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Modeling of Content Dissemination Networks on Multiplexed Caching Hierarchies

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Outline

Analytical Model of Distributed Cache Mechanisms like CCN

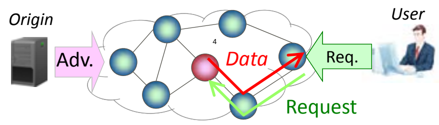
Background

- **IP Traffic Growth**
  - IP traffic is growing at an annual growth rate of about 25%
  - CDNs (Content Delivery Networks) have prevailed and are expected to carry 50% of Internet traffic by 2017.

- **CCN (Content-Centric Networking) / ICN (Information-Centric Networking)**
  - In-network caching technologies are highly expected to reduce the network traffic and improve network performance.

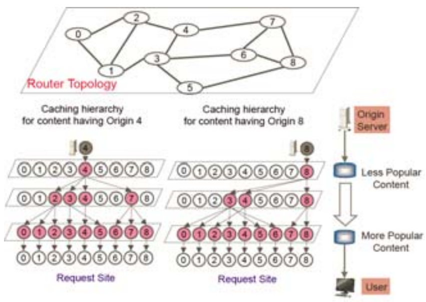
Content-Centric Networking

- **Content Advertisement**
  - Origin servers advertise newly released content in the network.
- **Content Discovery and Delivery**
  - A content request is forwarded on each *CR* (Content Router) until the requested content is found.
  - When the requested content is found on a *CR, Data* of the content are transmitted on the reverse route along the request forwarding route.
- **Content Store**
  - Data are cached on *CR*s along the transmission route.



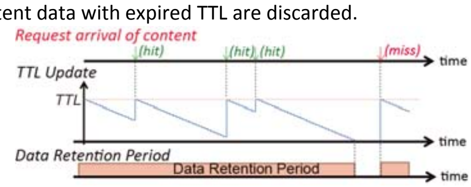
Caching Hierarchy in CCN

- *Data* of content are transmitted on the delivery tree rooted at its origin site.
- For content having the same origin site, the cache mechanism constructs a caching hierarchy rooted at the origin site.



Cache Management

- **LRU(Least Recently Used) / LFU(Least Frequently Used) Caching**
  - The least popular content is replaced with newly requested data when the memory overflows.
- **TTL-based Caching**
  - Each content has a limited period of time, called *Time-To-Live* (*TTL*) for content.
  - Content data with expired TTL are discarded.



Resource and Performance Tradeoffs

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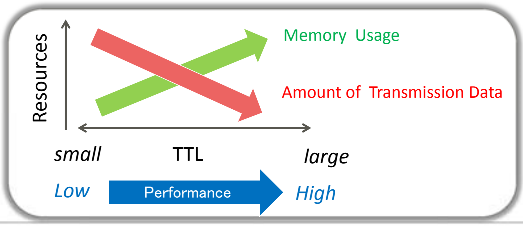
- **TTL Value: *Large***
  - Memory Usage: *Large*
  - Amount of Transmission Data: *Small*
  - Performance: *High*
    - Cache hit ratio: *High*
    - Communication latency: *Low*



Issue and Approach

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- **Issue**
  - To evaluate the impact of TTL-based caching on network resources and performance in the caching hierarchies
- **Approach**
  - To model the cache characteristics of the hierarchical cache system using a request propagation matrix for each caching hierarchy

Model of Cache Hit Ratio of a CR

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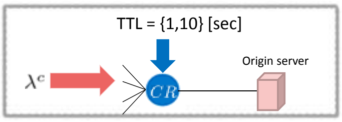
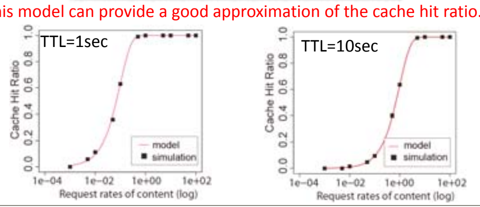
- **Cache Hit Ratio using TTL at a Cache Node** [8]

$$f(\lambda^c, TTL^c) = 1 - e^{-\lambda^c TTL^c}$$

λ^c: Request rate of content c based on an exponential distributed interval



This model can provide a good approximation of the cache hit ratio.



