CPS: Synergy: Resilient Wireless Sensor-Actuator Networks

M.D. Lemmon, Hai Lin, and J.N. Laneman
Department of Electrical Engineering, University of Notre Dame

Project Objectives

Wireless sensor-actuator networks (WSAN) are systems consisting of numerous sensing and actuation devices that interact with the environment and coordinate their activities over a wireless communication network. WSANs represent an important class of cyber-physical system (CPS) found in our national civil infrastructure.

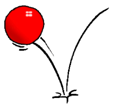
This project addresses the issue of resilience in WSANs. A resilient system is one that maintains an active awareness of surrounding threats and reacts to those threats in a manner that returns the system to operational normalcy in finite time. It has proven challenging to ensure resilience in large-scale WSANs because of the complexity such scale brings.

The objective of this project is to develop WSANs that are resilient to faults in the underlying communication network. This will be done through the coordinated management of the WSANs control and communication functions. The methods will be evaluated on a multi-robotic testbed consisting of unmanned ground vehicles using machine-to-machine (M2M) communication technologies.

What is a Resilient System?

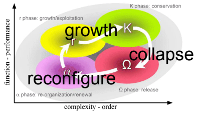
re·sil·ience
rəˈzilyəns/
noun

1. the ability of a substance or object to spring back into shape; elasticity.
   "nylon is excellent in wearability and resilience"
2. the capacity to recover quickly from difficulties; toughness.
   "the often remarkable resilience of so many British institutions"



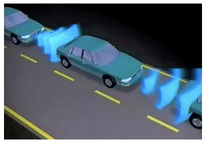
Systems are resilient if they exhibit a never ending cycle of growth, collapse, and reconfiguration.

1) The **growth** phase maximizes system function until unexpected large disturbances trigger a **collapse**.
2) Collapsed system **reconfigure** to recover lost function
3) at which point **growth** can resume once the external disturbances return to normal levels.



This adaptive renewal cycle (ARC) has its origins in eco-social systems, and this project applies those ideas to WSAN CPS.

Intelligent Highways as Resilient WSAN



Vehicles in an **automated highway systems** (AHS), may coordinate their actions over wireless links. Wireless communication, however, is inherently unreliable as the channel may fade for long time periods due to change in environmental conditions.

This project is developing methods to assure traffic resilience to such channel fading though the adaptive reconfiguration of both vehicular control systems and the ad hoc wireless communication network's physical layer. The methods are being evaluated on a multi-robotic testbed of autonomous ground robots.

Almost Sure Safety under Channel Fading

From the application's (control system) viewpoint, the communication channel should be characterized in terms of outage probabilities. In particularly these outages are characterized in terms of **"effective" bit rate**, *B(k)*

$$B(k) = \frac{\text{number of bits in } k^{\text{th}} \text{ message}}{\text{transmission delay of } k^{\text{th}} \text{ message}}$$

Channel fading is represented that the probability of the effective bit rate, *B(k)*, being greater than a specified level, *L*, is less than an exponential function of *L* (exponentially bounded burstiness).

$$\Pr\{B(k) \leq L\} \leq e^{-\gamma L}$$

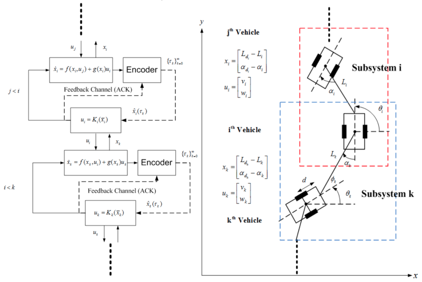
For such channels one can develop switching controllers that assure the system state is ***almost surely safe***.

$$\Pr\left\{\limsup_{k} |x(k)| > \epsilon\right\} = 0$$

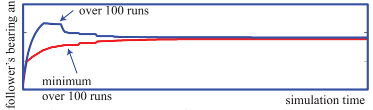
Leader-Follower Formation Control

These concepts were implemented on multi-vehicle leader follower application. The formation consists of a platoon of ground vehicles interacting over a communication tree where each leaf is a "follower".

System structure



Formation control uses a novel switching control structure that switches to a less aggressive controller when the channel state is poor. This switching decision uses information regarding the relationship between channel state and vehicle state. As a result, it becomes possible to assure almost sure practical formation stability even when the channel exhibits deep fades.



Monte Carlo simulation of Leader-Follower system demonstrates almost sure convergence since the max and min of all simulation runs asymptotically converge to the desired fixed point.

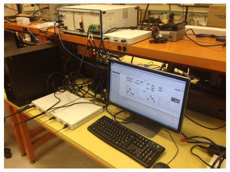
Bin Hu and M.D. Lemmon (2015). "Distributed Switching Control to Achieve Almost Sure Safety for LeaderFollower Vehicular Networked Systems". *IEEE Transactions on Automatic Control.* PP (99), . DOI:10.1109/TAC.2015.2418451

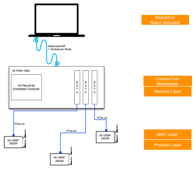
Reconfigurable Wireless for Sporadic Traffic

The preceding work reconfigured the ***physical*** part of the system with respect to deep fading events, but one may also reconfigure the wireless network (***cyber*** part) to control outage probabilities. We control the networking protocols to achieve this reconfiguration ability.

