Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

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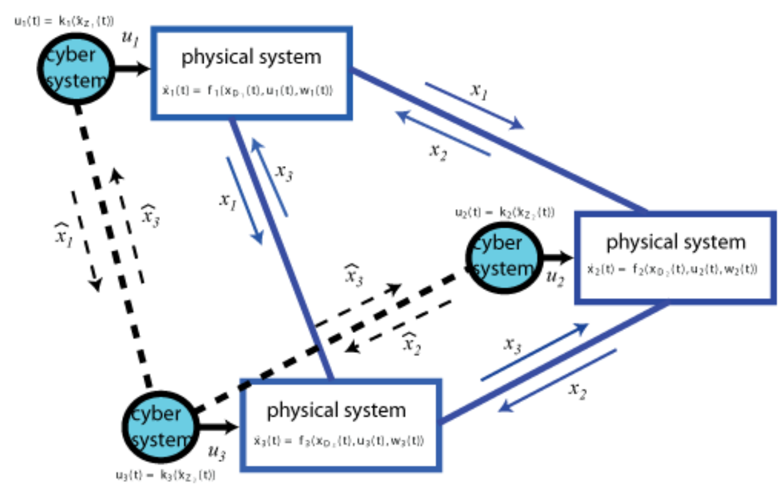
Wireless Sensor-Actuator Network:
Distributed feedback control system whose feedback links are implemented over wireless communication networks.

Objective:
Develop distributed algorithms supporting control applications over wireless networks.

