Control and Management of Future Internet – Integration of Heterogeneous Networks

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Motivation and Collaborators

- Motivation:
  - Evolution of the future Internet will require integration of **heterogeneous communication networks** (e.g., core wired networks, cellular networks, multi-hop wireless networks, disruption tolerant networks, etc.)
  - Demands not only technological advances, but also a better understanding of interactions among different networks and related economic issues
- Collaborators:
  - ISR (UMD) – Eyad H. Abed, Armand M. Makowski, and Steve I. Marcus
  - ECE (UMD) – Mark A. Shayman
  - Computer Science (UMD) – Bobby Bhattacharjee
  - External Collaborates – Vijay G. Subramanian (Hamilton Institute, Ireland), and Jeonghoon Mo (Yonsei University, Korea)

Congestion Control: Rate Control and Stability

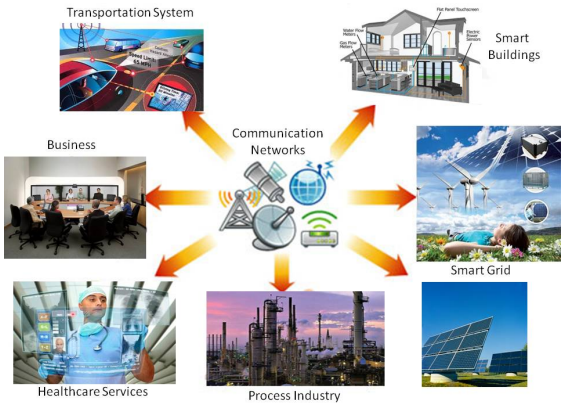
- Challenges facing today's Internet
  - Increasing demand in the Internet can create congestion in different parts of the network (Example: Congestion collapse of the Internet in 1986)
  - Current congestion control mechanism – Transmission Control Protocol (TCP)
    - Poor performance over wireless links with packet losses and large communication delays
    - Interaction with existing Active Queue Management (AQM) mechanisms unclear
- Investigated the following issues
  - **Stability of a family of rate control schemes** based on optimization framework (Kelly 1997) in the presence of communication delays
    - Proposed rate control schemes with provable stability in the presence of **arbitrary communication delays**
  - Interaction of TCP with Random Early Detection (RED) AQM
    - Demonstrated the **parametric sensitivity of network stability** and propagation of instability in multi-bottleneck scenarios
    - Showed that the presence of non-elastic traffic improves network stability

Traffic Engineering: Measurement-based Load Balancing

- Existing routing schemes do not utilize network resources efficiently
  - Mostly static configuration and do not adapt based on real-time traffic measurements
  - Hard to modify and customize with unexpected consequences
- Design an **application-layer overlay network architecture** for traffic engineering
  - Does not require modifications to underlying routing protocols (e.g., OSPF, OLSR)
  - Can utilized multiple routes between a pair of ingress-egress points of networks
  - **Simultaneous-perturbation stochastic approximation** (SPSA) technique used to estimate noisy gradients of cost function using real-time measurements reported by overlay nodes
  - Proved **convergence to optimal solution**

Multi-hop Wireless Networks (1): Connectivity and Routing Overhead

- Distribution of critical communication range needed for network connectivity
  - Tells us how much transmit power is required – determines battery consumption and interference to neighbors
  - Hard to characterize - Little known when node locations are correlated
  - Studied the cases with a family of **group mobility** models
  - Demonstrated **sensitivity of critical communication range to correlation**
- Past observation – location-based routing performs better than topology-based routing (AODV, DSR, etc.) in **large** multi-hop wireless networks
  - Studied overhead for topology discovery/maintenance (in topology-based routing) or location service (in location-based routing)
  - Scaling law of overhead under proactive and reactive location-based routing
  - Minimum overhead for location discovery/service in location-based routing
  - Identified an **order-optimal location service scheme**, based on distributed hash table
  - Comparison of overhead between topology-based routing and location-based routing
  - Smaller scaling law of overhead under position-based routing: With increasing number of nodes, n, we have $\Theta(n \cdot \log(n))$ vs. $\Omega(n^{1.5} \cdot \log(n))$



Cellular Networks: Beamforming and MAC Scheduling

- Growing access to information through cellular networks (e.g., smart phones)
  - Need for higher throughput and spectrum efficiency
  - More aggressive frequency reuse pattern
- Beamingforming exploits **spatial diversity** of users
  - Allows transmission to more than one user during each transmission opportunity
  - Proposed a **throughput optimal** MAC scheduling scheme with beamforming
- Caveat: Larger and faster fluctuation in inter-cell interference due to focused transmit power created by beamforming
  - Inter-cell interference harder to estimate in advance without coordination and communication among neighboring base stations
  - Designed new beamforming algorithms for dealing with **unknown** inter-cell interference at the users

Multi-hop Wireless Networks (2): Mobility and Stability of On-Demand Routes

- Increasingly, users accessing information are mobile (e.g., smart phones)
  - Affects various aspects of network management
    - e.g., Routing in multi-hop wireless networks and hand-offs in cellular networks
- Better understanding of **user mobility** and their statistical properties needed for good network management and resource allocation
  - Studied inter-contact times between a pair of mobile nodes in generalized hybrid random walks
  - Demonstrated that their distribution is approximately exponential
- **Duration of available on-demand routes** in multi-hop wireless networks has significant impact on the stability of information flow and routing overhead under on-demand routing schemes
  - Investigated the distribution of the duration of routes discovered by on-demand routing schemes
  - Illustrated that their distribution can be approximated by an exponential distribution
    - Parameter can be estimated from mean link durations

Dynamic Spectrum Access: Secondary Market for Spectrum Trading

- Feasibility of dynamic spectrum trading dependent on many factors
- Sellers of frequency spectrum will have paid a high price for exclusive use right
  - Unlikely to lend to other service providers even if underutilized
  - Selfish, private entities (as opposed to government agencies)
- Most studies employ "efficient" mechanism for allocation and pricing of spectrum
  - Not suitable for private entities that wish to maximize profit/revenue
- In addition, need to understand the behavior of participating players
- So far, for simple single market scenarios,
  - Designed an **optimal mechanism** for allocating multiple units of frequency bands, which is **incentive compatible** and **individually rational**
  - Demonstrated the **existence of an incentive for risk neutral sellers to cooperate** in order to increase their expected profit from sales
  - Designed a revenue sharing scheme for maintaining cooperation among sellers

Cooperation among Service Providers: Contract Design

- Most of previous studies on contract designs for task delegation assume **risk neutral** players (i.e., content or network service providers)
  - e.g., service level agreement (SLA) between service providers
- Presence of **risk averse players** significantly alter the equilibria (i.e., feasible operating points) and corresponding behavior of involved parties
- Demonstrated that
  - Some players may always have an **incentive to lie** about their private information
  - As a consequence, reduces overall social welfare from network services
    - It impedes introduction of new network services and applications
  - Other players cannot tell whether some players are lying or not!