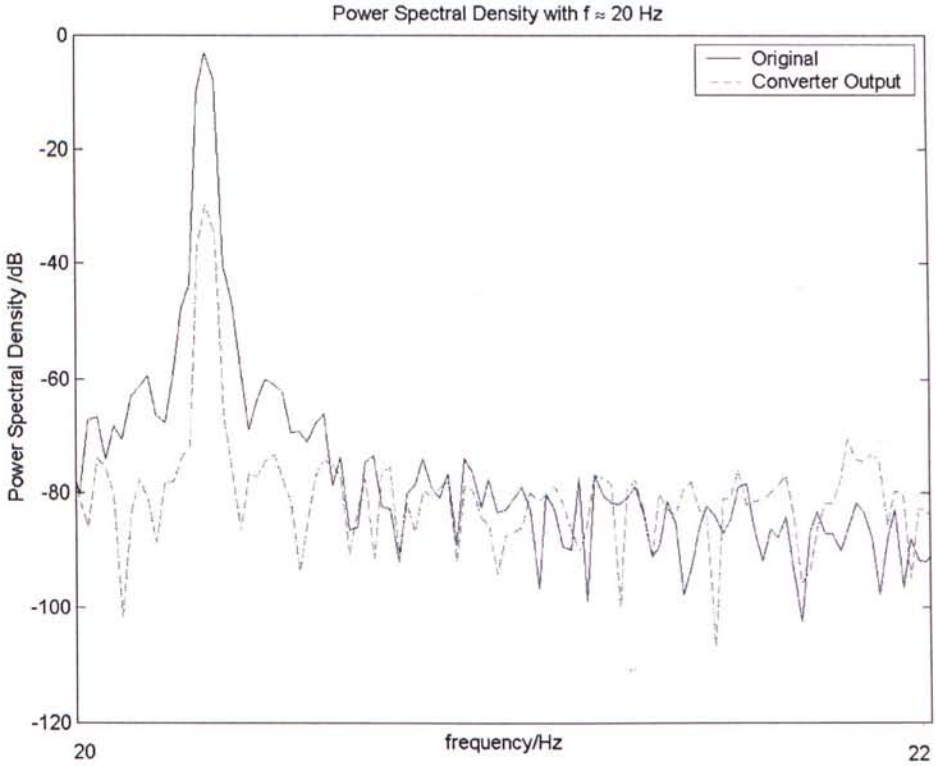


Figure 4.20 Zoomed PSD of Input Signal and Binary Output with f ≈ 20 Hz

Discussion

In Figure 4.16 to Figure 4.20, the solid line is for input signal spectrum and the dashed line is for the binary output. It is observed that input signal is corrupted with noise as there are distinct peaks in it spectrum which is not expected. The Binary output PSD contains the Input Signal Spectrum at lower frequencies. We can see that the high frequency noise of the binary output starts to rise at about 10 Hz. Therefore, for the sine tone of about 20 Hz, this tone is already in the midst of rising noise in the PSD of the binary output. Nevertheless, the in-band noise floor is always about –80dB for the 3 cases. The tone spectrum is shown to be about –40dB lower than that of input. Therefore, giving about 40dB higher than the noise floor. Therefore, signals can be faithfully recovered from the binary output by means of a low-pass filter that can be implemented in either analogue or digital form.

4.2.2.2 Experiment with Generated ECG Lead II Signal

Experimental Setup

In this part, the experiment was done earlier and another circuit was implemented. The converter is consisted of a quad operational amplifier LF444 and a CMOS D flip-flop (4013). The signal was attenuated to about 40mV peak-to-peak to be input to the circuit. The digital output was fed into a first-order low-pass filter to obtain the reconstructed signal. In order to allow for further analysis on various signals, we used the *WINDAQ* computer acquisition tools to record signals from the circuit to computer disk. The data obtained were then being imported to *MATLAB* for further analysis. The whole setup can be illustrated in Figure 4.21.

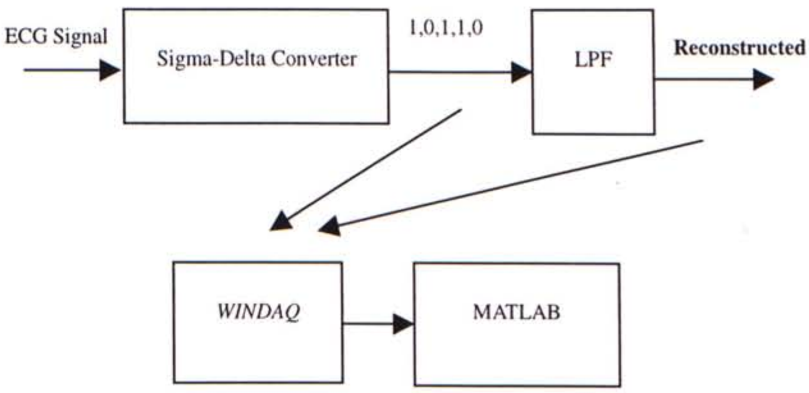


Figure 4.21 A Block Diagram for the Experimental Setup

Results

The experimental results obtained are shown in Figure 4.22.

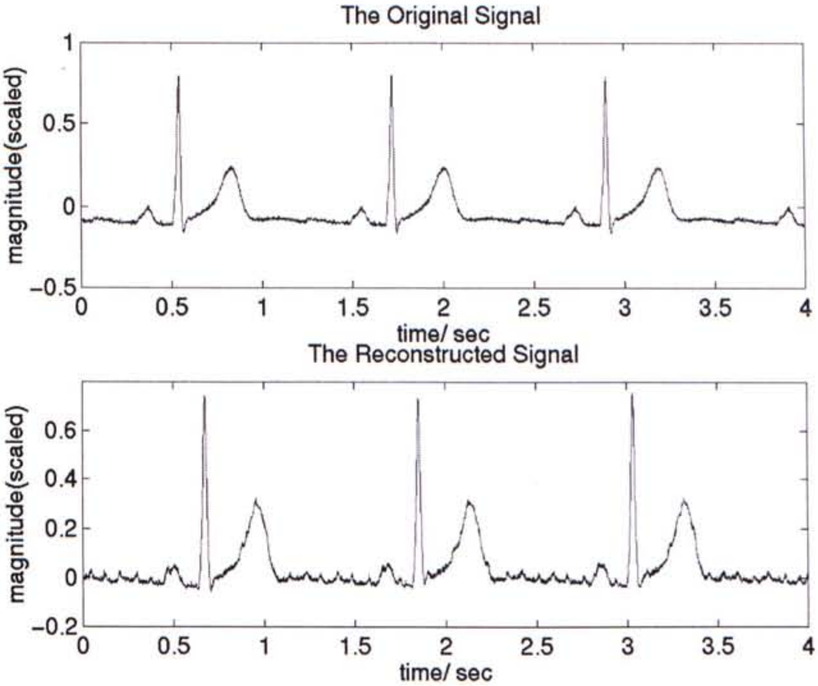


Figure 4.22 The Original and Reconstructed Signals

We can see from Figure 4.22 that the reconstructed signal resembles the original one. Objective metrics are applied to evaluate the system performance. The metrics here used are the percent root mean square difference (PRD) [54] and the percent mean absolute difference (PAD). They are defined as:

$$PAD = \frac{\sum |x[n] - \hat{x}[n]|}{\sum |x[n]|} \times 100\% \qquad (4.2.6)$$

$$PRD = \sqrt{\frac{\sum (x[n] - \hat{x}[n])^2}{\sum x^2[n]}} \times 100\% \qquad (4.2.7)$$

where $x[n]$ and $\tilde{x}[n]$ are the original and reconstructed signal respectively.

The original and reconstructed signals are first aligned to each other using the first R-wave of the ECG signal. And to minimize errors due to scaling, each of the signals is normalized according to their own first R-wave magnitude.

The PRD and PAD were found to be about 23 and 27% respectively. One of the main reasons for this error may be due to the excessive low-pass filtering especially to those higher frequency components in QRS complex.

Also from the output signal, some minute periodic noise occurred. Another measurement was undertaken with the intention of finding out the sources of the periodic noise about 12Hz (Figure 4.23). The setup for this time was different from that of last time. We use the YOKOGAMA signal monitor to obtain some hardcopies of the input and reconstructed signals.

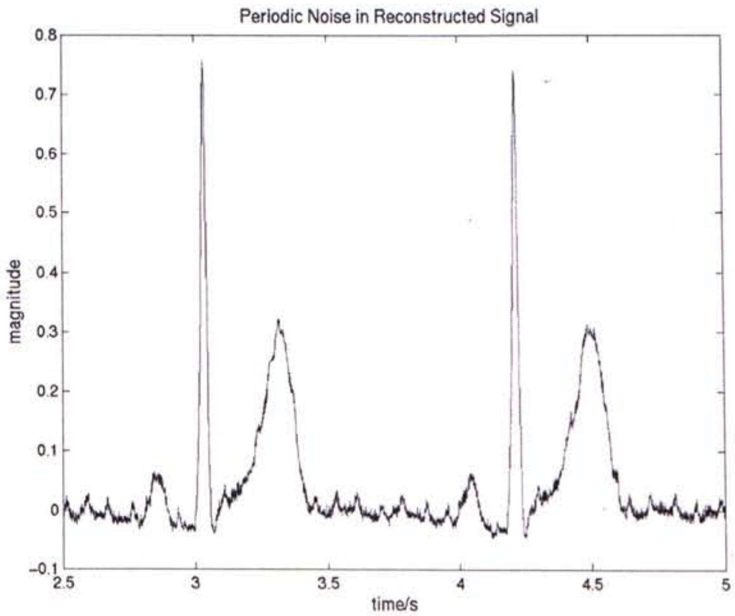


Figure 4.23 Excerpt from Reconstructed Signal in Time Domain

From Figure 4.23, we can observe that there are some periodic noises in the reconstructed waveform. They are most prevailed during the ST segment of the ECG viewed in the time domain. In order to find out the source of the 12Hz noise, another experiment was set up. This time, a digital oscilloscope manufactured by YOKOGAMA with hardcopy function monitored the signals. We monitored the signals and printed some hardcopies out. The results are interesting, the specific 12Hz periodic noises disappeared in this measurement. The reconstructed signals were very similar to the original one.

The following figures are the recorded results.

