Optimizing Cost and Performance for Content Multihoming

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Content Multihoming is Widely Used

Content Publisher

CDN-1

CDN-2

CDN-3

Content Viewers
Why Content Multihoming: Performance Diversity
Why Content Multihoming: Performance Diversity

Table: The fraction of successful deliveries for objects with streaming rate of 1Mbps | 2Mbps | 3Mbps.

<table>
<thead>
<tr>
<th></th>
<th>CloudFront</th>
<th>MaxCDN</th>
<th>Liquid Web</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>99.9</td>
<td>99.9</td>
<td>99.3</td>
</tr>
<tr>
<td>Brazil</td>
<td>100</td>
<td>99.9</td>
<td>99.6</td>
</tr>
<tr>
<td>Austria</td>
<td>99.9</td>
<td>99.9</td>
<td>97.0</td>
</tr>
<tr>
<td>Spain</td>
<td>99.9</td>
<td>99.9</td>
<td>99.4</td>
</tr>
<tr>
<td>Japan</td>
<td>99.9</td>
<td>99.9</td>
<td>99.7</td>
</tr>
<tr>
<td>China</td>
<td>99.9</td>
<td>99.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Australia</td>
<td>100</td>
<td>99.9</td>
<td>99.7</td>
</tr>
</tbody>
</table>

Diversity in different areas
Diversity in different streaming rates
## Why Content Multihoming: Cost Diversity

### Amazon CloudFront

<table>
<thead>
<tr>
<th>Charging Region</th>
<th>US</th>
<th>EU</th>
<th>SA</th>
<th>JP</th>
<th>S/HK</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 10 TB /month</td>
<td>$0.120/GB</td>
<td>$0.120/GB</td>
<td>$0.250/GB</td>
<td>$0.201/GB</td>
<td>$0.190/GB</td>
</tr>
<tr>
<td>Next 40 TB /month</td>
<td>$0.080/GB</td>
<td>$0.080/GB</td>
<td>$0.200/GB</td>
<td>$0.148/GB</td>
<td>$0.140/GB</td>
</tr>
<tr>
<td>Next 100 TB /month</td>
<td>$0.060/GB</td>
<td>$0.060/GB</td>
<td>$0.180/GB</td>
<td>$0.127/GB</td>
<td>$0.120/GB</td>
</tr>
<tr>
<td>Next 350 TB /month</td>
<td>$0.040/GB</td>
<td>$0.040/GB</td>
<td>$0.160/GB</td>
<td>$0.106/GB</td>
<td>$0.100/GB</td>
</tr>
<tr>
<td>Next 524 TB /month</td>
<td>$0.030/GB</td>
<td>$0.030/GB</td>
<td>$0.140/GB</td>
<td>$0.085/GB</td>
<td>$0.080/GB</td>
</tr>
<tr>
<td>Next 4 PB /month</td>
<td>$0.025/GB</td>
<td>$0.025/GB</td>
<td>$0.130/GB</td>
<td>$0.075/GB</td>
<td>$0.070/GB</td>
</tr>
<tr>
<td>Over 5 PB /month</td>
<td>$0.020/GB</td>
<td>$0.020/GB</td>
<td>$0.125/GB</td>
<td>$0.065/GB</td>
<td>$0.060/GB</td>
</tr>
</tbody>
</table>

### MaxCDN

<table>
<thead>
<tr>
<th>Charging Region</th>
<th>US/EU/SA</th>
<th>A/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 10 TB /month</td>
<td>$0.070/GB</td>
<td>$0.100/GB</td>
</tr>
<tr>
<td>Next 40 TB /month</td>
<td>$0.060/GB</td>
<td>$0.074/GB</td>
</tr>
<tr>
<td>Next 100 TB /month</td>
<td>$0.050/GB</td>
<td>$0.064/GB</td>
</tr>
<tr>
<td>Next 350 TB /month</td>
<td>$0.040/GB</td>
<td>$0.053/GB</td>
</tr>
<tr>
<td>Next 524 TB /month</td>
<td>$0.035/GB</td>
<td>$0.043/GB</td>
</tr>
<tr>
<td>Next 4 PB /month</td>
<td>$0.030/GB</td>
<td>$0.037/GB</td>
</tr>
<tr>
<td>Over 5 PB /month</td>
<td>$0.020/GB</td>
<td>$0.032/GB</td>
</tr>
</tbody>
</table>

