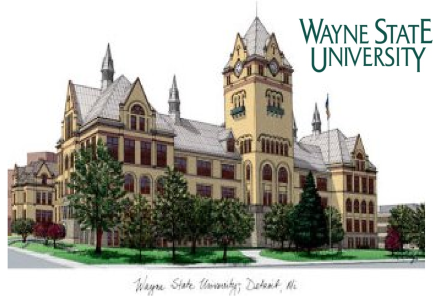

A Cross-Layer Approach to Taming Cyber-Physical Uncertainties in Vehicular Wireless Networking and Platoon Control

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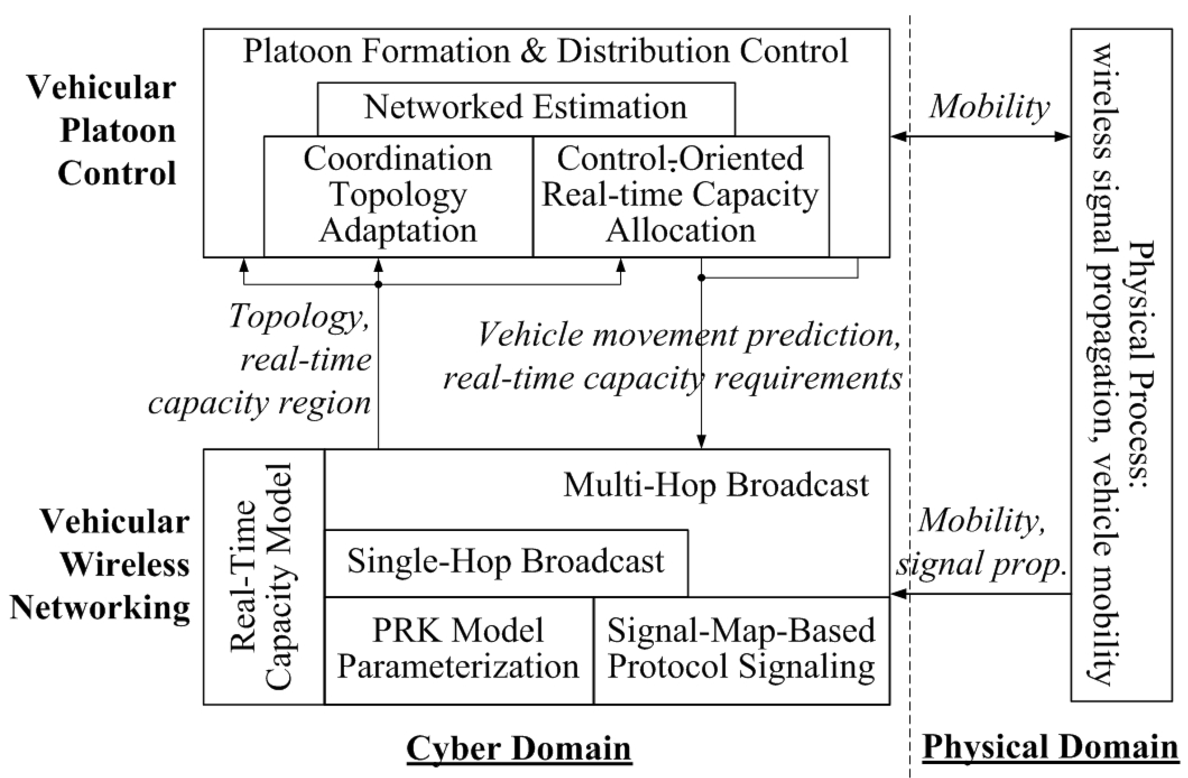
Overview

- ❑ Platooning as a basic enabler for optimal roadway usage and fuel economy in networked vehicle operation
- ❑ Complex cyber-physical uncertainties in vehicular wireless networking and platoon control
  - ✓ Physical domain: complex wireless signal propagation and attenuation, wireless interference; vehicle mobility; uncertainties in physical environment such as weather, road and vehicle traffic conditions
  - ✓ Cyber domain: dynamics in wireless networking and platoon control interact with one another during their adaptation to physical dynamics and uncertainties
- ❑ Lack of foundation for addressing cyber-physical uncertainties in vehicular wireless networking and control
  - ✓ Lack of a wireless interference model that is of high-fidelity and suitable for distributed, field deployable protocol design
  - ✓ Lack of theoretical foundation and engineering tools for addressing random delay, switching network topologies, and information exchange constraints in networked control

