A Low Power Control System for Wireless Body Area Sensor Networks using Adaptive Fuzzy Logic

Mahankali Mahesh Varma,Pg Student

Mr. K. Suresh, Assistant Professor

Dept Of Ece

Malla Reddy College of Engineering & Technology,Secunderabad

Abstract: Wireless body sensor networks (WBSNs) for medical applications, such as vital signal monitoring and the diagnose assistant has received tremendous attention in recent years. Wireless sensing system tends to focus on low power consumption. Firstly, an adaptive fuzzy controller is designed and a statistical analysis of the performance of the system is conducted. An adaptive-resolution control system based on a fuzzy control technique is designed for wireless body sensor networks in order to develop a high quality and low power system. The concept of the adaptive resolution control technique is to produce the control signals by selecting different clock frequencies with fuzzy decision technique. The results show that this work can improve the quality of ECG signals in abnormal region and also reduce transmission power for wireless body sensor networks. Results prove that adaptive fuzzy logic can adapt rapidly and successfully to the changing dynamic situation with which it is presented.

INDEX TERMS Adaptive, fuzzy control, healthcare monitoring, power-efficient, wireless body sensor network.

I. INTRODUCTION In recent years, homecare services [1], [2] have been widely discussed and investigated in the area of academic and commercial research. The advancement of wireless transmission techniques provides simplicity and comfort in health monitoring, specifically in identifying the health conditions of each individual. One of the famous topics in this field is the wireless body sensor network

(WBSN) [3], [4]. In practical applications, it is efficient to apply a wireless body sensor network in a hospital to monitor the vital signs of patients and build up a long-term wireless sensing system in a house to take care of chronically diseased patients. A WBSN provides an efficient instrumentation and measurement to monitor physiological parameters without affecting the normal life of patients. There are various kinds of bodily signals designed into WBSNs [5], [6], such as body temperature [7], heart rate, blood pressure [8], pH value [9], ECG, etc. In order to be compatible with the various bodily signals in the WBSN, a multi-sensor microcontroller unit (MCU) with an asynchronous interface was proposed in [10] and [11]. Although the cost and power have been reduced by the multi-sensor design, the power consumption still limits the lifetime usage of the WBSN. Similar to other wireless mobile applications, an ultra-low-power design is necessary for long-term monitoring of physiological variables (vital signs) [12], [13]. In the previous work [14], an adaptive low-power technique was proposed in which the power consumption of the WBSN systems has been successfully reduced. Although the most redundant communication power was saved by the adaptive low-power technique, the reduction of transmission power is still limited by the data rates of the transmission. Data rates of the transmission are limited a specific data rate because the various body signals are captured by the ADC with a fixed sampling rate. Although higher frequency of the sampling rate implicates more accurate detection, it consumes more power for transmitting huge amount of data. It is difficult to choose between the power consumption and resolution because higher resolutions of the sensing systems will consume more energy for transmission. has benefits of long-term usage and high resolution. In the previous work [15], a variable resolution control system had been proposed for WBSN system. Yazicioglu et al. [16] presented an adaptive sampling ADC for ECG compression. Kim et al. [17], [18] proposed a mixed-signal ECG processing platform with adaptive sampling by an analog signal processor (ASP). These adaptive resolution techniques were successfully developed to promote the quality of body signals and reduce the power consumption of the sensing system. However, the flexibility and the reduction of the power consumption were not efficient enough. In this paper, an adaptive-resolution control system based on a fuzzy control technique [19]–[21] has been proposed to develop a flexible, power-efficient, and high-resolution WBSN system. It provides an efficient methodology to develop a long-term usage and high-resolution wireless sensing system for healthcare monitoring applications. This paper is organized as follows: Section II introduces the principles of the adaptive fuzzy control system. Section III describes the architecture of a wireless body sensor node with the proposed adaptive fuzzy resolution control design. Section IV shows the simulation results and chip designs. Finally, in Section V, the conclusions are presented.

