On Content Delivery to Heterogeneous Devices

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Motivation

Content Delivery Networks

1. Large amount of content
2. Device heterogeneity

Motivation

Device Heterogeneity

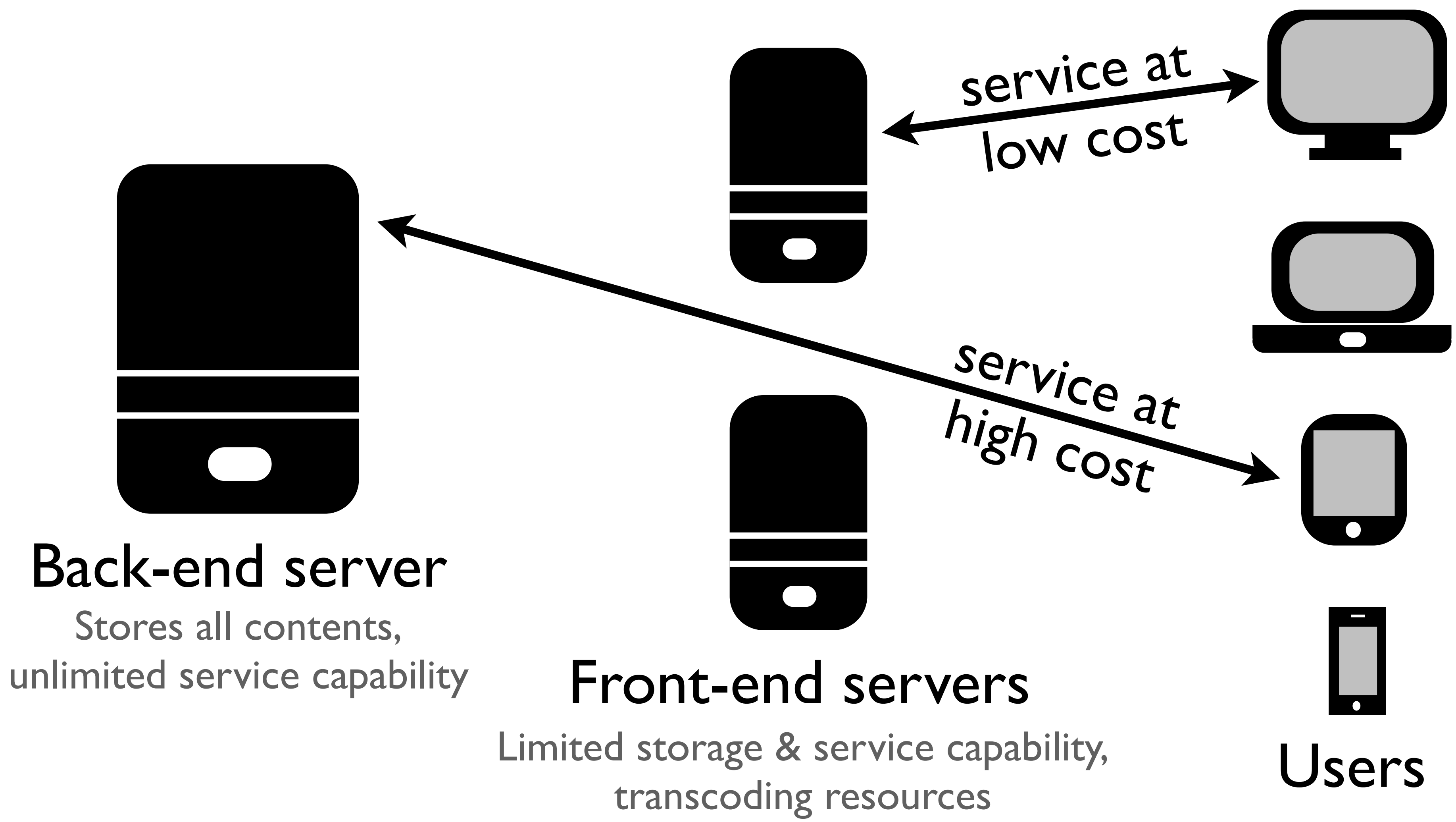
End-users

Different operating systems, screen sizes, bit-rate requirements, codec support etc.

New Challenge: Delivering content in multiple formats

New Resource: Computational power - transcoders

Content Delivery Network

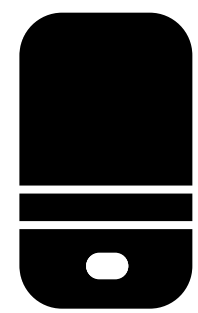


Tasks

- What to store on the front-end servers?
- How to use transcoding resources?

