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

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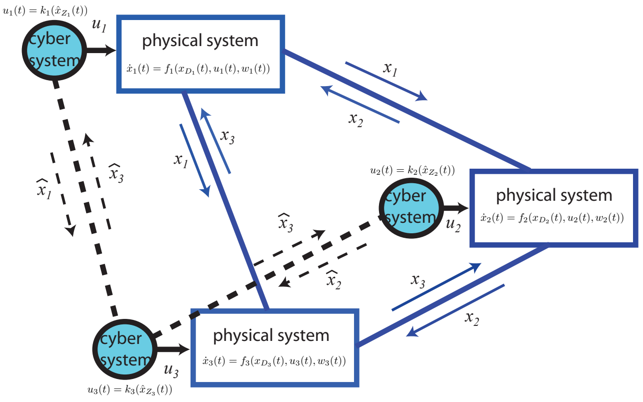
Wireless Sensor-Actuator Network:
Distributed feedback control system whose feedback links are implemented over wireless communication networks.

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

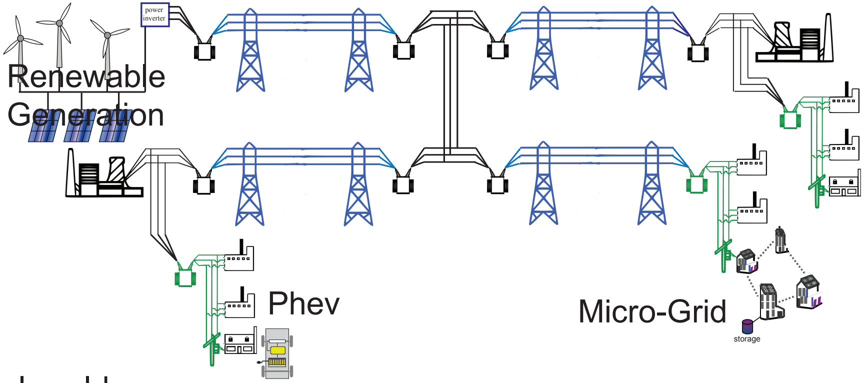


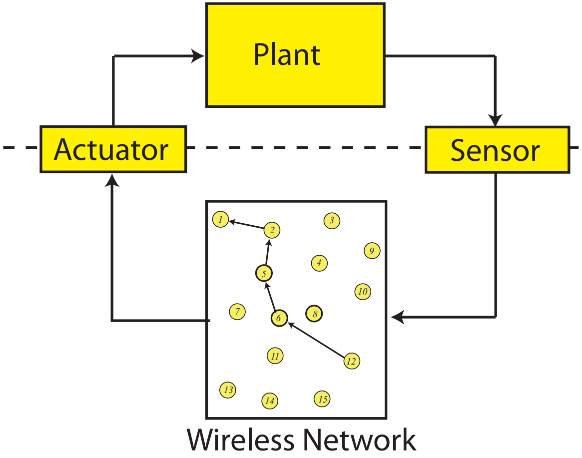
Keywords: firm real-time QoS over wireless channels

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 guarantees on message delivery





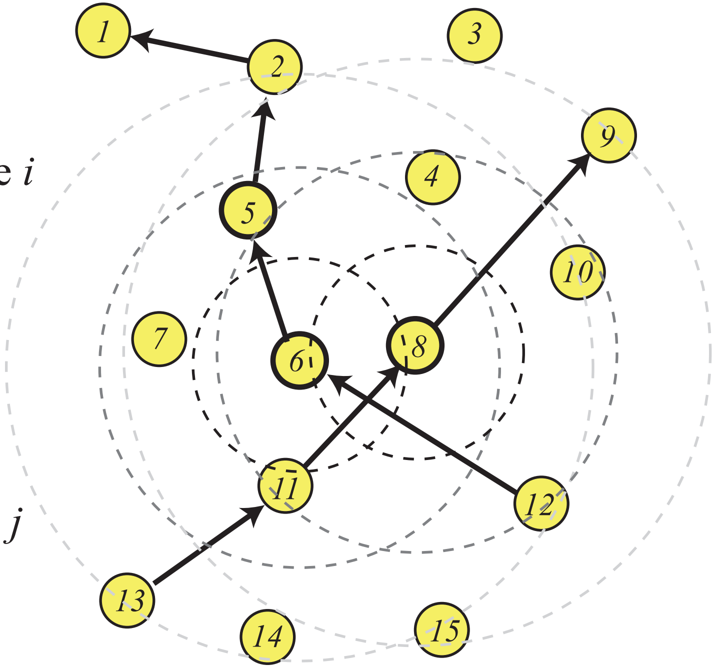
physical world

cyber world

Important examples of such systems are found in the controlling spatially distributed systems.

