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NOC

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Energy Efficient Content Distribution Optical Networks

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EPSRC

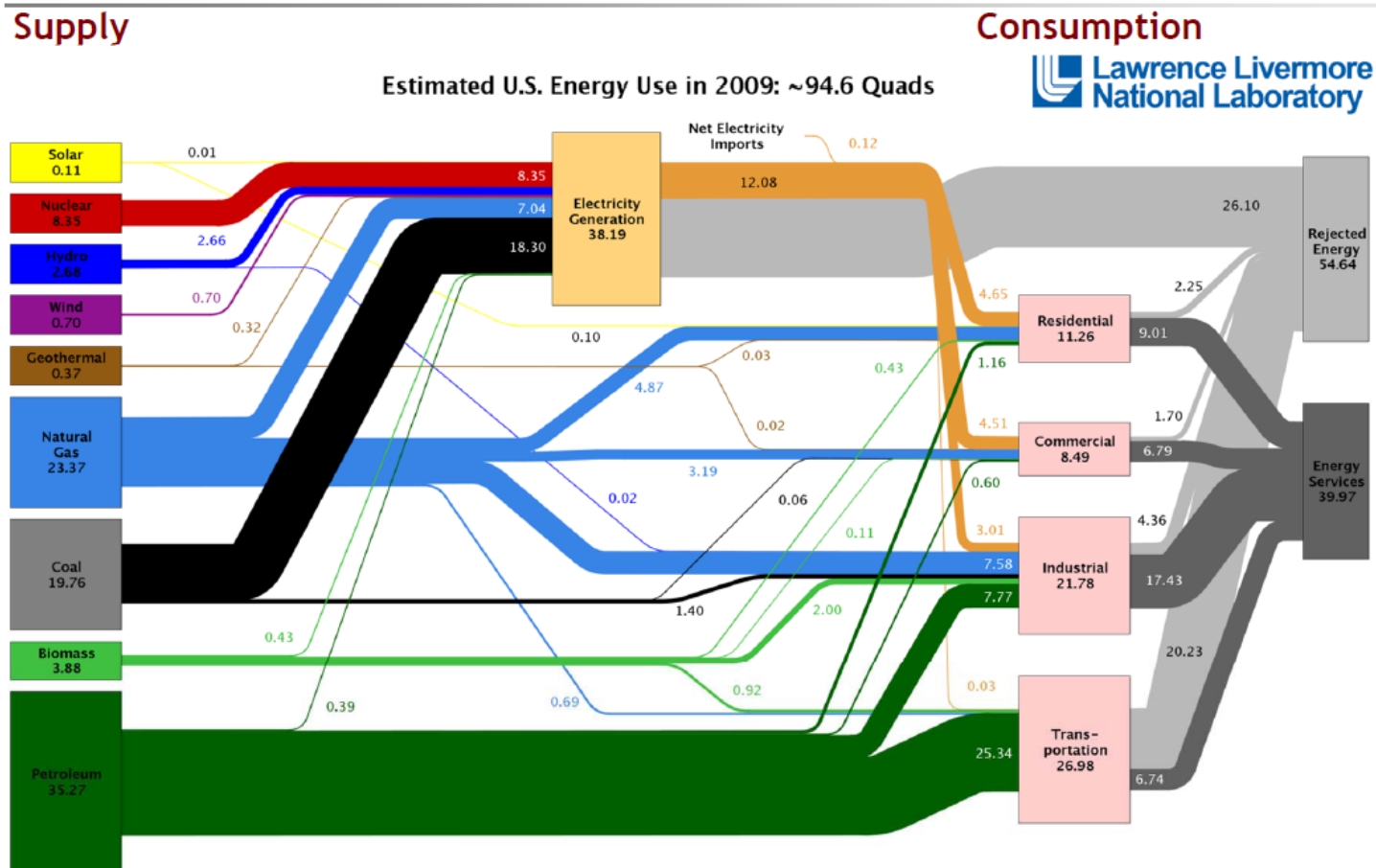
Pioneering research
and skills



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



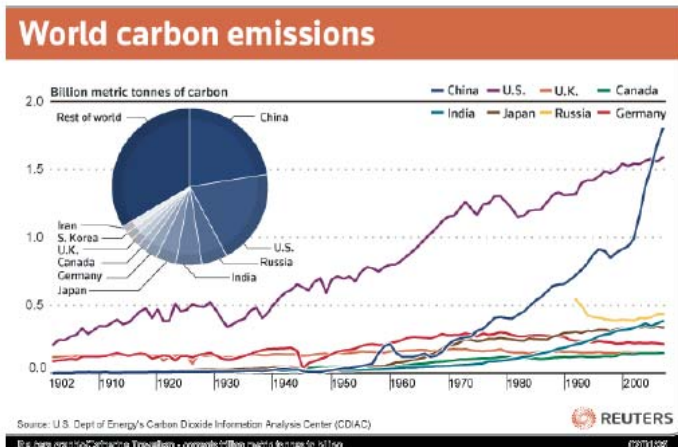
Most Energy is Lost!

Source: LLNL 2010. Data is based on DOE/EIA-0384(2009), August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Quads (10^{15} BTUs)

- The case for better use of energy

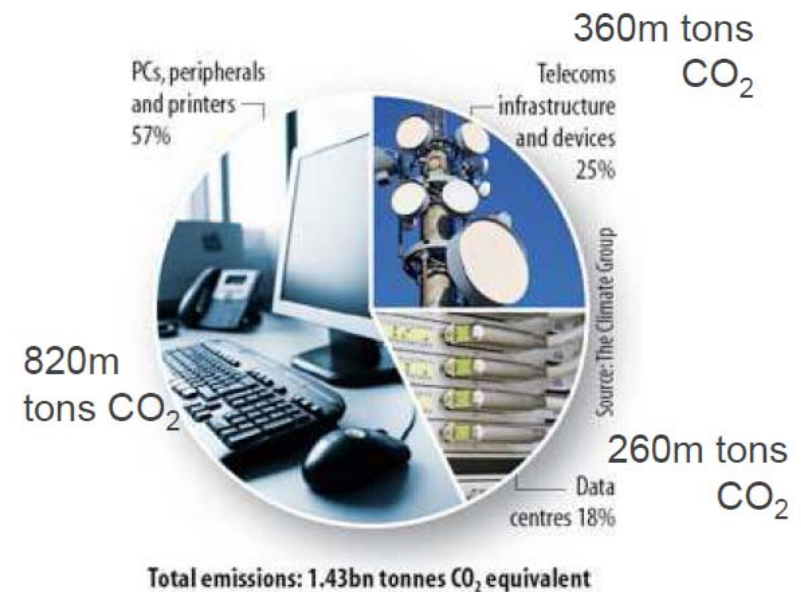
World wide ICT Carbon footprint



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%

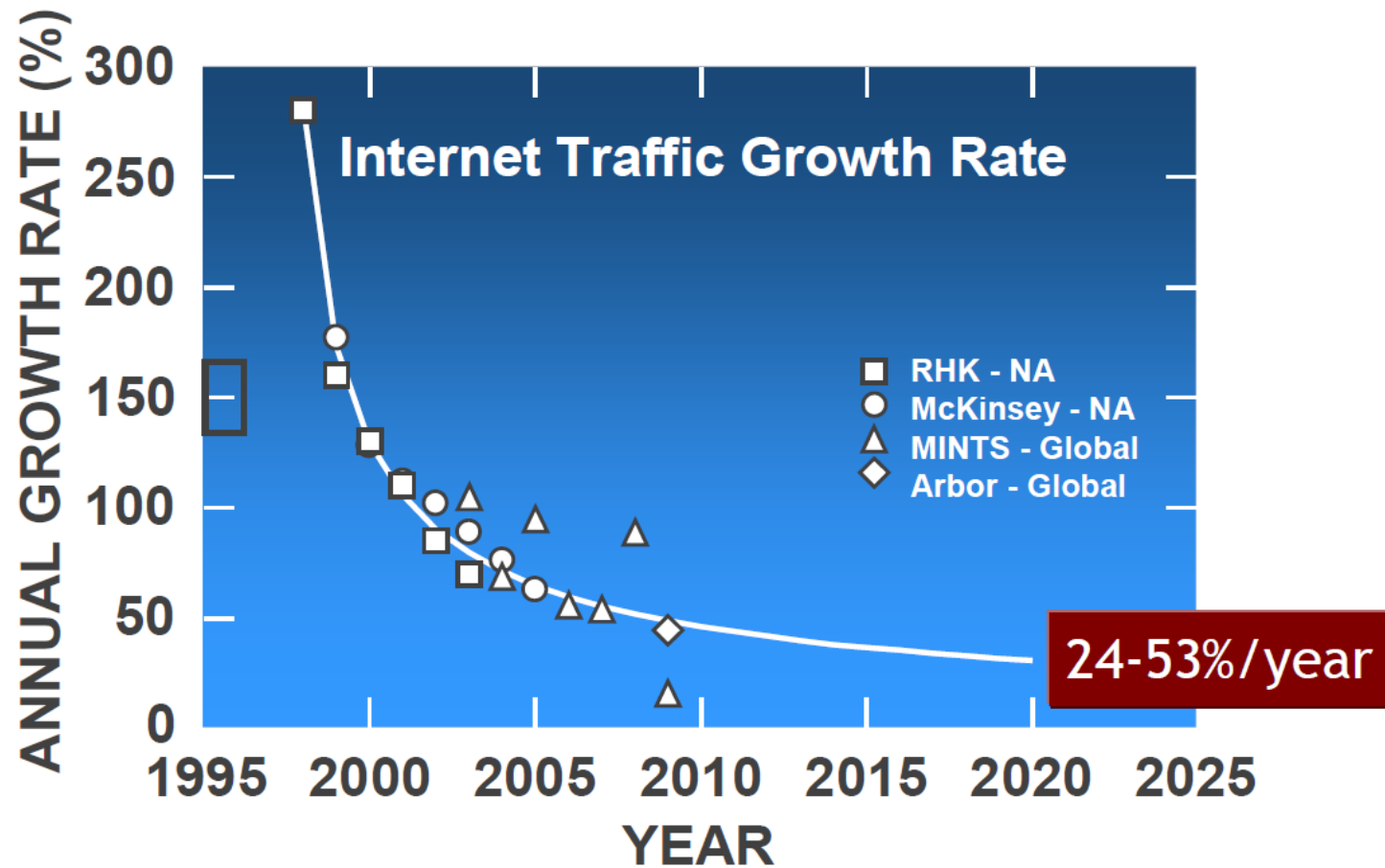
S.Roy, IEEE Intelec 2008

Smart Grids Smart Transportation
Smart Communities
Enabling a Low Carbon Economy
Smart Buildings E-Health



