New Results on Cache-Aided One-to-Many Compression and Communication

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Content Delivery Networks

- Mirror sites for large, frequently used programs such as software, media, etc.

Let’s bring caches even closer to users
Promising Solution: Distribute Caches at Various Locations in Network

- Can cache at main BSs, picoBSs, femtoBSs, or directly at end users
- Caches accessed with short delay and without loading parts of network

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Wigger — New Results on Cache-Aided One-to-Many Compression and Communication
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Wigger — New Results on Cache-Aided One-to-Many Compression and Communication
Questions to Address for Cache-Aided Networks

- Where to put caches? Sizes of caches?
- What to store in the caches?
- How to communicate in presence of cached data?
One-To-Many Communication with Caches at Receivers

- Communication in two phases → cache filled independently of delivery
- No file popularities

Outlook on this Talk

Part 1: Observation on Maddah-Ali & Niesen’s setup and results

Part 2: Delivery over noisy broadcast channel:
  - joint source channel coding $\rightarrow$ piggyback coding

Part 3: Correlated files $\rightarrow$ rate-distortion setup:
  - Wyner and Gács-Körner common information
  - Gray-Wyner source coding problem
  - Virtual binning scheme for two users
Part 1: Maddhah-Ali & Niesen Source Coding Setup

Library: IID Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits (no popularities)

Communication in two phases:
Part 1: Maddhah-Ali & Niesen Source Coding Setup

Library: IID Files $W_1, W_2, \ldots, W_D$ of $n \rho$ bits

Communication in two phases:

- **Placement phase**: Tx fills caches without knowing demands $d_1, \ldots, d_K$
Part 1: Maddhah-Ali & Niesen Source Coding Setup

Library: IID Files $W_1, W_2, \ldots, W_D$ of $n \rho$ bits

\[ T_x \]

demands $d_1, d_2, d_3, d_4, d_5$

\[ nR \text{ bits about } W_{d_1}, W_{d_2}, W_{d_3}, W_{d_4}, W_{d_5} \]

\[ \hat{W}_{d_1} \xrightarrow{\text{Rx 1}} \hat{W}_{d_5} \]

\[ \text{cache contents: } nM \text{ bits about messages } W_1, \ldots, W_D \]

Communication in two phases:

- **Placement phase:** $T_x$ fills caches without knowing demands $d_1, \ldots, d_K$

- **Delivery phase:** $T_x$ conveys $W_{d_1}, \ldots, W_{d_K}$ to Rxs 1, \ldots, $K$. 
Part 1: Maddhah-Ali & Niesen Source Coding Setup

Library: IID Files $W_1, W_2, \ldots, W_D$ of $n \rho$ bits

**Demands** $d_1, d_2, d_3, d_4, d_5$

$nR$ bits about $W_{d_1}, W_{d_2}, W_{d_3}, W_{d_4}, W_{d_5}$

Rx 1 $\rightarrow \hat{W}_{d_1}$

Rx 2

Rx 3

Rx 4

Rx 5 $\rightarrow \hat{W}_{d_5}$

Cache contents: $nM$ bits about messages $W_1, \ldots, W_D$

Rates-Memory Tradeoff

For which triples $(\rho, R, M)$ is error-free data transmission possible?
Naive Uncoded Caching for $K = 2$ Receivers

Library: Files $W_1, W_2, \ldots, W_D$ of $n \rho$ bits each

- Split $W_d = (W_d^{(c)}, W_d^{(u)})$ of length $(\frac{M}{D}n, (\rho - \frac{M}{D})n)$ bits
Naive Uncoded Caching for $K = 2$ Receivers

Library: Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each

Rates-Memory Trade-Off

Reconstruction is possible, if $R \geq 2 \left( \rho - \frac{M}{D} \right)$
Coded caching for $K = 2$ Receivers [Maddah-Ali&Niesen 2013]

Library: Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each

\[
\hat{W}_{d_1} 
\]

\[
\hat{W}_{d_2}
\]

\[
\begin{align*}
\text{cache contents: } nM \text{ bits about messages } W_1, \ldots, W_D
\end{align*}
\]

