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Energy Efficient Content Distribution Optical Networks

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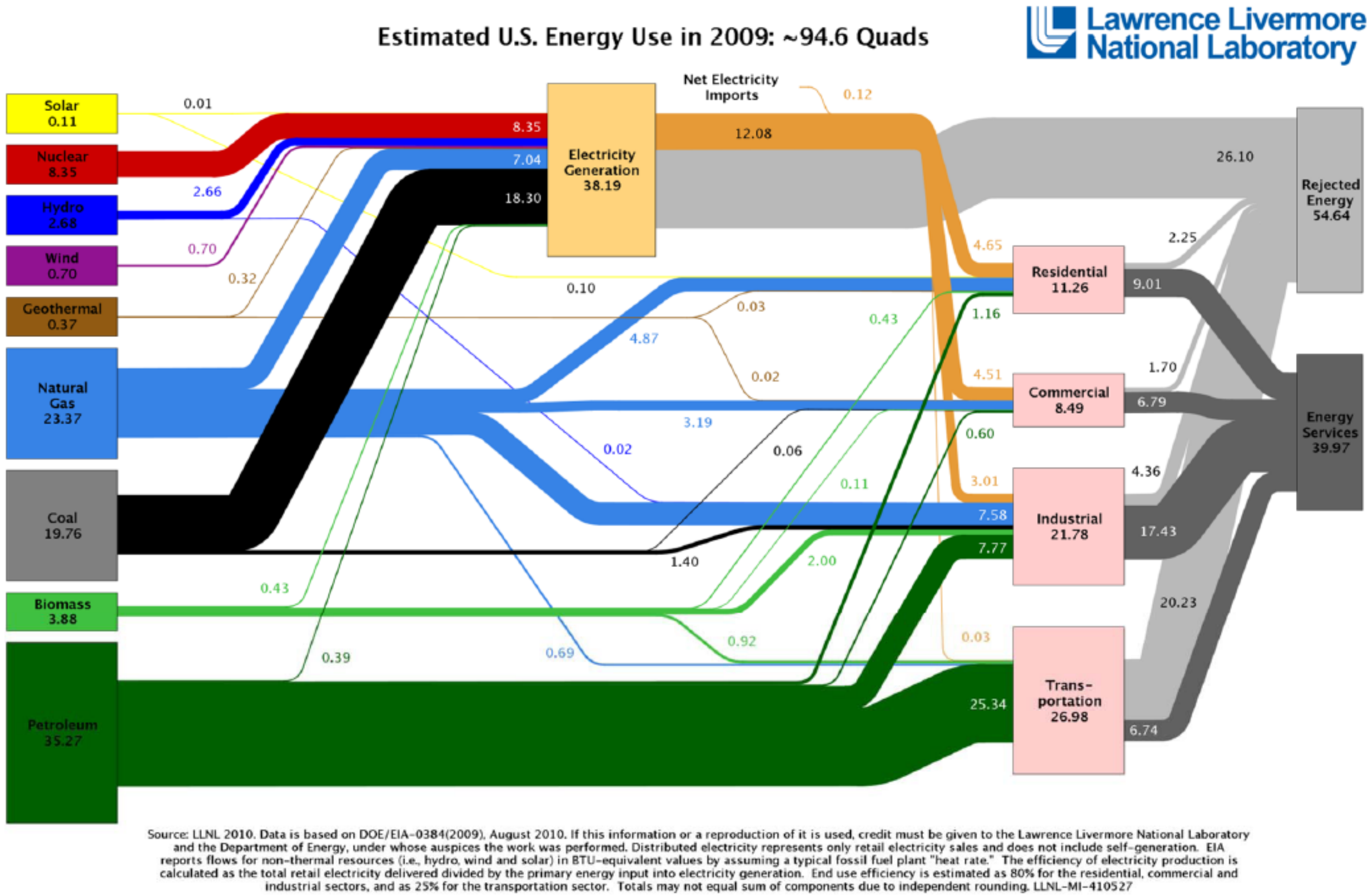
Outline

- Introduction, energy efficiency and traffic trends
- Caching and IPTV / VoD networks
- Peer-to-peer energy efficient networks
- Distributed Energy Efficient Clouds
- Future directions

Energy Supply and Consumption: Most Energy is Lost

Supply

Consumption

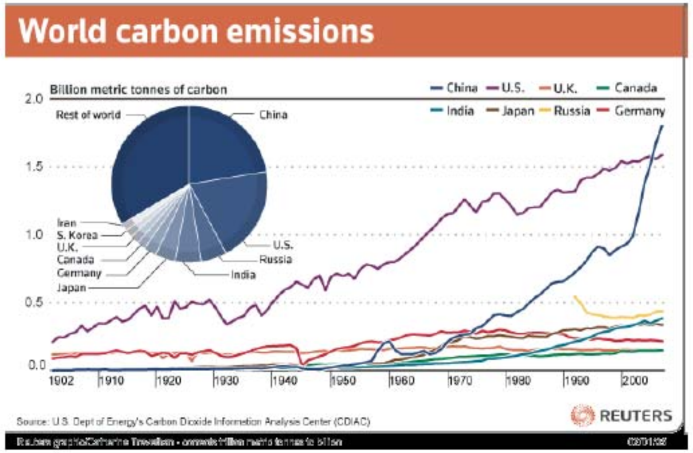


Most Energy is Lost!

Quads (10^{15} BTUs)

- The case for better use of energy

World wide ICT Carbon footprint



Country	Network	Energy Consumption	% of Country Total Energy Consumption
USA	Verizon 2006[1]	8.9 TWh	0.24%
Japan	NTT 2001[2]	6.6 TWh	0.7%
Italy	Telecom Italia 2005[3]	2 TWh	1%
France	France Telecom-Orange 2006[4]	2 TWh	0.4%
Spain	Telefonica 2006[5]	1.42 TWh	0.6%

S.Roy, IEEE Intelec 2008

Smart Grids

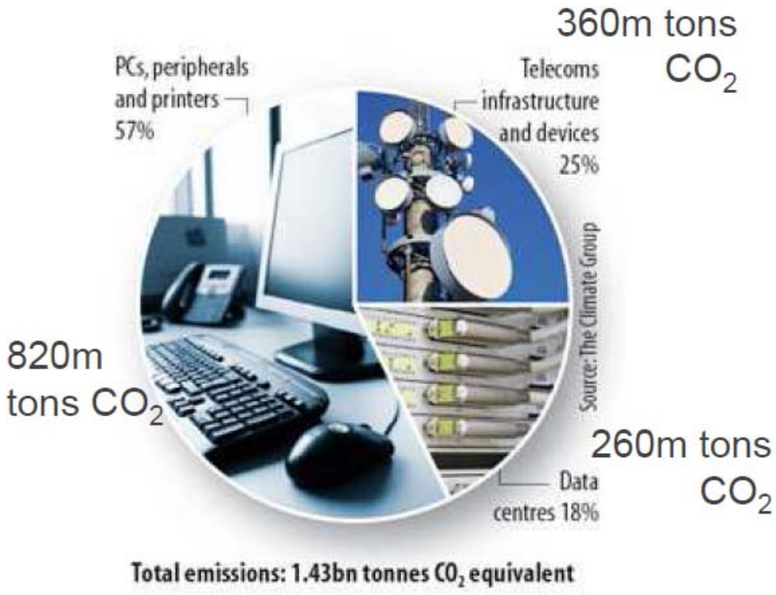
Smart Transportation

Smart Communities

Enabling a Low Carbon Economy

Smart Buildings

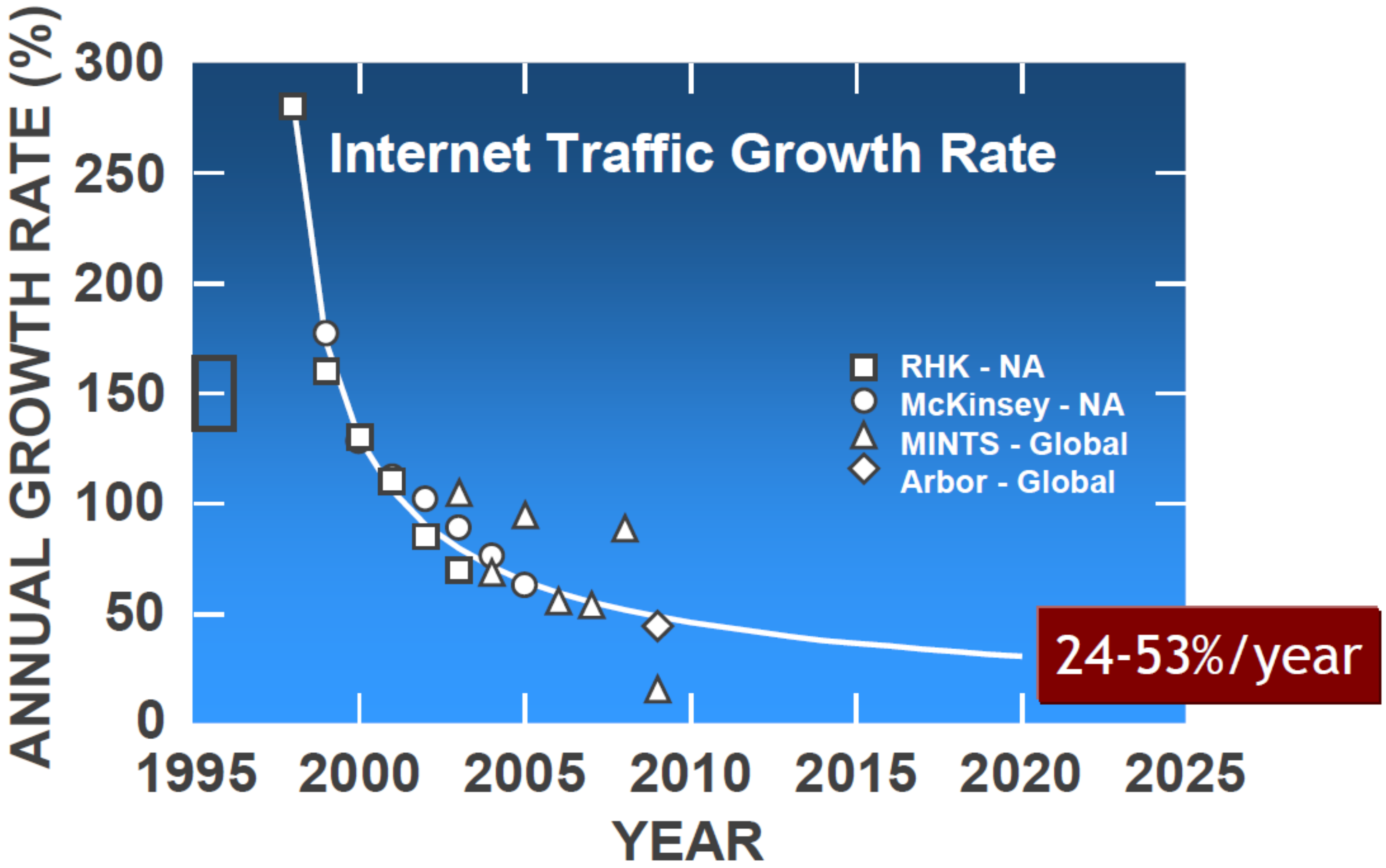
E-Health



- 2007 Worldwide ICT carbon footprint: 2% = 830 m tons CO_2
- Comparable to the global aviation industry
- Expected to grow to 4% by 2020