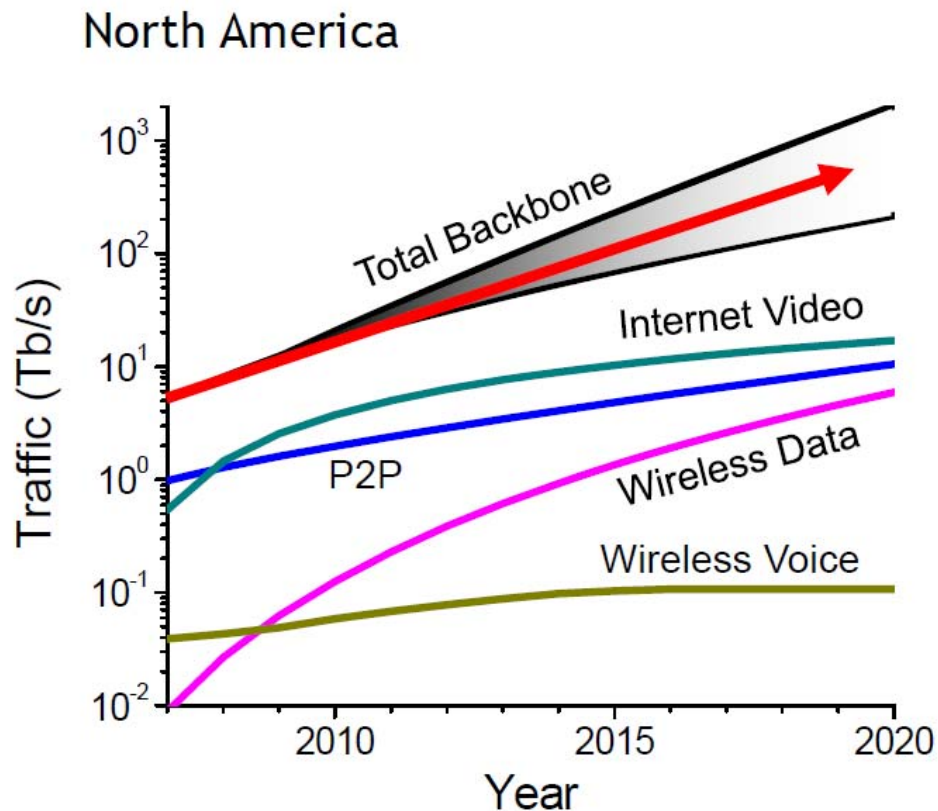
- 2007 Worldwide ICT carbon footprint: 2% = 830 m tons CO₂
- Comparable to the global aviation industry
- Expected to grow to 4% by 2020

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 $\log(\text{traffic growth rate})$
versus $\log(\text{time})$ with Bayesian learning to compute uncertainty

INTelligent Energy awaRe NETworks (INTERNET)

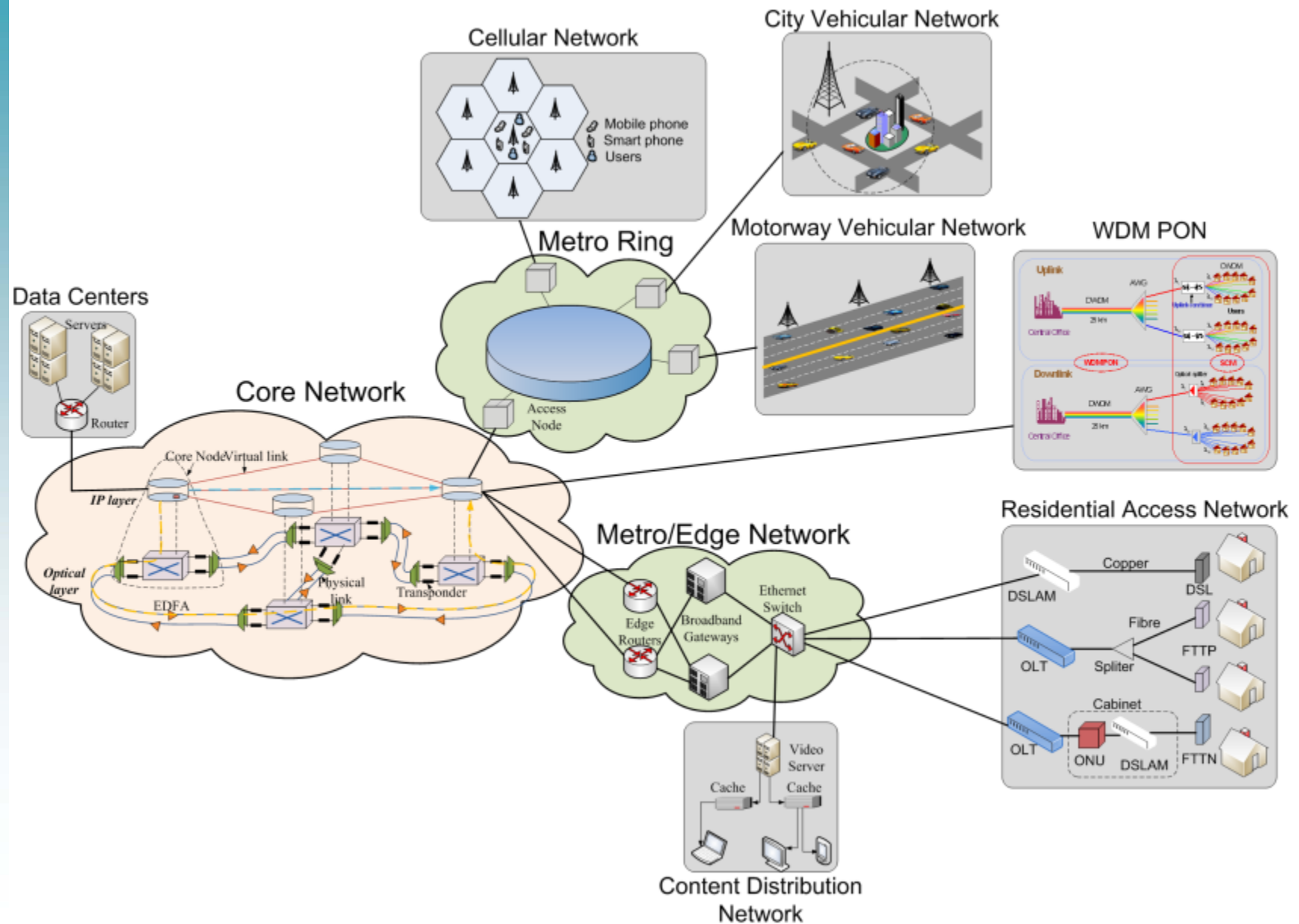
Project Goals

- 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.