Cross-Layer Framework for Taming Cyber-Physical Uncertainties



- Platoon control based on the real-time capacity region of wireless networking and the physical process of vehicle movement
- Reliable, real-time wireless networking for platoon control
- Joint optimization and information feedback between platoon control and wireless networking

Contributions to CPS Modeling, Design, Analysis and Architecture

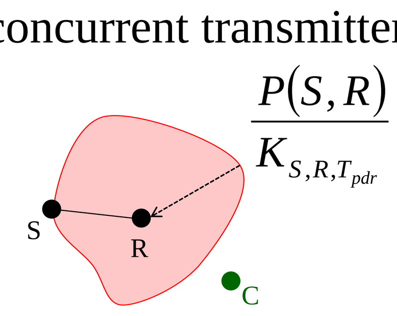
- ❑ Agile, predictable interference control enabled by the physical-ratio-K (PRK) wireless interference model
- ❑ Innovative techniques (e.g., signal map, virtual broadcast backbone, cyber-physical modeling of mobility) to address the physical challenges of large interference range, anisotropic, asymmetric wireless communication, collision of broadcast-receiver-feedback, and vehicle mobility
- ❑ New framework for platoon control (and control theory in general) through networked control with random topology switching and time delay as well as multi-timescale techniques
- ❑ Cross-layer framework for jointly optimizing wireless networking and platoon control
- ❑ Mathematical tools (e.g., stochastic approximation, switching ODEs, and switching diffusions) for reasoning about jointly-optimized wireless networking and platoon control

Control-Oriented Wireless Networking: PRK-Based Resource Allocation for Predictable Communication

Physical-Ratio-K (PRK) Interference Model as a basis for predictable interference control

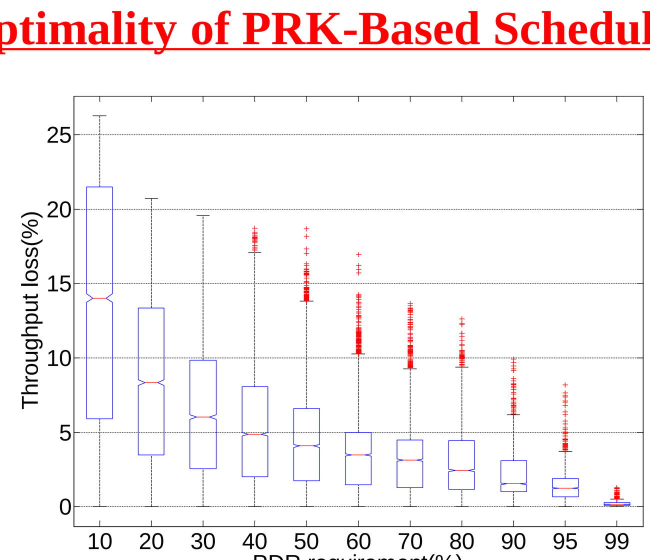
- ❑ Key idea: use link reliability requirement as the basis of instantiating the ratio-K model
- ❑ Model: given a transmission from node S to node R, a concurrent transmitter C does not interfere with the reception at R iff.

$$P(C,R) \le \frac{P(S,R)}{K(S,R,T_{pdr})}$$



- ❑ Integrates the locality of the protocol model with the high-fidelity of the physical model

