CS434/534: Topics in Networked (Networking) Systems

Introduction

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http://zoo.cs.yale.edu/classes/cs434/
Outline

- Topics to be covered
- Course planning
What are the Goals/Topics of this Course?

- Learn basic issues and design possibilities of **emerging, important** networking systems
- Learn the issues and designs in **real systems**
- Focus on both **design and implementation**
An Abstract View of a Networking System

Core

Link

End Device
End Device: Shift of End Devices
End Device: Devices and Connections Growth

“In many parts of the world, more people have access to a mobile [wireless] device than to a toilet or running water.” [Time Aug. 2012]
People and Mobile Devices

Where do you place your mobile device while sleeping at night?

Source: TIME survey

http://www.time.com/time/interactive/0,31813,2122187,00.html
# People and Mobile Devices

<table>
<thead>
<tr>
<th>AGE</th>
<th>FLIRT WITH SOMEONE?</th>
<th>SEND SUGGESTIVE PICTURES?</th>
<th>COORDINATE OR COMMIT ADULTERY?</th>
</tr>
</thead>
<tbody>
<tr>
<td>18–24</td>
<td>73%</td>
<td>48%</td>
<td>32%</td>
</tr>
<tr>
<td>25–29</td>
<td>76%</td>
<td>55%</td>
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<td>30–34</td>
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<td>35–44</td>
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<td>45–54</td>
<td>44%</td>
<td>26%</td>
<td>19%</td>
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<tr>
<td>55–64</td>
<td>22%</td>
<td>10%</td>
<td>13%</td>
</tr>
<tr>
<td>65+</td>
<td>16%</td>
<td>7%</td>
<td>3%</td>
</tr>
</tbody>
</table>

**Diagram:**

**Does Your Mobile Device Come at Times Between You and Your Spouse?**

- **0%**
- **20%**
- **40%**
- **60%**
- **80%**
- **100%**

- **U.S.**
- **Brazil**
- **China**
- **India**
- **S. Korea**
- **U.K.**

Source: TIME survey

http://www.time.com/time/interactive/0,31813,2122187,00.html
Link: From Wired to Wireless

- WiFi
- UWB
- satellite
- WiFi 802.11g/n
- WiFi Bluetooth NFC
- Bluetooth
- cellular
- Link: Core to End Device
Wireless Link: Almost Pervasive Cellular Coverage

- Wireless coverage, e.g.,
  - https://vzwmap.verizonwireless.com/dotcom/coveragelocator/

Wireless Link: Space Wi-Fi

Elon Musk wants to cover the world with internet from space

SpaceX requests permission from US government to operate network of 4,425 satellites to provide high-speed, global internet coverage

https://www.theguardian.com/technology/2016/nov/17/elon-musk-satellites-internet-spacex
Wireless Link: Habitat Monitoring

A 15-minute human visit leads to 20% offspring mortality
Wireless Links: Vehicular Networks

- Traffic crashes resulted in more than 41,000 lives lost/year

- Establishing
  - vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and
  - vehicle-to-hand-held-devices (V2D) communications

Link: Traffic Growth

Goal of Mobile Devices and Wireless Links (Networking)

“People and their machines should be able to access information and communicate with each other easily and securely, in any medium or combination of media – voice, data, image, video, or multimedia – any time, anywhere, in a timely, cost-effective way.”

Dr. G. H. Heilmeier, Oct 1992
Core: Toward Data Centers

Core: Toward Data Centers

Core: Simple Forwarding -> Network Control Functions: The Network Address Translation Example

- A local network uses just one public IP address as far as outside world is concerned
- Each device on the local network is assigned a private IP address

NAT gateway replaces source address with NAT IP address (e.g., 138.76.29.7) different source port numbers

All datagrams leaving local network cannot use private address use source address.
NAT: Network Address Translation

1: host 192.168.1.2 sends datagram to 128.119.40.186, 80

2: NAT router changes datagram source addr from 192.168.1.2, 3345 to 138.76.29.7, 5001, updates table