A. ADAPTIVE FUZZY RESOLUTION CONTROL TECHNIQUE The concept of the adaptive resolution control technique is to control the resolution of the signals by selecting different clock frequencies and then using these frequencies as the sampling clock of the ADC. Initially, the users can set the conditions, and then the controller will produce control signals automatically to select the most suitable frequency of the clock and use it as the sampling clock of the ADC. For example, the adaptive fuzzy controller will select a high-frequency clock (HCLK) as the sampling clock of the ADC when the specific body signal demands a high-quality resolution. Fig. 1 shows two window-conditions of the proposed adaptive resolution control technique. It includes a high-level condition-window and a low-level condition-window. The high-level condition window comprises of high-level plus and high-level minus, wherein the high-level plus is the upper bound of the high-level condition window while the high-level minus is the lower bound of the high-level condition window. The two window-conditions help users to set the resolution conditions for some specific applications. For example, the users or doctors can set the values of high-level plus and low-level minus into the proposed system when the values of the detected signals more than the value of FIGURE 1. Two window-conditions of the proposed adaptive resolution control. high-level plus or less than the value of low-level minus are important or dangerous. The sampling clock of the ADC can be adaptively selected from high-frequency clock (HCLK), medium-frequency clock (MCLK) or low-frequency clock (LCLK) according to outputs of the fuzzy sets. Fig. 2 illustrates an example of the adaptive resolution control technique, in which an adaptive clock (Adaptive_CLK) is integrated by three different sampling clocks (HCLK, MCLK, and LCLK). Initially, the user can set the Adaptive_CLK to LCLK. Later on, when the result of fuzzy logic control is High, the Adaptive_CLK is set to HCLK. Then, when the result of fuzzy logic control is changed to Medium, the Adaptive_CLK will be changed from HLCK to MCLK. Finally, the Adaptive_CLK is set to LCLK since result of fuzzy logic control is Low. By this adaptive fuzzy control technique, the resolution of the biomedical signals can be set to the most suitable condition by selecting the sampling clock of the ADC. B. FUZZY CONTROL TECHNIQUE Fuzzy logic is widely used in control, prediction [19], and detection [20], [21] of non-linear systems. It provides an efficient methodology to handle the concept of partial truth. In order to improve the performance of the adaptive resolution control, a fuzzy logic control based on if. . .then. . . rules was developed for adaptive resolution control, in which each rule illustrates the relation between input and output fuzzy sets. It was used to select different frequency of clocks as the sampling clock of the ADC. The rules, functions, and parameters of the fuzzy logic control can be set according to the applications. For example, the absolute values, slope, frequency, variation, transform, etc. of body signals can be selected as parameters for fuzzy logic control. In addition, the fuzzy rule can be obtained by the relation of the selected parameters and simulated results.

