Coded Caching for Content Distribution

Urs Niesen

MobiHoc 2018

Importance of Content Distribution

- Video on demand is driving network traffic growth
  - Netflix streaming service, Amazon Prime Video, Hulu, Verizon / Comcast on Demand, ...
- IP video traffic is predicted to make up 82% of all IP traffic by 2021[1]

[1] Cisco, "The Zettabyte era: Trends and analysis," Tech. Rep., Jun. 2017.

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- Places significant stress on service provider's networks
- Caching (prefetching) can be used to mitigate this stress

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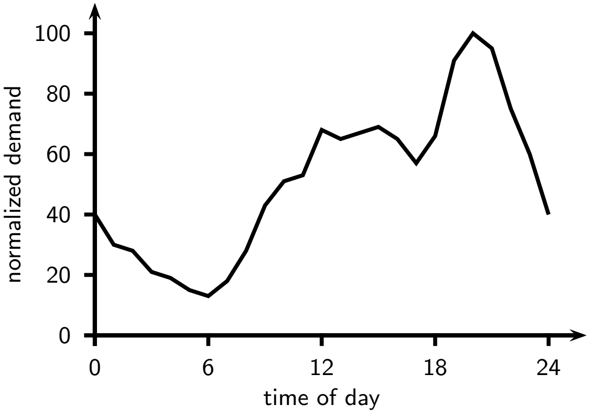
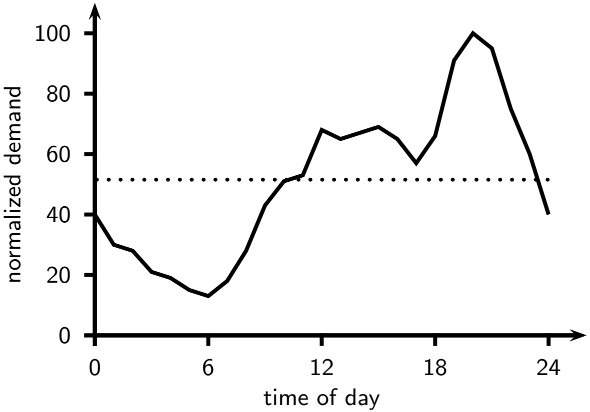
Caching (Prefetching)



Caching (Prefetching)



- High temporal traffic variability

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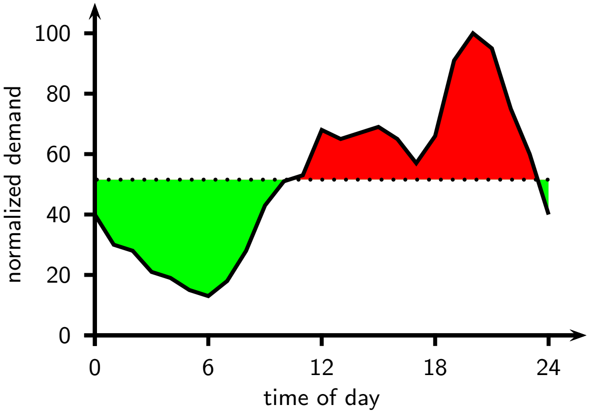

- High temporal traffic variability
- Caching can help smooth traffic

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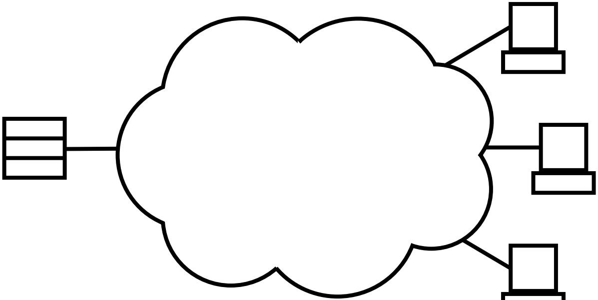

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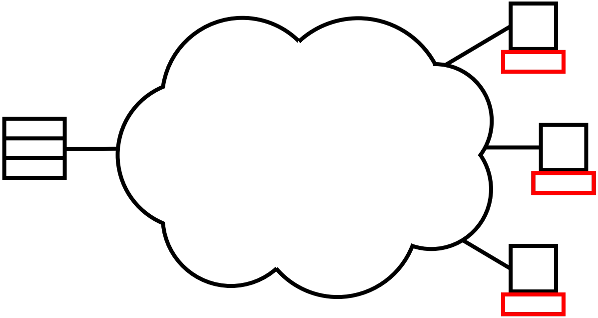
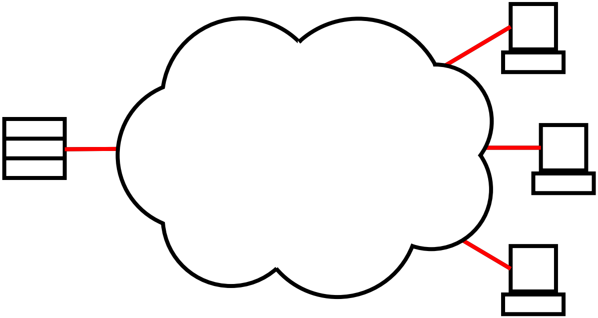


- Placement phase (5am): Populate caches

Caching (Prefetching)



- Placement phase (5am): Populate caches
- Delivery phase (8pm): Request and deliver movies

The Role of Caching

Conventional beliefs about caching:

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- The main gain in caching is global
- Global cache size matters
- Statistically identical users $\Rightarrow$ different cache content
- Coded multicasting as key enabler

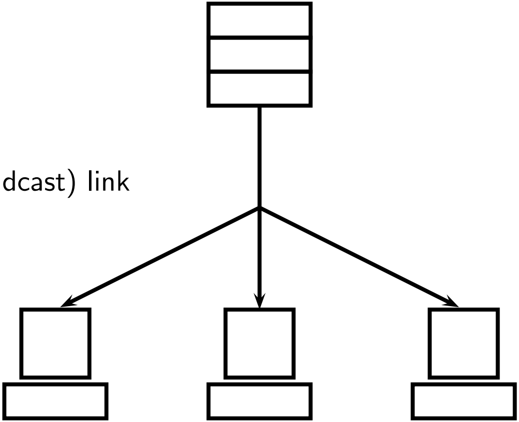
Problem Setting

server

shared (broadcast) link

K users

caches



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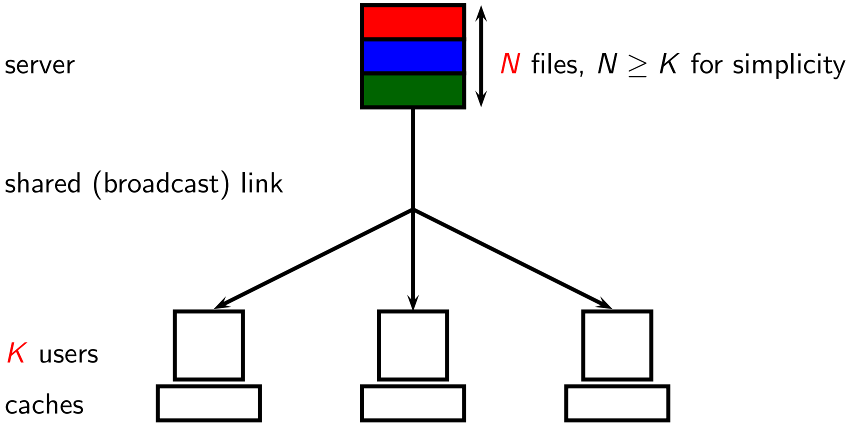

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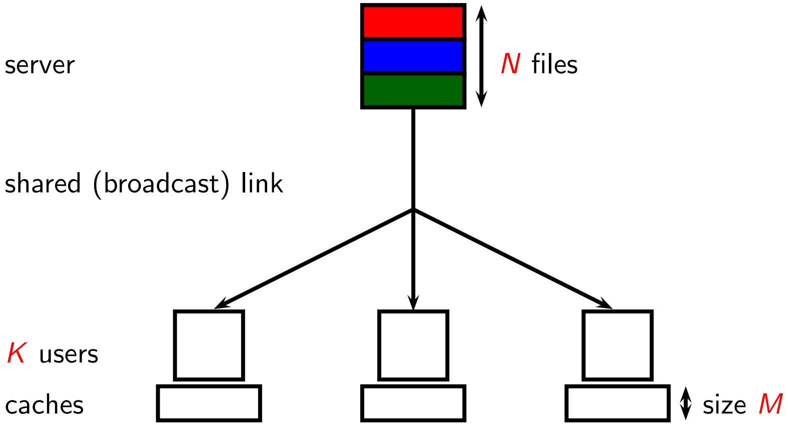

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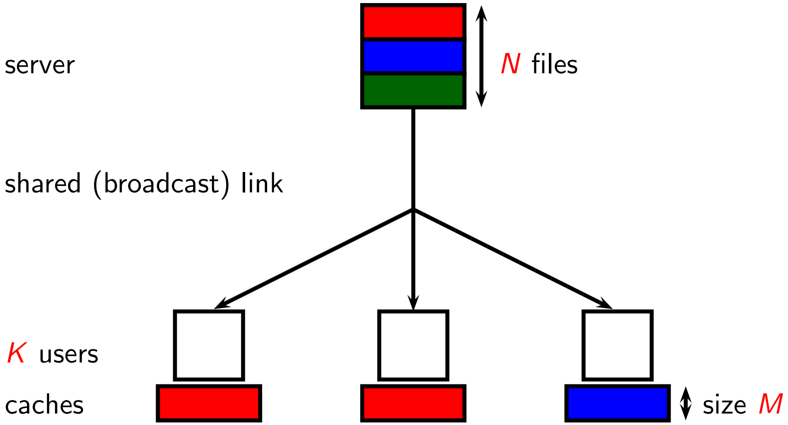
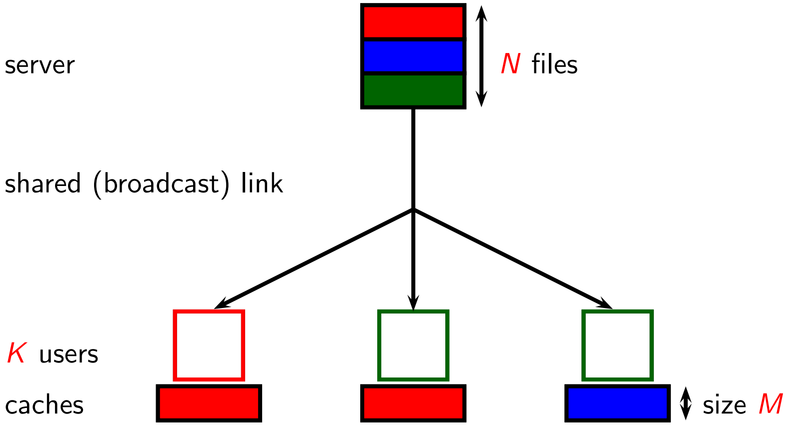


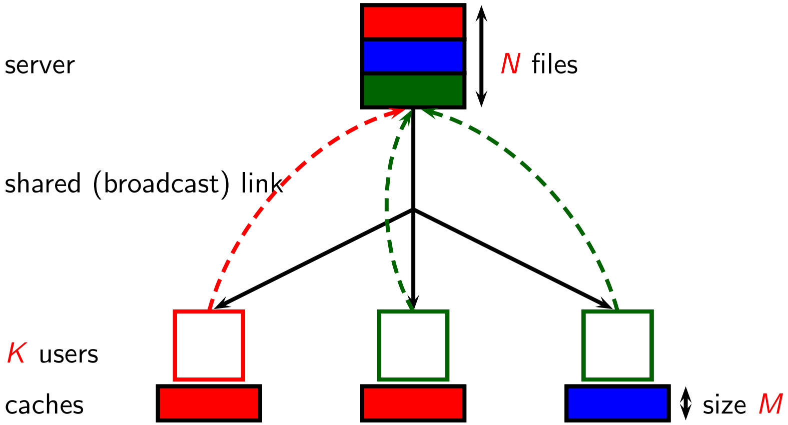
Placement: cache arbitrary function of files (linear, nonlinear, ...)

