Information Resilience through User-Assisted Caching in Disruptive Content-Centric Networks

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Motivation

- **Content-Centric Networking/Information-Centric Networking**
  - Main future networking environment (information retrieval is more important than location).
  - Flexible to adaptation through its native support to caching, mobility and multicast.
- **In-network opportunistic caching**
  - Salient characteristic of CCN/ICN.
  - Packets are opportunistically cached in passing by nodes.
  - Plenty of research on the optimization in-network caching system performance.
- **Disaster scenarios (earthquake, tsunami, etc.)**
  - Usage of ICN functional parts, even when these are disconnected from the rest of the network (IETF ICNRG working group).
  - Difficult for today's networks that mandate connectivity to central entities for communication (*e.g.* DNS).

Goal

- Investigate the potential of the in-network caching to prolong information/content lifetime and serve interests when fragmentation occurs and origin server is not reachable.
- Propose a simple and efficient scheme for realizing a caching mechanism, whose focus is to preserve content over time (not only improve response time, but also make content available to future users).
- Take advantage of users with similar interests and their cached content to assist in content retrieval.
- Dynamic/disruptive environment (aftermath of a disaster), where both users and content servers may dynamically join and leave the network (mobility or network fragmentation).

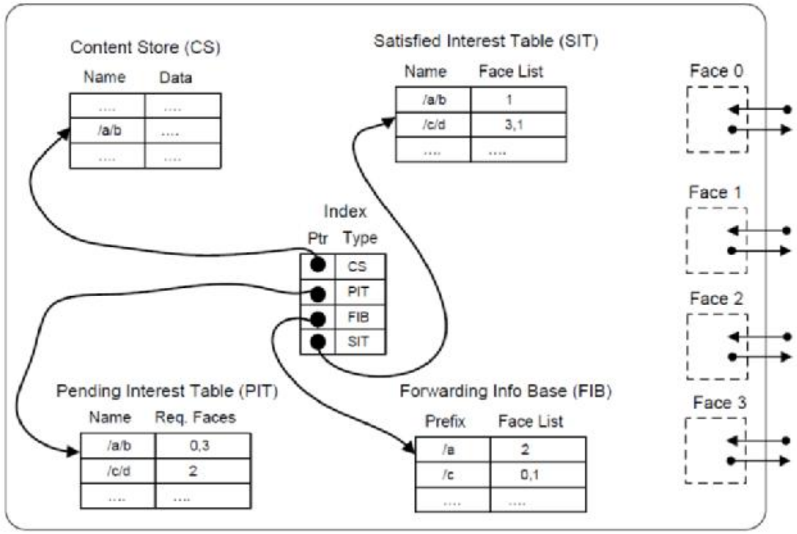
Key challenges

- **“Design”** challenges:
  - How to augment the original NDN content router to increase information resilience?
  - What changes are required to the various packets format and their processing?
- **“Caching”** challenges:
  - How to forward Interest after the network fragmentation?
  - Which items to cache in a passing by node and how to discard them in case of an overflow?

Contributions

- Enhance NDN router design to enable content retrieval when the network is fragmented.
- Enhance the Interest packet forwarding mechanism of the NDN to enable neighbouring users to assist in content retrieval.
- Decompose the information resilience scheme in a set of basic policies/strategies.
- Provide lower bounds using Markov processes for the probability and the time to absorption of an item (disappearance from the network caches).
- Validate and evaluate the resilience scheme for various system parameters.

Router Design



- Content Store (CS)
- Pending Interest Table (PIT)
- Forwarding Information Base (FIB)

Same to NDN original model

- ***Satisfied Interest Table (SIT)***
  - Keeps track of data packet next hop.
  - "*Bread crumbs*" for user-assisted caching.
  - Allows a list of outgoing faces.
  - Similar to Persistent Interests (PI) in Tsilopoulos and G. Xylomenos, ''Supporting Diverse Traffic Types in ICN,'' ACM SIGCOMM ICN 2011.

Packet Processing

- Interest Packet format
  - ***Destination flag** (**DF**)* bit to distinguish whether the Interest is headed towards content origin (DF=0), or towards neighbouring users (DF=1).
- Interest Packet processing
  - Same to NDN when the network is not fragmented.
  - If the Interest cannot find a match in CS, PIT and FIB then DF is set to 1 and follows entries in SIT (fragmentation detected).
  - An Interest with DF=1 can be replied both by routers and by users with matching cached content.
- Data packet processing
  - Exactly the same to NDN model; follow the chain of PIT entries.
  - A passing by Data packet initiates SIT entries.
  - Optionally cached in CS of each passing by router.

