Understanding Optimal Caching and Opportunistic Caching at “The Edge” of Information Centric Networks

Ali Dabirmoghaddam[1]

Maziar Mirzazad-Barijough[1]

J.J. Garcia-Luna-Aceves[1,2]

[1]UC Santa Cruz

[2]Palo Alto Research Center

jj@soe.ucsc.edu

Outline

How important is edge caching for ICNs?

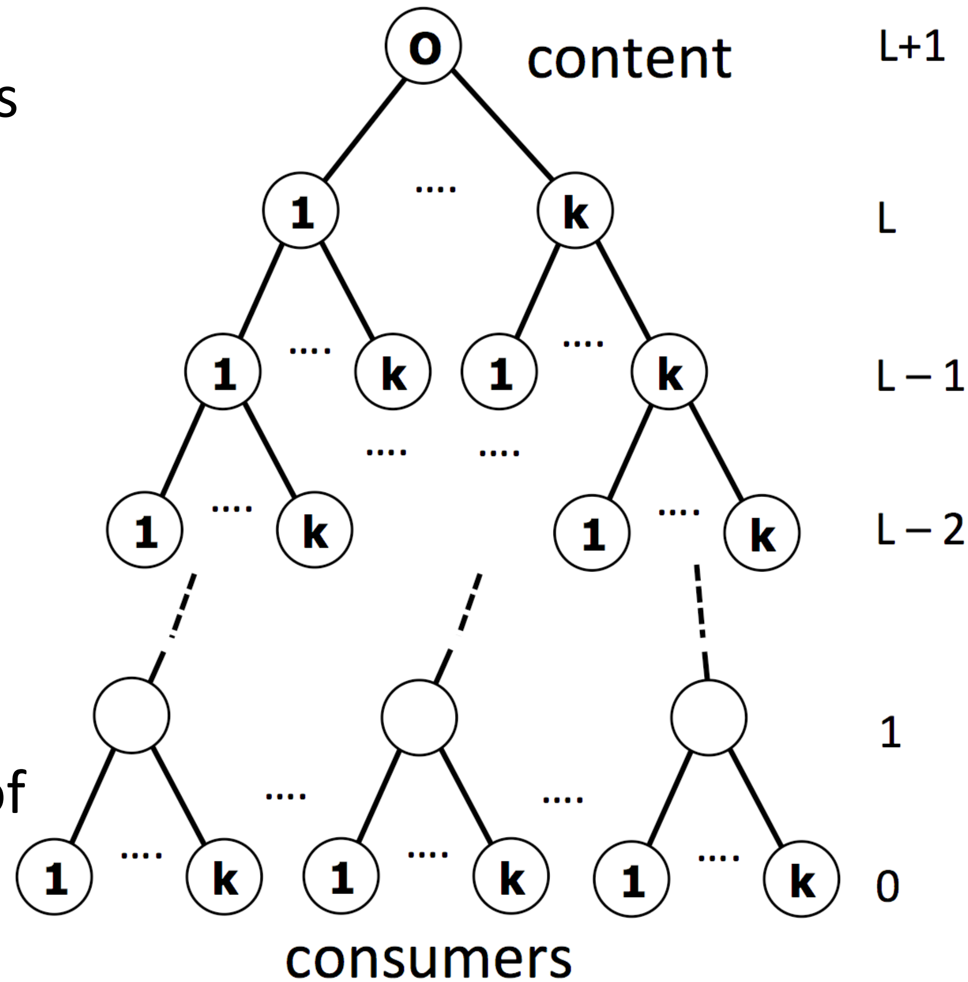
- Compare optimum on-path caching with opportunistic caching at the edge [near the consumers of content] using a hierarchical caching model (approximation).
- Model the spatio-temporal locality of reference in content requests. [just a start!]
- Compare on-path caching with caching at the edge in random networks (ndnSim simulations).
- Modeling and design implications.

Related Work

- Models rely on strong assumptions to simplify problem:
  - Equal size objects (unit size)
  - Independent reference model (IRM): requests for information objects arrive according to i.i.d. processes
- Caching used in most ICN approaches is on-path caching
  - All routers participate in content caching.
  - Caching done along path to origin sites.
  - Inconclusive results on impact of caching at the core of ICNs.
- Not enough comparison of on-path caching with edge caching.