Setting

Front-end Servers



Front-end server

Limited storage and service capability,
transcoding resources

- n contents, n large
- Storage - Vanishing fraction of all contents ($o(n)$, e.g., $\sqrt{n}$)
- Service - Limited requests served concurrently
- Non-uniform storage and service capabilities

Setting

Cost of serving requests

1. Serve using front-end server	C_{min}
2. Fetch and serve	$C_{min} + C_{Fetch}$
3. Transcode and serve	$C_{min} + C_{Transcode}$
4. Serve using back-end server	C_{max}

No queues

$C_{min} < C_{max}$

$C_{Fetch}, C_{Transcode} > 0$

Goal: Optimize content replication on front-end servers to minimize the cost of serving requests.

Setting

Content & Format Popularity

- Heavy tailed content popularity*

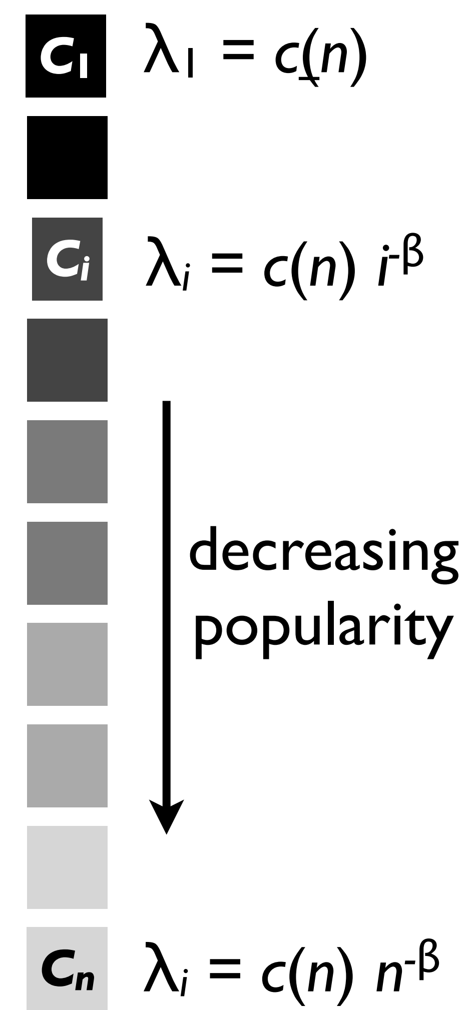
  Zipf distribution

  - Requests for $C_i \sim \text{Poisson}(\lambda_i)$
  - $\lambda_i \propto i^{-\beta}, \beta > 0$

- Format popularity

  Non-uniform & content dependent

- Supportable load



*Liu et al., **Measurement and analysis of an internet streaming service to mobile devices**, *IEEE Transactions on Parallel and Distributed Systems.*

Setting

- n contents, n large
- Heavy tailed content popularity
- K front-end servers, K is a constant
- o(n) contents on each front-end server

1. Serve using front-end server	C_{min}
2. Fetch and serve	$C_{min} + C_{Fetch}$
3. Transcode and serve	$C_{min} + C_{Transcode}$
4. Serve using back-end server	C_{max}

Goal: Optimize content replication on front-end servers to minimize the cost of serving request.

Candidate Strategies

I. Transcode on the fly* (ToF):

Store master format, transcode on demand to serve requests
e.g., VUCLIP - mobile VoD service, dynamic adaptive transcoding

II. Lazy Transcoding and Re-transcoding (LTR):**

Store transcoded versions, delete obsolete formats periodically

*U.S. Patent No. 8,869,218
**U.S. Patent No. 8,782,285

DIST-LTR

Routing	Random routing - Probability request routed to server *j* $\propto$ service capacity of server *j*
Content Replication	On a request arrival for $C_{i,f}$: Case 1 - Server busy: serve using back-end server Case 2 - $C_{i,f}$ available: serve request Case 3 - $C_{i,f}$ not available: fetch or transcode, replace content(s) not being used with $C_{i,f}$