- electric power grid
- water distribution and collection networks
- traffic networks

Radio Link Modeling Assumptions



Transmission success is influenced by multi-access interference (MAI)

P_i = node i's transmitted power
$h_{ij}P_i$ = received power at node *j* from node *i*

Signal-Interference Noise Ratio (SINR)

$$\gamma_{ij} = \frac{h_{ij}P_j}{N_0 + \sum_{k\neq i} h_{kj}P_k}$$

Bit Error Rate (BER) between nodes *i* and *j*
- BPSK Gaussian

$$\mathrm{BER}_{ij} = Q(\sqrt{2\gamma_{ij}})$$

Dropout Rate as Link Quality of Service Metrics

- Control application packets consist of Q bits transmitted every T seconds. These packets must be delivered by a specified deadline, D.
- Message bits are transmitted at rate R (bit/sec) with power P (watts)
- Deadline means no more than $K = R/D$ bits are transmitted.
- Message successfully received if Q information bits received out of K transmitted bits.
- The probability of dropped message (not delivered within deadline)

$$P_{drop} = 1 - \left(\begin{array}{c} K \\ Q \end{array} \right) \mathrm{BER}_{ij}^{K-Q} (1 - \mathrm{BER}_{ij})^{Q}$$

- Focus on the impact of *dropouts* on control application stability

- **Physical System:** data dropouts switch the system between stable closed-loop and unstable open loop processes

  $$x_{k+1} = \begin{cases} \alpha x_k + w_k & \text{if dropout} \\ \beta x_k + w_k & \text{otherwise} \end{cases}$$

  where $|\alpha| > 1$ and $|\beta| < 1$.

- **Almost sure stability:** probability of being far from origin goes to zero as time gets large

  $$\Pr\left\{\limsup_{k}\{|x_k| > \epsilon\}\right\} = 0$$

- **Question:** Under what type of dropout processes can we expect almost sure stability?

Almost Sure Stability under Bernoulli Dropouts

- **Dropout Process:** $\{d_k\}_{k=0}^{\infty}$ is a stochastic process where $d_k = 1$ if dropout occurs and is 0 otherwise. Assume $\{d_k\}$ is a Bernoulli process with dropout rate λ.

- **No Input Disturbance:** If there is no input disturbance $w_k = 0$, then the system is almost sure stable if $\lambda < \frac{-\log|\beta|}{\log|\alpha| - \log|\beta|}$.

- **Bounded Input Disturbance:** If $|w_k| < W$ (bounded input), then the system is almost surely unstable at any dropout rate.

$$\Pr\left\{\limsup_k \{|x_k| > \epsilon\}\right\} = 1$$

- **Conjecture:** Loss of almost sure stability occurs because there is a finite probability of an arbitrarily long burst of dropouts at any time. This suggests one may recover almost sure stability by constraining the burstiness of the dropout process.

Almost Sure Stability under EBB Dropouts

- **Exponentially Bounded Burstiness (EBB):** Given process $\{d_k\}$, let $d_{\ell,k} = \sum_{j=\ell}^{k} d_j$. Given $\rho, \sigma, \gamma > 0$, the dropout process is said to be (ρ, σ, γ)-EBB if

$$\Pr\left\{d_{\ell,k} \geq \rho(k-\ell) + \sigma\right\} < e^{-\gamma\sigma}$$

- **Slowly Decaying Inputs:** Assume $\{d_k\}$ is (ρ, σ, γ)-EBB where $\rho < \frac{-\log|\beta|}{\log|\alpha| - \log|\beta|}$ and assume the input $\{w_k\}$ is such that $\mu^k x_0 + \sum_{j=0}^{k-1} \mu^j w_{k-j} \leq C|x_0|k^{\xi}$ where $\mu = \alpha^{\rho}\beta^{1-\rho}$. If $\xi\gamma < -1$ then the driven system is almost sure asymptotically stable.

