Software Defined Networking
Applications in 5G Networks

IBSS 2015

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## Internet Evolution

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>User Traffic (per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>UCLA creates ARPANET, the beginning of INET</td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>e-Commerce appearance (ATM and telephone banking)</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>Official public face of INET</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>e-Commerce online appearance</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>ICQ launching</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>Dot-Com companies collapse</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>Internet Marketing beginning</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>SEO beginning</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>PAYPAL.COM official launching</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>OVERTURE.COM official launching</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>LIVE.COM official launching</td>
<td></td>
</tr>
</tbody>
</table>

* User traffic calculation per day

**Internet Global Traffic:**
- 1.1 Billion users on the network
- 640 million users on the network
- 300 million users on the network
- 255,000 users on the network
- 334 users on the network
Internet Penetration

Internet users in 2012 as a percentage of a country's population
Source: International Telecommunications Union
Fixed Internet Penetration
Mobile Internet Penetration
Internet Penetration

Internet users in 2012 as a percentage of a country's population
Source: International Telecommunications Union
World of Internet
## World of Internet

### Internet users by region

<table>
<thead>
<tr>
<th>Region</th>
<th>2005&lt;sup&gt;b&lt;/sup&gt;</th>
<th>2010&lt;sup&gt;b&lt;/sup&gt;</th>
<th>2013&lt;sup&gt;a,b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>2%</td>
<td>10%</td>
<td>16%</td>
</tr>
<tr>
<td>Americas</td>
<td>36%</td>
<td>49%</td>
<td>61%</td>
</tr>
<tr>
<td>Arab States</td>
<td>8%</td>
<td>26%</td>
<td>38%</td>
</tr>
<tr>
<td>Asia and Pacific</td>
<td>9%</td>
<td>23%</td>
<td>32%</td>
</tr>
<tr>
<td>Commonwealth of Independent States</td>
<td>10%</td>
<td>34%</td>
<td>52%</td>
</tr>
<tr>
<td>Europe</td>
<td>46%</td>
<td>67%</td>
<td>75%</td>
</tr>
</tbody>
</table>

### Worldwide Internet users

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2010</th>
<th>2013&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>World population</td>
<td>6.5 billion</td>
<td>6.9 billion</td>
<td>7.1 billion</td>
</tr>
<tr>
<td>Not using the Internet</td>
<td>84%</td>
<td>70%</td>
<td>61%</td>
</tr>
<tr>
<td>Using the Internet</td>
<td>16%</td>
<td>30%</td>
<td>39%</td>
</tr>
<tr>
<td>Users in the developing world</td>
<td>8%</td>
<td>21%</td>
<td>31%</td>
</tr>
<tr>
<td>Users in the developed world</td>
<td>51%</td>
<td>67%</td>
<td>77%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Estimate.<br><sup>b</sup> Per 100 inhabitants.<br>Source: International Telecommunications Union
Plain Old Telephone System (POTS)
Global Mobile System (GSM)

- Cellular radio network
- Interference with audio devices
- GSM frequencies
- Voice codec
- Network structure
- Subscriber Identity Module (SIM)
- GSM security
- Last mile backhaul provides connectivity between small cells and the PoP (point of presence)
- High number of backhaul links due to small cell mass deployment
- PoP can be fixed fiber access point or a macro cell backhaul
- Different options for backhaul derived from fiber, CAT5 and radio technologies.
Adoption of LTE technology as of May 8, 2012.
- Countries with commercial LTE service
- Countries with commercial LTE network deployment on-going or planned
- Countries with LTE trial systems (pre-commitment)
Wireless Spectrum Scarcity
RISING IMPACTS OF GLOBAL WARMING

With continued intensive reliance on fossil-fuels and emissions increases:

- **+5°C**: Extinction of more than 40% of known species, global economic losses of up to 5% GDP.
- **+4°C**: Commitment to at least partial melting of Greenland and W. Antarctic ice sheets, eventually raising sea-level 13-20 feet.
- **+3°C**: Substantial burden on health services, global food production decreases, about 30% of global coastal wetlands lost.
- **+2°C**: Major changes in natural systems cause predominantly negative consequences for biodiversity, water and food supplies, widespread coral mortality.
- **+1°C**: Millions more people face flooding risk every year.