Problem Setting



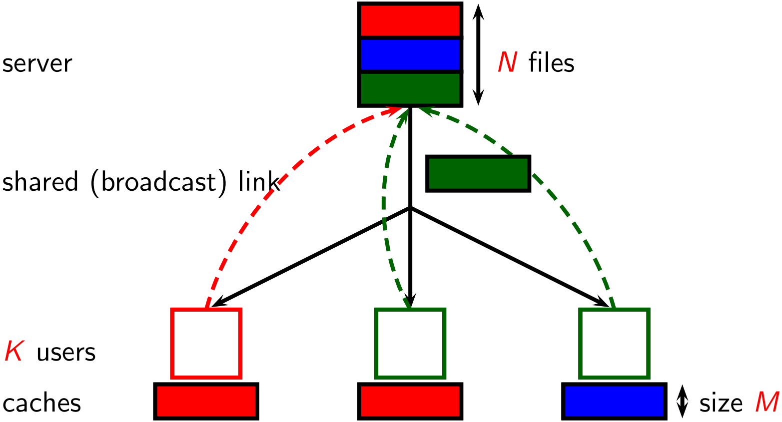
Delivery:

Problem Setting



Delivery: - requests are revealed to server

Problem Setting



Delivery: - requests are revealed to server

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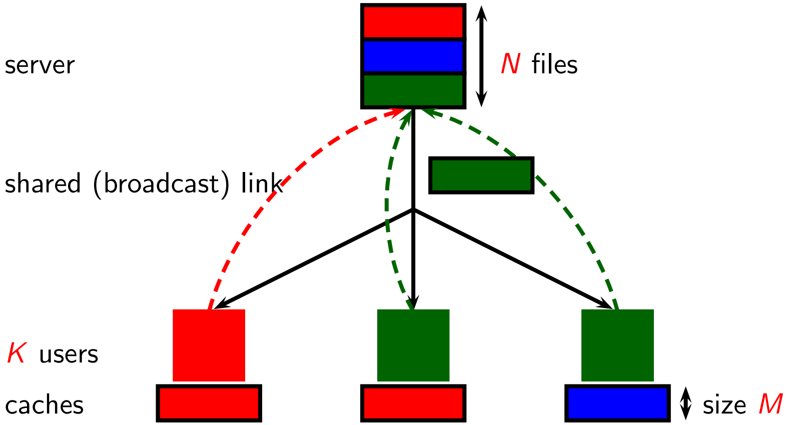

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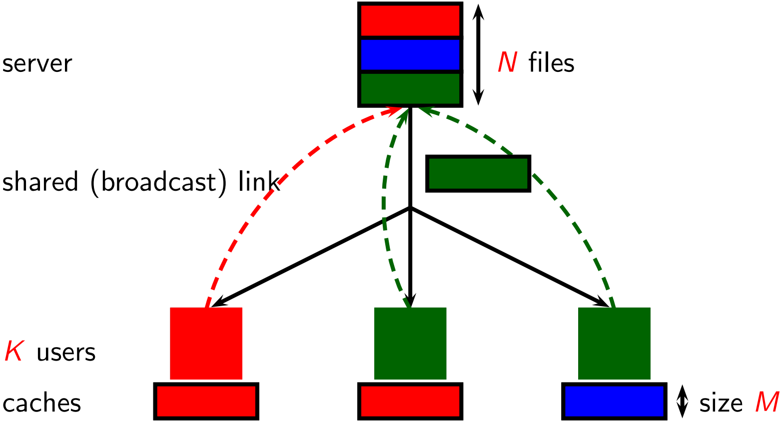
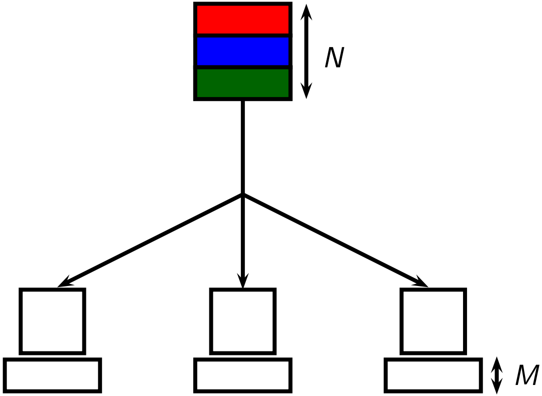


Question: smallest worst-case rate $R(M)$ needed in delivery phase?

Uncoded Caching Scheme

N files, K users, cache size M



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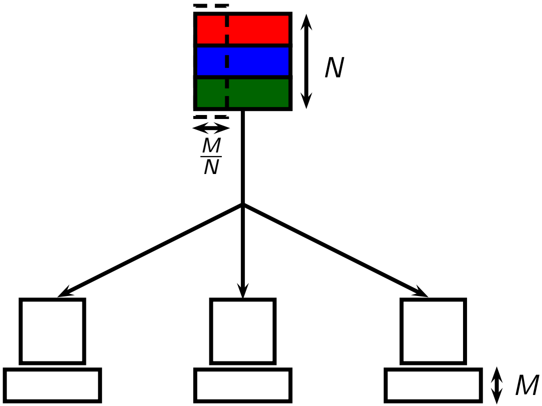

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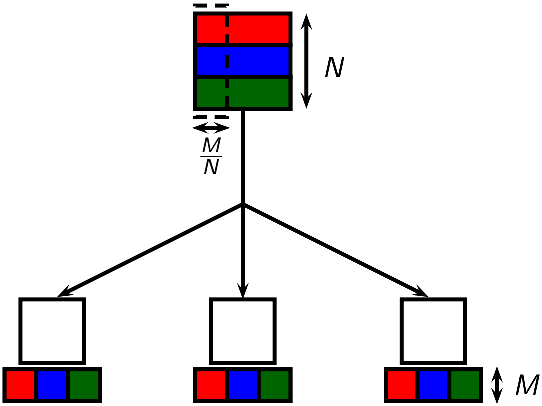

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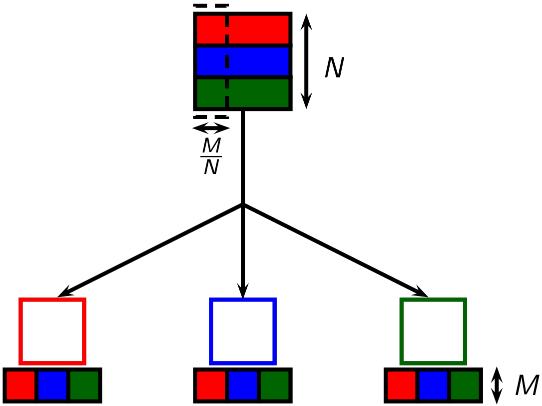

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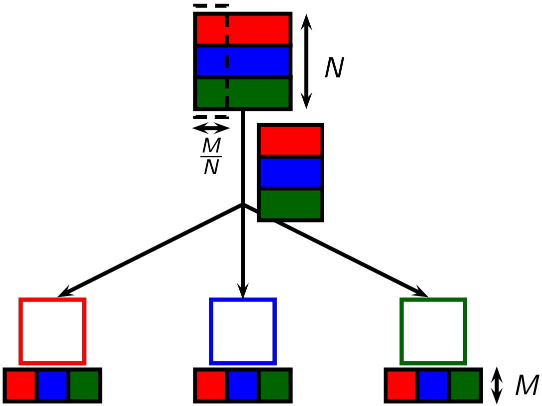

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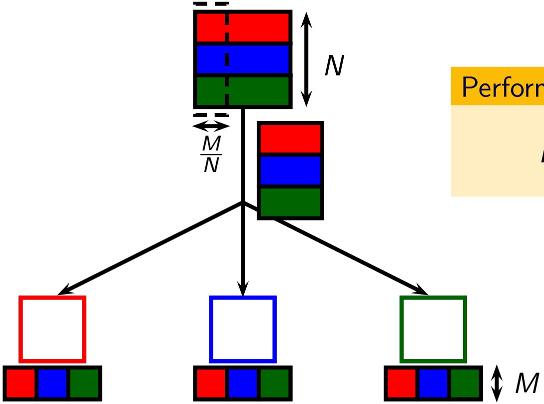

Performance of uncoded scheme:

$$R(M) = K \cdot (1 - M/N)$$

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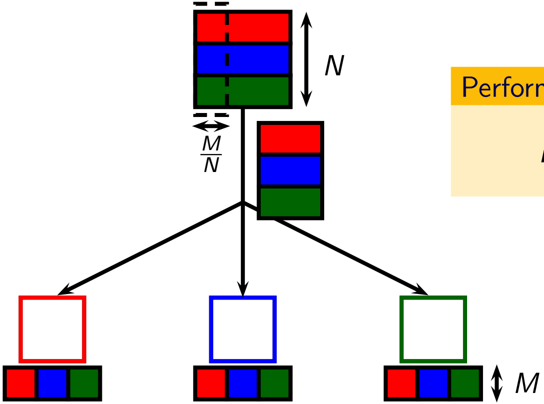

Performance of uncoded scheme:

$$R(M) = K \cdot (1 - M/N)$$

- Caches provide content locally $\Rightarrow$ local cache size matters
- Identical cache content at users

Uncoded Caching Scheme

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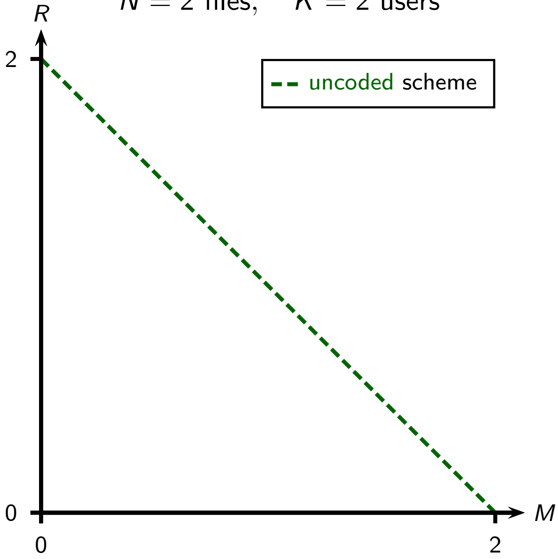
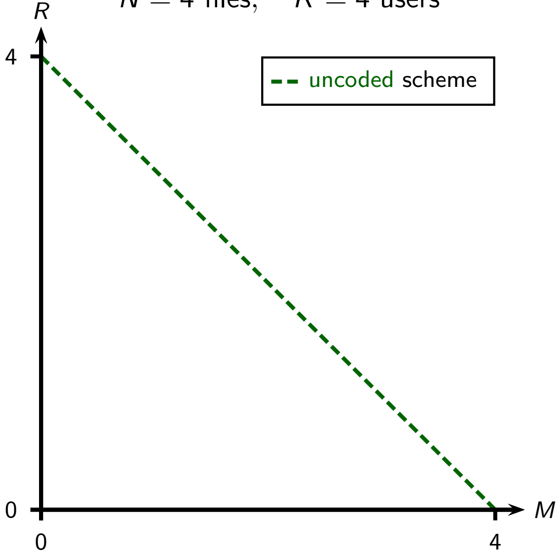


Uncoded Caching Scheme

$N = 4$ files, $\quad K = 4$ users



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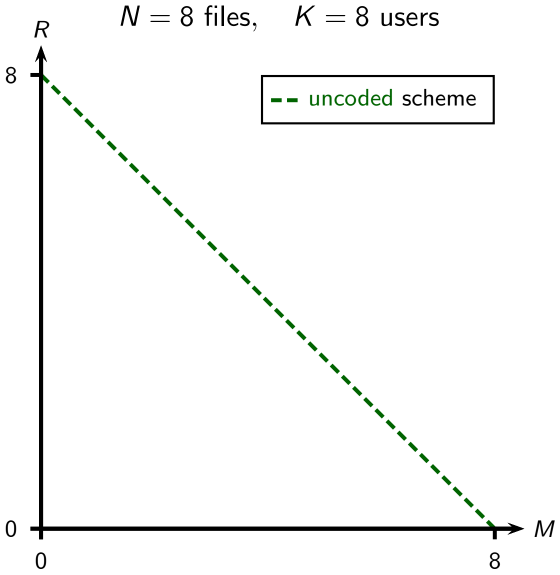

Uncoded Caching Scheme

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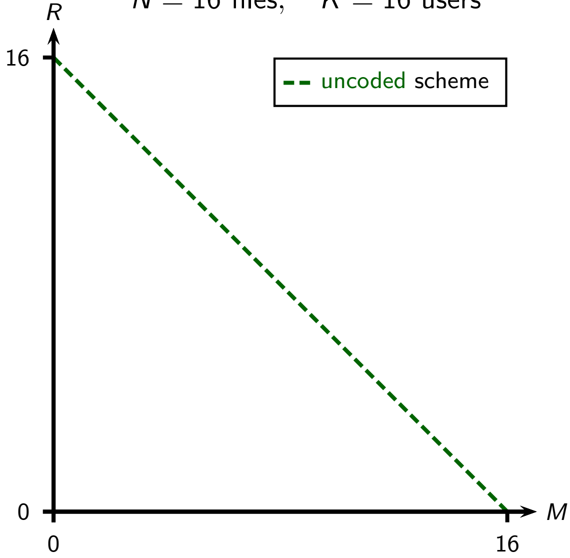