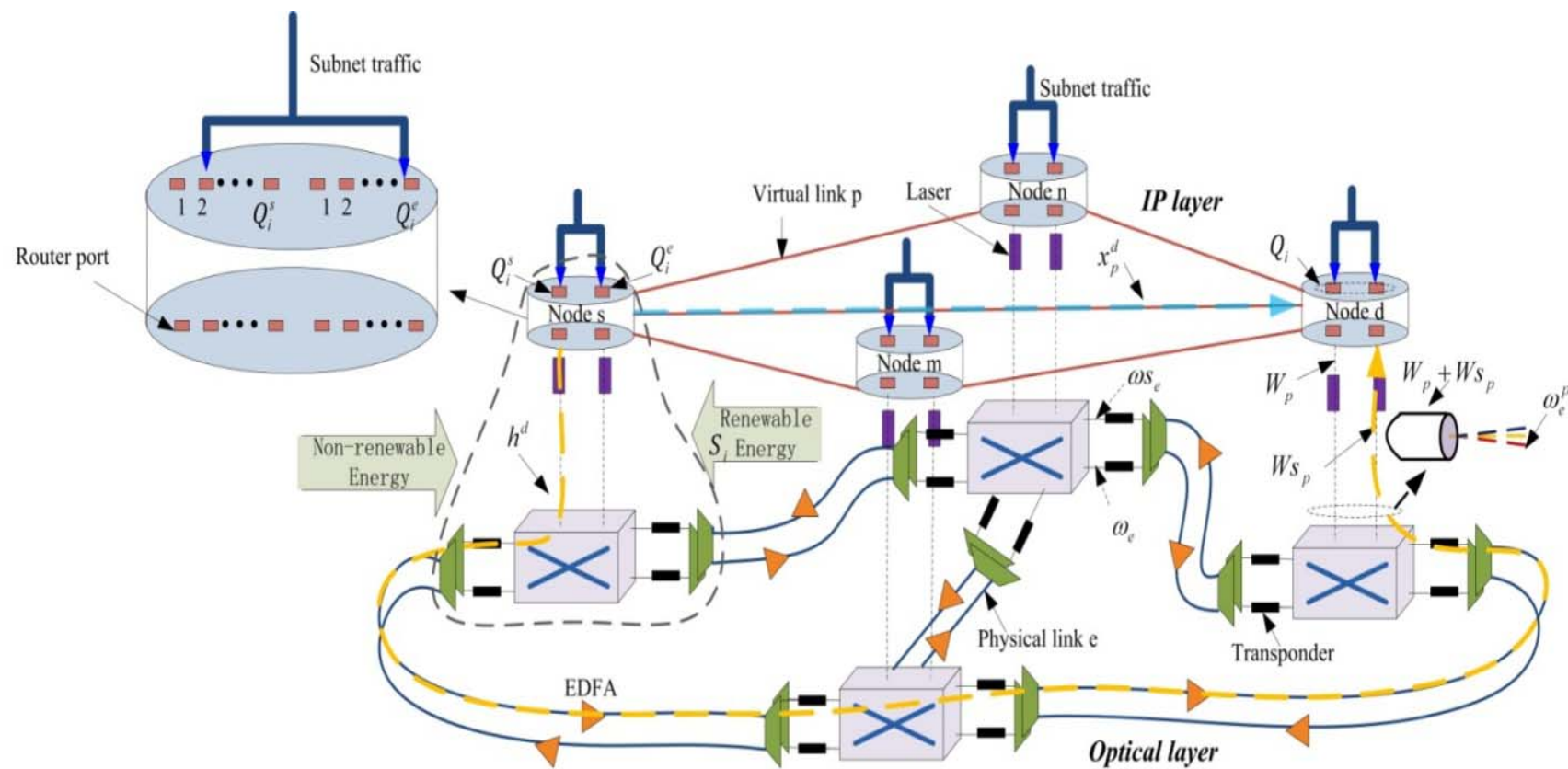
Collaborators



End-to-end network



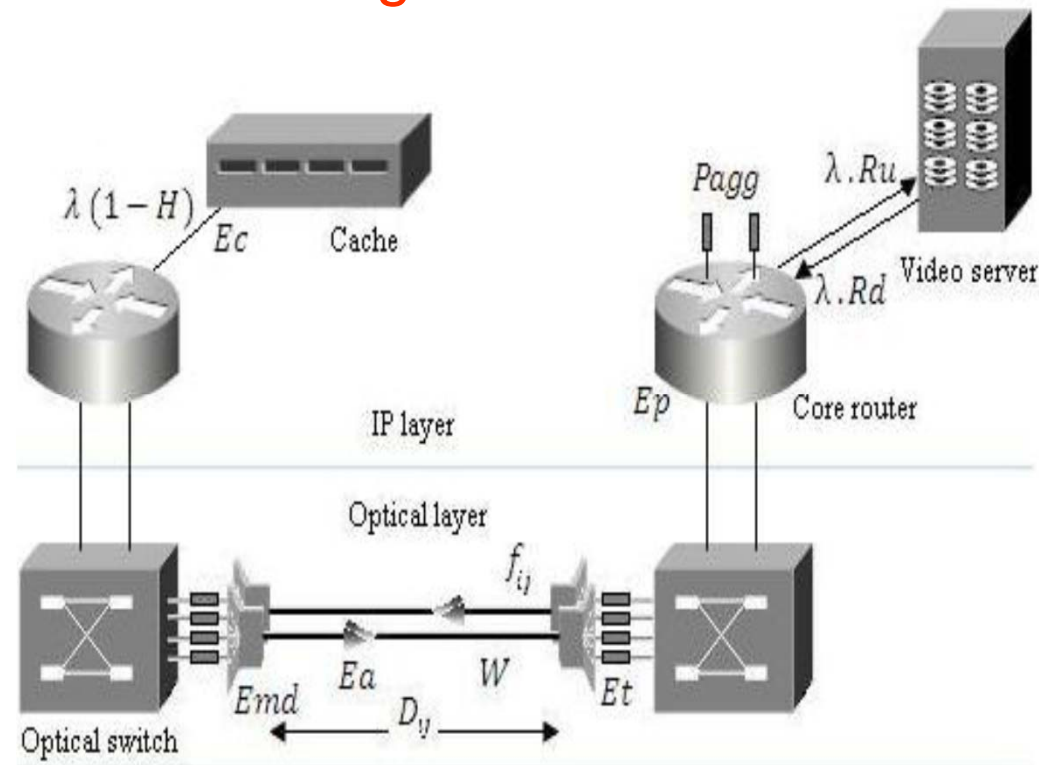
IP over WDM network architecture



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:

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

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:

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

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

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

Subject to:

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

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

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

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

Constraints on
number of router
ports available

Number of
wavelength used not
more than those in
fibre

LP Model for Energy Efficient Caching

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

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

Flow conservation constraint in the optical layer

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

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

Flow conservation constraint for regular traffic in the IP layer

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

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

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

LP Model for Energy Efficient Caching

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

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

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

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

Number of aggregation
ports used

$$\sum_{x \in N} \sum_{y \in N: x \neq y} (\lambda_{ijt}^{xy} + \lambda_{ijt} - u_{ijt}^{xy} + \lambda_{ijt} - d_{ijt}^{xy}) \leq C_{ijt} \cdot B \quad \forall i, j \in N, \forall t \in T$$

Traffic on a wavelength
does not exceed its
capacity

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

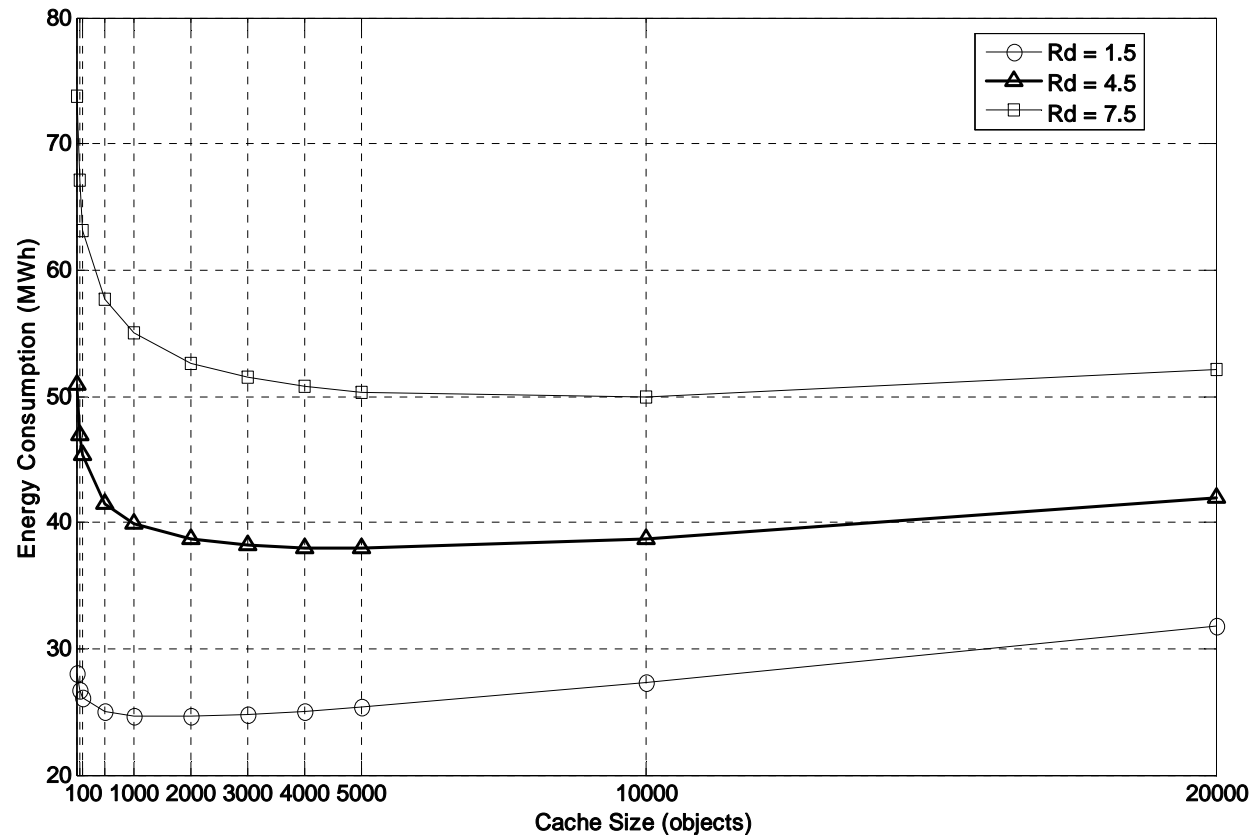
Piecewise
linear approximation of
convex hit ratio

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 (R_u) and downlink traffic ratios (R_d) to match the input and output rates of a typical video server and reflect the expected growth in VoD traffic:
 - 1) $R_d=1.5$ and $R_u=0.2$, 2) $R_d=4.5$ and $R_u=0.6$ and 3) $R_d=7.5$ and $R_u=1.0$
- A library of 2 million objects of the same size.
- Object popularities follow a Zipf-like distribution:

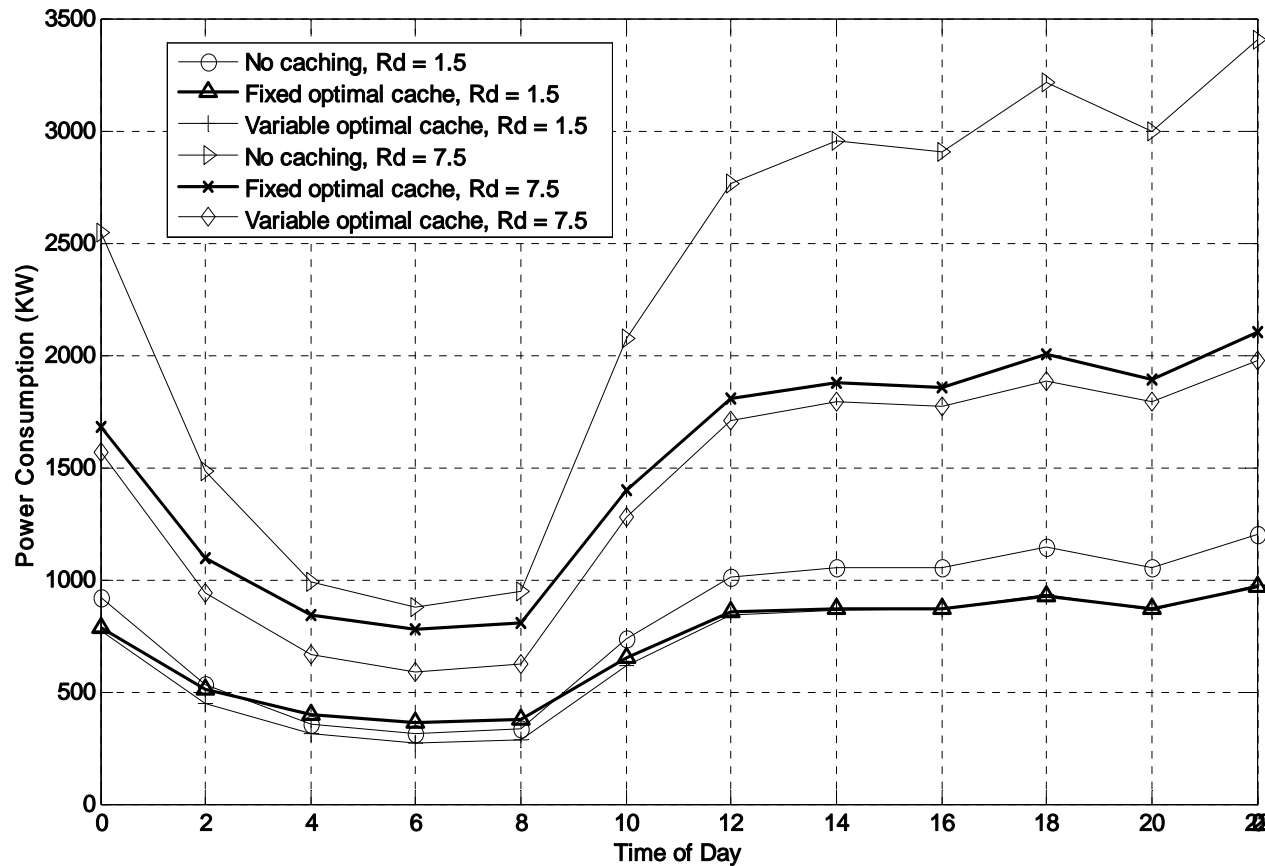
$$P_i = 1/(i \cdot \ln N)$$

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.

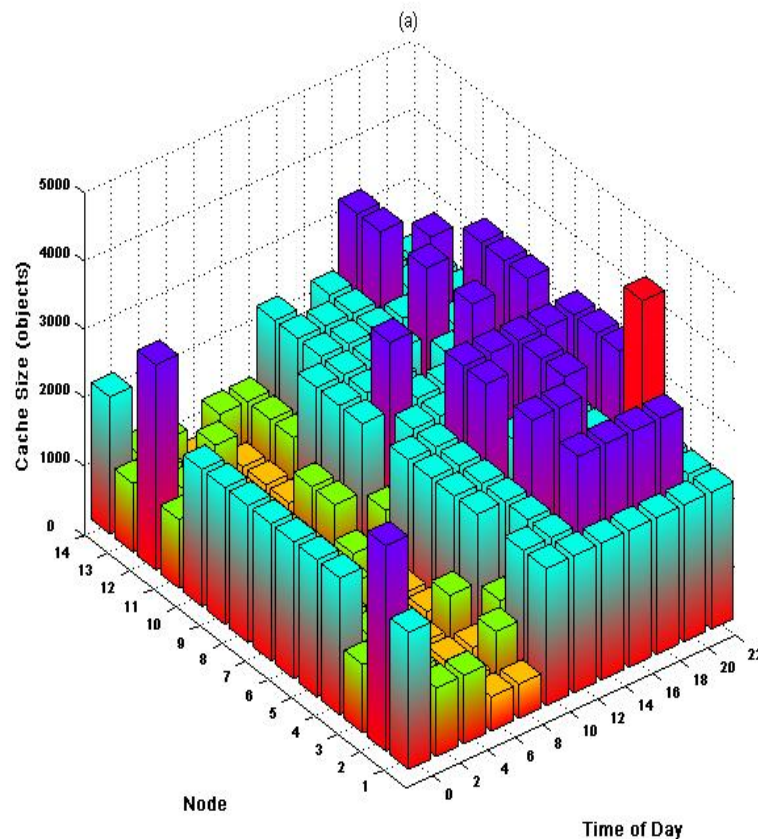
Cache size optimization



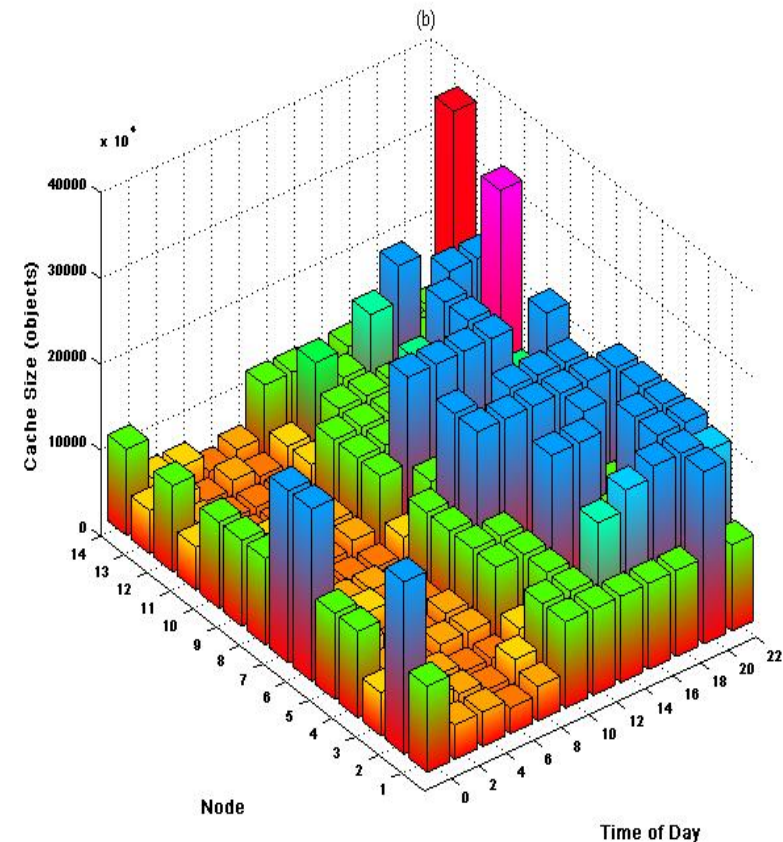
Variable
size cache
max
network
power
saving 42%

- 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 ($R_d=1.5, R_u=0.2$) and ($R_d=7.5, R_u=1$), respectively.

