Future Internet Architecture: From Network Virtualization to Clean-slate Post-IP

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@ Xidian U., Xi’an, China
Agenda

- Motivation: why FIA?
- Network Virtualization
- Post-IP Future Internet Architecture
- Converged Network & Service Test-bed
- Q&A
Challenges faced by Current Internet

IoM (Internet of Media), IoT (Internet of Things), IoS (Internet of Services) have pushed Internet to its limit in terms of:

- **Performance:**
  - 0.5 Million backbone routers, 9M BGP routes, 1T webpage items on Google, 15 hours video content added into video websites per minute, ... 60% increase in Internet traffic flow p.a.
  - Furthermore, IoT makes billions and trillions of “things” connected into the Internet!
  - The Internet becomes huge and more complex.

- **Security:**
  - e.g., 90M visa card users hacked in Europe and North America at 2007;
  - DNS server of Storm (Video) Co. being attacked at 2009, leading to 15 provinces’ network malfunction in China.
Challenges faced by Current Internet

- **Energy Consumption:**
  - ICT energy consumption in 2007 in China equals to the energy generated by Three-Gorge Power Station
  - 1 Google search = 11W bulb for 1 hour
  - Green!

- **Network Management:**
  - Becoming more difficult and almost unmanageable.
  - including content management (e.g., piracy)
Path to Future Internet: Dirty Slate

- Solutions: back-compatible, evolutionary, incremental
  - Quality of Service problem? Then IntServ/DiffServ
  - More efficient routing? -> MPLS (Multi-Protocol Label Switching)
  - Security problem? Then IP VPN: Virtual Private Network
  - Mobility problem? Then Mobile IP or MIPv6

- Initiatives:
  - NGI, Internet2 at US, Ambient Network in EU,
  - APAN in Japan, CNGI in China.

- Problems:
  - Adding patches and making the Internet more complex and thus more difficult to achieve global optimization.
  - Limiting the further development of the Internet.
Path to Future Internet: Clean-slate

- Revolutionary (bold!)
- Do endpoints really matter? Or is it the information that is more important?
  - IP may be “the” problem!

- Endpoint-centric services move towards information retrieval through, e.g., CDNs (Content Distribution Networks), YouTube, Twitter
  - But how about at the network layer?
Ossification of IP-based Infrastructure

Huge innovation in applications

Ossification of the core protocols

Relentless evolution of the underlying technology

Courtesy to M. Handley of UCL
Observations

- The current Internet is end point centric which has contributed to a number of its problems, such as
  - SPAM, virus, denial-of-service attacks,
  - poor support for mobility and multimedia content distribution.
- The current Internet is in favour of senders and receivers passively receive.
  - Economically, receivers are forced to carry the cost of unwanted traffic
- Google youTube’s content distribution networks get bigger and more expensive (also for ISPs).
- There is a consensus that a fundamental reform of the Internet is inevitable in the near future.
What is the Way Out?

Clean Slate
- Low Cost
- Not scalable
- Hard to Deploy
- Support Arch Innovation

Dirty Slate
- High Cost
- Frequent Update
- Easy to Deploy
- Reduce Deployment Complexity

More Feasible?
Net work Virtualization
Agenda

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IT Resource Virtualization - Cloud computing

Google App Engine
Salesforce, Gmail
Amazon EC2, Joyent

IaaS
PaaS
SaaS

Cloud Computing

Internet
Secondary Internet
Local area networks

IaaS: Infrastructure as a Service, e.g., XCP
PaaS: Platform as a Service, e.g., VMware
SaaS: Software as a Service, e.g., SPOON
Network Virtualization

