Delay-Aware Coded Caching for Mobile Users

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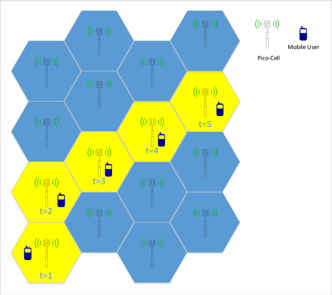
Motivation

- Video dominates Internet traffic:
  - In 2016, Youtube was responsible for %21 of mobile Internet traffic in North America (Sandvine 2016).
  - By 2021 size of Internet video traffic will be 4 times larger (Cisco 2017).
- Small number of viral video files are viewed by many users.
- Decreasing cost of high capacity storage.
- Densification of small-cells: mobility-aware coded storage

E. Ozfatura and D. Gunduz, Mobility and popularity-aware coded small-cell caching, IEEE Communications Letters, vol. 22, no. 2, pp. 288 - 291, Feb. 2018.

Network Model



- One macro base station (MBS)
- N small-cell base stations (SBSs) with a cache memory of size C bits.
- Library of K files, $\mathbb{V} = \{v_1, \ldots, v_K\}$, each of size F bits.
- v_k is the kth most popular file with request probability p_k.
- Within one time slot, MU can download B bits from a SBS.
- Duration of one streaming session: $T = F/B$ slots.

Video Streaming

- Mobility path: Sequence of SBSs visited within one streaming session.
- High mobility scenario: A mobile user (MU) connects to each SBS at most one time slot; that is, MU connects to T SBSs within one streaming session.
- Video display rate $\lambda = B$, i.e., it takes T time slots to play the downloaded file.
- Display can start before downloading all the segments of a file.
- Buffer starvation: MU buffer is empty.
- Rebuffering delay: When buffer starvation occurrs video display is frozen until next segment is downloaded.

Maximum Distance Separable (MDS) Codes

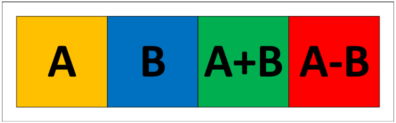


Figure: (2,4) MDS code

- Consider 4 SBSs and a user that can connect to any 2 over time ($T = 2$).
- Each file is divided into 2 fragments. Fragments are encoded into 4 fragments through a $(2, 4)$ MDS code.
- Each SBS caches a different coded fragment.
- User can recover the file by connecting to any 2 SBSs.

Conventional Coded Storage

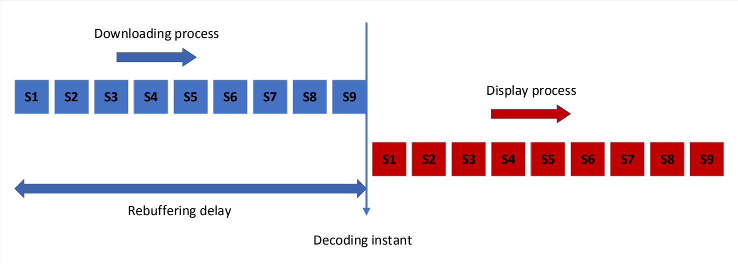


Figure: Video streaming process with conventional coded storage for $T = 9$

- Each file divided into T segments, and coded with (T, N) MDS code.
- Each SBS stores one coded segment (F/T bits) for each file.
- Rebuffering delay is T time slots

Delay-Aware Encoding

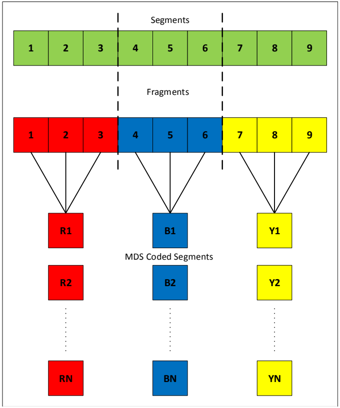


Figure: Video encoding for $T = 9$ and $M = 3$

- Segments are grouped into M disjoint fragments.
- Segments in each fragment are encoded with $(T/M, N)$ MDS code.