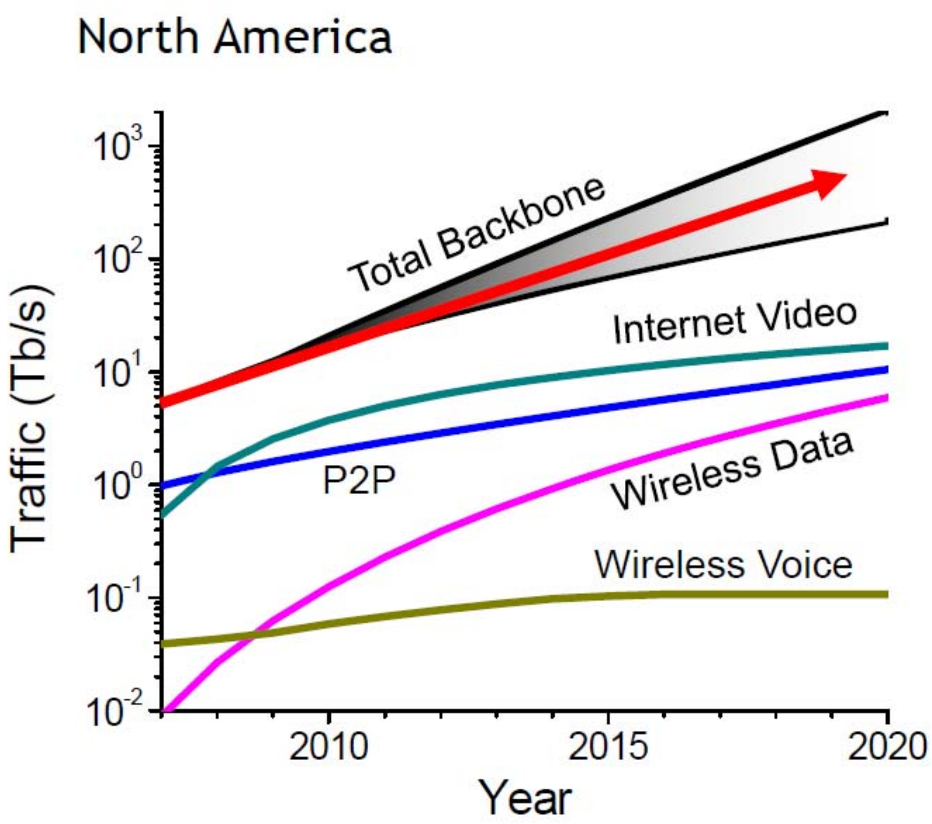
- Courtesy Thierry Klein, Alcatel-Lucent Bell Labs

Internet Traffic Growth Rate



- Courtesy Thierry Klein, Alcatel-Lucent Bell Labs, Sources: RHK, 2004; McKinsey, JPMorgan, AT&T, 2001; MINTS, 2009; Arbor, 2009

Exponential traffic growth



Doubling every 2 years

- 40% per year
- 30x in 10 years
- 1000x in 20 years

Mix of services is important from energy perspective:

- Mobile less efficient than fiber optics

Data from: RHK, McKinsey-JPMorgan, AT&T, MINTS, Arbor, ALU, and
Bell Labs Analysis: Linear regression on log(traffic growth rate) versus log(time) with Bayesian learning to compute uncertainty

INTelligent Energy awaRe NETworks (INTERNET) Project Goals

- The INTERNET project seeks to develop
  - New and disruptive energy efficient network architectures which are optimised for sustainable energy requirements, and are validated using national and pan-European and international models,
  - New protocols and communications techniques to support adaption within such a system, and
  - Novel hardware with low energy production and operating requirements.
- EPSRC funded, £5.9m, 2010-2015.

Collaborators

AVAGO TECHNOLOGIES

BBC

BT

BROADCOM. Connecting everything

CISCO

ERICSSON TAKING YOU FORWARD

oclaro

SOLARFLARE Communications

Connecting New Zealanders Telecom

BOEING

Alcatel·Lucent

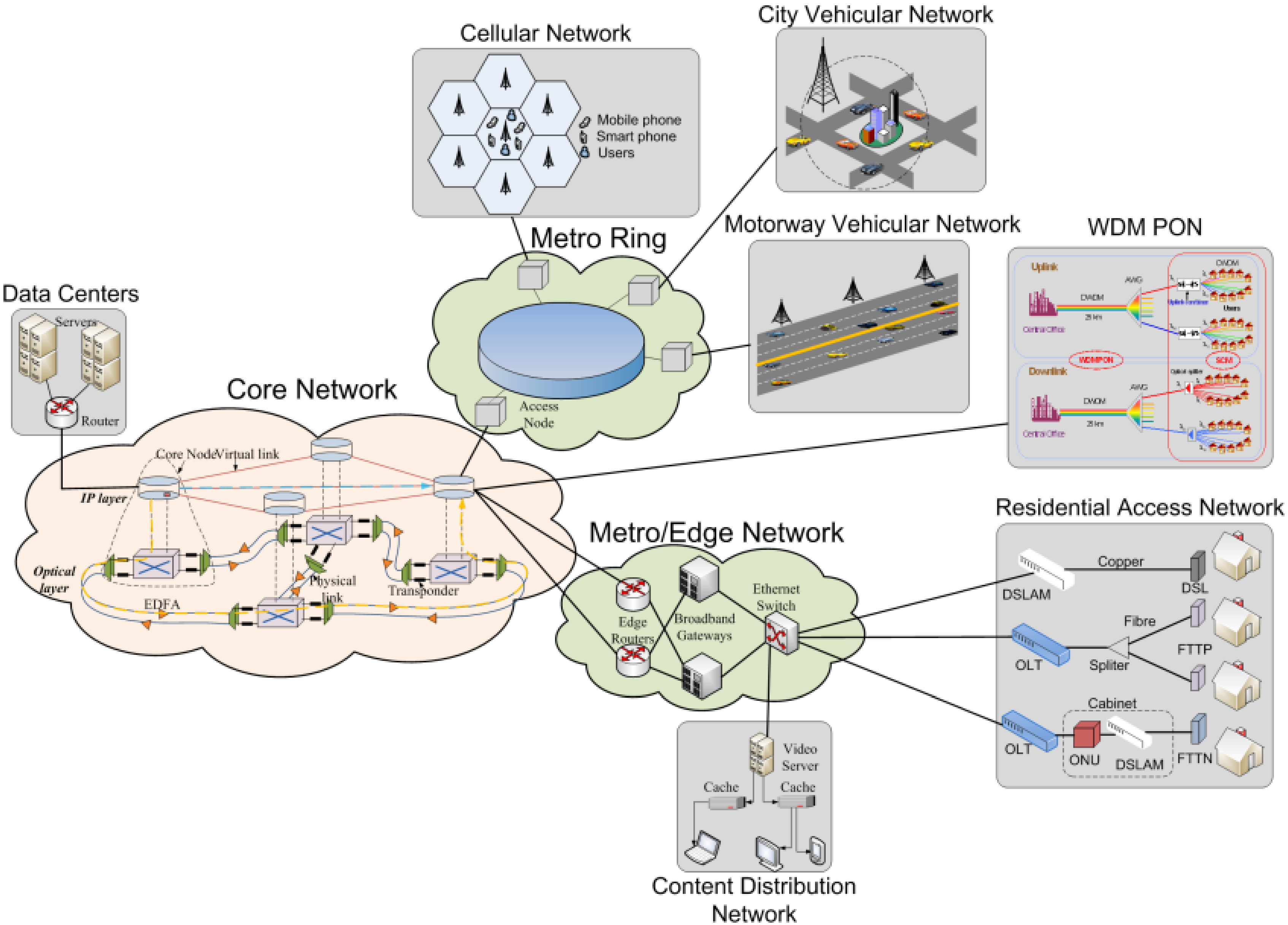
GreenTouch

O_2

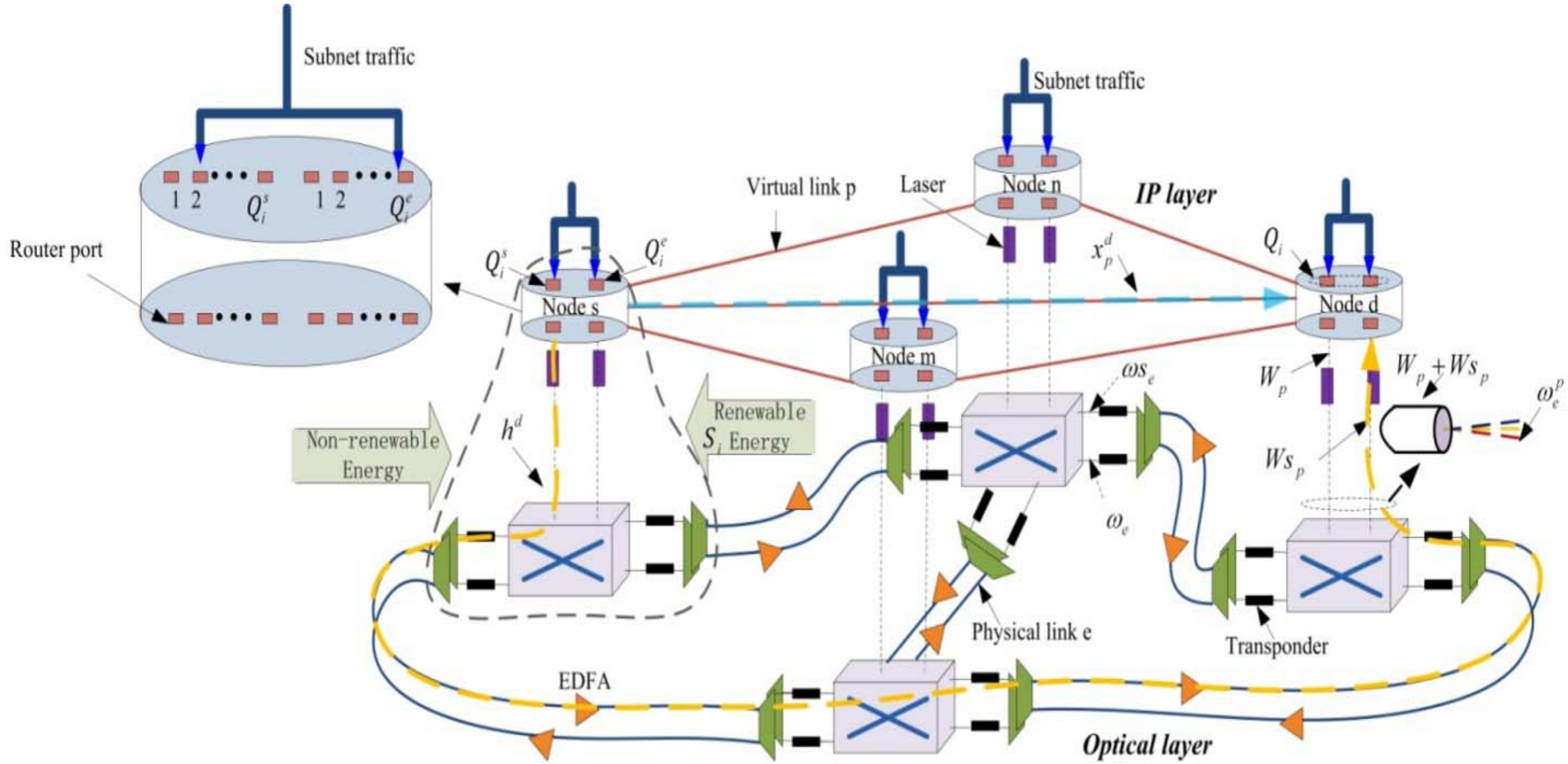
zinwave

ja.net

End-to-end network



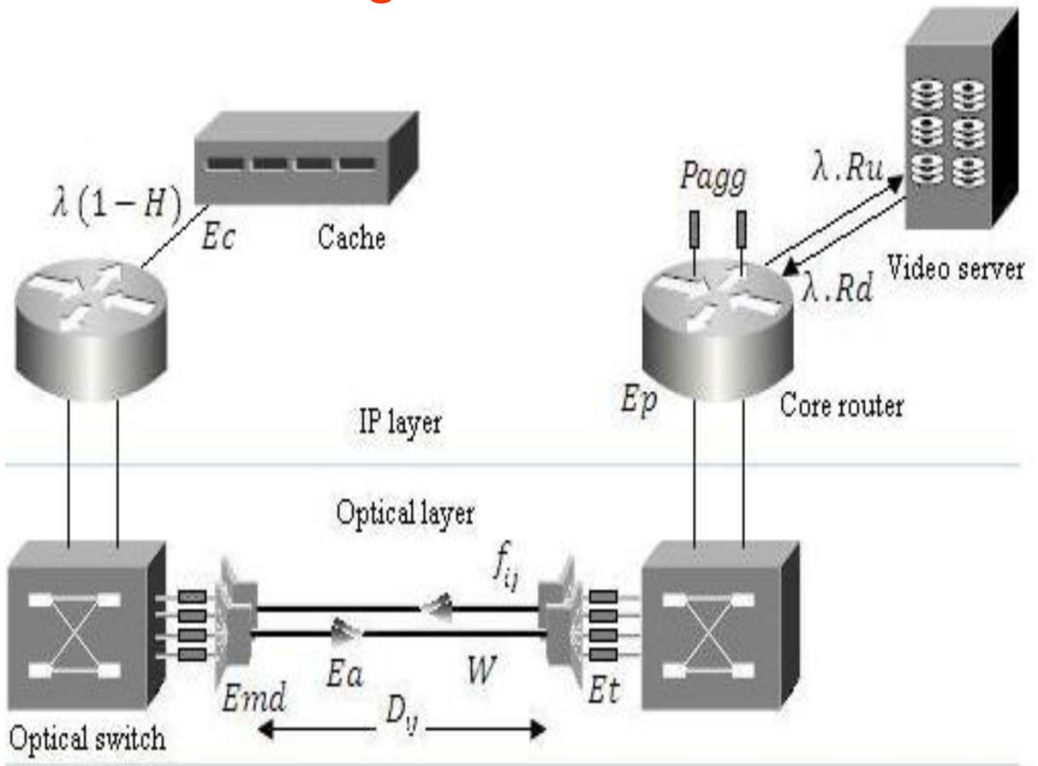
IP over WDM network architecture



Outline

- Energy Efficient Caching for IPTV On-Demand Services
  - MILP Model for Energy Efficient Caching
  - Energy-Minimised Cache Size Optimisation
  - The Impact of Caching the Most Popular Objects

Energy Efficient Caching for IPTV On-Demand Services



- By 2015 over 91% of the global IP traffic is projected to be a form of video (IPTV, VoD, P2P), with an annual growth in VoD traffic of 33%.
- In proxy-based architectures, proxies (or caches) are located closer to clients to cache some of the server's content.
- Our goal is to minimise the power consumption of the network by storing the optimum number of the most popular content at the nodes' caches.