Definition: Γ_{ALG} = Cost per request

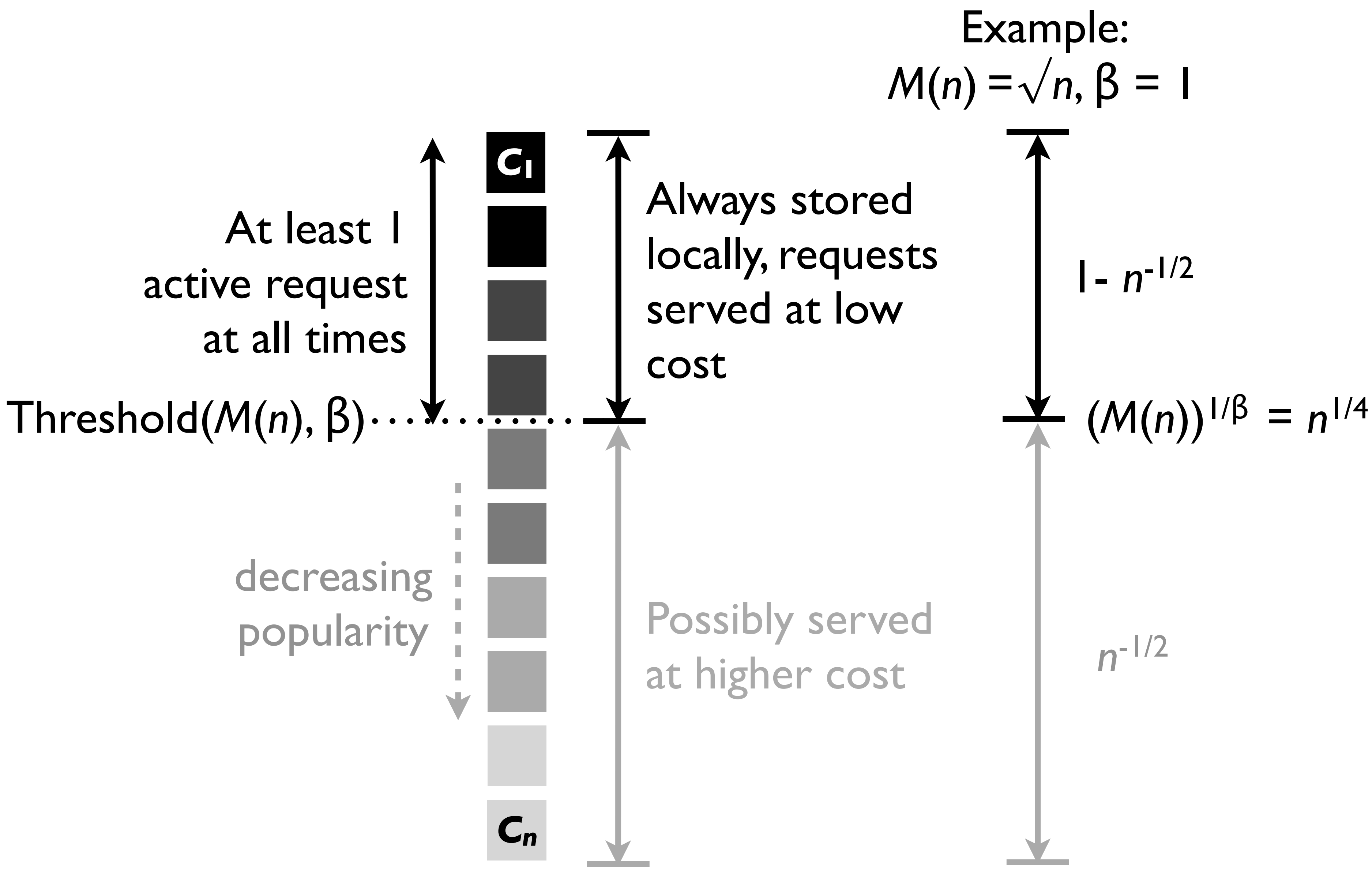
Theorem

$$\lim_{n \to \infty} E[\Gamma_{DIST\text{-}LTR}] = C_{min}$$

- "Blind" routing
- No coordination across front-end servers
- Content popularity statistics unknown

Proof Outline

Assume that the front-end server can serve $M(n)$ parallel requests
Recall: Content popularity ~ Zipf(β), β>1



Transcode on the Fly

Definitions

Γ_{ALG} = Cost per request
q = Expected fraction of requests for the master format

Theorem

$$\lim_{n\to\infty} E[\Gamma_{ToF}] \geq c_{min} + \min\{c_{Transcode}, c_{max}-c_{min}\}\,(1-q)$$

- ✦ Routing using global information
- ✦ Co-ordination across front-end servers
- ✦ Use knowledge of content popularity
- ✦ Static/adaptive content replication