- Network Virtualization is the logical next step after cloud computing.
- Network virtualization provides an *abstraction* layer that decouples physical network devices from business services delivered over the network to create a more agile and efficient infrastructure.
- It allows multiple applications to run side-by-side over the same physical network.
  - Each virtual network has *its own business or service oriented policies* while providing the security, availability and performance required for each service.
- Virtual networks optimize the manageability and control of physical networks that are shared between multiple applications.
  - Thus resulting in a quickly deployable, more reliable service.
- **Enable Agile Business:** Accelerate the roll-out of new services and advanced capabilities through automated multi-vendor provisioning.
Node Virtualization

- **Virtual node** is the virtual version representing the partition of a single physical node or the aggregation of multiple physical nodes (e.g. L3 router, L2 switch or L1/L0 optical cross connects - OXC).
**Virtual link** is a connection (e.g. a cable between a pair of routers, optical light path, wavelength, sub-wavelength) between one port of a virtual network element to a port of another virtual network element.
Virtual Resource Management: EU FP7 EVANS Project

- End-to-end Virtual Resource Management across Heterogeneous Networks and Services (EVANS)

“vertical” resource management and control by network infrastructure providers

“Horizontal” resource management and control by service providers

Mobile operator

Backbone provider (IP)

Backbone provider (Optical/GMPLS)

Mobile operator
NV Issues in Wired Networks

- Mapping and Embedding: static vs. dynamic
- Resource allocation & Scheduling
- Energy Efficiency: putting some nodes or links into sleep mode
Mapping or Embedding – Offline, Static

- One-off mapping done offline,
- e.g., Zhu and Ammar. “Algorithms for Assigning Substrate Network Resources to Virtual Network Components”, Infocom’06

Objective: to achieve load balancing in terms of stress across either:
- Node:
  \[ R_N(t) = \frac{\max_{v \in V_S} S_N(t, v)}{\left[ \sum_{v \in V_S} S_N(t, v) \right] / |V_S|} \]

- Link:
  \[ R_L(t) = \frac{\max_{e \in E_S} S_L(t, e)}{\left[ \sum_{e \in E_S} S_L(t, e) \right] / |E_S|} \]

- Bad assumption: the physical network resources is unlimited.
Yu et al. “Rethinking Virtual Network Embedding: Substrate Support for Path Splitting and Migration”, Sigcomm 08

Assume that the substrate network supports path splitting.

Path optimization (and thus path migration) is carried out at each time slot $t$. 
Resource Allocation & Scheduling

- Static: simple but not efficient; dynamic: more efficient but less stable
- Each substrate link periodically reassigns bandwidth shares between its virtual links.
- Method: to max/min a utility function subject to certain constraints such as link bandwidth.
- Problem: not too much flavour of network virtualization – not like in mapping

\[
\begin{align*}
\text{maximize} & \quad U(x) = \sum_i u_i(x_i) \\
\text{subject to} & \quad Rx \leq C \\
\end{align*}
\]

- Routing matrix or data rate
- Happiness of user \( i \), a function of flow rate
- Link bandwidths
**Issues in Wireless Network**

- Wireless links are totally different from wireline!
- There is no confined link and radio transmission is broadcast in nature.
- Wireless link data rate is varying along many factors such as path loss, LoS (line of sight) or not, surrounding interference, transmission power, modulation and coding mechanisms, link distance, link status, multiplexing techniques, ……
- There is no fixed link budget as in wired networks.
- There is no fixed connectivity. E.g., increasing power can enable a node to reach a node that was previously unreachable!
- Everything is so dynamic and mapping seems to be impossible.

![Diagram showing shadowing, reflection, scattering, and diffraction](image)
What Are People Doing in Wireless NV?

- More experimental than in wireline network.
- Virtualization on ARMS chips
- Virtualization on (Android) nodes – physically virtualize them and may involve OS (e.g., UML: User Mode Linux)
  - A bit more like cloud computing, e.g., using XEN
- Virtualization of WiFi adapter and WiFi Access Point, e.g., Microsoft Virtual-WiFi
- Virtualization of LTE – still on theoretic path-finding and no real system out there yet
- Link virtualization is largely based on the traditional x division multiplexing access technologies, such as SDMA, TDMA, FDMA, OFDMA
What is Essex Doing in Wireless NV?

