Analysis, Identification and Mitigation of Delay Performance Bottlenecks of Network Infrastructure in Cyber-Physical Systems

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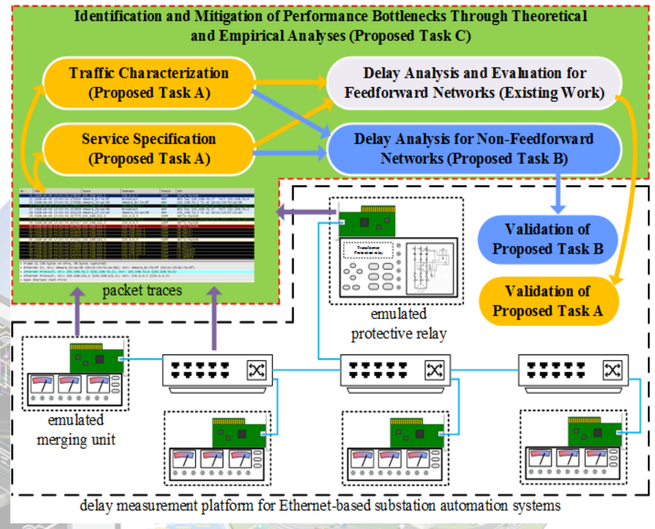
http://liangcheng.info/projects/cps-breakthrough/

Mission-critical CPS applications, such as industrial process control and avionic systems, require their network infrastructure to provide deterministic delay performance. However, the problem of integrating CPS theoretical concepts with network performance analysis remains largely unexplored due to the lack of a suitable framework for such analyses.

Key challenges: (i) limited tools in deterministic performance analysis of cyber-physical systems with random processes, and (ii) interdependencies among information flows in CPS network infrastructure. These challenges have been manifested as an open research problem called worst-case delay analyses of information flows with cyclic dependency in CPS.

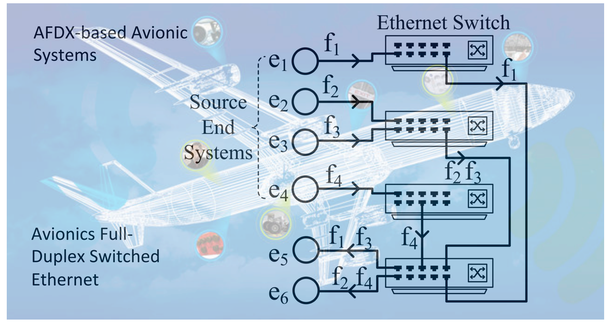
Image sources: http://interactive.aviationtoday.com/avionicsmagazine/june-july-2017/development-of-wireless-avionics-intra-communications/ and https://engineering.lehigh.edu/research/resolve/volume-1-2019/convergence-design

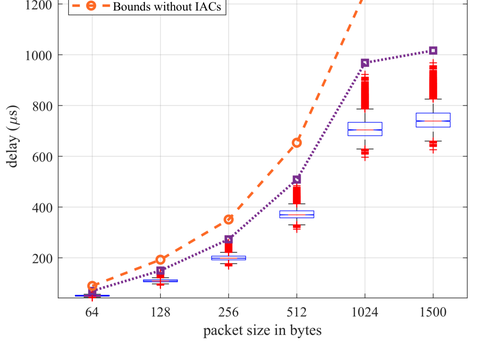


Solution: The proposed measurement-based analytical framework is the first work facilitating the analyses of network-induced delay for CPS of practical scale and with cyclic or non-feedforward traffic patterns. By combining measurement-based modeling and network-calculus-based analyses, it overcomes the weaknesses of direct measurements and facilitates quick verification of hard-real-time safety properties at different stages of the life cycle of networked CPS.

Findings: (i) The problem of worst-case delay bounding for a wireless parallel redundancy protocol network can be solved by performing network-calculus-based analysis on its non-feedforward traffic pattern; (ii) Replacing intermediate arrival curves (IACs) derived from network calculus by models obtained through measurements improved analytical bounds.

Scientific impact: The project result can be applied to many CPS application domains involving real-time control and adaptation, such as vehicular control and communication systems, industrial process control, and network-on-chip systems. The success of the project will lead to CPS designs with hard-real-time safety properties rigorously validated before system renovation or reconfiguration, implementation, and deployment, thus reducing the risks of hazards caused by irresponsive control.





Stakeholder	Benefit
CPS architects and engineers	1. Estimated worst-case delay bounds at early stages of networked CPS design, guiding the design process to ensure that hard-real-time constraints are met 2. Accurate delay bounds under different CPS operational scenarios using measurement-based models constructed for procured equipment 3. Accurate worst-case delay analyses throughout the life cycle of networked CPS to provide guidance on mitigating/eliminating performance bottlenecks
CPS operators	1. Worst-case delay bounds re-computed upon system changes (e.g., after new services are added or legacy devices are replaced) without interrupting system operations, allowing quick verifications of hard-real-time safety properties 2. Worst-case delay bounds provided in a flow-specific fashion, making it easier to identify causes to delay-induced system failures (as well as delay performance bottlenecks)

Education and Outreach	Plans and Impacts
CPS users	Videos showcase that hard-real-time constraints for safety-critical tasks can be evaluated at multiple phases of a CPS's life cycle, significantly reducing the risks of hazards related to irresponsive control.
CPS educators	Seminar modules for educating high-school students that demonstrate risks and/or hazards caused by not having a principled design and validation process for CPS safety, stability and resilience; tutorial/workshop materials for CPS researchers
CPS standardization organizations	Certification programs may leverage the proposed framework to ensure that worst-case delays experienced by traffic flows do not exceed those specified in domain-specific CPS standards.

The framework can be integrated into multiple phases of a CPS's life cycle to avoid design schemes that violate hard-real-time requirements and/or result in latent safety threats. The framework enables the reuse of measurement-based device models under different traffic patterns, and thus a guided CPS design procedure can be established to quickly verify hard-real-time safety properties without interrupting normal system operations and repeatedly taking measurements. The ultimate success and broader impacts of this project can be observed from its adoption by CPS research communities and industry.

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