- Split $W_d = (W_d^{(c_1)}, W_d^{(c_2)}, W_d^{(u)})$ of length $(\frac{M}{D}n, \frac{M}{D}n, (\rho - 2 \frac{M}{D})n)$ bits
Coded caching for $K = 2$ Receivers [Maddah-Ali&Niesen 2013]

**Library:** Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each

![Diagram of coded caching]

- **Rx 1:** $\hat{W}_{d_1}$
  - $W_{d_1}^{(c1)}$
  - \vdots
  - $W_{d_1}^{(c1)}$
  - $W_{d_1}^{(u)}$

- **Rx 2:** $\hat{W}_{d_2}$
  - $W_1^{(c2)}$
  - \vdots
  - $W_D^{(c2)}$

**Cache contents:** $nM$ bits about messages $W_1, \ldots, W_D$

- Split $W_d = (W_d^{(c1)}, W_d^{(c2)}, W_d^{(u)})$ of length $(\frac{M}{D} n, \frac{M}{D} n, (\rho - 2 \frac{M}{D}) n)$ bits

**Rates-Memory Trade-Off**

Reconstruction possible, if $R = 2 \left( \rho - \frac{M}{D} \right) - \frac{M}{D}$
Rate-Memory Curve for $\rho = 1$ and $K = D = 2$

- Coded caching gives right-star
- Can get left-star using symmetry arguments!
Expanded Demands Model & Cache-Rate Symmetry

- Demands-A: Rx1 wants $W_1$ and Rx2 $W_2$
- Demands-B: Rx1 wants $W_2$ and Rx2 $W_1$
- Demands-C: Rx1 wants $W_1$ and Rx2 $W_1$
- Demands-D: Rx1 wants $W_2$ and Rx2 $W_2$
Expanded Demands Model & Cache-Rate Symmetry

Demands-A: Rx1 wants $W_1$ and Rx2 $W_2$

Demands-B: Rx1 wants $W_2$ and Rx2 $W_1$

Demands-C: Rx1 wants $W_1$ and Rx2 $W_1$

Demands-D: Rx1 wants $W_2$ and Rx2 $W_2$

No assumption on knowledge of demands anymore!
Expanded Demands Model & Cache-Rate Symmetry

Library:
\(W_1, W_2\)

Transmitter

\[
\begin{align*}
W_1^{(1B)} & \quad \hat{W}_1^{(1A)} & \quad \hat{W}_2^{(1B)} \\
W_2^{(2B)} & \quad \hat{W}_2^{(2A)} & \quad \hat{W}_1^{(1A)} & \quad \hat{W}_2^{(1B)}
\end{align*}
\]

Duality:
\(r_1 \leftrightarrow m_1\)
\(r_2 \leftrightarrow m_2\)
Dec. Rx1B \(\leftrightarrow\) Dec. Rx2A

- Demands-A: Rx1 wants \(W_1\) and Rx2 \(W_2\)
- Demands-B: Rx1 wants \(W_2\) and Rx2 \(W_1\)

\(\rightarrow\) If \((R, M)\) achievable, also \((\tilde{R} = M, \tilde{M} = R)\) achievable!
Dualities between Rate $R$ and Memory $M$

- General duality for $K = D = 2$ and $M \geq 1$:

$$(R, \rho, M) \text{ achievable } \implies (\tilde{R} = M, \rho, \tilde{M} = R) \text{ achievable}$$

$(R, \rho, M)$ tradeoff already characterized by Maddah-Ali and Niesen

- For more general $K, D$?
  - need more involved dualities
  - $(R, \rho, M)$ tradeoff unknown

Communication links from BS to mobiles are noisy!

New coding elements? New cache designs?


[12] A. Ghorbel, M. Kobayashi, S. Yang, “Cache-enabled broadcast packet erasure channels with state feedback”.