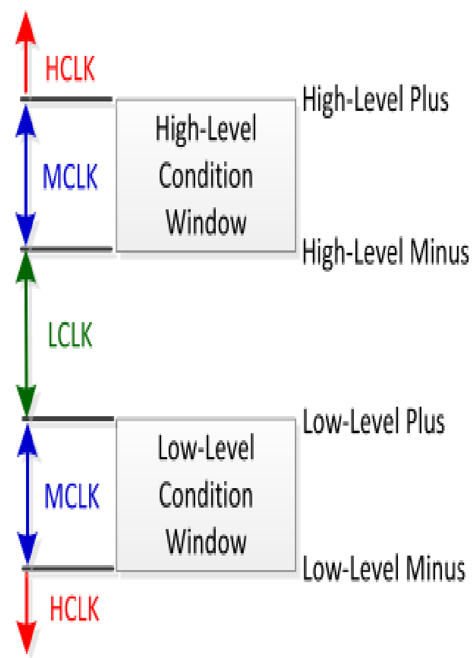

FIGURE 1. Two window-conditions of the proposed adaptive resolution control

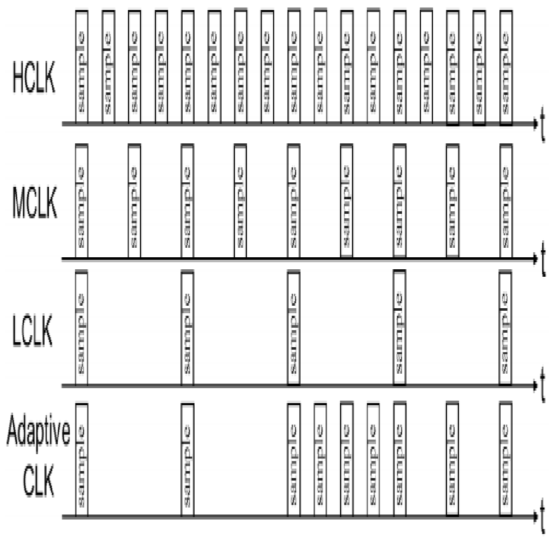

FIGURE 2. Samples schedule in HCLK, MCLK, LCLK, and Adaptive CLK.

concept of the proposed adaptive fuzzy control system. Users can use different parameters and fuzzy rules to produce the best fuzzy logic control models for their applications through the proposed adaptive fuzzy control system. The applications of the proposed system are not limited in this ECG example. In this example, the inputs are the absolute value of f (n) and slope value of g(n), as presented in Eq. (1) and (2), were selected as fuzzy parameters. Fig. 3 shows the relations between the ECG signals and fuzzy logic parameters. The parameters of the fuzzy logic control in this example are defined as follow: f (n) = abs(P(n)) (1) g(n) = abs(P(n) - P(n-1)) (2) where P(n) is amplitude of ECG signal in this example.

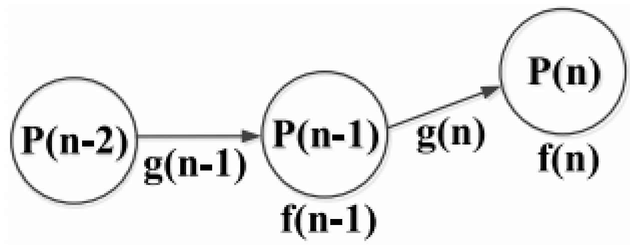

FIGURE 3. Relations between the value of ECG signal P(n), and the fuzzy logic parameters g and f.

Table 1 was designed for adjustment the frequency of the sampling clock of the ADC. Some of important considerations that have been taken into account for determining the rules are as follows. 1) The sampling clock of the ADC is selected as HCLK when the variations or values of the ECG signal are out of the condition windows as shown in Fig. 1. For example, if g is Very Low and f is Very Low then the sampling clock is selected as HCLK or if g is Very High and f is Very High then the sampling clock is HCLK. 2) The sampling clock of the ADC is selected as MCLK when the variations and values of the ECG signal are both within TABLE 1. Fuzzy adjustment rules for the frequency of the sampling clock. the condition windows as shown in Fig. 1. For example, if g is Medium and f is Medium then the sampling clock is MCLK. 3) The sampling clock of the ADC is selected as LCLK when the variations and values of the ECG signal are located in the interval between the High-Level and Low-Level condition windows as shown in Fig. 1. For example, if g is Low and f is Low then the sampling clock is LCLK. Table 1 tabulated the fuzzy adjustment rule table for the frequency of the sampling clock of the ADC. It maps the two input fuzzy sets to an output fuzzy set. After fuzzy logic control, the sampling rate (SR) of the X(n) can be calculated by SR(n) = w(n) × LCLK (3) where w(n) is the selected sampling clock of the ADC as ‘‘High’’, ‘‘Medium’’, or ‘‘Low’’, and LCLK is the low-frequency clock. The ‘‘High’’, ‘‘Medium’’, and ‘‘low’’ expresses 4, 2, and 1 times frequency of the LCLK respectively. The transmission power (TP) of the X(n) can be computed by TP(n) = SR(n) × 11 × PBPC (4) where 11 expresses that each sample in ECG signal is 11 bits and PBPC is the per bit power consumption of the wireless communication device. The ‘‘High’’, ‘‘Medium’’, and ‘‘low’’ expresses 4, 2, and 1 times frequency of the LCLK respectively. In traditional monitoring system, the sampling rate is a fixed on high-frequency clock (HCLK). Hence, by the proposed fuzzy logic control technique, the transmission.