Energy Efficient Caching for IPTV On-Demand Services

- MILP model to optimise the cache size at each node in the network at different times of the day.
- Each node in the network is allocated a cache with a limited capacity populated by M objects out of the total video server's objects N.
- The objects stored in the cache are the most popular objects available.
- The cache hit ratio H is defined as the ratio of the number of requests served from the cache to the total number of requests.
- The traffic demand between a node and a video server represents ($1-H$) of the total access network's demand.
- The relationship between the hit ratio H and the cache size M is represented by a convex function

LP Model for Energy Efficient Caching

1. The power consumption of router ports and optical switches at time t:

$$\sum_{i \in N} Pp \left(Pagg_{it} + \sum_{j \in N: i \neq j} C_{it} \right) \qquad \sum_{i \in N} Po_i$$

2. The power consumption of transponders at time t:

$$\sum_{m \in N} \sum_{n \in Nm[i]} Pt \cdot \omega_{ijt}$$

3. The power consumption of amplifiers at time t:

$$\sum_{i \in N} \sum_{j \in Nm[i]} \left(Pa \cdot Amp_{ij} \cdot f_{ij} \right)$$

4. The power consumption de/multiplexers at time t:

$$\sum_{i \in N} \sum_{j \in Nm[i]} Pmd \cdot f_{ij}$$

5. The power consumption of caches at time t:

$$\sum_{i \in N} Pc_{it}$$

LP Model for Energy Efficient Caching

Objective: minimise

$$\sum_{t\in T}\left(\sum_{i\in N} Pp\left(Pagg_{it}+\sum_{j\in N:i\neq j} C_{ijt}\right)+\sum_{i\in N} Po_i+\sum_{m\in N}\sum_{n\in Nm[i]} Pt\cdot\omega_{ijt}+\sum_{i\in N}\sum_{j\in Nm[i]}\left(Pa\cdot Amp_{ij}\cdot f_{ij}\right)+\sum_{i\in N}\sum_{j\in Nm[i]} Pmd\cdot f_{ij}+\sum_{i\in N} Pc_{it}\right)$$

Subject to:

$$Pagg_{it}+\sum_{j\in Nm[i]:i\neq j} C_{ijt}\leq Pmax_i \qquad \forall i\in N,\forall t\in T$$

$$Pagg_{it}+\sum_{j\in Nm[i]:i\neq j} C_{jit}\leq Pmax_i \qquad \forall i\in N,\forall t\in T$$

Constraints on number of router ports available

$$\sum_{x\in N}\sum_{y\in N:x\neq y}\omega_{ijt}^{xy}\leq W.f_{ij} \qquad \forall i\in N,\forall j\in Nm[i],\forall t\in T$$

$$\sum_{x\in N}\sum_{y\in N:x\neq y}\omega_{ijt}^{xy}\leq \omega_{ijt} \qquad \forall i\in N,\forall j\in Nm[i],\forall t\in T$$

Number of wavelength used not more than those in fibre

LP Model for Energy Efficient Caching

$$\sum_{j \in Nm[i]} \omega_{ijt}^{xy} - \sum_{j \in Nm[i]} \omega_{jit}^{xy} = \begin{cases} C_{xyt} & i = x \\ -C_{xyt} & i = y \\ 0 & otherwise \end{cases}$$

$$\forall\, i, x, y \in N, \forall\ t \in T$$

Flow conservation constraint in the optical layer

$$\sum_{j \in N: i \neq j} \lambda_{ijt}^{xy} - \sum_{j \in N: i \neq j} \lambda_{jit}^{xy} = \begin{cases} \lambda^{xyt} & i = x \\ -\lambda^{xyt} & i = y \\ 0 & otherwise \end{cases}$$

$$\forall\, i, x, y \in N, \forall\ t \in T$$

Flow conservation constraint for regular traffic in the IP layer

$$\sum_{j \in N, i \neq j} \lambda\_u_{ijt}^{xy} - \sum_{i \in N; i \neq j} \lambda\_u_{jit}^{xy} = \begin{cases} \lambda^{xyt}.Ru.\delta_y & i = x \\ -\lambda^{xyt}.Ru.\delta_y & i = y \\ 0 & otherwise \end{cases}$$

$$\forall\, i, x, y \in N, \forall\ t \in T$$

Flow conservation constraint for upload traffic (to server nodes) in the IP layer

LP Model for Energy Efficient Caching

$$\sum_{i \in N: i \neq j} \lambda\_d_{ijt}^{xy} - \sum_{i \in N: i \neq j} \lambda\_d_{jit}^{xy} = \begin{cases} \lambda^{xyt}.Rd.\delta_x(1-H_{it}) & i = x \\ -\lambda^{xyt}.Rd.\delta_x(1-H_{it}) & i = y \\ 0 & otherwise \end{cases}$$

$$\forall\, i, x, y \in N, \forall\ t \in T$$

Flow conservation constraint for upload traffic (to server nodes) in the IP layer

$$Pagg_{it} = \left(\sum_{y \in N: y \neq i} \lambda^{iyt} + \sum_{y \in N: y \neq i} \lambda^{iyt}.Ru.\delta_y + \sum_{x \in N: x \neq i} \lambda^{xit}.Rd.\delta_x (1 - H_{it}) \right) \Big/ B \qquad \forall i \in N, \forall t \in T$$

Number of aggregation ports used

$$\sum_{x \in N} \sum_{y \in N: x \neq y} \left(\lambda_{ijt}^{xy} + \lambda\_u_{ijt}^{xy} + \lambda\_d_{ijt}^{xy} \right) \leq C_{ijt}.B \qquad \forall\, i, j \in N, \forall\ t \in T$$

Traffic on a wavelength does not exceed its capacity

$$Pc_{it} \geq \alpha(a_k.H_{it} + b_k). \qquad \forall\, i \in N, \forall\ t \in T, \forall\ k \in K$$

Piecewise linear approximation of convex hit ratio

Scenario

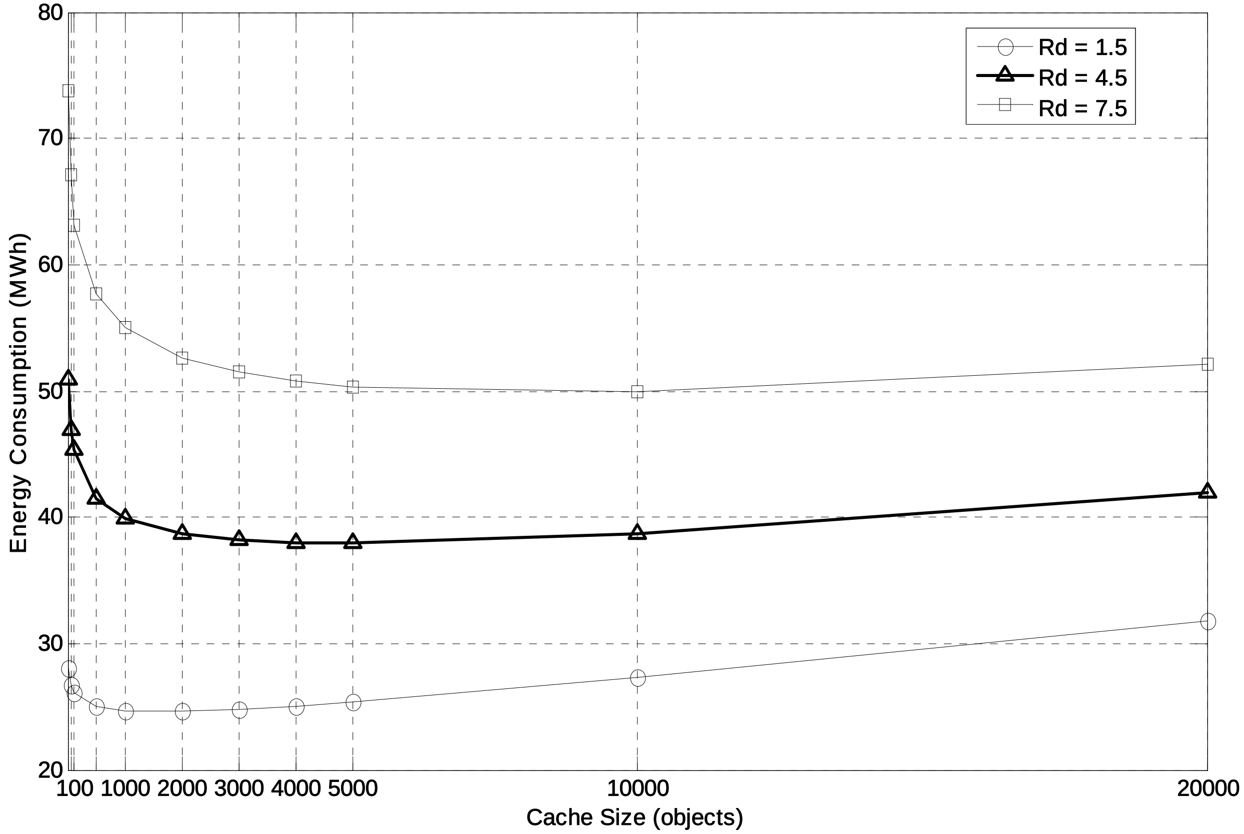
- We consider the NSFNET network with 7 nodes serving as video servers.
- The location of the video servers is optimised using the model (1, 3, 5, 8, 10, 12, and 14).
- The traffic demand between nodes and video servers is generated based on the regular traffic demand.
- We consider three different values of uplink (*Ru*) and downlink traffic ratios (*Rd*) to match the input and output rates of a typical video server and reflect the expected growth in VoD traffic:

  1) *Rd*=1.5 and *Ru*=0.2, 2) *Rd*=4.5 and *Ru*=0.6 and 3) *Rd*=7.5 and *Ru*=1.0

- A library of 2 million objects of the same size.
- Object popularities follow a Zipf-like distribution:

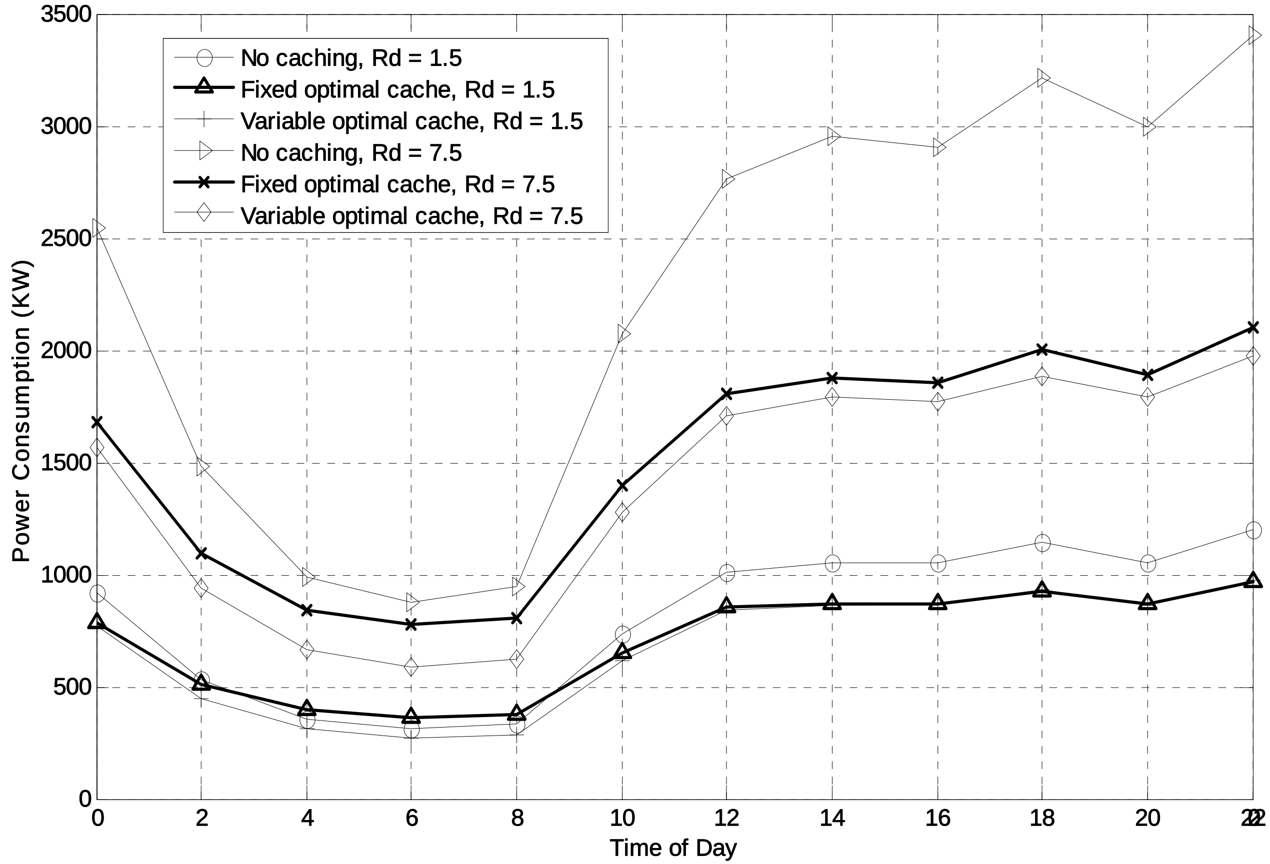
$$P_i = 1/(i.\, lnN)$$

Cache Size Optimization



- The power consumption of the network falls with the increase in the cache size to a certain cache size after which increasing the cache size results in increasing the total energy consumption.
- In this range, the energy consumed for storage exceeds the energy consumed if some of the requests are served remotely.

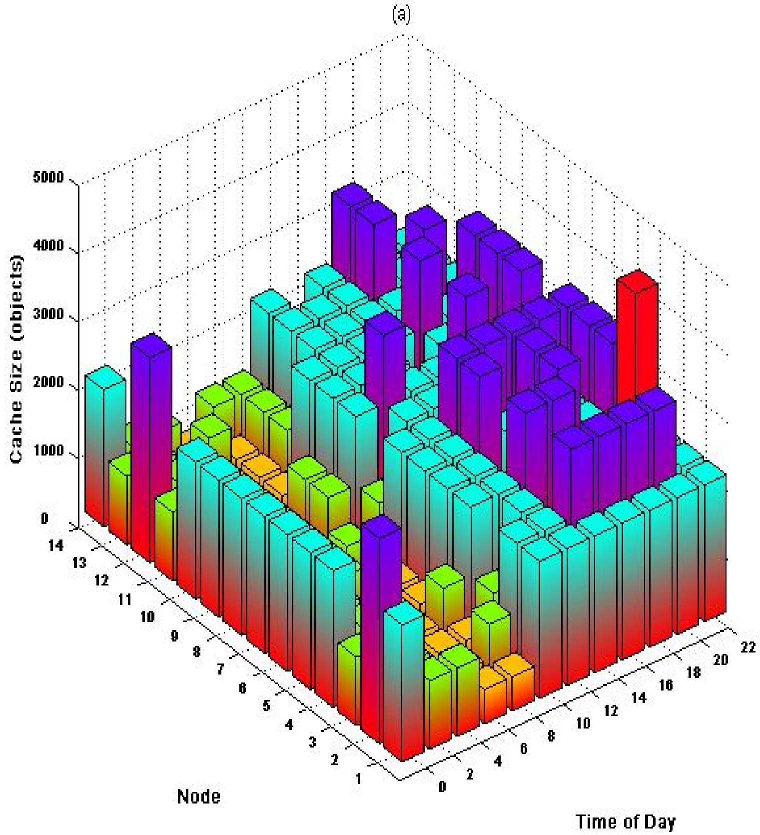
Cache size optimization



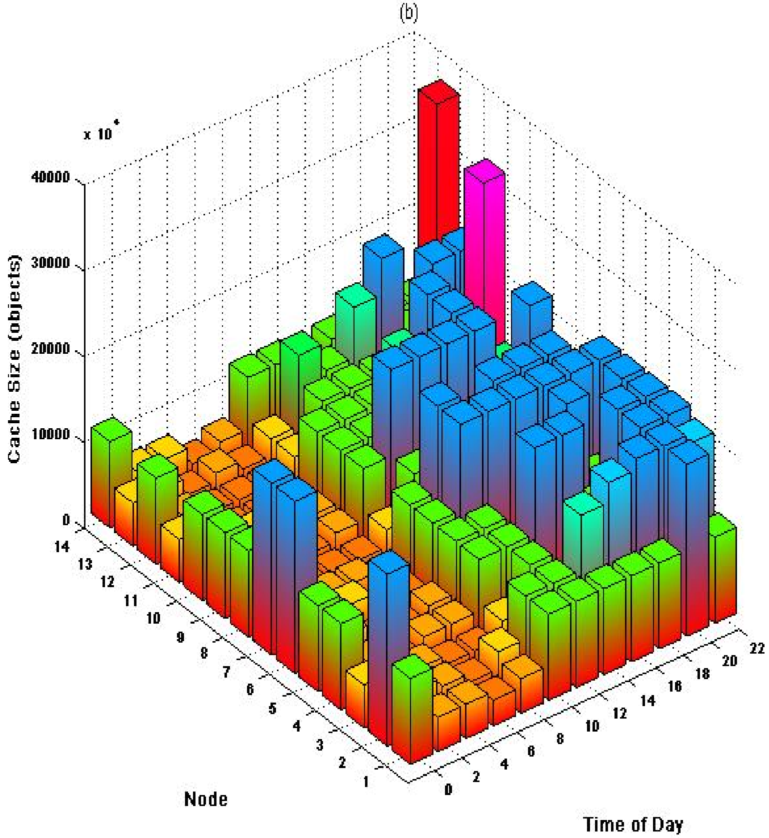
Variable size cache max network power saving 42%

- Fixed optimum cache is found considering all the nodes over the full day
- Fixed size caching reduces the network energy consumption by a maximum of 19% (average of 8%) and a maximum of 38% (average of 30%) for (Rd=1.5, Ru=0.2) and (Rd=7.5,Ru=1), respectively.

Optimum cache size at different nodes during the day (need cache size adaptation (sleep))