NAT translation table

<table>
<thead>
<tr>
<th>WAN side addr</th>
<th>LAN side addr</th>
</tr>
</thead>
<tbody>
<tr>
<td>138.76.29.7, 5001</td>
<td>192.168.1.2, 3345</td>
</tr>
<tr>
<td>…….</td>
<td>…….</td>
</tr>
</tbody>
</table>

3: Reply arrives dest. address: 138.76.29.7, 5001

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 192.168.1.2, 3345
Modern networks contain diverse types of equipment beyond simple routing/forwarding

Small: <=1k hosts; Medium: 1k-10k; Large: 10k-100k; Very Large: >= 100k

Source: [Sherry, et al SIGCOMM’12]
Enterprise/Cloud Structure

Tier-1
- S1
- IPS1
- LB1 (Load balancer)

Tier-2
- S2
- IPS2
- LB2

Tier-3
- S3
- IPS3
- LB3

VLAN 100
Tier-2
VLAN 200
Tier-3
VLAN 300
Tier-1
VLAN 400

Internet
CE

R1

Logger
OpenStack using OVS
Modern networks contain diverse types of equipment beyond simple routing/forwarding.
“We are focusing on a market transition involving the move toward more programmable, flexible, and virtual networks... This transition is focused on moving from a hardware-centric approach for networking to a virtualized network environment that is designed to enable flexible, application-driven customization of network infrastructures.

-- Cisco Annual Report (pp2), Nov. 2015
Course Topics

More programmable networking systems

Wireless Networking

Mobile Computing and Services

Core

Link

End Device
Challenge 1: Unreliable and Unpredictable Wireless Coverage

- Wireless links are not reliable: they may vary over time and space

What Robert Poor (Ember) calls “The good, the bad and the ugly”

*Cerpa, Busek et. al*
Challenge 2: Open Wireless Medium

- Wireless interference
  
  S1 → R1
  
  S2 → R1
Challenge 2: Open Wireless Medium

- Wireless interference

  S1 → R1
  S2 → R1

- Hidden terminals

  S1 → R1 ← S2
Challenge 2: Open Wireless Medium

- **Wireless interference**
  - S1 → R1
  - S2 → R1

- **Hidden terminals**
  - S1 → R1 ← S2

- **Exposed terminal**
  - R1 ← S1 → S2 → R2
Challenge 2: Open Wireless Medium

- Wireless interference
  - S1 → R1
  - S2 → R1

- Hidden terminals
  - S1 → R1 → R2

- Exposed terminal
  - R1 ← S1 ← S2 → R2

- Wireless security
  - eavesdropping, denial of service, ...
Challenge 3: Changing Terms, Standards, and Capacities
Challenge 3: Changing Terms, Standards, and Capacities

- Cellular phones:
  - 1981: NMT 450
  - 1986: NMT 900
  - 1991: CDMA
  - 1992: GSM
  - 1994: DCS 1800
  - 1991: D-AMPS
  - 1993: PDC
  - 1992: Inmarsat-A
  - 1983: AMPS
  - 1988: Inmarsat-C
  - 1991: DECT
  - 2000: GPRS
  - 2001: IMT-2000

- Satellites:
  - 1992: Inmarsat-B
  - 1992: Inmarsat-M
  - 1998: Iridium

- Cordless phones:
  - 1980: CT0
  - 1984: CT1
  - 1987: CT1+
  - 1989: CT 2
  - 1991: DECT

- Wireless LAN:
  - 1997: IEEE 802.11
  - 1999: 802.11b, Bluetooth
  - 2000: IEEE 802.11a