- Some experimental work to start with: AP slitting using MS VirtualWiFi
One PC Connected to Two WiFi APs

Network Connection Window

Wireless Connection Window
No Performance Gain After Virtualization

Throughput of one physical WiFi card

Throughput of two Virtual WiFi cards at 1Mbps
An Elastic Resource Allocation Algorithm for Wireless Network Virtualization

With Dr. Xiaofeng LU of XDU
Network Scenario

VoD: Video on Demand
MNO: Mobile Network Operator
WiMAX Network Virtualization

VMN #3: Foreign
VMN #2: Foreign
VMN #1: Local

Virtualization
Virtualization

One Physical Wireless Network
Design Goals

- Isolation: to ensure isolation of network resources across slices, meaning:
  - Passive mode: any change in one slice due to new users joining in, mobility of users, fluctuating channel conditions, etc., should not lead to reduction in resource allocation for other slices.
  - Active mode: slices should be able to choose their own resource allocation, scheduling, QoS mechanisms – sometimes also called customization, or elasticity as called in cloud computing.

- Resource efficiency: especially in the wireless domain, network operators often attempt to maximize their revenue by keeping the scarce wireless channels occupied as much as possible. Resources in terms of:
  - Time, Frequency, Code
  - Power: energy efficiency
Some OFDMA Terms

- 3G is CMDA; OFDMA is for 4G LTE.
- Slice: a section of the wireless links, in the form of a bundle of wireless channels; Virtual MNO is a slice owner.
- User: a mobile node, can have multiple flows (e.g., video, voice, data at the same time)
- Flow: an independent stream of data of certain characteristics. E.g., a video stream or a ftp session is a flow
- Channel: a physical wireless media, also called carrier
- Sub-channel is called symbol in OFDMA terms
- Sub-carrier, block,
- Frame and sub-frame
WiMAX/OFDMA Frames

- Downlink Subframe
- Adaptive
- Uplink Subframe
- Frame start preamble
- DL-MAP
- UL-MAP
- DL Data
- UL Data
- Channel Gain vs. Subcarrier
- Frequency vs. Time
- DL SubFrame
- UL SubFrame
- WiMax Resource Blocks
Problem Statement

Assumptions:

- Each VMNO submits a rate \( r_{Si} \) defining the maximum data rate it needs from the MNO. This is a natural requirement in practice but rarely considered in the literature.

- Any traffic exceeding this upper limit from this VMNO will not be satisfied but any traffic within this limit will be charged on a pay-as-you-use basis – and thus the corresponding resource allocation mechanisms should be in place to enable this business model.

- This work considers only uplink which is more difficult than the broadcast downlink.

To allocate sub-carriers on a per-flow per-slice basis while minimizing the number of sub-carriers used.
MAC Scheme
Block Diagram of a Multi-Slice Multi-flow OFDMA Transmitter
Resource Allocation Problem Illustration

Current focus

Next Step
<table>
<thead>
<tr>
<th>$r_{S_i}$</th>
<th>Data rate requested by slice $S_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{REQ-REAL}^{f,S_i}$</td>
<td>Real data rate requirement from flow $f$ of slice $S_i$</td>
</tr>
<tr>
<td>$r_{REQ-ALG}^{f,S_i}$</td>
<td>The data rate the algorithm can allocate to flow $f$ of slice $S_i$</td>
</tr>
<tr>
<td>$I_{f,c}$</td>
<td>Assignment index indicating flow $f$ being allocated to subcarrier $c$</td>
</tr>
<tr>
<td>$P_{f,c}$</td>
<td>Power allocated to flow $f$ in subcarrier $c$</td>
</tr>
<tr>
<td>$h_{f,c}$</td>
<td>Channel gain of flow $f$ in subcarrier $c$</td>
</tr>
<tr>
<td>$BER_{f,c}^{target}$</td>
<td>Target BER of flow $f$ in subcarrier $c$</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Total bandwidth of the system</td>
</tr>
<tr>
<td>$P_T$</td>
<td>Total transmission power of the system</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Noise power spectral density</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of subcarriers</td>
</tr>
<tr>
<td>$M$</td>
<td>Number of foreign slices</td>
</tr>
<tr>
<td>$A$</td>
<td>Universal set of system Subcarriers</td>
</tr>
<tr>
<td>$B$</td>
<td>The set of subcarriers that are allocated to local network flows</td>
</tr>
</tbody>
</table>