Request for other formats - transcode/serve using back-end server

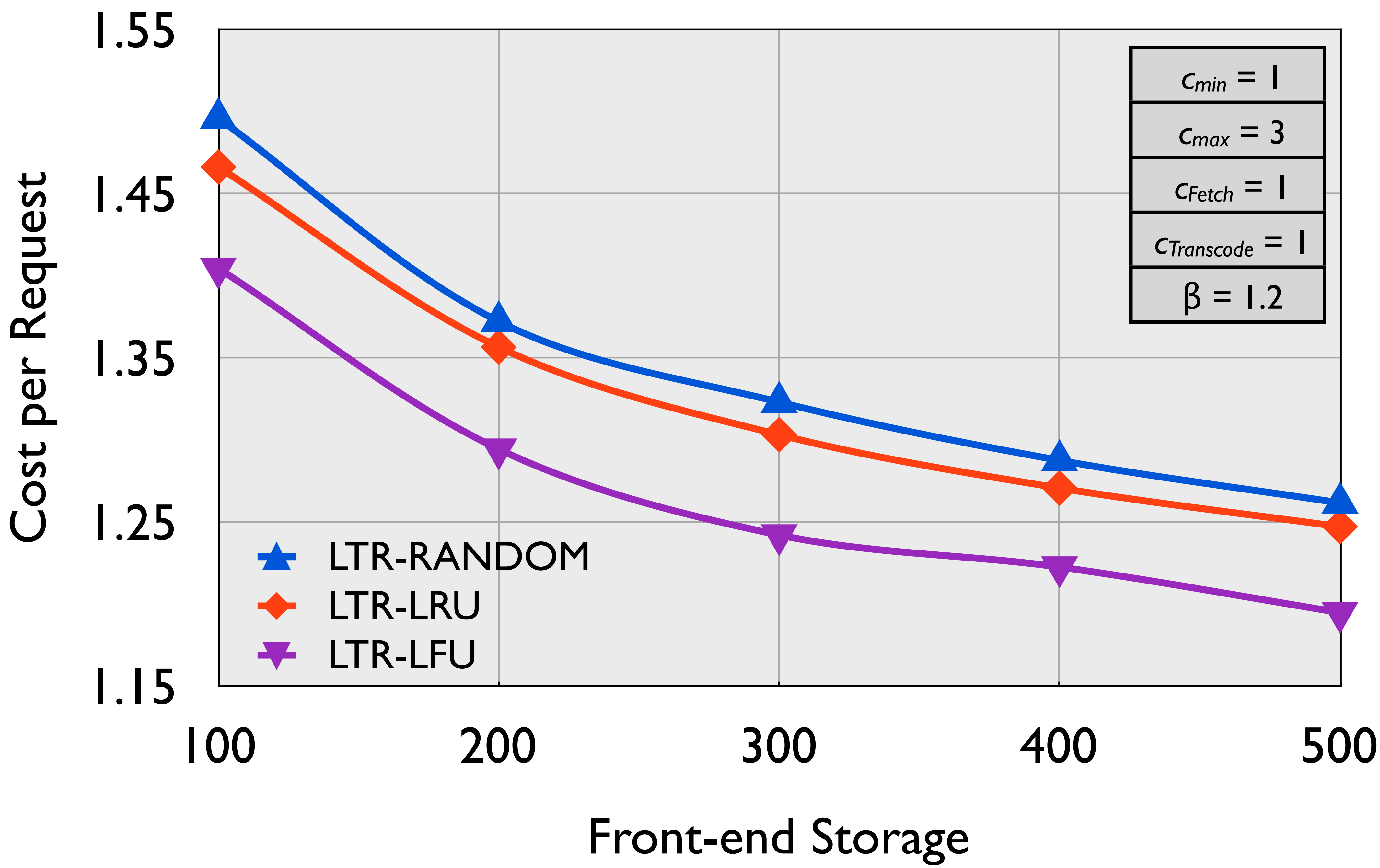
DIST-LTR

Routing	Random routing - Probability request routed to server *j* $\propto$ service capacity of server *j*
Content Replication	On a request arrival for $C_{i,f}$: Case 1 - Server busy: serve using back-end server Case 2 - $C_{i,f}$ available: serve request Case 3 - $C_{i,f}$ not available: fetch or transcode, replace content(s) not being used with $C_{i,f}$

- Randomly chosen content (LTR-RANDOM)
- Least recently used content (LTR-LRU)
- Least frequently used content (LTR-LFU)