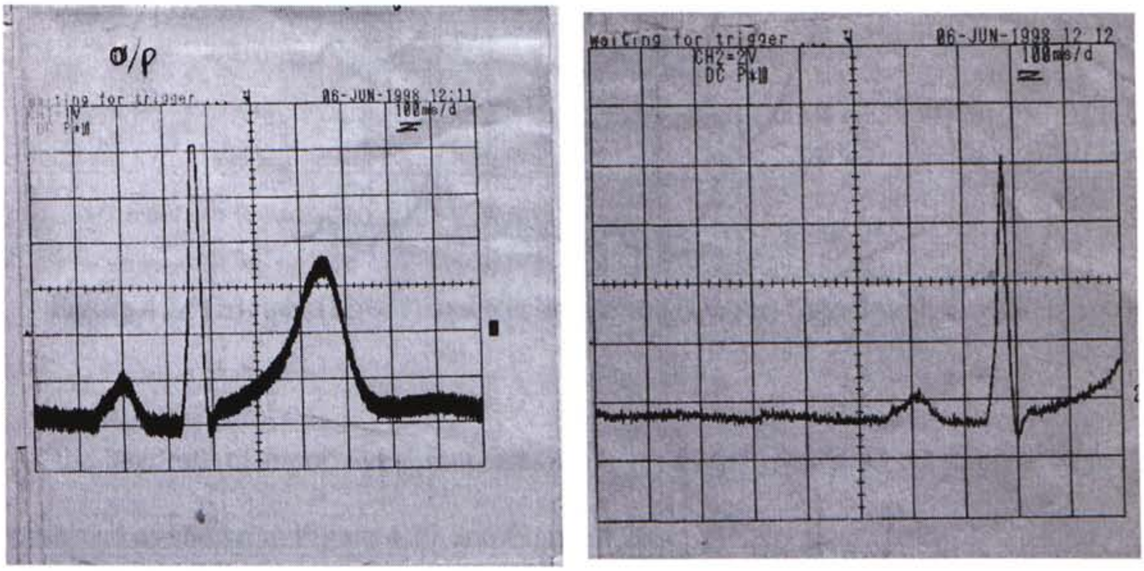


Figure 4.24 The Original (Right) and Reconstructed Signals (Left) with fs=6.21kHz
(fs stands for the sampling frequency of conversion)

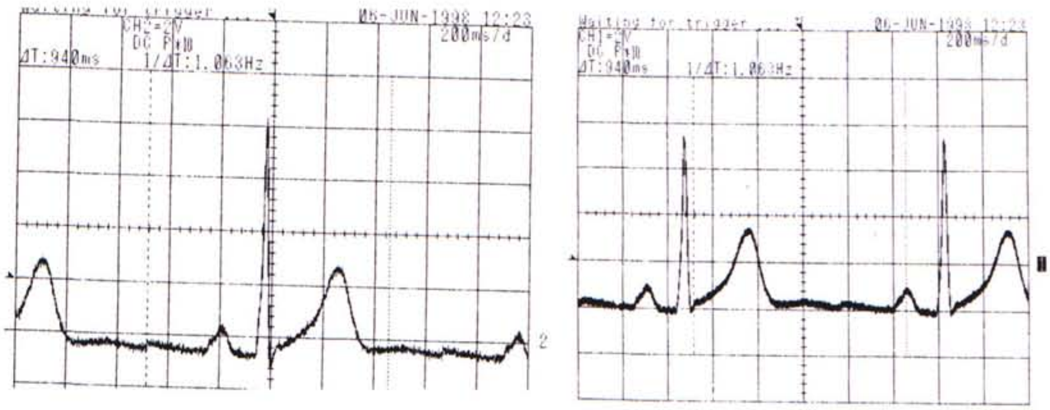


Figure 4.25 Original (Right) and Reconstructed (Left) Signal with fs=42kHz

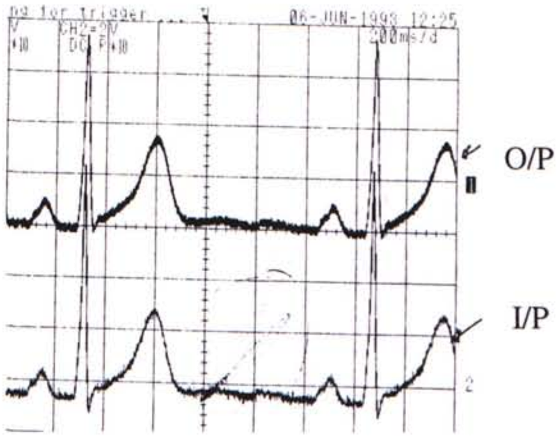


Figure 4.26 Original (Lower) and Reconstructed (Upper) Signal with fs=42kHz

As the beat rate of Input signal increases, changes to the recovered waveforms were observed as shown in Figure 4.27 and Figure 4.28.

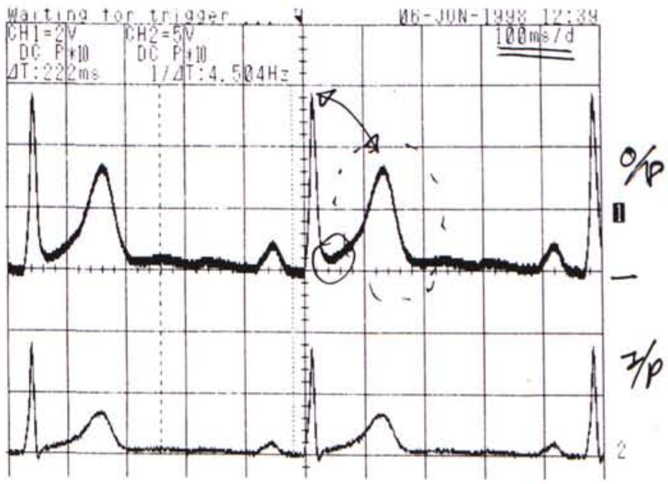


Figure 4.27 Original (Lower) and Reconstructed (Upper) Signals

(Beat Rate about two per second)

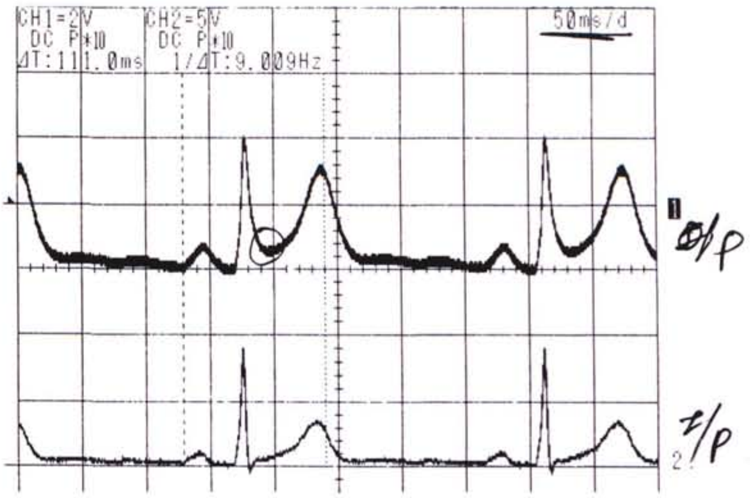


Figure 4.28 Beat Rate about 4 per second

In Figure 4.25 to Figure 4.26, it was noted that the reconstructed signal resembles the original one but distortions showed when the beat rate rose as shown in Figure 4.27 and Figure 4.28. It is because the reconstructed signal was obtained from a low-pass filter. Higher frequency components are therefore attenuated. As the beat rate rises, the frequency contents of ECG signal rises also making more information lost after passing through the low-pass filter.

4.3 Wireless Application

4.3.1 General Description

In previous subsection, we can see that the Sigma-Delta Converter performs better and better with the increase of sampling frequency. Theoretically, there is a decrease of 9 dB/octave of the total in-band quantization noise. Sampling frequency trades for better resolution in the case of Sigma-Delta converter. In a telemetric application, it is desirable to have simple circuitry so that the whole circuit can be miniaturized. The Sigma-Delta converter is well suited for this demand. In this subsection, we would like to investigate the wireless application of the converter. In this investigation, it is special that the 1-bit output of the converter is not processed digitally to give an N-bit PCM output immediately as what most of the present Sigma-Delta converter chips do. The digital signal processing (DSP) unit is instead separated from the 1-bit output. It will be linked wirelessly to the 1-bit output. The simple 1-bit circuitry is intended to be placed in the miniature patient-worn transmitter, while the digital processing unit is on the receiver side that can be a DSP chip or a personal computer. The motivation behind is that circuit complexity can be reduced in the miniature transmitter as there is no digital processing unit required. In the following subsections, two scenarios are given. In the first one, no digital processing is applied. A simple first-order butterworth opamp low-pass filter recovers the signals. In the second one, binary output data is picked up and power spectral densities are computed to anticipate the performance if a digital low-pass filter recovers them by a remote computer or a DSP chip. In addition, a simulation scenario is presented in the following subsection. It basically studies the effect of bit errors induced during transmission to the MSE (Mean Square Error) and the SNR of the converter. Comparison between the converter and conventional Ideal N-Bit is given as well.

4.3.2 Simulation Results

The simulation scenario can be depicted in Figure 4.29.

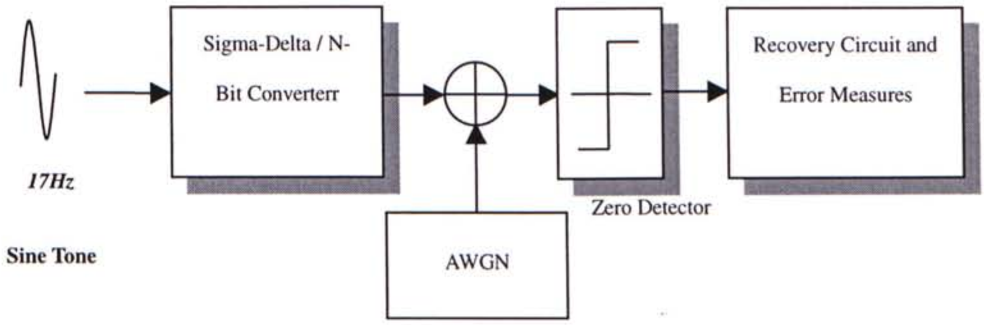


Figure 4.29 Block Diagram of Simulation Scenario

A pure 17 Hz sine tone is applied as the input signal. AWGN (Additive White Gaussian Noise) with different mean powers are applied simulating the occurrence of bit errors. Simulations are conducted with various signal amplitudes and sampling frequencies. The input sine tone was firstly digitized by either Sigma-Delta or N-Bit converter. AWGN was added on the binary bit stream. A zero detector was applied for recovering bit values from the noisy binary bit stream. Analogue signal was reconstructed by the recovery circuit and errors were measured between the original and the reconstructed signal. MSE (4.2.1) and SNR (4.2.2) and BER (Bit Error Rate) are applied for evaluation. The BER is calculated by counting the number of different bits between transmitted and received bit pattern divided by the total number of bits in the simulation. All the simulation is performed with *MATLAB*. Simulation results with 8-Bit converter are provided for comparison. Results will be shown in the following figures and a brief discussion will be given hereafter.