### LiquidWeb

<table>
<thead>
<tr>
<th>Charging Region</th>
<th>US/EU/SA</th>
<th>A/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TB monthly plan</td>
<td>$100</td>
<td>$200</td>
</tr>
<tr>
<td>2.5 TB monthly plan</td>
<td>$250</td>
<td>$500</td>
</tr>
<tr>
<td>5 TB monthly plan</td>
<td>$500</td>
<td>$1,000</td>
</tr>
<tr>
<td>10 TB monthly plan</td>
<td>$900</td>
<td>$1,800</td>
</tr>
<tr>
<td>100 TB monthly plan</td>
<td>$8,000</td>
<td>$16,000</td>
</tr>
</tbody>
</table>

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**Concave Function**

**Region Based**

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Yale LANS
Our Goal

- Design **algorithms** and **protocols** for content publishers to fully take advantage of content multihoming to optimize
  - publisher cost and
  - content viewer performance.
Key Question

- A content object can be delivered from multiple CDNs, which CDN(s) should a content viewer use?
Key Challenges

- Online vs statistical CDN performance
  - e.g., real-time network congestions or server overload

- Complex CDN cost functions
  - e.g., the cost of assigning one object to CDN(s) depends on other assignments => coupling
Our Approach: Two-Level Approach

1. Statistical Performance
2. Efficient Optimal Object Assignment Algorithm
3. Guidance from Content Publishers
4. Local, Active Clients

- Online Performance
Roadmap

• Motivations

• Global optimization
  – Problem definition
  – CMO: An efficient optimization algorithm

• Local active client adaptation

• Evaluations
Roadmap

- Motivations
- Global optimization
  - Problem definition
    - CMO: An efficient optimization algorithm
- Local active client adaptation
- Evaluations
Problem Definition: Network Partition

Global Network

Location Area $a$

Location Object $i^a$

Exclusion

Object-i
Problem Definition: CDN Statistical Performance

Global Network

Target Performance: 90%

Statistical Performance: e.g., probability of successful deliveries in an area

\[ F_k = \{ i^{a_1}, j^{a_7} \} \]

CDN-k
Problem Definition: Optimization Formulation

Problem Q

Charging function in region $r$ of CDN-$k$

$$\min_{\{x^a_{i,k}\}} \sum_k \sum_r C^r_k \left( \sum_{a \in r} x^a_{i,k} t^a_i \right)$$

Traffic volume in charging region-$r$ of CDN-$k$

$$\forall i, a, n^a_i > 0 : \sum_k x^a_{i,k} = 1$$

All requests are served

Performance constraints

$$\forall i, k, a, i^a \not\in F_k : x^a_{i,k} = 0$$

$$\forall i, k, a : x^a_{i,k} \geq 0$$

$x^a_{i,k}$ is the fraction of traffic put into CDN-$k$ for location object $i^a$
Solving Problem Q:
Why not Standard Convex Programming or LP

- To minimize a concave objective function
- Problem scale is too large to be tractable:
  - $N$ objects, $A$ locations and $K$ CDNs $\Rightarrow N \times A \times K$ variables, and $N \times K$ constraints
  - For example, given $N=500K$, $A=200$ and $K=3$ $\Rightarrow 300M$ variables and $100M$ constraints
Roadmap

• Motivations

➢ Global optimization
  – Problem definition
    ➢ CMO: An efficient optimization algorithm

• Local active client adaptation

• Evaluations
Developing the CMO Algorithm: Base

- **Problem Q** has an optimal solution which assigns a location object into a single CDN.