power will be reduced efficiently since the average frequency of the sampling rate (SR) is much less than that of HCLK. In traditional monitoring system, the sampling rate is a fixed on high-frequency clock (HCLK). Hence, by the proposed fuzzy logic control technique, the transmission power was reduced efficiently since the average frequency of the sampling rate (SR) is much less than that of HCLK. The main concept of the proposed adaptive fuzzy resolution control system is to select the base sampling rate (LCLK) in the normal regions and over sampling rate (HCLK or MCLK) in the abnormal regions of the body signals. The sampling rate in the proposed adaptive fuzzy resolution control system is controlled by the fuzzy logic control technique with the fuzzy logic parameters g and f . For example, the users can set the thresholds of the condition windows to make the status of g and f in the P, T or R waves as Medium or High when detects an ECG signal, which leads the adaptive fuzzy control system to select the sampling rates of the P, T or R waves as MCLK or HCLK. By this technique, the quality of P, T and R waves can be efficiently improved by this adaptive fuzzy control system. III. WIRELESS BODY SENSOR NODE DESIGN Wireless body sensor node serves a basic element in a WBSN system [10], [11], [14]. Fig. 4 depicted the block diagram of a wireless body sensor node. It includes an adaptive controller, a phase lock loop (PLL), two down-sample circuits, an ADC, a sensor, a RF transmitter, and an antenna. The details of each component in the wireless body sensor node are described as follows: FIGURE 4. Block diagram of a wireless body sensor node. 1) Adaptive Fuzzy Resolution Controller: The adaptive fuzzy resolution controller was implemented by combinational logic circuits and finite state machines (FSMs). It is used to select the sampling clock of the ADC from three different clocks. First, it compares the body values with the windowconditions, as shown in Fig. 1. Second, it obtains the variance between the current and the previous values which is defined in Eq. 2. After getting the variance, the second input parameter ‘‘g’’ can be acquired by comparing with the slope conditions. Finally, the adaptive fuzzy resolution controller can select the sampling rate from HCLK, MCLK, or LCLK according to the input parameters ‘‘f’’ and ‘‘g’’ which are listed in Table 1. 2) Down-Sampling Circuits: The down-sampling circuit is a digital circuit designed with a counter and several registers. The counter counts integer number of HCLK which is produced by the PLL. It triggers an output register to produce MCLK. Furthermore, the LCLK can be obtained by down-sampling from MCLK in the same way. The frequency of HCLK is an integer multiplied by the frequency of MCLK and LCLK. By the hierarchical design technique, three various frequencies of clocks can be produced efficiently by only two down-sampling circuits. 3) ADC: The analog to digital converter (ADC) is used to convert the signal from analog form to digital form. It can be realized by different architectures according to the characteristics of the signals. In this paper, an adaptive sigma-delta analog-to-digital converter (SDADC) [22] was selected. It consists of a sigma delta modulator (SDM), a digital filter (DF), a differential current comparator, and two 1-bit digitalto-analog (DAC) circuits. This design is useful for the proposed adaptive fuzzy resolution control system because the specified ADC converts the signals from

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analog form to digital form by various sampling rates. 4) RF Transceiver and Antenna: The transceiver is composed of two parts: a RF front-end and a baseband. At the RF front-end part of the receiver, the low noise amplifier (LNA) input for 2.4GHz is a single-ended structure without external balun [23]. The front-end of the transmitter part comprises of a LPF and a VGA stage. The LPF is realized to attenuate the undesired over-sampling clock or spurious signals. Furthermore, the antenna is used to convert the electric power into transmission wave.

