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Note	

Low-power and Low-noise Amplifier with Intermittent Operation for Compressed Sensing in EEG Measurement Systems

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***Abstract*— This study presents a solution to achieve low power consumption by the intermittent operation of low-noise amplifiers (LNAs) for wireless electroencephalographs, that need a smaller battery. The LNA operates intermittently synchronized with the sampling timing of the analog-to-digital converter (ADC) by using the random undersampling matrix utilized in a previously proposed compressed sensing (CS) electroencephalogram measurement system. Designed using a 0.18 μm CMOS process, the LNA includes an intermittent operation circuit. The simulation results, the start-up time of the LNA was set to 4ms and the intermittent operation was performed at compression ratio of 4.17 based on a sampling frequency of 200Hz. The intermittent operation reduced power consumption by 58% compared to constant operation. The normalized mean square error (NMSE) was used to evaluate the influence of intermittent LNA operation on the reconstruction accuracy of CS. The difference in NMSE between intermittent and constant operation was only 9% on average over 25 frames. This indicates that intermittent operation minimally influenced the reconstruction accuracy.**

***Index Terms* — compressed sensing, EEG, intermittent operation, low-noise amplifier, low power, random undersampling**

I. INTRODUCTION

In recent years, much research has focused on realizing wireless electroencephalogram (EEG) measurement devices [1, 2]. A notable advantage of such devices is the reduced burden on the user. EEG is used in healthcare and in new technologies such as brain-computer interfaces and brain-machine interfaces [3, 4]. Thus, lightweight and battery-powered wireless EEG measurement devices are expected to become increasingly pivotal in these applications. However, studies have shown that batteries occupy considerable space in wearable device chassis [3], posing a challenge to both miniaturization and extended operation. A low power consumption EEG measurement system utilizing compressed sensing (CS) has been proposed to address this [5, 6]. CS can substantially reduce the amount of information the circuits process and, therefore, the power consumption associated with wireless transmission. Research on power-saving wireless EEG transmission systems utilizing CS along with experimental measurements are underway to substantiate this [7]. Although challenges exist in CS, research has led to the proposal of technologies that correspond to actual EEG signal measurements. Historically, the use of CS has faced challenges since reconstruction accuracy was degraded by artifacts due to decrease in sparsity of EEG caused by contamination of artifacts has been a problem in utilizing CS; however, solutions that combine random undersampling and independent component analysis have been proposed [8]-[10]. Various methods have been proposed to improve reconstruction accuracy under highly compressed conditions, and these methods have been successful [6, 11]. Other research topics related to the realization of EEG measurement systems employing CS include high-speed reconstruction [1], communication technology [2], and the treatment of circuit noise in CS systems [12]. As mentioned, progress in implementing CS for EEG measurement systems has enabled reduced power consumption, especially for wireless communication. However, reducing the power consumption of analog ICs remains challenging. One approach focuses on the current consumption of the power supply IC [13]; however, the analog front end (AFE) accounts for a large proportion of the total power consumption and offers increasing scope for improvement. In particular, among AFEs, the low-noise amplifiers (LNAs), which amplify the EEG signals, tend to consume more power and require the same number of channels as the number of electrodes[14, 15], thereby increasing the system power consumption. In addition, the LNA amplifies weak EEG signals; however, it incurs a tradeoff between noise performance and power consumption, hindering the EEG measurement system from achieving low power consumption. To solve this problem, we designed a low-powered LNA for CS [16]. In this study, we proposed to operate the LNA intermittently and use random undersampling, which was previously used in a CS EEG measurement system to further reduce power consumption [5]–[7]. The remainder of this study is organized as follows: Section 2 provides an overview of the proposed CS EEG measurement system with random undersampling and intermittent LNA operation; Section 3 describes the circuit configuration and start-up time of the designed LNA; Section 4 reports the effect of power consumption reduction during intermittent LNA operation and its influence on the reconstruction of EEG signals; Section 5 summarizes this study.

II. RANDOM UNDERSAMPLING CS EEG MEASUREMENT SYSTEM WITH INTERMITTENT OPERATION

Fig. 1 shows the proposed CS EEG measurement system using random undersampling. In wearable devices, EEG signals amplified by LNAs are input to an analog-to-digital converter (ADC) via anti-aliasing filters. The sampling timing of the ADC is controlled by a timing controller based on a random undersampling matrix. This enables low-power operations by reducing the samplings and data volume [5]–[7]. The ADC, data management, transmitter, and timing controller are implemented using a microcontroller unit (MCU).