Delay-aware Coded Storage

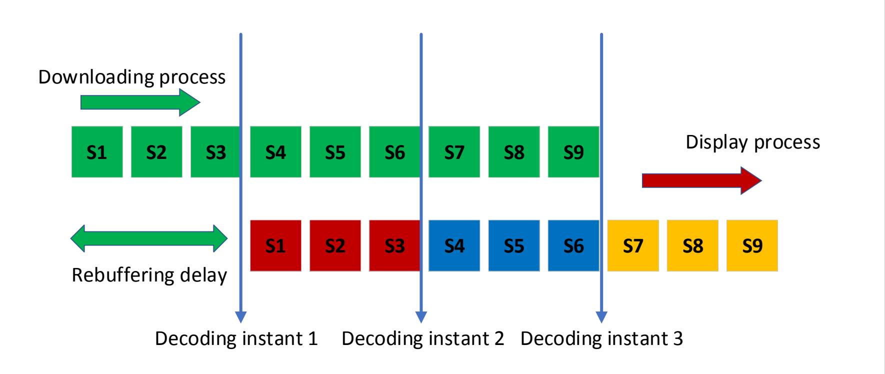


Figure: Video streaming with delay-aware coded storage for $T = 9$ and $M = 3$

- Each SBS stores $MF/T = MB$ bits for each file, and rebuffering delay is $\lceil T/M \rceil$ time slots

Delay-Memory Trade-off

- Delay-cache capacity function $\Omega(M) \triangleq \lceil T/M \rceil$:maps the number of fragments M to the rebuffering delay $D \in \mathcal{Z}^{+}$ (slots).
- $\Omega(M)$ is a monotonically decreasing step function.
- Delay levels, $D^{(l)}$: Possible values taken by $\Omega(M)$.
- Decrement points, $m^{(l)}$: minimum M that satisfies $\Omega(M) = D^{(l)}$

Delay-Memory trade-off

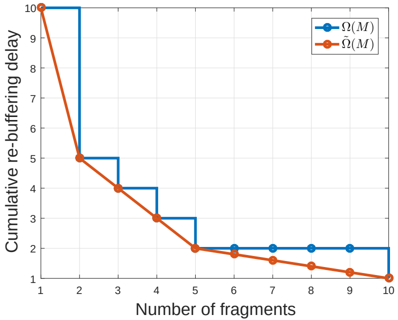


Figure: Delay-cache capacity function and its piece-wise linear approximation for $T = 10$

- $D^{(1)} = 10,\ D^{(2)} = 5,\ D^{(3)} = 4,\ D^{(4)} = 3,\ D^{(5)} = 2,\ D^{(6)} = 1$
- $m^{(1)} = 1,\ m^{(2)} = 2,\ m^{(3)} = 3,\ m^{(4)} = 4,\ m^{(5)} = 5,\ m^{(6)} = 10$

Problem Formulation

- For file v_k, expected delay-cache capacity function:

$$\Omega_k(M_k) \triangleq p_k \lceil T/M_k \rceil$$

- Average rebuffering delay, $\mathbf{M} = (M_1, \ldots, M_K)$

$$D_{avg}(\mathbf{M}) = \sum_{k=1}^{K} \Omega_k(M_k)$$

- D_{max}: Maximum allowable delay for a video file.

$$\begin{aligned} \textbf{P1:} \quad & \min_{\mathbf{M}} \; D_{avg}(\mathbf{M}) \\ \text{subject to:} \quad & D_k(M_k) \leq D_{max}, \; \forall k, \\ & \sum_{k=1}^{K} M_K B \leq C. \end{aligned}$$

Solution Approach

Observation

- Replacing $\Omega_k(M_k)$ with its linear approximation $\tilde{\Omega}_k(M_k)$, **P1** becomes a convex optimization problem
- Let $\gamma_{k,l}$ be the slope of $\tilde{\Omega}_k(M_K)$ in interval $(m^{(l)}, m^{(l+1)}]$, and an approximately optimal solution found in polynomial time by sorting $\gamma_{k,l}$

Lemma

- Approximate solution is equivalent to the optimal if M_k is equal to some decrement point $m^{(l_k)}$ for each k.
- Otherwise, the optimal solution can obtained by increasing cache size C by at most $\epsilon \leq F/2$.