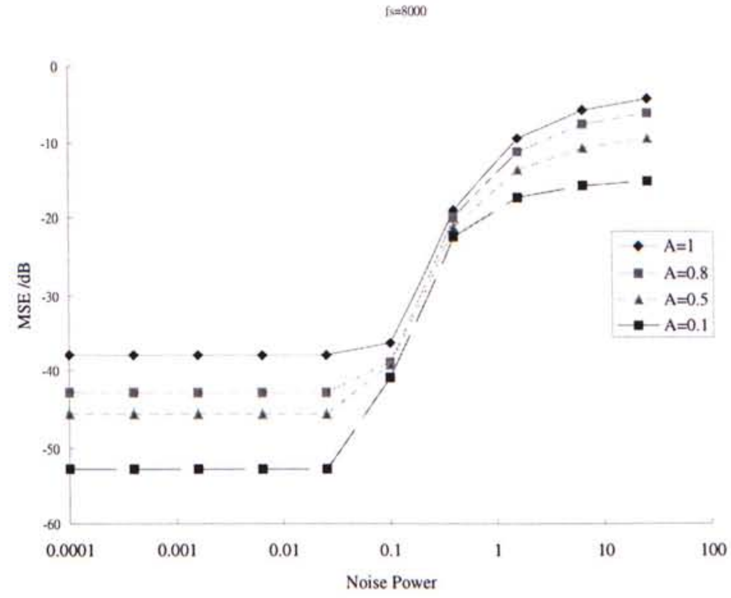


Figure 4.30 MSE versus Noise Power (fs=8000 Hz) with Sigma-Delta converter (SD)
(A stands for the Input Signal Amplitude)