**Some Notations**
Assume that identical power is allocated to each subcarrier and M-ary quadrature amplitude modulation (MQAM) is employed. The BER for an AWGN channel is given by:

\[
BER_{f,c} \approx 0.2 \exp \left( -\frac{1.5P_{f,c}h_{f,c}^2}{(2^{r_{f,c}} - 1)N_0 \frac{\Phi}{N}} \right)
\]

Then the maximum data rate of flow \( f \) in subcarrier \( c \) is:

\[
 r_{f,c} = \text{floor} \left( \log_2 \left( 1 - \frac{1.5P_{f,c}h_{f,c}^2}{\ln(5BER_{f,c}^{target})N_0 \frac{\Phi}{N}} \right) \right)
\]
Two Types of Slices

- There are two types of slices in the network:
  1. local slice, denoted as Slice 0, which is used by the local traffic that is initially generated towards this physical network;
  2. foreign slices, denoted as Slice 1 to \( M \), which serve traffic flows from VMNOs.

- Since the requirements of VMNOs need to be guaranteed, the resources (i.e., subcarriers) are firstly allocated to Slice 1 to \( M \) efficiently.
  - Careful admission control is needed but not covered in this work.
Resource Allocation to Foreign Slices

The general form of the subcarrier allocation to Slices 1 to \( M \) can be described as the following optimization problem:

\[
\min \sum_{f \in S_i} \sum_{c \in A} I_{f,c} \quad \text{To use as small number of the subcarriers as possible.}
\]

s. t.

AC1: \( \sum_{f \in S_i} I_{f,c} \leq 1 \quad \text{One carrier can only be allocated to one flow or to no flow.} \)

AC2: \( I_{f,c} = \{0,1\} \)

AC3: \( r_{f,S_i}^{AL} \geq r_{f,S_i}^{REQ-ALG} \)

AC4: \[
\begin{aligned}
r_{f,S_i}^{AL} &= \sum_{f \in S_i} \sum_{c \in A} I_{f,c} \cdot \text{floor}\left( \log_2 \left( 1 - \frac{1.5 P_{fc} h_{f,c}^2}{\ln(5 BER_{f,c}^{\text{target}}) N_0} \frac{\Phi}{N} \right) \right) \\
&= \sum_{f \in S_i} \sum_{c \in A} I_{f,c} r_{f,c}
\end{aligned}
\]
Office Assignment Problem

The above optimization problem is suitable to be converted to Office Assignment Problem (OAP), and use a linear programming (LP)-based branch-and-bound algorithm to solve the problem.

\[
\min q_c^T x
\]

s. t.

\[
A_{eq} x = b_{eq}
\]

\[
A_{neq} x \leq b_{neq}
\]

\[
x_i = \{0, 1\}, \quad x = [x_1, \ldots, x_i, \ldots, x_n]
\]