Hierarchical Caching Model

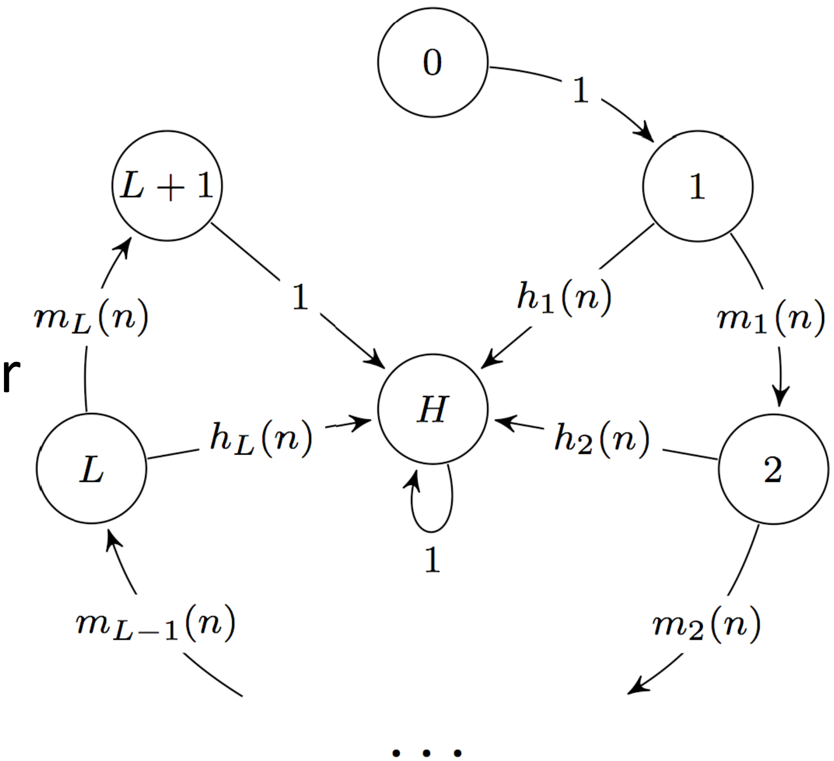
- Simple hierarchy of LRU caches in L+2 levels.
- Consumers are at level 0.
- Content source at level L+ 1.
- L levels of caching.
- Each tree node has k children.
- On-path caching:
  - Forward request from consumer to root until cache hit occurs.
  - Cache content along entire reverse path.
- Assume IRM.
- How much should each layer of the caching hierarchy store to get the most from a constrained caching budget?



Of course, Level 1 should have a much larger degree, but that would help make our case stronger

Hierarchical Caching Model

- Caching tree structure of $L+2$ levels, assume IRM.
- $\tau(n)$: Expected time to access content (ETTA):
  - Measured in terms of the number of hops between consumer and nearest copy of content.
  - $m_j(n)$: Miss probability of a given cache for object n at level i of the caching system.
  - $h_j(n) = 1 - m_j(n)$



$$\tau(n) = 1 + \sum_{i=1}^{L} \prod_{j=1}^{i} m_j(n)$$

Hierarchical Caching Model

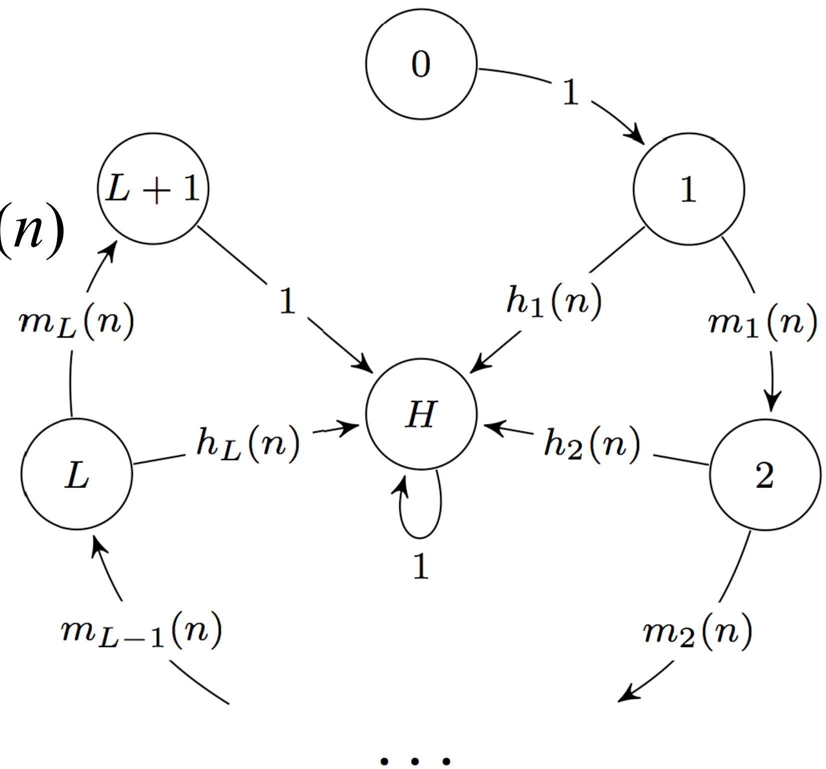
- $\tau_i(n)$: Expected time to visit state H from state i.
- $\tau_0(n)$ can be expressed recursively:

$$\begin{aligned}\tau_0(n) &= 1 + \tau_1(n) \\ &= 1 + 1 + m_1(n)\,\tau_2(n) + h_1(n)\,\tau_H(n) \\ &= 1 + 1 + m_1(n)\,\tau_2(n) + [1 - m_1(n)]\,\tau_H(n)\end{aligned}$$