Fourth Generation (Internet based)
# Changing Wireless Communication Standards

<table>
<thead>
<tr>
<th>Generation</th>
<th>Family</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0G (radio telephones)</td>
<td>MTS · MTA · MTB · MTC · IMTS · MTD · AMTS · OLT · Autoradiopuhelin</td>
<td></td>
</tr>
<tr>
<td>1G</td>
<td>AMPS family</td>
<td>AMPS · TACS · ETACS</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>NMT · Hicap · Mobitex · DataTAC</td>
</tr>
<tr>
<td>2G</td>
<td>GSM/3GPP family</td>
<td>GSM · CSD</td>
</tr>
<tr>
<td></td>
<td>3GPP2 family</td>
<td>CdmaOne (IS-95)</td>
</tr>
<tr>
<td></td>
<td>AMPS family</td>
<td>D-AMPS (IS-54 and IS-136)</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>CDPD · iDEN · PDC · PHS</td>
</tr>
<tr>
<td>2G transitional (2.5G, 2.75G)</td>
<td>GSM/3GPP family</td>
<td>HSCSD · GPRS · EDGE/EGPRS</td>
</tr>
<tr>
<td></td>
<td>3GPP2 family</td>
<td>CDMA2000 1xRTT (IS-2000)</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>WiDEN</td>
</tr>
<tr>
<td>3G (IMT-2000)</td>
<td>3GPP family</td>
<td>UMTS (UTRAN) · WCDMA-FDD · WCDMA-TDD · UTRA-TDD LCR (TD-SCDMA)</td>
</tr>
<tr>
<td></td>
<td>3GPP2 family</td>
<td>CDMA2000 1xEV-DO (IS-856)</td>
</tr>
<tr>
<td>3G transitional (3.5G, 3.75G, 3.9G)</td>
<td>3GPP family</td>
<td>HSDPA · HSUPA · HSPA+ · LTE (E-UTRA)</td>
</tr>
<tr>
<td></td>
<td>3GPP2 family</td>
<td>EV-DO Rev. A · EV-DO Rev. B</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>Mobile WiMAX (IEEE 802.16e-2005) · Flash-OFDM · IEEE 802.20</td>
</tr>
<tr>
<td>4G (IMT-Advanced)</td>
<td>3GPP family</td>
<td>LTE Advanced</td>
</tr>
<tr>
<td></td>
<td>WiMAX family</td>
<td>IEEE 802.16m</td>
</tr>
<tr>
<td>5G</td>
<td>unconfirmed</td>
<td>unconfirmed</td>
</tr>
</tbody>
</table>
-changing processing capability: javascript benchmark

<table>
<thead>
<tr>
<th>Laptop/Chrome Mac OS X 10.7.2</th>
<th>Tested in Nov, 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPhone 4S/Safari iOS 5.0.1</td>
<td>Tested in Nov, 2011</td>
</tr>
<tr>
<td>HTC/Default</td>
<td></td>
</tr>
<tr>
<td>Android 2.2.1</td>
<td></td>
</tr>
<tr>
<td>Samsung/IE</td>
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<tr>
<td>Windows Phone 7.5</td>
<td></td>
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<tr>
<td>G1/Default</td>
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<td>Android 1.6</td>
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<tr>
<td>Android 1.6</td>
<td></td>
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<tr>
<td>iPhone/Safari iOS 3.0</td>
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<tr>
<td>Samsung/IE</td>
<td></td>
</tr>
<tr>
<td>Windows Mobile 6.5</td>
<td></td>
</tr>
</tbody>
</table>

Time to finish JavaScript benchmark (sec)

- Laptop/Chrome Mac OS X 10.7.2: 0.41s
- iPhone 4S/Safari iOS 5.0.1: Tested in Nov, 2009
- HTC/Default: Tested in Nov, 2011
- Android 2.2.1: Tested in Nov, 2011
- Samsung/IE: Tested in Nov, 2011
- Windows Phone 7.5: Tested in Nov, 2011
- G1/Default: Tested in Nov, 2011
- Android 1.6: Tested in Nov, 2011
- G1/Default: Tested in Nov, 2011
- Android 1.6: Tested in Nov, 2011
- iPhone/Safari iOS 3.0: Tested in Nov, 2011
- Samsung/IE: Tested in Nov, 2011
- Windows Mobile 6.5: Tested in Nov, 2011

210.97s
Changing Processing Capability: Javascript Benchmark

<table>
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<td>117.41s</td>
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<tr>
<td></td>
<td></td>
<td>210.97s</td>
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</tr>
</tbody>
</table>
### Changing Processing Capability: Javascript Benchmark