1. Initialization:
2. Set \( A = \{C_1, \ldots, C_N\} \), \( P_{f,c} = P_r / N \), \( I_{f,c} = 0 \), \( A_{eq} = [] \), \( b_{eq} = [] \)
3. Create optimization coefficients:
4. for all \( f \in S_t, c \in A \)
5. \( (x)_j = I_{f,c} \)
6. \( (q_c)_j = 1 \)
7. \( r_{f,c} = \text{floor}\left\{ \log_2 \left( 1 - \frac{1.5 P_{f,c} h^2_{f,c}}{\ln(5BER_{\text{target}}) N_o \Phi N} \right) \right\} \)
8. end for
9. for all \( f \in S_t \)
10. \( A_{neq}(i,:) \), \( b_{neq}(i,:) \) = the constraint of (AC1)
11. \( A_{neq}(M+i,:) \), \( b_{neq}(M+i,:) \) = the constraint of (AC3)
12. end for
13. Solve OAP to get \( I_{f,c} \)
Resource Allocation to Local Slice

\[
\begin{align*}
\text{max} & \quad \sum_f r_{f,S_0}^{AL} \\
\text{s. t.} & \\
\text{BC1:} & \quad r_{f,S_i}^{AL} = \sum_{f \in S_i} \sum_{c \in B} I_{f,c} \text{floor} \left( \log_2 \left( 1 - \frac{1.5 P_{f,c} h_{f,c}^2}{\ln(5 \text{BER}_{f,c}^{\text{target}}) N_0 \frac{\Phi}{N}} \right) \right) \\
& \quad = \sum_{f \in S_i} \sum_{c \in B} I_{f,c} r_{f,c} \\
\text{BC2:} & \quad \sum_{f \in S_i} I_{f,c} = 1 \\
\text{BC3:} & \quad I_{f,c} = \{0, 1\}
\end{align*}
\]

• to maximize its throughput.  
• And there is no rate requirement and only BER constraint is considered  
• can use OAP to solve the problem.
1. Initialization:
2. Set \( P_{f,c} = P_T / N \), \( I_{f,c} = 0 \), \( A_{neq} = [ ] \), \( b_{neq} = [ ] \)
3. Create optimization coefficients:
4. for all \( f \in S_i, c \in B \)
5. \( (x)_j = I_{f,c} \)
6. \( r_{f,c} = \text{floor} \left( \log_2 \left( 1 - \frac{1.5 P_{f,c} h_{f,c}^2}{\ln(5BER_{f,c}^{\text{target}}) N_0 \Phi} \right) \right) \)
7. \( (q_c)_j = r_{f,c} \)
8. end for
9. for all \( f \in S_i \)
10. \( A_{eq}(i,:) \), \( b_{eq}(i,:) \) = the constraint of (BC2)
11. end for
12. Solve OAP to get \( I_{f,c} \)
Input: \( M, r_s, r_{req\text{-}real} \)

1. for \( i = 1 \) to \( M \) \( // \) foreign slice

2. if \( \sum_{f \in S_i} r_{f,S_i}^{req\text{-}real} \leq r_{S_i} \), then

3. \( r_{f,S_i}^{req\text{-}alg} = r_{f,S_i}^{req\text{-}real} \)

4. else

5. \( r_{f,S_i}^{req\text{-}alg} = \frac{r_{f,S_i}^{req\text{-}real}}{\sum_{f \in S_i} r_{f,S_i}^{req\text{-}real}} r_{S_i} \)

6. end for

7. Choose \( \{S_i\}, i = 1 \cdots M \) \( // \) foreign slices

8. Call ALG #1

9. Set \( B = \left\{ C_l \left| \sum_{f \in A} I_{f,l} = 0 \right. \right\} \)

10. Choose \( \{S_i\}, i = 0 \) \( // \) local slice

11. Call ALG #2
Future Thoughts: Resource Allocation

- How to combine resource allocation/scheduling with mapping, e.g.,
  - How to change power to enable otherwise impossible mapping on one hand; and how to carry out proper mapping in order to save power on the other hand
  - How to use control theory to model this interactive system
  - Cross-layer design (CLD)
  - ...