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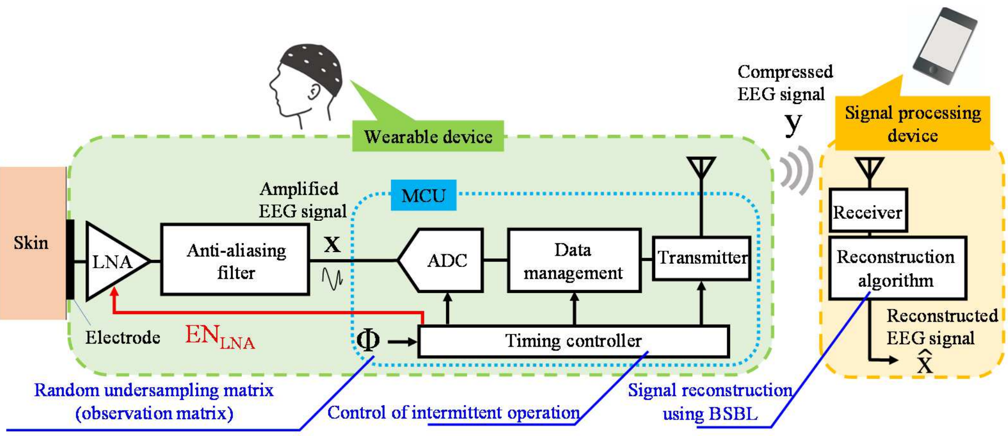

Fig. 1. The proposed CS EEG measurement system with random undersampling.

Via wireless communication, the compressed EEG signal is sent to the signal-processing device, which reconstructs the compressed EEG signal based on a reconstruction algorithm. A block-sparse Bayesian learning (BSBL) algorithm is used for reconstruction. In a conventional system, the LNA operates constantly [7]. However, in this study, the LNA was operated intermittently by the control signal, EN_{LNA} , to reduce power consumption. The proposed technique of reducing power consumption is only possible because of the use of random undersampling. The EN_{LNA} is based on the random undersampling matrix shared with the ADC, which facilitates intermittent LNA operation. Fig. 2 shows the EEG signal and sampling timing with a compression ratio (*CR*) of 4.17 at a sampling frequency of 200 Hz. *CR* means the ratio of sample points before and after compression. *CR* is determined by the number of points of random undersampling in one frame of EEG, and 4.17 was used in this study. *CR* of 4.17 corresponds equivalently to a sampling frequency of 48 Hz. In Fig. 2, 1 s is depicted in a single frame. In Sections 4, the sampling pattern shown in Fig. 2 was used to verify intermittent operation via a simulation. In this study, we designed the low-power LNA suitable for the above operation and show the results of Pre-simulation to prove the usefulness of the proposed technique. Although signal compression is applied to EEG in this study as shown in Fig.1, the proposed CS system is not restricted to EEG signals.

III. The Designed LNA : Circuit and Start-up Time

We used a circuit modified from our previous capacitively-coupled chopper instrumentation amplifier (CCIA) architecture-based low-consumption LNA for CS [16]. Fig. 3 shows the circuit blocks controlled by the EN_{LNA} in the LNA.

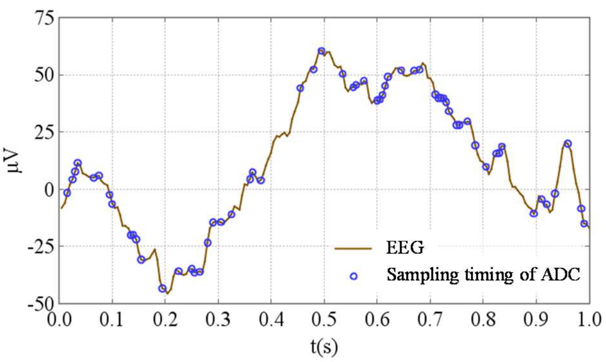

Fig. 2. EEG signal and sampling timing of ADC.

