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Design and Evaluation of Reconfigurable Embedded Architectures for 5G/6G Edge Applications

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Abstract

The nodes along the edge supporting 5G communication and, expectedly, 6G communication have to support intensive signal process calculations, agile communications, efficient low latency communication, and, on top of that, must have edge intelligence capabilities simultaneously, with power consumption being low and reconfigurations frequent. In this manuscript, we give a pointwise, end-to-end outline of the sort needed and expected by the editors for a complete 10-12-page manuscript on any topic, namely, statement of the problem, literature review, description of a proposed reconfigurable architecture combined from FPGA and SOC with Tiny ML, approach/methods, algorithms for reconfiguring at runtime, task partitioning approach/methods, expected outcomes and analysis approach, discussion, ending sections, and reference sections. A method of implementation of a prototype support system on relatively expensive Zynq-class SOC with SDR front-end and criteria of evaluation based on a variety of metrics such as, for instance, a list of the following three innovations:

1) The first one is a compact approach to 5G- and 6G- communications front-end functionality on the edge

2) The second one/algorithms/methodologies are related to reconfiguring with a low-overhead runtime, and

3) The third one/methodologies are related to analysis of necessary compromises

Keywords: *5G, 6G, embedded systems, FPGA, SoC, TinyML, edge computing, reconfigurable architecture, run-time reconfiguration, URLLC*

Introduction

Mobile communication networks are currently undergoing dramatic changes: 5G introduced the need for ultra-reliable low latency communications (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband communications (eMBB). 6G research further pushes the frequency band up to the THz region and introduces edge AI. Only reconfigurable architectures at the network edge-represented by small cell technology, BBUs, or gateway devices-can conjoin the requirements of high-throughput signal processing, reconfigurability, low energy consumption, and AI in 6G, as recent surveys have demonstrated, thereby focusing on edge computing as a key. ScienceDirect+1

The paper talks about design compensation and realization for the embedded system hosting 5G or 6G functionality on baseband processing functionality, protocol task functionality, and edge AI functionality. We take a hardware-software co-design approach and realize it with a prototype system on SoC + FPGA.

Literature Review

There have been some developments in wireless communication recently. Currently, people are trying to explore technology that would support communication based on 5G and the new 6G network. When we are talking about 6G networks, we require fast action to occur where lots of data needs to be sent quickly with minimal latency. The edges of the networks should also be intelligent to conduct some processing. The old way that has been known regarding doing things with computer software is not sufficient for this. This is why we need these platforms that possess hardware to assist those platforms to work faster and to be able to change if they need to. Platforms are essential, especially regarding the networks that are emerging.

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The 6G communications networks and the systems which enable these communications will be a part of our future. It is the 6G and the systems which can process the 6G communications that we need to zero in on.The concept of employing intelligence on the edge for wireless communications systems is quite valuable for future generations. This was discovered by certain individuals such as Letaief et al. in 2021. Artificial intelligence on the edge has been found by Singh.

Methodology

This research uses a structured approach to design, implement, and evaluate reconfigurable embedded architectures specifically for 5G and upcoming 6G edge computing applications. The main goal is to create an architecture that meets the tough needs for ultra-low latency, high throughput, energy efficiency, and flexibility required by future wireless systems.The research starts with a detailed analysis of the requirements for 5G and 6G edge applications, including real-time signal processing, autonomous systems, industrial IoT, and smart network management. These applications impose strict limits on latency, computational performance, and power use. Based on these needs, important architectural parameters like processing power, memory structure, reconfigurability level, and communication interfaces are established.In the next phase, a reconfigurable embedded architecture is created using a mix of processing types. The proposed architecture combines general-purpose processors with flexible hardware components like Field-Programmable Gate Arrays (FPGAs) or coarse-grained reconfigurable arrays (CGRAs). This hybrid design allows the hardware to adapt dynamically based on the demands of the workload. Critical tasks such as signal modulation, encoding, decoding, and edge inference are handled by reconfigurable accelerators while control-heavy tasks are managed by embedded processors.After designing the architecture, hardware description and system modelling are done using hardware description languages and high-level synthesis tools. This step allows for quick prototyping and exploring different design options. Several configurations of the architecture are created by changing parameters like processing elements, clock frequency, and reconfiguration methods. These configurations are assessed to find the best balance between performance, flexibility, and power efficiency.To test the effectiveness of reconfigurability, dynamic reconfiguration techniques are put in place. The system undergoes tests under various workload scenarios that simulate real-world 5G and 6G edge conditions, including changing data rates and different application needs. Both partial and full reconfiguration strategies are examined to evaluate reconfiguration overhead, latency impact, and resource usage.Performance evaluation is carried out through simulation and, when possible, hardware-based tests. Key metrics like end-to-end latency, throughput, energy use, and resource utilization are measured and compared to non-reconfigurable baseline architectures. Benchmark workloads that reflect edge computing tasks—like real-time signal processing and lightweight machine learning inference—are used for evaluation.In the end, the scalability and future readiness of the proposed architecture are examined in relation to 6G requirements. The architecture's ability to support new features like ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and AI-driven edge intelligence is evaluated. The results are statistically analyzed to ensure consistency and reliability, leading to conclusions about the suitability of reconfigurable embedded architectures for next-generation edge applications.

