Research Statement

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1. Research Objective

The overarching goal of my research is to design and analyze emerging safety-critical and mission-critical network protocols, while developing novel resource management techniques that enable large-scale heterogeneous networked and computing systems across industrial sectors such as aerospace & defense, utilities & energy, manufacturing, transportation & logistics, and agriculture. As shown in Fig. 1, the research in my group is organized in a bottom-up manner, spanning real-time wireless edge and core network design, critical cyberinfrastructure resource management, and edge/cloud data processing and analytics.

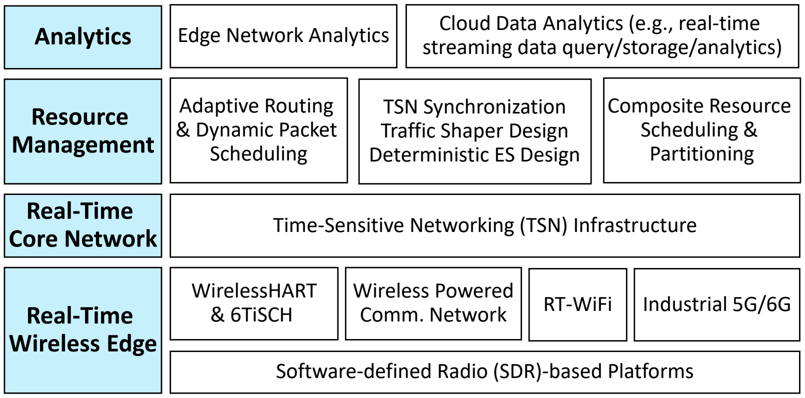

Figure 1: Research Roadmap of UConn CPS Lab

Since 2013, my research has been supported by more than $13.8M in grants, including approximately $6.16M as my share, from NSF, NASA, AFRL, DOT, FHWA, NIH, DOE, industrial sponsors such as Emerson, TI, and Microsoft, as well as internal grants from UConn and UConn Health. In addition to publishing technical innovations in premier conferences, including RTSS, RTAS, ECRTS, NSDI, S&P, VLDB, ICDCS, ICCPS, EMSOFT, DAC, ICML, and AAAI, and leading journals, including PIEEE, CSUR, TMC, TC, TKDE, TCPS, TOSN, TCAD, and JSAC, my group emphasizes full-stack system design, implementation, and real-world deployment. Our participated industrial wireless solutions, including WirelessHART [1], 6TiSCH [2], and RT-WiFi [3], have been incorporated into a range of industrial systems, and our Time Sensitive Networking (TSN) benchmarks [4] have been adopted by numerous academic and industrial research groups.

Building on these accomplishments, my research plan for the next 3-5 years will focus on three interrelated directions: a unified programmable wireless fabric design for future industrial systems; end-to-end resource orchestration for heterogeneous industrial systems; and agentic intelligence for NextG industrial systems. I will continue to pursue support from federal agencies and industrial sponsors that have funded my work, while also expanding into new programs and partnerships with companies whose needs align with these research directions. Below, I summarize my ongoing research projects and future plans.

2. Selected Ongoing Research Topics

Topic 1. Wireless Protocol Design for Real-Time Mission-Critical Industrial Applications

Supported by multiple NSF awards and research gifts from industry partners, including Emerson and TI, this long-term research effort focuses on the design of next-generation wireless communication protocols for mission-critical sensing, monitoring, and control systems. Through close collaboration with industry, my research group has made significant contributions to industrial wireless networking, including: (i) WirelessHART [1], the first international wireless communication standard for process automation; (ii) 6TiSCH [2], a standards-based protocol enabling IPv6 networking over IEEE 802.15.4e TSCH networks; and (iii) RT-WiFi [3], a configurable high-speed real-time wireless protocol for factory automation applications. Beyond protocol development, we have created complete wireless solutions encompassing hardware platforms, network management software, and testing and validation tools to support real-world deployment. These efforts have facilitated technology transfer and adoption across a broad range of industrial applications.

Building on these accomplishments, our recent work has expanded in two emerging directions. First, we are investigating real-time Wireless Powered Communication Networks (WPCNs) [5], which integrate wireless energy transfer and communication to reduce battery maintenance costs and enable large-scale sensor deployments in hard-to-access environments. Second, we are developing resource management frameworks for 5G Radio Access Networks (RANs), including real-time downlink scheduling algorithms with performance guarantees [6], configured-grant mechanisms for uplink communications [7], and QoS-guaranteed coexistence of enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communications (URLLC) traffic [8].