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

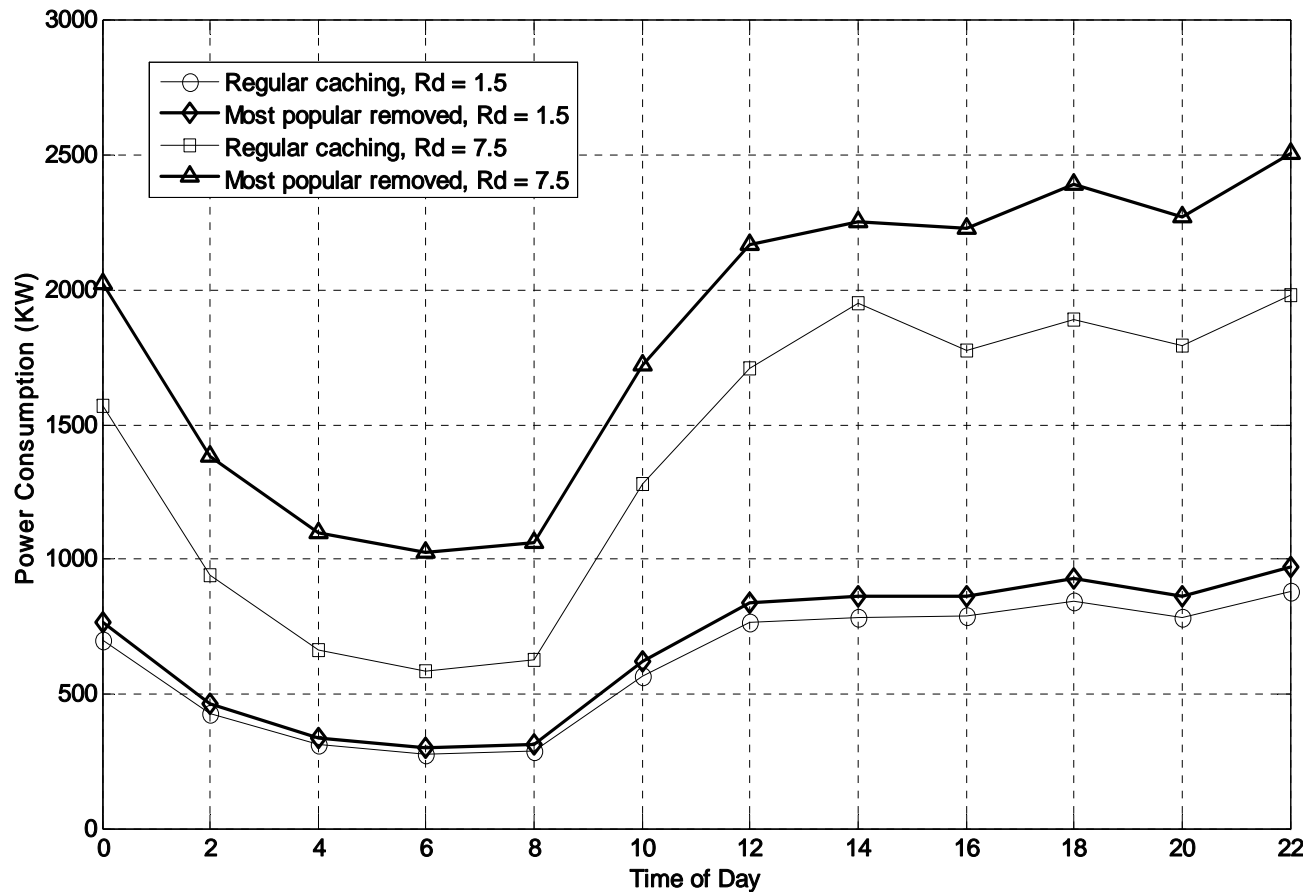


(a) $Rd = 1.5$



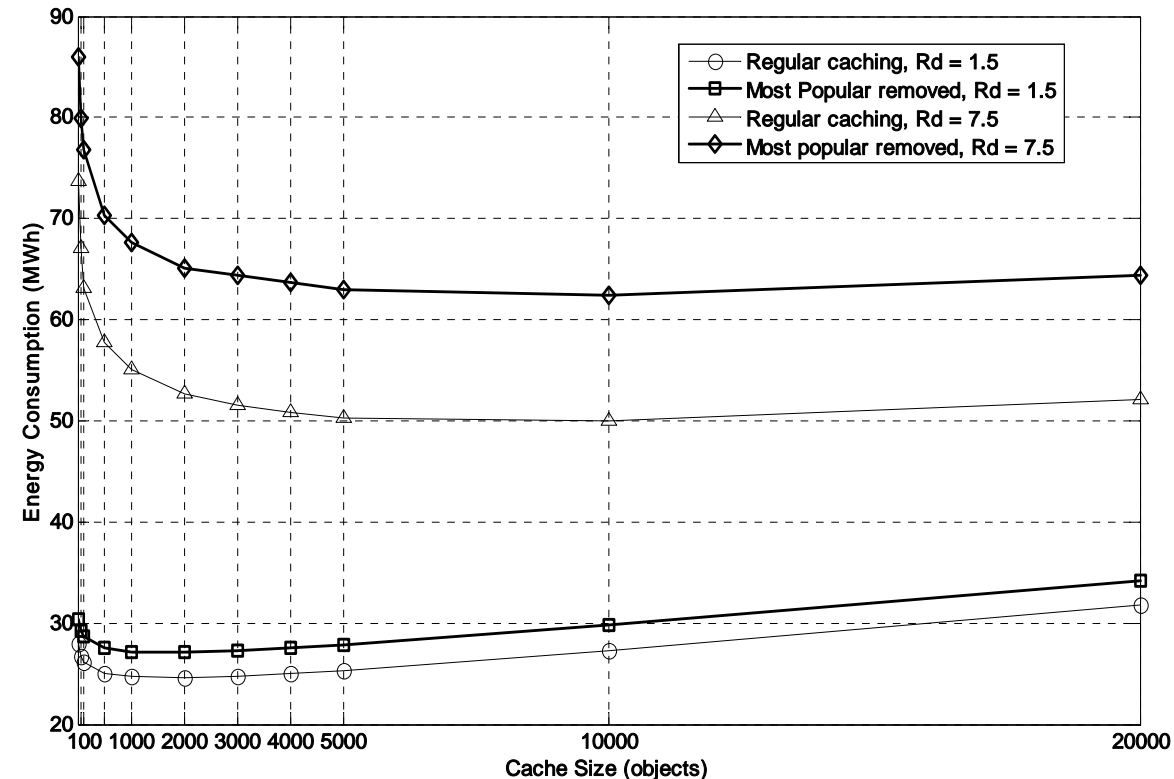
(b) $Rd = 7.5$

The Impact of removing the most popular objects



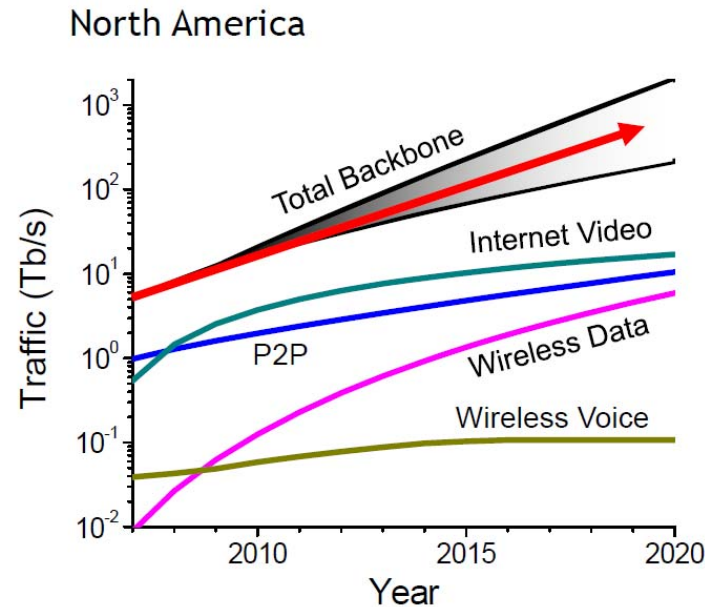
- The power consumption increases by removing the 10 most popular items.
- Increase in the power consumption of the network by over 20% (average 18.4%) for ($R_d=7.5$, $R_u=1$).

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 $\log(\text{traffic growth rate})$
versus $\log(\text{time})$ with Bayesian learning to compute uncertainty

Doubling every 2 years

- 40% per year
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Mix of services is important
from energy perspective:

- Mobile less efficient than
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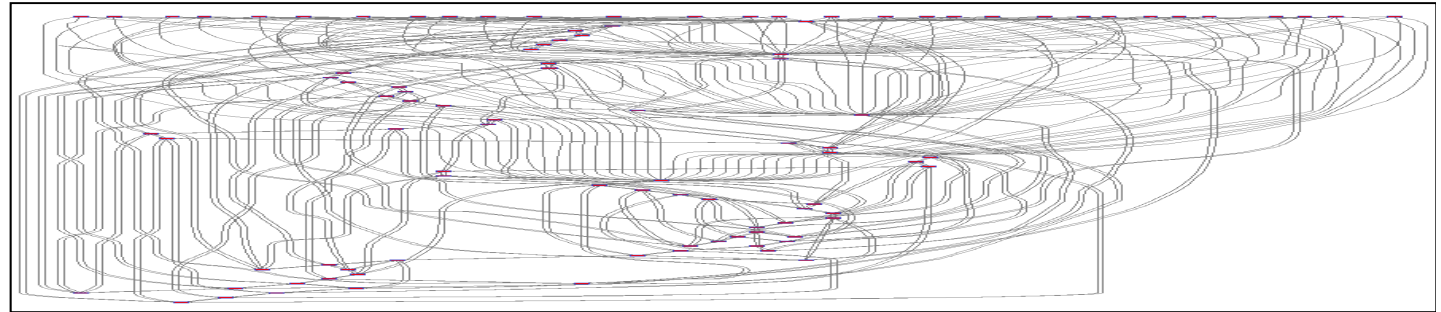
- The two content distribution schemes, Client/Server (C/S) and Peer-to-Peer (P2P), account for a high percentage of the Internet traffic.
- We investigate the energy consumption of BitTorrent in IP over WDM networks.
- We show, by mathematical modelling (MILP) and simulation, that peers' co-location 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

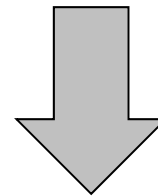
- The file is divided into small pieces.
- A **tracker** monitors the group of users currently downloading.
- Downloader groups are referred to as **swarms** and their members as **peers**. Peers are divided into **seeders** and **leechers**.
- As a leecher finishes downloading a piece, it selects a 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

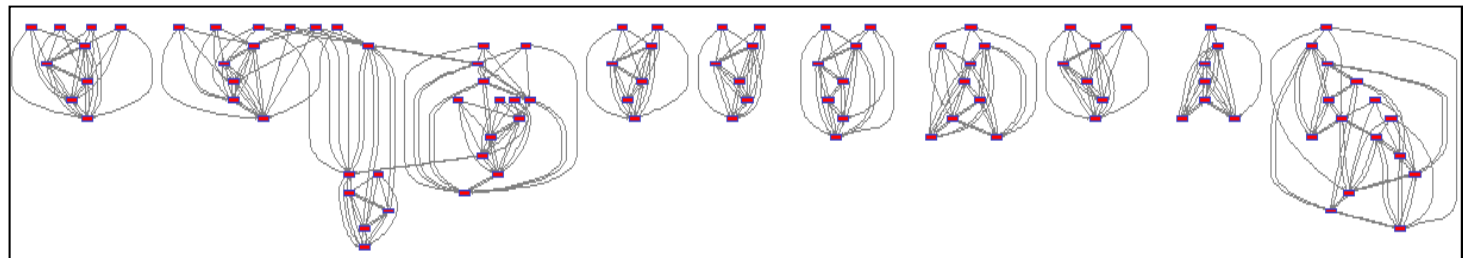
(100 Peer: 30 Seeders and 70 Leechers in Swarm 1)



Original BitTorrent (Random Selection)