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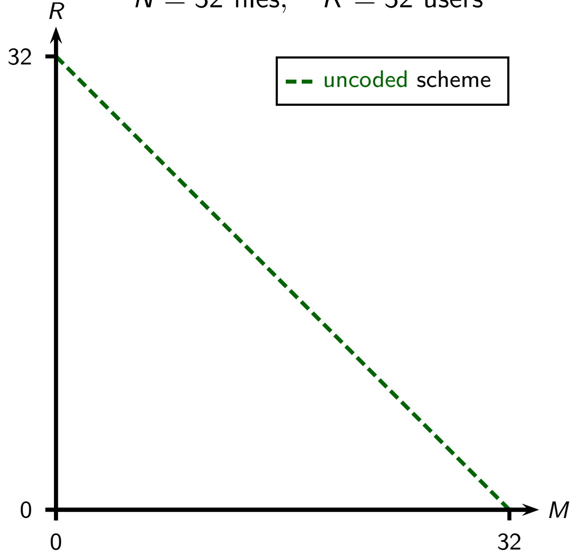

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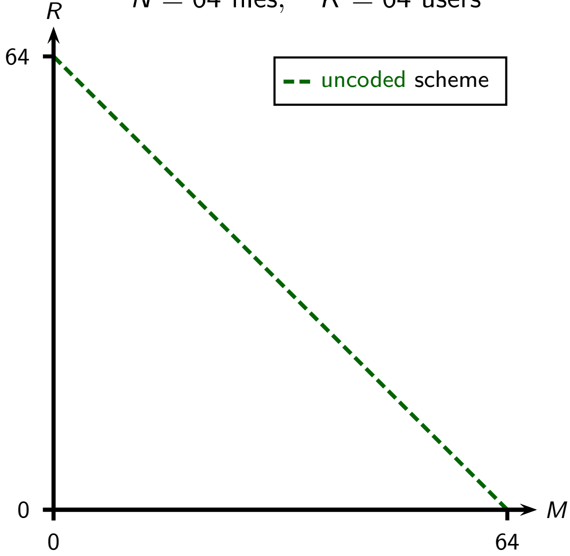

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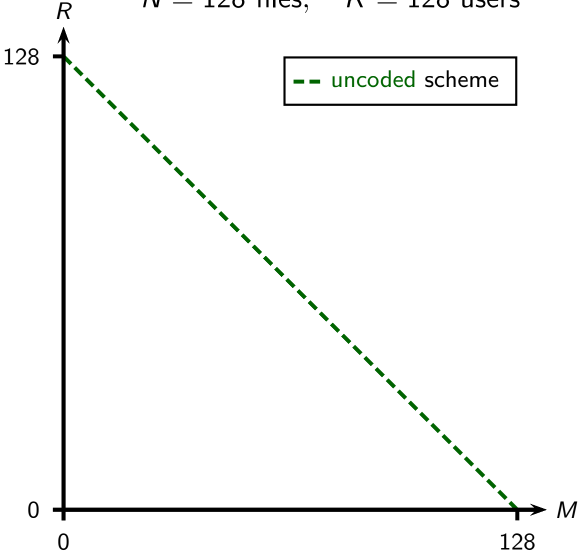

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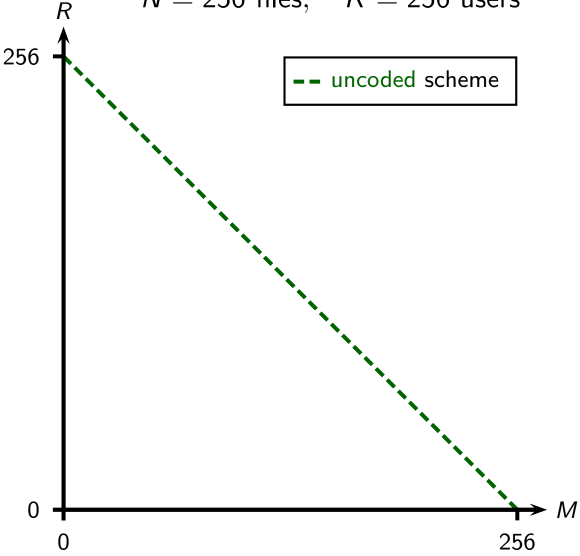

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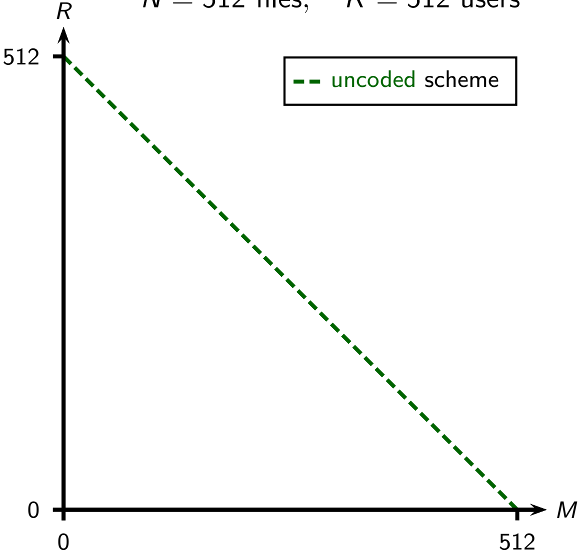

Proposed Coded Caching Scheme

N files, *K* users, cache size *M*

Design guidelines advocated in this talk:

- The main gain in caching is global
- Global cache size matters
- Different cache content at users
- Coded multicasting

[2] M. A. Maddah-Ali and U. Niesen, "Fundamental limits of caching," *IEEE Trans. Inf. Theory*, vol. 60, no. 5, pp. 2856–2867, May 2014.

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Performance of coded scheme:[2]

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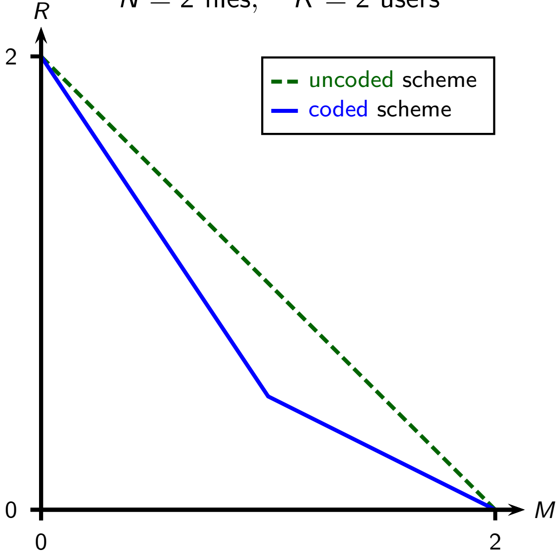

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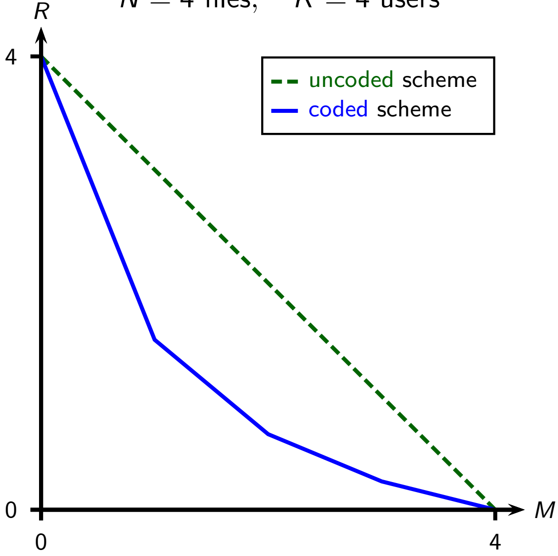
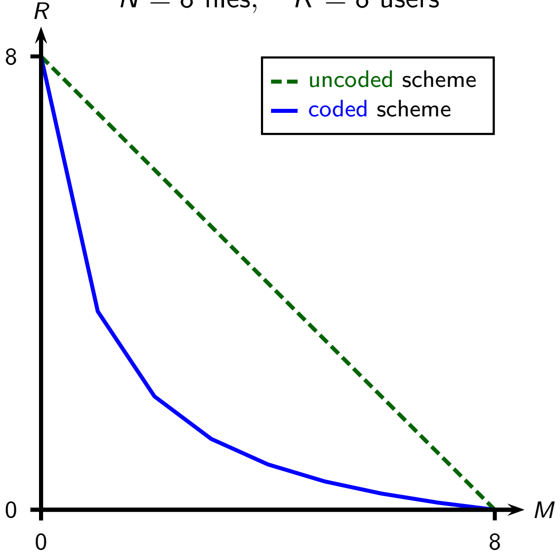


Proposed Coded Caching Scheme

$N = 8$ files, $K = 8$ users



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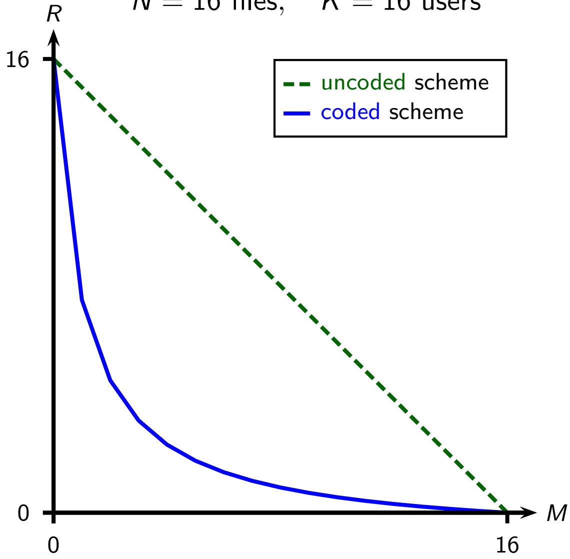

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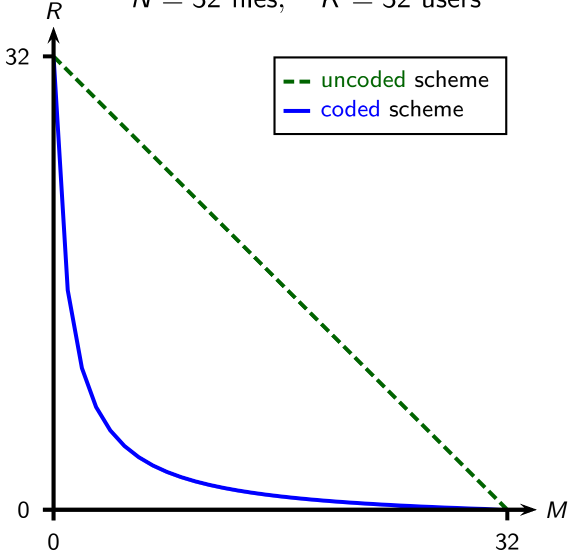

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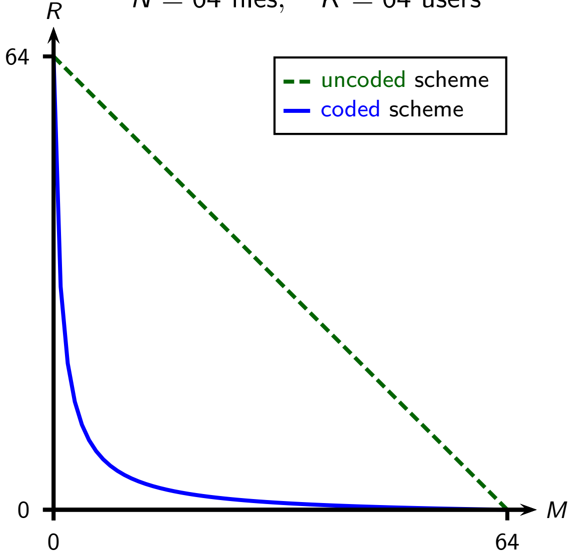

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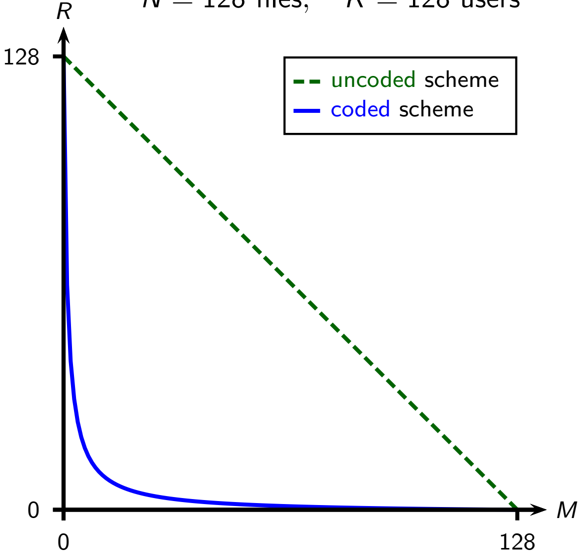

