4G Wireless Networks

Need for Improved Loss Tolerance

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Adaptive Wireless: Goal is to Make Wireless As Good As Wired

Adaptive modulation and coding exploits previously inaccessible capacity enabling higher rates

Shannon Limit

4G Technologies e.g. MIMO, Small-Cells (802.11n)

Potential Improvement (3G, 802.16)

2.5G Systems

Fixed modulation and coding provides the same rate to all users, even if their links could provide higher rates

Multiple Antennas and Space-Time Coding Combined with Better Cell Propagation Predictability Provide “Wire-Like” Performance

Adaptive Modulation and Error Correction Coding Provide Higher Throughputs if Propagation Allows

Users in this region could get some connectivity rather than no service

Signal to Noise Ratio

User Rate
Reach-Data rate Tradeoff

- **Higher Rate, Lower-Speed Mobility**
  - **4G H/S Wireless LAN**: 2.4 & 5 GHz Unlicensed
  - **4G Wireless NAN**: 2.4 & 5 GHz

- **Peak Data Rate**
  - **100 Megabits per Second/ User**
  - **10 Megabits per Second/ User**
  - **1 Megabit per Second/ User**
  - **0.1 Megabit per Second/ User**

- **Reach**
  - **10 feet**
  - **100 feet**
  - **1 mile**
  - **10 miles**

- **Wider Area, Higher-Speed Mobility**
  - **3G/802.16 Wireless**: Various Bands
  - **2/2.5G Wireless**: 800 MHz, 2 GHz

- **3G/802.16 Wireless**
  - **3G/MAN Fixed or Pedestrian**
  - **3G/MAN Mobile**

- **2.5G Mobile/Pedestrian**
  - **Bluetooth**
  - **PANs 2.4GHz and UMB**
  - **Zigbee**
  - **Zigbee (US)**
  - **Zigbee (Europe)**
- Increased Bandwidth Demand/User
- Battery/Dissipation Device Constraints
- Moore’s Law Radios
- Increased Edge Intelligence
- Distributed Control Techniques
How Might A Wireless Deployment Look?
The Muni Network Concept Gets “Legs”

The number of municipalities operating, installing, or planning Wi-Fi networks is growing rapidly, driven by...

- User acceptance/use of Wi-Fi
- Large number of devices already equipped (instant customer base)
- Availability of low-cost networking systems (including mesh)
- Ability to transport Ethernet-like throughputs
- Desire to project “Cybercity” image
- “Digital Divide” amelioration
- Improvement in public service communications capabilities
- Leverage existing municipal infrastructure and fiber
- Revenue opportunities/new business models
- Ability to raise bond capital for infrastructure
Fiber, 4G, and Multi-Tier Wireless: A NanoNet
“NanoNet” Indoor Coverage Using “Window Bridging”

3G / Metro Area Wireless
Hub (PTMP Fixed Service to Businesses, MDUs, EcoPoles w/o fiber availability)

Fiber Ring

Fiber PON
Local PON Hub
City Fiber Hub

Eco-Pole AP
NAN Cell

LAN Indoor Cell
Window Bridge

Eco-Pole AP

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Motivation for our work on LT-TCP

- Dense wireless deployments in urban areas/high rises will cause disruptions/burst errors due to interference
- Protocols need to be loss tolerant and provide reliability
  - Especially as we move to multi-hop wireless environments
- Divide the burden of reliability between link and transport layers
- Keep Residual Loss Rate low; Delay small; Link and Transport Layer Goodput high
TCP-SACK Performance under Lossy Conditions

- Sharp drop-off in performance with PER (degrades beyond an error rate of 5% PER)
- Performance is poorer as combination of PER and RTT grows

![Graph showing TCP-SACK Degradation with Increased Erasure Rate and RTT (Uniform Loss Probabilities, 10 Mb/s Capacity, 1 flow)]

Fig. 1. TCP-SACK Degradation with Increased Erasure Rate and RTT (Uniform Loss Probabilities, 10 Mb/s Capacity, 1 flow)
Goals for our Enhancements to TCP

- **Dynamic Range:**
  - Can we extend the dynamic range of TCP into high loss regimes?
  - Can TCP perform close to the theoretical capacity achievable under high loss rates?

- **Congestion Response:**
  - How should TCP respond to notifications due to congestion?
  - ... but *not* respond to packet erasures that do not signal congestion?

- **Mix of Reliability Mechanisms:**
  - What mechanisms should be used to extend the operating point of TCP into loss rates from 0% - 50% packet loss rate?
  - How can Forward Error Correction (FEC) help?
  - How should the FEC be split between sending it *proactively* (insuring the data in anticipation of loss) and *reactively* (sending FEC in response to a loss)?

- **Timeout Avoidance:**
  - Timeouts: Useful as a fall-back mechanism but wasteful otherwise especially under high loss rates.
  - How can we add mechanisms to minimize timeouts?

- **Our Enhancements to TCP: Loss Tolerant-TCP (LT-TCP)**
LT-TCP Performance

Fig. 4. LT-TCP performance with increased Erasure Rate and RTT (Uniform Loss Probabilities. 10 Mb/s Capacity, 1 flow)

- Performance of LT-TCP is much better compared to that of TCP-SACK
- LT-TCP degrades gracefully (nearly linear degradation with loss rate)
Transport layer performance with loss tolerance across layers

- Combining Loss Tolerance at the Transport layer with Link layer enhancements allows us to strike a balance in providing the appropriate loss tolerance over a wide range of losses
- Limiting ARQ at link layer to manage latency
- Manageable link level residual loss rate
- Reasonable Goodput even under extreme conditions

**High Loss Rates:** Both LL-HARQ + LT-TCP needed to get better performance

**Low Loss Rates:** Just LL-HARQ (link) helps to get better performance