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EEG dynamic noise floor measurement with stochastic flash A/D converter

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ABSTRACT

The noise floor is the measure of the signal at the output of a measurement system, produced by internal and external noise sources. The dynamic noise floor quantifies the effects of non-uniform noise. The main objective is to quantify accurately the noise floor in an EEG system, as the measurement error of the biopotential signals is in the microvolts voltage range. Signals measured by an EEG range down to 0.01 Hz, so measurements require long time and produce large quantities of data that needs to be measured with high accuracy. This paper presents a novel idea for the noise floor quantification using stochastic method of measurement over a long time interval. The accuracy of the method is independent of the input noise type, and it depends only on duration of the measurement interval and the flash A/D converter accuracy. The method is based around the 4-bit Stochastic Flash ADC with fast processing time of recorded data and high precision. A mathematical model of the stochastic measurement results is given. When the length of the measurement interval is 100 s, the relative measurement error falls below 0.004%. Long time of measurement and high precision allow this method to be integrated into the mixed-mode system on a chip, as a part of self-calibration process in a wearable wireless medical monitoring device, such as an EEG. The prototype with the integrated EEG chip is described and its noise floor is measured using the 4-bit Stochastic Flash ADC. In conclusion, the measurement results are analyzed and compared to the product datasheet figures, showing the significance of the presented measurement method which does not depend on the type of measured noise.

1. Introduction

Electroencephalographic (EEG) measurement is commonly used in medical and research areas [1]. EEG signals are nonstationary, low-level electrical biopotentials (generally less than 300 μV) originating from physiological processes in the brain [1,2]. The frequencies of these voltages can range from 0.01 to 100 Hz, and their characteristics are highly dependent on the level of activity of the cerebral cortex. From a hardware complexity perspective [2], electroencephalograms have traditionally been the most difficult electrophysiological measurements to acquire.

Standard EEG measurement system consists of electrodes and cables, a conditioning module, a digitizing module and a module for performing data processing, recording and presenting. The microvolt level EEG voltage is subjected to noise, often many times greater than the signal itself. To achieve satisfactory amplification of such low level EEG signal, the conditioning module incorporates amplifying circuits with a high gain (5000–20,000 times), but also implements Driven Right Leg (DRL) method [3] and high-order analog filters with a sharp roll-off to ensure that only the desired signal is detected [4]. EEG data processing has a highly important role, because of the significance of many spectral and nonlinear measures [1,2].

The low frequency components of the inherent noise impose limitations on the EEG frequency band. Low frequencies of the order of 0.1 Hz are significant when measuring phenomena with very slow shifts of electric potential, such as the contingent negative variation (CNV) and the Bereitschaftspotential (BP). Frequency components of 0.5 Hz are present during slow-wave sleep, corresponding to the ultraslow oscillations measured intracellularly from cortical neurons through layers II to VI, consisting of prolonged depolarizing and hyperpolarizing components. Signal amplitudes of 1–300 μV can be obtained in an EEG, so any noise present in the system can affect the accuracy of the measurement thus producing false results or even masking the entire signal. Low-pass filters can reduce high frequency components of the noise, but

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frequencies below 100 Hz cannot be filtered as most of the information recorded by an EEG lies in that band. Some specific frequencies, like 50 Hz of the mains power line, are filtered with notch filters for frequencies in a narrow band [5].

If noise is reduced to the acceptable level of at least 10 times lower than the EEG signal, then uncontaminated EEG records can be obtained [1].

2. Noise floor

When low-level signals are processed in modern communication systems, they often tend to be masked by the noise added by the system itself. Sensitivity, bit-error ratio and noise figure are the system parameters that characterize low-level signal processing ability. The noise figure (NF) of a system is defined as a ratio of its signal-to-noise power ratio at the input to its signal-to-noise power ratio at the output. NF characterizes the entire system and its components, and differentiates one system from another. Controlling the noise figure of the system components controls the noise figure of the whole system. The relevance of these specifications implies that highly repeatable and accurate measurements of the system noise properties are very important. The measurement of noise properties of a network serves to minimize the problem of noise generated in receiving systems [6].

An EEG instrument is a form of communication system where electrodes and AFE represent the network, and ADC and processing unit represent the receiving part of the system. The noise floor figure is the main component of NF in an EEG. The importance of the noise floor level measurement in all aspects of modern communications is illustrated by the global man-made RF spectrum noise floor research by NASA [7].