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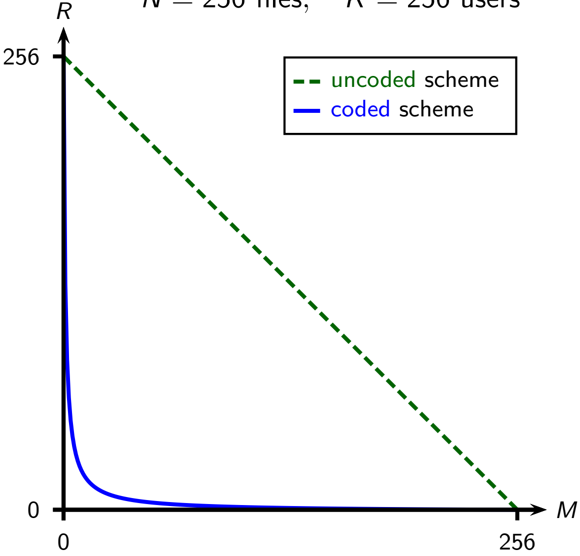

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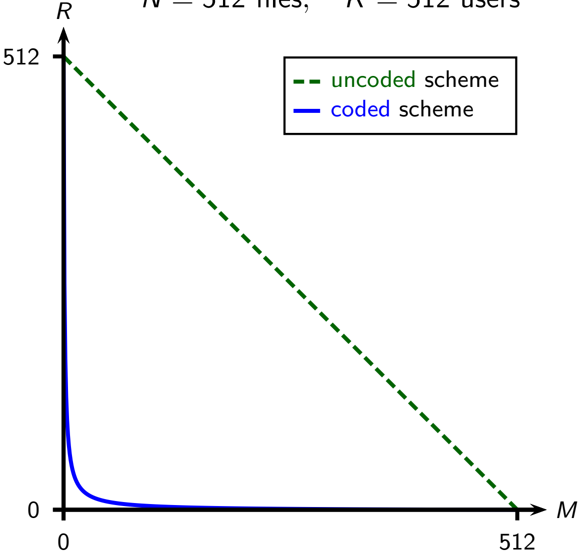

Recall: Uncoded Scheme

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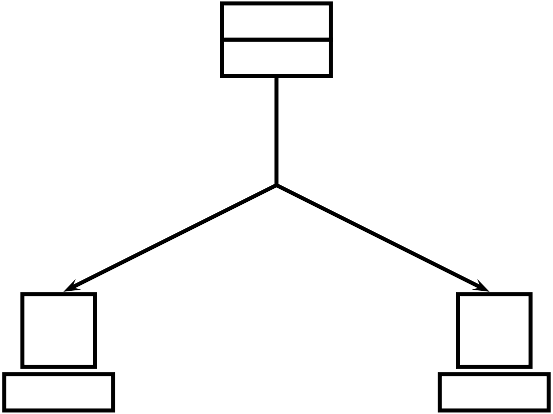

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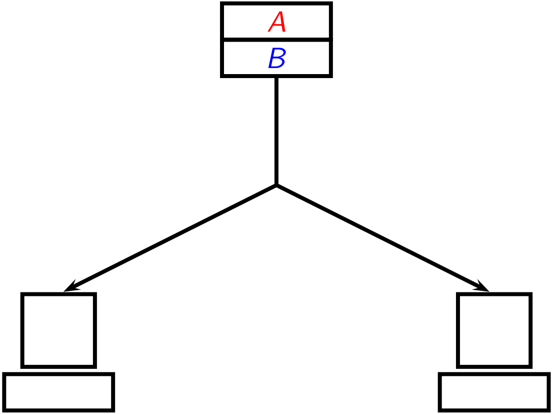

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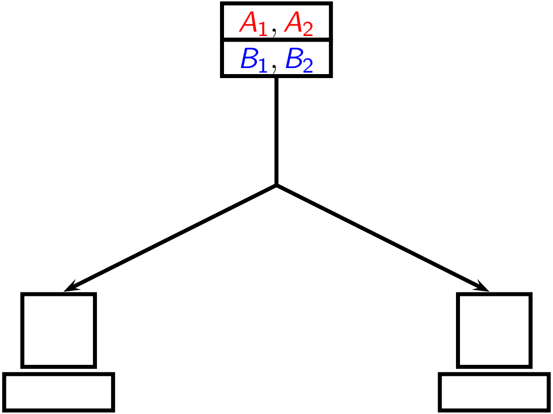

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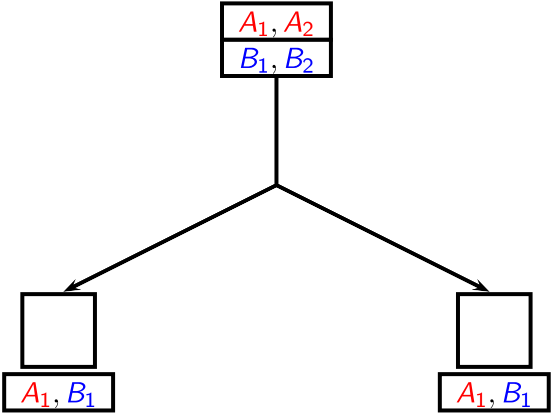

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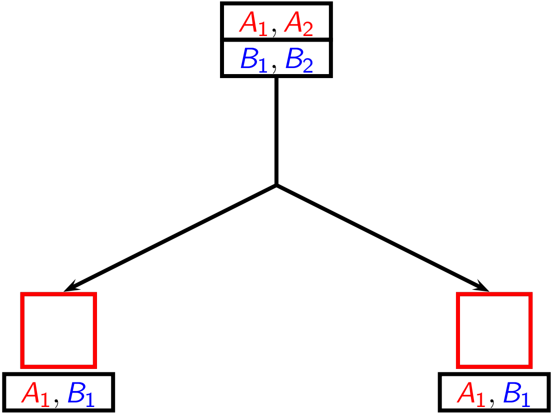

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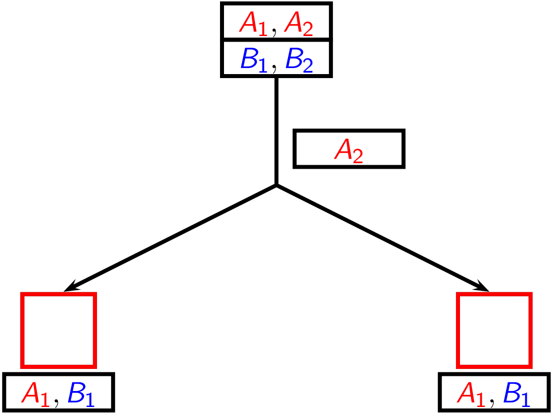

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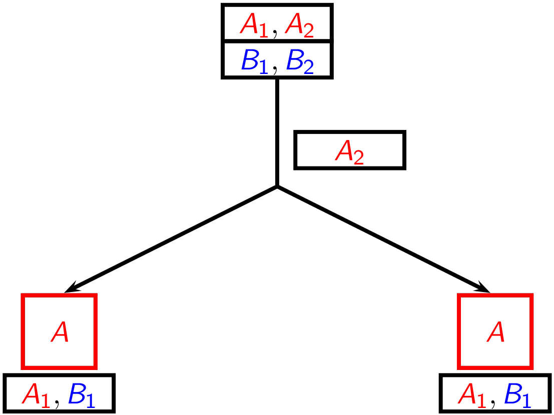

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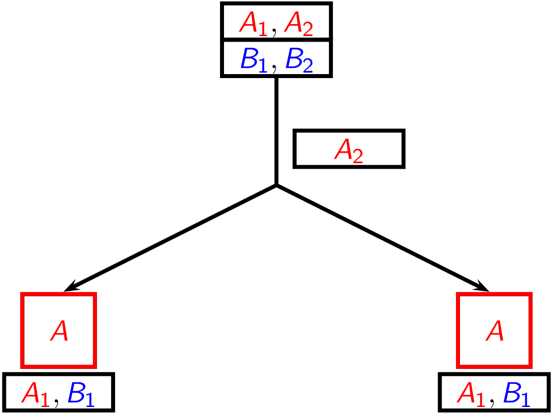

$\Rightarrow$ Identical cache content at users

$\Rightarrow$ Gain from delivering content locally

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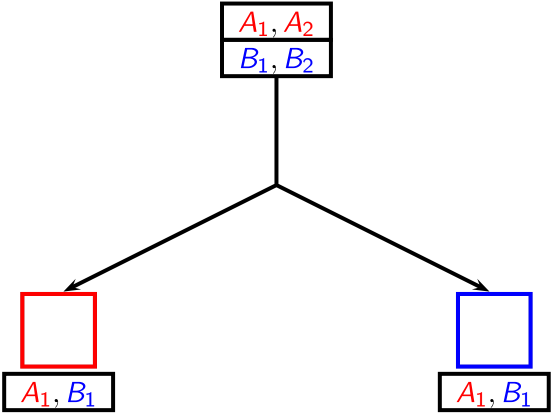

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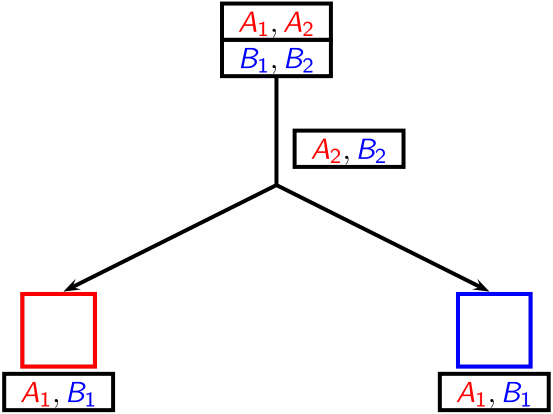

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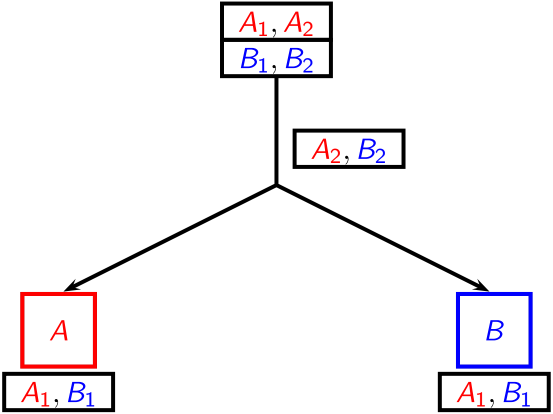

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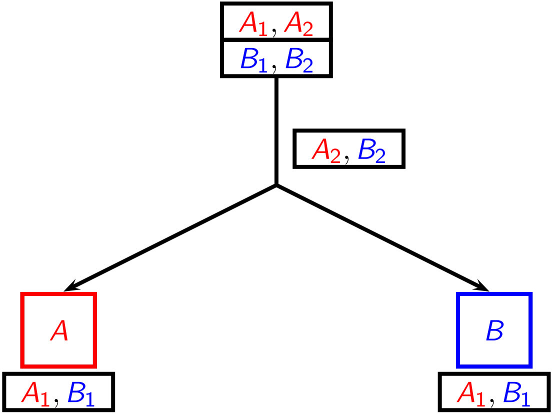

$\Rightarrow$ Multicast only possible for users with same demand

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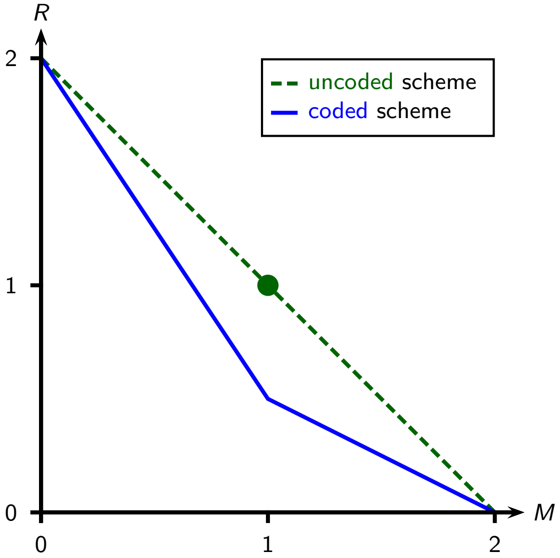

