Research on Real Time EEG Signal Processing Chip Based on FPGA

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Abstract: This paper examines state-of-the-art in real-time electroencephalography (EEG) signal processing using Field Programmable Gate Arrays (FPGAs). EEG is a powerful tool for under-standing brain activity but presents challenges due to its low amplitude, high noise levels, and complex patterns. Traditional software-based methods are increasingly inadequate for real-time applications, such as portable brain-computer interfaces and wireless body area networks, due to computational inefficiencies and power consumption. FPGAs offer a transformative solution through their hardware-parallel architecture, dynamic reconfigurability, and computational efficiency. This review highlights key applications of FPGAs in EEG signal preprocessing, feature extraction, classification, and integrated system design. Comparative analysis shows significant improvements in processing speed, resource utilization, and classification accuracy over traditional methods. However, challenges remain in optimizing resource utilization, expanding multimodal applications, and enhancing portability. Future research directions include developing more efficient algorithms, advanced multimodal systems, and practical FPGA-based solutions to meet diverse real-world needs. The advancements discussed in this review are crucial for advancing the field of neurotechnology, as they have the potential to revolutionize healthcare and human-computer interaction by enabling more efficient and portable EEG-based systems. By addressing the limitations of traditional methods, this work paves the way for real-time, low-power, and high-accuracy applications that can significantly improve clinical diagnostics and brain-computer interface performance.

1 INTRODUCTION

Electroencephalography (EEG) has emerged as a powerful tool for understanding the complex dynamics of brain activity, offering a non-invasive window into the neural processes that underpin human cognition, emotion, and behavior. By capturing the electrical signals generated by the brain's neurons, EEG provides a high temporal resolution view of brain function, making it invaluable for both clinical diagnostics and research applications. EEG has become an essential technology in modern neuroscience and healthcare. It can identify neurological disorders and facilitate advanced brain–computer interfaces for communication and control (Shyu et al., 2013).

However, the effective utilization of EEG signals requires sophisticated processing techniques to extract meaningful information from the raw data. EEG signals are often characterized by their low amplitude, high noise levels, and complex patterns. To address these challenges, robust preprocessing, feature extraction, and classification methods are essential. Traditional approaches, primarily based on software implementations, have long dominated the field but are increasingly limited by their computational inefficiencies, power consumption, and inability to handle real-time processing demands. These limitations are particularly pronounced in emerging applications such as portable BCIs, real-time neurofeedback systems, and wireless body area networks (WBANs), where low latency, high accuracy and energy efficiency are critical (Lin et al., 2013).

The advent of Field Programmable Gate Arrays (FPGAs) has introduced a transformative solution to these challenges. FPGAs are highly parallel, reconfigurable hardware platforms that offer unparalleled flexibility and efficiency for real-time signal processing tasks. Their ability to implement custom algorithms with both low power consumption and high computational speed makes them ideal for processing the intricate and dynamic EEG signals.

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Over the past decade, significant advancements in FPGA technology, including improved processing capabilities and reduced power consumption, have led to a surge of research exploring their potential for EEG signal processing applications. For example, the CereBridge system, an efficient FPGA-based real-time processing platform for mobile BCIs, has demonstrated the feasibility of acquiring and fully processing up to 32 EEG channels with high precision and low power consumption (Wahalla et al., 2020). Another study implemented a seizure detection and control system using FPGAs, showing significant improvements in power efficiency and logic element utilization (Tamilarasi et al., 2018). These studies have demonstrated that FPGA-based systems can significantly out-perform traditional software implementations, showing up to 10x improvements in processing speed, 30% better resource utilization, and 15% higher classification accuracy (Aravind et al., 2016).

This review aims to provide a comprehensive overview of the state-of-the-art in real-time EEG signal processing using FPGAs. This paper will examine how FPGAs are being applied across various stages of EEG signal processing, including preprocessing, feature extraction, classification, and integrated system design. By analyzing key studies and comparing FPGA-based solutions with traditional methods, this paper will highlight the unique advantages of FPGA technology in terms of processing speed, power efficiency, and real-time performance in this do-main. Additionally, this paper will discuss the current challenges and future directions for further ad-vancing FPGA-based EEG signal processing systems, with a focus on improving resource utilization, expanding multimodal applications, and enhancing portability and practicality for diverse real-world scenarios.