This project's control applications, however, generate short messages that are transmitted in an ***event-triggered*** manner. This means that network traffic is sporadic in nature and that the primary quality-of-service measure is the ***effective bit rate*** defined earlier. Existing 802.11 networking protocols are ill-suited for this traffic environment since they attempt to maximize average throughput. So we needed to develop a radio platform that gave us greater control over the network protocols than is possible using existing WiFi dongles.

To achieve this goal the project has assembled a **machine-to-machine (M2M)** communications testbed based upon **software-defined radio (SDR)** using NI USRP-2953R hardware with LabVIEW Communications 802.11 Application Framework Ettus Research B210 hardware with GNU radio software. This testbed provides the flexibility of controlling the communication protocols all the way down to the physical layer. The testbed was used to evaluate the performance of a flexible SDR implementation of OFDM packet radio transmissions similar to IEEE 802.11ac n.

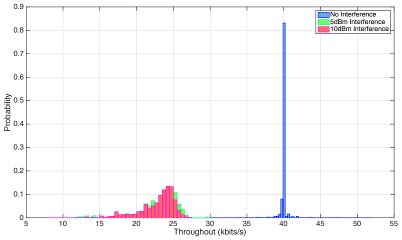




The SDR networking testbed is being used to

1. develop networking protocols that adaptively minimize outage probability during slow fades.
2. integrate the SDR testbed with a MobileSim simulation model of the project's unmanned ground vehicle (UGV) testbed.

The integrated testbed will investigate how the coordinated reconfiguration of the physical system and the wireless network can improve system resilience.



Regime Shifts in Large Networked CPS

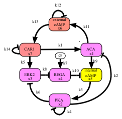
The preceding tasks focused on reconfiguration of **either** the physical (UGV formation) or cyber (wireless network) subsystems to assure overall resilience. Reconfiguring **both parts at once**, however, may have unexpected consequences that trigger large shifts in the system's qualitative behavior. We refer to this as a ***regime shift***. A good example of a regime shift is the shift from a free-flowing to congested state in a communication network.

We have begun studying the problem of assessing the vulnerability of a large networked system to regime shifts caused by variations in network parameters. In particular, we model the large-scale CPS as a *non-negative polynomial system.*

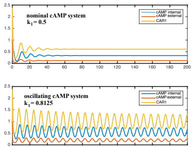
$$\dot{x} = f(x;k) = Nv(x;k)$$

where *x* are link states and *k* are the system parameters. We use this model to determine the smallest change in *k* that gives rise to a local bifurcation. We refer to this as the ***distance-to-bifurcation*** *or D2B.*

Solving the D2B problem in large-scale multi-parametric systems is computationally difficult. We use the concept of ***elementary flux models*** *(EFM)* found in systems biology to obtain an affine parameterization of the system's linearization. This allows us to use **linear matrix inequalities (LMI)** to search for the minimum D2B, thereby providing a computationally efficient scheme for assessing a network's vulnerability to regime shifts.



$$\begin{aligned}
\dot{x}_1 &= k_1x_7 - k_2x_1x_2 \\
\dot{x}_2 &= k_3x_5 - k_4x_2 \\
\dot{x}_3 &= k_5x_7 - k_6x_2x_3 \\
\dot{x}_4 &= k_7 - k_8x_3x_4 \\
\dot{x}_5 &= k_9x_1 - k_{10}x_4x_5 \\
\dot{x}_6 &= k_{11}x_1 - k_{14}x_7 \\
\dot{x}_7 &= k_{13}x_6 - k_{14}x_7
\end{aligned}$$



The above methods were used to predict the distance to Hopf bifurcation in the cAMP regulatory network controlling chemotaxis in amoeba. We are currently working to apply these concepts to the wireless sensor-actuator networks being studied in this project.

M.D. Lemmon and T. Tamba (2015). "Using Elementary Flux Modes to Estimate the Distance to Regime Shifts in Kinetic Systems". *IFAC Conference on the Analysis and Design of Hybrid Systems (ADHS 2015)*. Atlanta, Georgia

Contact information

- **M.D. Lemmon** (lemmon@nd.edu)
  Dept. of Electrical Engineering, University of Notre Dame
  - WSAN and Event-Triggered Control
- **Hai Lin** (Hai.Lin.24@nd.edu)
  Dept. of Electrical Engineering, University of Notre Dame
  - Task Coordination and Multi-robotic Testbeds
  - Director, DISCOVER Lab
- **J. Nicholas Laneman** (jnl@nd.edu)
  Dept. of Electrical Engineering, University of Notre Dame
  - M2M communication and Wireless Networking
  -Director of Wireless Institute, University of Notre Dame

TEMPLATE DESIGN © 2008
www.PosterPresentations.com