Strategies/Policies (after the network fragmentation)

- **Interest forwarding policies**
  - SIT based forwarding policy (STB)
  - Flooding forwarding policy (FLD)
- **Caching policies**
  - No caching policy (NCP)
  - Edge caching policy (EDG)
  - En-route caching policy (NRT) – NDN basic policy (LCE)
- **Placement/Replacement policies**
  - Least Recently Used policy (LRU)

Performance Bounds

System model

Graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, $|\mathcal{E}| = E$ and $|\mathcal{V}| = V$.

$\mathcal{M}$ uint size information items.

ζ_v and ϕ_v connection and disconnection rate of users at node v.

At each node v requests generated with rate $r_v = \{r_v^1, \ldots, r_v^M\}$, r_v^m aggregate incoming request for item m.

$\{X_m(t),\, 0 \leq t < \infty\}$ the Markov process with stationary transition probabilities that depicts the number of users which have already retrieved item m and are connected in the network at time t.

$X_m(t)$ is a birth/death process with one absorbing state.

λ_n^m birth rate of the process at state n:

$$\lambda_n^m = \begin{cases} 0 & \text{if } n = 0, \\ \sum_{v \in \mathcal{V}} r_v^m & \text{if } n > 0, \end{cases}$$

$\mu_n^m = n \cdot \phi_v = n \cdot \phi$; the death rate of the process.

Probability to absorption into absorbing state

$$u_s^m = \begin{cases} 1 & \text{if } \sum_{i=1}^{\infty} \rho_i^m = \infty, \\ \frac{\sum_{i=s}^{\infty} \rho_i^m}{1 + \sum_{i=1}^{\infty} \rho_i^m} & \text{if } \sum_{i=1}^{\infty} \rho_i^m < \infty. \end{cases}$$

where

$$\rho_i^m = \begin{cases} 1 & \text{if } i = 0, \\ \frac{\mu_1^m \mu_2^m \cdots \mu_i^m}{\lambda_1^m \lambda_2^m \cdots \lambda_i^m} = \frac{\phi \cdot 2\phi \cdots i\phi}{\lambda^m \lambda^m \cdots \lambda^m} = \left(\frac{\phi}{\lambda^m}\right)^i \cdot i! & \text{if } i > 0. \end{cases}$$