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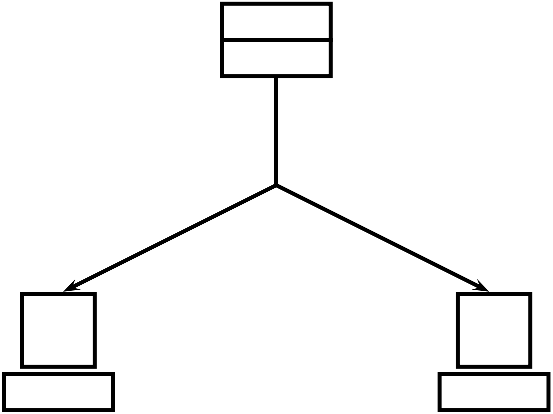

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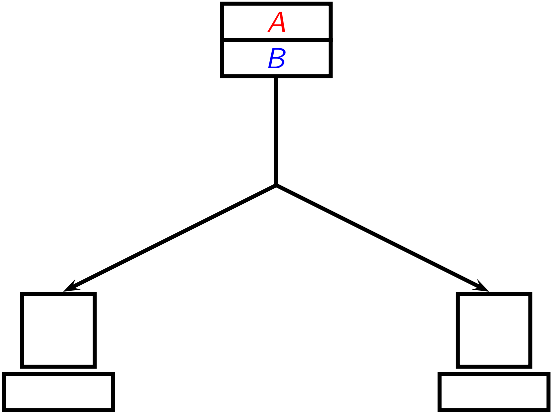
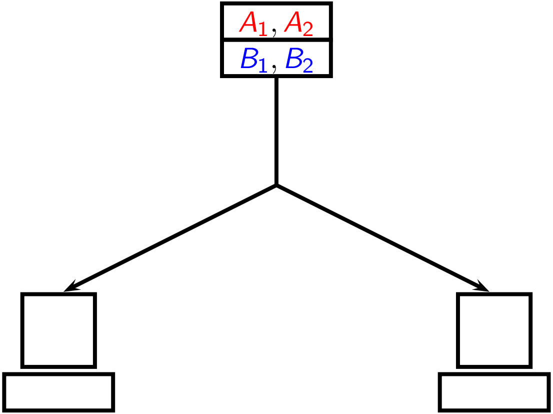


Proposed Coded Scheme

$N = 2$ files, $K = 2$ users, cache size $M = 1$



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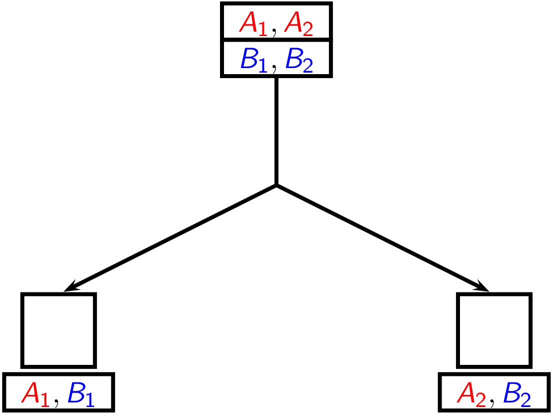

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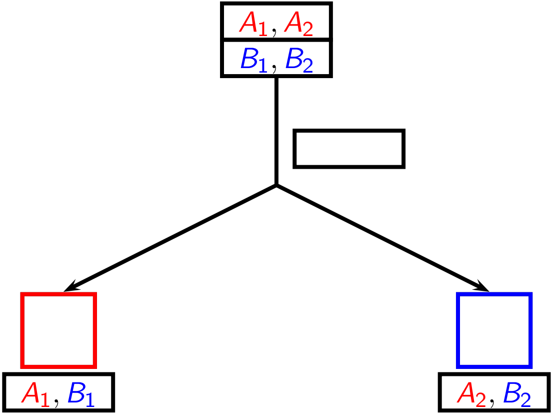
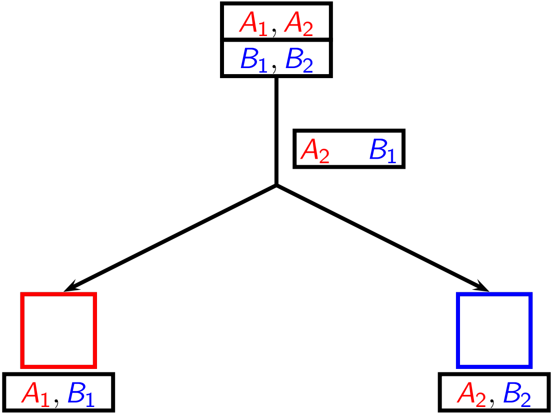


Proposed Coded Scheme

$N = 2$ files, $K = 2$ users, cache size $M = 1$



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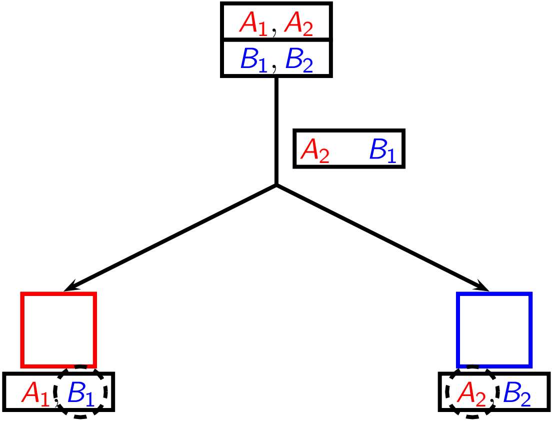

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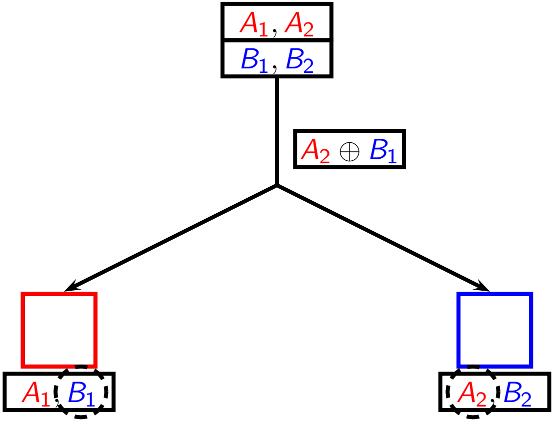

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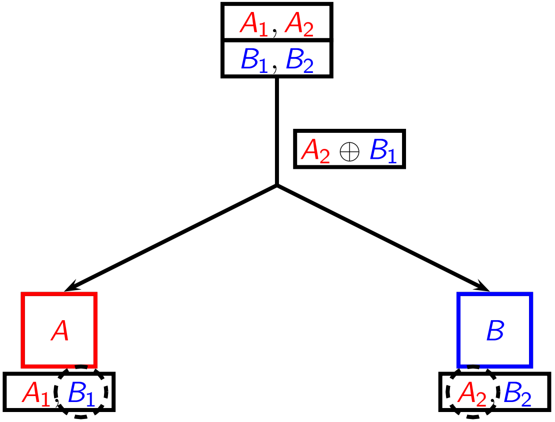

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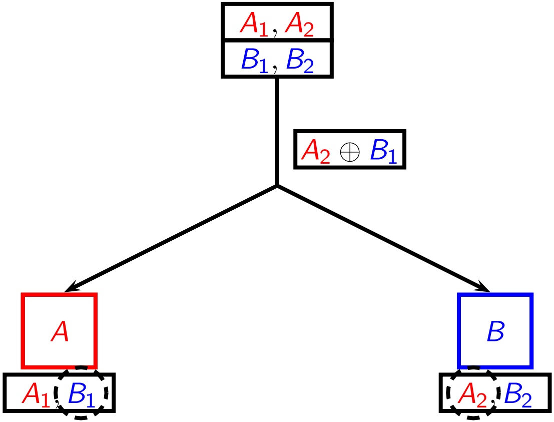
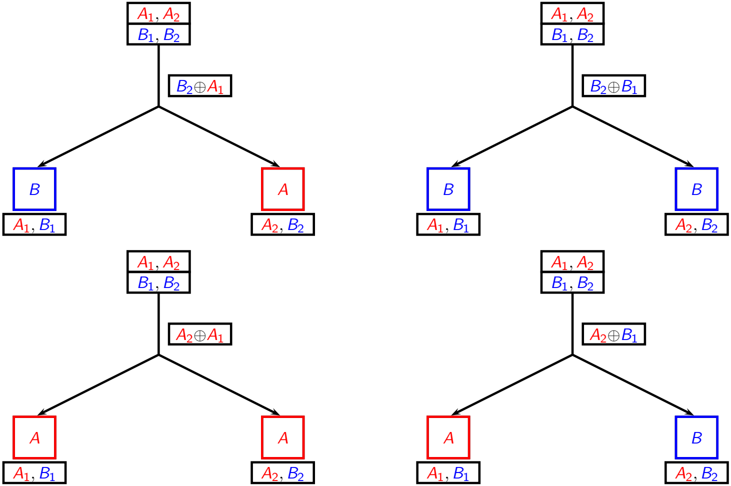


$\Rightarrow$ Different cache content at users

$\Rightarrow$ Coded multicast to 2 users with different demands

Proposed Coded Scheme

$N = 2$ files, $K = 2$ users, cache size $M = 1$

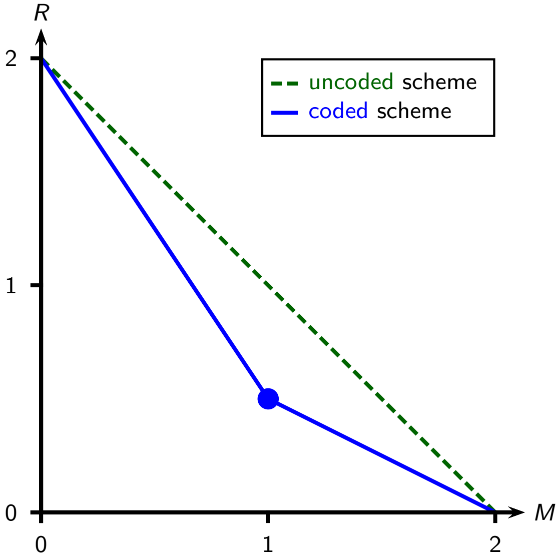


$\Rightarrow$ Works for all possible user requests

$\Rightarrow$ Simultaneous coded multicasting gain

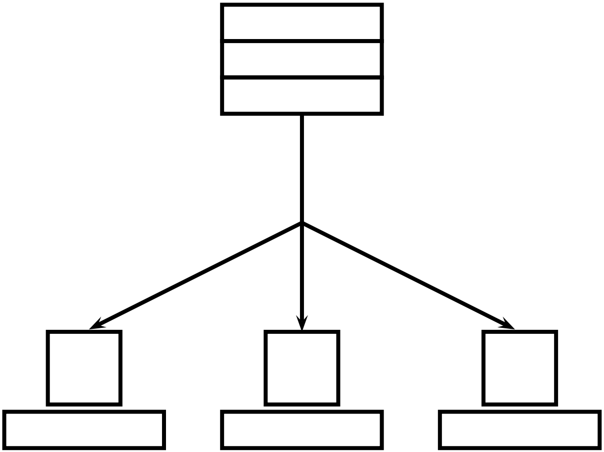
Proposed Coded Scheme

$N = 2$ files, $K = 2$ users, cache size $M = 1$



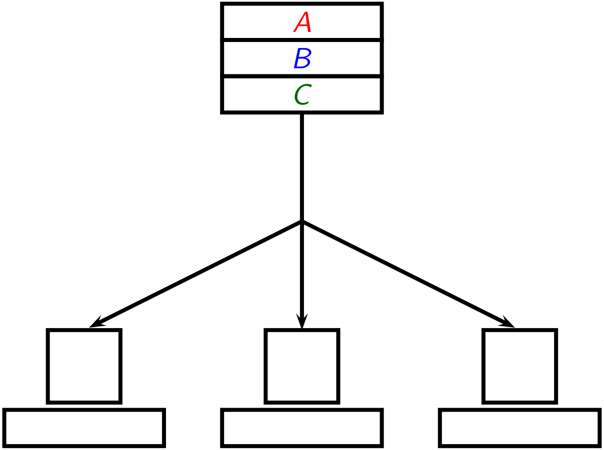
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 1$



Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 1$



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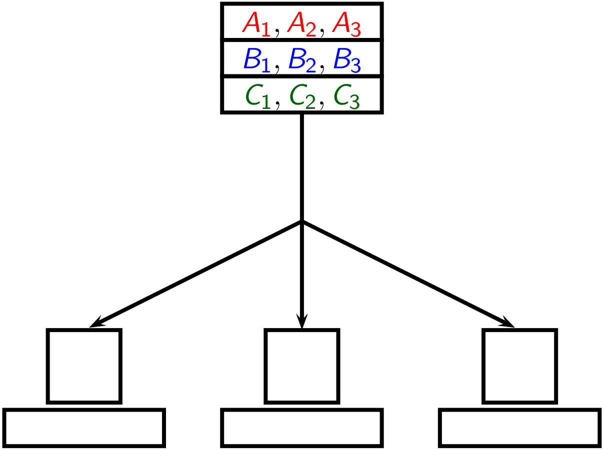