- The object assignment problem is still hard:
  
  **Assignment Space**
  
  K CDNs and N location objects
  =>
  K^N assignment possibilities
CMO Key Idea:
Reduction in the Outcome Space

Assignment Space

Outcome (CDN Usage) Space
CMO Key Idea:
Reduction in the Outcome Space

Assignment Space

Outcome (CDN Usage) Space
CMO Key Idea: Reduction in the Outcome Space

Assignment Space

Outcome (CDN Usage) Space

Infeasible Assignments
CMO Key Idea: 
Reduction in the Outcome Space

Assignment Space

Outcome (CDN Usage) Space

Infeasible Assignments
CMO Key Idea: Reduction in the Outcome Space

**Assignment Space**

There are up to $K^N$ points with $K$ CDNs and $N$ location objects.

**Outcome (CDN Usage) Space**

There are only $N^{KR}$ vertices points, where $R$ is the # of charging regions (a small #).
## Mapping From Object Assignment to Outcome

<table>
<thead>
<tr>
<th>Location Objects</th>
<th>$v^1_1$</th>
<th>$v^2_1$</th>
<th>$v^1_2$</th>
<th>$v^2_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic in Area-1</td>
<td>$t^1_1$</td>
<td>0</td>
<td>$t^1_2$</td>
<td>0</td>
</tr>
<tr>
<td>Traffic in Area-2</td>
<td>0</td>
<td>$t^2_1$</td>
<td>0</td>
<td>$t^2_2$</td>
</tr>
</tbody>
</table>

- $x^1_{i,1} = 1$
- $x^2_{i,1} = 1$
- $x^1_{i,2} = 1$
- $x^2_{i,2} = 1$

<table>
<thead>
<tr>
<th>CDNs</th>
<th>CDN-1</th>
<th>CDN-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic in Region-1</td>
<td>$t^1_1 + t^1_2$</td>
<td>0</td>
</tr>
<tr>
<td>Traffic in Region-2</td>
<td>$t^2_1$</td>
<td>$t^2_2$</td>
</tr>
</tbody>
</table>

**Example assumption:** Area-i is in charging Region-i
Extensions

• CDN subscription levels (e.g. monthly plan)
  – Introducing CDN capacity constraints

• Per-request cost
  – Adding a row which indicates the #request in outcome

• Multiple streaming rates
  – Considering each video at each encoding rate as an independent object
## Extension Example: Per-request Cost

### Location Objects

<table>
<thead>
<tr>
<th></th>
<th>$v_1^1$</th>
<th>$v_1^2$</th>
<th>$v_2^1$</th>
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</tr>
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<tbody>
<tr>
<td>Traffic in Area-1</td>
<td>$t_1^1$</td>
<td>0</td>
<td>$t_2^1$</td>
<td>0</td>
</tr>
<tr>
<td>Traffic in Area-2</td>
<td>0</td>
<td>$t_1^2$</td>
<td>0</td>
<td>$t_2^2$</td>
</tr>
</tbody>
</table>

### #Request

<table>
<thead>
<tr>
<th></th>
<th>$n_1^1$</th>
<th>$n_1^2$</th>
<th>$n_2^1$</th>
<th>$n_2^2$</th>
</tr>
</thead>
</table>

### CDNs

<table>
<thead>
<tr>
<th></th>
<th>CDN-1</th>
<th>CDN-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic in Region-1</td>
<td>$t_1^1 + t_2^1$</td>
<td>0</td>
</tr>
<tr>
<td>Traffic in Region-2</td>
<td>$t_1^2$</td>
<td>$t_2^2$</td>
</tr>
</tbody>
</table>

### #Request

<table>
<thead>
<tr>
<th></th>
<th>$n_1^1 + n_1^2 + n_2^1$</th>
<th>$n_2^2$</th>
</tr>
</thead>
</table>

**Example assumption:** Area-i is in charging Region-i.
From Algorithm to System

- Optimizer
  - Long-term scale statistics
- CPDNS
- CDN1
  - CloudFront
- Passive Client
- CDN2
  - MaxCDN
From Algorithm to System