The noise floor of a measurement system is the amplitude of the output signal, created by the sum of all internal and external noise sources. Noise in this context refers to any unwanted signal affecting the measurement system. The noise floor is measured when all system inputs are grounded. In [8] it is defined that the noise floor of an instrument is important because: it determines the lowest possible signal that can be measured, it limits dynamic range of the input signal and it affects the standard deviation (repeatability) of the measurements. When measuring the signal close to the noise floor, the measurement uncertainty increases. In this case, repeatability can be achieved by averaging.

Modern biomedical measurements are based on acquisition and conversion of analog signals into digital form using A/D converters (ADCs). In ADC theory, the noise floor is a frequency spectrum parameter used in testing, but it has no uniform definition [9]. The computational formula for the *ideal noise floor* of an ideal ADC is given in [10] and is described as the function of the number of ADC accuracy bits and the signal to noise ratio (SNR). The *thermal (Johnson) noise floor* is the consequence of the noise generated by thermally agitated electrons, and it presents the physical lower limit of the noise floor. This noise floor definition is also applied to other electronic instruments – in telecommunications, audio processing, biomedicine, etc.

Depending on the type of noise present at the input of the system, two distinct cases are observed:

Common noise floor is used when white noise is present in the system. White noise has normal probability density function (PDF) of its amplitudes, without harmonic distortions, transients or voltage spikes. It represents background ambient noise, produced by the atmospheric noise and the cosmic background radiation.

Dynamic noise floor is the case that is more general. It is used when various types of fabricated (non-white) noise are present in the system, including short bursts in surrounding electromagnetic (EM) field. Main sources of a non-white noise are switched-mode power supplies, wireless RF emitters, electronic equipment with fast CPUs, etc. [11,12].

The measurement method presented in this paper is not dependent on the type of input noise. It measures the noise floor in the system, regardless of the noise harmonic content, relying only on the measurement over a long period. The *dynamic noise floor* measurement implies that any type of noise floor can be measured, as the common *noise floor* is a subtype of the *dynamic noise floor*. In addition, it is important to distinguish the *dynamic noise floor* from the *ideal noise floor*.

The noise floor is a critical parameter in an electronic measurement system operating with low-level signals, such as an electroencephalograph (EEG). Acquisition of EEG data in an ideal, low-noise environment is highly effective [13], but when measurements are performed in non-ideal, noisy surroundings, low-level EEG signals are often masked by high noise floor of the instrument. A typical example is a setting of every-day surroundings of a human subject, with various EM noise sources. Highly accurate and precise quantification of the noise floor enables the compensation of measurement error and the reduction of measurement uncertainty. The dynamic noise floor is measured when no external signal is applied to the input, and the only noise signal present in the system comes from the internal circuitry crosstalk and the parasitic coupling with the external noise sources. Measurements of the low frequency signals over long time intervals produce large amount of data, so fast data processing is also a necessity [14].

Least significant bit (LSB) represents the smallest voltage step in an n-bit ADC, where $LSB = 2R/2^n$. Table 1 gives the specifications of several typical commercial EEGs [15–17]. Large number of ADC sampling bits produce the system with very high sensitivity, but the high noise floor figure masks lower bits of resolution. As the noise floor is one order of magnitude larger than the LSB, the effective resolution of the ADC is lower. USBamp EEG [16] is declared with 24 bits of resolution, but noise floor is 10 times the LSB. In effect, ADC now has only 19 noise-free, useful bits with 0.763 mV LSB. For 20 bits, the voltage step is 0.381 mV, still lower than 0.4 mV noise level. All other bits are masked by the noise floor level, thus degrading the resolution and measurement accuracy. If we analyze the characteristics of commercial EEG instruments, we can notice that LSB voltage step is getting increasingly lower, but the decrease in the high noise floor of the instruments is practically negligible. It appears that the improvement of EEG instruments resolution is not followed by the decrease of high noise floor level.

3. Denoising

There are several standard mathematical methods of noise reduction (denoising) which are used for the removal of noise present in the EEG signals [18]: a) Principal component analysis (PCA) is a mathematical procedure that transforms a number of correlated variables into a smaller number of uncorrelated variables (principal components), b) Independent Component Analysis (ICA) based denoising where components of many signals are often very sparse so noises in the ICA domain can be removed, c) Wavelet (time limited oscillatory vanishing wave) based denoising where an analysis of non-stationary or transient phenomena is performed, d) Wavelet Packet (linear combinations of wavelets) transform, where EEG signal is decomposed into both high and low frequency components. One of the principal components/variables in all given methods is the noise present in the EEG system. An accurately determined level of internal noise (noise floor) improves the denoising process and improves the accuracy of the final result.

The methods of denoising used in practice are described in [19]. The simplest form of denoising is by filtering. In order to be filtered, the noise frequency needs to be either below or above the