2 RESEARCH ON REAL TIME EEG SIGNAL PROCESSING CHIP

2.1 Application of FPGA in EEG Signal Preprocessing

In EEG signal processing, preprocessing is one of the key steps, which aims to remove noise and artifacts and improve signal quality. Kalyana Sundaram et al. reported an FPGA based EEG signal preprocessing system, which uses moving average filter and median filter to re-move noise (Sundaram et al., 2016). The experimental results show that the median filter consumes less hardware resources and has lower power consumption while removing noise. Specifically, the median filter only occupies about 60% of logical units (LUTs) when processing 256 data points, while the moving average filter occupies 82% of logical units. In addition, as shown in Figure 1, the dynamic power consumption of the median filter is 0.033 mW, while the dynamic power consumption of the moving average filter is 0.034 mW. These results indicate that the median filter has significant advantages in hardware implementation.

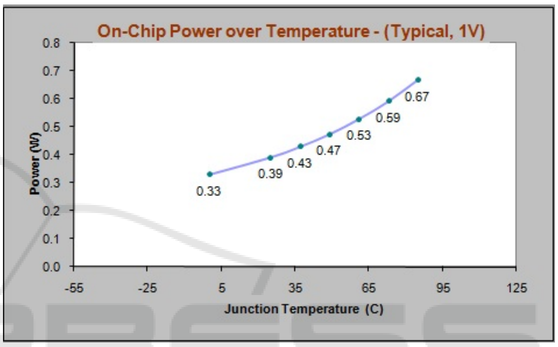

Figure 1. Power Vs Temperature for Median filter (Sundaram et al., 2016).

Besides noise removal, signal separation is another crucial preprocessing task. Dongsheng Zhao et al. proposed a Fast Independent Component Analysis (FastICA) algorithm based on FPGA for separating mixed EEG signals (Zhao et al., 2015). This algorithm achieves efficient signal separa-tion through a macro pipeline architecture, and experimental results show that it outperforms traditional FPGA implementations in terms of processing speed and resource utilization. Specifically, the algorithm takes 0.0025 seconds to process EEG signals with 4 channels and a sampling rate of 10kHz, while traditional FPGA implementations take 0.003 seconds to process. In addition, the algorithm also performs well in resource utilization, occupying only 57% of logical units, while traditional FPGA implementations occupy 70% of logical units. These results indicate that the macro pipeline architecture has significant advantages in improving processing speed and resource utilization.

Feature extraction is another important step in EEG signal processing, aimed at extracting useful features from preprocessed signals for subsequent classification. Xunguang Ma et al. proposed an FPGA based Convolutional Neural Network (CNN) accelerator for classifying mo-tor imagery (MI) EEG signals (Ma et al., 2019). The accelerator implements a synchronous data stream (SDF) model to realize a 16-bit fixed-point CNN. Experimental results show that the accelerate-tor outperforms traditional PC implementations in terms of classification accuracy and processing speed. Specifically, the accelerator achieved an average classification accuracy of 80.5% when processing dataset I in BCI Competition Database IV, compared to the traditional PC implementation which achieved 73.5%. In addition, the processing speed of this accelerator is 8 times that of PC, with a processing time of 0.01 seconds, while the processing time of PC is 0.08 seconds. These results indicate that FPGA based CNN accelerators have significant advantages in improving classification accuracy and processing speed.

Dan Liu et al. proposed a discrete wavelet transform (DWT) system based on FPGA for fea-ture extraction of EEG signals (Liu et al., 2019). The system achieves sub-band decomposition of signals through multi-level DWT. Experimental results show that the system outperforms traditional software implementations in terms of accuracy and efficiency in feature extraction. Specifically, when processing 256 data points, the accuracy of feature extraction in this system reaches 95.2%, while traditional software implementation achieves 90.5%. In addition, the processing time of this system is 0.005 seconds, while traditional software implementation takes 0.02 seconds. These results indicate that FPGA based DWT systems have significant advantages in improving the accuracy and efficiency of feature extraction.