- By induction:

$$\tau_0(n) = 2 + \sum_{i=1}^{L}\prod_{j=1}^{i} m_j(n)$$

- Given that state H has the content, $\tau(n) = \tau_0(n) - 1$ and the result follows.



$$\tau(n) = 1 + \sum_{i=1}^{L}\prod_{j=1}^{i} m_j(n)$$

Hierarchical Caching Model

Optimal cache allocation problem:

- Given a total cache budget C and a caching tree of L levels with each node having k children
- **Find the optimum breakdown of C across all levels that minimizes ETTA.**

$$\boldsymbol{c}^* = \operatorname*{argmin}_{\boldsymbol{c}} \sum_{n=1}^{N} q(n)\, \tau(n; \boldsymbol{c})$$

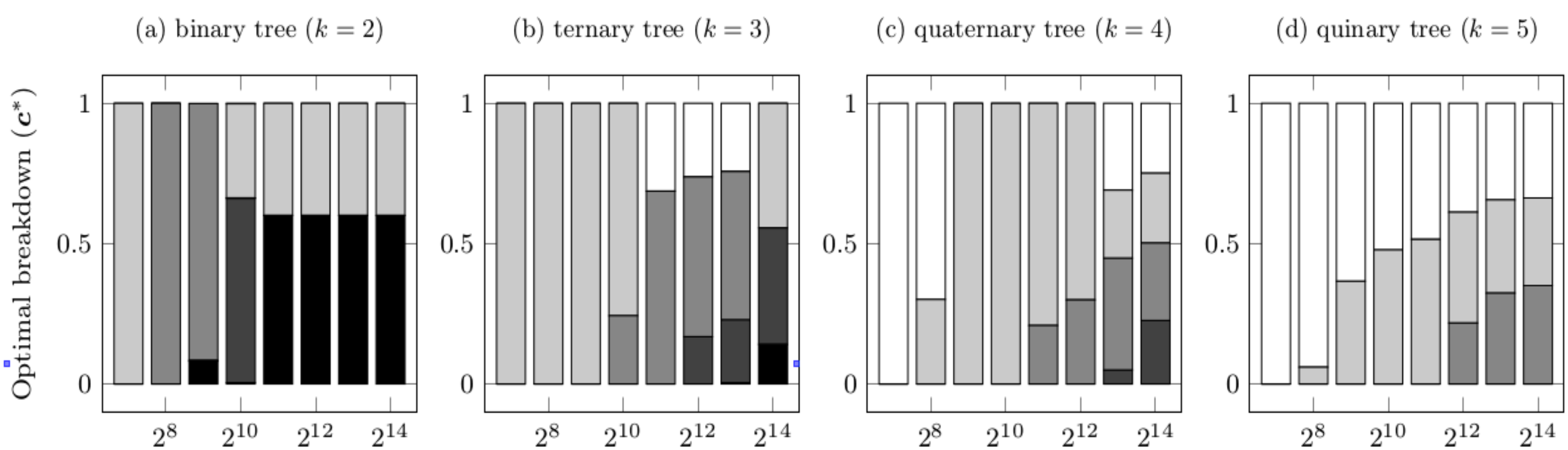
$$\text{s.t.} \quad \sum_{\ell=1}^{L} c(\ell)\, k^{(L-\ell)} = C\,, \quad \text{and}$$

$$c(\ell) \geq 0 \text{ and integer } \forall \ell \in \{1, \ldots, L\}$$

- $q(n)$ = popularity of content n.
- $c(l)$ = capacity of a cache at level l.
- $\boldsymbol{c}^*$ = vector of optimal cache sizes.

