FPGA based model of processing EEG signal

Platon Sovilj, *Member, IEEE,* and Nebojša Pjevalica, *Member, IEEE*

***Abstract* — The paper presents a field-programmable gate array (FPGA) based model for measurement of electroencephalography (EEG) signal. The novelty of this system is implementation of digital stochastic block based on stochastic analog-to-digital (A/D) conversion and accumulation, with a novel hardware structure tailored for harmonic measurements. Simulated stochastic measurement EEG system measured DC component of the signal and 200 harmonics with the base frequency of 0.5 Hz, and results showed consistency with the developed theory.**

***Keywords* — Electroencephalography, harmonic analysis, digital measurements, noise, stochastic processes, uncertainty.**

I. INTRODUCTION

ELECTROENCEPHALOGRAMS are recordings of the small electrical potentials (generally less than 300μV) produced by the brain [1-2]. The frequencies of these brain produced signals range from 0.5 to 100 Hz, and their characteristics are highly dependent on the degree of activity of the cerebral cortex [3]. From a hardware standpoint EEG is the most difficult electrogram measurement to acquire [2].

EEG signal is non-stationary signal but power spectral analysis of EEG not only provides a summary of the EEG in a convenient graphic form but also facilitates statistical analysis of EEG changes that may not be evident on simple inspection of the records [1]. The first application of EEG power spectral analysis by general-purpose computers was reported in 1963 by Walter, but it was not until the introduction of the Fast Fourier Transform (FFT) by Cooley and Tukey in 1965 that machine computation of the EEG became commonplace. Although an individual FFT is usually calculated for a short section of EEG data (e.g., from 1 to 8 seconds), the signal segmentation with subsequent averaging of individual modified periodograms has been shown to provide a consistent estimator of the power spectrum [1].

Development of method for stochastic measurements is reported in [4-6] and it appeared to be an efficient method for replacing FFT in mains voltage and current harmonic analysis. A digital stochastic instrument based on this method is reported in [7, 8]. This instrument performs harmonic analyses for the direct current (DC) component and up to 49 harmonics (both cosine and sine components over the measuring interval of 20 ms) in each of seven different input channels. Its operation is based on stochastic A/D conversion and accumulation, with a novel hardware structure designed for harmonic measurements. The method and the predicted uncertainty for fifty harmonics are validated in [7] by simulation and experiments using sampling frequency of 250 kHz per channel.

The concept of digital stochastic instrument reported in [7] is adjusted for a model of EEG harmonics measurement. The properties of the model are: 8-bit dithered A/D converter word and ability to measure up to 201 harmonics (DC component as well as 200 sine and 200 cosine components).

Platon Sovilj is with the Faculty of technical sciences, University of Novi Sad, Serbia (phone: 381-21-6350122; fax: 381-21-6350122; e-mail: platon@uns.ac.rs).

Nebojsa Pjevalica is with the Faculty of technical sciences, University of Novi Sad, Serbia (e-mail: pjevalica@uns.ac.rs).

II. DIGITAL STOCHASTIC MEASUREMENT

A. The method compared with FFT approach

Common practice in EEG power spectral analysis is to calculate an individual Discrete Fourier Transform (by FFT algorithm) for a short section of EEG signal data [1]. This FFT approach is based on calculating Fourier coefficients after all analog samples over the section of the signal are digitized by A/D converter.

Instead of waiting for digitalization of all analog samples over interval T (T is a variable which will represent duration of the section in the paper) before begining calculations of Fourier coefficients, digital stochastic measurement method (by appropriate interfacing and use of FPGA structure, memory and A/D converter) simultaneously perform digitalization of the samples and calculations of Fourier coefficients. The algorithm of these calculations is based on FPGA implementation of Discrete Fourier Transform and dithering analog samples.