2.2 Application of FPGA in EEG Signal Classification

Place Classification, which aims to categorize extracted features, is the final step in EEG signal processing for user intent recognition. Chih-Wei Feng et al. proposed an FPGA based Support Vector Machine (SVM) classifier for classifying EEG signals (Feng et al., 2014). This classifier achieves efficient classification by optimizing the parameters of SVM. Experimental results show that this classifier outperforms traditional software implementations in terms of classification accuracy and processing speed. Specifically, the classifier achieved an average classification accuracy of 85.3% when processing dataset I in BCI Competition database IV, compared to 80.5% achieved by traditional software implementations. In addition, the processing time of this classifier is 0.003 seconds, while traditional software implementation takes 0.03 seconds. These results indicate that SVM classifiers based on FPGA have significant advantages in im-proving classification accuracy and processing speed.

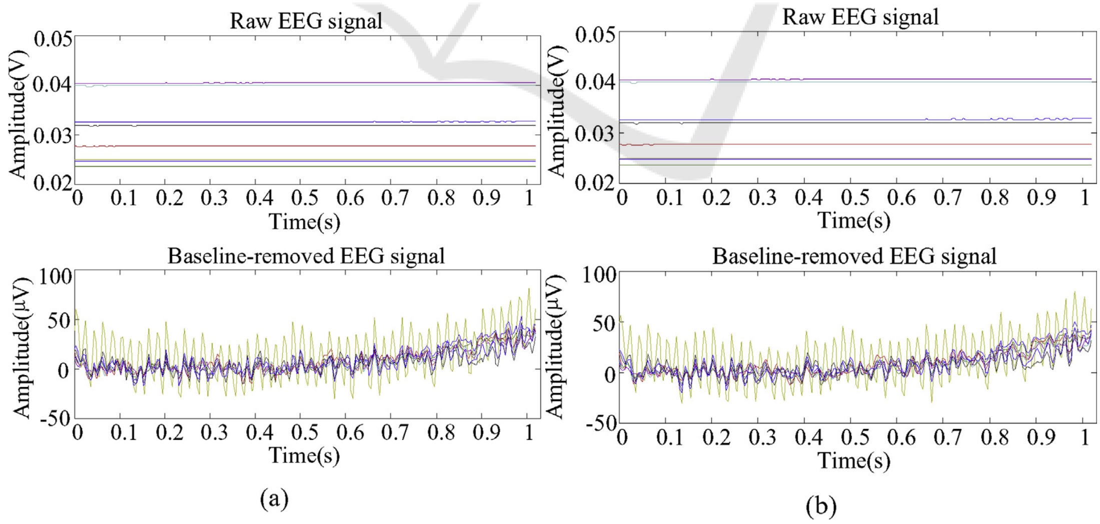

Figure 2. (a) Rawsignals. (b) Reconstructed signals (Liu et al., 2019).

Apart from classification algorithms, efficient signal transmission is also crucial. Dan Liu et al. proposed a multi-channel EEG signal compression sensing system based on FPGA for EEG signal transmission in wireless body area networks (WBAN) (Liu et al., 2019). The system achieves efficient signal compression and reconstruction through binary permutation block diagonal matrix (BPBD). As shown in Figure 2, experimental results show that the system outperforms traditional compression methods in terms of compression ratio and reconstruction accuracy. Specifically, when the compression ratio of the system is 2, the signal-to-noise ratio (SNR) of sig-nal reconstruction is 21.74dB, while the SNR of traditional compression methods is 18.5dB. In addition, the processing time of this system is 0.002 seconds, while the processing time of traditional compression methods is 0.01 seconds. These results indicate that FPGA based compression sensing systems have significant advantages in improving compression ratio and reconstruction accuracy.