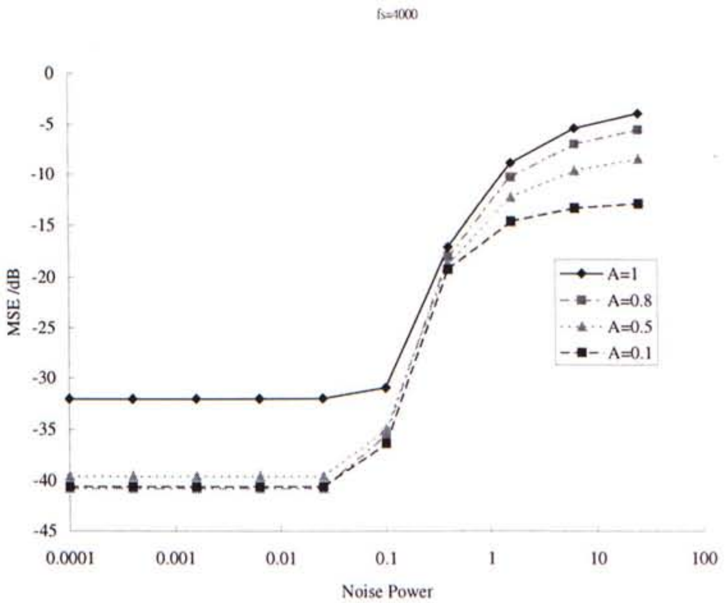


Figure 4.31 MSE versus Noise Power (fs=4000 Hz) with SD

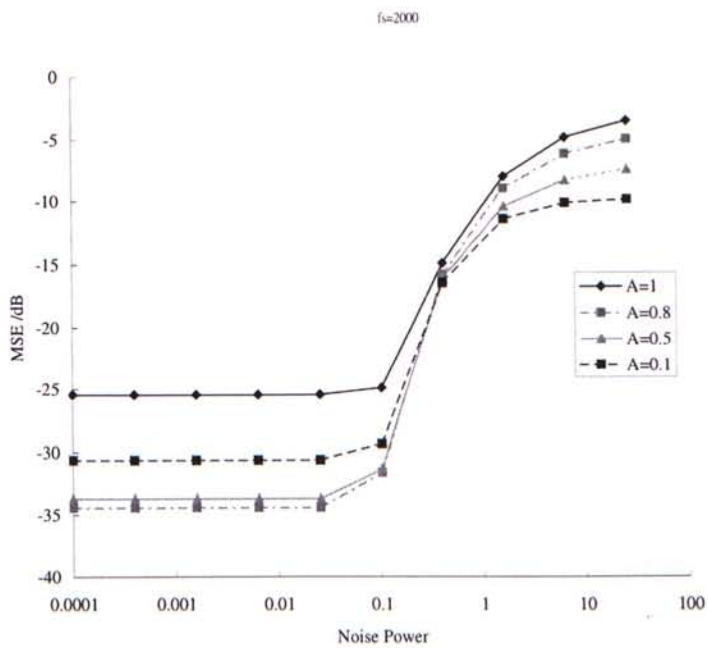


Figure 4.32 MSE versus Noise Power (fs=2000 Hz) with SD

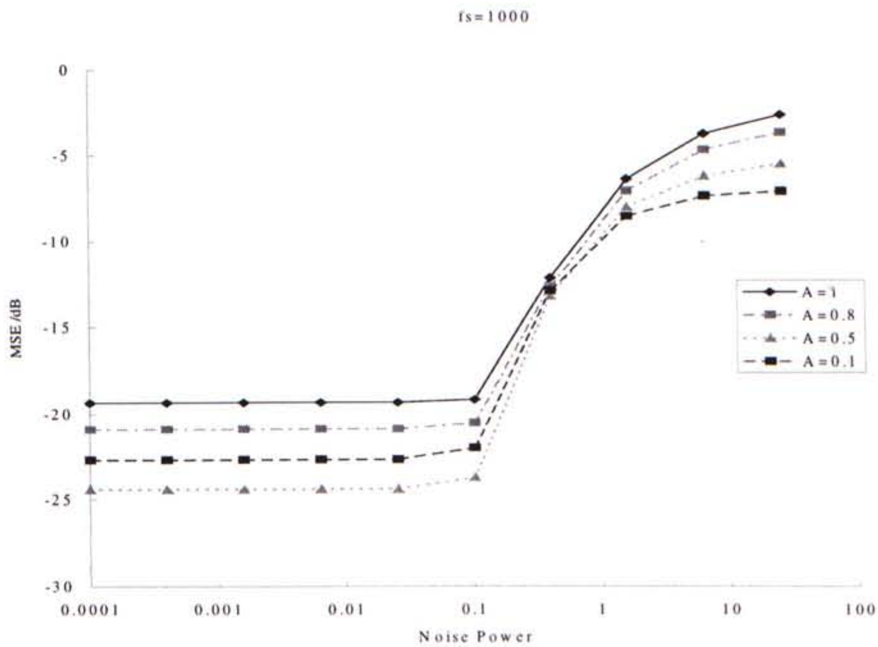


Figure 4.33 MSE versus Noise Power (fs=1000 Hz) with SD

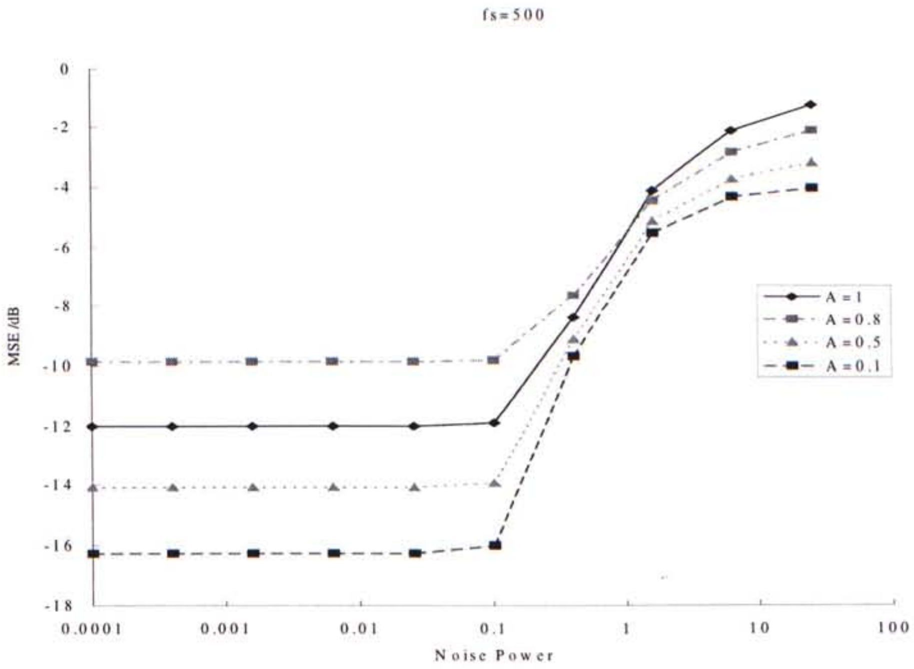


Figure 4.34 MSE versus Noise Power (fs=500 Hz) with SD

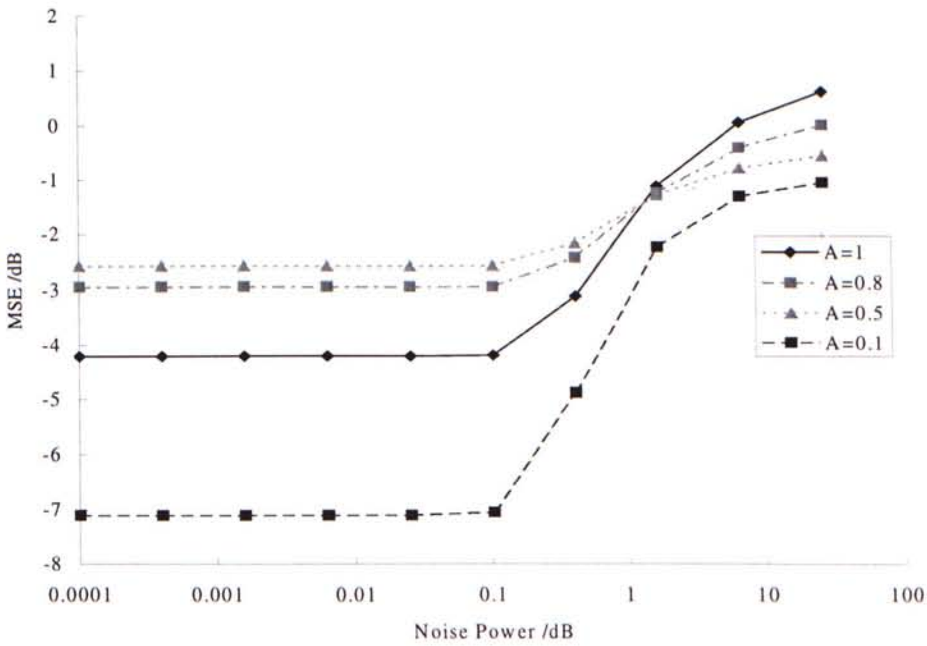


Figure 4.35 MSE versus Noise Power (fs=250 Hz) with SD

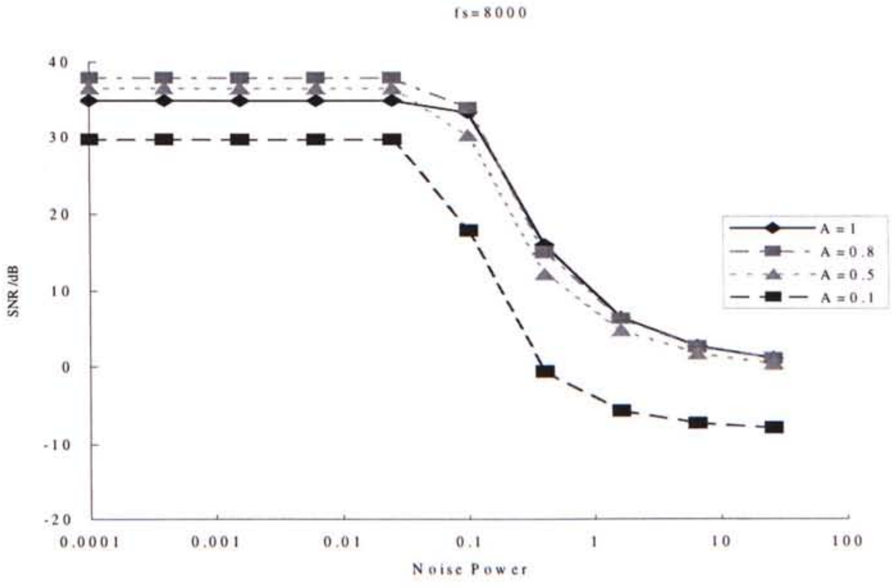


Figure 4.36 SNR versus Noise Power (fs=8000 Hz) with SD

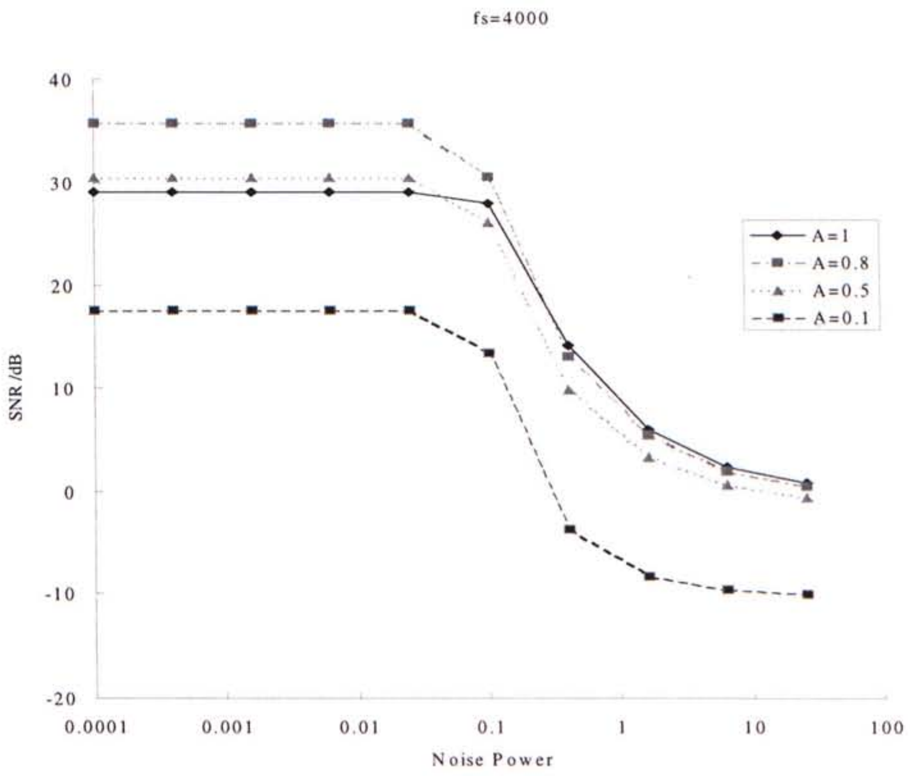


Figure 4.37 SNR versus Noise Power (fs=4000 Hz) with SD