Collectively, these technologies offer a broad spectrum of industrial connectivity solutions, enabling system designers to balance energy efficiency, communication reliability, bandwidth utilization, and real-time performance according to application-specific requirements.

Topic 2. Time-Sensitive Networking (TSN) Core Design

Primarily supported by the NASA RETH Institute, this research area seeks to advance TSN as a real-time, high-speed, and resilient communication backbone for safety-critical and mission-critical cyber-physical systems. Motivated by the need for resilient networking infrastructures in future extraterrestrial habitats and deep-space exploration missions, our work addresses fundamental limitations of current TSN technologies and develops solutions that provide deterministic, fault-tolerant end-to-end communication guarantees.

To address these challenges, we conducted the first comprehensive study of IEEE 802.1Qbv Time-Aware Shaper (TAS)-based scheduling techniques, culminating in a systematic review and large-scale experimental evaluation of representative approaches [4]. Through high-fidelity simulations and real-world testbed experiments, we characterized the schedulability, scalability, and performance tradeoffs of existing methods, providing valuable insights for both researchers and practitioners. To improve reproducibility and accelerate innovation, we developed TSNKit [9], an open-source toolkit that offers standardized implementations of representative TSN scheduling algorithms, an end-to-end workflow for test generation, scheduling, and validation, and comprehensive benchmarking capabilities for fair and reproducible evaluation.

In parallel, we addressed the "last-inch" challenge of deterministic packet transmission at TSN end stations. Most notably, we developed KeepON [10], a software-based driver architecture that enables highly accurate packet transmission on commodity network interfaces and extends TSN capabilities to legacy devices without specialized hardware support. Experiments on a real-world TSN testbed demonstrated up to a 130× improvement in transmission accuracy over standard network drivers and a 2.1× improvement over state-of-the-art hardware-assisted solutions.

Collectively, these contributions advance the state of the art in TSN scheduling, benchmarking, and implementation, while laying the foundation for deterministic communication across heterogeneous infrastructures that integrate TSN, advanced wireless (e.g., 5G/6G) and edge computing platforms supporting various industrial automation systems [11].

Topic 3. Dynamic and Composite Resource Management in Large-scale IIoT Systems

Primarily supported by NSF, this research area develops dynamic packet scheduling and resource management frameworks for large-scale Industrial Internet of Things (IIoT) systems. A central goal is to provide reliable and predictable wireless communication in harsh industrial environments, where unexpected system and network disturbances can disrupt communication schedules and degrade real-time performance.

One major thrust focuses on dynamic and distributed packet scheduling for real-time wireless networks. Beginning with centralized scheduling approaches [12], this work evolved into hybrid and fully distributed scheduling frameworks [13, 14] that leverage local computation to mitigate disturbances while maintaining network-wide consistency. These frameworks significantly reduce scheduling overhead, improve scalability, and provide provable guarantees on disturbance response time. More recently, we have incorporated channel uncertainty into multi-hop scheduling, enabling probabilistic timing guarantees under diverse network conditions [15].

A second major thrust investigates resource partitioning, virtualization, and orchestration techniques for cyber-physical systems operating under dynamic workloads and heterogeneous resource constraints. Representative contributions include the Regular Composite Resource Partition (RCRP) framework [16] and online reconfiguration techniques [17] that preserve real-time guarantees for coexisting applications under changing workloads, as well as composite scheduling frameworks [18] that jointly manage computation and communication resources to provide end-to-end timing guarantees. Building on these foundations, we further developed adaptive resource partitioning [19] and flexibility-aware resource virtualization techniques [20] for real-time wireless networks and mission-critical applications.

Collectively, these contributions establish a foundation for software-defined resource management across computing and communication infrastructures and provide key enabling technologies for the design, deployment, and evolution of future IIoT systems.

Topic 4. Applying Real-Time Wireless Solutions to Address Practical Challenges

In addition to advancing fundamental research, my research group actively collaborates with multidisciplinary teams to translate innovations in networking, computing, and data analytics into real-world solutions with broad societal impact. These efforts leverage our expertise in cyber-physical systems, real-time communications, edge computing, and AI-enabled decision making to address critical challenges in energy, transportation, healthcare, and advanced manufacturing. Representative projects include surface fouling monitoring for gasification systems (DOE), structural health monitoring of bridge expansion joints to enhance transportation resilience (DOT), gait-speed assessment for primary care and health monitoring (NIH), collaborative perception and adaptive V2X communications for connected and autonomous vehicle safety (DOT), and IoT-enabled, AI-driven collaborative robotics for next-generation manufacturing systems (AFRL).