Optimality of PRK-Based Scheduling

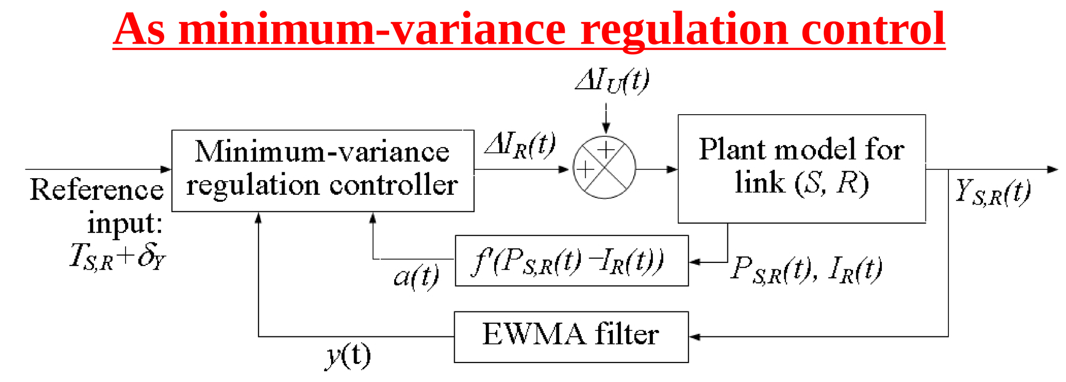


Throughput loss is small, and it tends to decrease as the PDR requirement increases

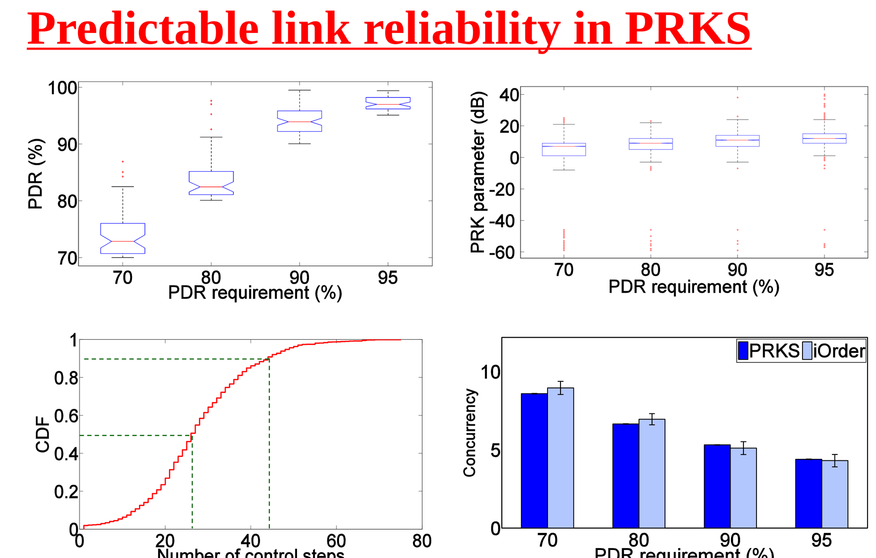
Challenges of PRK-Based Scheduling

- ❑ On-the-fly instantiation of the PRK model parameter $K_{S,R,T_{S,R}}$
  - ✓ Dynamics and uncertainties in application requirements as well as network and environmental conditions
- ❑ Protocol signaling in the presence of large interference range as well as anisotropic, asymmetric, and probabilistic wireless communication

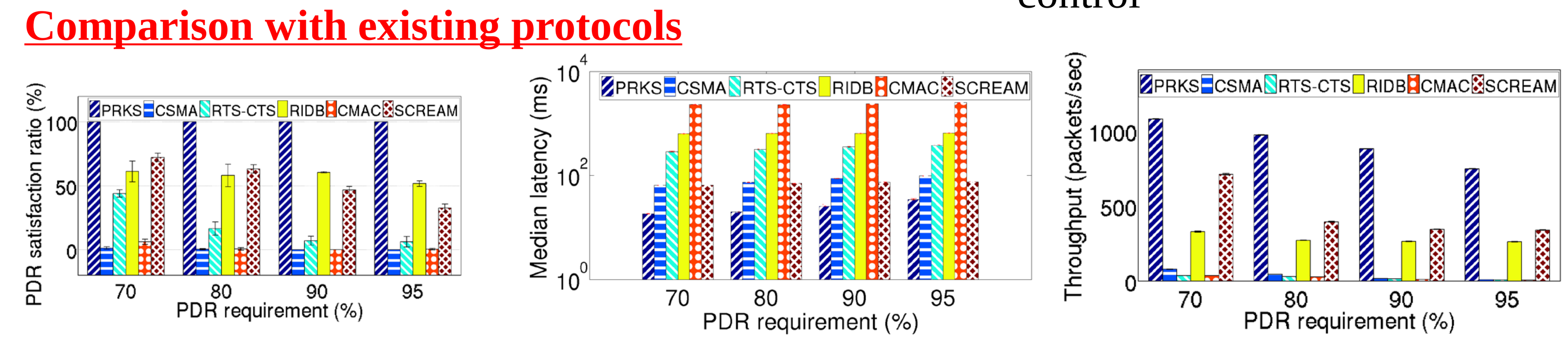
PRK model instantiation: As minimum-variance regulation control