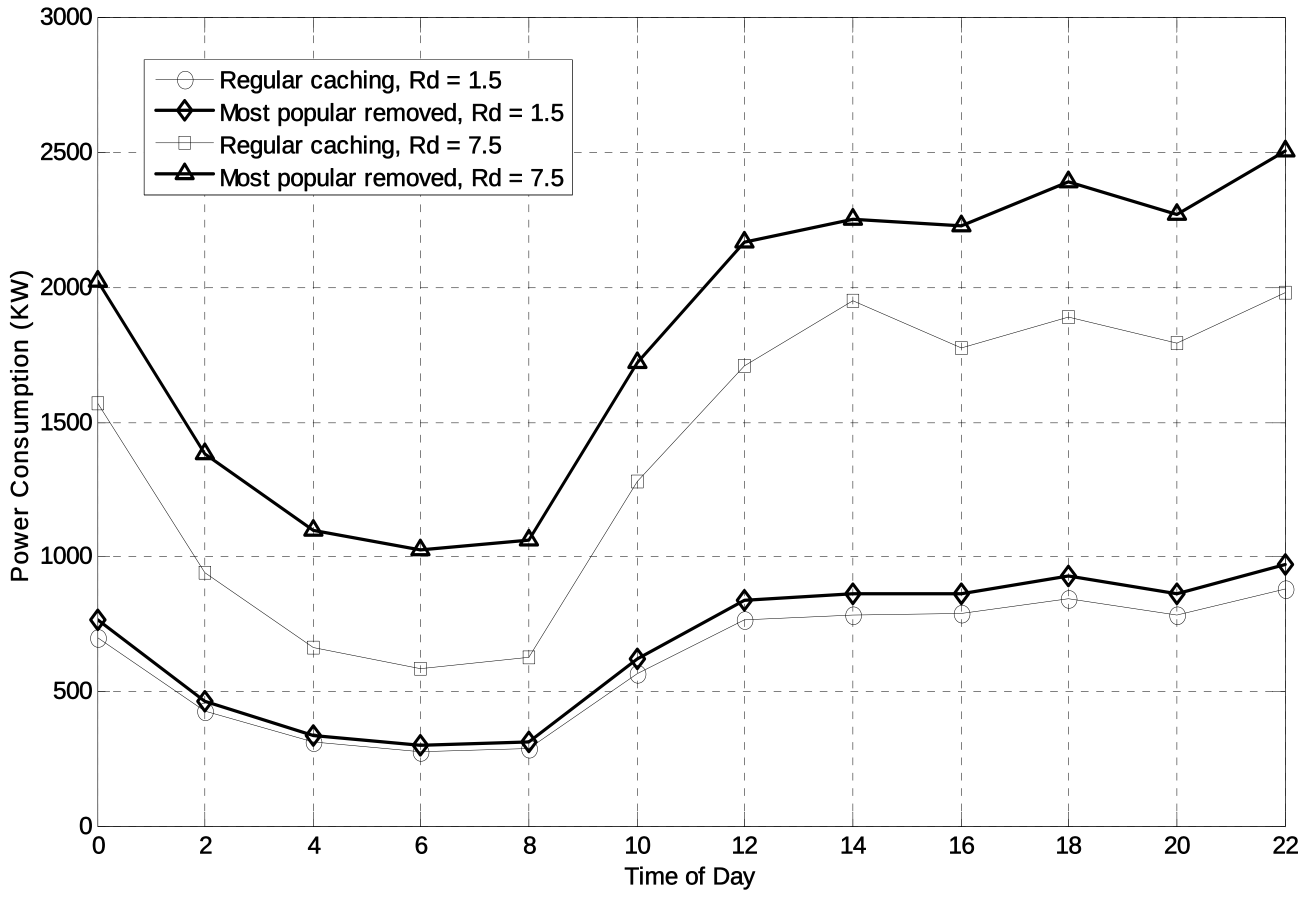


(a) Rd = 1.5



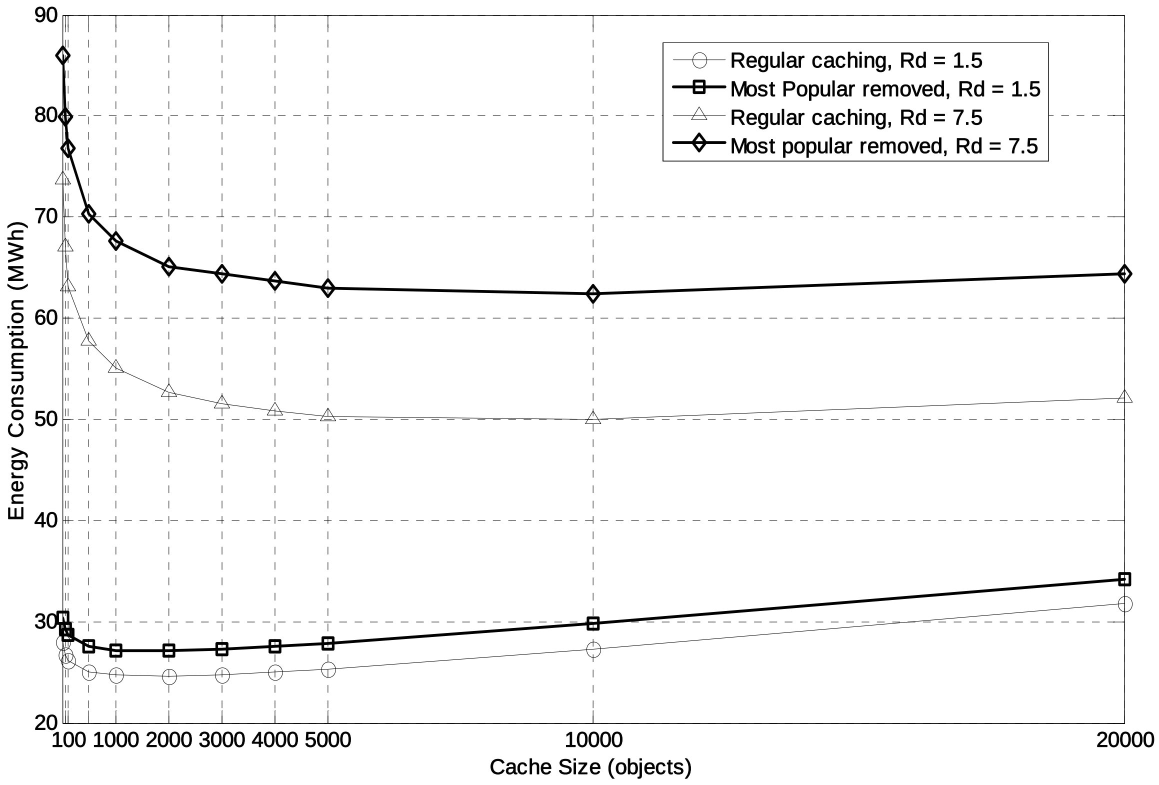
(b) Rd = 7.5

The Impact of removing the most popular objects



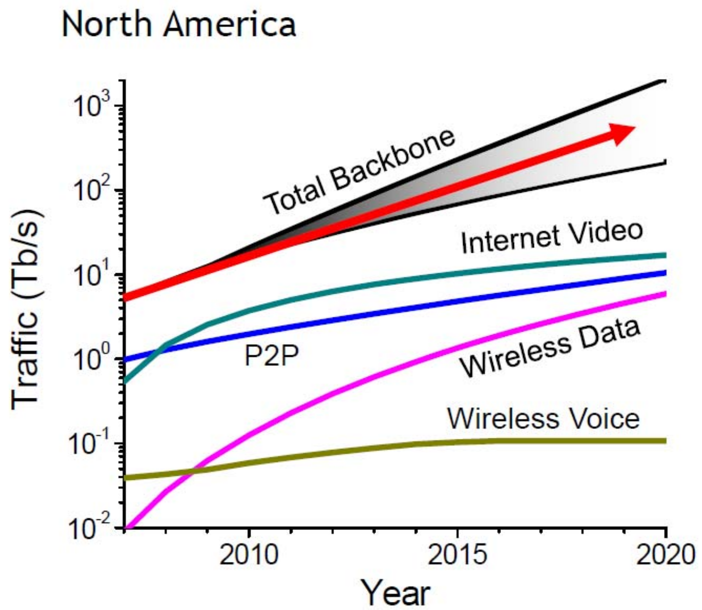
- The power consumption increases by removing the 10 most popular items.
- Increase in the power consumption of the network by over 20% (average 18.4%) for (*Rd*=7.5, *Ru*=1).

The Impact of removing the most popular objects



- Increasing the cache size by storing more of the less popular objects does not compensate for the energy loss caused by displacing the most popular objects (due to their high popularity).
- 2 Million objects, Zipf distributed, 10 most popular removed

Energy-Efficient BitTorrent



Data from: RHK, McKinsey-JPMorgan, AT&T, MINTS, Arbor, ALU, and Bell Labs Analysis: Linear regression on log(traffic growth rate) versus log(time) with Bayesian learning to compute uncertainty

Doubling every 2 years

- **40% per year**
- **30x in 10 years**
- **1000x in 20 years**

Mix of services is important from energy perspective:

- **Mobile less efficient than fiber optics**

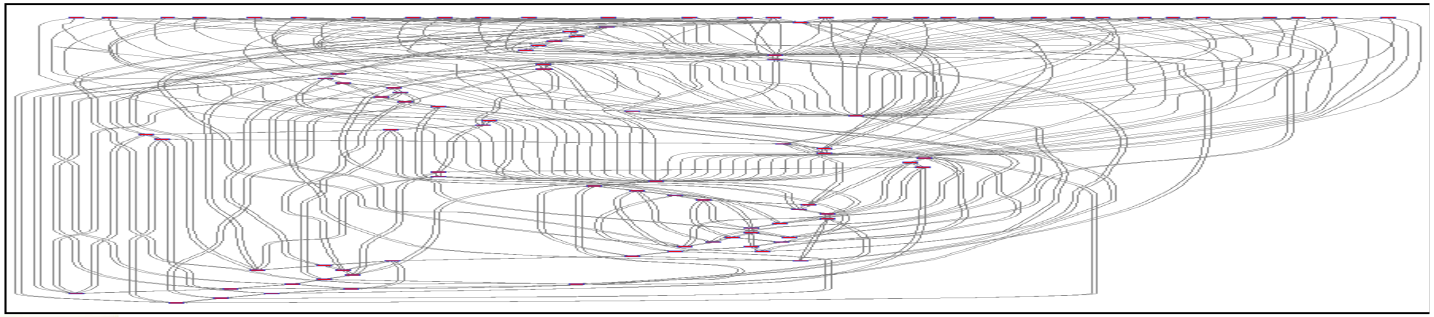
- The two content distribution schemes, Client/Server (C/S) and Peer-to-Peer (P2P), account for a high percentage of the Internet traffic.
- We investigate the energy consumption of BitTorrent in IP over WDM networks.
- We show, by mathematical modelling (MILP) and simulation, that peers' co-location awareness, known as locality, can help reduce BitTorrent's cross traffic and consequently reduces the power consumption of BitTorrent on the network side.

Energy-Efficient BitTorrent

- The file is divided into small pieces.
- A tracker monitors the group of users currently downloading.
- Downloader groups are referred to as swarms and their members as peers. Peers are divided into seeders and leechers.
- As a leecher finishes downloading a piece, it selects a fixed number (typically 4) of interested leechers to upload the piece to, ie unchoke, (The choke algorithm).
- Tit-for-Tat (TFT) ensures fairness by not allowing peers to download more than they upload.
- We consider 160,000 groups of downloaders distributed randomly over the NSFNET network nodes.
- Each group consists of 100 members.
- File size of 3GB.
- Homogeneous system where all the peers have the same upload capacity of 1Mbps.
- Optimal Local Rarest First pieces dissemination where Leechers select the least replicated piece in the network to download first.
- BitTorrent traffic is 50% of total traffic.
- Flash crowd where the majority of leechers arrive soon after a popular content is shared.
- We compare BitTorrent to a C/S model with 5 data centers optimally located at nodes 3, 5, 8, 10 and 12 in NSFNET.
- The upload capacity and download demands are the same for BitTorrent and C/S scenarios (16Tbps).

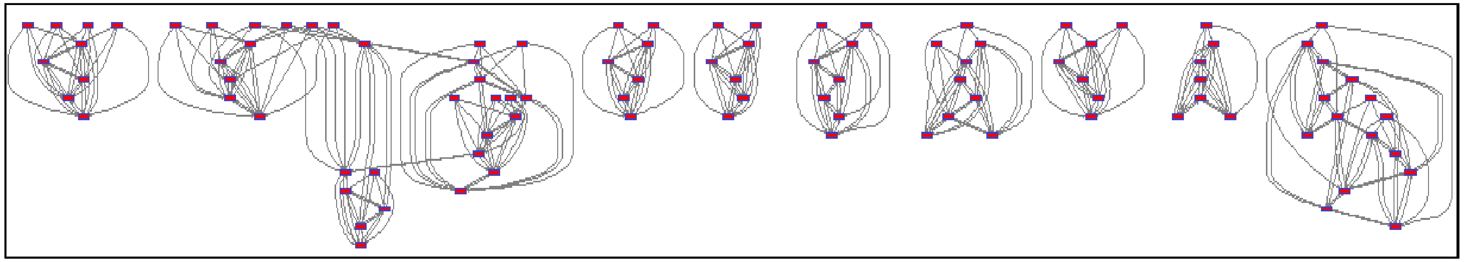
Peer Selection

(100 Peer: 30 Seeders and 70 Leechers in Swarm 1)



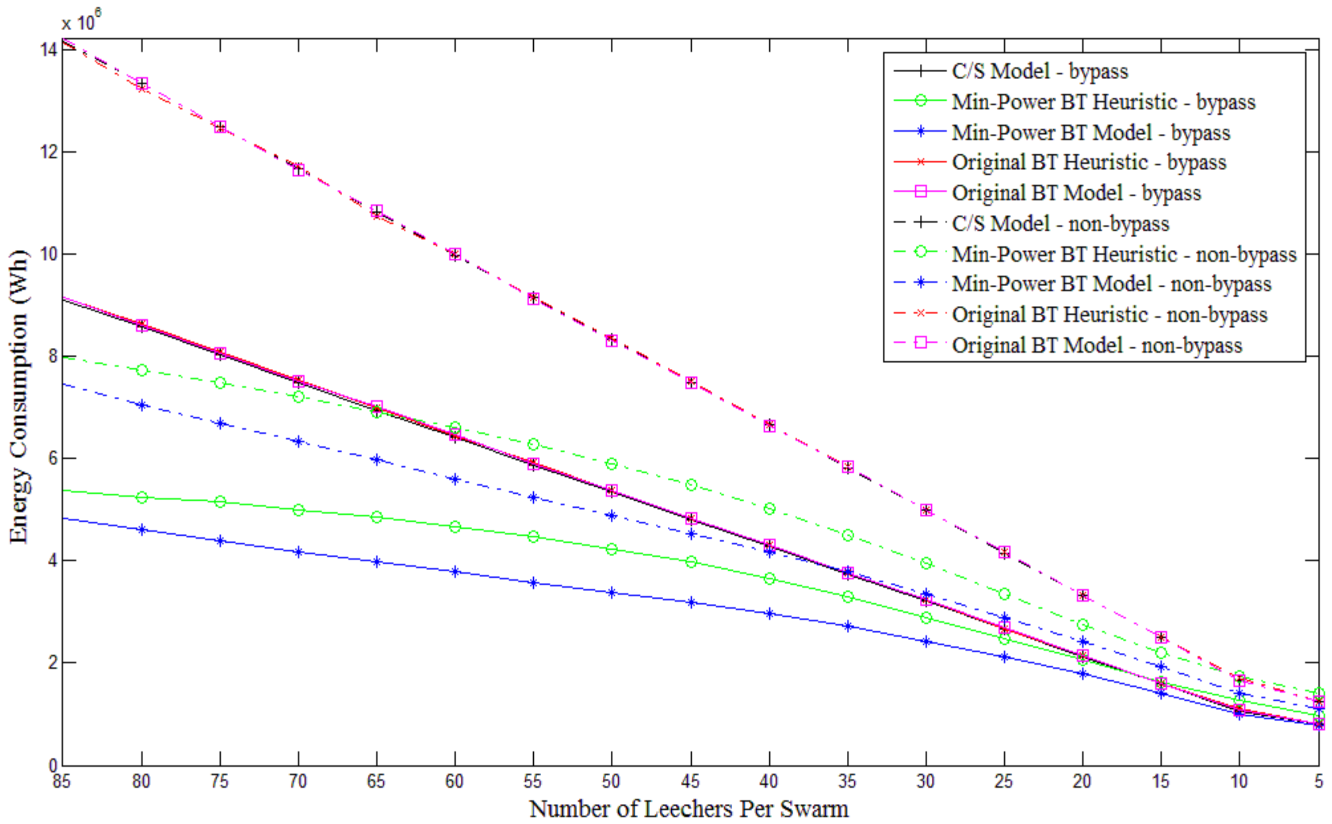
Original BitTorrent (Random Selection)