Power consumption is reduced by controlling the active or disabled of the Opamp of CCIA, which has the largest current consumption in the LNA. Owing to the long start-up time required, the bias generator circuit for the amplifier, the V_{CM} generator circuit and operational transconductance amplifier for common-mode feedback (CMFB) are always active. To reduce the start-up time caused by intermittent operation, a one-shot circuit was used to increase the bias current for a certain time. For the same purpose, the V_{OUT} nodes are connected to the V_{CM} using a rise delay circuit when the LNA is disabled. The amount of bias current increase was determined by considering the settling time at start-up. The rise-delay circuit holds the voltage of the V_{OUT} nodes at V_{CM} by the delay time until the circuit stabilizes owing to the current being increased by the one-shot circuit. The one-shot circuit and the rise delay circuit are realized in the behavior model that does not cause power consumption, and fixed time of 500 μs is used for both in consideration of settling time at start-up. Fig. 4 shows an Opamp of the CCIA with additional switches for the intermittent operation. As mentioned, when the LNA is disabled, V_{CM} is connected to the V_{OUT} nodes; thus, the output of the amplifier is maintained in a high-impedance state. The LNA is designed using 0.18 μm CMOS process and has four channels. Pre-simulation conditions are V_{dd} = 1.8 V, process corner is TT, and T_j is 27 ºC. The simulation results show that the LNA power consumption was 1.567 μW for 4 channels and 0.392 μW/ch under the chopping frequency = 5 kHz. The bandwidth is 100 Hz and the input referred noise (IRN) is 2.7 μVrms for the integration from 0.5 Hz to 100 Hz. Since the IRN is on the same level as the previous study [16], signal compression and reconstruction in the proposed CS system is achievable. Above results are obtained under constant operating conditions. The LNA start-up time of 4 ms, was based on the time required for recovery of the V_{OUT} voltage to reach 95 % of the normal operating level. In the next section, the EN_{LNA} signal is prepared based on this start-up time and used for verification. The verification of next section will also verify the robustness for input conditions of the designed LNA by using 25 frames of EEG.

IV. Impact of Intermittent LNA Operation on Power Consumption and Reconstruction Accuracy

This section describes the low power consumption performance and its influence on the reconstruction accuracy provided by intermittent operation with the EN_{LNA} signal. Fig. 5 shows the two types of EN_{LNA} waveforms used for simulation to verify the effect of power consumption reduction by intermittent operation.

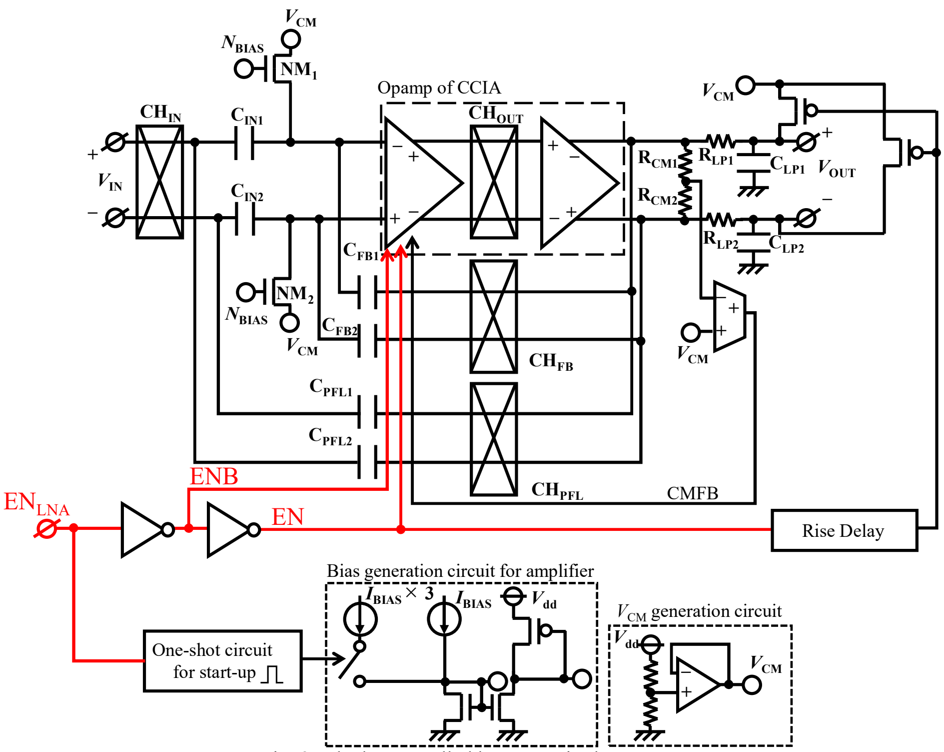

Fig. 3. Blocks controlled by EN_{LNA} in the LNA.