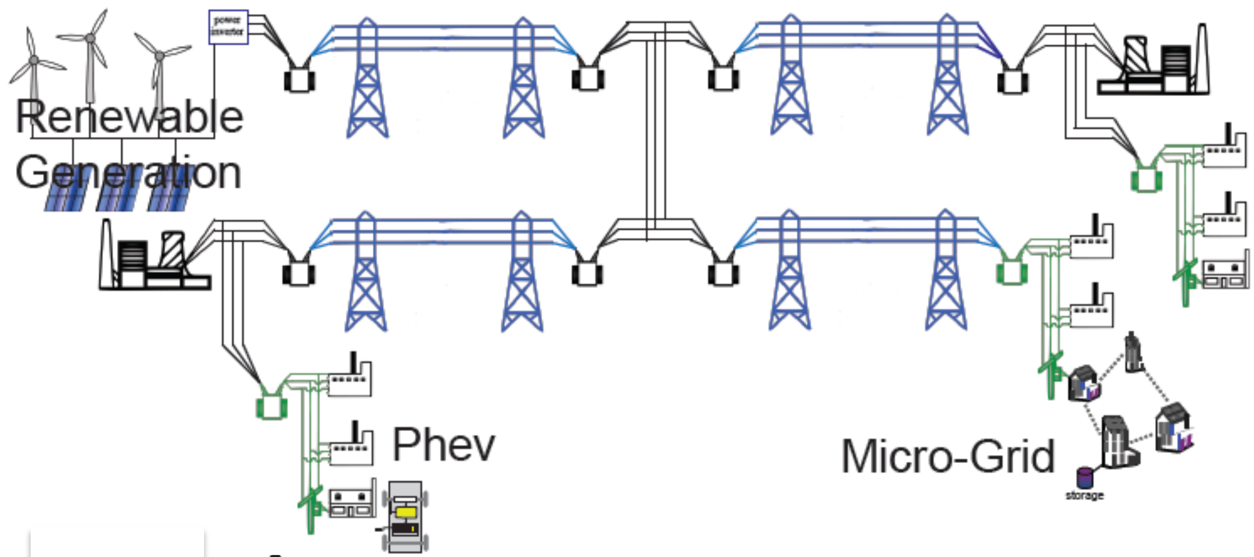


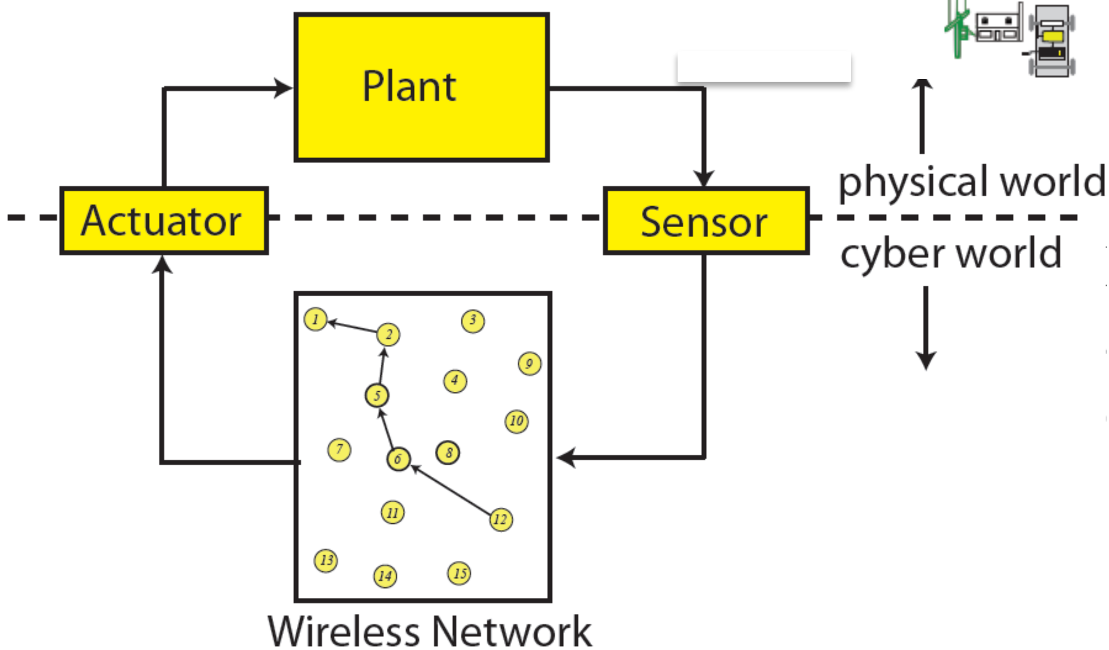
Keywords: firm real-time QoS over wireless channels

Project Website: http://www.nd.edu/~lemmon/projects/NSF-08-611/

Wireless Sensor Actuator Networks

Feedback Channel implemented over a multi-hop wireless comm. network with stochastic





Examples are found in controlling spatially distributed systems:

- **Electric power grid**
- **Water distribution and collection networks**
- **Traffic networks**

Main Tasks

- "Physical" side
  - Adapt controller to changes in network Quality of Service
- "Cyber" side
  - Provide controller with desired network Quality of Service
- Metrics of interests
  - Controller performance
  - Network energy consumption
- Experimental validation
  - Implementation in hardware
  - Technology transfer

Energy Saving in WSAN

- Conflicts facing WSAN
  - Nodes are powered by batteries & store a limited amount of energy
  - Violating message deadlines deteriorates controller performance
  - Low transmission rates can save energy, but cause messages to miss their deadlines

- Dynamic transmission rate adjustment
  - When to change the rate?
  - What rate to use?
  - Overhead?