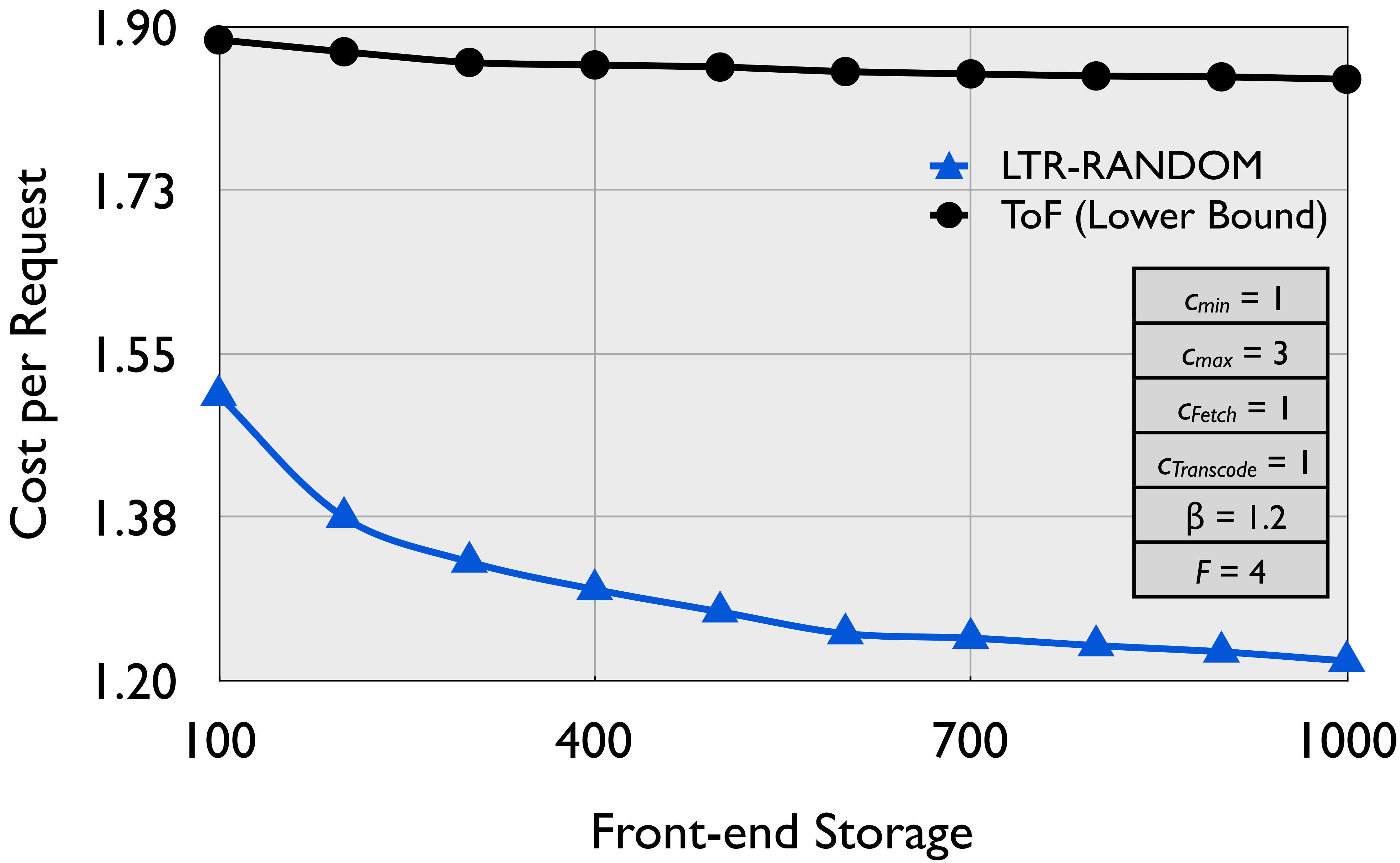
Simulations

Cost vs Zipf Parameter



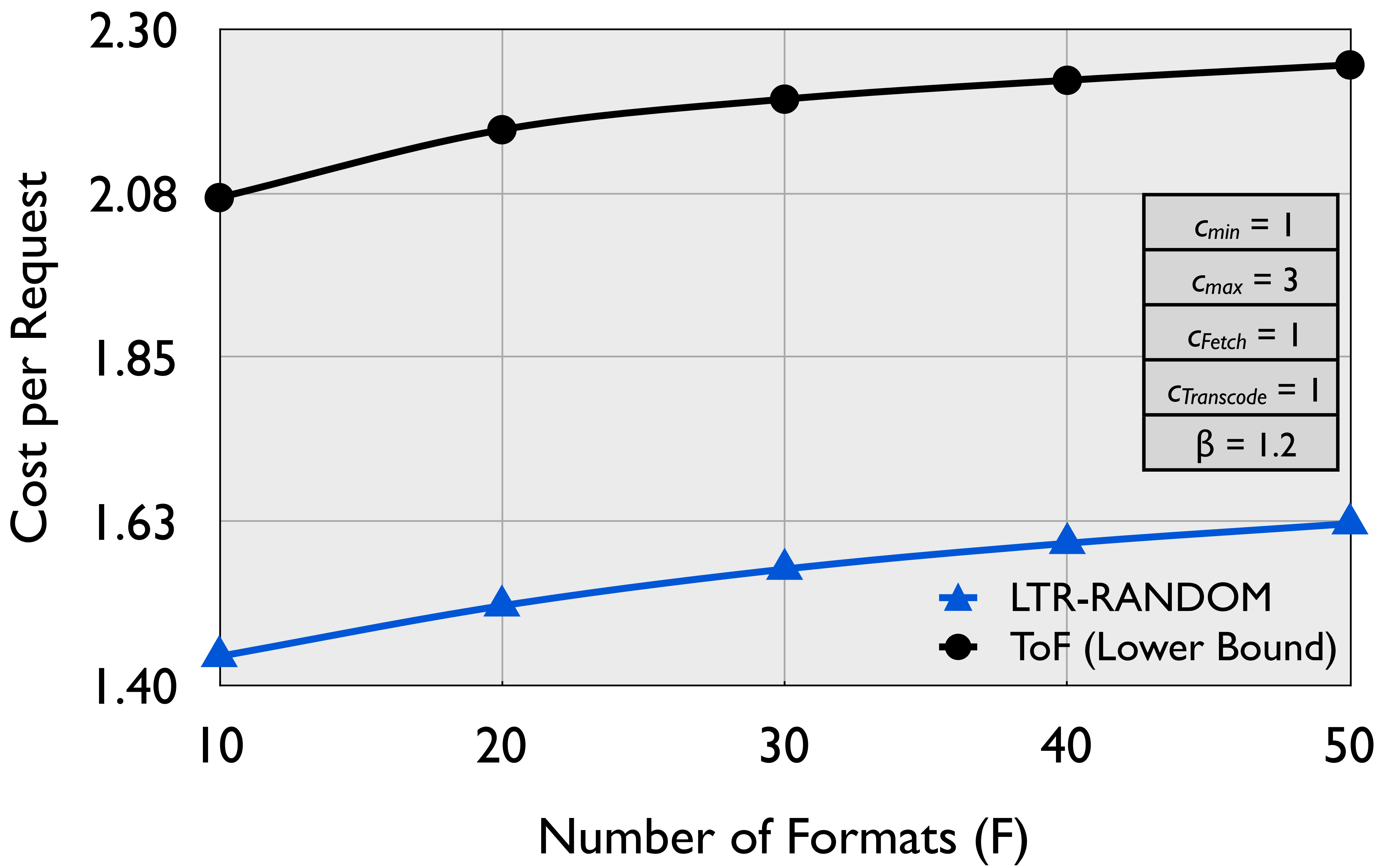
Simulations

Cost vs Front-end Storage



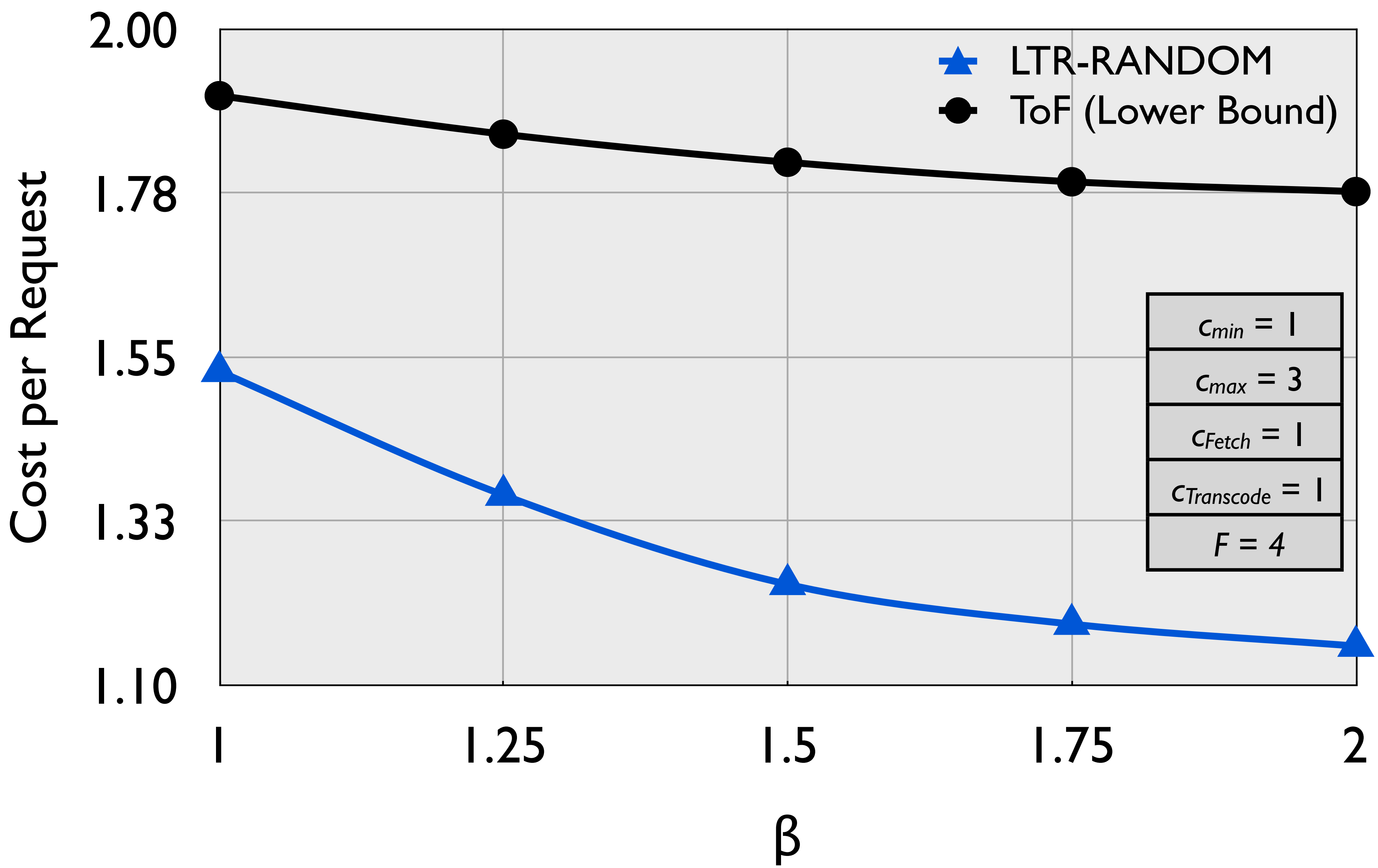
Simulations

Cost vs Number of Formats



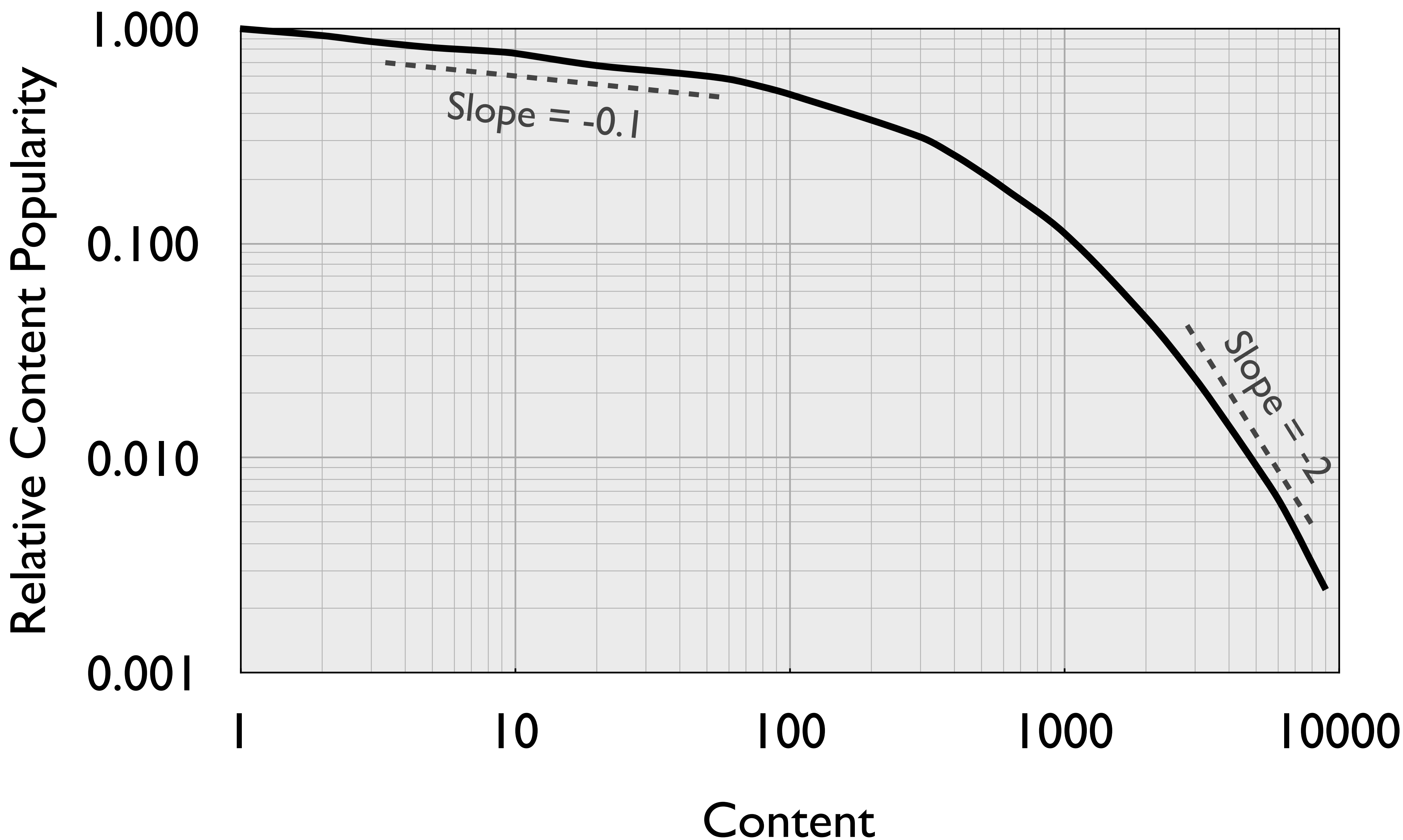
Simulations

Cost vs Zipf Parameter



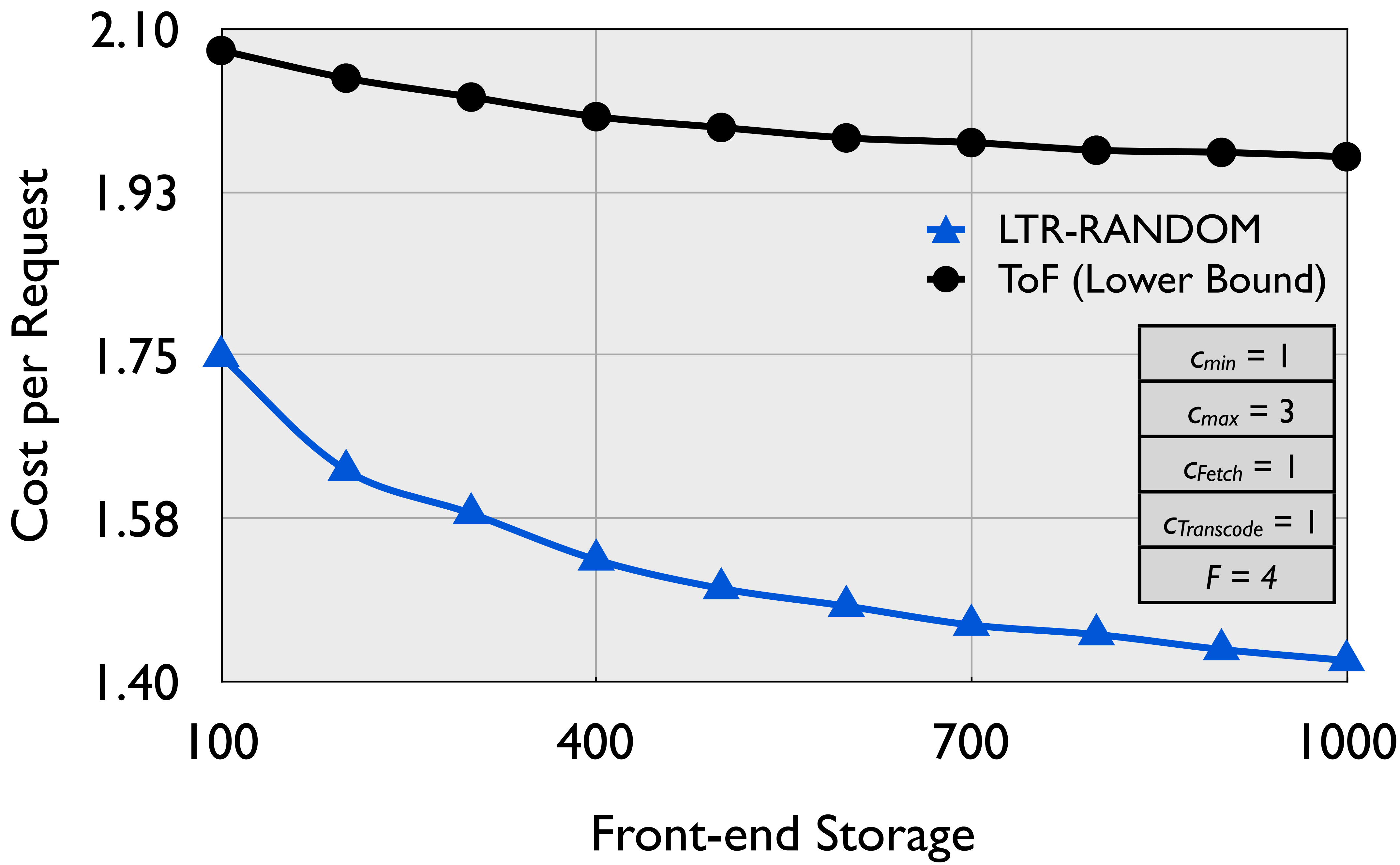
Netflix Data

Content Popularity



Simulations