Optimal Breakdown of Caching Budget

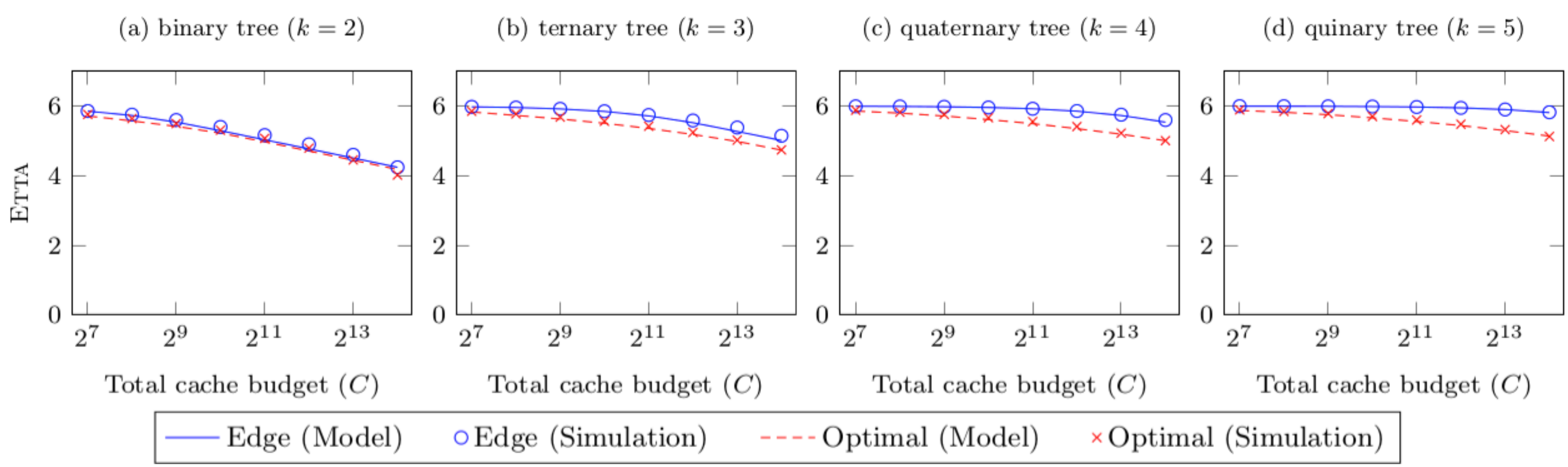
- Consumers at level 0, four caching levels, content at level six.
- 1M objects, IRM.
- Identical objects have same popularity among all users.
- Proportion of caching for increasing degree k and budget C.



Edge caching becomes more important as C increases!

ETTA for Optimal Caching and Edge Caching

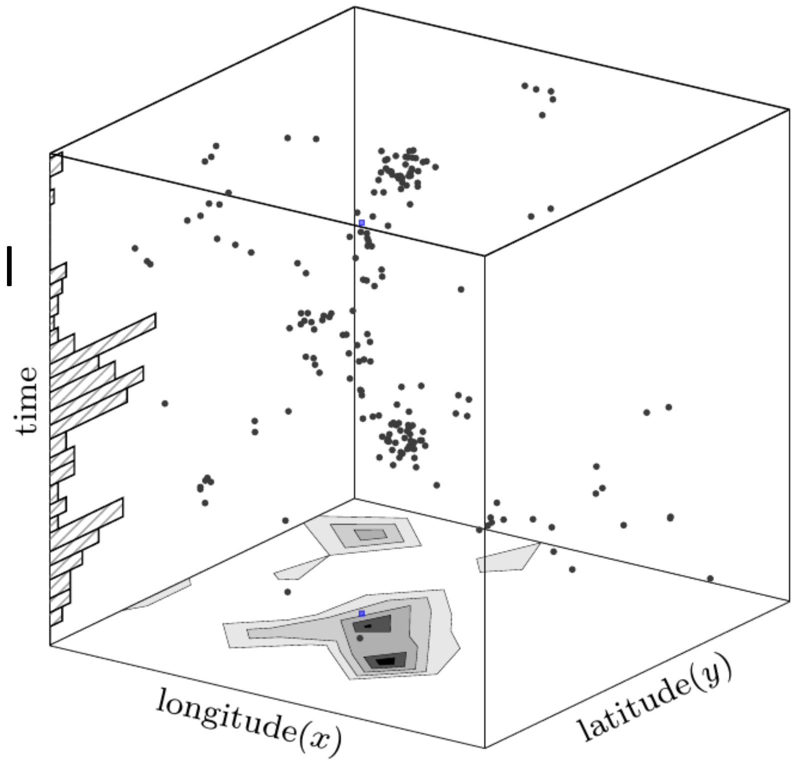
- Same assumptions as before for optimal caching.
- Edge caching: All caching budget C only at Level 1.
- Results based on model and ndnSim simulations.



Edge caching is within 10% of the optimum!

Capturing Spatio-Temporal Reference Locality

- **Spatial locality of reference:** Impact of user geographical diversity on content requests.
- **Temporal locality of reference:** Temporal evolution of content popularity.



- Generate "center points" of a Poisson process that generate off-springs and so on based on number of objects, object popularity [Zipf distribution], and localization factor.