Request Propagation Model

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- **Request Propagation Model in a Caching Hierarchy**

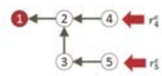
$$\mathbf{\Lambda}^c[s+1] = \mathrm{D}^c[s] \cdot \mathbf{\Lambda}^c[s] + \mathbf{R}^c, \forall c$$

$$\mathbf{\Lambda}^c[s] := \begin{bmatrix} \lambda^c_{(1,1)}[s] & \cdots & \lambda^c_{(1,N)}[s] \\ \vdots & \ddots & \vdots \\ \lambda^c_{(M,1)}[s] & \cdots & \lambda^c_{(M,N)}[s] \end{bmatrix} \quad [\mathbf{R}^c]_{ij} := \begin{cases} r^c_j, \text{when } CR_i \text{ is located on } j\text{-th request site} \\ 0 \quad \text{otherwise} \end{cases}$$

$$\mathrm{D}^c[s] := \begin{cases} 1 - f(\sum_j^N \lambda^c_{(n,j)}[s], TTL^c), \forall m = parent\_node(n) \\ 0 \quad \text{otherwise} \end{cases}$$ ← Cache Miss Ratio of *CRn*

s : The number of steps that each request propagates to the next CR
$\lambda^c_{i,j}$: Request rate of content c from the requesting user in site j to CR_i
r^c_i : Request rates r^c_i of content c from users in site i

Example



$$\mathbf{\Lambda}^c[s] = \begin{bmatrix} \lambda^c_{(1,4)}[s] & \lambda^c_{(1,5)}[s] \\ \lambda^c_{(2,4)}[s] & \lambda^c_{(2,5)}[s] \\ \lambda^c_{(3,4)}[s] & \lambda^c_{(3,5)}[s] \\ \lambda^c_{(4,4)}[s] & \lambda^c_{(4,5)}[s] \\ \lambda^c_{(5,4)}[s] & \lambda^c_{(5,5)}[s] \end{bmatrix} \quad \mathrm{R}^c = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ r^c_4 & 0 \\ 0 & r^c_5 \end{bmatrix}$$

$$\mathrm{D}^c[s] = \begin{bmatrix} 0 & e^{-\sum_{j=4}^5 \lambda^c_{(2,j)} TTL^c} & 0 & 0 & 0 \\ 0 & 0 & e^{-\sum_{j=4}^5 \lambda^c_{(3,j)} TTL^c} & e^{-\sum_{j=4}^5 \lambda^c_{(4,j)} TTL^c} & 0 \\ 0 & 0 & 0 & 0 & e^{-\sum_{j=4}^5 \lambda^c_{(5,j)} TTL^c} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Model of Resources / Performance

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- **Memory usage of content *c* at *CRi***

$$\mathrm{U}^c_i := \theta_c f(\sum_j^N \lambda^c_{(i,j)}, TTL^c). \qquad \theta_c\text{: Data size}$$

- **Total amount of data delivery of content *c* through all *CRs***

$$\mathrm{Dt}^c := \theta_c \sum_j Tr^c_j$$

Hop-length between two *CRs*

$$\mathbf{Tr}^c := [Tr^c_1 \cdots Tr^c_j \cdots Tr^c_N]^{\mathrm{T}} = (\mathbf{H} * \mathbf{\Lambda}^c)^{\mathrm{T}} \begin{bmatrix} f(\sum_j \lambda^c_{(1,j)}, TTL^c) \\ \vdots \\ f(\sum_j \lambda^c_{(M,j)}, TTL^c) \end{bmatrix}.$$

