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Special issue on "Energy-efficient and environmentally sustainable edge computing and communications for artificial intelligence"

Editorial

As the global demand for Artificial Intelligence (AI), wireless communications and Internet of Things (IoT) technologies continue to grow, so too does the urgency of addressing their environmental impact. The Information and Communication Technology (ICT) sector could account for as much as 7%–20% of global energy demand by 2030, making energy efficiency and carbon neutrality pressing concerns for our research community. At the same time, we are witnessing an exciting shift towards edge computing, where AI is increasingly performed closer to the data source, on billions of mobile and IoT devices worldwide. This trend brings new challenges: edge devices are resource-constrained and often lack access to green energy, even as AI model complexity continues to scale.

In response to this dual challenge, advancing AI for sustainability and ensuring the sustainability of AI, we organized this special issue on energy-efficient and environmentally-sustainable edge computing and communications for AI. After a 12-week rigorous peer review process, eight regular papers have been selected for this issue. These papers collectively provide novel insights spanning hardware-software co-design, energy-aware decision-making, sustainable AI applications and benchmarking methodologies, which reflect an exciting diversity of approaches across these themes.

Scanning the issue

This special issue highlights research contributions across four key themes:

I. Architectural innovations for energy-efficient edge computing

At the foundation of sustainable edge AI lies efficient system architecture. Two papers in this special issue address novel hardware-software co-design for enhanced energy efficiency and robustness.

- **Energy-efficient data-driven routing for hybrid interconnection networks: A machine learning approach**

Authors: Md Tareq Mahmud, Uma Maheswar Reddy Nagirireddi, Ke Wang

This paper introduces a data-driven, machine learning-based dynamic routing framework for chiplet-based high-performance computing systems. The proposed framework intelligently adapts to communication needs and directs traffic to wired, interposer, or hybrid communication links in order to meet the stringent latency and energy efficiency requirements of edge computing systems. The findings of this paper underscore the potential of data-driven routing in advancing energy-efficient and high-performance interconnection network designs for future edge computing platforms.

- **Decision-driven fault-tolerant architecture for vision transformers with real-time error mitigation**

Authors: Indhuja Gudluru, Chunyuan Shen, Ke Wang

This paper considers error-prone environments in vision transformer implementations and proposes a dynamic way to Error-Correcting Code (ECC) adaptation, supported by a specialized hardware architecture featuring multiple Processing Element (PE) arrays configured for fault tolerance. The proposed approach employs reinforcement learning to address fault conditions during inference while minimizing the resource overhead, thereby achieving greater resource efficiency.

II. Energy-aware decision and scheduling for edge robotics and distributed AI

Energy-aware optimization remains a key lever for improving the sustainability of edge AI operations. Two papers in this special issue contribute important insights in this area.

- **Towards energy-aware operational decisions for automated guided vehicles: A review**

Authors: KyuJin Kyung, GaHyun Lee, SeongJae Chu, Joseph John Cherukara, SVSLN Surya Suhas Vaddhiparthy, Tanniru Abhinav Siddharth, Deepak Gangadharan, BaekGyu Kim

Battery-powered Automated Guided Vehicles (AGVs) are widely used for material handling across various industries, such as warehouses, manufacturing plants and automated container terminals. This review paper presents a comprehensive analysis of how an AGV's energy is consumed or recharged in a given operational environment, to optimize both operational efficiency and energy consumption. This paper provides important insights into the impact of the operational environment, energy consumption modelling and energy-aware decision-making for scheduling and path planning of AGVs.

- **Incentive mechanism design for semi-asynchronous blockchain-based federated edge learning**

Authors: Xuanzhang Liu, Jiyao Liu, Xinliang Wei, Yu Wang

Federated learning at edge systems not only mitigates privacy concerns by keeping data localized but it also leverages edge computing resources to enable real-time AI inference and decision-making. To overcome the impractical assumption that edge servers will voluntarily join training or mining, this paper proposes a novel incentive mechanism for federated edge learning systems which motivates the participating edge server in federated learning to achieve optimal training and mining outcomes.