- Optimizer
  - Long-term scale statistics

- CPDNS
  - Resolve obj-i.cp.com

- Passive Client

- CDN1
  - CloudFront

- CDN2
  - MaxCDN
From Algorithm to System

Client IP → area

Optimizer

Long-term scale statistics

CPDNS

Resolve obj-i.cp.com

Passive Client

CDN1
CloudFront

CDN2
MaxCDN

Yale LANS
Roadmap

• Motivations
• Global optimization
  – Problem definition
  – CMO: An efficient optimization algorithm
  ➢ Local active client adaptation
• Evaluations
Active Clients

Primary CDN

- h11
- h12

Backup CDN

- h21
Informing Active Client

Resolve obj-i.cp.com

Get CNAME d3ng4btfd31619.cloudfront.net

Passive Client

Optimizer

CDN1
CloudFront

CDN2
MaxCDN

Active Client
Informing Active Client

Resolve obj-i.cp.com
Get CNAME d3ng4btfd31619.cloudfront.net

Passive Client

Optimizer

Manifestation Server

CDN1 CloudFront

CDN2 MaxCDN

Active Client
Informing Active Client

Resolve obj-i.cp.com

Get CNAME d3ng4btfd31619.cloudfront.net

CDN1 CloudFront

Request cp.com/sample.flv

CDN2 MaxCDN

Passive Client

Optimizer

Active Client

Manifestation Server
How to Select Multiple CDNs?

• The same CMO algorithm, where input CDNs are virtual CDNs (ranked CDN combinations)

• Example: Select 2 CDNs (primary + backup) for an active client:
  - Each pair of CDNs is a “virtual CDN”: \( k' = (k, j) \)
  - \( F_{k'} \): the set of location objects that CDN \( k \) and CDN \( j \) together can achieve performance requirement
    • Each with 90% statistics => together > 90%
  - Objective function: for each location object \( i^a \), primary CDN \( k \) delivers the normal amount of traffic and backup \( j \) incurs backup amount of traffic.
Active Clients: Adaptation Goals

- **QoE protection (feasibility):**
  - Achieve target QoE through combined available resources of multiple CDN servers

- **Prioritized guidance:**
  - Utilize the available bandwidth of a higher priority server before that of a lower priority server

- **Low session overhead (stability):**
  - No redistributing load among same-priority servers unless it reduces concurrent connections
Active Clients: Control Diagram

Primary

h_{11} < R \text{ and } h_{12} > R

h_{11} > R \text{ and } h_{12} < R

Backup

h_{11} < R \text{ and } h_{12} < R?
Realizing Control Diagram: Key Ideas

- Controlling the windows
  - AIMD
  - Total load control
- Using the sliding windows
  - Priority assignment

$\text{h}_{12}$

# pieces can be downloaded from the server in a period $T$

$\text{h}_{21}$

Pieces to request in $T$
Realizing Control Diagram: Key Ideas

- Controlling the windows
  - AIMD
  - Total load control
- Using the sliding windows
  - Priority assignment

# pieces can be downloaded from the server in a period $T$

Pieces to request in $T$
Realizing Control Diagram: Key Ideas

- Controlling the windows
  - AIMD
  - Total load control
- Using the sliding windows
  - Priority assignment

$h_{21}$

$h_{12}$

$h_{11}$

$\#$ pieces can be downloaded from the server in a period $T$

Pieces to request in $T$
Roadmap

- Motivations
- Global optimization
  - Problem definition
  - CMO: An efficient optimization algorithm
- Local active client adaptation
  
  Evaluations
CMO Evaluation Setting

- 6-month traces from two VoD sites (CP1 and CP2):
  - Video size
  - #request in each area (learned from clients’ IP)

- Three CDNs
  - Amazon CloudFront
  - MaxCDN
  - CDN3 (private)

- #request prediction
  - Directly using #request last month in each area

- Compare 5 CDN selection strategies:
  - Cost-only, Perf-only, Round-robin, Greedy, CMO
Cost Savings of CMO