- *Reference locality* (β) = ave. # off-springs for each center point ($0 \leq \beta < 1$);

$$q_\ell(n) = \begin{cases} q(n) & \ell = 0\,, \\ k\, q_{\ell-1}(n)\, m_{\ell-1}(n) & 0 < \ell \leq L\,, \end{cases}$$

$$q_u(n,t) = \begin{cases} \lim\limits_{\Delta t \to 0} \dfrac{\mathbb{E}[N_u(n, t+\Delta t]}{\Delta t} & u \in \{\ell_1\}\,, \\ \sum\limits_{c \in \mathcal{C}_u} q_c(n,t)\, m_c(n,t) & u \notin \{\ell_1\}\,. \end{cases}$$

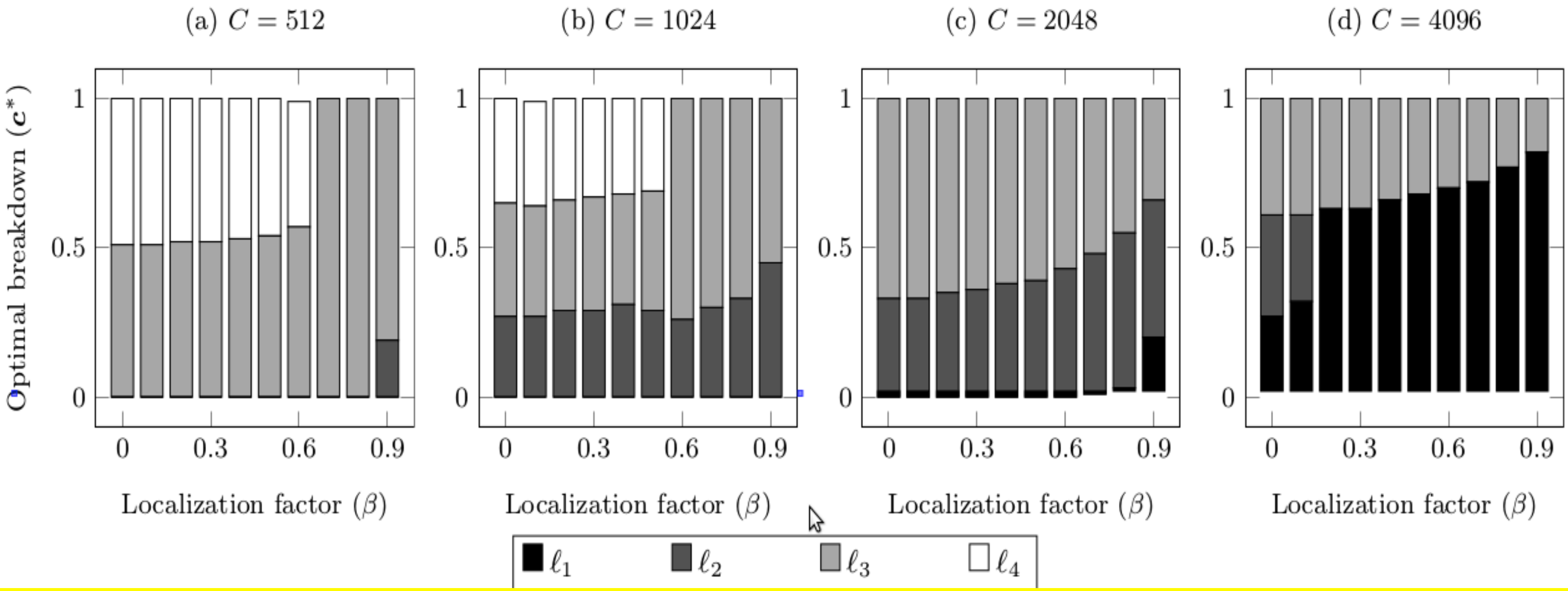
Algorithm for Generating Object References with Localization in a d-dimensional Space

```
Generate_Trace(α,β)
   X ← Ø
   for every object n {
   q_n ∝ n^-α
   Π_n ← Hawkes(q_n,β)
   X ← X U Π_n
   }
   return X
```

```
Hawkes(ρ,β)
   n_t ← Poisson(ρ)
   for i ← 1 to n_t
      Π_i ← Uniform(0,1)
   idx ← 1
   end ← n_t
   While idx < n_t {
      n_c ← Poisson(β)
      for j ← 1 to n_c
         Π ← Π U (Π_idx + N(0,1))
      n_t ← n_t + n_c
   }
   return Π
```

Optimal Breakdown of Caching Budget

- Consumers at level 0, four caching levels, content at level six.
- Reference locality (β) varied from 0 (IRM) to 1.
- Proportion of caching for increasing β and budget C.