Energy Efficient BitTorrent (Optimized Selection)



Results

Energy Consumption



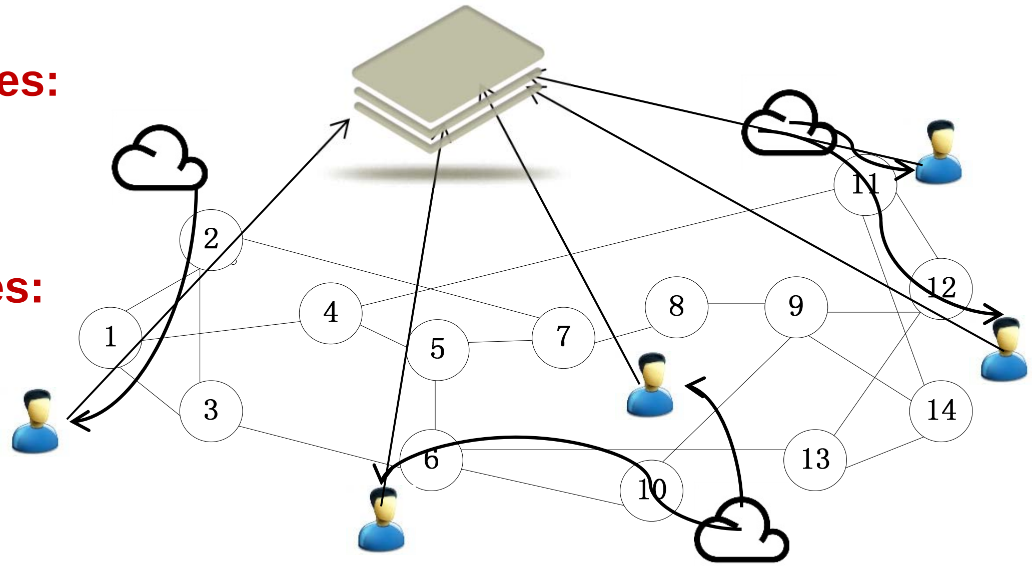
Non-bypass:
MILP average Energy Saving=36%
Heuristic average Energy Saving =25%

Bypass:
MILP average Energy Saving=30%
Heuristic average Energy Saving =15%

Distributed vs. Centralised Content Delivery Energy Efficiency

We develop a MILP model for cloud content delivery in IP/WDM networks to answer whether centralised or distributed content delivery is the most energy efficient solution. Two types of decision variables are optimized for the cloud service model:

- **External decision variables:**
  - Number of clouds
  - Location of clouds
- **Internal decision variables:**
  - Number of servers
  - Number of switches
  - Number of routers
  - Storage capacity



Given a particular client requests/demands, the model responds by deciding the optimum number of clouds that should be built and their location in the network as well as the capability of each cloud so that the total energy consumption is minimised

Definitions

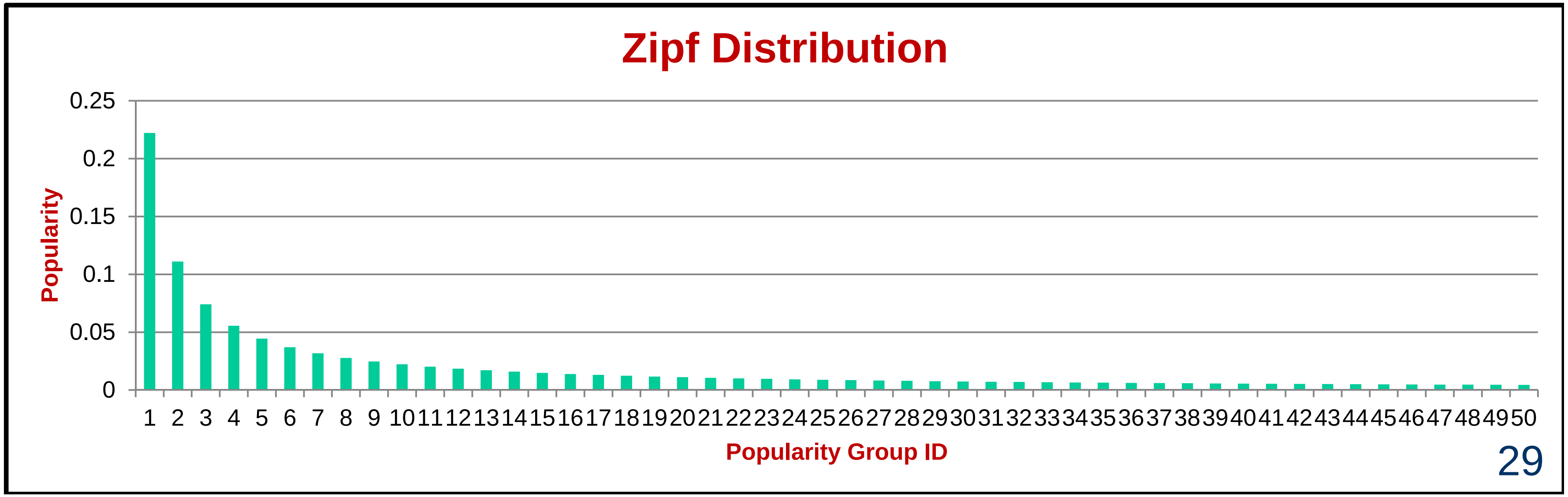
- **Popularity group:** Content requested with similar frequency by users is placed in a popularity group.
- **Zipf distribution:** The Zipf popularity distribution for a stored object i is given by

$$P(i) = {}^{\varphi}/_{i}$$

where $P(i)$ is the relative popularity of object i and

$$\varphi = \left(\sum_{i=1}^{N} i \right)^{-1}$$

- We analyse 50 popularity groups where the cloud storage is equally divided among the groups



IP/WDM Power Consumption: Non-Bypass

The total IP/WDM network power consumption is composed of:

1) The power consumption of router ports

$$\sum_{i \in N} Prp \cdot Q_i + Prp \cdot \sum_{m \in N} \sum_{n \in Nm_m} W_{mn}$$

2) The power consumption of transponders

$$\sum_{m \in N} \sum_{n \in Nm_m} Pt \cdot W_{mn}$$

3) The power consumption of EDFAs

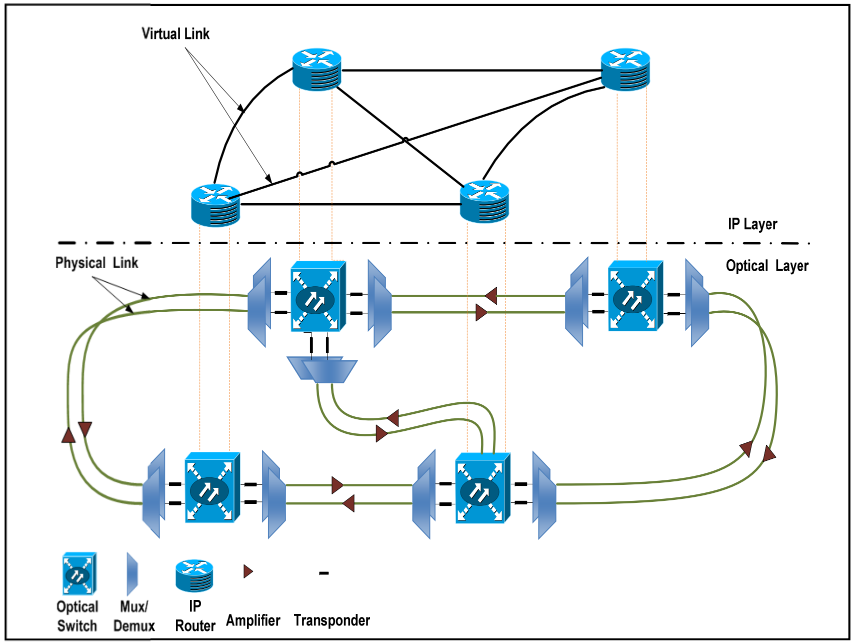
$$\sum_{m \in N} \sum_{n \in Nm_m} Pe \cdot A_{mn} \cdot F_{mn}$$

4) The power consumption of optical switches

$$\sum_{i \in N} PO_i$$

5) The power consumption of Multi/Demultiplexers

$$\sum_{m \in N} \sum_{n \in Nm_m} Pmd \cdot F_{mn}$$



IP/WDM Network

Cloud Power Consumption

The total cloud power consumption is composed of:

1) Power consumption of content servers ($SrvPC$):

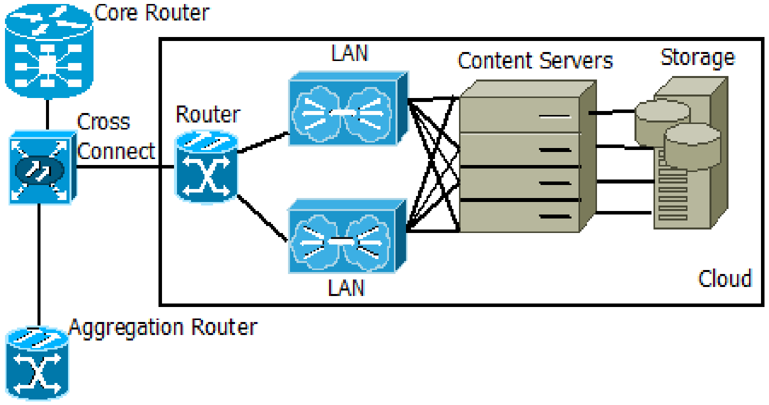
$$\sum_{s \in N} Cup_s \cdot CS_{EPB}$$

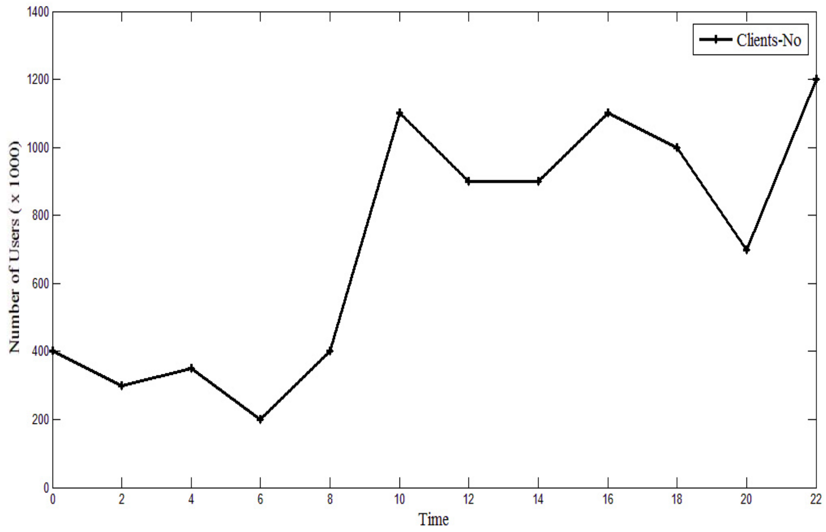
2) Power consumption of switches and routers ($LANPC$):

$$\sum_{s \in N} Cup_s \cdot (Sw_{EPB} \cdot Red + R_{EPB})$$

3) Power consumption of storage ($StPC$):

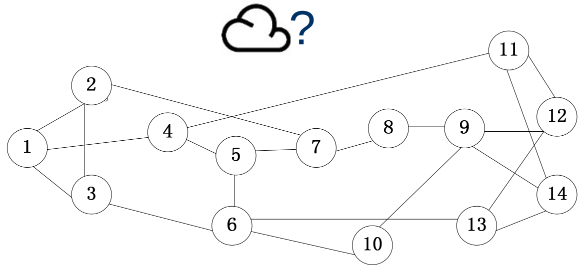
$$\sum_{s \in N} StrC_s \cdot S_{PPGB} \cdot Red$$



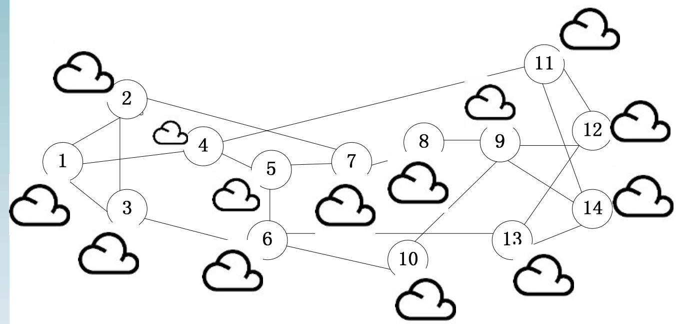


We assume number of users fluctuates between 200k and 1200k users in a day in our analysis.