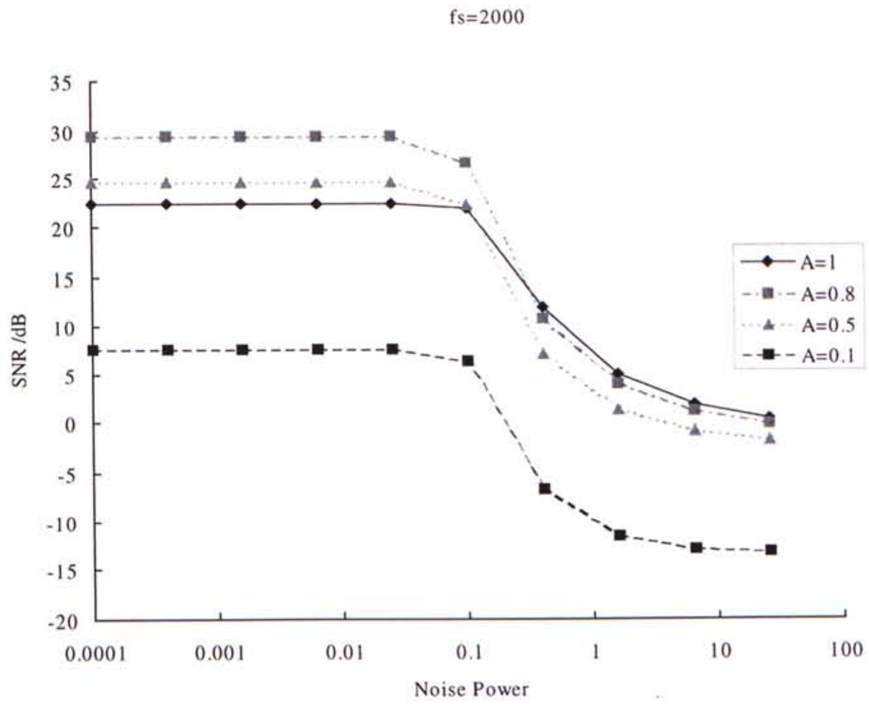


Figure 4.38 SNR versus Noise Power (fs=2000 Hz) with SD

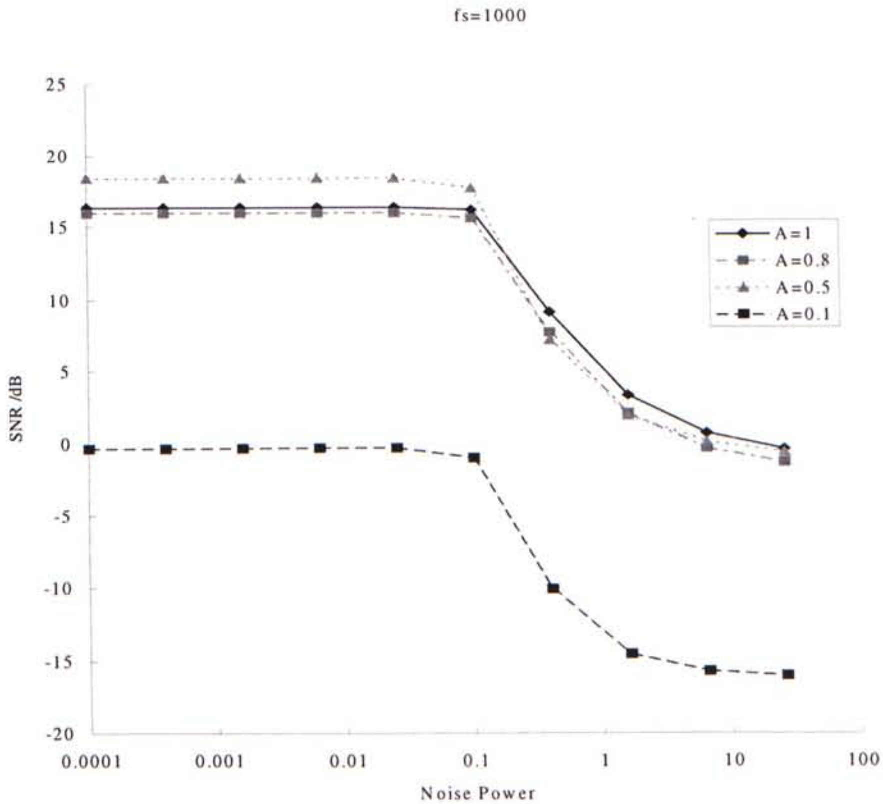


Figure 4.39 SNR versus Noise Power (fs=1000 Hz) with SD

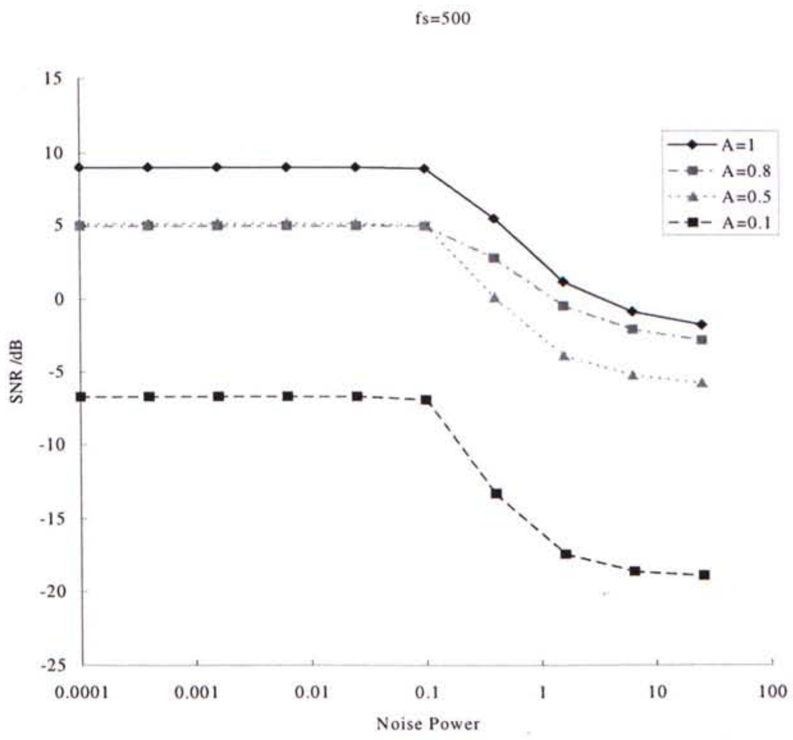


Figure 4.40 SNR versus Noise Power (fs=500 Hz) with SD

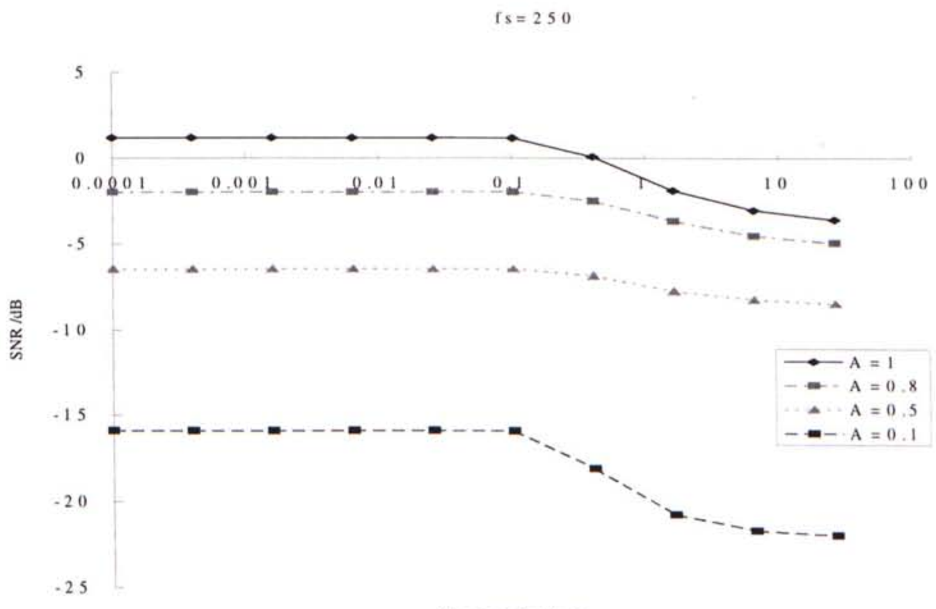


Figure 4.41 SNR versus Noise Power (fs=250 Hz) with SD

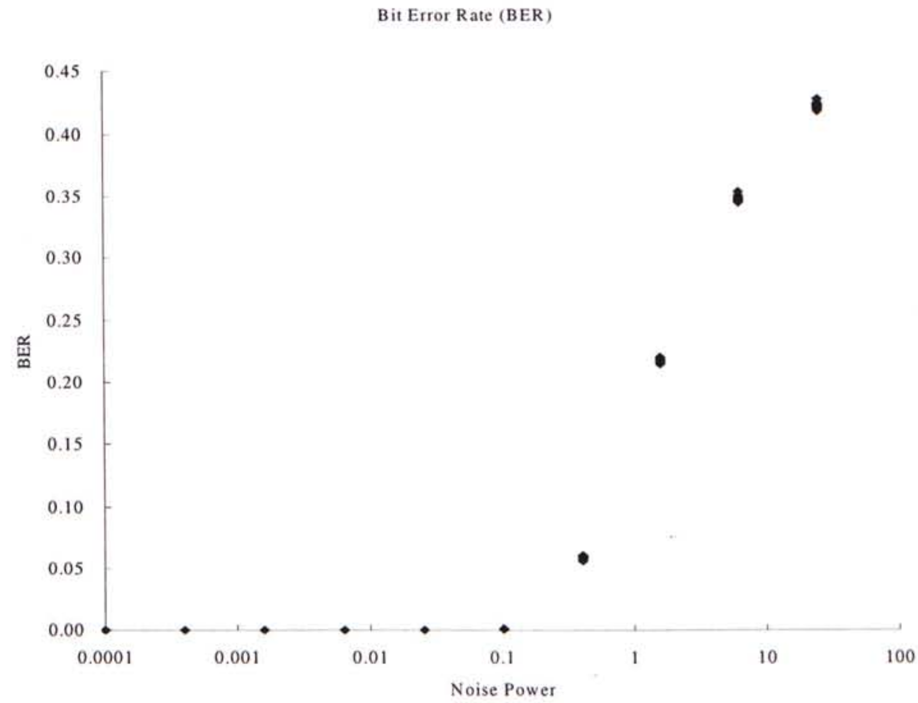


Figure 4.42 BER (Bit Error Rate) versus Noise Power for Simulation with First-Order Sigma-Delta Converter

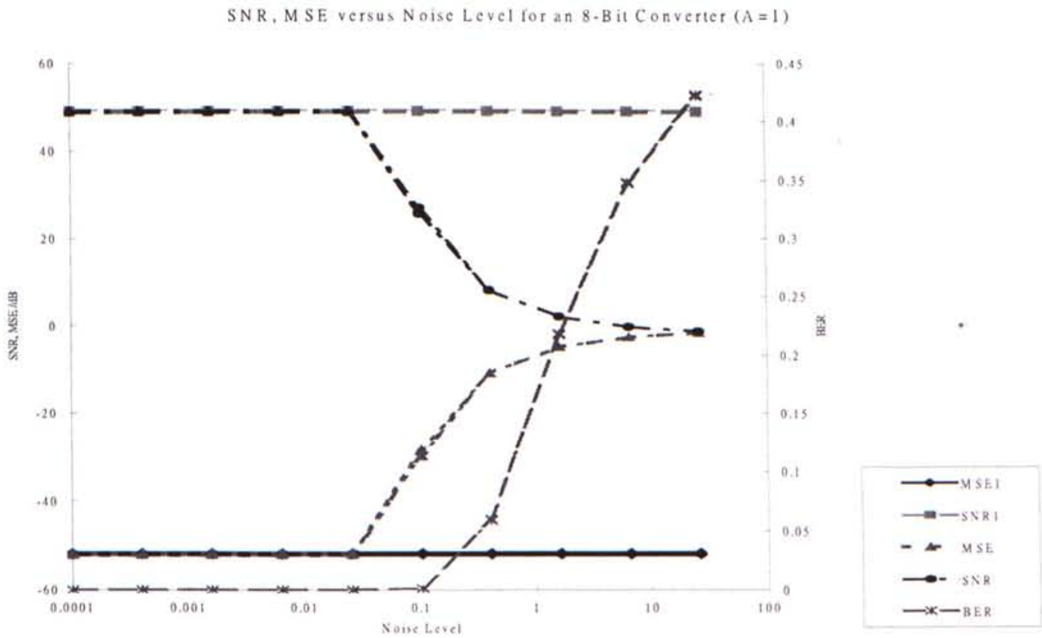


Figure 4.43 SNR, MSE, and BER versus Noise Power for a 8-Bit ADC with A=1

(MSE1, SNR1 are simulation results when there is no noise)