B. The input signal

The signal at the input of digital stochastic measurement block is the conditioned EEG signal. The motivation of this conditioning is to amplify weak EEG signal obtained by electrodes, and also to reject noise. In this paper the focus of analysis is the implementation of digital stochastic measurement, neglecting the non-ideality issues of amplifiers and filters in conditioning block. Hence, it is proposed that conditioned signal s is the sum of linearly amplified EEG signal s_e (which will be called just "amplified EEG signal" in further text) and the white noise n with uniform or Gaussian amplitude distribution:

$$s = s_e + n \qquad (1)$$

Over the above defined interval T, in ideal situation (when there is no noise), signal s is equal to s_e, and from viewpoint of Fourier analysis it can be interpolated as:

$$s_e(t) = \frac{a_0}{2} + \sum_{n=1}^{M} a_n \cos n\omega_0 t + \sum_{n=1}^{M} b_n \sin n\omega_0 t \quad (2)$$

$\omega_0 = 2\pi / T$, a_i are cosine Fourier coefficients, b_i are sine Fourier coefficients and M is the last index of the coefficients (interpolation of the signal is more accurate for greater M).

C. Measurement of one Fourier coefficient

The instrument presented in [7, 8] is designed to measure harmonics of mains voltages and currents, but its concept can be applied to measurement of harmonics of any signal that can be presented as (2). Therefore its concept is the base for conceptual block diagram of digital stochastic measurement of one Fourier coefficient of the conditioned EEG signal. (Fig. 1)

Auxiliary signal s_a is a dithered base (cosine or sine) function. If R is input range of A/D converter from Fig. 1 then $s_a = R \cos k\omega_0 t$, for measuring *kth* cosine Fourier coefficient and $s_a = R \sin k\omega_0 t$, for measuring *kth* sine Fourier coefficient.

d_1 and d_2 are generated dithering signals and they satisfy the following conditions that limit their amplitude and define their probability density function:

$$0 \le |d_i| \le \frac{\Delta_i}{2} \quad (3)$$

$$p(d_i) = \frac{1}{\Delta_i} \text{, for } i = 1, 2 \quad (4)$$

Sampled values of conditioned EEG signal s and auxiliary signal s_a at every time instant within the measurement interval (T) are Ψ_e and Ψ_a, respectively. The measured value Ψ (multiplier output) differs from the input signals' product by the measurement error e, which includes effect of quantization within A/D converter and the introduced dither:

$$\Psi = \Psi_e \cdot \Psi_a = s \cdot s_a + e \quad (5)$$

As the measured conditioned signal consists of the amplified EEG signal and the noise, then:

$$\Psi = s_e \cdot s_a + n \cdot s_a + e \quad (6)$$

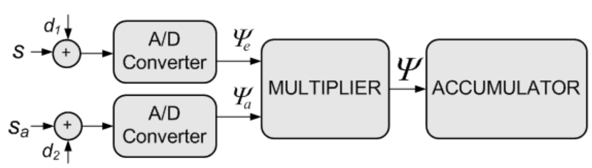

Fig 1. Conceptual block diagram for digital stochastic measurement of one Fourier coefficient. s is conditioned EEG signal. The accumulator output is used for calculation of the coefficient.

The first term of the multiplier output is the signal that is to be measured and the second term is caused by noise. The three terms in (6) are statistically independent, and average $\overline{\Psi}$ is the sum of their average values.

The average value of the third term in (6) is zero, as shown in [6] and does not affect the average value of the expected output $\overline{\Psi}$ over the measurement period. A finite input range of $\pm R$ of digital stochastic measurement block defines the boundary of the average noise integration. Therefore the remaining two terms in the average value are [4]:

$$\overline{\Psi} = \frac{1}{T}\int_0^T s_e \cdot s_a dt + \left(\int_{-R}^{R} n \cdot p(n) dn \right) \frac{1}{T}\int_0^T s_a dt \quad (7)$$

If we assume that the noise has a Gaussian unbiased nature, its average value is zero so that the second term in (7) becomes zero, and then:

$$\overline{\Psi} = \frac{1}{T}\int_0^T s_e \cdot s_a dt \,. \quad (8)$$

In digital measurements, for N samples of the conditioned signal over the interval T, the average value is [7]:

$$\overline{\Psi} = \frac{1}{N}\sum_{k=1}^{N} \Psi_k \quad (9)$$

Summing of samples during the measurement subinterval is done by the accumulator and this sum is the output of the accumulator (Fig. 1). This output can be processed by microprocessor which divide the accumulator output by the number of samples N, and also calculates each sine (or cosine) component of the *kth* harmonic of the output as in [7] (subscripts *sink* and *cosk* indicates that *kth* sine and *kth* cosine Fourier coefficient is measured) :

$$a_k = \frac{2\overline{\Psi}_{\cos k}}{R} \qquad b_k = \frac{2\overline{\Psi}_{\sin k}}{R} \quad (10)$$