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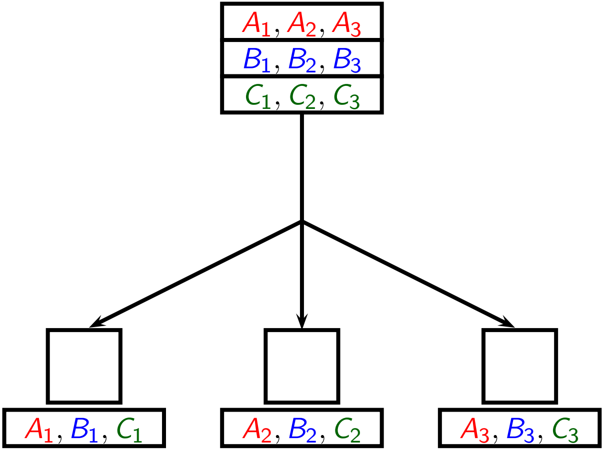

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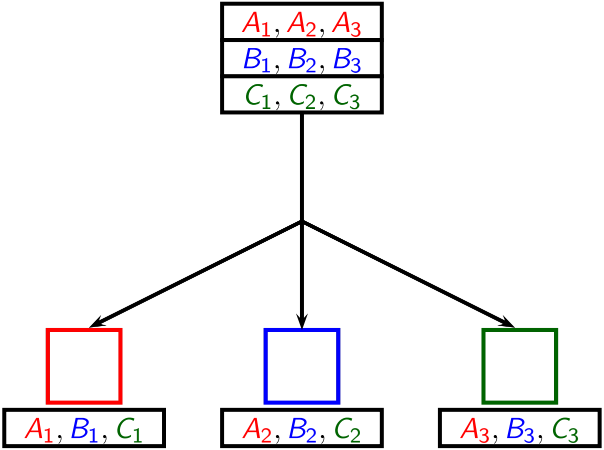

Proposed Coded Scheme

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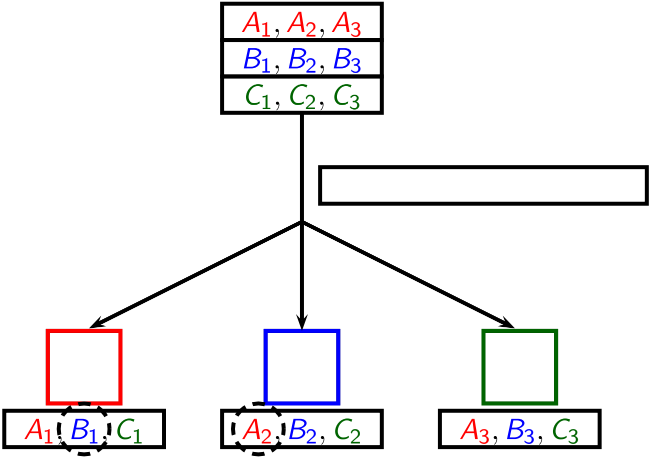
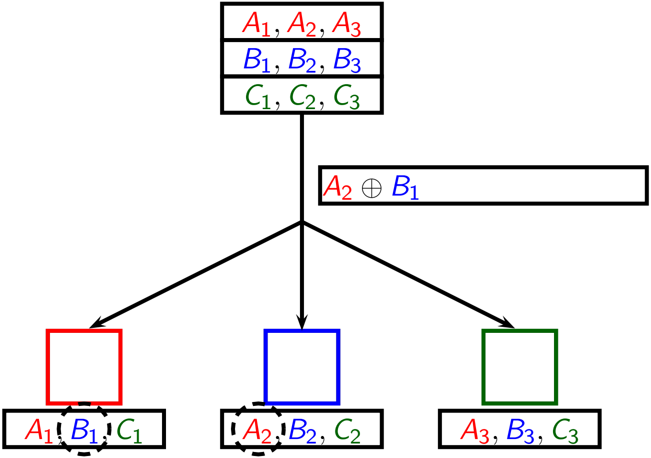


Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 1$



Proposed Coded Scheme

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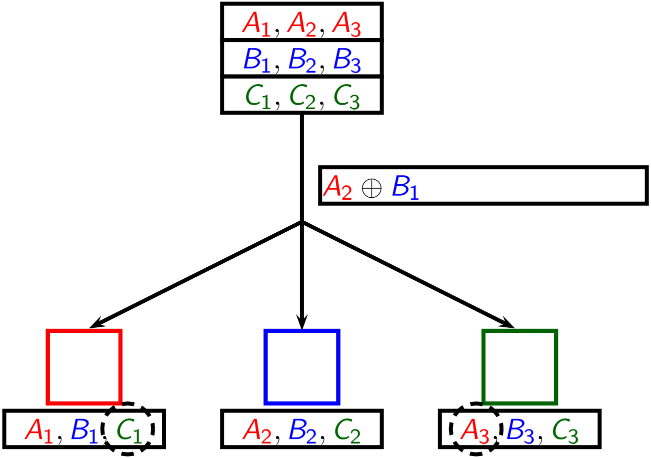

Proposed Coded Scheme

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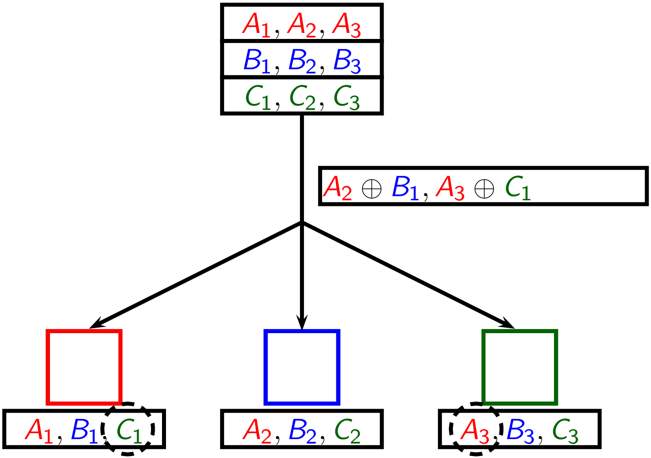
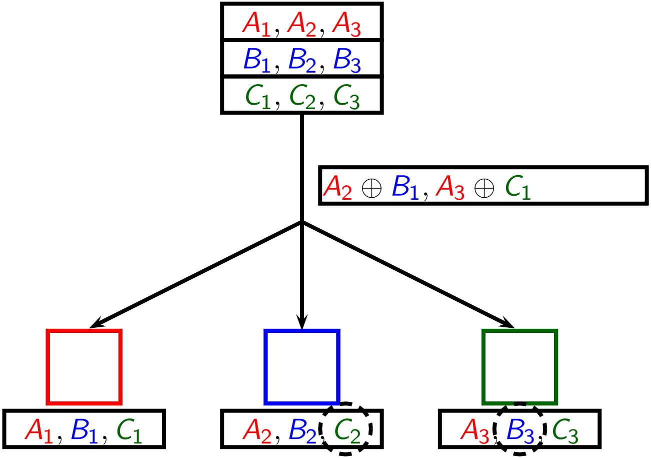


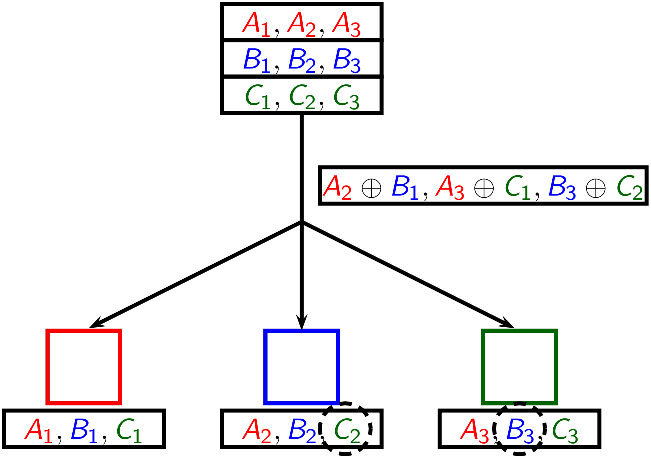
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 1$



Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 1$



Proposed Coded Scheme

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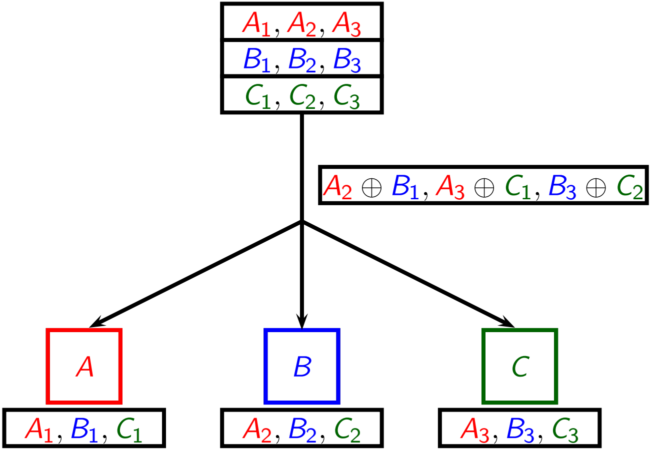
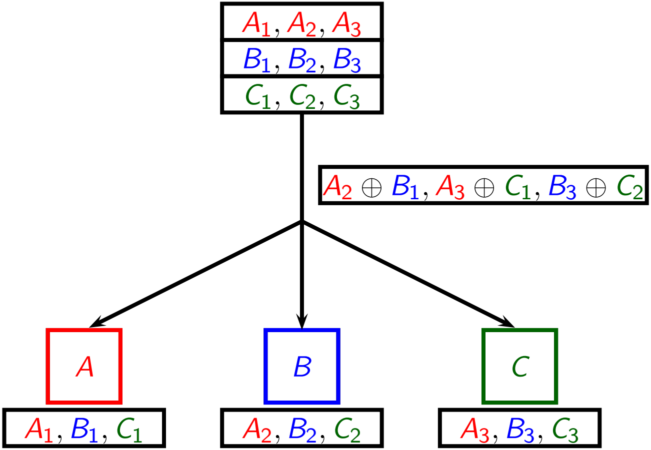


Proposed Coded Scheme

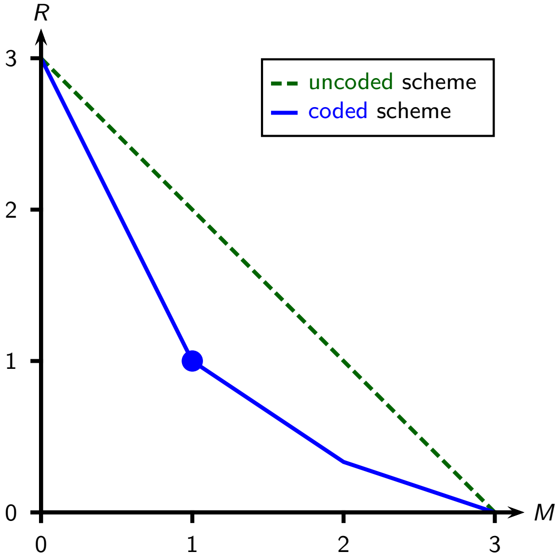
$N = 3$ files, $K = 3$ users, cache size $M = 1$



$\Rightarrow$ Coded multicast to 2 users with different demands

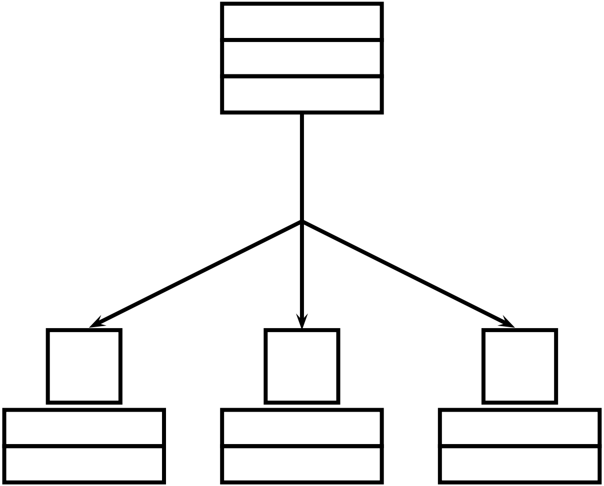
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 1$