Our Problem

- **Minimize transmission energy of a given time interval**

$$\min_{r(t)} \int_{t_0}^{t_1} P(r(t))dt$$

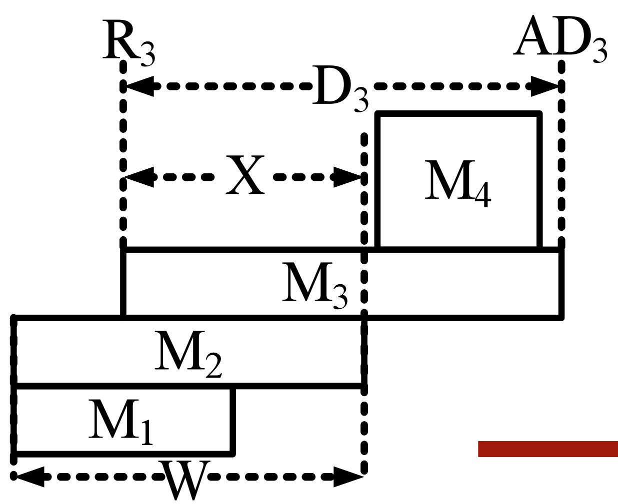
where P(r) and r(t) are the transmission power and transmission rate of a sensor respectively, and t_0 and t_1 are the start time and the end time of a given time interval.

- **Guarantee the real-time requirement of messages under EDF**
  - **Some factors, such as the jitters, the packet non-preemptive property, and the dynamic interference, makes it difficult to meet deadlines of all the messages**
  - **Make as many messages as possible to meet their deadlines**

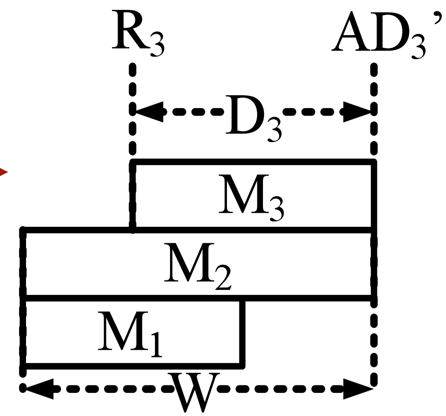
Dynamic Transmission Rate Adjustment

- Original Lp-EDF
  - Original Lp-EDF is a DVFS algorithm proposed by Yao et al. (FOCS 1995), which is optimal to schedule preemptive jobs on a single processor under EDF scheduling
  - Require the release times of all the jobs & job can be preemptive arbitrarily
- Modified Lp-EDF
  - Respect the non-preemptive property of a packet during the transmission
  - When computing the transmission rates, not only consider the messages already released, but also predict some future messages
  - Proportional prediction (Lp-EDF-p) & complete prediction (Lp-EDF-c)