According to [7] the standard measurement uncertainty $u(\overline{\Psi})$ and the relative measurement uncertainty u are limited by:

$$u(\overline{\Psi}) \le \frac{S_a \cdot (\sigma_n + \frac{\Delta_1}{2})}{\sqrt{N}}, \; u \le \frac{S_a \cdot (\sigma_n + \frac{\Delta_1}{2})}{\overline{\Psi} \cdot \sqrt{N}} \quad (11)$$

Limit of the standard measurement uncertainty (6) is determined by the Root Mean Square (RMS) value of the auxiliary signal (S_a), noise (σ_n), the resolution in A/D converter (Δ_1), and by the number of samples within the measurement interval (N). R is the amplitude of the auxiliary signal, therefore:

$$S_a = \frac{R}{\sqrt{2}} \quad (12)$$

According to [7], (11) and (12) standard measurement uncertainty of any Fourier coefficient measured by this method is limited by:

$$u(a_k) = u(b_k) \le \frac{\sqrt{2} \cdot (\sigma_n + \frac{\Delta_1}{2})}{\sqrt{N}} \quad (13)$$

The quantum Δ_1 is defined by the A/D converter resolution, and the number of samples N can be a compromise between the necessary measurement speed and the required accuracy [7]. Therefore the system can have a very good accuracy even when the measurement noise is significant, due to the increased number of samples N.

D. Measurement of predefined set of EEG harmonics

Similarly to [7] the conceptual block diagram from Fig. 1 can be implemented as in Fig. 2 having Ψ_a digital values stored in the memory thus resulting in elimination of second A/D converter from Fig. 1. If the system should measure DC component and N_h harmonics this structure requires $2N_h+1$ multipliers and $2N_h+1$ accumulators.

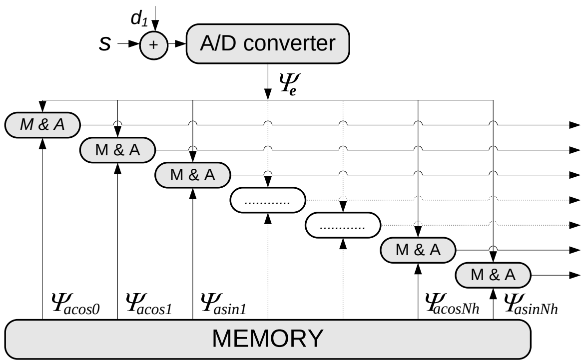

Fig 2. Conceptual block diagram for measuring predefined set of conditioned EEG signal harmonics. Each element marked with M&A is consisted of one multiplier and one accumulator.

At first sight, block diagram from Fig. 2 seems to require complex hardware structure but its hardware implementation can be relatively simple. These multipliers and accumulators are implemented by field-programmable gate array (FPGA) structure (Cyclone chip EP1C6Q240C8 was used*)* which finally calculates Fourier coefficients, while microprocessor interfaces this block with recording block (as it is done in [7-8]).

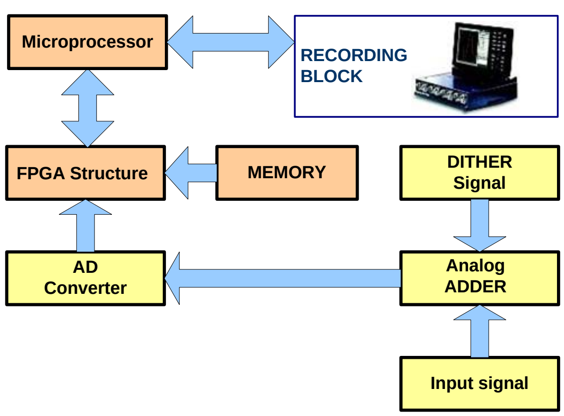

Fig 3. Hardware block diagram of digital stochastic measurement block interfaced to recording block.