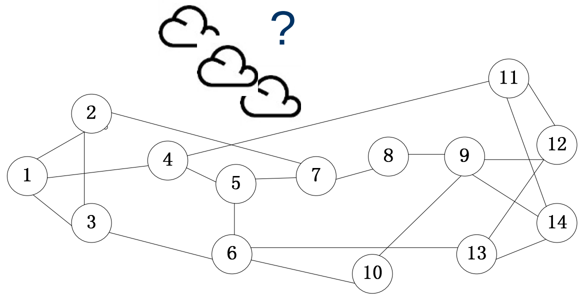
Scenarios



Forcing Single Cloud:
No Power Management (SNPM)
Using Power Management (SPM)



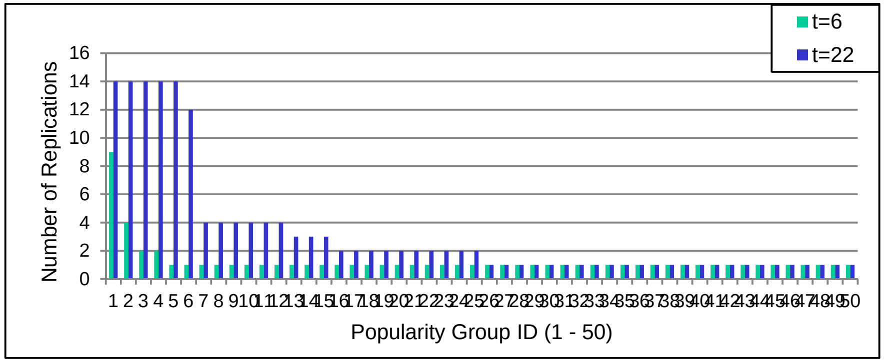
Forcing Max Number of Clouds (14):
Full Replication (MFR)
No Replication (MNR)
Popularity Based Replication (MPR)

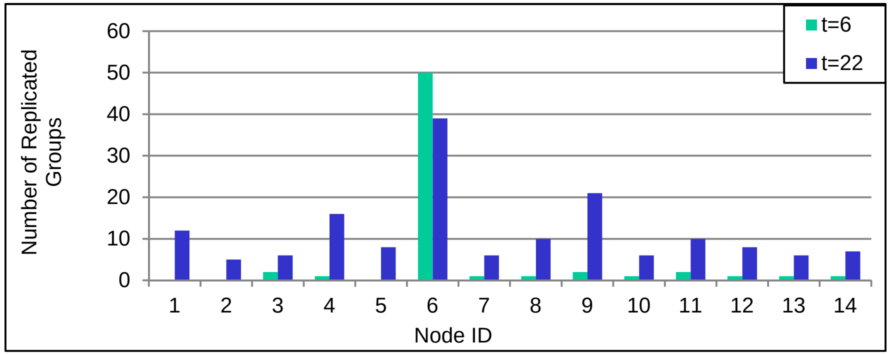


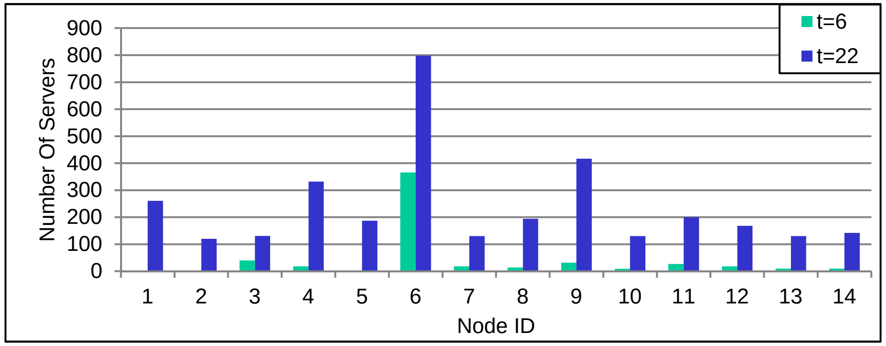
Optimal Number of Clouds:
Full Replication (OFR)
No Replication (ONR)
Popularity Based Replication (OPR)

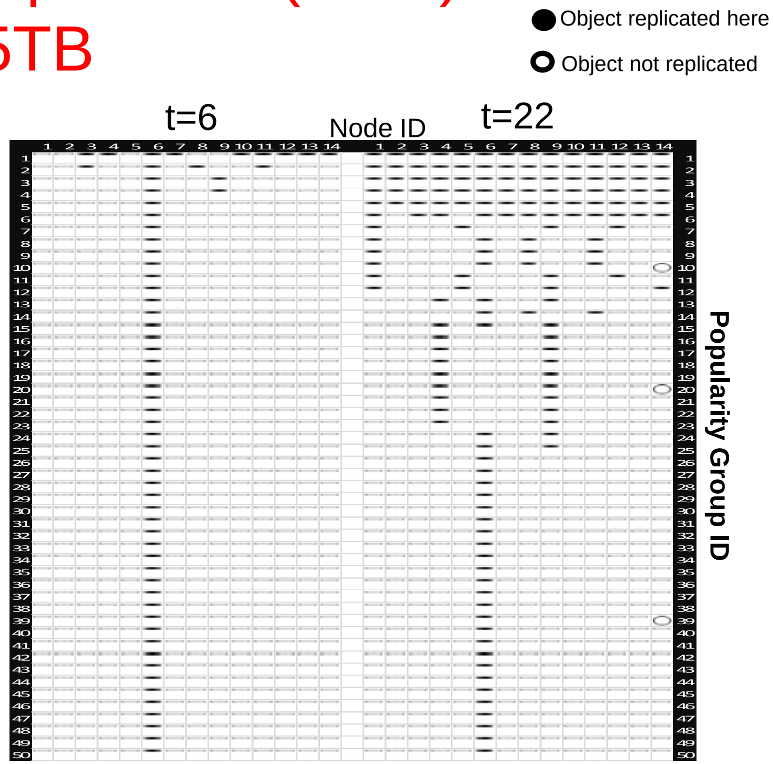
With Power Management

Popularity Based Content Replication (OPR)
Storage=75.6*5TB









OPR Content Replication Scheme

Scenario	Total Savings	Network Saving
OPR	40%	72%
MPR	40%	72%
OFR	37.5%	56.5%
SPM	36.5%	37%
ONR	36.5%	37%
MNR	36.4%	36.5%
MFR	25.5%	99.5%

Energy Efficient Storage as a Service (StaaS)

Scenario & Assumptions

- Special case of the content delivery service where only the owner or a very limited number of authorised users have the right to access the stored content.
- All content is stored in one (or more) central locations
- StaaS should achieve trade-off between serving content owners directly from the central cloud/clouds and having clouds near to content owners.
- Upon registration for StaaS, users are granted a certain size of free storage. DropBox, for instance, grants its users 2GB.
- Different users might have different levels of utilization of their StaaS facility.
- Different users have different documents access frequency.
- High access frequency means:
  - The content owner accesses the content frequently

  and/or
  - Other authorised users become interested in the content.

Energy Efficient Storage as a Service (StaaS)

Scenario & Assumptions

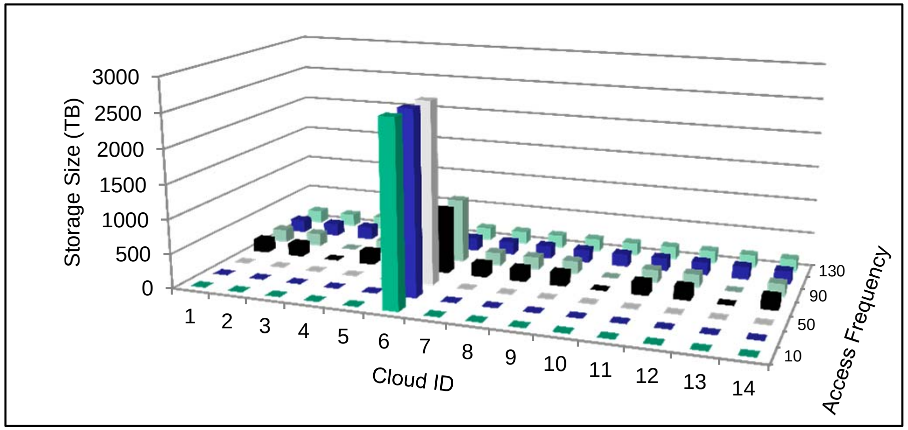
- Two Average document sizes are evaluated, 45MB and 22.5MB
- Number of users evaluated are 1.2M
- Users are uniformly distributed in the network.
- Users download rate (*Drate*: in Gb/s) depends on:
  - Document access frequency (*Freq: Number of downloads per hour*)
  - Document size (*Dsize*: in Gb)

$$Drate = 2 \cdot Freq \cdot Dsize/3600$$

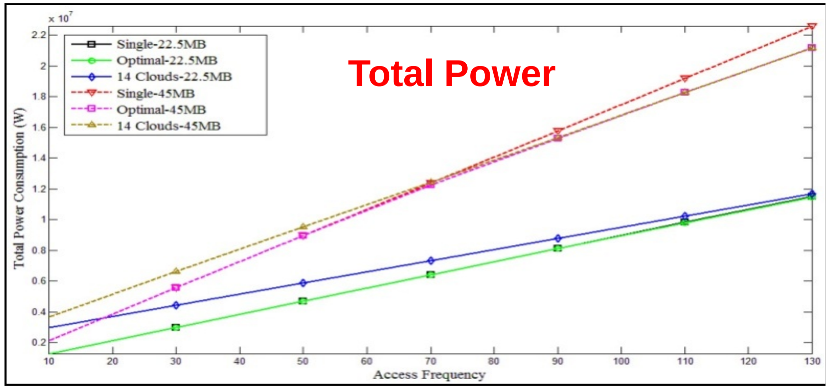
The factor of 2 is to take the fact that users usually re-upload their content after downloading it back to their *StaaS* drive into account.

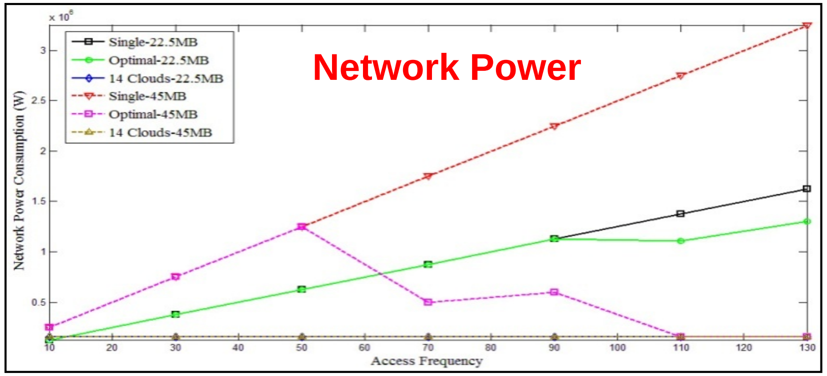
StaaS Model Results

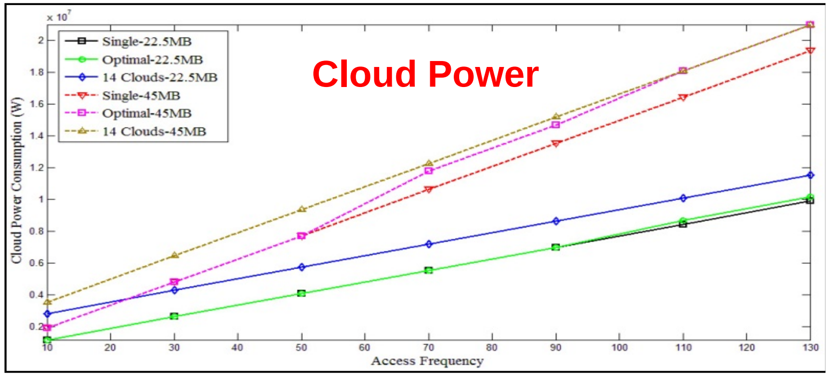
- **Single Cloud:** Users are served by the central cloud only.
- **Optimal Clouds:** The model selects to serve users at each node either from the central cloud or from a local cloud by migrating content from the central cloud.
- **14 Clouds:** Users at each node are served by a local cloud.