IV. SIMULATION RESULTS AND CHIP DESIGNS In order to verify the proposed adaptive fuzzy resolution control system, a digital to analog converter (DAC) device, an analog to digital converter (ADC) device, a FPGA board (including Altera EP4CE115F29C7N FPGA core) and a personal computer (PC) were used. Fig. 5 shows the block diagram of the verification flow and experimental environment. First, the ECG test patterns from MIT-BIH data base [24] were downloaded to SRAM of the FPGA board. Second, the testing ECG signals in digital form were read from FPGA board and then sent to a DAC device to convert the signals to analog form by using the highest sampling rate which was used to avoid distortion of the testing ECG patterns. Third, the ECG signals in analog form, which were produced by the highest sampling rate, were sent to the ADC device. Fourth, the ADC converted the ECG signals 746 VOLUME 3, 2015 S.-L. Chen: Power-Efficient Adaptive Fuzzy Resolution Control System for WBSNs FIGURE 5. Block diagram of the verification flow and experimental environment for the proposed adaptive fuzzy resolution control system. to digital form by using the Adaptive_CLK (HCLK, MCLK, or LCLK). Finally, the digital ECG signals were sent to the adaptive fuzzy resolution controller. After decisions being made by the fuzzy controller, a resolution control signal was sent to down-sample circuits and a signal Adaptive_CLK was produced as a sampling clock of the ADC. Simultaneously, the adaptive fuzzy resolution results were sent to the PC through a RS-232 interface. After receiving the data from the FPGA, the PC refined the adaptive fuzzy resolution results by using the fuzzy decision rule. Finally, the refined and original ECG signals which were read from SRAM of the FPGA board were used to evaluate the quality of the proposed adaptive fuzzy resolution control methodology. In the WBSN systems, the base sampling rate and thresholds of condition windows can be selected and set by the users according to the characteristics of each biomedical signal. In order to show the performance of the proposed adaptive fuzzy resolution control system, an abnormal region of ECG signal in MIT-BIH Arrhythmia data [24] was used as test patterns. Since the abnormal region of ECG signal was selected from MIT-BIH Arrhythmia data, in which each ECG signal has 360 samples per second, the 360 Hz was selected as the high-resolution sampling rate for simulation. In real applications, the users can set the high-resolution sampling rate as 1024 Hz [16] or higher frequency [17]. The original ECG signal of MIT-BIH Arrhythmia data is 360 samples per second and each sample is 11 bits. In this simulation, the HCLK was set to produce 360 samples per second of the ADC. The MCLK was down-sampled by HCLK as well as LCLK is down-sampled by MCLK, which is equivalent to produce 180 or 90 samples per second by the ADC. Fig. 6 (a) shows the original ECG by 1000 sampling points from MIT-BIH Arrhythmia data. Fig. 6 (b) shows the refined ECG results which were produced by the proposed adaptive fuzzy resolution control technique. First sampling points were selected by using the proposed adaptive fuzzy resolution controller according to the relations of the window-conditions. Second, the down-sampled points were refined back to 1000 points by a linear interpolation as shown in Fig. 6 (b). In this case, the conditions of high-level condition window were set to 1250 as a high-level plus condition and 1000 as high-level minus condition. The conditions of low-level condition window were set to 800 as a low-level plus condition and 750 as a low-level minus condition.

The Adaptive_CLK was selected from the HCLK, MCLK, or LCLK by the adaptive fuzzy resolution controller according to the immediate feature of the ECG signal. Fig. 6 (c) shows the selected clock information and the distribution of the transmitting power consumptions in this case. To be able to evaluate the qualities of the refined ECG signals, a signal to noise ratio (SNR) was used to quantify a noise approximation of the refined signal and the original signal. The SNR can be defined as SNR (dB) = 10 log10 □ □ □ □ Pn i=1 original(i) 2 Pn i=1 [original(i) − refined(i)] 2 □ □ □ □ (5) where original(i) is ith sample of the original ECG signal and refined(i) is ith sample of