Edge caching dominates as β and C increase!

ETTA for Optimal Caching and Edge Caching

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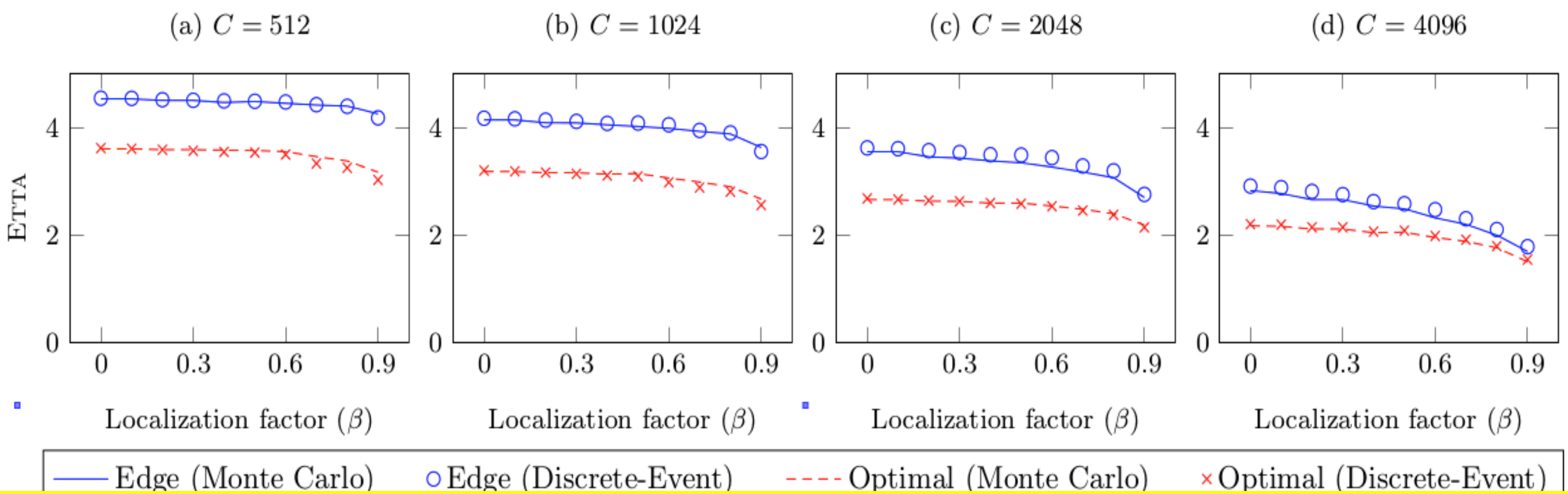
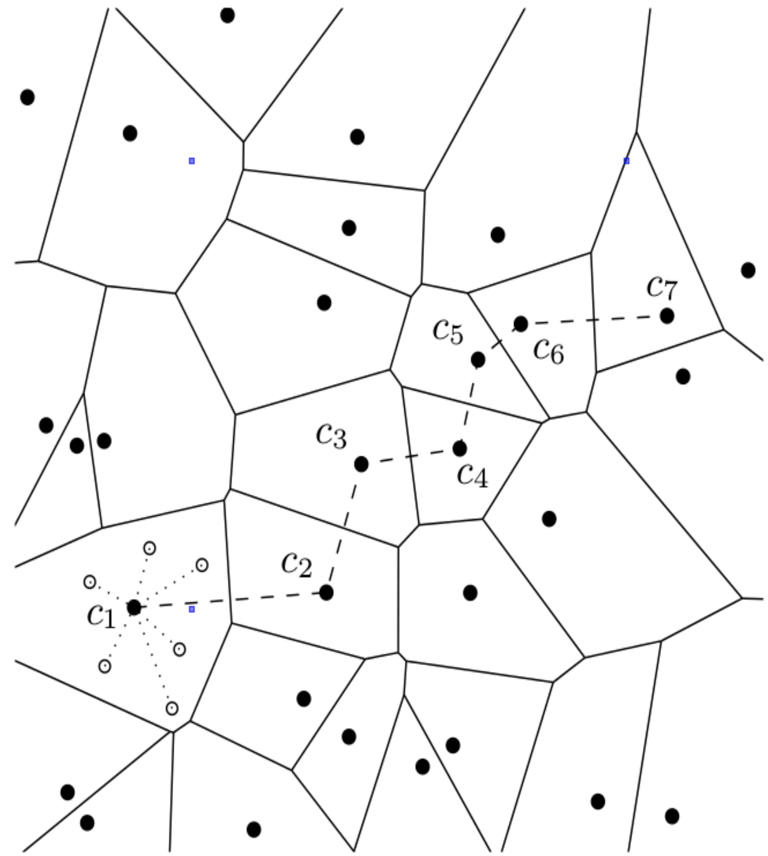