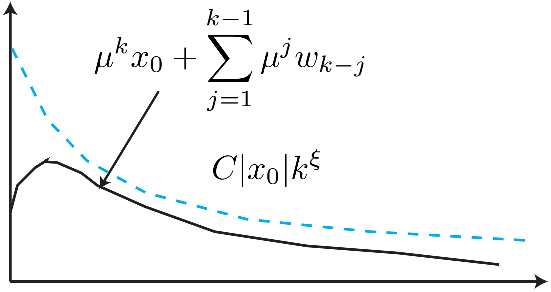
- **Conclusion:** Use exponential bounded burstiness as a firm real-time QoS constraint that must be enforced on the wireless link.

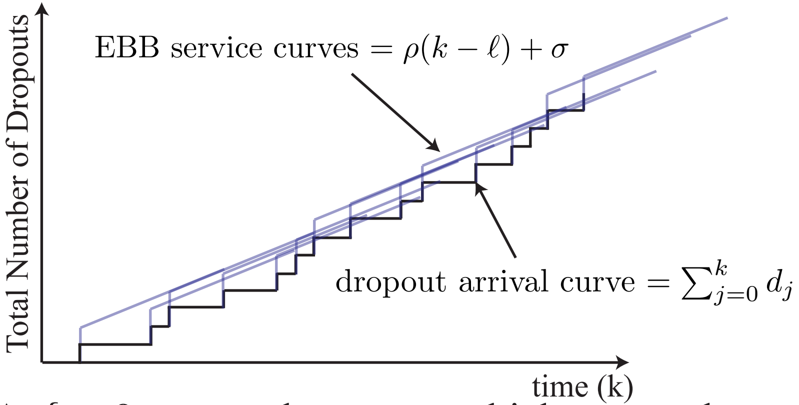
Bounded Burstiness as Firm Real-time QoS Constraint

EBB firm real-time QoS constraint restricts the probability with which long burst of dropouts can occur.

$$\Pr\{\text{burst of length greater than } \sigma\} < e^{-\gamma\sigma}$$

Almost sure stability achieved when the probability for bursts (γ) and the decay rate of input (ξ) satisfy γξ<−1.





As ξ→0 we see that γ→∞, which means that in the limit we can assure almost sure stability provided the likelihood of having bursts greater than a critical length goes to zero.

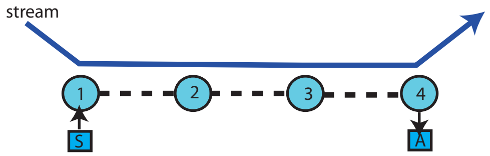
This agrees with recent results on the almost sure stability of quantized control systems with dropouts

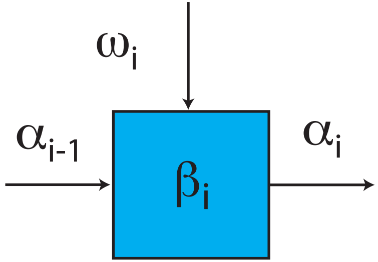
Network Calculus view of Exponential Burstiness

- $\alpha_{i-1}(k)$ = total number of dropouts generated over time interval $[0,k]$ in traversing links $(1,2),(2,3),\ldots,(i-1,i)$.
- $\omega_i(k)$ = total number of dropouts generated over time interval $[0,k]$ in traversing link $(i,i+1)$.
- View node i as accepting two streams of dropouts $\alpha_{i-1}(k)$ and $\omega_i(k)$ and generating a dropout stream $\alpha_i(k)$. We say node i that provides service curve (ρ,σ,γ) if

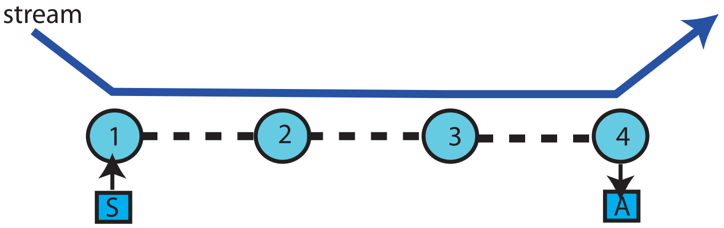
$$\Pr\left\{\alpha_i(k) > \beta_i(k) \otimes (\alpha_{i-1}(k) + \omega_i(k))\right\} < e^{-\gamma\sigma}$$