Proposed Approach



Message Pattern



$$C_3' = C_3 \frac{X}{D_3}$$

$$AD_3' = W$$

C_3' : modified size of M_3,

AD_3': modified absolute deadline of M_3

Proportional Prediction

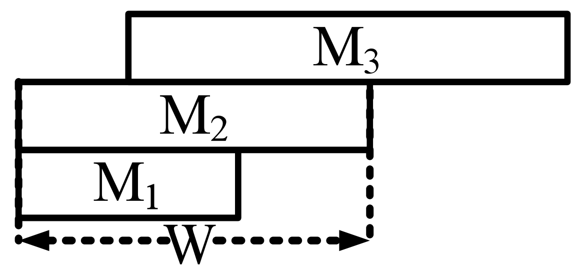
M_i: message M_i

R_i: release time of M_i

D_i: relative deadline of M_i

AD_i: absolute deadline of M_i

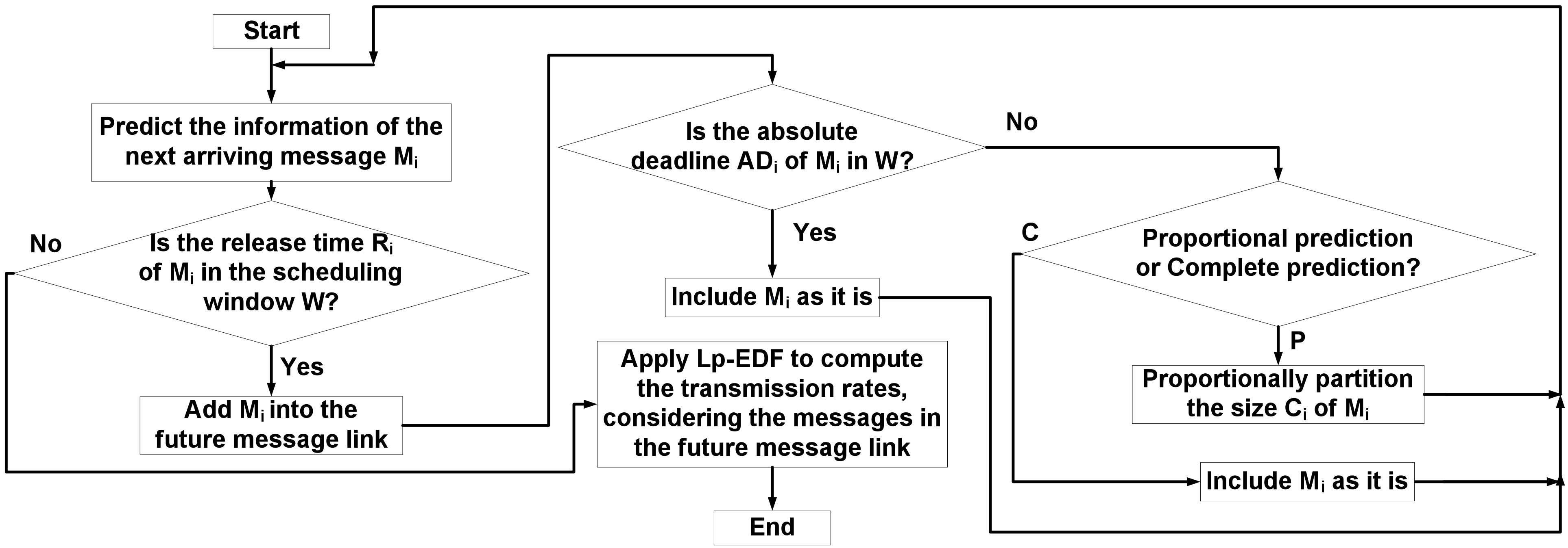
W: scheduling window



Complete Prediction

include M_3 as it is

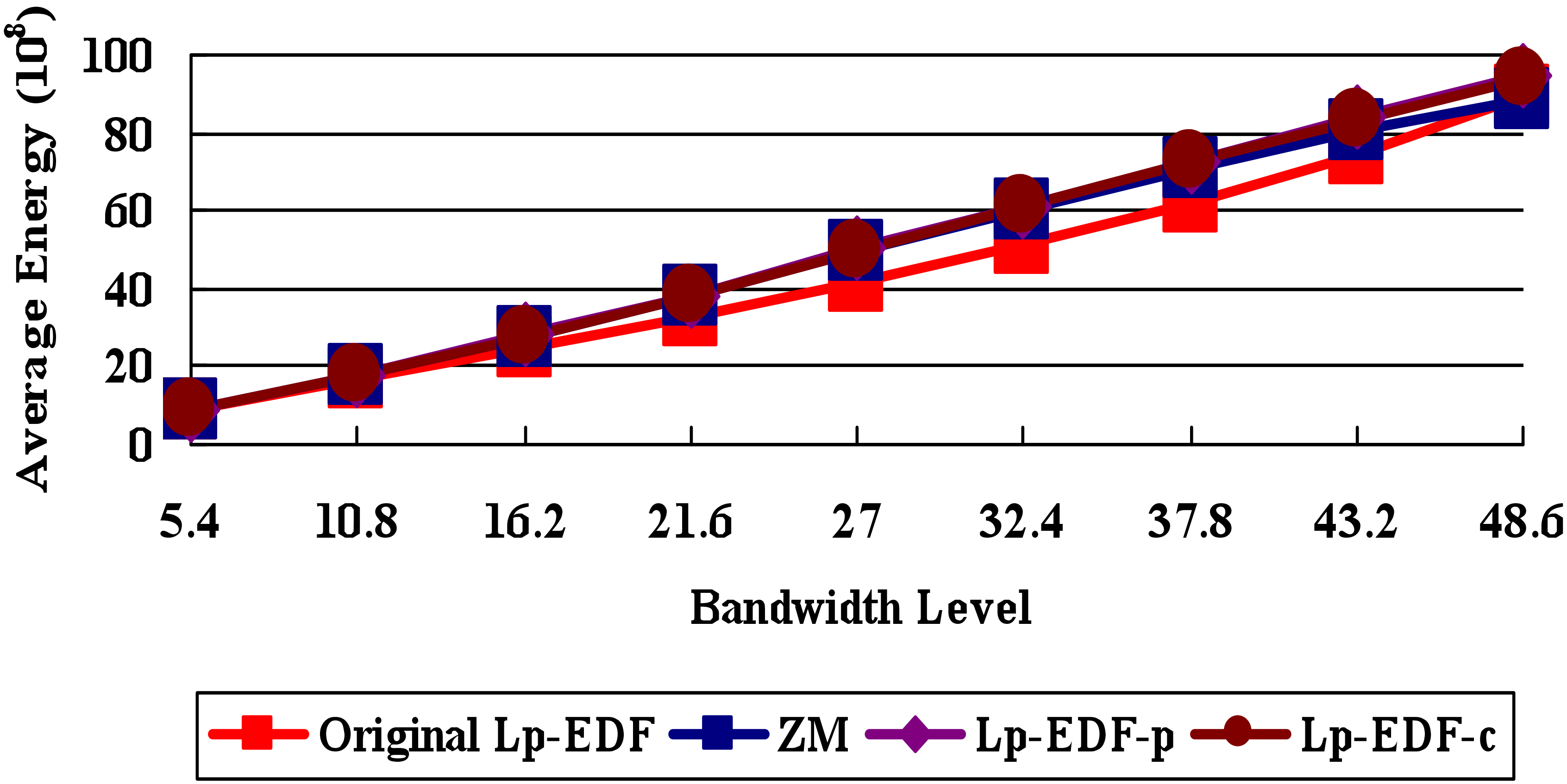
Algorithm Framework



Experimental Study

- **Assumptions employed in the approach**
  - **Messages sporadically generated by real-time streams**
  - **Jitter of the message release time is unknown *apriori***
  - **A message arriving later can have an earlier deadline**
  - **Each message is fragmented to multiple packets, and each packet is non-preemptive**
- **MAC protocol employed**
  - **802.11a**
  - **Time overhead is included in transmitting the preamble, the "Signal" part and the "Service" part of the PLCP header**