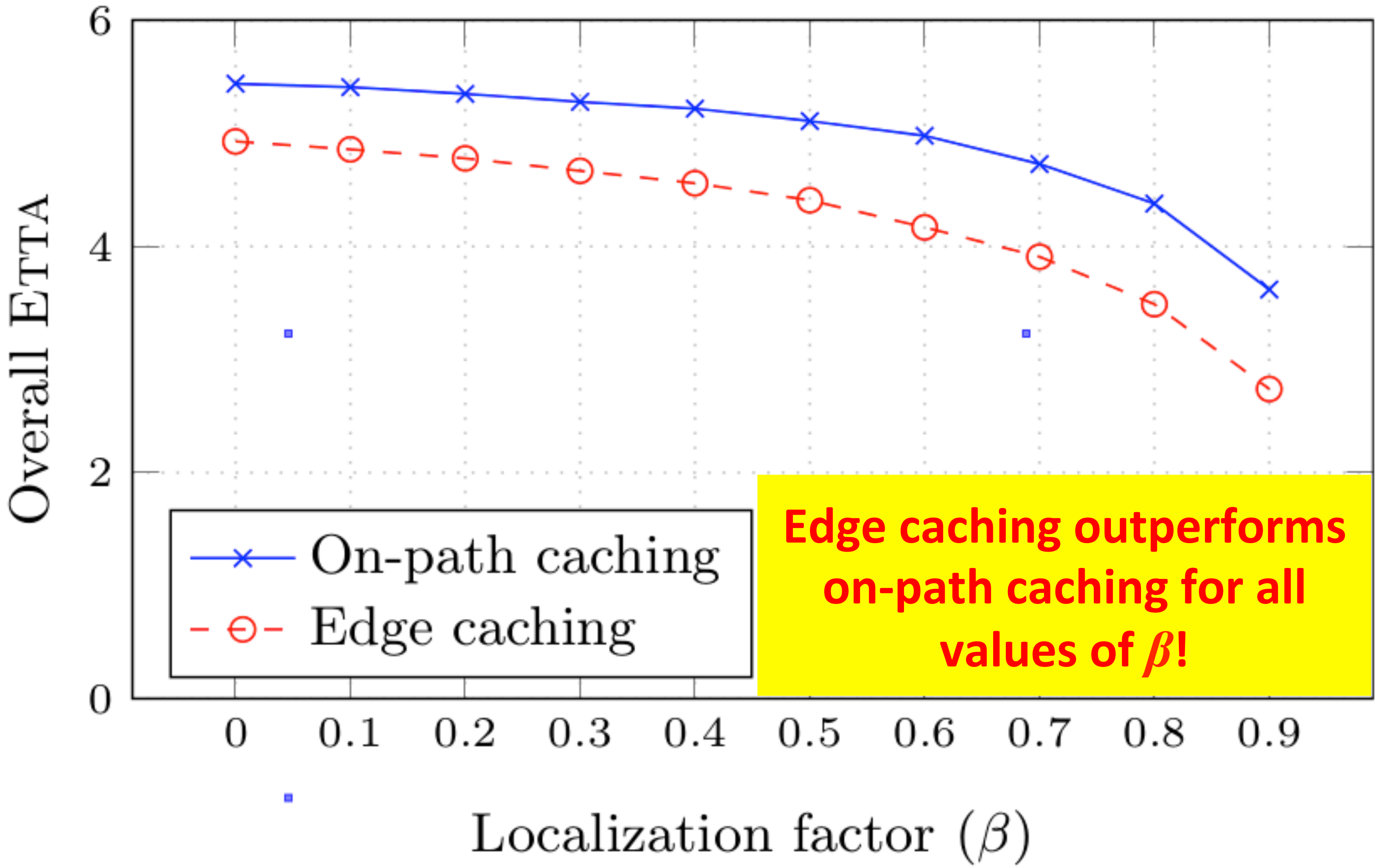
Edge caching is within 8% of the optimum as C and β increase.