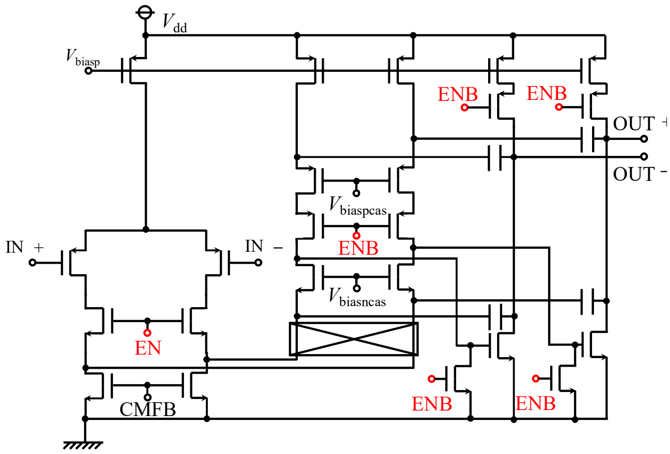

Fig. 4. Opamp for CCIA with additional switches for start-stop control.

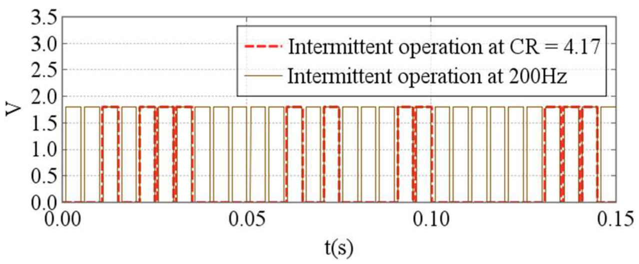

Fig. 5. EN_{LNA} waveforms used to simulate intermittent LNA operations.

One of the waveforms shown in Fig. 5 is for an intermittent operation of the LNA at 200 Hz, considering EEG signals below 100 Hz and the Nyquist frequency. Based on the results given in the previous section, the LNAs were activated for 4 ms during each sampling period.

The other is the waveform for the intermittent operation of the LNAs representing the sampling timing of the ADC with random undersampling, as shown in Fig. 2. In the following section, we compare the LNA power consumption when the EN_{LNA} signals shown in Fig. 5 are used. The average power consumption of LNA was 0.42 μW/ch with intermittent operation at 200 Hz, and 0.165 μW/ch with intermittent operation at CR = 4.17. The power consumption of the LNA presented in the previous section and the above results indicate that controlling the EN_{LNA} can reduce power consumption by up to 58 %. However, when using intermittent operation at 200 Hz, the power consumption exceeds that with constant operation because the start-up bias current from the one-shot circuit increases each time the LNA starts. Comparing the results for the two types of EN_{LNA} in Fig. 5, even the EN_{LNA} controlled with CR = 4.17 achieved a 61 % power reduction for the LNA, which did not achieve the ideal power reduction ratio of 76 %. This is owing to the effect of the blocks without intermittent operation, as shown in Fig. 3.

Table I is a performance comparison with LNAs for similar applications [16]–[18]. This study exhibits excellent low-power performance owing to its intermittent operation. The power consumption performance in the previous study was also excellent[18], but the V_{dd} differed from this study. The LNAs of this study were designed with a supply voltage of 1.8 V, the standard for ICs, and the comparison based on quiescent current I_Q shows that this study produced superior performance. Furthermore, since researches are underway to suppress the degradation of the reconstruction accuracy even at high compression ratios [6, 11], the solution presented in this study is expected to achieve further power reduction performance by using higher CR. Next, we evaluated how much intermittent operation influenced the reconstruction accuracy of the EEG signals under proposed CS system.

The data used and the signal processing flow in the evaluation are shown in Fig. 6.

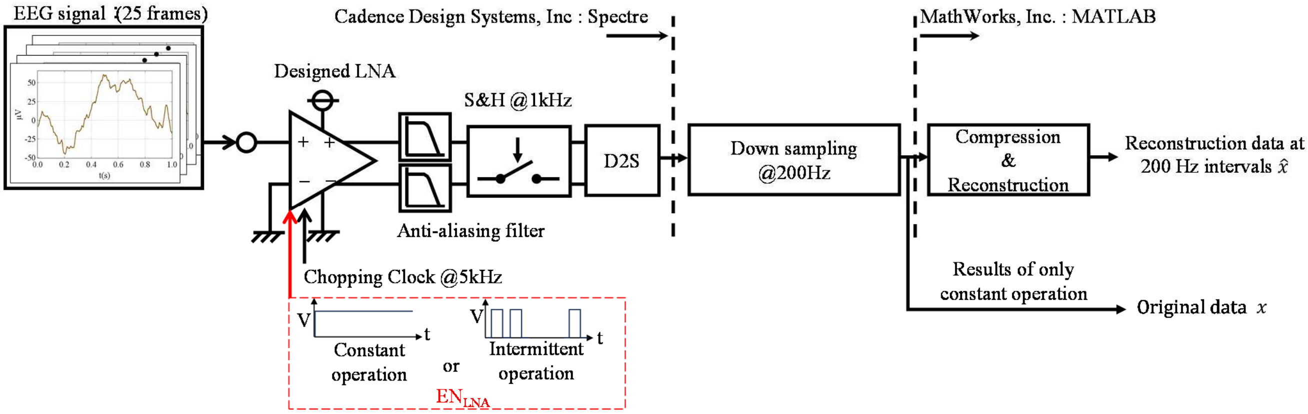

Fig. 6. The data and signal processing used for evaluation.

