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

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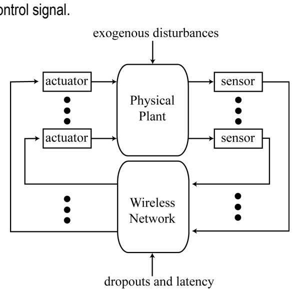
Project Objectives

Wireless sensor-actuator networks (WSAN) consist of numerous sensing and actuation devices that share information over an ad hoc wireless communication network. 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. Controlling such physical processes usually requires some type of hard real-time suppport. This means that each packet of feedback data must be serviced within a specified deadline to assure the control application's performance level. It has, in practice, been difficult to provide such guarantees in real-life wireless networks. This project addressed that issue by developing algorithms that allow control applications and network routers to work together in a way that ensures system performance under firm real-time service constraints.

Wireless Sensor-Actuator Networks as CPS

The "physical" part of this system is the plant that is being controlled. Control is based on signals from sensors that are transmitted over a wireless communication network to an actuator that implements the control signal.



The "cyber"-side of this system is the wireless communication network. Information is transmitted in discrete packets that may be corrupted or lost during transmission.

Project's Approach

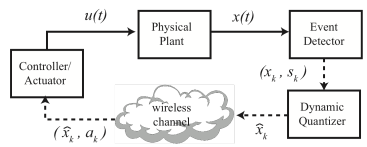
The approach is based on the following ideas

- One can dramatically reduce the amount of information transmitted over the channel through **event-triggered sampling and dynamic quantization**
- Event-triggered schemes can be viewed as "sporadic" real-time tasks, so the problem of servicing such tasks can be viewed as a **real-time scheduling problem**.
- A number of different **applications** were examined as potential examples of wireless sensor-actuator networks.

Minimizing Feedback Information

Problem Statement:

- reduce the amount of feedback information needed to attain a desired control performance level



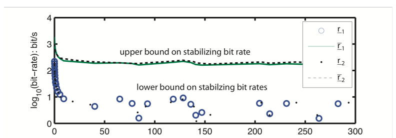
- $\{s_k\}$ = sequence of transmission times
- $\{a_k\}$ = sequence of reception times
- $x_k = x(s_k)$ = sampled state in k^{th} *packet*
- $\hat{x}_k = Q(x_k) = \text{quantized state}$
- $u(t)$ = control input

We reduce the amount of transmitted information by

- only sampling the system state when the error between the last sampled signal and the current signal exceeds a specified threshold. In recent years, this has come to be known as **event-triggered samlpling**
- We also **dynamically quantize** the measured information.

Since we discretize the information flow in both space and time, the information rate can be characterized by a *bit-rate.*

There is a *stabilizing* bit-rate for the system, so that transmitting information at this rate or higher assures the overall system's stability. It is possible to bound this stabilizing bit-rate as a function of the system state.



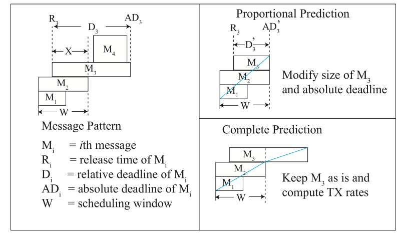
The fact that these stabilzing bit-rates can be determined as a function of the sampled system state, means that it is possible to predict the intersampling times and required bit-rate to assure system stability.

These predictions represent a time-varying requirement on the channel's quality-of-service, which the networking middleware must provide. If the networking middleware cannot guarantee the requested Quality-of-Srvice, then it must alert the application to this problem.

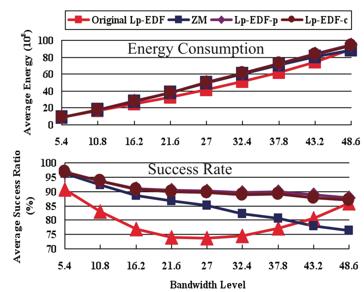
Dynamic Transission Rate Adjustement

One way of enforcing the application's bit-rate requirement is to treat it as a deadline and then adjust the actual transmission rate in a manner that meets the deadline while minimizing transmission energy.

We used an approach that modifies an earlier dynamic voltage frequency scaling (DVFS) algorithm known as Lp-EDF (Yao 1995) that is optimal for scheduling pre-emptive jobs on a single processor under EDF scheduling.

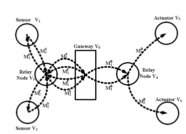


Our work applies Lp-EDF scheduling to determine rate schedules in wireless single-hop network. The proposed rate adjustment algorithm is similar to one proposed by Zafer and Modiano (ZM 2009). Our algorithm performs better than either ZM2009 or the earlier Lp-EDF algorithm.

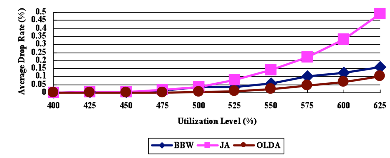


Meeting End-to-End Deadline in WSAN

We have studied the distributed local deadline assignment problem which appears in Wireless HART networks. In this problem, messages must be transmitted over a sequence of agents to a gateway by a specified end-to-end-deadline.

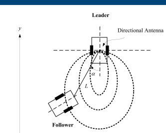


This work introduced a distributed approach that combines local-deadline assignment with feasibility analysis such that the resulting deadline assignment is guaranteed to be schedulable. The local-deadline assignment problem is posed as a mathematical programming problem that maximizes the minimum time slack among all the messages relayed by each node on the route. This is done using an on-line, iterative technique to efficiently solve the mathematical program. The algorithm has polynomial time complexity.

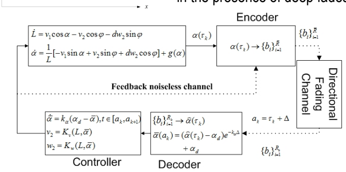


Comparison with BBW (Buttazzo – ECRTS'10) and JA (Jayanchandran – ECRTS'08). BBW and JA on average drop 89% and 379% more messages than OLDA.

Leader-Follower Formation Control



The project recently examined leader-follower formation control as a potential WSAN application. In particular, we developed controls that switch their structure in the presence of deep fades.



The algorithm uses an EBB model of the channel state that is a function of the formation state. The leader's information is dynamically quantized and transmitted to the follower. The follower uses both channel state information and the received data to adaptively switch to a less aggressive controller when the formation state estimate is highly uncertain. Software simulations suggest that this approach can provide almost-sure guarantees on overall system safety.

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