Mean Time to Absorption

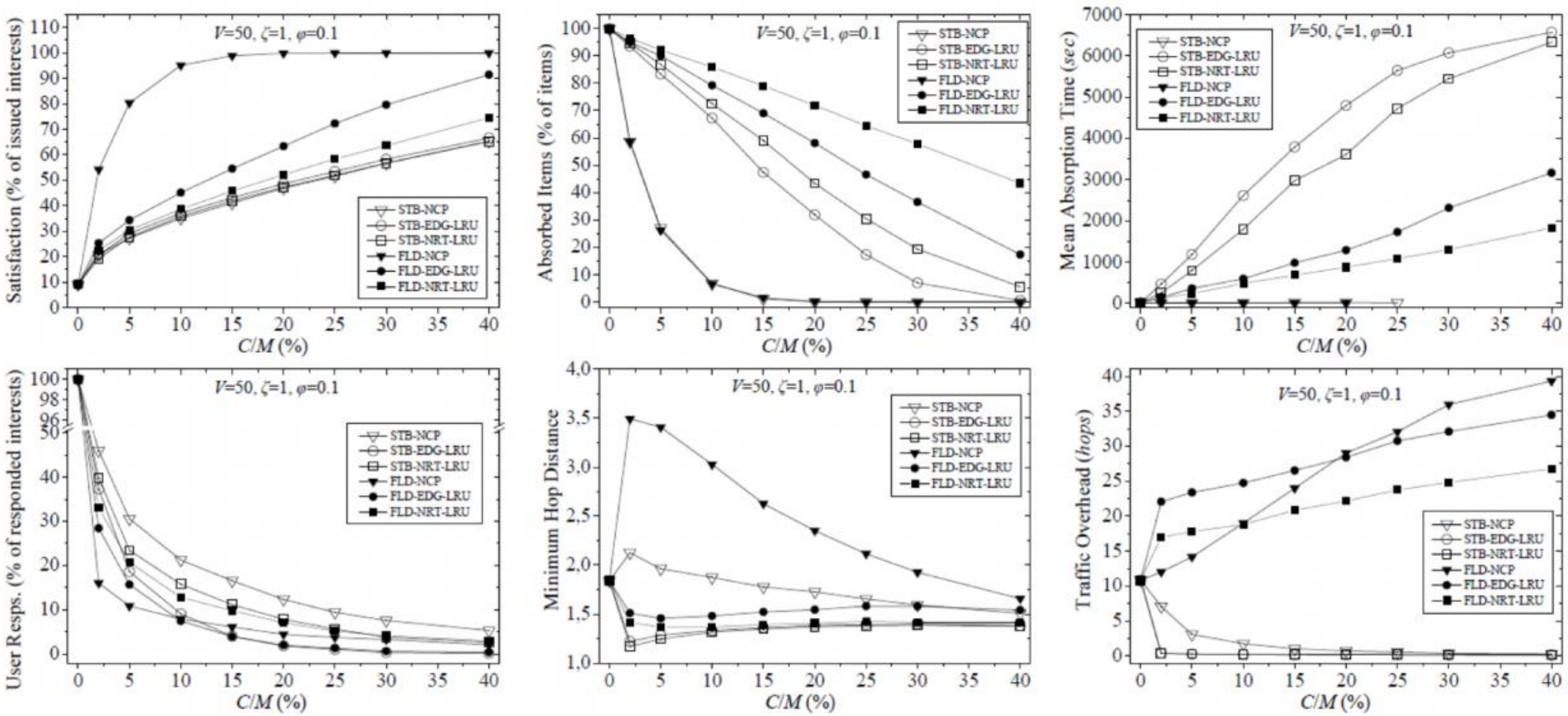
$$T_s^m = \begin{cases} \infty & \text{if } \sum_{i=1}^{\infty} \frac{1}{\lambda_i^m \cdot \rho_i^m} = \infty, \\ \sum_{i=1}^{\infty} \frac{1}{\lambda_i^m \cdot \rho_i^m} + \sum_{k=1}^{s-1} \rho_k^m \sum_{j=k+1}^{\infty} \frac{1}{\lambda_j^m \cdot \rho_j^m} & \text{if } \sum_{i=1}^{\infty} \frac{1}{\lambda_i^m \cdot \rho_i^m} < \infty. \end{cases}$$

- The proof is similar in rationale to: H. M. Taylor and S. Karlin, “An Introduction to Stochastic Modeling, 3rd edition”, Academic Press, 1998.
- When the death rate of the users interested in a content item is larger than the corresponding birth rate, the item will finally get absorbed when the content origin is not reachable.

