Leveraging Virtualization Technologies to Build the World’s First Open Programmable Smart City

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‘Bristol Is Open’ Programmable City

Digital city testbed where an SDN-based **Network Operating System (City OS)** controls a programmable city infrastructure
A Test-bed for Diverse Requirements

Users

Applications

| Media | Transport | eHealth | ... |

Services

| Clouds | IMS | Service Delivery Platforms | ... |

Infrastructures

| Wireless / Sensors | Fixed/ Wired | Compute/ Storage | Peripherals/ Device |

Demand

Enabling Technology
Bristol Is Open (BIO)

• We built a research network integrating optical, wireless, IoT and computing to provide an open and experimental platform in the centre of Bristol

• We offer the test-bed as utility for experimentation: City Experimentation as a Service

• It supports City-driven digital innovation

• Three main technology pilars:
  • Technology agnostic
  • SDN
  • Hardware programmability
An Open Infrastructure for Innovation

Manage a diverse “Network-of-Networks”
Optical, packet wired, wireless, compute, storage, IoT, cameras, etc
Multi-Technology Support

Eliminate Vendors Lock-ins
Abstractions of the underlying hardware, SDN Control
Technology Agnostic-Future Proof-White Box?

Multi-Tenant Solution
Network to share resources among many users (Virtualization)
Efficient utilization & monetization

 Courtesy Zeetta Networks
Develop a **NETWORK TECHNOLOGY USB** which will enable any network device to be pluggable, discoverable, describable, interoperable and programmable in the network.
Add outdoor LiFi
Anna, 09-Sep-14
The Infrastructure
The “Bristol Is Open” Network

Optical Network
- 144-fiber core network connecting 4 nodes

Wireless Network
- 1Gbps access network
- Wi-Fi, LTE, LTE-A, 60Ghz, Massive MIMO

IoT Network
- 54 Fiber-connected lamppost
- Clusters & canopy of 1500 sensors

Cloud Infrastructure
- HPC and commodity compute and storage centralised & edge
A New Way to Think About Network Control
Software Defined Networking

Orchestrator

SDN Controller and Virtualisation

Network Technologies

Applications

Compute

Storage

Hypervisor

Controller

SDN Controller and Virtualisation

Network Technologies

University of BRISTOL
City Operating System (CityOS)
Extended OpenFlow Protocol
Resource Model
Technology specific interface

SDN Controller
OpenFlow Agent

Li-Fi  802.11ac  Flex-grid ROADM  WDM ROADM  Space Switch  LTE
Multi-dimension Resource Abstraction Mechanism

1. **Input Matrix**
   - \( \lambda_1 \ldots \lambda_{160} \)
   - 4 \times 3 \times \ldots \times = 3 \times 2 \ldots \times
   - 2 \times 3 \ldots \times
   - 1 \times 2 \ldots \times

2. **Output Matrix**
   - \( \lambda_1 \ldots \lambda_{160} \)
   - 3 \times 2 \ldots \times
   - 4 \times 3 \ldots \times
   - 6 \times 4 \ldots \times

3. **Optical Switching Element**
   - \( \lambda_1, \lambda_2, \lambda_3 \)

4. **Wireless Access Point or ENodeB**

5. **Resources Allocation**

6. **Frequency Allocation**

7. **Time**

\[ \begin{align*}
\text{Flow 1} & : 0 & 25 & 55 & 0 \\
\text{Flow 2} & : 0 & 30 & 0 & 50 \\
\text{Flow 3} & : 0 & 35 & 0 & 0 \\
\text{Flow 4} & : 0 & 40 & 0 & 0 \\
\end{align*} \]
## Multi-dimension Resource Abstraction Mechanism

### Multi-Dimensional Optical Flow

<table>
<thead>
<tr>
<th>Port</th>
<th>Lambda/ Centre Frequency</th>
<th>Bandwidth</th>
<th>Signal Type</th>
<th>Constraints</th>
</tr>
</thead>
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<tr>
<td>Fibre</td>
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<td>Option</td>
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</tr>
</tbody>
</table>

**Abstraction**

- Li-Fi
- 802.11ac
- Flex-grid ROADM
- WDM ROADM
- Space Switch
- LTE

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[University of Bristol Logo]
Network Infrastructure Virtualisation

Virtual Infrastructure Control & Management

Virtual Infrastructure Composition Layer

Virtual Infrastructure 1

Virtual Infrastructure n

SDN

Abstraction Layer

Abstracted Resource Pool

Physical infrastructure Layer (Opt. Net. + DC)

Optical Network

Data Centre

Physical Infrastructure

Access Point

Users
We can define network ‘slices’ by any combination of:
- Switch ports
- Wavelengths
- Spectrum (layer 0/1)
- Ethernet address or type (layer 2)
- IP address or type (layer 3)
- TCP/UDP port or ICMP code (layer 4)

Physical Layer impairments are taken into account before network ‘slicing’. The network ‘slices’ have guaranteed Quality of Transmission (QoT).

Many Virtual Networks (‘slices’) can coexist. They are isolated and can be controlled and operated individually.
Physical Layer Impairment Assessment

A. Analytical PLI Assessment Model for SLR Networks

In the PLI assessment model for SLR networks \cite{10}, the linear impairment amplified spontaneous emission (ASE) and the nonlinear impairment XPM and four wave mixing (FWM) are considered.

