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Reliability of Edge Offloading

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Content

1 Introduction

The research is focused on enabling reliable real-time execution of resource-intensive and latency-sensitive mobile applications in distributed and resource-constrained edge environments. The research output of underlying work is an edge offloading framework called FRESCO (Fast and Reliable Edge Offloading with Reputation-based Hybrid Smart Contracts) which addresses critical challenges of distributed unreliable edge environments and optimizes performance by respecting heterogeneous edge resource limitations and application strict timing deadlines for ensuring required qualify-of-service. The document presents general information, results, planned future activities, and potential usage or extension of presented research work by third parties for academic or industrial use.

2 General

Latency-sensitive mobile applications are subject to strict quality-of-service (QoS) requirements such as response time. Any prolongation of response time can lead to performance degradation (e.g. motion sickness in augmented reality) or even life-threatening situations (e.g. car accidents with autonomous vehicles). These applications require high resource demands such as CPU cores, RAM capacities, and hard drives to achieve fast performance and satisfy strict timing deadlines. However, local devices like AR headsets or car vehicles have limited resources. Unable to provide sufficient resources makes it impossible to achieve (near-)real-time performance and violates QoS timing requirements. The main goal is to offload resource-intensive application tasks from resource-limited mobile devices to nearby resourceful edge servers that have greater computational power. Edge servers accelerate application execution performance (e.g. shorter response time) and thus satisfy tight QoS timing requirements for achieving real-time performance necessary for latency-sensitive mobile applications.

Edge offloading has its own set of challenges that have to be overcome. The edge environment is usually unreliable due to limited resources and unstable connections. Moreover, distributed edge servers have heterogeneous resources ranging from micro data centers to single-board computing devices (e.g. Raspberry Pi). Deciding which edge server has sufficient available resources to execute application tasks timely is of paramount importance for achieving high performance. Also, mobile devices are constantly exposed to new edge servers due to mobility. The edge servers can change behavior between interactions due to dynamic failures, thus making it difficult to identify a reliable one based on local historical experience. Lastly, edge environments are usually shared between many mobile devices which makes them susceptible to highly volatile workloads, which can drastically limit available edge resources.

To address the aforementioned challenges, the ultimate end goal of our research was to find an offloading solution that can formally guarantee the required (near-)real-time performance amid an unreliable and volatile edge environment. The focus is on guaranteeing the performance instead of optimizing it. Optimization solutions can obtain near-optimal solutions but cannot guarantee performance which is vital for latency-sensitive mobile applications that require a high level of reliability. Hence, we target a solution that can compute offloading decisions timely and can formally guarantee the feasibility of offloading decisions for achieving a high rate of reliable offloading.

The resulting output of our conducted research is summarized in the following chapter.

3 Results

We introduce a reputation-based edge offloading framework called FRESCO, which optimizes both offloading and reliability in distributed unreliable edge scenarios for latency-sensitive applications. FRESCO is a two-fold approach that consists of offloading and reliability components.

Regarding offloading, we employ satisfiability modulo theory (SMT) which provides formal guarantees for offloading decisions to ensure feasibility under strict timing constraints. The SMT provides formal proof assurance that relevant edge resource limitations and application timing constraints are satisfied, which fits resource-constrained and latency-sensitive environments. SMT relies on input constraints and logic rather than environmental variables like heuristics or machine learning, which makes it an environment-agnostic approach, suitable for distributed edge environments.

Concerning reliability, we employ a blockchain-based reputation system for estimating the reliability levels of edge servers in terms of edge failures. Reputation systems assess edge server historical performance in the form of a reputation score, which is a performance-tracking metric stored in a distributed database and accessible for mobile devices as input information for offloading on reliable edge servers. Integrating a reputation system with blockchain is sensible in malicious environments where different actors can tamper with a reputation to unjustifiably inflate selected servers while downgrading others to gain incentives unfairly, potentially leading to QoS timing violations. Blockchain secures sensitive stored information like reputation scores thanks to a consensus mechanism where all participant blockchain nodes have to agree about the blockchain state. It makes it hard for malicious actors to manipulate reputation scores because they have to control the majority of blockchain networks which is hard to achieve, especially in public large-scale blockchain networks such as Ethereum.

However, consensus latencies can be long, especially in large-scale blockchain-based systems, which conflicts with our latency objective. To enable a blockchain-based reputation system for latency-sensitive applications, we employ a hybrid smart contract (HSC) as a reputation state manager. HSC allows off-chain (i.e., outside of blockchain) transactions like fast offloading decisions that require performance while retaining secured on-chain storage (i.e., on the blockchain) of sensitive reputation information against malicious tampering. The HSC, deployed on the blockchain, is queried by mobile devices to retrieve secured reputation scores about servers' reliability levels to the SMT-based offloading decision engine on the device for reliable offloading decisions. In summary, FRESCO bypasses slow blockchain consensus with HSC for fast-performant off-chain offloading decisions on reliable edge servers while preserving secured on-chain sensitive reputation information.

To evaluate our proposed FRESCO solution, we implemented the edge offloading simulator in Python. The FRESCO is evaluated against several baselines including Markov Decision Process (MDP), Mixed Integer Nonlinear Programming (MINLP), and Social Queueing (SQ) approaches, which are taken from the state-of-the-art literature. The infrastructure is simulated based on the publicly available OpenCellID dataset that represents radio cell tower locations in Austria, and each location is used as an edge server location. The workload on the nodes is simulated through the dynamic queueing network. For SMT solving, we use Z3 as an SMT solver. We used the Ganache blockchain emulator for emulating real blockchain system behavior implemented a real-world HSC in the Solidity programming language and deployed it on the Ganache blockchain. For simulating failures on the infrastructure, we selected publicly available Skype traces. The motivation for selecting the Skype dataset over others is that Skype represents the middle ground in availability ratio (60-70%) and latency (up to ~50 ms). Traces are collected over 2,081 servers for 400 days.

Experimental results have shown performance gains of FRESCO over baselines where response time is reduced by up to 7.86x. The energy efficiency was achieved up to 5.4% of energy savings. Reliability levels were high where QoS violations were minimized to 0.4%, demonstrating robustness in distributed environments. Decision efficiency was achieved with an average decision time of 5.05 milliseconds, suitable for latency-sensitive applications that require short decision time with minimum impact on application response time. Lastly, cost-effectiveness was achieved when computational and resource utilization monetary costs were balanced through optimal server selection, which implies the practical application of FRESCO in commercial environments where edge and cloud services are usually provided as commercial services.

4 Planned Further Activities

We plan to submit the finished work to IEEE Transactions on Service Computing journal venue by end of the 2024 year. The submission evaluation can last up to one full year. In pararell, we plan to continue the current work of runtime verification of edge offloading which formally verifies non-functional application requirements in edge offloading with the goal of assuring performance reliability of edge offloading in runtime. More detailed plan is noted in Excel document Stip6851_Planupdate_EB.

5 Suggestions for Continuation by Third Parties

FRESCO can be applied in cross-domain applications like healthcare, autonomous systems, or industrial Internet of Things, where reliability and latency are critical. FRESCO can also be used in interoperability studies to explore how FRESCO can integrate with existing edge computing frameworks and blockchain ecosystems, including integration with machine-learning-based solutions where balancing between guaranteeing and optimizing performance for diverse set of applications in terms of resource allocation and failure prediction.

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