

Guest Editorial: Ultralow-Power Technologies for Edge Computing in Human-Machine Interface Applications

WEARABLE healthcare devices are revolutionizing how we monitor and manage health, offering real-time data and personalized insights that empower both patients and clinicians. From tracking heart rhythms to detecting neurological disorders and enhancing prosthetic control, these devices promise to transform the delivery of healthcare. However, despite their immense potential, wearable devices face persistent challenges, including the need for ultralow power consumption to prolong battery life, computational limitations in resource-constrained environments, and maintaining accuracy across diverse users and real-world conditions. Addressing these hurdles requires a multidisciplinary approach, combining advances in biosignal processing, innovative hardware-software co-integration, and energy-efficient architectures. The research articles presented in this Special Section exemplify this synergy, showcasing state-of-the-art solutions that push the boundaries of what wearable healthcare technology can achieve.

This Special Section serves as a pivotal platform to propel research in biomedical circuits and systems within the CAS community, advancing the state-of-the-art in this rapidly evolving field. It comprises 8 selected papers from a competitive pool of 23 submissions, representing an acceptance rate of $\sim 35\%$. These contributions highlight the latest breakthroughs in ultralow-power technologies and provide a glimpse into the future of wearable healthcare systems.

A recurring theme in this Special Section is the challenge of handling variability in biosignals while maintaining low-power consumption. In Loh et al. [1], the authors tackle domain generalization (DG) for electrocardiography (ECG) signals, introducing correction layers that enhance robustness against domain shifts without significantly increasing computational complexity. This novel approach improves classification accuracy while optimizing memory and energy use, making it highly suitable for wearable edge devices. Lee et al. [2] addresses arrhythmia detection, proposing a lightweight convolutional neural network (CNN) combined with R-peak interval features to capture long-term rhythm information. The resulting system, implemented in custom hardware, achieves high classification accuracy with ultralow latency and power consumption, demonstrating the effectiveness of hardware-software co-design for ECG analysis.

The need for continuous and real-time monitoring is particularly evident in epilepsy management. Zhang et al. [3] presents a distributed-aggregated classification architecture that leverages spiking neural networks (SNNs) for event-driven, energy-efficient seizure detection. By reusing hardware resources and

avoiding redundant standby systems, the architecture achieves remarkable energy savings while maintaining high detection accuracy. Similarly, in another study, Lee et al. [4], proposes a RISC-V-based deep learning accelerator capable of real-time seizure detection and model personalization. This programmable architecture supports both inference and training directly on the device, addressing the unique challenges of adapting to individual patient needs in real-world settings.

Neuromorphic computing emerges as a powerful approach in several studies, highlighting its potential for wearable healthcare. In O’Leary et al. [5], the authors develop a brain-state classification processor that integrates resonate-and-fire neurons and decision forests to deliver high accuracy for electroencephalography (EEG)-based closed-loop neuromodulation. With its multiplierless architecture and state-of-the-art energy efficiency, this work showcases the potential of neuromorphic designs for low-power, real-time brain monitoring. Another neuromorphic innovation, from Scrugli et al. [6], leverages SNNs to process surface electromyography (sEMG) signals for prosthetic control. The proposed FPGA-based system efficiently handles both discrete gesture recognition and continuous finger force modelling, offering a glimpse into the future of low-power human-machine interfaces.

System-level innovations also feature prominently in this Special Section, providing frameworks for optimizing edge healthcare applications. The ACE methodology presented by Wang et al. [7] introduces an iterative classification framework that adapts computational complexity during runtime, ensuring efficiency without sacrificing accuracy. By automating the optimization and deployment of algorithms on edge platforms, this work reduces runtime and energy costs significantly, making it accessible for a wide range of biomedical applications. In another direction, a study on analog computing by Alimisis et al. [8] highlights the resurgence of analog architectures in healthcare. By implementing a low-power voting classifier for diabetes prediction, the authors demonstrate how analog computing can achieve exceptional accuracy while minimizing energy use, offering a compelling alternative to purely digital systems.

Collectively, these studies push the boundaries of what is possible in wearable healthcare technologies. By addressing challenges at every stage—biosignal acquisition, algorithm design, hardware optimization, and system integration—they lay the groundwork for devices that are not only energy-efficient but also capable of delivering real-time, personalized insights. This Special Section celebrates the convergence of innovative engineering and practical medical applications, heralding a future

where wearable devices seamlessly integrate into our lives to enhance health and well-being.

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