Part 2: Delivery over Noisy Broadcast Channel
Caching over Packet Erasure BCs

Library: Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each (no popularities)

Packet Erasure Broadcast Channel

$X^n = (X_1, \ldots, X_n) \in \mathcal{F}^n$

Cache contents: arbitrary functions of messages $W_1, \ldots, W_D$

- Receiver $k$ gets erasure with probability $\delta_k$ where $\delta_1 \geq \delta_2 \geq \ldots \geq \delta_K$

  $Y_k^n = (X_1, X_2, \Delta, X_4, \Delta, \ldots, X_{n-1}, \Delta)$

  $\rightarrow$ fraction of $\Delta$s $\approx \delta_k$
Example: Asymmetric Caches and Separate Channel Coding

**Library:** Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each

Library: Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each

Packet Erasure Broadcast Channel

Split $W_d = (W_d^{(c1)}, W_d^{(u)})$ of rates $(2\frac{M}{D}, \rho - 2\frac{M}{D})$
Example: Asymmetric Caches and Separate Channel Coding

\[ X^n = \begin{cases} W_{d_1}^{(u)} & \text{to Rx 1} \\ W_{d_2}^{(c_1)} & \text{to Rx 2} \\ W_{d_2}^{(u)} & \text{to Rx 2} \end{cases} \]

- Split \( W_d = (W_d^{(c_1)}, W_d^{(u)}) \) of rates \( (2 \frac{M}{D}, \rho - 2 \frac{M}{D}) \)

Asymmetric Cache Assignment Can Help

\[ p(\text{error}) \to 0 \text{ if: } \frac{\rho - 2 \frac{M}{D}}{F(1 - \delta_1)} + \frac{\rho}{F(1 - \delta_2)} \leq 1 \]

No Global Caching Gain
Example: Our Joint-Cache Channel Scheme for $K = 2$

Library: Files $W_1, W_2, \ldots, W_D$ of $n\rho$ bits each

Packet Erasure Broadcast Channel

$X^n = W_{d_1}^{(u)} W_{d_2}^{(c1)} W_{d_2}^{(u)}$ and “piggyback-coding!”

- Split $W_d = (W_d^{(c1)}, W_d^{(u)})$ of rates $(2^M_D, \rho - 2^M_D)$

- Sending $W_d^{(c)}$ does not affect weaker receiver!

Sending $W_d^{(c)}$ does not affect weaker receiver!

Joint Cache-Channel Coding gives back Global Caching Gain

\[
p(\text{error}) \to 0 \text{ if: } \frac{\rho - 2^M_D}{F(1 - \delta_1)} + \frac{\rho - 2^M_D}{F(1 - \delta_2)} \leq 1 \quad \text{and} \quad \frac{2\rho - 2^M_D}{F(1 - \delta_2)} \leq 1
\]
Piggyback Coding

- For the phase where we send \((W_{d_1}^{(u)}, W_{d_2}^{(c_1)})\) to both receivers

- Rx 1 already knows \(W_{d_2}^{(c_1)}\) and restricts decoding to corresponding row
  \(\rightarrow\) Transmission of \(W_{d_2}^{(c_1)}\) does not bother Rx 1

codebook of codewords \(X^{n'}(W_{d_1}^{(u)}, W_{d_2}^{(c_1)})\)
Our Example for $\delta_1 = 4/5$ and $\delta_2 = 1/5$ and $M \leq \rho 3D/8$

2. Asymmetric caches $M_1 = 2M$ and $M_2 = 0$ & separate source-channel coding

$$\rho \leq \frac{4}{5} F(1 - \delta_1) + \frac{8}{5} \frac{M}{D}$$

3. Asymmetric caches $M_1 = 2M$ and $M_2 = 0$ & joint cache-channel coding

$$\rho \leq \frac{4}{5} F(1 - \delta_1) + 2 \frac{M}{D}$$
Our Example for $\delta_1 = 4/5$ and $\delta_2 = 1/5$ and $M \leq \rho 3D/8$

1. Symmetric caches $M_1 = M_2 = M$ & coded caching as before & separate source-channel coding

$$\rho \leq \frac{4}{5} F(1 - \delta_1) + \frac{6}{5} \frac{M}{D}$$

2. Asymmetric caches $M_1 = 2M$ and $M_2 = 0$ & separate source-channel coding

$$\rho \leq \frac{4}{5} F(1 - \delta_1) + \frac{8}{5} \frac{M}{D}$$

3. Asymmetric caches $M_1 = 2M$ and $M_2 = 0$ & joint cache-channel coding

$$\rho \leq \frac{4}{5} F(1 - \delta_1) + 2 \frac{M}{D}$$
Our General Joint Cache-Channel Scheme and Cache Design