- **Cache hit ratio of content *c* in the network**

$$\mathrm{CHR}^c := 1 - \frac{\sum_j^N \lambda^c_{(o,j)} \left(1 - f(\sum_j^N \lambda^c_{(o,j),TTL^c})\right)}{\sum_k^M r^c_k}.$$

- **Average Hop Length of content *c***

$$\mathrm{AHL}^c := \frac{\sum_j^N \left(Tr^c_j + \mathrm{Hp}^o \lambda^c_{(o,j)}(1 - \mathrm{f}(\sum_k^N \lambda^c_{(o,k)}, TTL^c)\right)}{\sum_j^N r^c_j}$$

Model of Power Consumption

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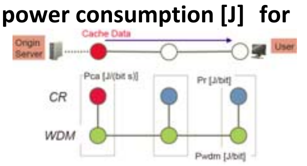
- **Cache Allocation Power: power consumption [J] for storing data of content *c* in 1 sec**

$$\mathrm{CP}^c := \theta_c P_{ca} \sum_i^M f(\sum_j^N \lambda^c_{(i,j)}, TTL^c),$$

- **Traffic Transmission Power: power consumption [J] for delivering content *c***

$$\mathrm{TP}^c := (P_r + P_{wdm})\mathrm{Dt}^c$$



Assumption

- *Energy Proportional Networks* which power consumption of each device is proportional to its usage for a network composed of *CRs* and Wavelength Division Multiplexing (WDM)

Example

TABLE II: POWER DENSITY PARAMETERS

Device (Product)	Power / Spec	Power Density
DRAM	10 W / 4 GB	$P_{ca} = 3.125 \times 10^{-10}$ J/(bit · s)
Content Router (CRS-1)	4185 W / 320 Gbps	$P_r = 1.3 \times 10^{-8}$ J/bit
WDM (FLASHWAVE9500)	800 W / 480 Gbps	$P_{wdm} = 1.67 \times 10^{-9}$ J/bit

Evaluation1: Model Verification

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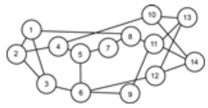
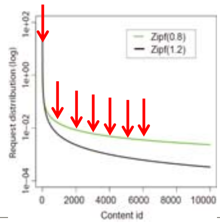
- **Approach**
  - To compare "cache hit rate" and "average hop length" for 7 contents measured by simulation with those estimated by the proposed model
- **Evaluation Conditions**
  - Target network: NSF network
  - TTL value :{1,20,40,60} [sec]
  - 7 content items in 10000 content items:
    - {1,1000,2000,…,6000}
  - Origin site: Uniform distribution
  - Content size: Geometric distribution
    - Average size 10 Mbytes
  - The total number of requests from each site:
    - 100 [requests/sec]
  - Content popularity: Zipf(0.8)
  - Memory size of each *CR:* sufficiently large
  - Simulation time: 3200 [sec]





Verification Results

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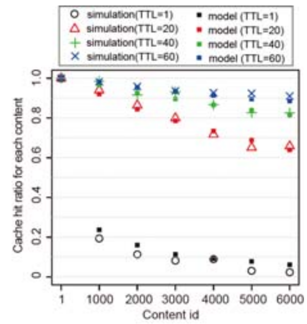
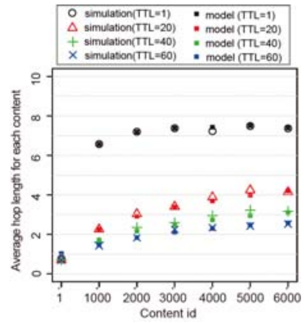
- The cache hit ratio and average hop length for each content provide suitable approximations of the simulation results.