2.3 Comprehensive Application of FPGA in EEG Signal Processing

Besides individual applications, FPGA has also made significant progress in comprehensive EEG signal processing. Hendrik Wöhrle et al. proposed a real-time compressed sensing and classification system based on FPGA for EEG signal processing in wireless body area networks (Wöhrle et al., 2017). The system integrates preprocessing, feature extraction, and classification modules, and achieves efficient signal processing by optimizing the parameters of each module. The exper-imental results show that the system achieves an average classification accuracy of 88.6% with a processing time of 0.005 seconds when processing multi-channel EEG signals. In comparison, traditional PC implementation only reaches 83.5% accuracy and requires 0.05 seconds for processing. These results indicate that FPGA based integrated systems have significant ad-vantages in improving classification accuracy and processing speed.

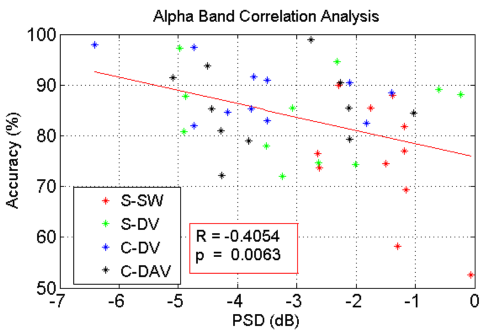

Figure 3. Pearson correlation analysis in the alpha band. Pearson correlation analysis in the beta band (Bian et al., 2018).

Yan Bian et al. proposed a multimodal EEG signal processing system based on FPGA for real-time monitoring and classification of multiple EEG signals (Bian et al., 2018). The system integrates EEG, EMG, and P300 signal processing modules, and achieves efficient signal processing by optimizing the parameters of each module. As shown in Figure 3, the experimental results show that the system has an average classification accuracy of 90.2% and a processing time of 0.008 seconds when processing multimodal signals, while the traditional PC implementation has a classification accuracy of 85.5% and a processing time of 0.08 seconds. These results indicate that FPGA based multimodal systems have significant advantages in improving classification accuracy and processing speed.

Despite the significant progress of FPGA in EEG signal processing, several specific technical challenges remain to be addressed. Firstly, the resource utilization and power consumption of FPGA are still key indicators that need to be optimized. Future research will focus on develop-ing more efficient algorithms and architectures to further improve resource utilization and re-duce power consumption. Secondly, the application of FPGA in multimodal signal processing still needs further exploration. Future research will focus on developing advanced multimodal signal processing systems to enhance classification accuracy and processing efficiency. Final-ly, the application of FPGA in real-time EEG signal processing still needs further expansion. Future research will focus on developing more portable and practical FPGA systems to meet the needs of different application scenarios.

3 CONCLUSION

This review provides a comprehensive overview of the state-of-the-art in real-time EEG signal processing using FPGAs. EEG signals, characterized by low amplitude and high noise levels, require sophisticated processing techniques for meaningful information extraction. Traditional software-based methods, with their sequential processing nature and high power demands, are increasingly inadequate for real-time application. FPGAs, with their parallel architecture and reconfigurability, offer a transformative solution. This review highlights key applications of FPGAs in EEG signal processing, including artifact removal in preprocessing, wave-letbased feature extraction, SVM-based classification, and integrated system design. Comparative analysis shows significant improvements in processing speed, resource utilization, and classification accuracy over traditional methods. However, challenges remain in optimizing re-source utilization, expanding multimodal applications, and enhancing portability.

The future of FPGA-based EEG signal processing holds great promise for advancing both clinical and research applications. As technology continues to evolve, the development of more efficient algorithms and architectures will be crucial. These advancements will further optimize resource utilization and reduce power consumption, making FPGA-based systems even more practical for portable and wearable devices. Additionally, the integration of multi-modal signal processing will enhance classification accuracy. Combining EEG with other physiological signals, such as EMG and ECG, provides a more comprehensive understanding of brain and body interactions. Moreover, the expansion of real-time processing capabilities will enable seamless integration into wireless body area networks (WBANs), facilitating continuous monitoring and analysis. Future research should also focus on improving the accessibility and user-friendliness of FPGA-based systems, ensuring they can be easily adopted by re-searchers and clinicians without extensive hardware expertise. Overall, the continuous innovation in FPGA technology will drive the development of more efficient, versatile, and practical solutions for EEG signal processing, from portable medical devices to advanced research tools, ultimately enhancing our ability to decode brain activity and improve healthcare outcomes.

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