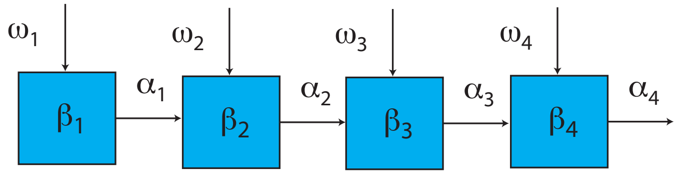
  where $\otimes$ is min-plus convolution and $\beta_i(k) = \rho k + \sigma$.
- In other words, node i enforces exponentially bounded bursts over the multi-hop path traversed by the control packets.



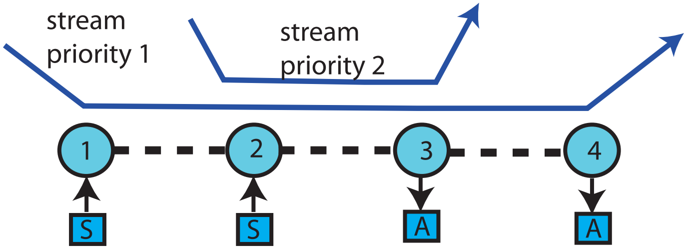


End-to-end Burstiness in Wireless Network





- Real-time fabric of the wireless sensor-actuator network is obtained by composing each nodal subsystem to the left.
- In this case, one must select service curves, $\beta_i(k)$, such that the end-to-end probability of dropout bursts is exponentially bounded. Thereby assuring almost sure stability of the networked control application.
- These results suggest that stochastic network calculus may predict end-to-end QoS for differentiated service streams. Future work will explore this direction.



Progress to Date and Future Plans

- **Major Findings:**
  - Almost sure stability provides a good way of characterizing performance of safety-critical systems.
  - Established conditions for almost sure stability in wireless sensor-actuaor networks assuming exponentially-bounded bursts of dropouts (EBB).
  - EBB dropouts process provide a local QoS link metric that can be used to determine a path's end-to-end QoS.
- **Future Plans:**
  - Develop rate control algorithms for EBB compliant dropout processes.
  - Explore tradeoff between delays and dropouts.
  - Network calculus analysis of distributed power, rate, and channel control.
  - Implementation of proposed algorithms on wireless testbed.

Project Activities - Sept 1, 2009 - August 31, 2010

Journal Papers

- J. Yi, C. Poellabauer, X.S. Hu, and L. Zhang, Minimum bandwidth reservations for periodic streams in wireless real-time systems, accepted for publication in IEEE Transactions on Mobile Computing (2010).
- Q. Ling and M.D. Lemmon, A necessary and sufficient feedback dropout condition to stabilize quantized linear control systems with bounded noise, accepted for publication in IEEE Transactions on Automatic Control, Nov. 2010.

Conference Papers

- 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.
- 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
- 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.

Educational Materials

- M.D. Lemmon, Formal Methods in the Design and Verification of Cyber-Physical Systems, Spring semester 2010, Dept. of Electrical Engineering and Dept. of Computer 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 LL, South Bend Indiana: developing wireless hierarchical control architecture for electrical microgrids.
  Notre Dame's Environmental Change Initiative: wireless sensor network development for nutrient monitoring of 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.

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 [1,2,3]. Third, if the network's quality of service falls below application requirements, then the application must use controllers that demand less of network resources [4,5]. 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. 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 and a textbook is being written from the course's lecture notes. 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).

References

1. Shengyan Hong, Xiaobo Sharon 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.
2. 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
3. J. Yi, C. Poellabauer, X.S. Hu, and L. Zhang (2010), Minimum Bandwidth Reservations for Periodic Streams in Wireless Real-time Systems, accepted for publication in IEEE Transactions on Mobile Computing, 2010.
4. Q. Ling and M.D. Lemmon, A necessary and sufficient feedback dropout condition to stabilize quantized linear control systems with bounded noise, to appear in IEEE Transactions on Automatic Control, November 2010
5. Q. Ling and M.D. Lemmon, Input-to-state stabilizability of quantized linear control systems under feedback dropouts, Proceedings of the American Control Conference, Baltimore, 2010