- Assign larger cache sizes to weaker receivers

- Do Maddah-Ali&Niesen coded caching:
  - Cache submessages to groups of $t$ receivers
  - Deliver x-ors of submessages to $t + 1$ receivers

- For the delivery phase piggyback information to stronger receivers on x-or messages to weaker receivers!

A caching/delivery scheme cannot have $p(\text{error}) \to 0$ as $n \to \infty$, if

$$\frac{\rho - M_1}{F(1 - \delta_1)} + \frac{R - M_2}{1 - \delta_2} \leq 1$$

$$2\rho \leq 2F(1 - \delta_1) + M_1$$

$$2\rho \leq 2F(1 - \delta_2) + M_2$$

$$3\rho \leq F(1 - \delta_1) + F(1 - \delta_2) + M_1 + M_2$$


Achievable and Infeasible Maximum Rates $\rho(M)$

- $K = 2$ users and symmetric cache sizes $M_1 = M$ and $M_2 = 0$
- $\delta_1 = 0.4$ and $\delta_2 = 0.25$
- Maximum rates $\rho(M)$ in bits per channel use
How to Prove the Infeasibility Results

- Need to show: $p(error)$ cannot tend to 0 if one of four bounds violated

Library: Files $W_1, W_2$ of $n\rho$ bits each

Packet Erasure Broadcast Channel

$X^n$

$\hat{W}_{d1}$ $\hat{W}_{d2}$

Cache1 Cache2
How to Prove the Infeasibility Results

- Need to show: $p(error)$ cannot tend to 0 if one of four bounds violated

- Input/receivers $a$ for demand $(d_1 = 1, d_2 = 2)$; input/receivers $b$ for demand $(d_1 = 2, d_2 = 1)$
How to Prove the Infeasibility Results

- Need to show: \( p(\text{error}) \) cannot tend to 0 if one of four bounds violated

- Bound 2: \( 2\rho < 2F(1 - \delta_1) + M_1 \)
How to Prove the Infeasibility Results

- Need to show: $p(\text{error})$ cannot tend to 0 if one of four bounds violated

- Bound 4: $3\rho < F(1 - \delta_1) + F(1 - \delta_2) + M_1 + M_2$

**Library:**

Files $W_1, W_2$ of $n\rho$ bits each

Diagram:

- $X^n_a$ and $X^n_b$
- Packet Erasure Broadcast Channel
- $\hat{W}_1^{(1a)}$, $\hat{W}_1^{(2b)}$, $\hat{W}_2^{(2a)}$, $\hat{W}_2^{(1b)}$
Insights/Extensions

- Because of cache-content, joint cache-channel coding beneficial!
  \[ \rightarrow \text{even larger global caching gain!} \]

- Piggyback coding idea combines with any previous delivery scheme, in particular for degraded BCs.

- When all rxs have identical demands (which is a priori unknown) joint cache-channel coding based on Tuncel’s virtual binning optimal for delivery
Part 3: the Files Might be Correlated!

- The files are frames of videos, e.g., future interactive videos
  → users can choose angle, screen segments etc...

- Before: Caching creates common message parts for many receivers

- Now: Messages inherently have common parts →
  - Store these common parts in caches → common information!
  - Additional benefits expected!

Questions

- New coding elements?
- New cache designs?
Standard Lossy-Source Coding with Caching

Library:
Files $X_1^n, \ldots, X^n_D$ with $(X_{1,t}, \ldots, X_{D,t}) \sim P_X$ (no popularities)

Caching phase: $nM$ bits $m = \text{caching}(X_1^n, \ldots, X^n_D)$

Delivery phase: $nR$ bits $r = \text{delivery}(X_1^n, \ldots, X^n_D, d)$

Lossy reconstruction: $\hat{X}_d^n(m, r, d)$ s.t. $\forall d: \mathbb{E} \left[ \sum_{t=1}^{n} \delta_d(\hat{X}_t, X_{d,t}) \right] \leq \Delta_d$.