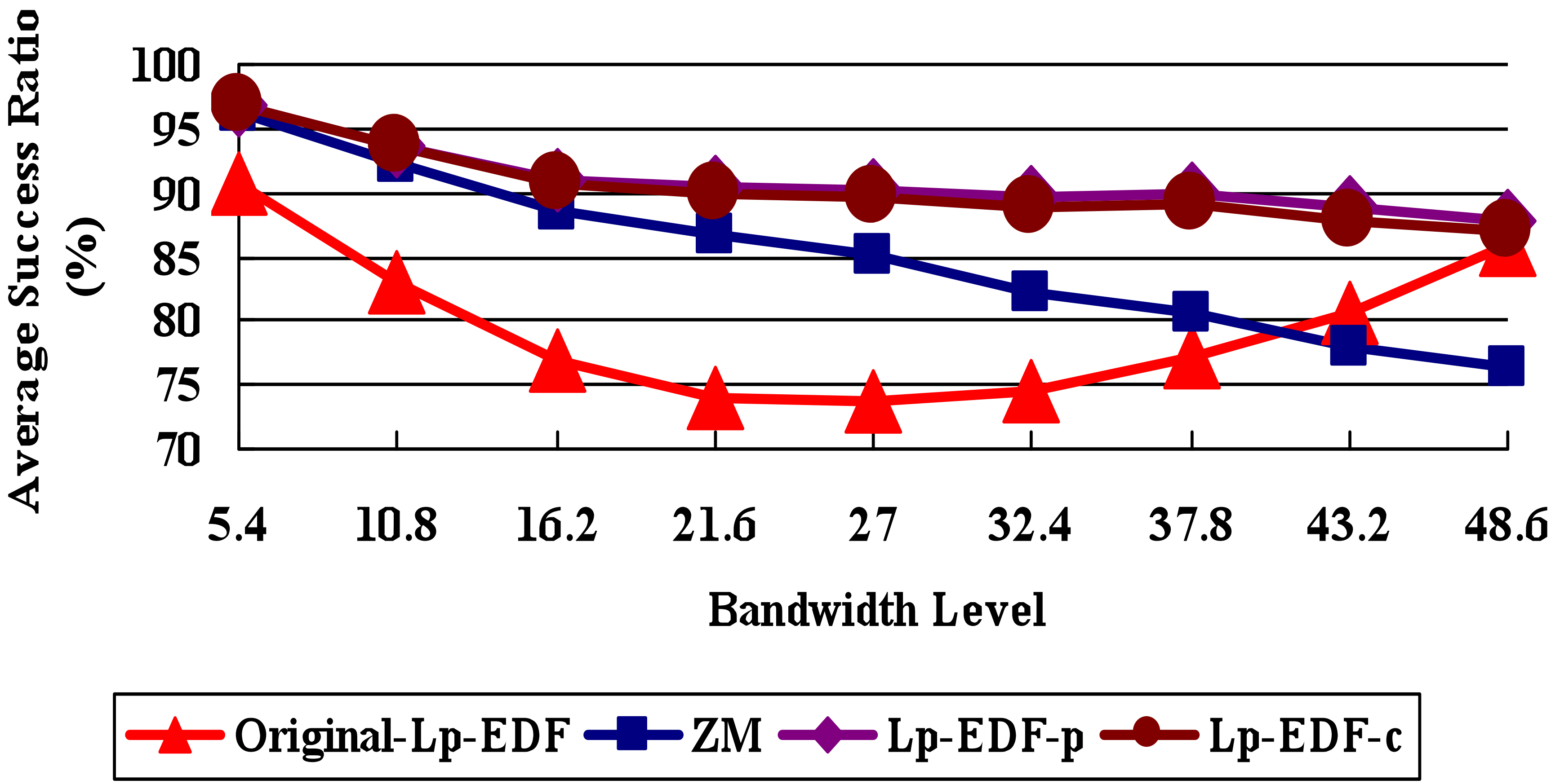
Preliminary Results (1)



Lp-EDF: Yao, et. al., FOCS 1995

ZM: Zafer and Modiano, IEEE Trans. Net.m 2009

Preliminary Results (2)



Lp-EDF: Yao, et. al., FOCS 1995

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Meeting End-to-End Deadline in WSAN (1)

- **Objective**
  - Meeting end-to-end deadlines of messages to guarantee controller performance
- **Challenges**
  - Resource competition among messages
  - Different message have different paths
  - Demands at different nodes may be dissimilar
- **Approach**
  - Distributed local deadline assignment
  - Optimal in the local processors
  - Adaptive to immediate dynamic changes of job workloads and paths
  - Avoid global time synchronization

Meeting End-to-End Deadline in WSAN (2)

- Progress-to-date
  - Proposed a locally optimal and globally efficient distributed algorithm to solve the end-to-end deadline decomposition problem assuming messages paths can be modeled as a directed-acyclic graph [Hong11b]
  - Developed a heuristic algorithm which considers both processing and communication delays in order to meet deadline-to-deadline constraints [Chantem11]
- Future plans
  - Extend the deadline decomposition approach to general message models
  - Incorporate other practical considerations such as non-preemptive packets into the scheduling study
  - Implement the developed algorithms first in widely accepted network simulators and then in WSAN testbed