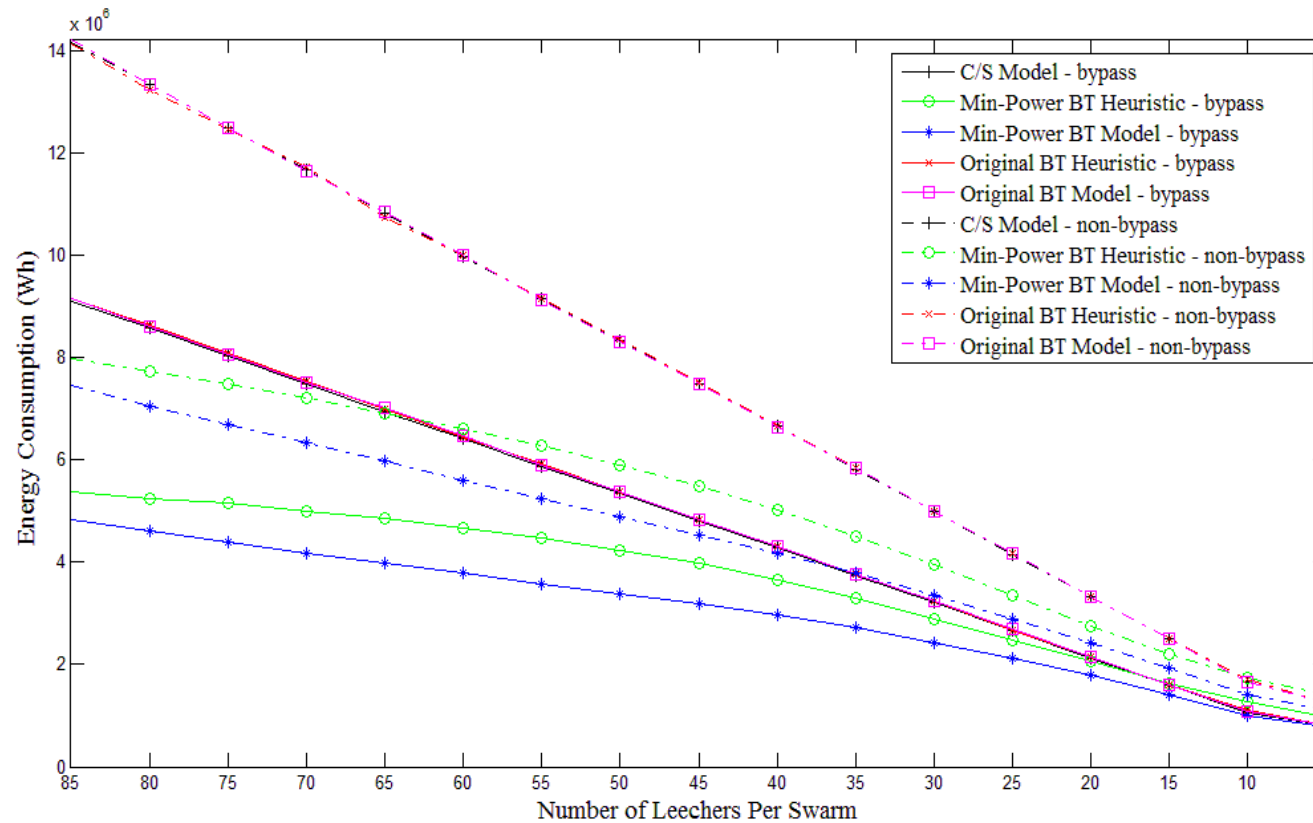


Energy Efficient BitTorrent (Optimized Selection)



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

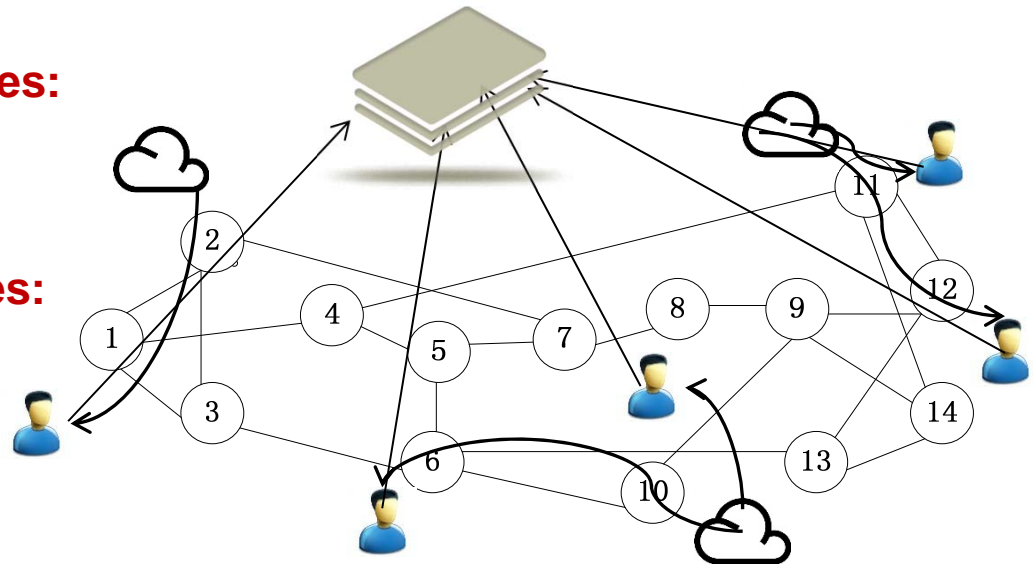
We develop a MILP model for cloud content delivery in IP/WDM networks to answer whether centralised or distributed content delivery is the most energy efficient solution. Two types of decision variables are optimized for the cloud service model:

- **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

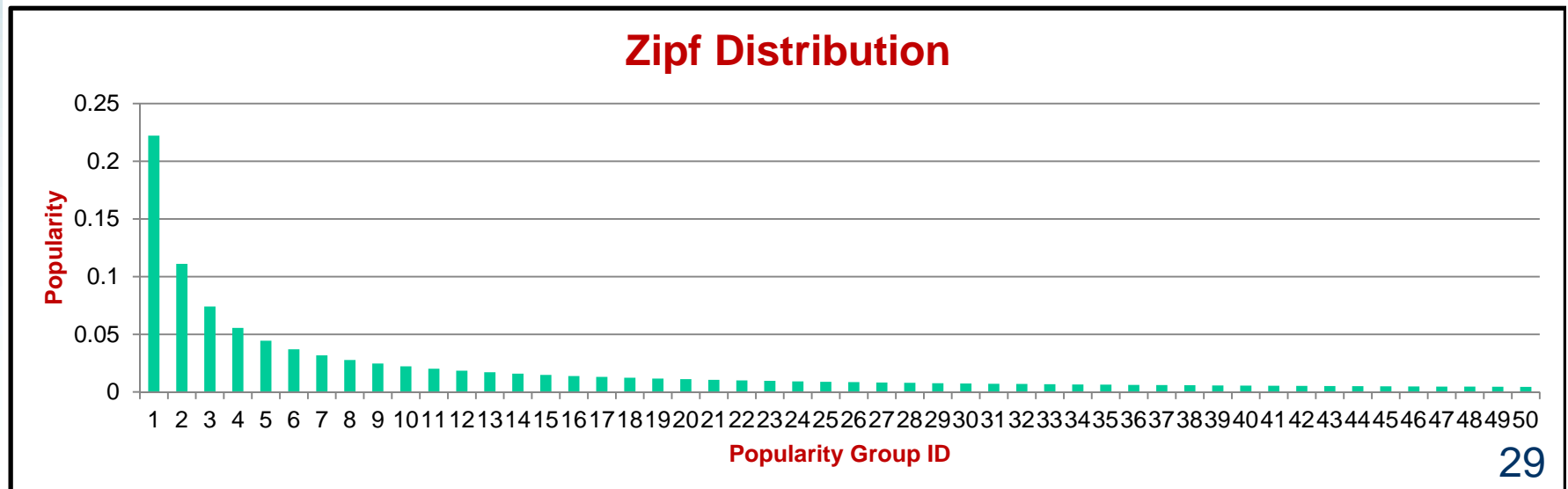
- **Popularity group:** Content requested with similar frequency by users is placed in a popularity group.
- **Zipf distribution:** The Zipf popularity distribution for a stored object i is given by

$$P(i) = \varphi / i$$

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

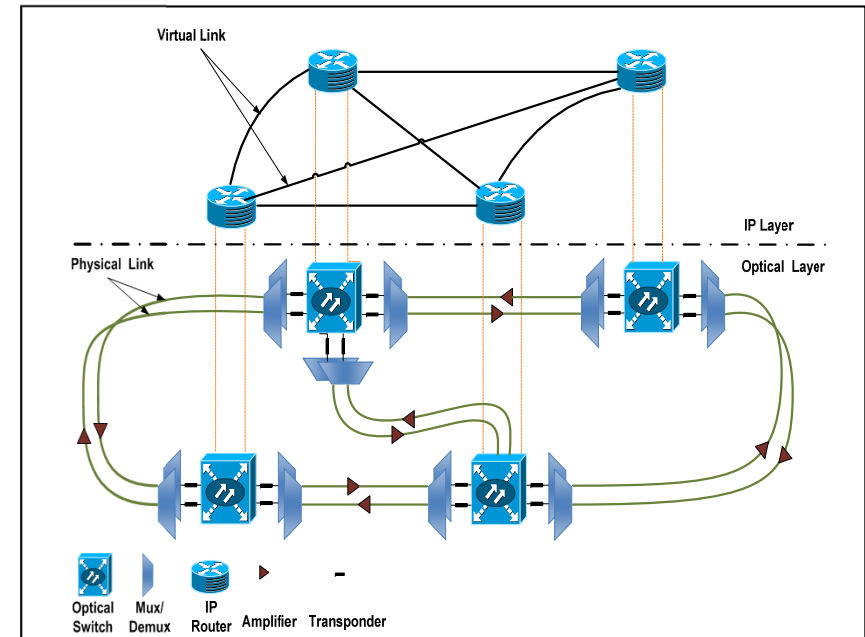
$$\sum_{m \in N} \sum_{n \in Nm_m} Pe \cdot A_{mn} \cdot F_{mn}$$

- 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*):