Through these partnerships, we not only validate our research in operational environments but also accelerate the deployment of innovative technologies that improve safety, efficiency, resilience, and quality of life. These collaborations further create new opportunities for fundamental research while ensuring that our work delivers tangible benefits to industry and society.

3. Future Research Plans

Direction 1. Toward a Unified Programmable Wireless Fabric for Future Industrial Systems: Looking ahead, we envision a new generation of industrial wireless infrastructure that transcends the limitations of today's application-specific and protocol-siloed solutions. Rather than deploying and managing multiple incompatible wireless technologies, future industrial environments will require a unified communication fabric capable of seamlessly supporting diverse sensing, monitoring, and closed-loop control workloads on a common platform.

To realize this vision, we will pursue the development of a full-stack, SDR-based programmable real-time industrial wireless architecture that decouples wireless functionality from fixed hardware implementations. By enabling protocol reconfigurability, cross-protocol interoperability, and software-driven evolution, the platform will support both existing and emerging wireless standards on a shared programmable hardware substrate. Beyond reducing infrastructure complexity and deployment costs, such a platform will enable industrial networks to adapt dynamically to changing application requirements, operational conditions, and technology advancements.

Ultimately, we envision this programmable wireless foundation serving as a unifying communication layer for future Industry 4.0 and Industry 5.0 systems, delivering deterministic performance, timing guarantees, and resilient operation across heterogeneous industrial applications while accelerating innovation in industrial sensing, intelligence, and autonomous control.

Direction 2. End-to-end Resource Orchestration for Heterogenous Industrial Systems: Future industrial systems will increasingly depend on tightly integrated wired and wireless communication infrastructures to support mission-critical sensing, monitoring, and closed-loop control applications. While technologies such as TSN and 5G individually provide mechanisms for deterministic communication, achieving end-to-end timing guarantees across heterogeneous network domains remains an open challenge. The fundamental difficulty lies in reconciling the deterministic scheduling paradigm of TSN with the dynamic and adaptive nature of wireless systems, where channel conditions and resource availability continuously evolve. As industrial systems become larger, more interconnected, and increasingly autonomous, maintaining predictable end-to-end performance will require a fundamentally new approach to cross-domain resource coordination.

To address this challenge, we envision an end-to-end resource orchestration framework that bridges heterogeneous communication domains through unified timing abstractions and coordinated resource management. Rather than treating TSN and 5G as independently managed networks, the framework will enable timing requirements, resource reservations, and performance guarantees to be coordinated across domain boundaries. Building on our recent insight that reducing the long-term frequency of system reconfigurations can yield greater benefits than optimizing individual adaptation events, we will investigate contract-based mechanisms that capture timing guarantees across heterogeneous networks and develop orchestration strategies that dynamically allocate resources while preserving long-term system stability. By enabling deterministic performance across converged wired-wireless infrastructures, this research will lay the foundation for scalable, resilient, and adaptive industrial systems capable of supporting the next generation of autonomous manufacturing and cyber-physical applications.

Direction 3. Agentic Intelligence for NextG Industrial Systems: Future industrial systems will comprise large-scale interconnected networks of sensors, robots, autonomous vehicles, edge/-cloud computing resources, and programmable communication infrastructures. As these systems become increasingly dynamic, distributed, and autonomous, traditional management approaches based on static configurations, predefined control policies, and human-in-the-loop decision making will become increasingly difficult to scale. Ensuring efficient operation while simultaneously satisfying stringent requirements on timing, reliability, safety, and resilience will require industrial systems that can continuously perceive their environments, reason about system-wide objectives, and autonomously adapt to changing conditions.

To address this challenge, we envision a new generation of agentic industrial systems in which AI agents serve as intelligent orchestrators across communication, computing, and control domains. Rather than managing networking, computation, and physical processes independently, these agents will leverage real-time observations and predictive reasoning to coordinate resources holistically, proactively responding to workload fluctuations, network dynamics, equipment degradation, and operational disruptions. Building upon emerging advances in foundation models, digital twins, and autonomous decision-making, we will investigate architectures that enable agents to reason across heterogeneous cyber-physical resources while respecting application-level performance objectives and system constraints. At the same time, we will develop mechanisms that provide guarantees on safety, timing, and reliability, ensuring that autonomous adaptation remains predictable and trustworthy in mission-critical industrial environments. Ultimately, this research aims to establish the foundations of self-managing industrial infrastructures capable of continuously optimizing their operation while supporting the next generation of autonomous manufacturing and cyber-physical systems.

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