III. Benchmarking and edge-cloud optimization for sustainability

To guide future progress, robust benchmarking and optimized edge-cloud architecture are essential. This special issue includes two timely contributions on this theme.

- **AIEnergy: An energy benchmark for AI-empowered mobile and IoT devices**

Authors: Xiaolong Tu, Anik Mallik, Haoxin Wang, Jiang Xie

This paper presents AIEnergy, the first energy benchmark suite and benchmarking methodology to allow accurate energy measurement and performance evaluation of AI-empowered mobile and IoT devices with diverse AI chipsets and software stacks. AIEnergy collects over 8.8 GB measurement data from 264 configuration combinations of 8 commercial AI-empowered mobile and IoT devices with diverse chipsets, six deep learning applications with unique end-to-end processing pipelines and 12 deep neural network models under CPU, GPU, and Neural Networks API (NNAPI) delegates. AIEnergy serves as a ready-to-adopt benchmark that is accessible by both mobile and IoT end users with non-technical backgrounds and researchers with varying levels of expertise.

- **Edge-assisted user-centric real-time 3D remote near-eye rendering for AR/MR headsets**

Authors: Bishakha Rani Biswas, Xueyu Hou, Yongjie Guan

Augmented and Mixed Reality (AR/MR) headsets are transforming computing by enabling immersive 3D experiences, yet inherent size and power limitations prevent them from matching desktop systems in delivering complex graphics. This paper introduces a novel edge-assisted low-latency remote rendering system that enables real-time 3D graphics on AR/MR headsets. The proposed rendering system leverages image-based rendering with advanced 3D image warping techniques and synthesizes headset displays from server-generated depth images, achieving reduced interaction latency while maintaining high rendering quality through careful optimization.

IV. Edge AI for intelligent and secure autonomous systems

Edge AI is critical to the evolution of autonomous and intelligent systems. This special issue features two papers on this theme advancing state-of-the-art solutions for secure and efficient edge deployment in autonomous vehicles.

- **CTLane: An end-to-end lane detector by CNN-transformer and fusion decoder for edge computing**

Authors: Mian Zhou, Guoqiang Zhu, Zhikun Feng, Haoyi Lian, Siqi Huang

This paper proposes CTLane, an end-to-end lane detector for advanced driving assistance systems and autonomous vehicles. CTLane includes a convolutional neural networks transformer, which extracts the overall semantics of the lanes and speeds up convergence, and a fusion decoder, which combines high-level semantics with low-level local features to improve accuracy and robustness. By using these two components together, CTLane is able to effectively detect lanes in a variety of conditions, even in the presence of interference, such as darkness, shadows and strong light, ensuring the safety and stability of autonomous vehicles during driving.

- **Edge ML for CAN bus intrusion detection in AVs**

Authors: Prosenjit Paul, Xingya Liu, Helen H. Lou, Ruhai Wang

This paper addresses the critical challenge of detecting real-time cyber-intrusions in self-driving vehicles. It studies four high-impact attacks, Denial of Service (DoS), spoofing, replay and fuzzy attacks, and develops two lightweight neural network architectures for intrusion detection. Through explainable AI techniques, this paper uncovers unique forensic fingerprints of each attack type, offering actionable insights for feature engineering and proactive defence. This research sets a new benchmark for Autonomous Vehicle (AV) cybersecurity, underscores the urgent need for security-by-design AI, and offers a leap toward safer and more secure autonomous transportation.

Looking ahead

The eight papers in this special issue demonstrate that achieving sustainable AI at the edge is a rich, multidisciplinary challenge, requiring innovations in hardware, algorithms, system design and evaluation methodology. We hope this collection will inspire continued research at the intersection of AI, edge computing and environmental sustainability.

We would like to express our sincere gratitude to all authors for their outstanding contributions, and to the reviewers for their time and thoughtful feedback. We also thank the ITU Journal editorial team for their excellent support throughout this process.

Finally, we warmly invite the research community to continue advancing this important field. We look forward to seeing further progress in designing sustainable, energy-efficient, and intelligent edge systems, for the benefit of both technology and our planet.

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TABLE OF CONTENTS

Page