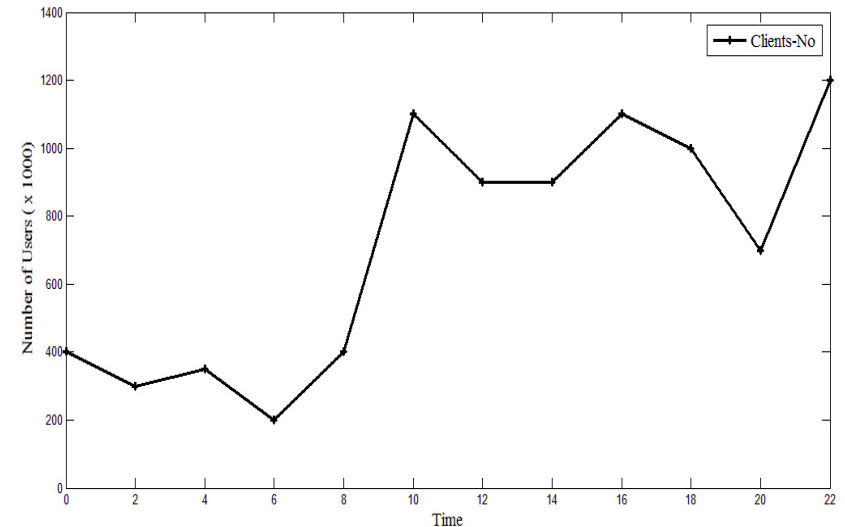
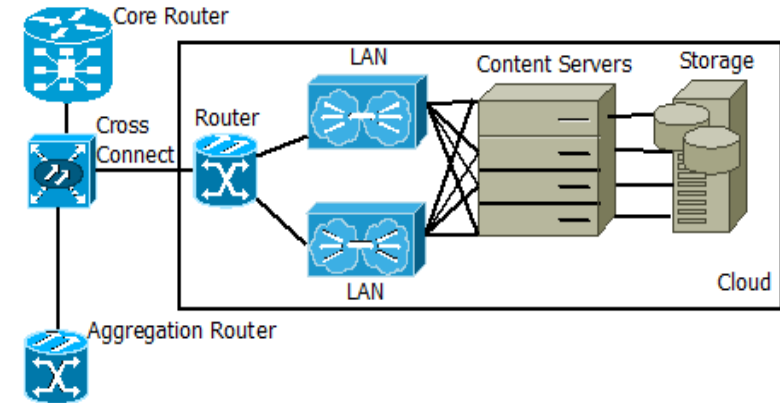
$$\sum_{s \in N} Cup_s \cdot CS_{EPB}$$

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

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

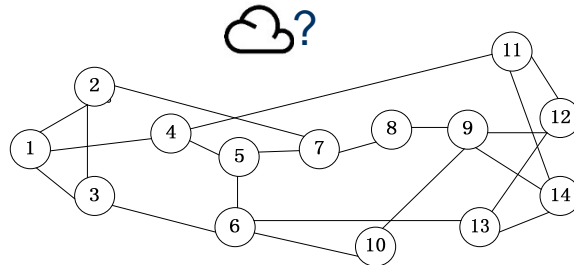
3) Power consumption of storage (*StPC*):

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

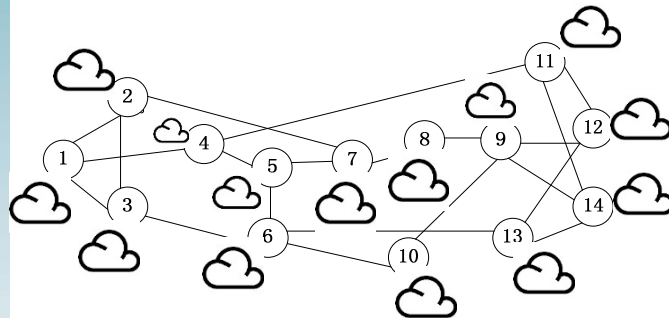


We assume number of users fluctuates between 200k and 1200k users in a day in our analysis.

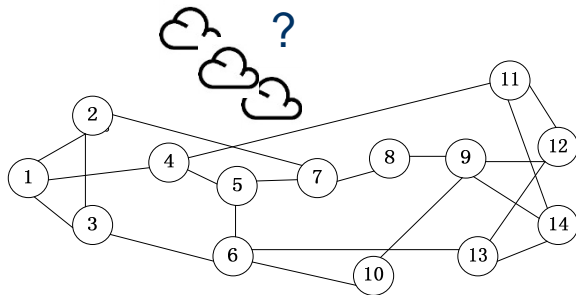
Scenarios



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)

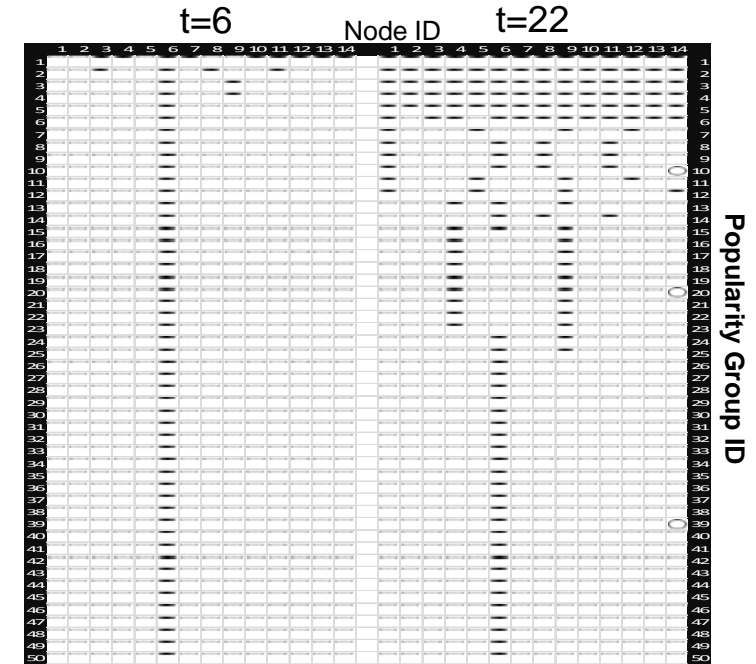
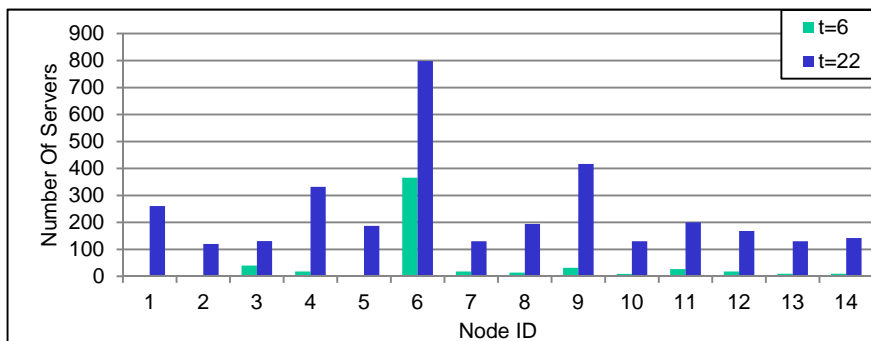
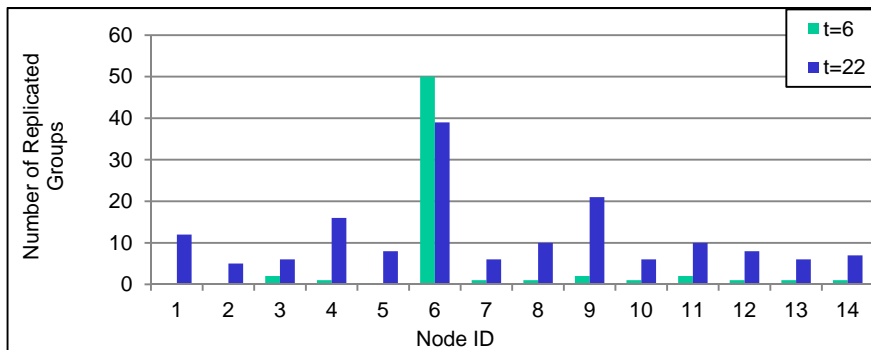
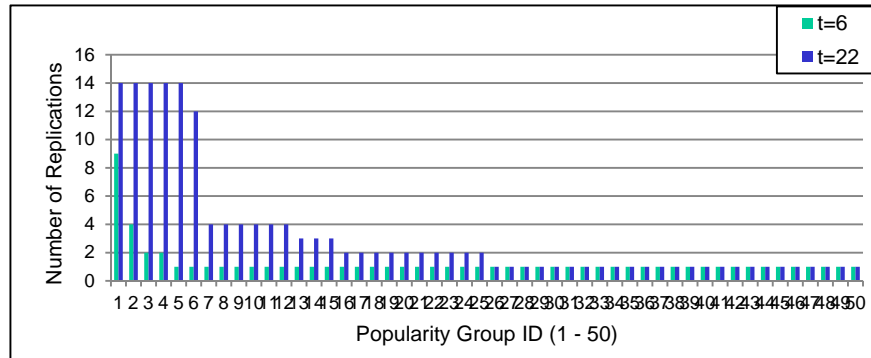
With Power Management

Popularity Based Content Replication (OPR)

Storage=75.6*5TB

● Object replicated here

○ Object not replicated



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

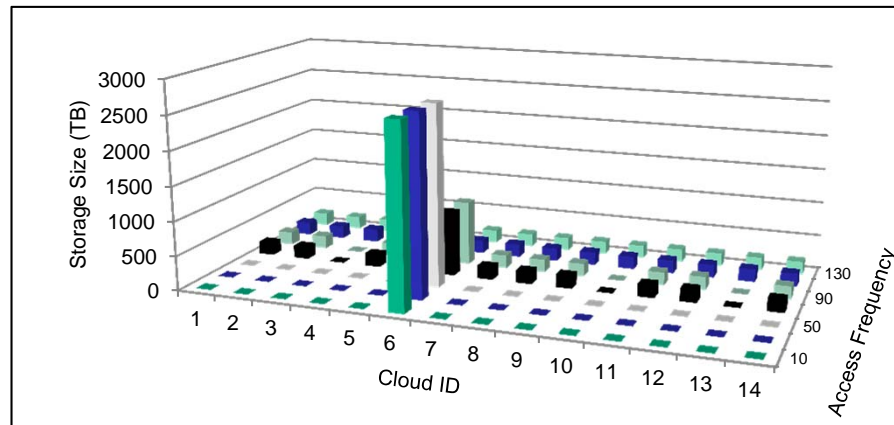
- Two Average document sizes are evaluated, 45MB and 22.5MB
- Number of users evaluated are 1.2M
- Users are uniformly distributed in the network.
- Users download rate (D_{rate} : in Gb/s) depends on:
 - Document access frequency ($Freq$: *Number of downloads per hour*)
 - Document size (D_{size} :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