<table>
<thead>
<tr>
<th>Device</th>
<th>Tested in</th>
<th>Time to Complete</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop/Chrome</td>
<td>2009</td>
<td>0.41s</td>
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<tr>
<td>Mac OS X 10.7.2</td>
<td>2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iPhone 4S/Safari</td>
<td>2009</td>
<td>95.08s</td>
<td></td>
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<td>iOS 5.0.1</td>
<td>2011</td>
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<td>iPhone 4/Safari</td>
<td>2009</td>
<td>95.66s</td>
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<tr>
<td>iOS 5.0.1</td>
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<td>2011</td>
<td></td>
<td></td>
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<tr>
<td>Samsung/IE</td>
<td>2009</td>
<td>210.97s</td>
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<tr>
<td>Windows Phone 7.5</td>
<td>2011</td>
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<td></td>
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<td>iPhone/Safari</td>
<td></td>
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</tr>
<tr>
<td>iOS 3.0</td>
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<tr>
<td>Samsung/IE</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Windows Mobile 6.5</td>
<td></td>
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</tr>
</tbody>
</table>

Notes: # indicates tested in 2009, with 2011 results indicating improvement.
7. APPLICATION PERFORMANCE IMPACT

7.1 JavaScript execution

Changing Processing Capability: Javascript Benchmark

- Laptop/Chrome
  - Mac OS X 10.7.2
- iPhone 4S/Safari
  - iOS 5.0.1
- iPhone 4/Safari
  - iOS 5.0.1
- HTC/Default
- Android 2.2.1
- Samsung/IE
- Windows Phone 7.5
- G1/Default
- Android 1.6
- G1/Default
- Android 1.6
- iPhone/Safari
  - iOS 3.0
- Samsung/IE
- Windows Mobile 6.5

Table 6: HTTP object statistics.

<table>
<thead>
<tr>
<th>Website</th>
<th># objects</th>
<th>Avg size (KB)</th>
<th>Max obj size (KB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Website X</td>
<td>11</td>
<td>160.7</td>
<td>87.6</td>
</tr>
<tr>
<td>Website Y</td>
<td>59</td>
<td>509.9</td>
<td>124.2</td>
</tr>
<tr>
<td>YouTube</td>
<td>33</td>
<td>334.8</td>
<td>93.0</td>
</tr>
<tr>
<td>Website Z</td>
<td>17</td>
<td>145.4</td>
<td>59.9</td>
</tr>
<tr>
<td>Website A</td>
<td>35</td>
<td>158.3</td>
<td>99.7</td>
</tr>
</tbody>
</table>

From 2009 to 2011, iOS has a speedup of 29.88 for iPhone 4 and 29.82 for iPhone 4S, while 21.64 for Android and 22.30 for Windows Mobile 6.5. In Figure 22, the test results on the same G1 phone in 2009 benchmark (version 0.9) to quantify the JavaScript execution speed. In this section, we observe that LTE consumes up to 23 times in JavaScript execution speed. Possible causes significant signaling overhead when transferring multiple web objects; however, no HTTP pipelining is applicable. First, loading time comparison shows that LTE and WiFi have 200% larger response time. The application loading time for LTE slightly lags behind WiFi. On one hand, though LTE has faster throughput, the average low throughput, CPU usage, and energy consumption for five applications are shared by the other LTE parameters and we leave the reasonable settings and adjustment around the default configurations to the implementation. Similar to 3G network, 3G UMTS network is still a key contributor for the low energy efficiency for LTE. Similar to 3G network, LTE consumes up to 23 times in JavaScript execution speed. Possible work for LTE as future work. For 3G network, network performance appears to be the bottleneck, and the energy usage is 5.5 times in JavaScript execution speed. Possible reasons for this improvement include fast CPU, larger memory, and dropped to 5.5 times in JavaScript execution speed.
Changing Processing Capability: Javascript Benchmark

![JavaScript Execution Speed Comparison](image)

<table>
<thead>
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<tbody>
<tr>
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<tr>
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<td>4.42s</td>
<td>9.46s</td>
</tr>
<tr>
<td>HTC/Default Android 2.2.1</td>
<td>95.08s</td>
<td>117.41s</td>
</tr>
<tr>
<td>Samsung/IE Windows Phone 7.5</td>
<td>95.66s</td>
<td>210.97s</td>
</tr>
</tbody>
</table>