Diagram:
- Virtual Resource Pool
- Physical Network Resource
- Dynamic Resource Allocation
- Mapping/Embedding
Future Thought: Node Virtualization

- Not possible to use commercial product
- To use USRP (Universal Software Radio Peripheral) so as to:
  - Introduce two different protocol stacks -> isolation
  - Design different MAC mechanisms in terms of resource allocation and scheduling, etc -> elasticity, resource efficiency, energy efficiency
  - Even have different RF fronts (e.g., both WiFi and WiMAX and LTE)! Or even turn a WiFi AP into a WiMAX base station – too elastic?
  - Ettus Ltd. – bought by NI
Agenda

- Motivation: why FIA?
- Network Virtualization
- Post-IP Future Internet Architecture: Information Centric Networking
- Converged Network & Service Test-bed
- Q&A
ICN: Information Centric Networking

■ IP may be “the” problem! Get rid of IP so called post IP or beyond IP.

■ ICN: Information Centric Networking
  ▪ CCN: Content Centric Networks by Van Jacobsen

■ EU FP7 Project PURSUIT (Publish-Subscribe Internet Technology)
  ▪ It is information rather than machine (or IP) that is named and addressed.
  ▪ U. of Essex is a partner of the PURSUIT Consortium.
Some Features of ICN

- **Source routing:**
  - source nodes, rather than intermediate nodes (routers), to decide the route
  - *(ref. DSR – Dynamic Source Routing in Wireless Sensor Networks)*

- **Publish-subscribe:**
  - At network layer, not application layer (like P2P)
  - Inherently content centric;
  - Natural to some applications
  - Seems to solve some current problems, especially the power of senders over receivers
A Post-IP System Architecture – PURSUIT View

- **Rendezvous**: matching pub and sub
- **Topology Manager (TM)**: topology knowledge, path (or delivery tree) calculation
- **Forwarding**: store and forward, fast delivery (separation of control and data plane), using Bloom Filter (next slide)
- **More**: in-network caching, security, scoping, naming, …
Creation of Forwarding ID

Links are named with Link-IDs

not the nodes!

Each link has two identifiers (Link-ID)

Each Link-ID is a m-bit name where only k bits are set to 1 with k<<m

\[
\begin{align*}
\text{Example} & : \\ k=5 & \\ m=248 & \\ n. \ of \ links &= \frac{m!}{(m-k)!} \approx 9 \times 10^{11}
\end{align*}
\]

The multicast route

The whole multicast route is encoded in the Bloom filter called z-filter and it is written in the packet header.
When a packet reaches a node the z-filter $ZF$ is **ANDed** with the Link-ID of all the outgoing links of the node.

The packet is forwarded through the link if:

$$ZF \text{ AND } \text{Link-ID} = \text{Link-ID}$$

This kind of routing is completely **STATELESS**. It is source routing based where forwarding and routing are independent.

<table>
<thead>
<tr>
<th>Interface</th>
<th>Link</th>
<th>Link-ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1in</td>
<td>AB</td>
<td>10010000000001</td>
</tr>
<tr>
<td>B1out</td>
<td>BA</td>
<td>00100001000001</td>
</tr>
<tr>
<td>B2in</td>
<td>ZB</td>
<td>00000000010101</td>
</tr>
<tr>
<td>B2out</td>
<td>BZ</td>
<td>10000000001001</td>
</tr>
<tr>
<td>B3in</td>
<td>CB</td>
<td>10001100000000</td>
</tr>
<tr>
<td>B3out</td>
<td>BC</td>
<td>10000000010001</td>
</tr>
</tbody>
</table>

In each node the forwarding table contains only the Link-ID of the links connecting that node.
A Setup Example

1080p HD Camera (3Gbit/s) 1080p HD Monitors (3Gbit/s)

Ethernet (270Mbit/s)

Emulators generate background pub/subs and data traffic

Publish/subscribe messages
Link ID (P, S1, S2), Metadata

Rendez-vous Point (RVP)