We resampled the EEG data from the FP1-FP7 channels of the CHB14 dataset from the CHB-MIT database [19], excluding periods of epileptic seizures, and used them as inputs for the LNA. Twenty-five frames of EEG signals were used for evaluation, with one frame having a duration of 1s. The pattern of intermittent operation in Fig. 6 is the same regardless of the EEG frame. The output voltage of the LNA is input to off-chip ideal anti-aliasing filters with a cutoff frequency of 0.54 kHz and sampled at 1 kHz for flexibility in post-processing. The sampled voltage information was converted to a single-phase voltage via differential-to-single-phase conversion (D2S) using a calculation tool. The above simulation and signal processing were performed using Spectre of Cadence Design Systems, Inc. The aforementioned single-phase voltage information was downsampled to 200 Hz, which is the assumed sampling frequency of a typical EEG measurement system. MATLAB (MathWorks, Inc.) was used for the compression and reconstruction signal processing. The downsampled data were compressed using the measurement matrix and reconstructed using the BSBL algorithm. As shown in Fig. 6, the voltage data before compression in the case of the LNA under constant operation were used as the original data x as the basis for comparison. In addition to the above, we used the data after compression and reconstruction as the evaluation target data $\hat{x}$ and evaluated the reconstruction accuracy. Since the effect of CR and LNA noise on the reconstruction accuracy of the proposed CS system has been shown in previous study [16], this study only shows the impact of intermittent operation on the reconstruction accuracy.

Since each application has different demands on reconstruction accuracy, the widely used normalized mean square error (NMSE) was adopted for the evaluation in this study. The NMSE was calculated using x and $\hat{x}$ in equation (1).

$$\mathrm{NMSE} = \frac{||x-\hat{x}||_2^2}{||x||_2^2} \tag{1}$$

The NMSE calculation results are shown in Fig. 7, which shows that the difference in the NMSE caused by the difference in EN_{LNA} was minimal, 0.017 at most. The NMSE difference was only 9 %, on average, over 25 frames. These results indicate that the intermittent LNA operation little influences the reconstruction accuracy of CS.

V. Conclusion

This study proposed a low-power LNA solution for a CS EEG measurement system with random undersampling. Simulation verification using the designed LNA showed that intermittent operation can reduce power consumption by up to 58% compared with constant operation also confirming that intermittent LNA operation had little influence on the reconstruction accuracy of the CS. These results indicate that intermittent LNA operation is feasible, thus potentially resolving the trade-off between battery size and operation time in wireless EEG measurement devices.

TABLE I.
Performance Comparison with LNAs for Similar Applications

	[16]	[17]	[18]	This work
Application	EEG	EEG	EEG etc.	EEG
Technology (μm)	0.18	0.18	0.18	0.18
V_{dd} (V)	1.8	1.5	1	1.8
Average I_Q (nA)	200	570	148(1)(2)	92(3)
Power consumption (μW/channel)	0.36	0.855	0.148	0.165
Bandwidth (Hz)	100	500	128	100
IRN (μVrms)	4.47	1.22	1.5	2.7
NEF	7.69	2.91	2.23(1)(2)	3.14

(1)Mode for EEG, (2) LNA only, and (3) CR = 4.17

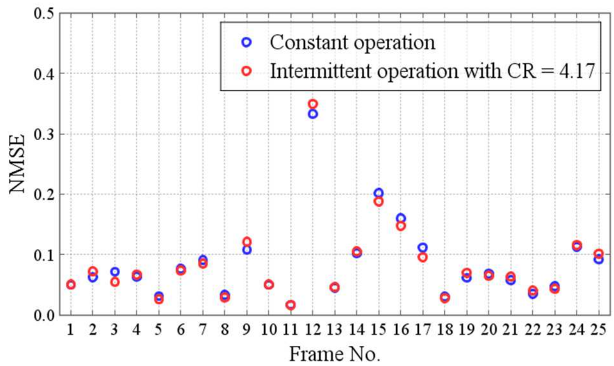

Fig. 7. NMSE calculation results for each frame.

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