Avg Saving: ~35% compared with Greedy

(a) monthly cost: CP1
Cost Savings of CMO

Avg Saving: ~40% compared with Greedy

All three CDNs have good performance in US/EU
Active Client Evaluation Setting

- **Clients**
  - 500+ Planetlab nodes with Firefox 8.0 + Adobe Flash 10.1

- **Two CDNs**
  - Amazon CloudFront
  - CDN3
Active Client Test Cases

- **Stress test**
  - CDN3 as primary; CloudFront as backup
    - Two servers in two CDNs: primary1, backup1
    - Two servers in the primary CDN: primary1, primary2
  - Control primary1’s capacity
    - Step-down
    - Ramp-down
    - Oscillation

- **Large scale performance test:**
  - CloudFront as primary, CDN3 as backup
  - We saw real performance degradations
Stress Tests (Step-down)

Different Priority

Same Priority

Step-down
Recovery
Stress Tests (Ramp-down)

Different Priority

Same Priority
Stress Tests (Oscillation)

Different Priority

Same Priority
Active Client QoE Gain (CloudFront + CDN3)

Freezes Per View Statistics

CDF[x<pct]

Active Clients

Passive Clients
Active Client: Cost Overhead

Cost (Kilo USD)

Per-request Traffic

Ideal-CMO  Real-CMO  greedy
Conclusions

• We develop and implement a two-level approach to optimize cost and performance for content multihoming:
  – CMO: an efficient algorithm to minimize publisher cost and satisfy statistical performance constraints
  – Active client: an online QoE protection algorithm to follow CMO guidance and locally handle network congestions or server overloading.
Q&A
Related Work and Conclusions

• CDN switchers: seamless switch from one CDN to another
  – One Pica Image
• CDN Load Balancers: executing traffic split rules among CDNs
  – Cotendo CDN
  – LimeLight traffic load balancer
  – Level 3 intelligent traffic management
• CDN Agent: CDN business on top of multiple CDNs
  – XDN
  – MetaCDN
• CDN Interconnection (CDNi)
  – Content multihoming problem still exists in the CDN delegations.
Backup Slides
Searching Extremal Assignments

(1) **Separation Lemma:**  \( \phi^* \) is extremal \( \iff \exists P, \forall \phi \neq \phi^* : \langle P, V_\phi - V_{\phi^*} \rangle > 0 \)

(2) **Recall:**  \( V_\phi = \sum_v v \otimes e_{\phi(v)} \rightarrow \phi^* \) is extremal \( \iff \exists P, \forall \phi \neq \phi^* : \sum_v \langle P, v \otimes e_{\phi(v)} \rangle > \sum_v \langle P, v \otimes e_{\phi^*(v)} \rangle \)

(3) **We prove:**  \( \phi^* \) is extremal \( \iff \exists P, \forall v, k \neq \phi^*(v) : \langle P, v \otimes e_k \rangle > \langle P, v \otimes e_{\phi^*(v)} \rangle \)

(4) **With a proper** \( P \), we can find an extremal assignment:
  - For each object \( v \), there is a **unique minimum** element in set \( \{ \langle P, v \otimes e_k \rangle | \forall k \} \)
Picking Proper $P$

A Proper $P$:
- $\forall v$ there is a **unique** minimum element in set $\{\langle P, v \otimes e_k \rangle | \forall k \}$

A special subset of $P$ ($S'$): all elements in $\{\langle P, v \otimes e_k \rangle | \forall k \}$ are distinct

\[ \forall v, k \neq j: \langle P, v \otimes e_k \rangle \neq \langle P, v \otimes e_j \rangle \]

\[ \Rightarrow \langle P, v \otimes (e_k - e_j) \rangle \neq 0 \]

We prove:
- Each extremal assignment can be found by an element in $S'$
- Two interior points from the same cell find the same extremal assignment

Conclusion:
- All possible extremal assignments are exhausted by $S'$.
- The number of extremal assignments is no more than the $\#\text{cell}$ (polynomial with $\#\text{object}$).

Cell Enumeration of Hyperplane Arrangements
Realizing Control Diagram: Key Ideas

• Yry (revise next slide) Draw a figure w/
  – An active client
  – 3 cdn servers
  – Label a sliding window to conn. to each CDN

  – Say 3 key techniques to control and use the sliding window: total