**Chart Notes:**
- Time to finish JavaScript benchmark (sec)
- Tested in Nov, 2009: Red
- Tested in Nov, 2011: Green
- Laptop/Chrome Mac OS X 10.7.2: 0.41s
- iPhone 4S/Safari iOS 5.0.1: 4.42s
- HTC/Default Android 2.2.1: 95.08s
- Samsung/IE Windows Phone 7.5: 95.66s
- Samsung/IE Windows Mobile 6.5: 210.97s
Changing Processing Capability: Javascript Benchmark

<table>
<thead>
<tr>
<th>Device Configuration</th>
<th>Time to Finish JavaScript Benchmark (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laptop/Chrome, Mac OS X 10.7.2</td>
<td>0.41s Tested in Nov, 2009</td>
</tr>
<tr>
<td>iPhone 4S/Safari, iOS 5.0.1</td>
<td>3.93s</td>
</tr>
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<td>iPhone 4/Safari, iOS 5.0.1</td>
<td>4.42s</td>
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<td>Android 1.6</td>
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</tr>
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<td>iPhone/Safari, iOS 3.0</td>
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Table 6: HTTP object statistics.

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<th>Avg size</th>
<th># objects</th>
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</thead>
<tbody>
<tr>
<td>Market</td>
<td>35.3KB</td>
<td>109.4KB</td>
<td>33</td>
</tr>
<tr>
<td>YouTube</td>
<td>124.2KB</td>
<td>8.6KB</td>
<td>59</td>
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<td>364.2KB</td>
<td>169.5KB</td>
<td>17</td>
</tr>
<tr>
<td>Website Y</td>
<td>509.9KB</td>
<td>87.6KB</td>
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</tr>
<tr>
<td>Website Z</td>
<td>87.8KB</td>
<td>599.7KB</td>
<td>11</td>
</tr>
</tbody>
</table>
## 7. APPLICATION PERFORMANCE IMPACT

### 7.1 JavaScript execution

In this section, we observe that LTE consumes up to 23 times more energy than WiFi, with energy usage for LTE ranging from 68.8% to 84.3%, averaging at 79.3%, compared with WiFi's 78.2%.

### 7.2 Application case study

Along with improvements in mobile client processing power, work has narrowed because of LTE's better network performance. For example, from 2009 to 2011, iOS has a speedup of 29.88 for iPhone 4 and 56.79 for iPhone 4S.

### Table 6: HTTP object statistics

<table>
<thead>
<tr>
<th>Object Type</th>
<th># objects</th>
<th>Avg size</th>
<th>Max obj size</th>
<th>50% obj size</th>
<th>90% obj size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Website X</td>
<td>30</td>
<td>17KB</td>
<td>62KB</td>
<td>159KB</td>
<td>319KB</td>
</tr>
<tr>
<td>Website Y</td>
<td>60</td>
<td>33KB</td>
<td>124KB</td>
<td>999KB</td>
<td>1.0MB</td>
</tr>
<tr>
<td>YouTube</td>
<td>30</td>
<td>11KB</td>
<td>34KB</td>
<td>149KB</td>
<td>343KB</td>
</tr>
<tr>
<td>Market App</td>
<td>10</td>
<td>40KB</td>
<td>109KB</td>
<td>999KB</td>
<td>1.0MB</td>
</tr>
</tbody>
</table>

In terms of energy usage, WiFi clearly has significantly higher impact than LTE. For example, for Website Y, WiFi represents 55.6% of the total energy due to tail, while for LTE, it is only 12.0 times of WiFi, with 32.2% reduction in energy consumption.