Predictable link reliability in PRKS



Comparison with existing protocols



Protocol signaling via local signal maps

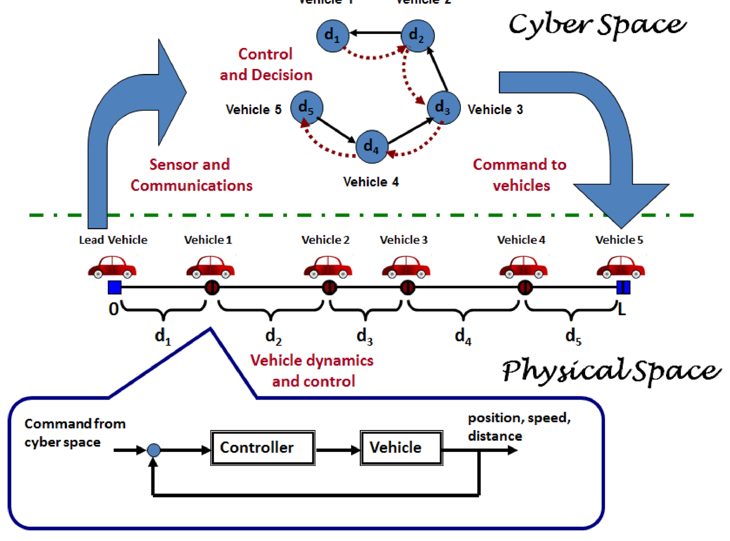
- ❑ Local signal map: maintains wireless signal power attenuation between nodes close-by
- ❑ Simple approach to online estimation of wireless signal power attenuation

Foundation for Predictable CAV Communication and Control

- ❑ Multi-scale approach to address vehicle mobility
- ❑ Multi-scale approach to joint scheduling, power control, rate control, channel allocation
- ❑ Predictable control of real-time capacity operation point for CAV control

Cyber-Physical Vehicular Platoon Control: Networked Consensus and Mean-Variance Control

- ❑ Platoon formation control: ensure that all the vehicles move in the same lane at the same speed with desired inter-vehicle distances
- ❑ Platoon distribution control: adjusts vehicle spatial distribution such that road utilization and fuel economy is maximized while the risk of collision is minimized (within an acceptable bound)



Fundamental Features

1. The algorithm is convergent, and with post-iterate averaging it achieves asymptotically the Cramer-Rao lower bound.
2. It can deal with communication latency, packet erasure, noises.
3. It remains convergent under network topology switching, correlated noise, and asynchronous control updating.
4. It achieves fast team coordination and formation.
5. It restores team formation after large disturbances.
6. It restores platoon formation after adding or removing vehicles.

Platoon Cyber-Physical Coordination : Control-Communication Co-design

Cyber Algorithm Structure for Network Consensus

$$x_{n+1} = x_n + \mu_n (M(\alpha_n) x_n + W(\alpha_n) d_n)$$

- Subsystem states are updated by a stochastic approximation type algorithm
- The step sizes ensure convergence to consensus
- The Markov chain captures network topology changes, subsystem addition and deletion.
- The network noises, either i.i.d. or mixing types, accommodate communication uncertainties.
- The network matrix ensures updating is limited by local information only