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Single-User Rate-Distortions-Memory (RDM) Tradeoff

\[ R^*(\Delta, M) = \min_{d \in \{1, \ldots, D\}} \max I(X_d; \hat{X}_d | U) \quad \text{where min. over } P_{\hat{X}, U | X} \text{ s.t.} \]

- \( I(X_1, \ldots, X_D; U) \leq M; \) and
- \( \mathbb{E}[\delta_d(\hat{X}_d; X_d)] \leq \Delta_d, \quad \forall d \in \{1, \ldots, D\}. \)

\textbf{Achievability:}

- Caching phase: Index from covering \((X_1^n, \ldots, X_D^n)\) by \(U^n\)
- Delivery phase: Lossily describe \(X_d^n\) under side-info \(U^n\) at tx and rx
Example 1: Independent and Identical Sources

- \( X_1^n, \ldots, X^n_D \) IID according to \( P^n_X \)
- \( \delta_1 = \ldots = \delta_D = \delta \)
- \( \Delta_1 = \ldots = \Delta_D = \Delta \)

### Rate-Distortion-Memory Tradeoff

\[
R(\Delta, M) = \max \left\{ 0, \ R_X^*(\Delta) - \frac{M}{D} \right\}
\]

\( \rightarrow \) Compress sources independently and cache first \( \frac{M}{D} \) bits of each description
Demands-Extension of our Lossy Setup: The Gray-Wyner Problem

Library:
Files $X^n_1, \ldots, X^n_D$ with $(X^n_1,t, \ldots, X^n_D,t) \sim P_X$
(no popularities)

Problem solved

Lower bound 1:
- All receivers can cooperate $\rightarrow R_{super}(\Delta, M)$

Lower bound 2:
- $D$ rate-$M$ private links replace comm. link $\rightarrow R_{genie}(\Delta, M)$
Demands-Extension of our Lossy Setup: The Gray-Wyner Problem

Library:
Files $X_1^n, \ldots, X_D^n$
with $(X_1^t, \ldots, X_D^t) \sim P_X$
(no popularities)

- Problem solved
- Lower bound 1:
  - All receivers can cooperate $\rightarrow R_{super}(\Delta, M)$
  - Tight when $M$ above Wyner common-Info (for $R_1, \ldots, R_D$ unequal)
- Lower bound 2:
  - $D$ rate-$M$ private links replace comm. link $\rightarrow R_{genie}(\Delta, M)$
  - Tight when $M$ below Gács-Körner common-info (for $R_1, \ldots, R_D$ unequal)
Typical Rates-Memory Function for Fixed Distortions

\[ R^*(\Delta, M) \]

\[
\max_{d \in \{1, \ldots, D\}} R^*_X(\Delta_d)
\]

- \( R_{\text{genie}} = \max \left\{ 0, \max_{d \in \{1, \ldots, D\}} \left( R^*_X(\Delta_d) - M \right) \right\} \)

- \( R_{\text{super}} = \max \left\{ 0, \max_{d \in \{1, \ldots, D\}} \frac{1}{D} \left( R^*_X(\Delta) - M \right) \right\} \)
Typical Rates-Memory Function for Fixed Distortions

\[
\max_{d \in \{1, \ldots, D\}} R^*_X(\Delta_d)
\]

In lossless, symmetric case:

- \(M_{\text{super}}(\Delta)\) is Wyner common-info \(\rightarrow\) above this store more than Wyner common-info

- \(M_{\text{genie}}(\Delta)\) is Gàcs-Körner comm.-info \(\rightarrow\) below this store part of Gàcs-Körner comm.-info
Two-User Lossy-Source Coding with Caching

Library: Files $X_1^n, \ldots, X_D^n$ with $(X_1, t, \ldots, X_D, t) \sim P_X$ (no popularities)