Over 1980-1999 temperature levels:

- **2020s**: Increased risk of extinction for 20-30% of known species, most corals bleached, increasing mortality from heat waves, floods and droughts.
- **2050s**: Decreasing water availability, increasing drought in many regions.
- **2080s**: Increasing wildfire risk, increased flood and storm damage, increasing burden from malnutrition, diarrhoeal, cardio-respiratory and infectious diseases.

NET www.net.org
Project 25 (P25)

- January 1982 Air Flight 90 crash in Washington D.C.
- April 1995 Oklahoma City Bombing. Search and Rescue could not communicate
- September 2001 Terrorist Attacks on world trade center, New York City

- Common standard would allow any number of manufacturers to produce compatible equipment.
- Common standard would increase competition and lower prices.
- Avoid locking customers into a proprietary system from a single manufacturer.
Countries with Project 25-Interoperable Equipment or Networks

Argentina, Australia, Austria, Azerbaijan, Bahrain, Bermuda, Botswana, Brazil, Brunei, Canada, Chile, China, Colombia, Costa Rica, Croatia, Côte d'Ivoire, Czech Republic, Denmark, Eritrea, Estonia, Finland, France, Georgia, Germany, Greece, Hong Kong, Hungary, India, Indonesia, Ireland, Israel, Italy, Jamaica, Japan, Kazakhstan, Korea, Kuwait, Latvia, Lebanon, Lesotho, Liberia, Liechtenstein, Lithuania, Luxembourg, Macau, Malaysia, Maldives, Malta, Mexico, Monaco, Montenegro, Mozambique, Netherlands, New Zealand, Nicaragua, Nepal, Nigeria, Norway, Oman, Pakistan, Panama, Peru, Philippines, Portugal, Qatar, Russia, Rwanda, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Samoa, Saudi Arabia, Senegal, Singapore, Slovakia, Slovenia, South Africa, South Korea, Spain, Sri Lanka, Sweden, Switzerland, Syria, Tanzania, Thailand, Tunisia, Turkey, Turkey, Uganda, United Arab Emirates, United Kingdom, United States, Uruguay, Ukraine, United Nations, Vietnam, Zambia, Zimbabwe.
P25 Basic Elements
addresses phase 1 P25

**Trunking**
- Control Channel
- Trunking Signal Blocks
- Unit & Group Addressing

**Conventional**
- Talk Around
- Conventional Signal Blocks
- Unit & Group Addressing

**Encryption**
- Multi-algorithm
- Multi-key
- Encrypted Voice, Data, & Control

**CAI**
- 12.5 kHz channels
- 9.6 kbps
- C4FM modulation
- FDMA channel access
- Error correction codes
- IMBE vocoder

**Data**
- IP packets
- Integrated with Voice and Control

**Over the Air Rekeying**
Total 22 Telecom Circles or Service Areas.

The 'metro' circles cover very dense population centers: Delhi, Kolkata, and Mumbai.

The 'A', 'B', and 'C' circles cover geographic territories of varying population sizes.

'A' circles - largest population coverage.
'C' circles - smallest population.
• India is the world’s fastest growing telecom market

• Present: 811.59 million mobile phone subscribers.

• Projected Growth: 1.2 billion mobile subscribers by 2015.
Network Trends
Global Mobile technology coverage