Optimal cloud scenario with the 45MB saves about 48% (averaged over the range of access frequency considered) in network power consumption compared to the single cloud scenario







Virtual Machine (VM) Placement for Energy Efficiency

Assumptions

- Number of users fluctuates between 200k and 1200k users per day.
- Users rate 5 Mb/s,
- Users are uniformly distributed among network nodes.
- 1000 Virtual machines are evaluated due to MILP restriction on number of variables
- The problem is defined as finding the optimal location of each virtual machine

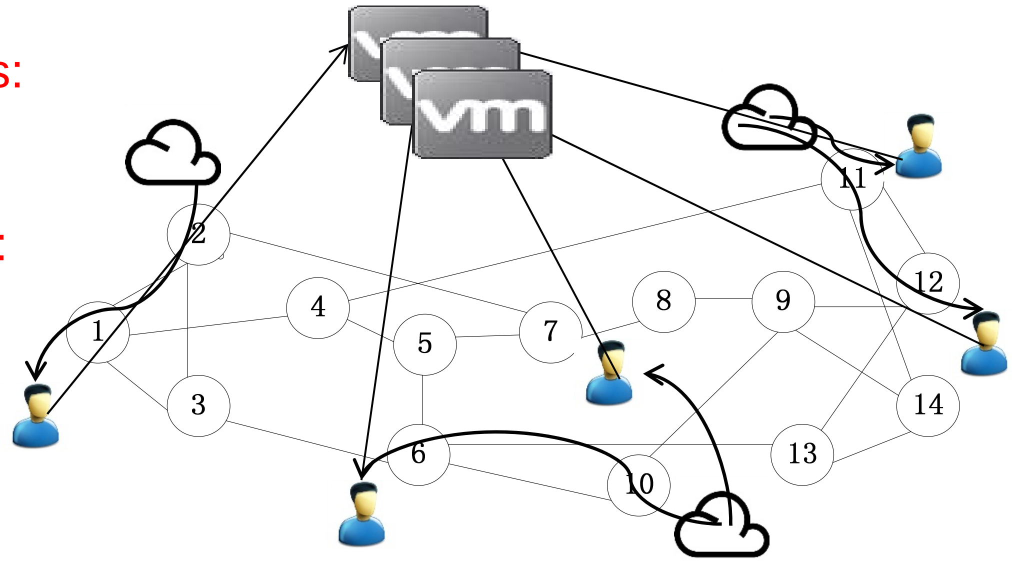
Scenarios

- **VM Migration**: Only one copy of each VM is allowed in the network
- **VM Replication**: More than one copy of each VM is allowed in the network but each copy uses full VM power
- **VM Slicing**: VMs can be divided into smaller slices to serve a smaller number of users. Sum of slices power equal VM power. We enforce a limit on the minimum size of the VM CPU utilization

Virtual Machine (VM) Placement for Energy Efficiency

We develop an MILP model to optimize cloud VM service delivery in IP/WDM networks. Two kinds of decision variables are optimized for the cloud service model:

- External decision variables:
  - Number of clouds
  - Location of clouds
- Internal decision variables:
  - Number of servers
  - Number of switches
  - Number of routers

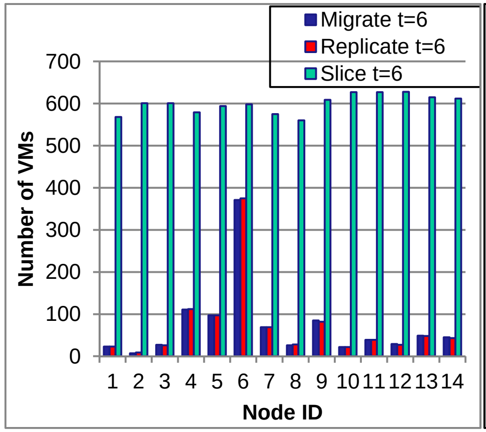


Scenario	Total Savings	Network Saving
Migrate	5%	23.5%
Replicate	6%	26%
Slice	27.5	86%

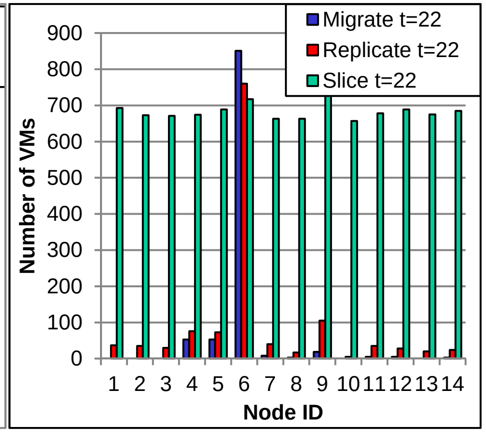
The saving are compared to single cloud at node 6

DEER-VM Heuristic

- **Migrating** VMs yields a little saving compared to single cloud solution.
- **Replicating** the full VM also yields lower saving because of the many VMs with high CPU utilization.
- **Slicing** the VMs by distributing the incoming requests among them is the most energy efficient solution.



Model VMs Distribution Scheme at t=06:00

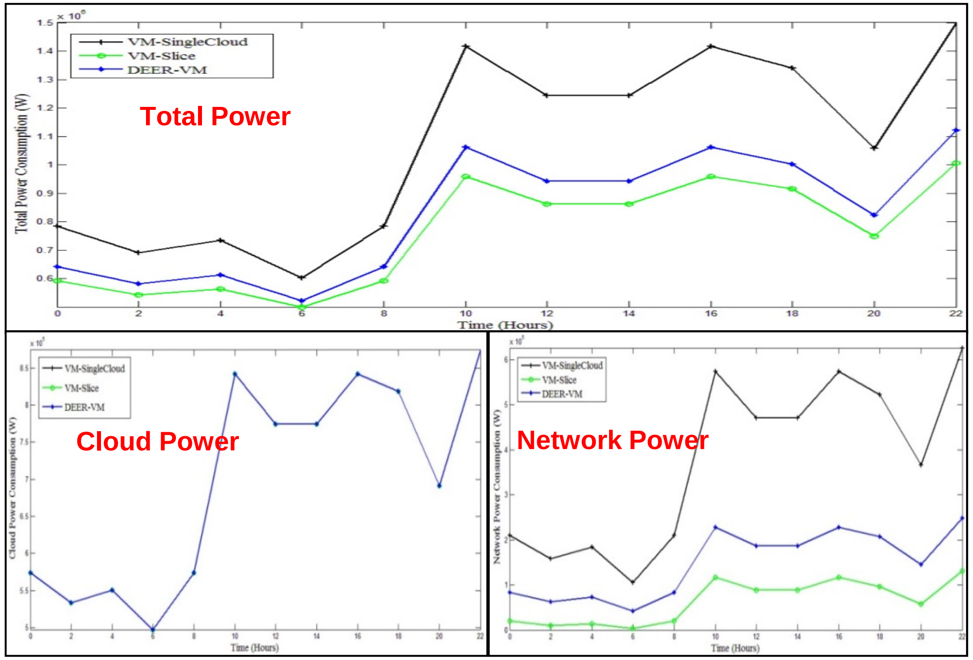


Model VMs Distribution Scheme at t=22:00

DEER-VM Heuristic

Input:	LIST= {6, 5, 4, 3, 7, 9, 13, 10, 11, 12, 14, 1, 8, 2}, $VM = \{1..NVM\}$
Output:	Optimal Placement(J'), Total Power Consumption (TPC)
	For each Virtual Machine $v \in VM$ **Do**
	For each Placement $J \subseteq$ List **Do**
	For each node $d \in N$ **Do**
	For each location candidates $\in J$ **Do**
	Add$\{cost_{sd}\} = MinHop\ (s,d)$
	$CW_{vjs} = W_v$
	End For
	Get s where: $cost_{sd} = Min\{cost_{sd}\}$
	$L_{vJsd} = D_{vd}$
	End For
	$NPC_{vJ} = MultiHopHeuristic\{N, N_m, L_{vJsd}\}$
	$CPC_{vJ} = PUE\_c \cdot (SrvPC + LANPC)$
	$TPC_{vJ} = NPC_{vJ} + CPC_{vJ}$
	End For
	$TPC_v = Min\{TPC_{vJ}\}$,
	$J' = J$
	End For
	Calculate $TPC = \sum_{v \in VM} TPC_v$

Scenario	Total Savings	Network Saving
VM-Slice-MILP	27.5%	86%
DEER-VM	21%	60%



Future Directions

- Optimisation of wired wireless access architectures, metro rings - wireless mesh, PON, RoF.
- Architectures that support photonic switching instead of electronic routing.
- Auction based and self-organising dynamic architectures for energy minimisation.
- Study optimum caching location in an end-to-end network
- Develop optimisation and simulation tools to address energy efficiency specifically.

Related Publications

1. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "IP Over WDM Networks Employing Renewable Energy Sources," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, No. 1, pp. 3-14, 2011.
2. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "Green IP over WDM Networks with Data Centres," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, 2011.
3. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "On the Energy Efficiency of Physical Topology Design for IP over WDM Networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 28, 2012.
4. Lawey, A., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "Distributed Energy Efficient Clouds over Core Networks," *IEEE Journal of Lightwave Technology*, vol. 32, No. 7, pp. 1261 - 1281, 2014.
5. Osman, N. I., El-Gorashi, T.E.H., Krug, L. and Elmirghani, "Energy-Efficient Future High-Definition TV," *IEEE Journal of Lightwave Technology*, 2014.
6. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "Use of renewable energy in an IP over WDM network with data centres," *IET Optoelectronics*, vol. 6, No. 4, pp. 155-164, 2012.
7. Osman, N. I., El-Gorashi, T.E.H. and Elmirghani, "Caching in green IP over WDM networks," *Journal of High Speed Networks*, vol. 19, No. 1, pp. 33-53, 2013.
8. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., "Renewable Energy for Low Carbon Emission IP over WDM networks," *Proc. 15th IEEE Optical Network Design and Modelling conference* (*ONDM'11*), Bologna, Italy, 8-10 Feb 2011.

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9. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Low Carbon Emission IP over WDM network,” *IEEE International Conference on Communications* (*ICC’11*), Koyoto, Japan, June 2011.
10. Osman, N.I., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Reduction of Energy Consumption of Video-on-Demand Services using Cache Size Optimization,” *Proc IEEE 8th International Conference on Wireless and Optical Communications Networks WOCN2011*, Paris, 24-26 May 2011.
11. Lawey, A.Q., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Impact of Peers Behaviour on the Energy Efficiency of BitTorrent over Optical Networks,” *Proc IEEE 14th International Conference on Transparent Optical Networks* (ICTON’12), 2-5 July, 2012, UK.
12. Lawey, A.Q., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Energy-Efficient Peer Selection Mechanism for BitTorrent Content Distribution,” *IEEE Global Telecom Conf* (GLOBECOM’12), Anaheim, 3-7 Dec, 2012.
13. Osman, N.I., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “The impact of content popularity distribution on energy efficient caching,” Proc IEEE 15th International Conference on Transparent Optical Networks ICTON 2013, Cartagena, Spain, June 23-27, 2013.
14. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Energy Efficiency of Optical OFDM-based Networks,” Proc. IEEE International Conference on Communications (ICC’13), Budapest, 9-13 June 2013.
15. Dong, X., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Joint Optimization of Power, Electricity Cost and Delay in IP over WDM networks,” Proc. IEEE International Conference on Communications (ICC’13), Budapest, 9-13 June 2013.
16. Lawey, A.Q., El-Gorashi, T.E.H. and Elmirghani, J.M.H., “Energy Efficient Cloud Content Delivery in Core Networks,” IEEE Global Telecommunications Conference (GLOBECOM’13), Atlanta, 9-13 Dec, 2013.