Caching phase: $nM$ bits $m = \text{caching}(X_1^n, \ldots, X_D^n)$

Delivery phase: $nR$ bits $r = \text{delivery}(X_1^n, \ldots, X_D^n, d_1, d_2)$

Lossy reconstructions $\hat{X}_1^n(m, r, d_1, d_2)$ and $\hat{X}_2^n(r, d_1, d_2)$ s.t. $\forall d_1, d_2$:

$$\mathbb{E} \left[ \sum_{t=1}^{n} \delta_{d_1} \left( \hat{X}_{1, t}(m, r, d_1, d_2), X_{d_1, t} \right) \right] \leq \Delta_{d_1},$$

$$\mathbb{E} \left[ \sum_{t=1}^{n} \delta_{d_2} \left( \hat{X}_{2, t}(r, d_1, d_2), X_{d_2, t} \right) \right] \leq \Delta_{d_2}.$$
Two-User Rate-Distortions-Memory Tradeoff, Achievability Result

Achievability Result

\[ R_{2\text{Users}} \leq \min_{(d_1,d_2)} \max \left\{ I(U, X; \hat{X}_2(d_1, d_2)) + I(X; \hat{X}_1(d_1, d_2)|U, \hat{X}_2(d_1, d_2)), \right. \]
\[ \left. I(X; U, \hat{X}_1(d_1, d_2), \hat{X}_2(d_1, d_2)) - M \right\} \]

where minimum over \((U, \hat{X}_1, \hat{X}_2)\) s.t. \(\forall (d_1, d_2):\)

\[ \mathbb{E}\left[ \delta_{d_1}(\hat{X}_1(d_1, d_2), X_{d_1}) \right] \leq \Delta_{d_1} \quad \text{and} \quad \mathbb{E}\left[ \delta_{d_2}(\hat{X}_2,t(d_1, d_2), X_{d_2}) \right] \leq \Delta_{d_2}. \]
Coding Scheme based on Virtual Binning

Our caching problem

- Describe $\hat{X}_2^n(d_2)$ to Rx 2 (and Rx 1)
- Describe $U^n, \hat{X}_1^n(d_1, d_2)$ to Rx 1 which has SI $\hat{X}_2^n(d_2)$
- Store parts of description of $U^n$ into cache

\[ \sum_{d_1, d_2} 2^n I(U; X) \text{ seq.} \approx 2^n I(U; \hat{X}_2(d_2=1)) \text{ seq.} \approx 2^n I(U; \hat{X}_2(d_2=D)) \text{ seq.} \]
Converse based on Successive Refinement

Our caching problem

Successive Refinement $\forall (d_1, d_2)$

Demands revealed before caching

Converse Result

$$R_{2\text{Users}} \leq \min_{(d_1, d_2)} \max_{\hat{X}_1, \hat{X}_2} \left\{ I(X; \hat{X}_2(d_1, d_2)), I(X; \hat{X}_1(d_1, d_2), \hat{X}_2(d_1, d_2)) - M \right\}$$

where minimum over $(U, \hat{X}_1, \hat{X}_2)$ s.t. $\forall (d_1, d_2)$:

$$\mathbb{E}\left[ \delta_{d_1}(\hat{X}_1(d_1, d_2), X_{d_1}) \right] \leq \Delta_{d_1} \quad \text{and} \quad \mathbb{E}\left[ \delta_{d_2}(\hat{X}_2,d_2, t(d_1, d_2), X_{d_2}) \right] \leq \Delta_{d_2}.$$
Bounds Tight in Special Cases:

- If $d_1$ is fixed or $d_2$ is fixed
- In lossless case, if $D = 2$ (only two files)
Summary

- In the expanded-demands model, caching and delivery links are equivalent to traditional (complicated) source coding and channel coding problems.
  - Duality between delivery rate $R$ and caching rate $M$.

- Joint cache-channel coding is required for delivery over a noisy network.
  - Piggyback coding for asymmetric BCs.
  - Brings global caching gain even with only local caches.

- Correlated files store "common informations".
  - Genie-aided and super-user lower bounds can be tight.
  - Two-user setup: need virtual binning because demands a priori unknown.