Adaptation of Controller to Network QoS (1)

- **Objective**
  - Adapt controller to changes in network Quality-of-Service (QoS) to maintain a minimum level of control performance.
  - How is controller performance related to network QoS and what aspects of controller structure should be adjusted?
  - Experimentally verify the ability to control physical processes over wireless communication networks
- **Approach**
  - Model channel throughput using a bounded-exponentially burstiness (EBB) approach
    This allows the use of network calculus methods to evaluate end-to-end delays
  - Study the impact that channel's EBB has on control system's input-to-state stability or noise-to-state stability
  - Identify those components of the controller that have the greatest impact on control performance under network delays and dropouts
  - Develop methods to adaptively reconfigure the controller in response to changes in network's end-to-end QoS
  - Demonstrate methods on WSAN testbed.

Adaptation of Controller to Network QoS (2)

- **Progress-to-Date**
  - Initial studies [HSCC2011] have identified fundamental tradeoffs between the control system's almost-sure stability and the channel's end-to-end burstiness.
  - Recent work [Ling10a,Ling10b] suggests that adjusting the quantization levels used in the controller as the best way of reconfiguring the controller to changes in channel burstiness. In particular, a fundamental relationship between quantization level and noise-to-state stability has been established that allows the selection of quantization protocols that assure minimum levels of controller performance.
  - Development of preliminary WSAN testbed to allow experimental validation of the proposed adaptation schemes
- **Future Plans**
  - Development of adaptive quantization methods that adapt to observed changes in end-to-end network QoS
  - Development of protocols estimating end-to-end QoS based on local QoS
  - Implementation of proposed quantization schemes on experimental wireless HART testbed.
  - Investigation of the use of Network Coding in wireless sensor-actuator networks

Project Outcome (1)

- **Journal Papers**
  - [Yi11] J. Yi, C. Poellabauer, X.S. Hu, and L. Zhang, Minimum bandwidth reservations for periodic streams in wireless real-time systems, IEEE Transactions on Mobile Computing, volume 10, issue 4, pages 479-490, 2011.
  - [Ling10a] Q. Ling and M.D. Lemmon, A necessary and sufficient feedback dropout condition to stabilize quantized linear control systems with bounded noise, IEEE Transactions on Automatic Control, volume 55, number 11, pages 2590-2596, Nov. 2010.
  - [Ling10b] Q. Ling, M.D. Lemmon and H. Lin, Asymptotic stabilization of dynamically quantized nonlinear systems in feedforward form, Journal of Control theory and Applications, vol 8(1):27-33, 2010
- **Conference Papers**
  - [Hong09] Shengyan Hong, X.S. Hu and M.D. Lemmon, An adaptive approach to reduce control delay variations, Real-time Systems Symposium, work-in-progress session, Washington D.C., December 2009
  - [Hong10] S. Hong, X.S. Hu, and M.D. Lemmon, Reducing delay jitter of real-time control tasks through adaptive deadline adjustments, Euromicro Conference on Real-time Systems (ECRTS10), Brussels, Belgium, July 2010
  - [Ling10] Q. Ling and M.D. Lemon, Input-to-state stabilizability of quantized linear control systems under feedback dropouts, Proceedings of the American Control Conference, Baltimore, MD, June 29 - July 2, 2010
  - [Lemmon11] M.D. Lemmon and X.S. Hu, Almost sure stability of networked control systems under exponentially bounded bursts of dropouts, Hybrid Systems: Computation and Control, Chicago, USA, April 2011.
  - [Hong11] S. Hong, X.S. Hu and M.D. Lemmon, An adaptive transmission rate control approach to minimize energy consumption. Work-in-Progress session, IEEE Real-time and Embedded Technology and Applications Symposium, Chicago IL, USA, April 2011.