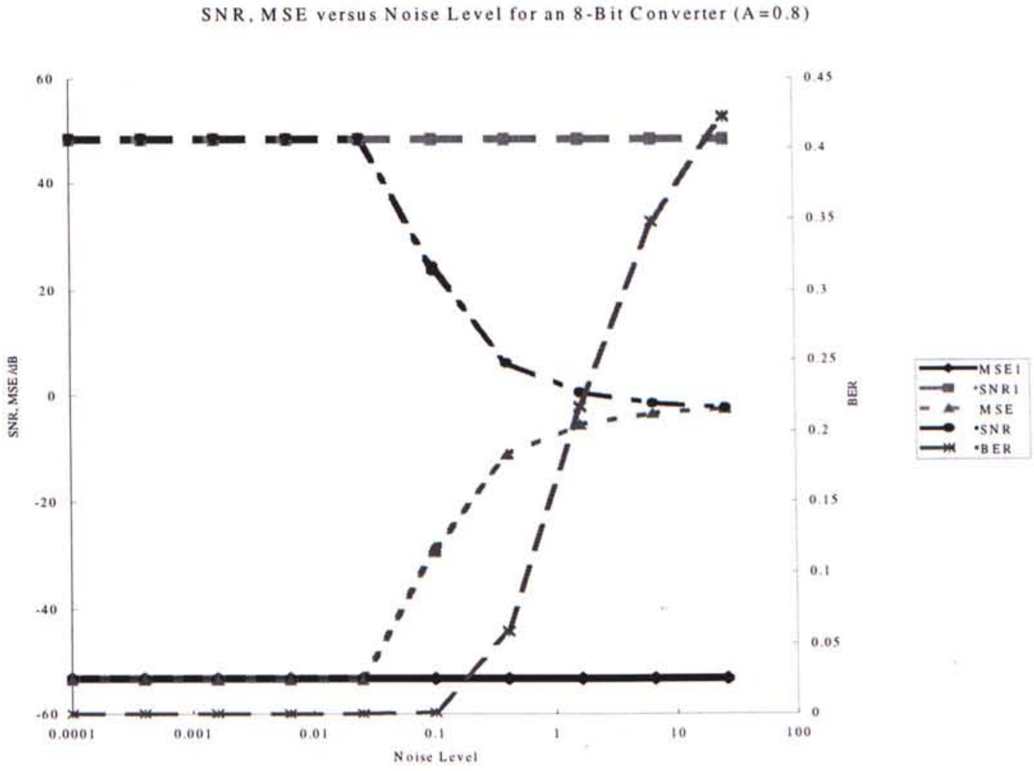


Figure 4.44 SNR, MSE, and BER versus Noise Power for a 8-Bit ADC with A=0.8

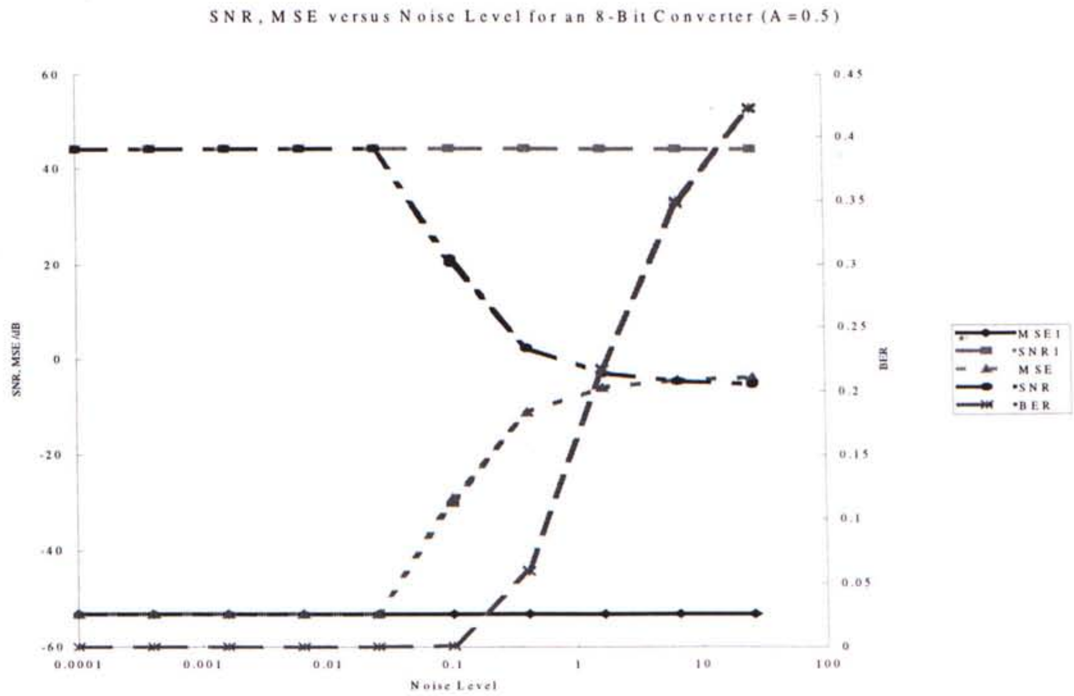


Figure 4.45 SNR, MSE, and BER versus Noise Power for a 8-Bit ADC with A=0.5

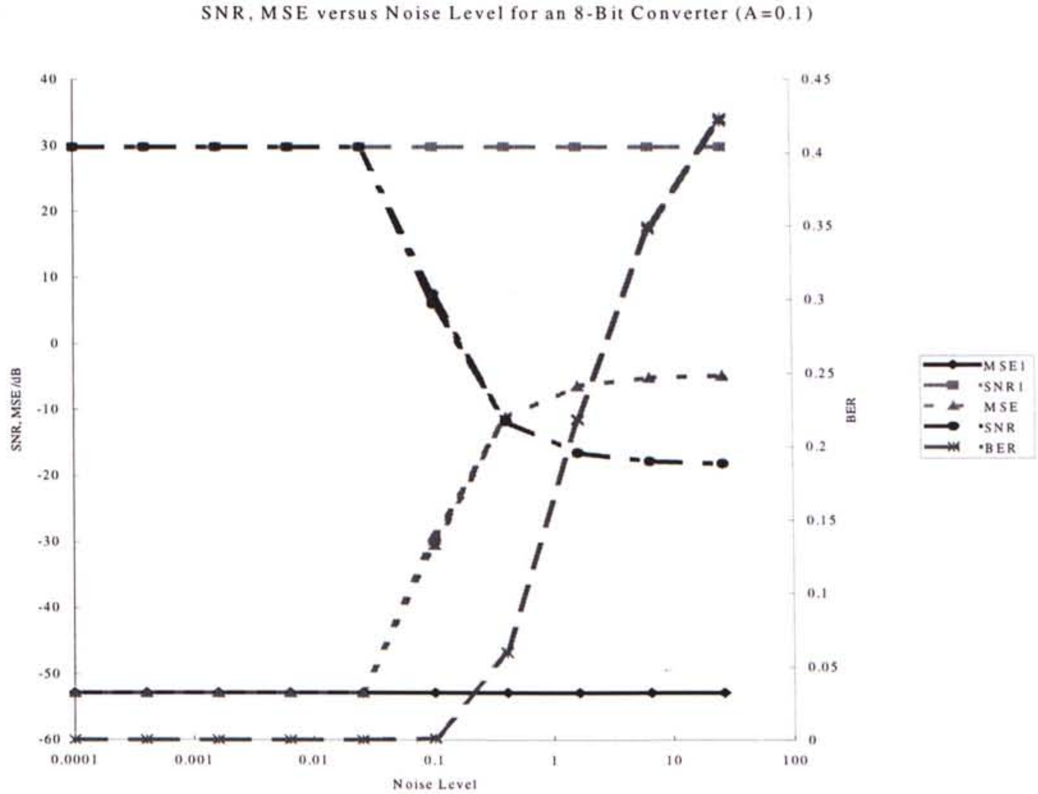


Figure 4.46 SNR, MSE, and BER versus Noise Power for a 8-Bit ADC with A=0.1

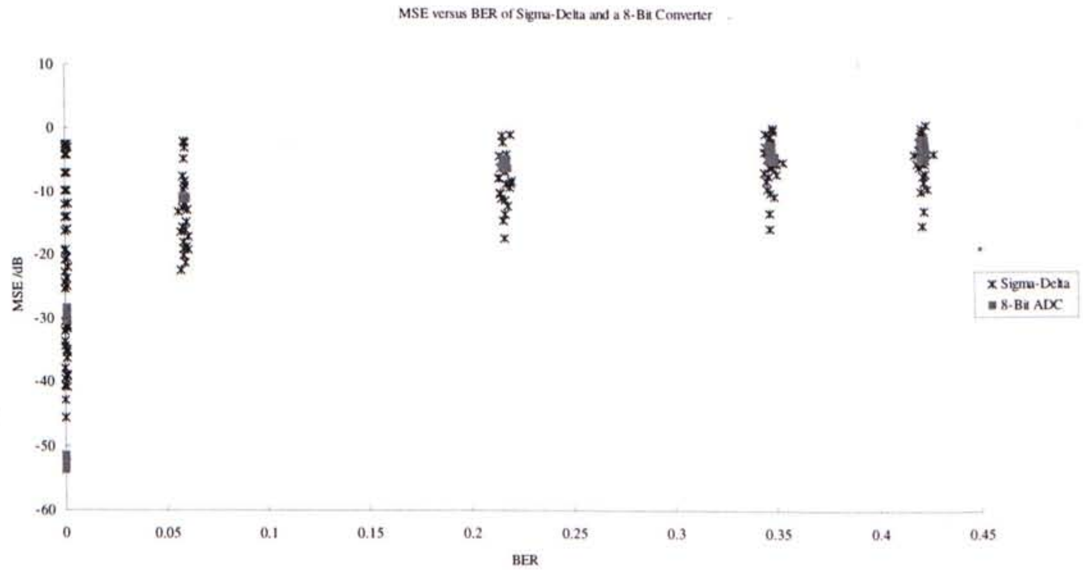


Figure 4.47 MSE versus BER of First-Order Sigma-Delta and 8-Bit Converter

Discussion

It is observed that all the MSE's plots (Figure 4.30 to Figure 4.35 and Figure 4.43 to Figure 4.46) rise suddenly at the sixth data point that coincide with the rise of BER (Figure 4.42 and Figure 4.43-4.46). It is because the MSE's performance is dependent on the amount of BER. BER, on the other hand, is given by the error function that changes rapidly beyond some point of error. It can be shown in Figure 4.48.

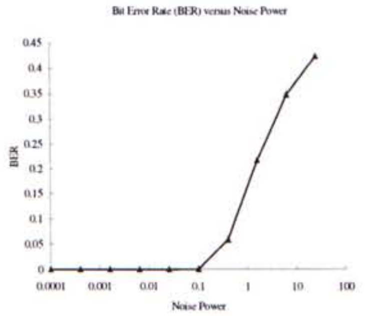


Figure 4.48 BER Given by Error Function

Mathematically, BER with +1,-1 binary symbols and AWGN is given as (4.3.1)

$$BER = \frac{1}{2} erfc(\frac{1}{\sqrt{2\sigma^2}}) \quad (4.3.1)$$

where σ^2 is the noise power and Figure 4.48 is plot according to (4.3.1).

From Figure 4.48, it can be observed that the BER rises rapidly after the fifth data point that coincides with the simulated BER. For an N-Bit ADC, there are chances that significant errors can be generated from bit errors if the bit errors occur at the MSB (Most Significant Bit) of the data sample word. For the case of Sigma-Delta converter, bit errors tends to be smoothed out due to the fact that signal is recovered by low-pass filtering in either analogue or digital form. It can be observed that in Figure 4.47 the MSE's are lower in most cases for the Sigma-Delta converter. However, MSE for the Sigma-Delta converter rises with the decrease of sampling frequency as discussed previously in section 4.2.