Cost-Aware Delay-Constrained Caching

Problem Definition

- It may not be possible to satisfy maximum delay constraint D_{max} for all files.
- We can also impose a QoS constraint $\bar{D}_{max}$ on $D_{avg}(\mathbf{M})$.
- Some files not cached at SBSs and served directly by MBS with an additional cost.
- Objective: Minimize cost while satisfying constraints $\bar{D}_{max}$ and D_{max}

Solution Approach

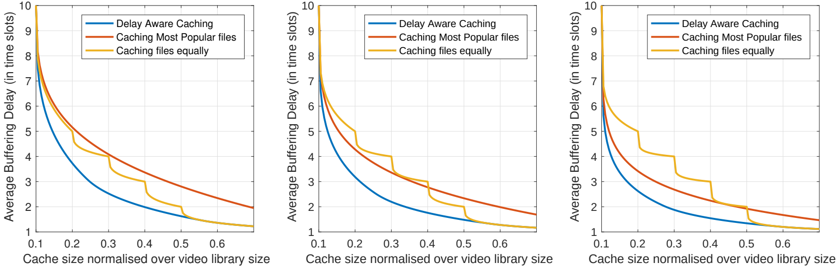
- At each iteration remove the least popular file and apply the delay-aware coded caching method. Continue until constraints D_{max} and $\bar{D}_{max}$ are met.

Simulation Results: Benchmarks

- Cache most popular files: First, all files are cached to meet D_{max}, then starting from the most popular file, rebuffering delays are sequentially reduced to minimum.

- Cache files equally: All files are cached with same delay.

Minimizing Average Rebuffering Delay

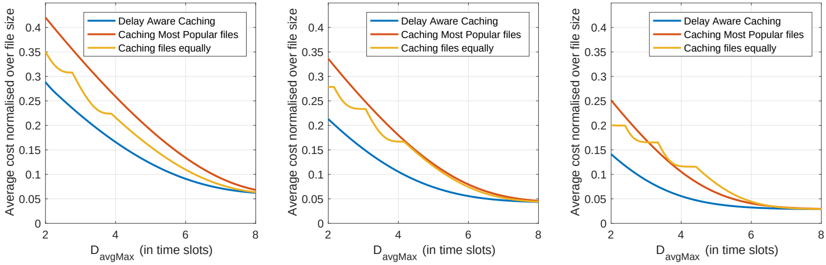


(a) $w = 0.75$ (b) $w = 0.85$ (c) $w = 0.95$

Figure: Average buffering delay versus cache size for $D_{max} = 10$ slots

- Video library of 10000 files: popularity is modeled using a Zipf distribution with coefficient $w \in \{0.75, 0.85, 0.95\}$.
- Video download duration $T = 10$ slots, and $D_{max} = 10$ time slots.
- Consider cache sizes $\hat{C} \in [0.1, 0.7]$.

Minimizing Average Cost



(a) $w = 0.75$ (b) $w = 0.85$ (c) $w = 0.95$

Figure: Average cost versus maximum average delay constraint for $T = 10$ slots

- Set cache size $\hat{C} = 0.08$ and $D_{max} = 10$.
- Consider $\bar{D}_{max} \in [2, 8]$.

Conclusions

- Analyzed storage-delay trade-off focusing on continuous video streaming.
- Introduced fragment-based coded caching to reduce rebuffering delay
- Future directions:
  - Consider more general user mobility models.
  - Consider a video display rate higher than the download rate from SBSs.