% Population coverage

World population distribution

World record: 168 Mbps

Current capability in India

Need for speed & low latency = 5G
# LTE versus LTE-A

We have tried all the techniques that we know

<table>
<thead>
<tr>
<th>Technology</th>
<th>LTE</th>
<th>LTE-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak data rate Down Link (DL)</td>
<td>150 Mbps</td>
<td>1 Gbps</td>
</tr>
<tr>
<td>Peak data rate Up Link (UL)</td>
<td>75 Mbps</td>
<td>500 Mbps</td>
</tr>
<tr>
<td>Transmission bandwidth DL</td>
<td>20MHz</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Transmission bandwidth UL</td>
<td>20MHz</td>
<td>40 MHz (requirements as defined by ITU)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Optimized for low speeds (&lt;15 km/hr) High Performance At speeds up to 120 km/hr Maintain Links at speeds up to 350 km/hr</td>
<td>Same as that in LTE</td>
</tr>
<tr>
<td>Coverage</td>
<td>Full performance up to 5 km</td>
<td>a) Same as LTE requirement b) Should be optimized or deployment in local areas/micro cell environments.</td>
</tr>
<tr>
<td>Scalable Band Widths</td>
<td>1.3, 3, 5, 10, and 20 MHz</td>
<td>Up to 20–100 MHz</td>
</tr>
<tr>
<td>Capacity</td>
<td>200 active users per cell in 5 MHz.</td>
<td>3 times higher than that in LTE</td>
</tr>
</tbody>
</table>
Internet of Things

TECHNOLOGY ROADMAP: THE INTERNET OF THINGS

Supply-Chain Helpers
- RFID tags for facilitating routing, inventorying, and loss prevention

Vertical Market Applications
- Surveillance, security, healthcare, transport, food safety, document management

Ubiquitous Positioning
- Locating people and everyday objects
- Teleoperation and telepresence: Ability to monitor and control distant objects

Physical-World Web

Minimization, power-efficient electronics, and available spectrum
- Ability of devices located indoors to receive geolocation signals

Software agents and advanced sensor fusion

Source: SRI Consulting Business Intelligence
We lost our way

Routing, management, mobility management, access control, VPNs, ...

- Million of lines of source code
- 5400 RFCs

- 500M gates
- 10Gbytes RAM

Specialized Packet Forwarding Hardware

Operating System

App... App... App...
Limitations of Current Networks

Intelligent Communication Lab
Many complex functions baked into the infrastructure

*OSPF, BGP, multicast, differentiated services, Traffic Engineering, NAT, firewalls, MPLS, redundant layers, ...*

An industry with a “mainframe-mentality”
Innovation to Deployment

- Driven by vendors
- Consumers largely locked out
- Glacial innovation
Providers Like it !!

In a nutshell

Driven by **cost** and **control**
Started in data centers….

What New Generation Providers have been Doing Within Data centers

Buy bare metal switches/routers
Write their own control/management applications on a common platform
Change in non-traditional markets
The “Software-defined Network”

1. Open interface to hardware

2. At least one good operating system Extensible, possibly open-source

3. Well-defined open API

App

Network Operating System

Simple Packet Forwarding Hardware

Simple Packet Forwarding Hardware

Simple Packet Forwarding Hardware

Simple Packet Forwarding Hardware
Recent Trend

Computer Industry

Simple common stable hardware substrate below + programmability + strong isolation model + competition above = Result: faster innovation

Network Industry
Software Defined Networking
Rethinking the “Division of Labor”
Data plane:
Packet streaming

Forward, filter, buffer, mark, rate-limit, and measure packets
Traditional Computer Networks

Control plane:
Distributed algorithms

Track topology changes, compute routes, install forwarding rules
Management plane:
Human time scale

Collect measurements and configure the equipment
Software Defined Networking (SDN)

- Logically-centralized control
- API to the data plane (e.g., OpenFlow)

Smart, slow

Dumb, fast

Switches
Google’s Take on SDN

- **Benefits**
  - Unified view of the Network Fabric
  - High utilization
  - Faster failure handling
  - Faster time to market/deployment
  - Hitless upgrades
  - Elastic compute

- **Challenges**
  - OpenFlow Protocol
  - Fault tolerant OpenFlow controllers
  - Partitioning Functionality
  - Flow Programming
Heterogeneous Switches

- Number of packet-handling rules
- Range of matches and actions
- Multi-stage pipeline of packet processing
- Offload some control-plane functionality (?)