4.3.3 Scenario I (Analogue Decoding)

4.3.3.1 Experimental Setup

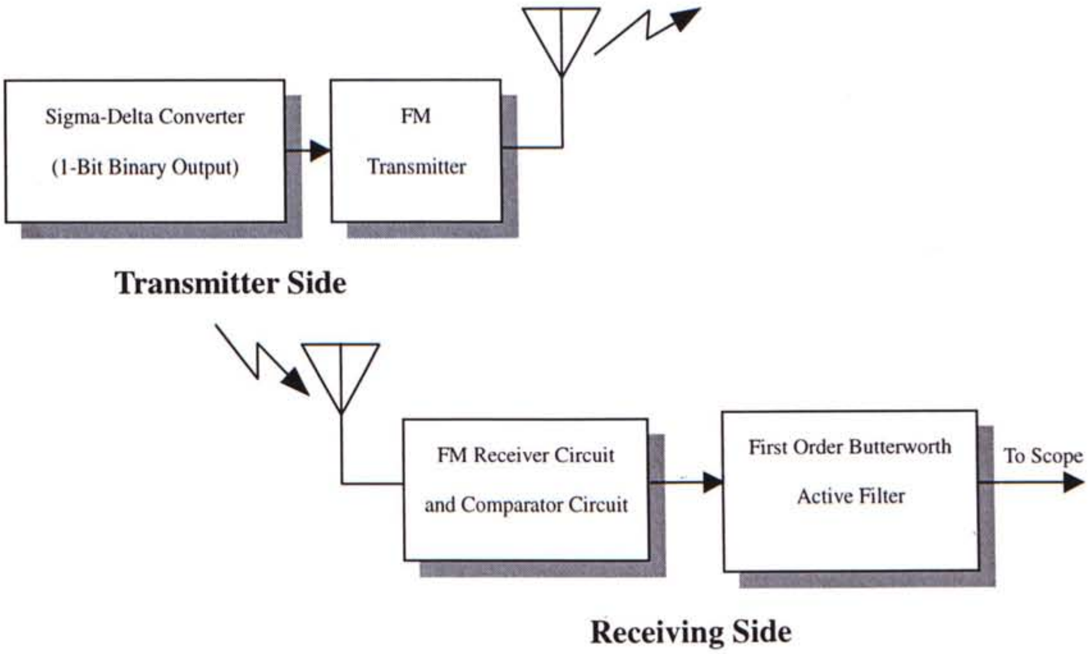


Figure 4.49 Experiment Setup of Scenario I of Wireless Application of Sigma-Delta Converter

The experimental setup is depicted in Figure 4.49. From the signal generator, sine tone of about 2 Hz was applied to the self-made first-order Sigma-Delta converter. The converter output was fed into a FM transmitter (carrier frequency 88-100 MHz). On the receiving end, a commercial FM receiver demodulated the transmitted signal and a comparator was used for deciding whether the incoming signal represents "1" or "0". A first-order low-pass active filter recovered the input signal that was shown on scope. Brief circuit diagram for the converter is shown in Figure 4.50. It was built with ten resistors, seven capacitors, one quad opamp, one D Flip-Flop, two NAND gates and one instrumentation amplifier. Compared to the case with an 8-Bit Successive-Approximation ADC, an 8-Bit D/A converter and a Register are required which consumes more power and components in implementation.

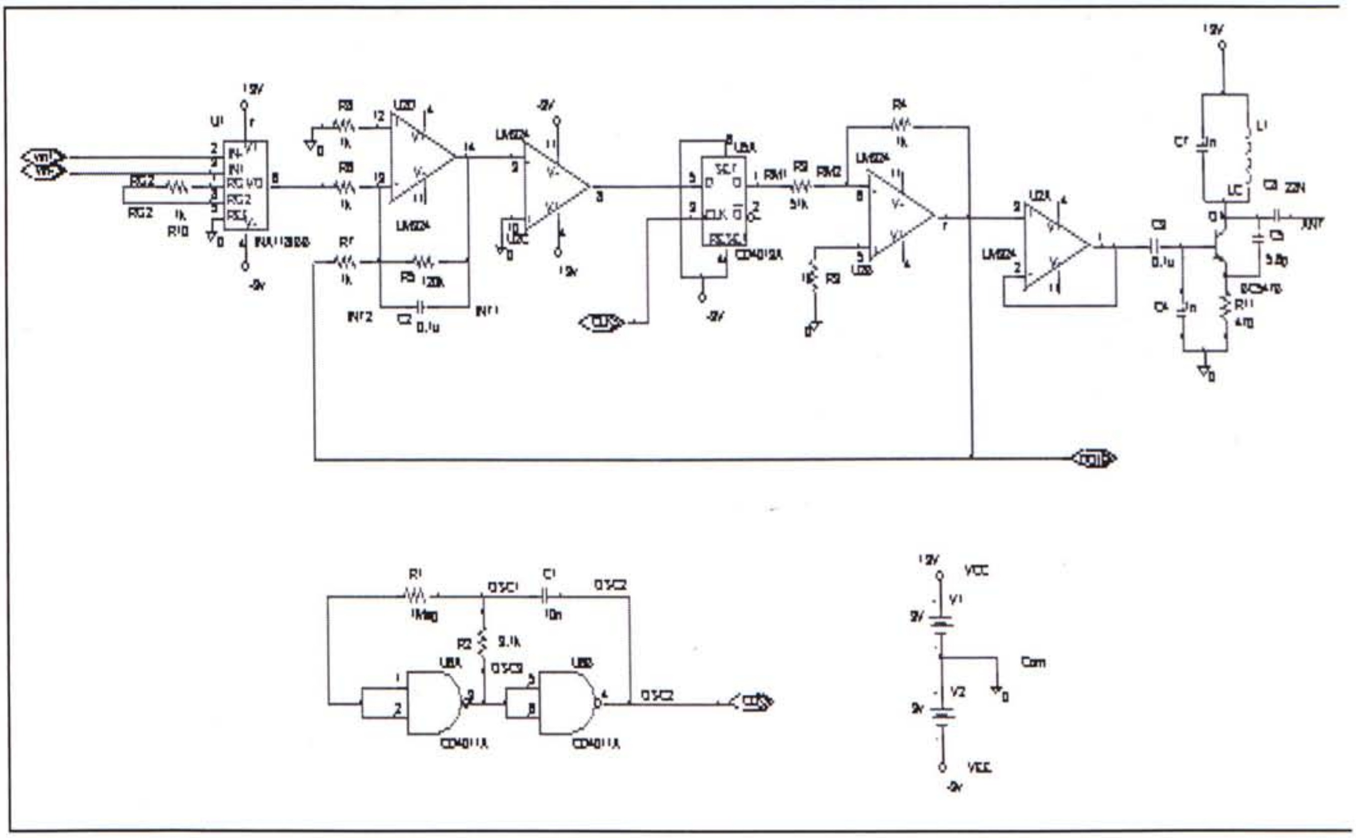
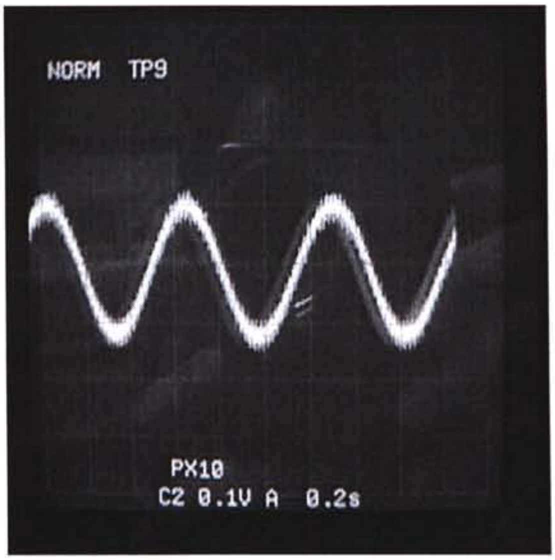


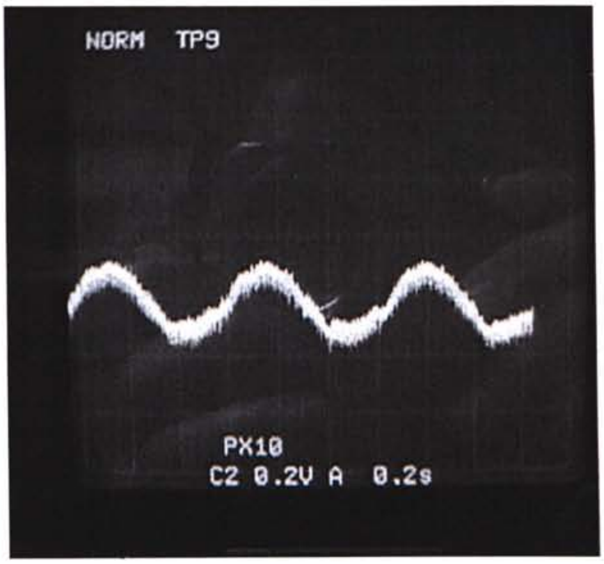
Figure 4.50 Circuit Diagram for the Telemetric Device with Sigma-Delta Converter

Photographs were picked up by a digital camera and will be shown in the next section .

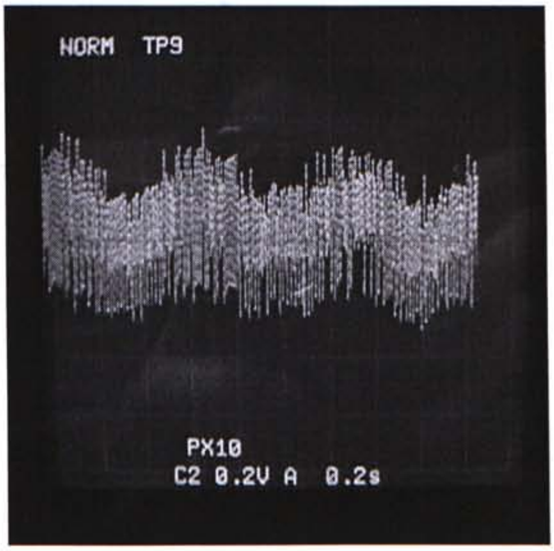
4.3.3.2 Results



a)



b)



c)

Figure 4.51 Results of Scenario I (with Decreasing Sampling Frequencies: a) Highest, c) Lowest)

4.3.3.3 Discussion

From Figure 4.51, it is observed that the noise increases as the sampling frequency decrease. Better performance can be anticipated if higher order low-pass filter can be applied for recovering digitized signal.

4.3.4 Scenario II (Digital Decoding)

4.3.4.1 Experimental Setup

The experimental setup is depicted in Figure 4.52. From the signal generator, sine tones of about *1.4* and *14* Hz (peak-to-peak voltages of 0.2 and 0.4 respectively) are applied to the Sigma-Delta converter. The sampling frequency for the Sigma-Delta converter is about *800* Hz. Similar to the setup of Scenario I, the converter output is fed into a FM transmitter (carrier frequency 88-100 MHz) and a commercial FM receiver demodulates the transmitted signal. A comparator is used for deciding whether the incoming signal represents "1" or "0". The WINDAQ acquisition unit with sampling frequency of 40kHz digitizes the binary bits. Data acquired is then saved to files and further processing was performed by *MATLAB*. The Power Spectral Densities of the converter output for *1.4* and *14* Hz signals are shown in subsection 4.3.4.2 (Figure 4.53 and Figure 4.54). The Power Spectral Densities is obtained from 262144 (2^{18}) point FFT of the acquired data with Hanning window applied.