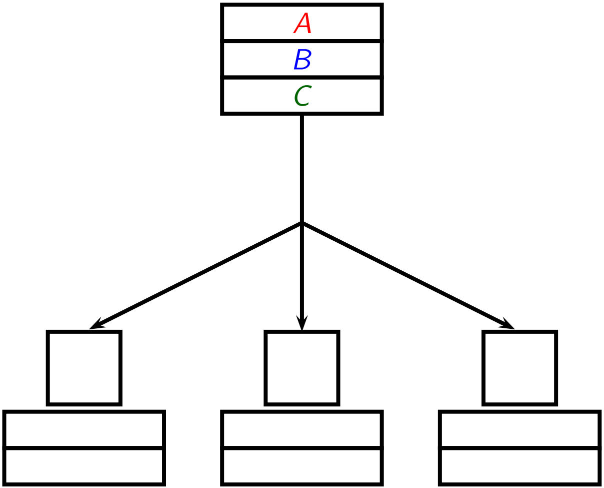
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



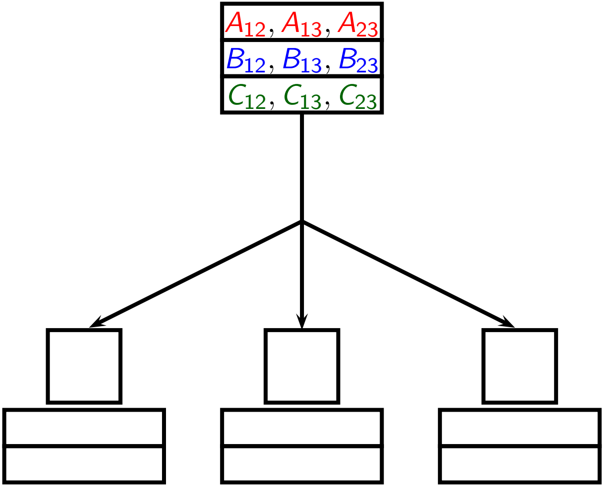
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



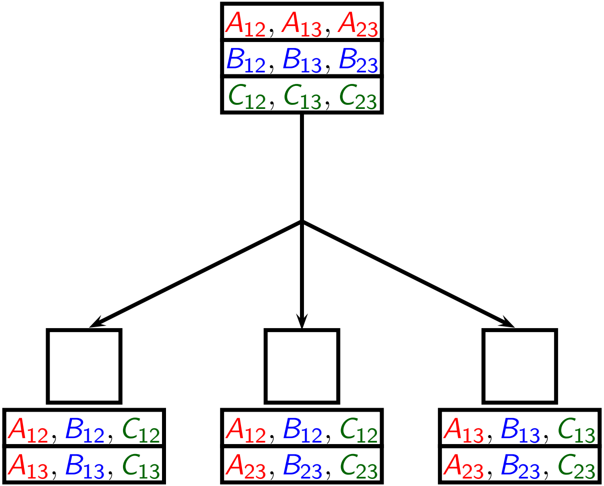
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



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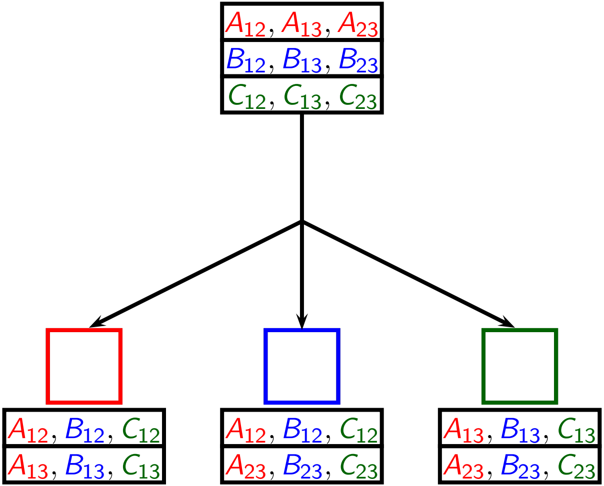
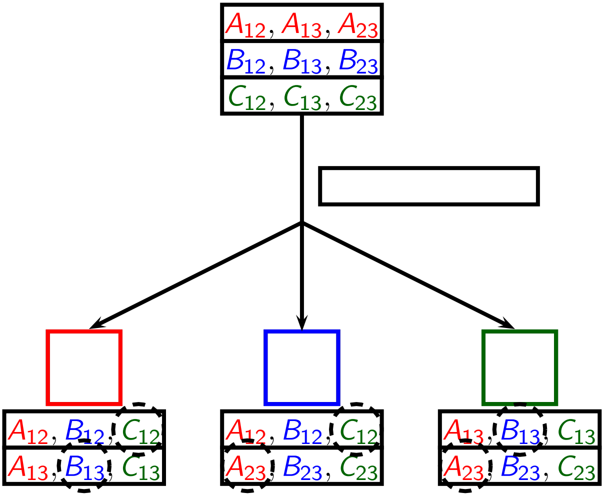
$N = 3$ files, $K = 3$ users, cache size $M = 2$



Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



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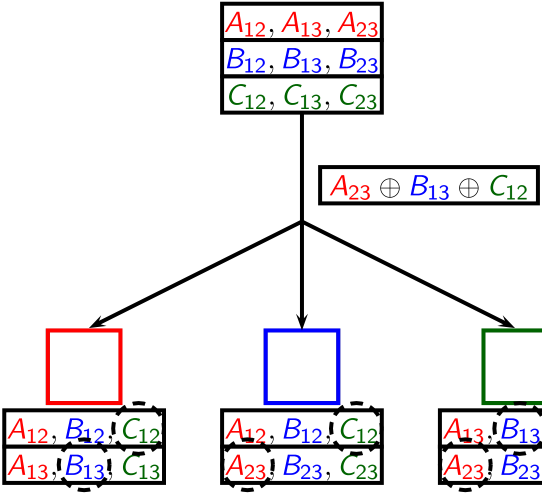
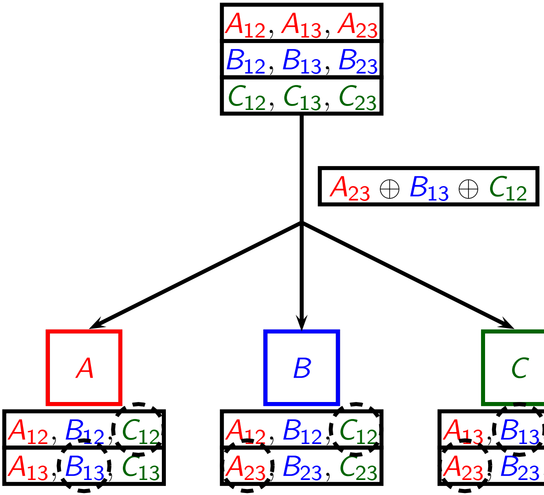


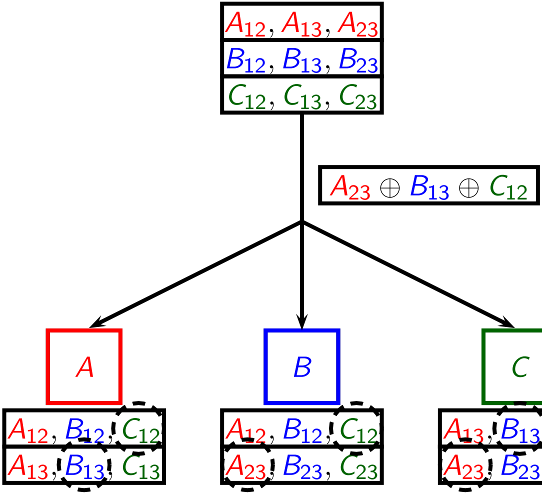
Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



Proposed Coded Scheme

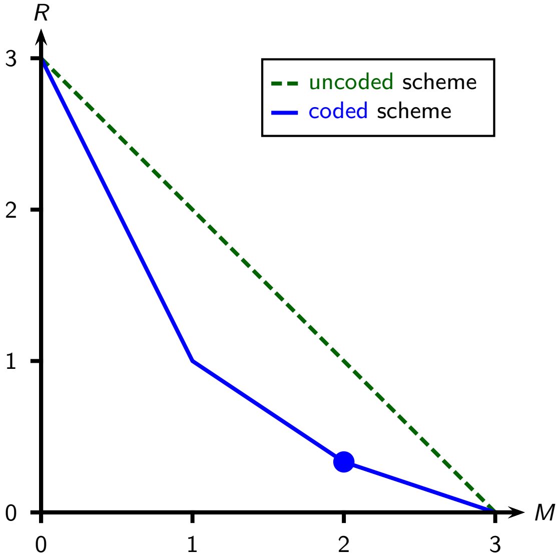
$N = 3$ files, $K = 3$ users, cache size $M = 2$



$\Rightarrow$ Coded multicast to 3 users with different demands

Proposed Coded Scheme

$N = 3$ files, $K = 3$ users, cache size $M = 2$



Proposed Coded Scheme

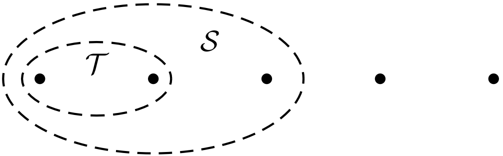
$N = K$ files and users, cache size M

- Goal: coded multicast to $M + 1$ users with different demands

Proposed Coded Scheme

$N = K$ files and users, cache size M

- Goal: coded multicast to $M + 1$ users with different demands
- Need to place content such that in delivery phase:
  1. for every possible user demands...
  2. and for every possible subset $\mathcal{S}$ of $M + 1$ users...
  3. and for every possible subset $\mathcal{T} \subset \mathcal{S}$ of M users...
  4. users in $\mathcal{T}$ share content that is required at the user in $\mathcal{S} \setminus \mathcal{T}$



Proposed Coded Scheme

$N = K$ files and users, cache size M

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  3. and for every possible subset $\mathcal{T} \subset \mathcal{S}$ of M users. . .
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Example: $N = K = 3$, $M = 2$

Every two users have a piece of content the remaining user needs

Proposed Coded Scheme
$N = K$ files and users, cache size M

Placement phase:

Proposed Coded Scheme

$N = K$ files and users, cache size M

Placement phase:

- N files: $W_1, \ldots, W_N$

Proposed Coded Scheme

$N = K$ files and users, cache size M

Placement phase:

- N files: $W_1, \ldots, W_N$
- Split each file into $\binom{K}{M}$ parts

  $\Rightarrow\ W_n = \big(W_{n,\mathcal{T}} : \mathcal{T} \subset [K], |\mathcal{T}| = M\big)$

Proposed Coded Scheme

$N = K$ files and users, cache size M

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- Cache k: $\big(W_{n,\mathcal{T}} : n \in [N], \mathcal{T} \subset [K], |\mathcal{T}| = M, k \in \mathcal{T}\big)$

Proposed Coded Scheme

$N = K$ files and users, cache size M

Placement phase:

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- Cache k: $\big(W_{n,\mathcal{T}} : n \in [N], \mathcal{T} \subset [K], |\mathcal{T}| = M, k \in \mathcal{T}\big)$

Example: $N = K = 3$, $M = 2$

Consider files A, B, C $\Rightarrow$ cache 2: $\big(A_{12}, A_{23}, B_{12}, B_{23}, C_{12}, C_{23}\big)$

Proposed Coded Scheme

$N = K$ files and users, cache size M

Delivery phase:

Proposed Coded Scheme

$N = K$ files and users, cache size M

Delivery phase: Assume users k requests W_{d_k}

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Delivery phase: Assume users k requests W_{d_k}

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Example: $N = K = 3$, $M = 1$

Consider files A, B, C and user requests $d_1 = A, d_2 = B, d_3 = C$

$\Rightarrow$ Server sends $A_2 \oplus B_1,\ A_3 \oplus C_1,\ B_3 \oplus C_2$

Comparison of the Two Schemes

N files, K users, cache size M

- Uncoded scheme: $R(M) = K \cdot (1 - M/N)$
- Coded scheme: $R(M) = K \cdot (1 - M/N) \cdot \frac{1}{1+KM/N}$

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- Rate without caching K

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- Local caching gain $1 - M/N$
  - Significant when local cache size M is of order N

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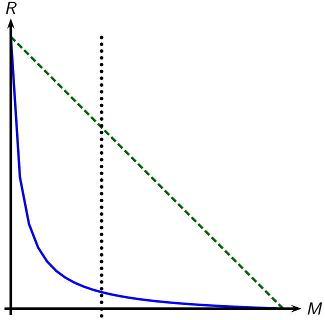
- Local caching gain $1 - M/N$
  - Significant when local cache size M is of order N
- Global caching gain $\frac{1}{1+KM/N}$
  - Significant when global cache size KM is of order N

$\Rightarrow$ Global gain can be $\Theta(K)$ smaller than local gain

Example

$N = 30$ files, $K = 30$ users, cache size $M = 10$

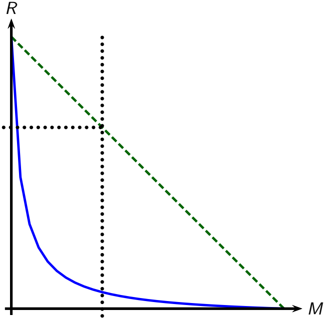


Example

$N = 30$ files, $K = 30$ users, cache size $M = 10$

- Uncoded scheme:

$$R(M) = K \cdot (1 - M/N)$$
$$\approx 30 \cdot 0.67 \approx 20$$



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$$R(M) = K \cdot (1 - M/N)$$
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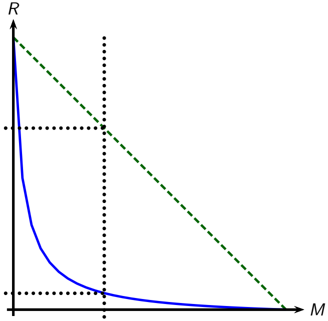
- Coded scheme:

$$R(M) = K \cdot (1 - M/N) \cdot \frac{1}{1 + KM/N}$$
$$\approx 30 \cdot 0.67 \cdot 0.09 \approx 1.8$$



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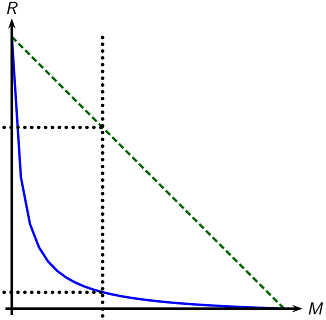
$\Rightarrow$ Factor 11 reduction in rate!