Evaluation setup

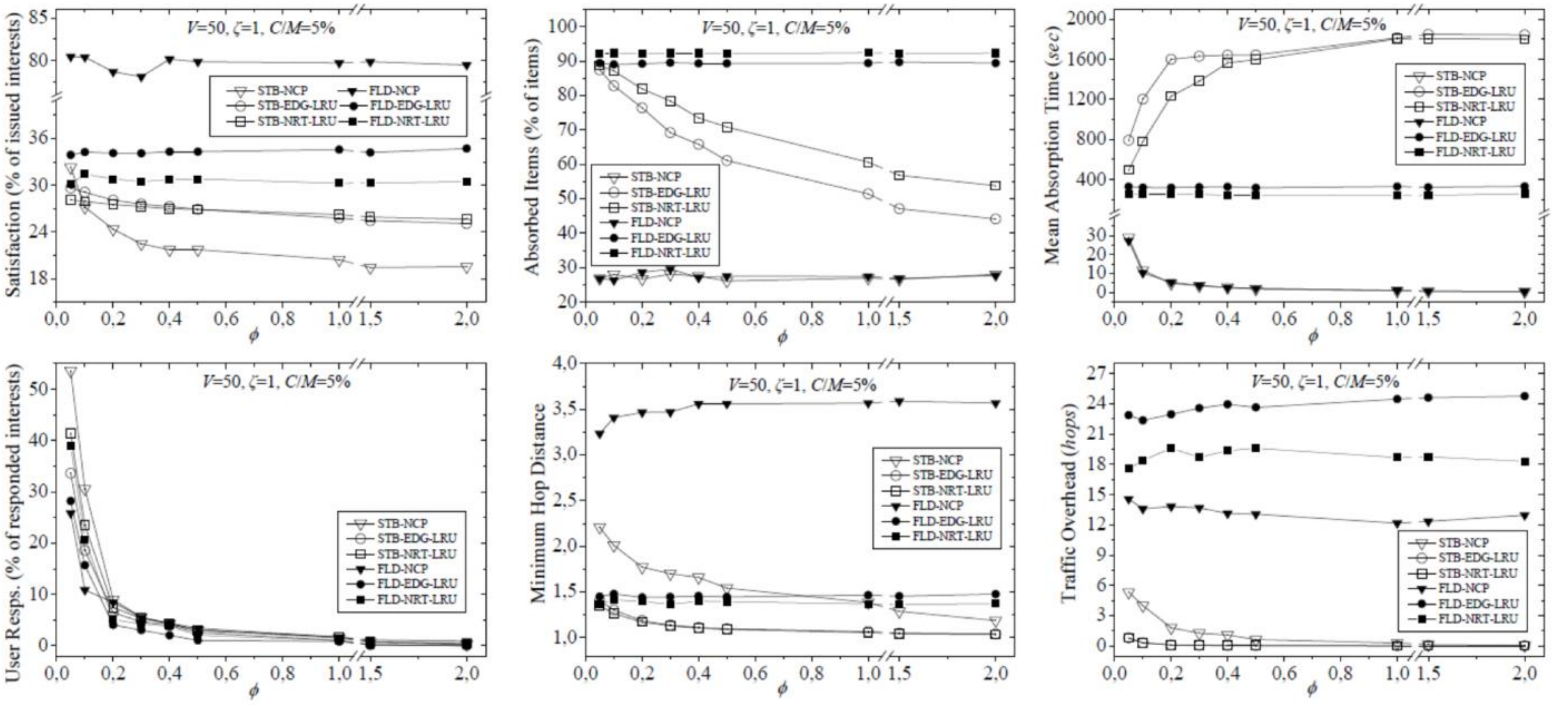
- Custom, discrete event simulator.
- Network topology of 50 nodes from Internet topology Zoo dataset.
- 1*req/sec* traffic demand at each node assuming Zipf distribution of content popularity. 1 *user/sec* connection rate.
- Localized request model (different Zipf exponent between different regions).
- 1000 content items.
- “Initialization period” of 1 *hour. “*Observation period” of 3 *hours.* Network fragmentation and origin servers of all items are not reachable.

Impact of the cache size



- The flooding policy - larger satisfaction ratios with substantial increase in the overhead.
- For small caching capacities, up to 45% of the satisfied interests are serves by neighbouring users.

Impact of users' disconnection rate



When disconnection rate is larger than 0.2, less than 5% of the satisfied interests are served from users.

Conclusions

- Each mechanism has its owns pros and cons and is a matter of the network manager which one to enforce after the fragmentation of the network.
- The simulated scenario is a extreme case where all content origins disappear simultaneously and no replication points are assumed.

Future work

- Study of the impact of the proposed scheme in the memory of the routers (inflated by the number of users in the network).
- Integration of a scope based content prioritization scheme within the proposed information resilience scheme.

Related Work

- Users contribution to caching by sharing their downloaded content with other users:
  - H. Lee and A. Nakao, “User-assisted in-network caching in information-centric networking,” Computer Networks - Elsevier, 2013.
- Exploitation of ICN to support the aftermath of a disaster:
  - Architecture and Applications of Green Information Centric Networking (GreenICN), http://www.greenicn.org/
  - T. Ogawara, Y. Kawahara and T. Asami, ‘‘Information Dissemination Performance of Disaster Tolerant NDN-based Distributed Application over Disrupted Cellular Networks,’’ IEEE Peer-to-Peer Computing (P2P) Conference, 2013.
- Scope based prioritization of ICN packets in disaster (user-defined priority, space and temporal validity):
  - I. Psaras, L. Saino, M. Arumaithurai, K. Ramakrishnan and G. Pavlou, ‘‘Name-Based Replication Priorities in Disaster Cases,’’ IEEE INFOCOM NOM, 2014.
- Resilience management function to support link failure detection and recovery:
  - M. Al-Naday, M. Reed, D. Trossen, Kun Yang, ‘‘Information resilience: source recovery in an information-centric network,’’ IEEE Network, 2014.

Questions?

Thank you!!