Project Outcome (2)

- Conference Papers (cont'd)
  - [Hong11a] S. Hong, T. Chantem, and X. S. Hu, Meeting end-to-end deadlines through distributed local deadline assignment, IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), WIP session, Chicago IL, USA, April 2011.
  - [Chantem11] T. Chantem, J. Yi, S. Hong, X. S. Hu, C. Poellabauer and L. Zhang, An online holistic scheduling framework for energy-constrained wireless real-time systems, IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), Toyama, Japan, July 2011.
  - [Hong11b] S. Hong, T. Chantem, and X. S. Hu, Meeting end-to-end deadlines through distributed local deadline assignment, IEEE real-time symposium (RTSS), Vienna, Austria, December 2011.

- Educational Materials
  - M.D. Lemmon, Formal Methods in the Design and Verification of Cyber-Physical Systems, Spring semester 2010, 2011, Dept. of Electrical Engineering, University of Notre Dame, http://www.nd.edu/~lemmon/courses/cps/
- Outreach and Technology Transfer
  - Emnet LLC, South Bend Indiana: collaborative work developing wireless sensor-actuator networks for monitoring and controlling municipal wastewater systems
  - Odyssian Technologies, South Bend Indiana: developing wireless hierarchical control architecture for electrical microgrids.
  - Notre Dame's Environmental Change Initiative: wireless sensor networks for nutrient monitoring in aquatic ecosystems.

CPS:Small:
Dynamically Managing the Real-time Fabric of a Wireless Sensor-Actuator Network

Project Number: CNS-09-31195
Investigators: M.D. Lemmon and X. Hu
Start Date: 9/1/2009 – 8/31/2012

Wireless sensor-actuator networks (WSAN) consist of numerous sensing and actuation devices that share information over an ad hoc wireless communication network. WSANs may be used to manage networked systems that distribute goods and services over large spatially distributed domains. Examples of such systems include the national power grid, ground/air traffic networks, and water/gas distribution networks.

This project studies the implementation of feedback control algorithms over WSANs, particularly with regard to the management of large-scale networked systems such as the electric power grid or water distribution networks. Controlling such physical processes usually requires some form of hard real-time support, so that each packet of feedback data must be serviced within a specified deadline. It has, in practice, been difficult to provide such guarantees in real-life wireless networks. This project addresses that issue by developing algorithms that allow control applications and wireless network nodes to work together in maximizing application performance subject to hard real-time service constraints. Given that energy is a precious resource in WSANs, additional effort is devoted to investigate how to effectively trade off energy with control performance, again subject to hard real-time service constraints.

The algorithms being developed by this project are based on a three-prong approach. First, one must control network interference to provide a stable platform upon which real-time guarantees become possible. Second, network flows must be scheduled in a manner that achieves the real-time capacity of the stabilized network. Third, if the network's quality of service falls below application requirements, then the application must modify the controllers that maintain minimum levels of performance under reduced network capacity. Furthermore, to include energy into consideration, transmission rate must be treated as an additional "knob" in all the approaches under study. These approaches are being developed through a novel extension of distributed power control algorithms to real-time flows, recent advances in elastic scheduling of real-time tasks, and recent advances in our understanding of sporadic sampled-data control systems. Energy-aware real-time scheduling theory is also being extended to handle unique challenges present in WSNs. This project's algorithms will be implemented on a wireless test bed consisting of software-defined radios and/or sensor network modules (Mica).

The impact of this project is being broadened through interactions with local industry and graduate curriculum development. A first year graduate course (EE67036) on cyber-physical systems focusing on modeling, verification, and control synthesis has been developed. The project is also working with two small businesses to develop real-time WSAN applications for environmental monitoring (EmNet LLC) and microgrid control (Odyssian LLC).