

Research Statement – Chuanchao Gao

My research focuses on the mathematically rigorous modeling and algorithmic analysis of real-time systems under resource constraints. In particular, I study task mapping, resource allocation, and scheduling problems in network-integrated computing systems, with Mobile Edge Computing (MEC) serving as a primary application domain. In such systems, computation and communication resources are inherently limited, and placement and scheduling decisions must satisfy strict end-to-end timing constraints across multiple sequential stages and heterogeneous resource types. This setting provides a concrete yet representative context for understanding how resource coupling and timing requirements shape system-level performance. Methodologically, my work emphasizes approximation techniques with provable guarantees rather than purely heuristic approaches.

A central theme of my doctoral research has been the formulation of system-level decision problems that capture essential timing and resource constraints while remaining sufficiently general to represent a class of systems rather than a specific deployment. To achieve this balance, I developed abstractions for complex real-time systems that preserve critical operational constraints without oversimplifying real-world system behavior. In particular, I adopted a modeling approach based on enumerating *schedule instances*, where each instance represents a locally feasible scheduling configuration that satisfies task-level execution semantics and internal timing requirements. By resolving task-local feasibility independently, the resulting optimization problems focus on global constraints such as shared communication and computation capacities and cross-component coupling, thereby exposing the underlying combinatorial structure that determines computational difficulty.

Using this framework, I studied deadline-constrained task mapping, resource allocation, and scheduling problems in MEC systems. These systems exhibit strong coupling among placement, allocation, and scheduling decisions across multiple stages and resource dimensions, subject to joint communication and computation capacity constraints and end-to-end deadlines. Such tight interdependence renders classical decomposition approaches insufficient. For joint task mapping and resource allocation formulations, I developed the first constant-factor approximation algorithms for several problem classes, establishing provable performance guarantees while clarifying structural trade-offs between solution quality and computational complexity. These results were published in RTSS 2025 and accepted to appear in RTAS 2026.

Beyond partially integrated formulations, I investigated the fully integrated problem of task mapping, resource allocation, and scheduling, where placement, allocation, and scheduling decisions directly determine end-to-end deadline feasibility. I proposed a probabilistic constant-factor approximation framework that provides the first theoretical guarantees for this generalized class of tightly coupled real-time problems (RTSS 2024). By identifying structural parameters that influence feasibility and performance, this framework characterizes the approximability of the problem while preserving its inherent combinatorial complexity.

To ensure that theoretical insights remain grounded in practice, I developed an open-source simulator, *mecRT*, which supports full task-lifecycle management for network-integrated real-time systems, as well as fault detection and recovery under link and server failures. This system-level evaluation incorporated network dynamics, resource heterogeneity, and timing behavior, and reinforced the importance of aligning modeling abstractions with implementation realities.

Overall, my research integrates scheduling theory, approximation algorithms, and system-aware modeling to address tightly coupled real-time decision problems, providing a foundation for further investigation into analyzable scheduling policies within model-based design tool-chains.