### Figure 22: JavaScript execution speed comparison.

- **Laptop/Chrome Mac OS X 10.7.2**: 0.41s
- **iPhone 4S/Safari iOS 5.0.1**: 2.26s
- **iPhone 4/Safari iOS 5.0.1**: 3.93s
- **HTC/Default**: 4.42s
- **Android 2.2.1**: 9.46s
- **Samsung/IE Windows Phone 7.5**: 95.08s
- **G1/Default Android 1.6**: 95.66s
- **G1/Default Android 1.6**: 117.41s
- **iPhone/Safari iOS 3.0**: 210.97s
- **Samsung/IE Windows Mobile 6.5**: Tested in Nov, 2009
- **三星/Samsung/IE Windows Mobile 6.5**: Tested in Nov, 2011

Time to finish JavaScript benchmark (sec)
Challenge 3: Changing Terms, Standards, and Capacities

- OpenFlow is the new standard of programmable networks

- OpenFlow is dead and the new future is P4.

- ....
Challenge 4: Mobility

- Mobility causes poor-quality wireless links

- Mobility causes intermittent connection
  - under intermittent connected networks, traditional routing, TCP, applications all break

- Mobility changes context, e.g., location

- Mobility can be objective
Controlled Mobility
Challenge 5: Portability

- Limited battery power
- Limited processing, display and storage

Sensors, embedded controllers

Mobile phones
- voice, data
- simple graphical displays
  - GSM/3G/4G

Smart phone
- data
- smaller graphical displays
  - 802.11/3G

Tablet/Laptop

Performance/Weight/Power Consumption
Challenge 6: Programmability is not a Native Goal of Networking Systems

Outline

- Topics to be covered
- Course planning
Class Info: Personnel

- Instructor
  - Y. Richard Yang, yry@cs.yale.edu, AKW 208A
  - office hours: to be posted

- Teaching fellow
  - Geng Li
  - office hours: to be posted on class page

- Course home page
  - http://zoo.cs.yale.edu/classes/cs434/
Course Topic: Programmable Networks

- OpenFlow as a standard network device programming interface
- Maple as a high-level network programming system
- P4 as a next-generation network device programming interface
- Magellan as a high-level networking programming system
- OpenDaylight and ONOS open-source NetworkOS
- Case study: Implementing OpenStack using programmable networks
Course Topic: Mobile OS/App Framework, Services

- **Mobile OS**
  - TinyOS
  - Android app framework
    - Activity, service, intent, content provider, handler/AsyncTask, ...
  - Basic mobile services, including localization, location based services (GPS, lateration, acoustic, signature)

- **Mobile and network interactions**
  - Why are web browser slow on smartphones?
  - Why did some small percentage of Pandora’s traffic is responsible for a large fraction of energy use on my phone? ...
Course Topic: Programmable, Wireless, Mobile Networks

- Wireless networking foundations
- Software defined radio
- 5G network
Class Materials

- Selected conference and journal papers
- Chapters of reference books
- Documents of open source software
- Other resources
  - MOBICOM, SIGCOMM, Mobisys proceedings
  - IEEE Network, Communications, Pervasive magazines
What You Need to Do

督办prerequisite
- motivated, critical
- basic programming skill
  - Android: Java, C (if you decide to hack into the kernel)
  - OpenDaylight/ONOS: Java
  - Software defined radio: C++/python

督办workload
- class participation
  - actively participate in class discussions
- 3-4 assignments
- One project
- One midterm
Class Project

- Goal: obtain hands-on experience
- We’ll suggest potential topics
- You may also choose your own topic
- Initial proposal + midterm progress report + final report + [presentation]
- We provide help in logistics such as
  - Mobile devices
  - Programmable network devices
  - Cloud (amazon/Google) cloud service accounts
- Expectation: modify one real, large-scale system (ONOS/ODL/OpenStack/Gnuradio/Android, ...)

## Grading

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project</strong></td>
<td>45%</td>
</tr>
<tr>
<td><strong>Assignments</strong></td>
<td>25%</td>
</tr>
<tr>
<td><strong>Exam</strong></td>
<td>15%</td>
</tr>
<tr>
<td><strong>Class Participation</strong></td>
<td>15%</td>
</tr>
</tbody>
</table>

- More important is what you realize/learn than the grades
Class Survey

- Please take the class survey
  - help me to determine your background
  - help me to determine the depth and topics
  - suggest topics that you want to be covered
Questions?