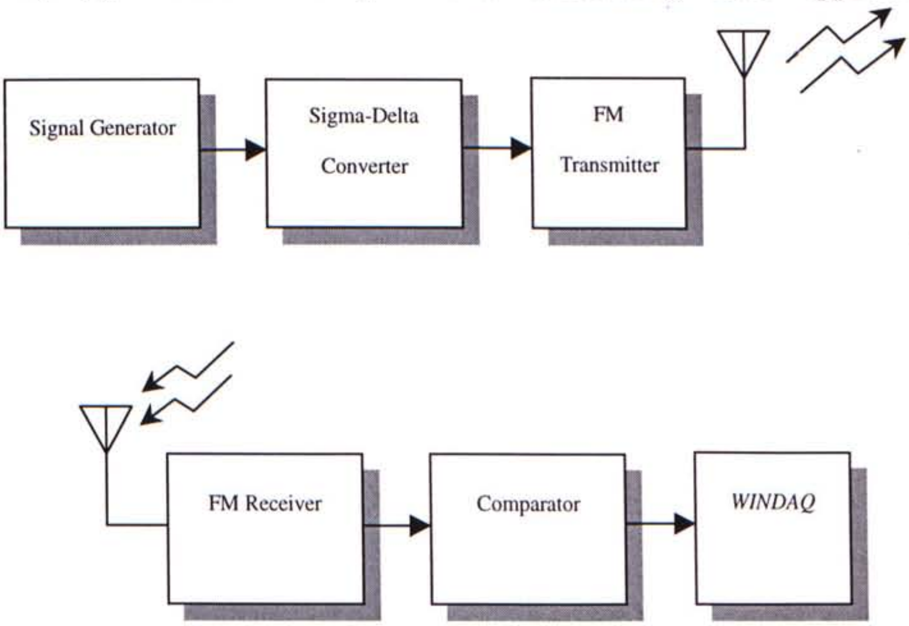


Figure 4.52 The Experimental Setup for Wireless Application of Sigma-Delta Converter

Another experiment with the same circuit was done. Signals this time were picked up from a subject with the concentric electrode in real time. Photographs showing two excerpt of received signal have been shown in Figure 3.7 of Chapter 3.

4.3.4.2 Results

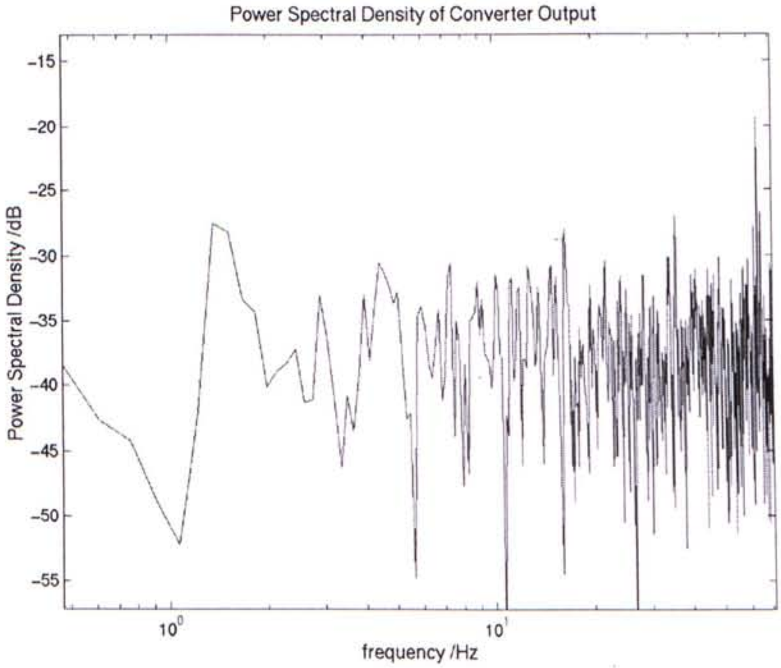


Figure 4.53 Power Spectral Density of Converter Output (Signal of about 1.4 Hz)

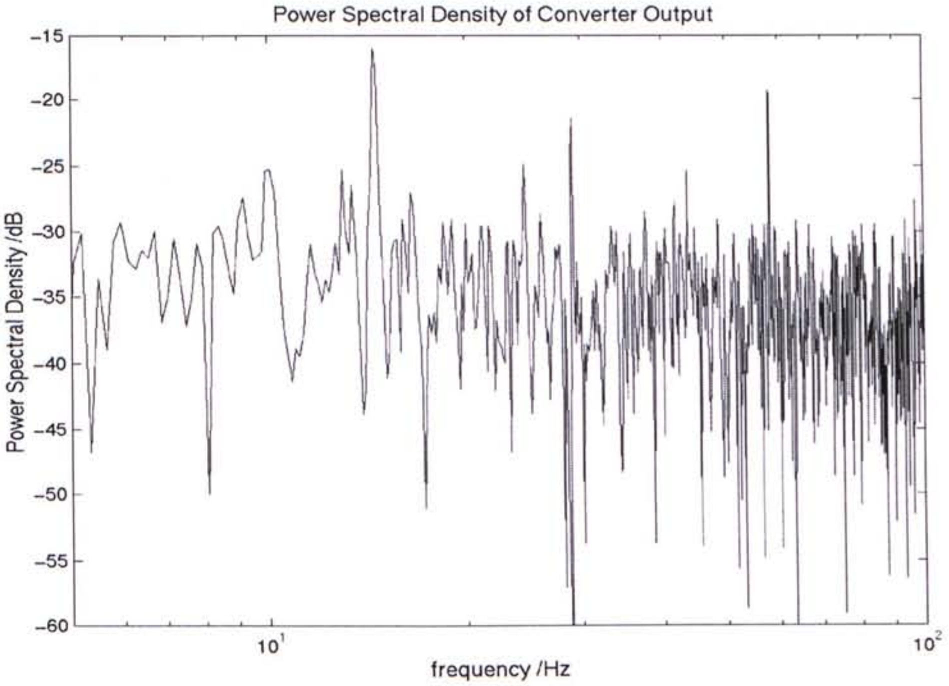


Figure 4.54 Power Spectral Density of Converter Output (Signal of about 14 Hz)

4.3.4.3 Discussion

From Figure 4.53 and Figure 4.54, input sine tone can be noted in the power spectrum of the binary output received wirelessly. Noise was intense at the vicinity of the input tone especially for the case of input frequency about *1.4* Hz. Sources of excessive noise can be due to the low sampling frequency of the Sigma-Delta converter and external noise since measurements were made by the side of a notebook computer.

4.4 Discussion and Conclusion

Due to the relatively lower bandwidth of ECG signals, over-sampling is feasible. By using one of the over-sampling techniques, namely the delta-sigma modulation, both the modulating and recovering circuitry are simpler. The analog signal can be reconstructed from the digital bit stream by simply using a low-pass filter either in analogue or digital form. The original signal, as shown in the simulation results, can be recovered by low-pass filtering. This is also verified in the experimental results. It is noted that the performance of Sigma-Delta converter is related to the sampling frequency. There is an improvement of 9 dB when sampling frequency is doubled theoretically. From simulation results in section 0 and 0, the improvements are from 5 to 12 dB among various sampling frequencies, signal amplitudes and signal types.

In wireless application, it is shown from Scenario I (section 4.3.3, Analogue Decoding) that the recovered signal was better with higher sampling frequency. However, in Scenario II (section 4.3.4, Digital Decoding), it is observed strong noise existed and a good quality signal cannot be recovered. The source of strong noise is attributed to the low sampling frequency (*800* Hz) and external noise from notebook computer nearby the measurement site.

Nevertheless, good quality results can be achieved by digital decoding. Even with a first-order low-pass analogue active filter, good quality results can be obtained. It can be anticipated that with better filter characteristic provided by digital decoding, filtering methods, better quality results can be obtained with suitable sampling frequency.

Chapter 5 Conclusion and Future Work

5.1 General Conclusion

With the goal of rendering easy and prompt monitoring of ECG signal, the idea of Wireless Electrode (WE) is roused. A WE is consisted of a "Single-Electrode" and radio telemetric circuitry. The "Single-Electrode" is for minimizing the number of electrodes attached to the body surface while the radio telemetry capability provides patients with ambulatory freedom.

"Single-Electrode" is indeed a virtual one. Within the "Single-Electrode", two contact points are still required by means of a concentric electrode assembly. The concentric electrode scheme provides more localized information on the body surface ECG as noted by various researchers as discussed in Chapter 3. Typical signals are shown in this work.

Radio telemetry applies to the "Single-Electrode" making it a WE (Wireless Electrode). Analogue and digital transmissions can be implemented. In case of digital transmission, a first-order Sigma-Delta converter is used and results are shown in this work. The Sigma-Delta converter is attractive due to its simplicity in analogue circuitry and its being tolerant to component imperfections.

High-resolution output is provided by the Sigma-Delta converter by means of digital signal processing unit. Sigma-Delta converter originally gives only one bit binary output with simple analogue circuitry. The digital signal processing unit process on the one bit stream to give multi-bit output. This unit is usually fabricated with the basic, simple analogue circuitry of the Sigma-Delta converter as a single chip. The inclusion of the digital processing unit increase the circuit complexity. An idea is to separate the two by a wireless link. The transmitted single bit binary stream is received and processed to provide high-quality recovered signal. This scenario is implemented and tested with the concentric electrode.

5.2 Future Work

In this study, the idea of WE is demonstrated. However, the size of device is not fully minimized. The whole circuit can be further minimized in size by using VLSI or ASIC technology. The impact of the WE can be exploited more if the size is minimized. The circuit implemented is on the first-order Sigma-Delta converter architecture that is the simplest one. Other architectures can be investigated for better performance.

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List of Abbreviations

ADC	**Analogue-to-Digital Converter:** A device that converts an analogue signal into binary digits
AWGN	**Additive White Gaussian Noise:** One kind of noise that is white and Gaussian in nature and it is added to signal in concern
BER	**Bit Error Rate:** Probability of a Binary Bit in error
DSP	**Digital Signal Processing:** Processing on digitized signals
ECG	**Electrocardiogram:** Electrical Signal picked from the body surface
MSE	**Mean Square Error:** Mean of Square of Difference (or Error) between two Signals
SNR	**Signal-to-Noise Ratio:** The Ratio of Signal Power to that of Noise