Topology Manager
Multi-layer delivery tree computation

GUI

Video Adaptor (HD to SD Dirac CODEC + Ethernet encapsulation)

BA Blackadder (Forwarding ID Encapsulation)

EN Forwarding Nodes (based on FID)

Application layer
FID encapsulation

Electrical layer
Electrical forwarding based on FID
(currently Blackadder)

Optical layer
Optically switched wavelengths

Control layer
Signalling between nodes and TM to optical/electrical switches
(currently IP based)

Optical nodes (optical wavelength switches)

Topology Manager (out-of-band signalling) – using \( \lambda_c \)

Pub/sub emulators. Create random or pre-defined pub/sub requests with subsequent data plane traffic
Network Resiliency - 1

Information Graph

Movie X

Pub₁ deliver to Sub on Path₁

Pub₁ deliver to Sub on Path₁

ON₁ ON₂ ON₃

FW FW FW FW

TM/RV

Pub₂ Pub₁
Network Resiliency - 2

Information Graph

Pub₁ deliver to Sub on Path₂

Pub₂
FW

TM/RV
FW

Sub
FW

Pub₁
FW

Path₁

ON₁

ON₂

ON₃

Path₂

Movie X
Information Resiliency

Pub₂ FW

Pub₁ disconnected
Pub₂ deliver to Sub

TM/RV

FW

FW

FW

Sub

Path₁

Path₂

ON₁

ON₂

ON₃

Movie X
How to Proceed?

- Simulator: developed by Essex NCL
  - Open source, on top of OMNet++
  - [https://sourceforge.net/projects/pubsubsim/](https://sourceforge.net/projects/pubsubsim/)
  - Major functions: pub-sub, bloom filter, path calculation, packet forwarding, etc.

- Experiments: Blackadder from PURSUIT (by Cambridge)
  - Open source
  - Link: upon request
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Converged Network Testbed @ NCL

Essex University

Campus Perimeter (<10km)
Campus Outskirts
Central Campus

3G/3.5G/LTE

WiMAX

100+ WiFi APs

Quays

Isolated WiFi hot-spots
Sports Grounds
Car Parks

Traffic Generator

Fibre (2km)

Optical Splitters

ONU
Traffic Generator

Optical 10/40Gbits/s

Heterogeneous Access Technologies (Wired and Wireless)

Radio over fibre network

Traffic Generators
Access Network Emulator

Optical 10/40Gbits/s

Multi-Services Access Node

Introduction of packet delay & jitter

Ethernet

NG-SDH

WDM

Introduction of optical impairments

Multi-Layer Switching Nodes (Circuit and Packet-Switched)

Public IP

Converged Network and Service Management

Cambridge University

Storage

Video

>50 LAN Clients

Fast Optical Switching

Multi-Services Access Node

Voice

Video (IPTV/VoD)

Storage

Cloud

Campus Network

BT

MIT

THU

Internet

planetLab
Bertrand Russell Tower (65m)

**WiMAX/WiFi Network**

- Pan/tilt 60° sector antennas (2.5, 3.5 & 5.8GHz)
- Fixed 60° sector antenna (5.8GHz) towards Wivenhoe
- Dome surveillance camera
- Camera and antenna GPS coordinate controlled

- Wivenhoe subscriber unit (2mile)
- 20Mbit/s symmetrical services

- WiMAX to Wi-Fi units
- WiFi hotspots
- WiMAX connected cameras for excellent wireless quality

WiMAX antenna

WiFi antenna (100m radius)

Wivenhoe
High Performance Media Networks

Audio Multichannel System

Audio mixer
Loudspeakers

4K Video over Wireless (IEEE 802.11ac)

4K cinematographic camera

4K stereo camera system

2K high-speed camera

Network infrastructure

Uncompressed signal

Uncompressed signal

100 TB NAS storage

3D 4K Projector

4K LCD Display

8K tiled display

video server
Contact, Q&A

Thanks for your attentions!

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