$$D_{rate} = 2 \cdot Freq \cdot D_{size} / 3600$$

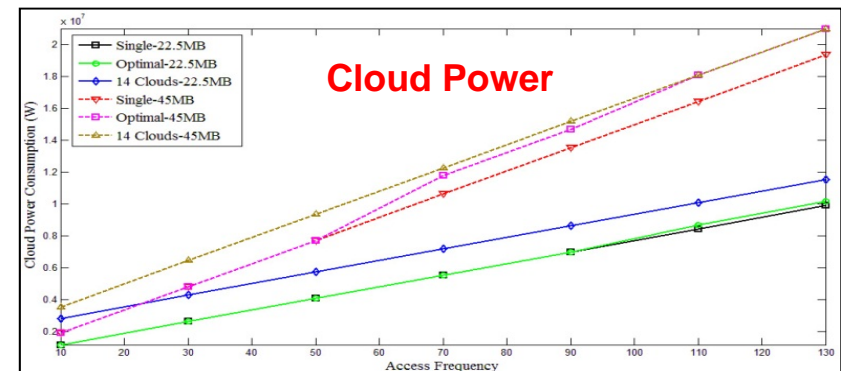
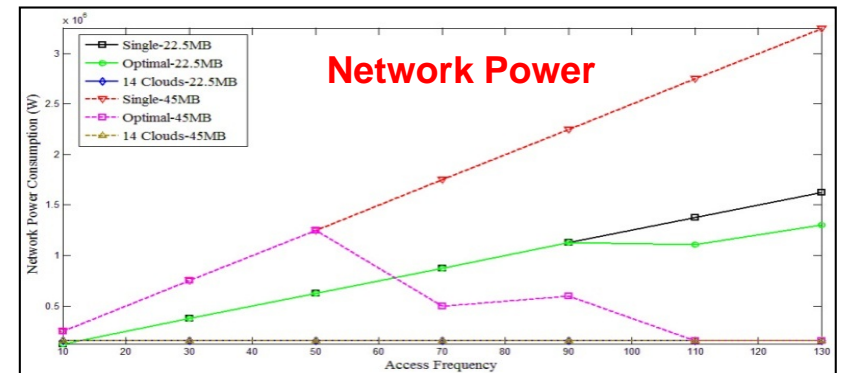
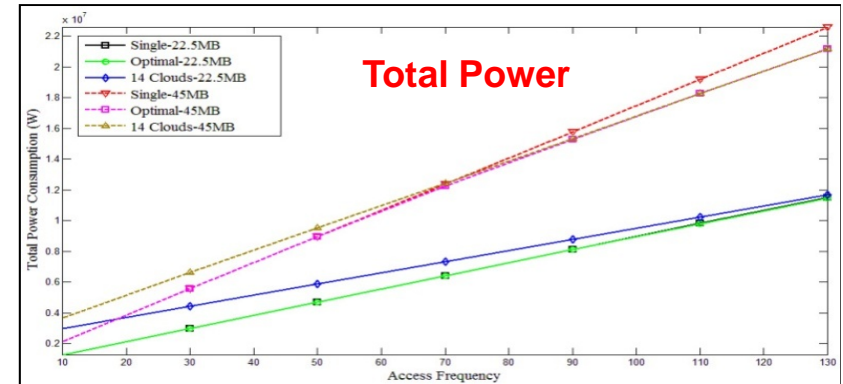
The factor of 2 is to take the fact that users usually re-upload their content after downloading it back to their *StaaS* drive into account.

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

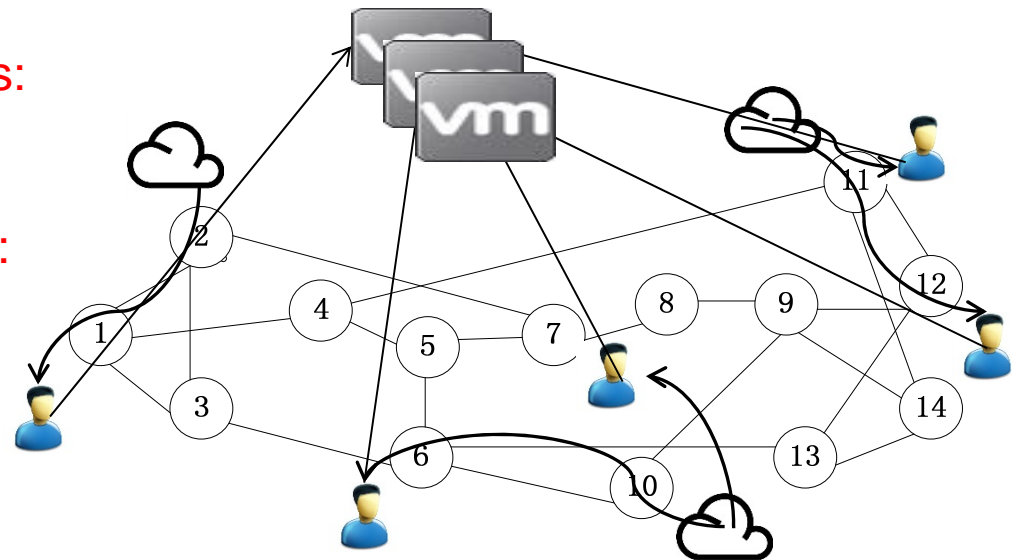
Scenarios

- **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

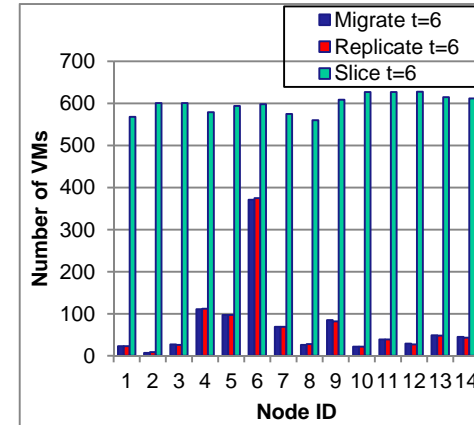
DEER-VM Heuristic

- **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.

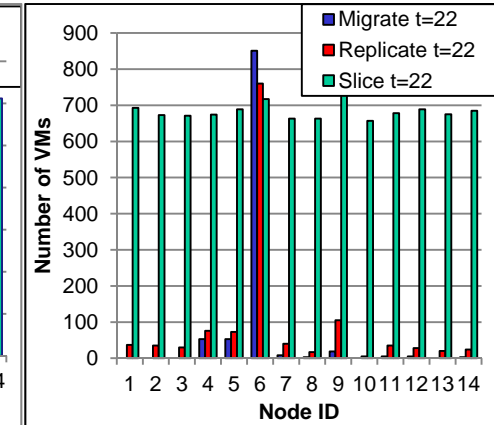
DEER-VM Heuristic

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)
1.	For each Virtual Machine $v \in VMD$ Do
2.	For each Placement $j \subseteq List$ Do
3.	For each node $d \in N$ Do
4.	For each location candidates $e \in J$ Do
5.	Add{cost _{sd} } = MinHop (s,d)
6.	CW _{vjs} = W _v
7.	End For
8.	Get s where: cost _{sd} = Min{cost _{sd} }
9.	L _{vjsd} = D _{vd}
10.	End For
11.	NPC _{vj} = MultiHopHeuristic(N, N _m , L _{vjsd})
12.	CPC _{vj} = PUE _c · (SrvPC + LANPC)
13.	TPC _{vj} = NPC _{vj} + CPC _{vj}
14.	End For
15.	TPC _v = Min{TPC _{vj} }
16.	J' = j
17.	End For
18.	Calculate TPC = $\sum_{v \in VM} TPC_v$

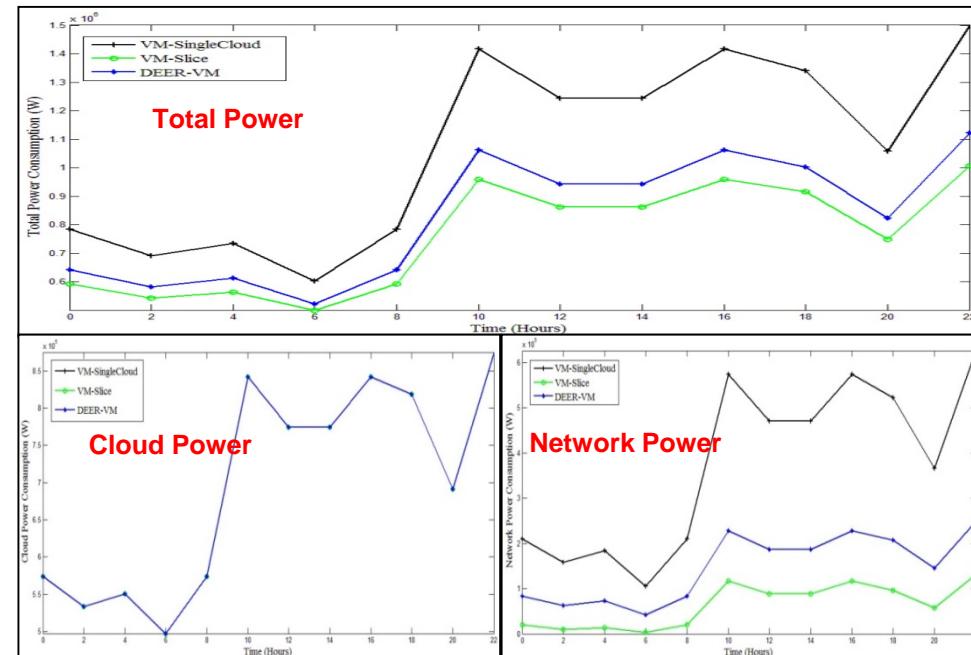
Scenario	Total Savings	Network Saving
VM-Slice-MILP	27.5%	86%
DEER-VM	21%	60%



Model VMs Distribution Scheme at t=06:00



Model VMs Distribution Scheme at t=22:00



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.

Related Publications

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.