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the refined ECG signal. In order to show the qualities of the adaptive fuzzy resolution control, another measurement index peak signal to noise ratio (PSNR) was also used to measure the qualities of the refined ECG signal and the original ECG signal. The PSNR value can be obtained by PSNR (dB)=10 log10 □ □ □ □ D 2 Pn i=1 [original(i) − refined(i)] 2 □ □ □ □ (6) where original(i) is ith sample of the original ECG signal, refined(i) is ith sample of the refined ECG signal, and D is the maximum peak-to-peak swing of the signal (2048 for 11-bit ECG signals). Fig. 6 (d) shows the variation of PSNR value in this case. In order to analyze the performance of the proposed adaptive which was only designed with window-conditions without using fuzzy technology and the adaptive fuzzy resolution controllers, six software models were realized. The six models consist of the variable resolution methodology of the previous work [15], three adaptive sampling methodologies based on slope [16]–[18], the adaptive and adaptive fuzzy resolution methodologies in this work. The technique of the previous work [15] used the threshold-conditions to select one of the various clocks as the sampling clock of the ADC, in which the H_CLK would be selected as the sampling clock of the ADC when the signal value is over the threshold-conditions.

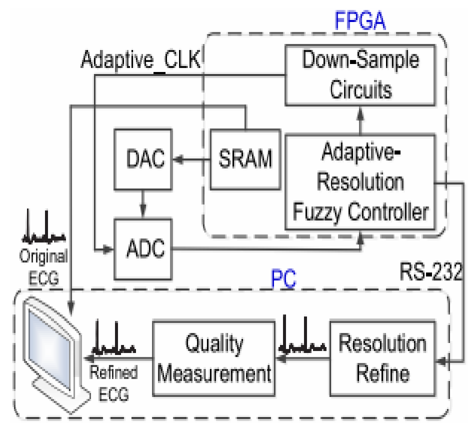
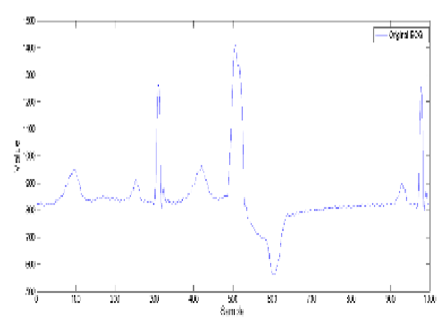


FIGURE 5. Block diagram of the verification flow and experimental environment for the proposed adaptive fuzzy resolution control system.



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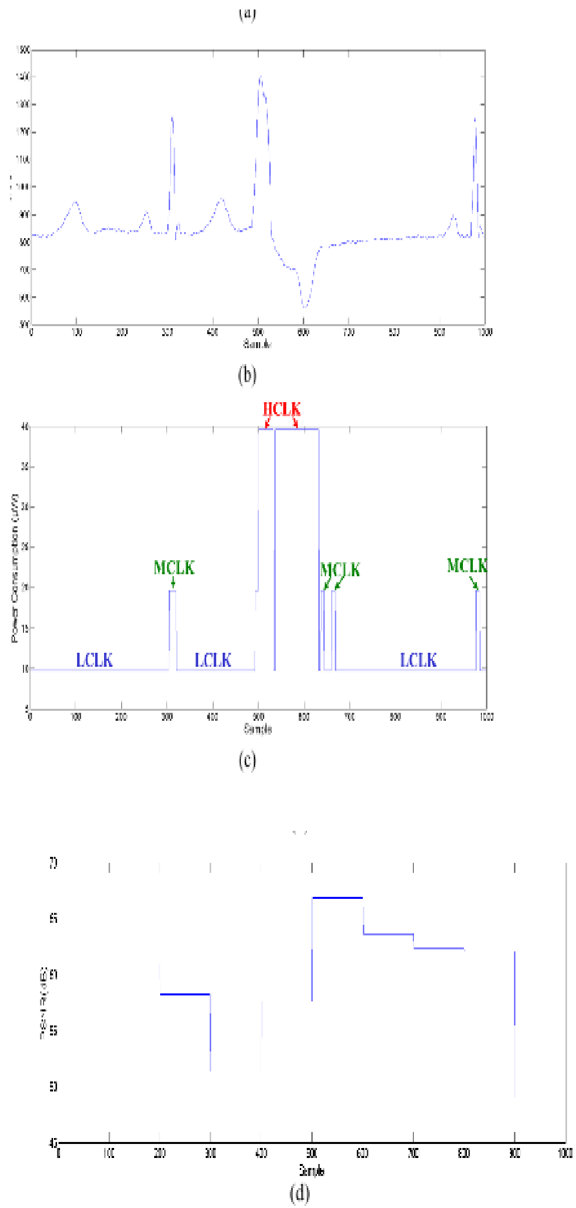