Regarding A/D converter, an important thing is that this A/D converter can have lower resolution and faster conversion time than the one in typical EEG measurement, which can be useful for parallelization of measurements necessary for multichannel recordings. Block diagram of hardware implementation is given at Fig. 3. Pseudostochastic dither signal can be generated by FPGA chip, analog adder is required for performing addition of dither, and finally interface to recording block can be implemented by microprocessor too.

III. RESULTS

2 seconds of digitally filtered EEG measurement data had been extracted (Fig. 4), and it was the input for simulations.

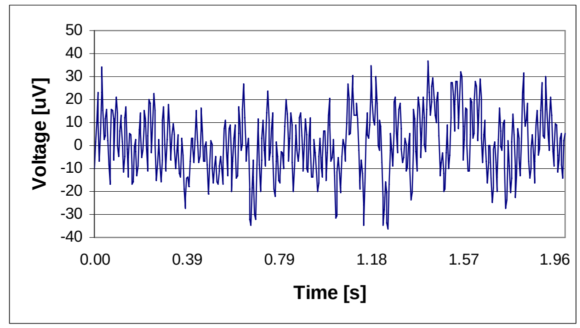

Fig 4. 2 seconds of EEG signal voltage as simulation input.

The first aim of the simulation was to compare the calculations of developed theory for measurement uncertainty (13) with measurement uncertainty obtained by simulations of measuring amplified EEG signal harmonics by digital stochastic measurement block.

Input signal for all simulations was the sum of previously measured signal (Fig. 4) and the white noise (uniform and Gaussian amplitude distributions of the noise were used and the signal-to-noise ratio was varied from 20dB to -10dB). The input signal amplitude was limited with the input range (*R*) of A/D converter.

The simulation sampling frequency of stochastic measurement EEG system varied from 2560 to 256000 Hz, giving up to 512000 samples per fundamental period of the measured amplified EEG signal. The resolution of A/D converter was 8-bit and dither signals d_1 and d_2 were generated in 64-bit resolution (for reasons of appropriate randomness), but then scaled to be up to $\Delta_1/2$ and $\Delta_2/2$ in amplitude, so that (3) is fulfilled. The digital dithered base functions of auxiliary signal ($R\sin\omega t + d_2$ or $R\cos\omega t + d_2$) were stored in memory in 64-bit floating point resolution but passed to the multiplier in 10-bit resolution, thus making faithful simulation of a 10-bit A/D converter. The simulated system measured DC component and 200 harmonics, with fundamental frequency f_0 = 0.5 Hz.

Totally 12 sets of simulations for stochastic EEG measurement system was performed – for three sampling frequencies (2560Hz, 25600Hz and 256000Hz) and for four values of SNR (-10 dB, 0 dB, 10 dB and 20 dB), which gives 12 points of frequency-SNR pairs. Each set of simulations was consisted of 100 simulations performed.

The final result of one simulation set (average standard uncertainty) is calculated by averaging results of all simulations in the set; the result of one simulation is actually average value of standard uncertainties for each Fourier coefficient (of course, measuring interval was 2 seconds).

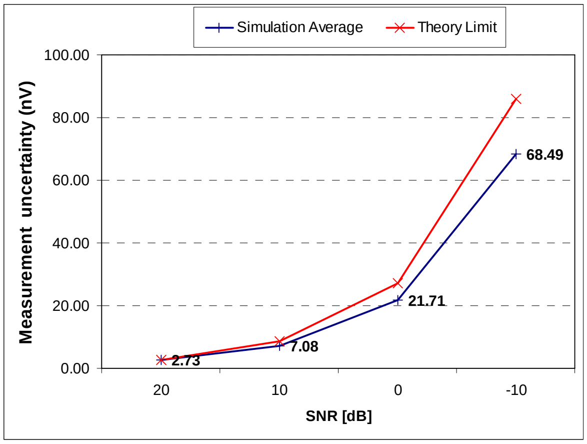

Fig 5. Measurement uncertainty for Fourier coefficients (sampling frequency is 256 kHz): theory calculation is confirmed by simulation result. The noise is white noise with uniform distribution of amplitudes.