The $Q$ factor \cite{18} is given as follows:

$$Q = 10 \log \left( \frac{P_{in}}{\sqrt{\sigma_{\text{ASE}}^2 + \sigma_{\text{XPM}}^2 + \sigma_{\text{FWM}}^2}} \right). \quad (5)$$

where $P_{in}$ is the input power of a wavelength channel, $\sigma_{\text{ASE}}^2$ represents the ASE noise, and $\sigma_{\text{XPM}}^2$ and $\sigma_{\text{FWM}}^2$ represent XPM and FWM impairments, respectively.

The ASE is generated from the optical amplifier and modeled as:

$$\sigma_{\text{ASE}}^2 = \Phi hB_0 (G-1)B_0. \quad (6)$$

where $\Phi$ is the erbium-doped fiber amplifier (EDFA) noise figure, $h$ is Planck’s constant, $f_i$ and $B_0$ are the carrier frequency and the optical bandwidth of the probe channel, respectively, and $G$ is the EDFA optical gain.

XPM is modeled as:

$$\sigma_{\text{XPM}}^2 = \frac{1}{2} \sum_{j \neq i} \int_{-\infty}^{\infty} |H_i(w)^2|PSD_j(w)\text{d}w. \quad (7)$$

where $H_i(w)$ is the XPM transfer function of the pump channel $j$, and PSD$_j(w)$ is the power spectrum of the channel $j$. $c$ is the speed of light, $N$ is the number of spans, $\alpha$ is the attenuation parameter, $D$ is the dispersion parameter, and each span is fully compensated.

FWM is modeled as:

$$\sigma_{\text{FWM}}^2 = \sum_{i \neq f \neq N} P_i P_j P_k \left[ \pi D(1 + e^{-\alpha_0} - 2e^{-\alpha_0}\cos(kNl)) \right], \quad (9)$$

$$k = \frac{2\pi^2 (f_1 - f_i)(f_1 - f_j)2\pi D - \pi^2 S(f_1 + f_j - 2f_i)}{2e^2}. \quad (10)$$

B. Analytical PLI Assessment Model for MLR Networks

Three modulation formats are adopted for different bitrates: 10 Gbps non-return-to-zero on-off keying (NRZ-OOK) with direct detection, 40 Gbps differential quadrature phase shift keying (DQPSK) with differential detection, and 100 Gbps dual-polarization quadrature phase shift keying (DP-QPSK) with coherent detection, in order to increase the reach of high bitrate channels \cite{19}.

Based on Gaussian approximation, the bit error rate (BER) \cite{21} is approximated as:

$$\text{BER} = \frac{1}{Q} \exp \left( \frac{-Q^2}{2} \right). \quad (11)$$

The $Q$ factor for NRZ-OOK \cite{21} is given as:

$$Q = \sqrt{2B_0 T + \sqrt{B_0 T + 4\rho^2}}, \quad (12)$$

where $B_0$ is the optical filter bandwidth and $T$ is the symbol time. $\rho$ is the signal-to-noise ratio (SNR) per symbol.

$$\rho = \frac{nB_0 TP_{in}}{F + h\nu \Delta f TN}. \quad (13)$$

where $n$ is the ratio between the number of noise and signal polarizations, $B_{\text{ref}}$ is the reference bandwidth that measures the optical SNR, $\nu$ is the carrier frequency, $\Delta f$ is the bandwidth that measures $F$, and $\gamma$ is the span loss. The $Q$ factor for DQPSK and DP-QPSK \cite{19} is given as:

$$Q = \frac{\pi}{4} \left( k + \frac{2\nu \sigma_{\text{SNL}}^2}{c} \right) \left( \sin \left( \frac{\pi}{4} \sqrt{k + 2\nu \sigma_{\text{SNL}}^2} \right) \right)^2 + \sigma_{\text{SNL}}^2 \right)^{-1/2}. \quad (14)$$

where the variance of nonlinear phase noise $\sigma_{\text{SNL}}^2 = \sigma_{\text{SPM}}^2 + \sigma_{\text{XPM}}^2$, including SPM $\sigma_{\text{SPM}}^2$ and XPM $\sigma_{\text{XPM}}^2$.

For SPM,

$$\sigma_{\text{SPM}}^2 = m\phi_{NL}^2/\beta_p. \quad (15)$$

where $\phi_{NL}$ is the nonlinear phase shift,

$$\phi_{NL} = \frac{2\pi}{\Delta} \left( P_{in} L_{\text{eff}} N \frac{n_2}{A_{\text{eff}}} \right). \quad (16)$$

where $L_{\text{eff}}$ is the effective length \cite{22}, $n_2$ is nonlinear index coefficient, and $A_{\text{eff}}$ is effective area.
Fully Programmable Network Fabric

Back Plane (192 × 192 Polatis)

ToR1 (FPGA)

ToR2 (FPGA)

ToR3 (FPGA)

Agent

OPS

Extended modules

SDN Controller

Application

REST

Forwarding Rules Manager

Topology Manager

Service Abstraction Layer

Plugin

OF lib with proposed extension

Extended modules

Raw socket

Raw socket

extended OF msg.
City Experimentation As a Service

Virtual City Control & Management

City Slice

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City Slice
What is on offer?

- First SDN-based solutions for Smart Cities & Smart Venues
- New applications
  - User
  - Administrator
- Showcases at Bristol as leading innovator in smart environment technologies
- Access to SDN & Network Virtualization expertise
- Opportunity to commercially exploit the solutions through an ecosystem of encouraging and supporting technology SMEs/spin-outs
Thank you for your attention!

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