Diagram:
- access control
- MAC look-up
- IP look-up
Controller Delay and Overhead

- Controller is much slower than the switch
- Processing packets leads to delay and overhead
- Need to keep most packets in the “fast path”
Distributed Controller

For scalability and reliability
Partition and replicate state
Testing and Debugging

- OpenFlow makes programming possible
  - Network-wide view at controller
  - Direct control over data plane

- Plenty of room for bugs
  - Still a complex, distributed system

- Need for testing techniques
  - Controller applications
  - Controller and switches
  - Rules installed in the switches

Debugging Sucks!  Testing Rocks!
OpenFlow: Enable Innovations “within” the Infrastructure

- Add/delete flow entries
- Encapsulated packets
- Controller discovery
Sliced and Virtualized OpenFlow Infrastructure

- Intelligent Communication Lab
- Research Team A Controller
- Research Team B Controller
- Production Net Controller
- OpenFlow Protocol
- FLOWVISOR
- Isolated Network Slices
- Physical Infrastructure Packet & Circuit Switches: wired, wireless, optical media
OpenFlow as GENI

A nationwide network before end of 2010
Software Defined Networking

Research Goal: Packet and Circuit Flows Commonly Controlled & Managed

Simple, network of Flow Switches

Flow Network

... that switch at different granularities: packet, time-slot, lambda
Converged packets & dynamic circuits opens up new capabilities

OpenFlow Protocol
Multi-Layer, Application-Aware Provisioning and Grooming Using OpenFlow
Example: New Data Center

Cost
- 200,000 servers
- Fanout of 20 ⇒ 10,000 switches
- $5k commercial switch ⇒ $50M
- $1k custom-built switch ⇒ $10M

Savings in 10 data centers = $400M

Control
1. Optimize for features needed
2. Customize for services & apps
3. Quickly improve and innovate

The value prop applies to enterprise and service provider networks
Consequences

• **More innovation in network services**
  – Owners, operators, 3rd party developers, researchers can improve the network
  – E.g. energy management, data center management, policy routing, access control, denial of service, mobility

• **Lower barrier to entry for competition**
  – Healthier market place with reducing Capex & OpEx
Ecosystem Coming Together
Role for Everyone to Contribute

- Researchers and R&E Networks
- Providers: old and new
  - Google, Amazon, Yahoo!, (Microsoft, Facebook),
  - DT, DoCoMo, BT (Level3, Verizon, …)
- Box vendors
  - Enterprise and backbone
  - Packet and circuit (electronic and photonics)
  - Incumbents and startups
- Chip vendors
  - Broadcom, Dune, Marvell, ….
Controller: Programmability

Controller Application

Network OS

Events from switches
- Topology changes,
- Traffic statistics,
- Arriving packets

Commands to switches
- (Un)install rules,
- Query statistics,
- Send packets
OpenFlow Enabled Switches/Routers

- Juniper MX-series
- NEC IP8800
- WiMax (NEC)
- WiFi
- HP Procurve 5400
- Cisco Catalyst 6k
- Cisco Catalyst 3750 (2010)
- Ciena CoreDirector
- Quanta LB4G
- Arista 7100 series (2010)
Example OpenFlow Applications

- Dynamic access control
- Seamless mobility/migration
- Server load balancing
- Network virtualization
  - Using multiple wireless access points
  - Energy-efficient networking
  - Adaptive traffic monitoring
  - Denial-of-Service attack detection

See http://www.openflow.org/videos/
Dynamic Access Control

- Inspect first packet of a connection
- Consult the access control policy
- Install rules to block or route traffic
Seamless Mobility/Migration

- See host send traffic at new location
- Modify rules to reroute the traffic
Server Load Balancing

- Pre-install load-balancing policy
- Split traffic based on source IP

src=0*

src=1*
OpenFlow in the Wild

- Open Networking Foundation
  - Google, Facebook, Microsoft, Yahoo, Verizon, Deutsche Telekom, and many other companies
- Commercial OpenFlow switches
  - HP, NEC, Quanta, Dell, IBM, Juniper, …
- Network operating systems
  - NOX, Beacon, Floodlight, Nettle, ONIX, POX, Frenetic
- Network deployments
  - Eight campuses, and two research backbone networks
  - Commercial deployments (e.g., Google backbone)
Satellite Communications

Inter Satellite Routing
Optical Modulation Techniques for Space/Ground Segment
Antenna Design for 70 GHz Band
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Thanks!