FIGURE 6. Simulation results of (a) Original ECG signal by 360 1/s sampling rate. (b) Simulation results of the ECG signal with the proposed adaptive fuzzy sampling rate design. (c) Selected clock information and distribution of transmitting power consumptions with the proposed adaptive fuzzy resolution design. (d) Distribution of PSNR with the proposed adaptive fuzzy resolution design.

down sampled by the proposed fuzzy algorithm, the signals should be refined by the same fuzzy algorithm and inserting the loss sampling points by the linear interpolation. In order to evaluate the qualities of the refined ECG signals by [15]–[18] and the two methods of this work, a signal to noise ratio (SNR) and a peak signal to noise ratio (PSNR) were used to quantify the refined signal and the original signal. The adaptive sampling techniques [16]–[18] selected one of the various sampling clocks for the ADC according to the slope of the ECG signals. In this work, two resolution control techniques of adaptive and adaptive fuzzy resolution control methods were realized. The adaptive resolution control method selects between the available sampling clocks by determining which condition-window the signal falls into, as illustrated in Fig. 1. Otherwise, the adaptive fuzzy resolution control method selects between the available sampling clocks by the fuzzy control rule in Table 1. Although the operating frequency of the proposed adaptive and the adaptive fuzzy resolution controller designs achieved 100 MHz and the controllers can produce resolution control signals within 10-ns, a period of sampling delay was wasted when used adaptive resolution control in this system. The reason for this is the ADC cannot achieve changing the sampling rate and getting the new result simultaneously. Hence, it spent a period of sampling delay when the sampling rates of ADC are changed. Table 2 lists the control methodology, sampling rate, PSNR, SRN, abnormal region PSNR, abnormal region SNR, transmission data rate, and transmission power consumption in these six methodologies. The test region was set to 1000 sampling points. It was obtained from MIT-BIH Arrhythmia data [24]. The abnormal region was set to 100 sampling points. The MCLK was 180 samples/s, which was derived from HCLK with 360 samples/s. The LCLK was derived from MCLK with 90 samples/s in the same way. The adaptive and adaptive fuzzy control methodologies in this work were selected the sampling rate of the ADC from LCLK, MCLK, or HCLK by the adaptive resolution and the adaptive fuzzy resolution techniques. The transmission data rates and power consumptions were increased with the sampling rate since the more data consumed the more transmission power. The PSNR value was improved to 2.28 dB, 16.07 dB and 22.21 dB in comparison with the previous work [15]–[18] and the adaptive fuzzy control of this work respectively. In addition, the SNR value showed improvement of 2.32 dB, 16.08 dB and 22.21 dB respectively. While in the abnormal region is also advanced to 15.47 dB, 26.31 dB and 31.44 dB in PSNR and SNR respectively. According to our previous experience [14], it consumes 10-µW to transmit a bit through a transmitter and modulator. The transmission power consumptions in Table 2 were evaluated by products of the transmission data rates and transmission power consumption per bit. The evaluated transmission power consumption of the proposed adaptive fuzzy controller is 14.3-mW, which is lower than 16.28-mW and 14.61-mW in the previous works of [15] and [17], [18], respectively. Comparing the results of the adaptive and adaptive fuzzy control methodologies in this work, the fuzzy control technique improved PSNR or SNR value by 1.9 dB or 1.34 dB when an abnormal situation occurs and only increases 1.4% of power consumption. The proposed two controller designs namely, adaptive and adaptive with fuzzy control, were both implemented by using a hardware description language (HDL). The electronic design automation (EDA) tool, Design Vision, was used to synthesize the VLSI circuit based on TSMC 0.18-µm process standard cells. The auto placement and routing tool IC Compiler was used to generate the layout of the proposed two controller designs. The photo of chip layout with pads of the proposed adaptive fuzzy resolution controller is illustrated in Fig. 7. Synthesis results show that the adaptive and adaptive fuzzy resolution controller design contains 203 and 539 NAND-equivalent gate counts, respectively. The synthesized area of the proposed adaptive or adaptive.