Goal: Weighted Consensus

$$\Psi x_n \to \beta \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$$

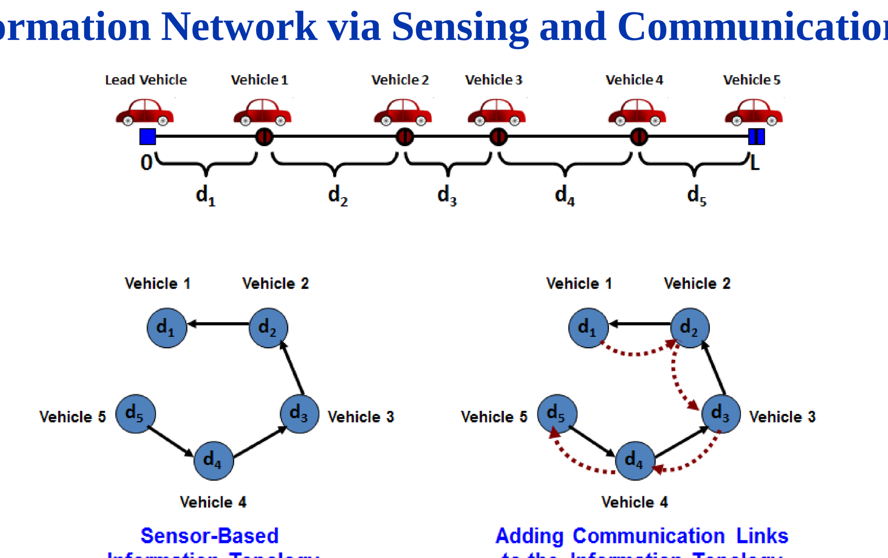
- Equal distance between highway vehicles
- Terrain-weighted area coverage of UAVs
- Capacity-rated load distribution among renewable power generators

Constraints

$$[1 \ \cdots \ 1] x_n = L$$

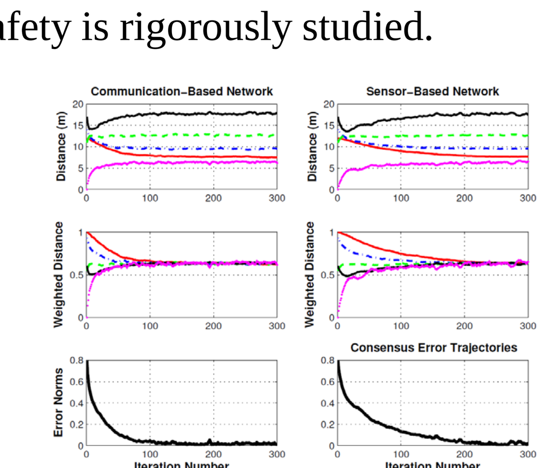
- Total length of a platoon remains a constant.
- All UAVs must cover the designated areas.
- Total power generated must be equal to the total load.

Information Network via Sensing and Communication



Physical Level: Platoon Dynamics, Vehicle Control, and Cyber-Physical Interaction

- ❑ Vehicle dynamics and platoon formation create a networked dynamic system.
- ❑ Sensing and communication signals are used for system decoupling (complexity reduction), platoon stability, string stability, and disturbance attenuation.
- ❑ Impact of communication packet loss, time delay, and random sampling on stability, performance and platoon safety is rigorously studied.



Communications add new information, improve convergence, and enhance robustness. Platoon formation errors are reduced faster when more communication (cyber) resources are provided to vehicle (physical). control

Distribution control modeled as mean variance control

- ❑ Mean-variance control was initially formulated for financial portfolio management problems with the objectives:
  - ✓ maximize the expected return
  - ✓ control the risk (min. the variance)
- ❑ Highway vehicle platoon control:
  - ✓ maximize highway utility
  - ✓ ensure zero accident
- ❑ Advantages of mean-variance control
  - ✓ Simple and rigorous
  - ✓ Computationally efficient
  - ✓ the form of the solution (i.e., efficient frontier) is readily applicable to assessing risks in platoon formation, thus practically appealing
- ❑ Achieving complexity reduction: reduce dimensionality for large-scale switching diffusion models through time-scale separation
- ❑ Treating partial information: address the challenges of hidden random switching processes which can only be observed with white noise