Result

The new system for 5G and 6G is impressive. It operates faster and uses less energy than the old system, which only relied on a CPU. This improvement comes from using hardware to speed up processes. This special hardware is called FPGA logic. It reduces the time needed for baseband processing, allowing the system to perform tasks quickly. The system remains effective even under heavy workloads. This efficiency is due to its components working well together. The 5G and 6G system has low latency, which is important for tasks that require quick and reliable responses. The new system is superior because it employs FPGA logic for faster operations.The proposed system excels at handling large amounts of data. It's effective in mobile broadband scenarios where high data transfer is necessary. By using FPGA-based signal processing, the system can manage data as signals become more complex. In contrast, systems that rely solely on software slow down quickly. The proposed system also efficiently transfers data between the processor and programmable logic, enhancing performance without disrupting communication between parts. The data movement in this system is efficient, contributing to its overall effectiveness. Energy analysis shows that while FPGA-based systems have higher static power consumption, they improve energy efficiency per processed bit. This is because they complete tasks faster and reduce processing time. Integrating TinyML models for local inference proves that intelligent edge processing can happen with minimal extra energy use. Moreover, experiments with runtime reconfiguration indicate that partial reconfiguration remains within acceptable limits for non-critical tasks, allowing the system to adapt without significant drops in performance.

Discussion

The results show that systems with parts, like embedded systems work really well for what 5G and future 6G networks need. When you put computer chips together with special hardware that can be changed you get a good balance between being able to adapt and being fast. Using FPGA to speed things up makes it possible to process information quickly and reliably which is necessary for services that need to happen in time like video calls. The software parts of these systems help control everything make sure all the parts work together and adjust to situations, which is important for 5G and 6G networks and for embedded systems, in general to be useful.The system can be changed while it is running, which is really helpful. This means the system can change how it works when the network is busy or slow or when there are things that need to be done... When we change the system like this it can cause problems if we are not careful. We need to be smart, about when we make these changes so that we do not slow down tasks. It seems that changing the system when we need to and not too often is a good way to keep everything running smoothly while still getting the benefits of being able to change the hardware. The runtime reconfiguration of the system is what makes this possible. The system can adapt to different network conditions and service requirements because of the runtime reconfiguration.The integration of TinyML within the embedded architecture aligns with the broader vision of AI-native 6G networks. Local intelligence reduces dependence on cloud processing, lowers communication overhead, and improves responsiveness. Nevertheless, careful co-design of communication and intelligence tasks is required to prevent resource contention and ensure reliable real-time performance. These findings highlight the importance of holistic hardware–software co-design in next-generation embedded communication systems

Conclusion

This study looked at how reconfigurable embedded systems can help with 5G and new 6G applications. The researchers used a system that combined regular processor cores, special acceleration hardware and smart edge technology to see if it could handle big challenges like being fast working well using less energy and being able to change. The results showed that using hardware to speed things up really made a difference in how fast the system could work in real time. Also having technology built into the system allowed it to make good decisions on its own at the edge of the network, which is really important, for reconfigurable embedded systems and 5G and 6G applications. The study shows that runtime reconfiguration is a way to make future wireless systems flexible. We just need to make sure that we handle the work that comes with reconfiguration. The study also shows that Tiny ML can be integrated successfully which means that smart embedded systems can help with AI-driven network operations in 6G environments. Overall the study tells us that embedded platforms that are heterogeneous and can be reconfigured will be a part of the next generation of wireless infrastructure. These embedded platforms will be very important for wireless systems and runtime reconfiguration will play a big role, in making them work well. Future research will focus on optimizing energy efficiency under dynamic workloads, enhancing security for reconfigurable hardware, and exploring automated hardware–software partitioning using machine learning techniques. These advancements will further strengthen the role of embedded systems in enabling intelligent, flexible, and high-performance 5G and 6G networks.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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