Fig. 5 and Fig. 6 shows that the values of standard uncertainties obtained by simulation, follow the predicted theoretical results (13) where the limit of standard uncertainty is determined by the standard deviation of the noise but not by the type of noise distribution.

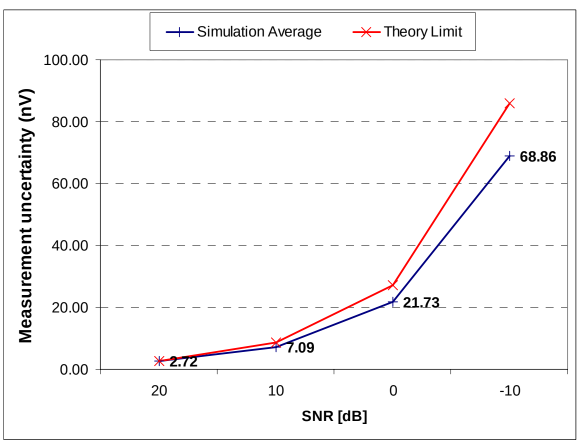

Fig 6. Measurement uncertainty for Fourier coefficients (sampling frequency is 256 kHz): theory calculation is confirmed by simulation result. The noise is white noise with Gaussian distribution of amplitudes.

IV. CONCLUSION

EEG signal is weak signal which can be easily contaminated by noise. Accurate measurement of EEG signal can be an especially great challenge when strong interference noise is greater than conditioned EEG signal.

The stochastic measurement EEG system was investigated by the developed theory and applied simulations. The simulated structure of one-channel stochastic EEG measurement system includes one flash A/D converter, a memory for storing dithered base functions, and as many signal multipliers and digital accumulators as the number of sine and cosine components of the measured EEG harmonics.

The research showed that stochastic measurement EEG system has possibility to increase accuracy and noise rejection by increasing number of samples in measurement interval.

ACKNOWLEDGMENT

The authors wish to thank Vladimir Vujičić, Ivan Županski, Slobodan Milovančev, Josif Tomić, Dragan Pejić, Velibor Pjevalica, and Branislav Santrač, for their contribution to the development of stochastic measurement method.

REFERENCES

[1] J.D. Bronzino, "Principles of Electroencephalography", in *Biomedical Engineering Handbook*, Vol. I, J.D. Bronzino, 2nd ed., New York: CRC Press LLC, 2000.

[2] J. G. Webster, *Medical Instrumentation Application and Design*, New York: Wiley, 1998.

[3] M. Abeles and M. Goldstein, "Multispike Train Analysis", *Proc. IEEE,* No. 65, pp (762-773), 1977.

[4] V. Vujičić, S. Milovančev, M. Pešaljević, D. Pejić and I. Županski, "Low frequency stochastic true RMS instrument," *IEEE Trans. Instrum. Meas.*, vol. 48, pp.467-470, Apr. 1999.

[5] D. Pejic, V. Vujicic, "Accuracy limit of high-precision stochastic Watt-hour meter," *IEEE Trans. Instrum. Meas.*, vol. 49, pp. 617-620, June 2000.

[6] V. Vujičić, "Generalized low frequency stochastic true RMS instrument", *IEEE Trans. Instrum. Meas.*, vol. 50, pp. 1089-1092, Oct. 2001.

[7] B. Santrač, M. A. Sokola, Z. Mitrović, Ivan Županski and V. Vujičić, "A Novel Method for Stochastic Measurement of Harmonics at Low Signal-to-Noise Ratio", *IEEE Trans. Instrum. Meas.*, vol. 58, pp. 3434-3441, Oct. 2009.

[8] V. Pjevalica, and V. Vujičić, "Further Generalization of the Low-Frequency True-RMS instrument", *IEEE Trans. Instrum. Meas.*, Revised IM 5499, to be published.