Evaluation2: Impact of TTL

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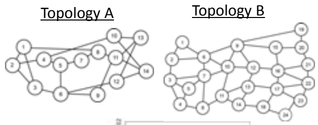
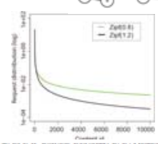
- **Approach**
  - To evaluate resource usage / power consumption / cache performance when TTL of all content is changed from 1 [sec] to 300 [sec]
- **Evaluation Conditions**
  - Target network: 2 Topologies
  - The number of content Items: 10000
  - Origin site: Uniform distribution
  - Content size: Geometric distribution
    - Average size 10 Mbytes
  - The total number of requests from each site:
    - 100 [requests/sec]
  - Content popularity: Zipf(0.8) , Zipf(1.2)
  - Memory size of each *CR:* sufficiently large
  - Power density parameters:Table2





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Memory Usage of Each CR

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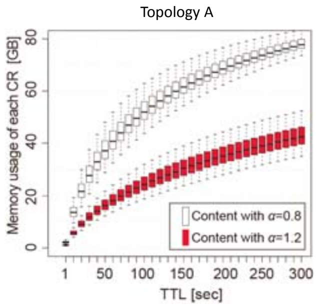
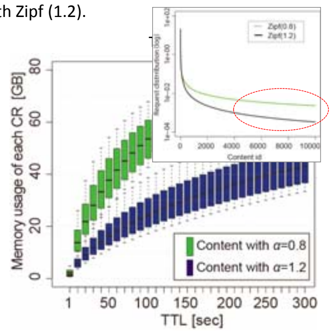
- The memory usage of each *CR* becomes larger as the TTL value becomes larger.
- The memory usage for content with Zipf (0.8) is larger than that for content with Zipf (1.2) because less popular content with Zipf (0.8) has higher request rates and is easier to be cached than that with Zipf (1.2).





Power Consumption

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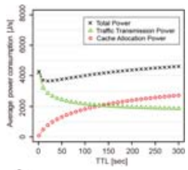
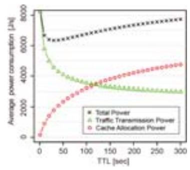
- These data demonstrate the tradeoff between "*cache allocation power*" and "*traffic transmission power*" for the change of the TTL value.
- The energy impact of TTL is also different depending on the network conditions.

The proposed model can search for the energy efficient TTL.

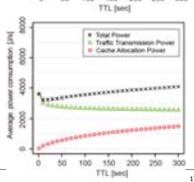
Content with Zipf(0.8) in Topology A



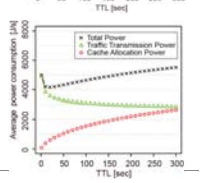
Content with Zipf(1.2) in Topology A



Content with Zipf(0.8) in Topology B



Content with Zipf(1.2) in Topology B



Cache Performance

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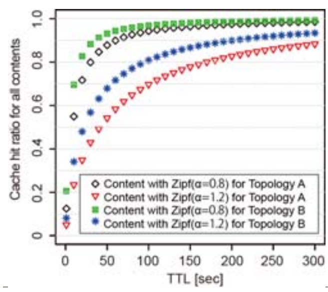
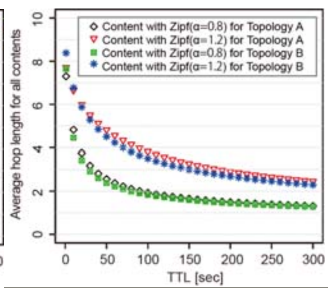
- The cache hit ratio approaches around 100 % as the average hop length is approaching 1 and the memory usage becomes larger.
  - The average hop length of 1 hop means that all content items are cached.
- The average hop length of all content items becomes smaller as the TTL becomes larger.





Conclusions

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Summary

- **Analytical Model using *TTL***
  - Evaluate the cache characteristics in the distributed cache system
  - Provide a design guideline for TTL of content in view of energy efficiency or efficient memory usage

Future Work

- We will study the following mechanisms using the proposed model.
  - “Memory Control Mechanism
  - “Cache Probability Control Mechanism”