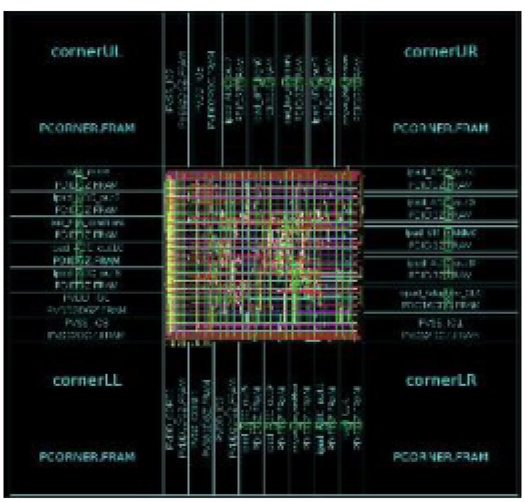

FIGURE 7. The photo of chip layout with pads.

fuzzy resolution controller is 3,376-µm2 and 7,124-µm2 , respectively, which has been synthesized by the 0.18-µm CMOS process. The power consumption of the proposed designs was measured by using SYNOPSYS PrimePower. It consumes 2.2-µW and 4.2-µW of the adaptive and adaptive fuzzy resolution controllers, respectively, at 1-MHz operating frequency with 1 V supply voltage. The specifications of the proposed two controller designs are listed in Table 3.

ADC in [14] was realized by the 0.18-µm CMOS process and its core area is 0.217-mm2 with the power consumption of 216-µW when it operates at 1 MHz. By combining the proposed adaptive and adaptive fuzzy controller design with the ADC in the previous work, the total areas are 0.2204-mm2 and 0.2241-mm2 , respectively. In addition, the power consumption of the two controllers is 218-µW and 220-µW. Table 4 lists the comparison results of two previous VLSI designs with this work. In order to compare with the previous design [16] objectively, the power consumption and core area listed in Table 4 were considered the ADC and sampling controller circuits only without including the analog front end and radio circuits. Also, the power consumption and core area in [17] listed in Table 4 included the ADC and ASP circuits, which achieved the function of the variable sampling rate by using the ASP to execute the sampling control program. As compared with the two previous designs, [17] including only ADC and ASP partitions as well as [16] including ADC and sampling controller, this work reduced at least 96.7% and 33.3% core area, which were normalized by 0.18-µm process, than the previous designs of [16] and [17], respectively. The adaptive fuzzy resolution controller achieved not only improving the SNR or PSNR values by at least 15.47 dB in abnormal region but also reduced 62.6% core area in the proposed ECG monitoring application. Thus, the proposed adaptive fuzzy resolution control system has the characteristics of low-power, high-performance, and cost-efficient. It provides a well base to develop a mixed signal chip including adaptive fuzzy controller, ADC, devices and circuits with more functions for healthcare monitoring sensing systems and wireless body sensor networks

CONCLUSION :

A new method adaptive control system using fuzzy logic had been presented for a wireless body area network (WBAN). For WBAN, along with wireless body sensor node an adaptive fuzzy resolution controller was added for better performance. The results show that this can improve the quality of ECG signals in abnormal region. It also reduces the transmission power for wireless body sensor networks. And also the proposed adaptive fuzzy resolution control system has the characteristics of low-power, high-performance, and cost efficiency.

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