Caching On Random Networks

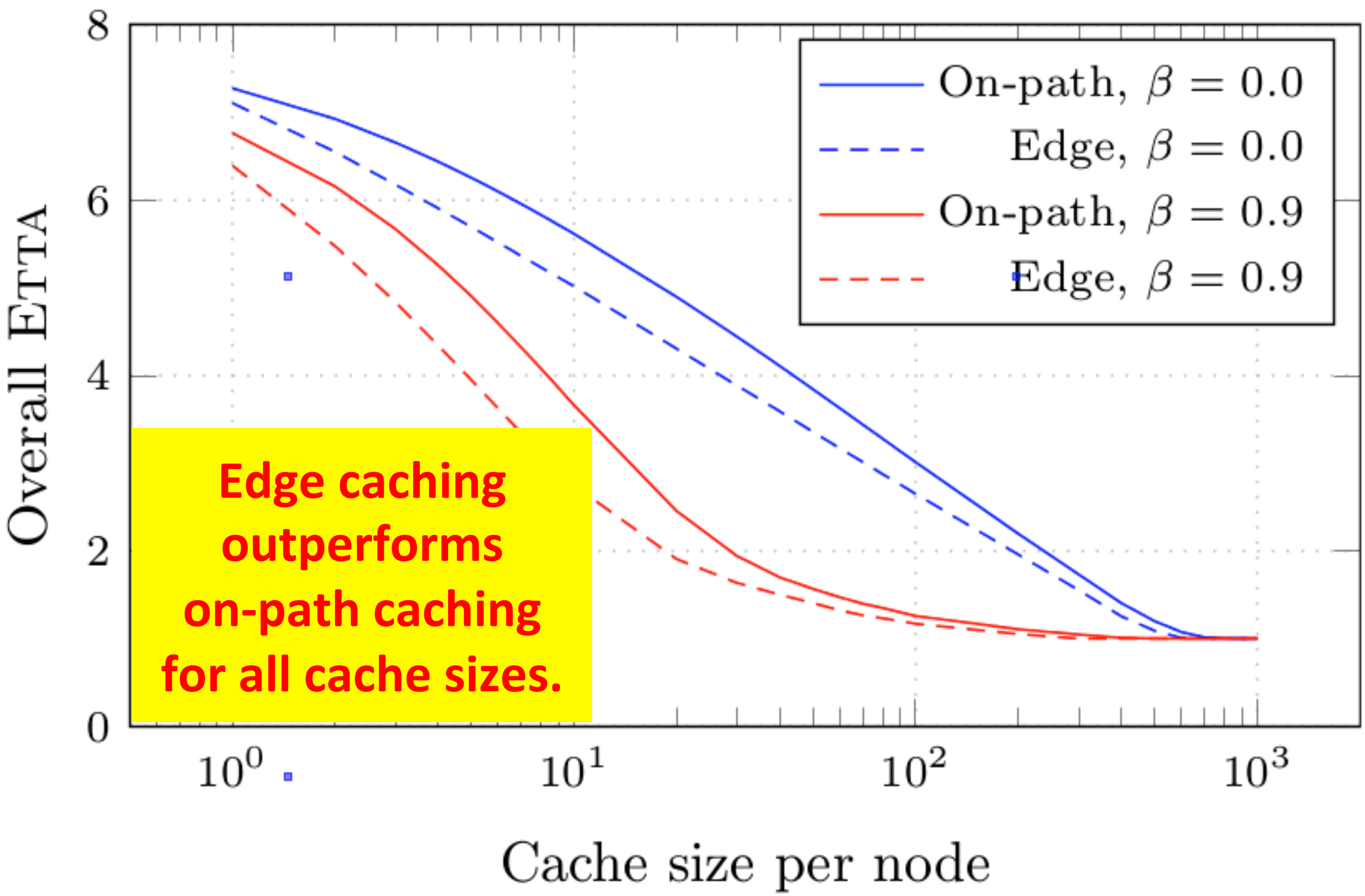
- Model random networks with random geometric graphs.
- Voronoi cells and local caches in each cell.
- On-path caching: Caching along entire path.
- Edge caching: Caching only within the cell in which request originated.
- Compare the two using ndnSim simulations:
  - 200 nodes; 8.9 average node degree
  - 1,000 objects with Zipf popularity distribution, uniformly distributed among nodes.



Edge vs. On-Path Caching in Random Networks



Edge vs. On-Path Caching in Random Networks



Summary

- Modeling framework for hierarchical caching:
  - Optimal on-path caching provides only marginal benefits over edge caching.
- Tool introduced to synthesize spatial and temporal locality in traces of object requests
  - Optimal caching tends towards the edge for both larger locality of reference and caching budget.
- Compared edge and on-path caching in random networks:
  - Edge caching outperforms on-path caching.
- **Edge caching provides "less pain, most of the gain" in ICNs.**

  [S. Fayazbakhsh et al., "Less Pain, Most of the Gain: Incrementally Deployable ICN," ACM SIGCOMM 13]

Next Steps and Implications

- More realistic topologies.
- Verify synthetic traces for locality of reference model with real traffic traces.
- Develop model for random networks.
- Since edge caching provides most of the caching gains:
  - Only edge routers in ICNs need large caches.
  - New approaches to integrate routing with edge caching.

THANK YOU!

ANY QUESTIONS?