Netflix Content Popularity



Related Work

Device Heterogeneity

- Measurement and analysis of an internet streaming service to mobile devices
  Liu, Li, Guo, Shen, Chen & Lan, *IEEE Transactions on Parallel and Distributed Systems*
- Joint online transcoding & geo-distributed delivery for dynamic adaptive streaming
  Wang, Sun, Wu, Zhu & Yang, *IEEE INFOCOM* 2014

Large content catalogs

- Serving content with unknown demand: the high-dimensional regime
  S.M., Ghaderi, Sanghavi & Shakkottai, *ACM Sigmetrics* 2014
- Adaptive replication in distributed content delivery networks
  Leconte, Lelarge & Massoulie, *ITC* 2015
- Bipartite graph structures for efficient balancing of heterogeneous loads
  Leconte, Lelarge & Massoulie, *Sigmetrics* 2012
- Queueing system topologies with limited flexibility
  Tsitsiklis & Xu, *Sigmetrics* 2013

Conclusions

Task - Content replication for content delivery in multiple formats

Candidate Approaches -

- *Transcode on the fly*: Store content in one high-quality master format
- *DIST-LTR*: Stores multiple formats of the same content

Results -

- The *transcode on the fly* approach is strictly suboptimal
- *DIST-LTR* is asymptotically optimal, even without coordination

Thanks