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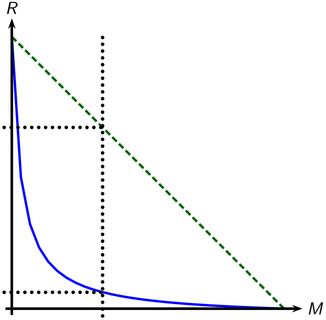

⇒ Factor 11 reduction in rate!

⇒ Local gain is 0.67

Example

$N = 30$ files, $K = 30$ users, cache size $M = 10$

- Uncoded scheme:

$$R(M) = K \cdot (1 - M/N) \approx 30 \cdot 0.67 \approx 20$$

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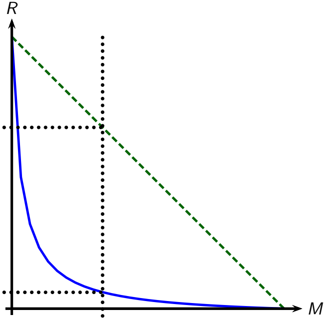
$$R(M) = K \cdot (1 - M/N) \cdot \frac{1}{1 + KM/N} \approx 30 \cdot 0.67 \cdot 0.09 \approx 1.8$$



$\Rightarrow$ Factor 11 reduction in rate!

$\Rightarrow$ Local gain is 0.67

$\Rightarrow$ Global gain is 0.09
(coded multicast to $M + 1 = 11$ users with different demands)

Can We Do Better?

Theorem

The coded scheme is optimal to within a constant factor in rate.[3]

[3] M. A. Maddah-Ali and U. Niesen, "Fundamental limits of caching," *IEEE Trans. Inf. Theory*, vol. 60, no. 5, pp. 2856–2867, May 2014.

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⇒ No other significant gain besides local and global

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Approach Can be Adapted to Handle...

- Asynchronous user requests[4]
- Nonuniform file popularities[5]
- Users joining and leaving the network[6]
- Several users sharing a cache[7]
- Online cache updates[8]
- More complicated network topologies[9]

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[4] Niesen and Maddah-Ali 2015.

[5] Niesen and Maddah-Ali 2017; Ji, Tulino, Llorca, and Caire 2017; Zhang, Lin, and Wang 2018.

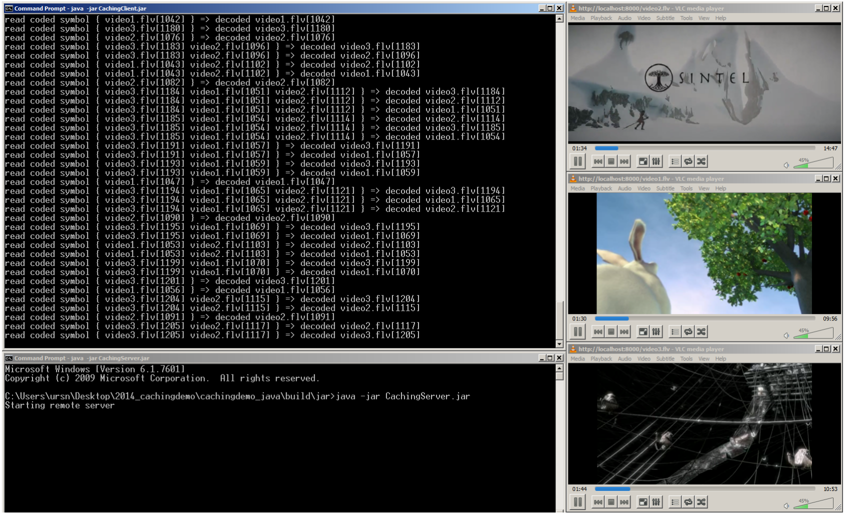
[6] Maddah-Ali and Niesen 2015.

[7] Hachem, Karamchandani, and Diggavi 2017.

[8] Pedarsani, Maddah-Ali, and Niesen 2016.

[9] Karamchandani, Niesen, Maddah-Ali, and Diggavi 2016; Ji, Caire, and Molisch 2016.

Video Streaming Demo[10]



[10] U. Niesen and M. A. Maddah-Ali, "Coded caching for delay-sensitive content," in *Proc. IEEE ICC*, Jun. 2015, pp. 5559–5564.

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  - So far only demo-sized implementation
  - Experimentation with large-scale systems are needed

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- Significant improvement over uncoded caching schemes
  - ⇒ Reduction in rate up to order of number of users
- Key open questions: block length, state, large-scale implementation

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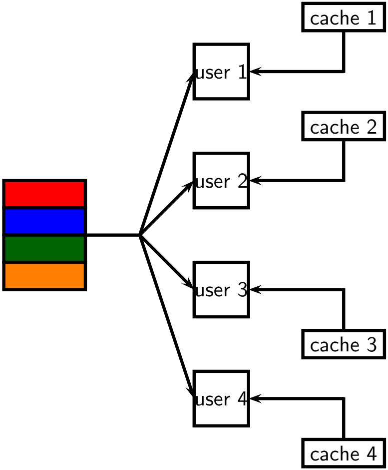

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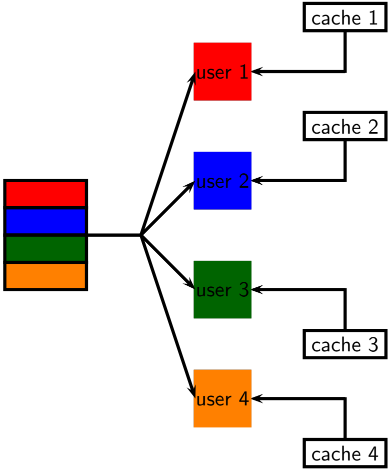

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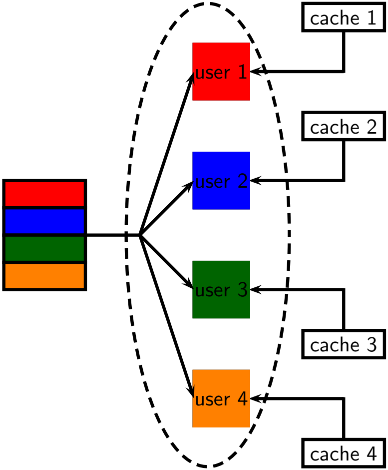

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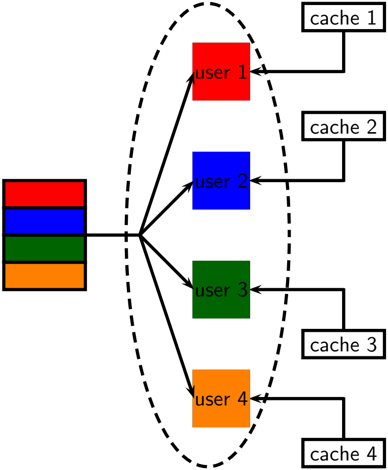

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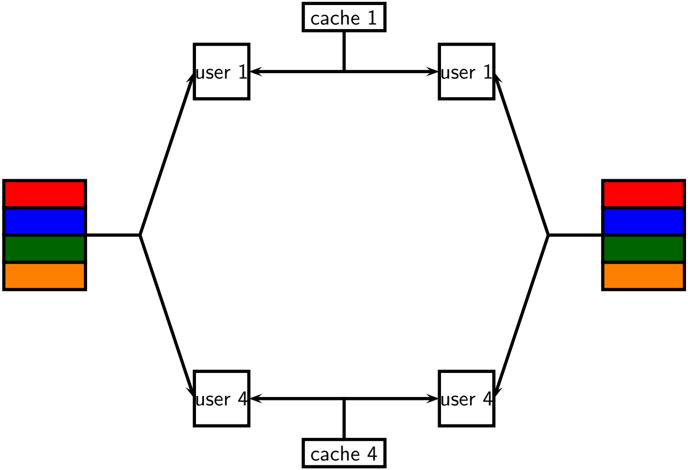

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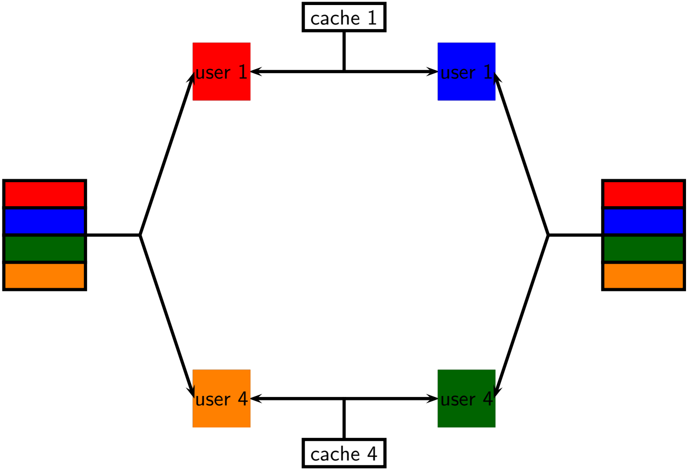

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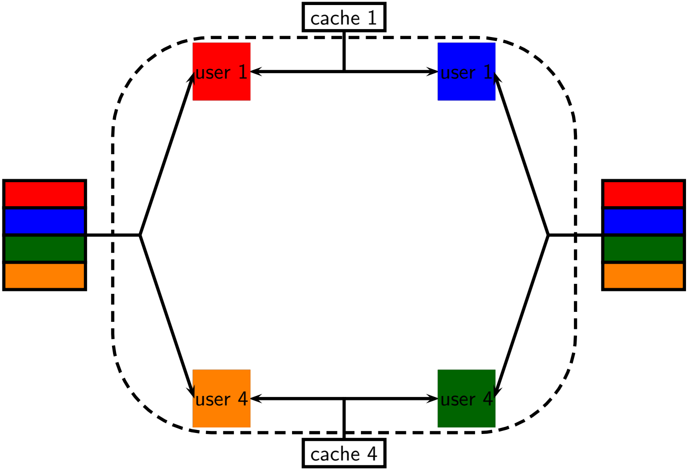

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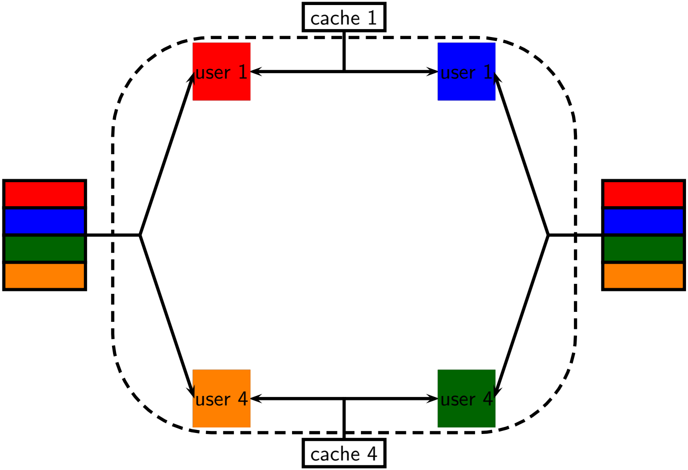

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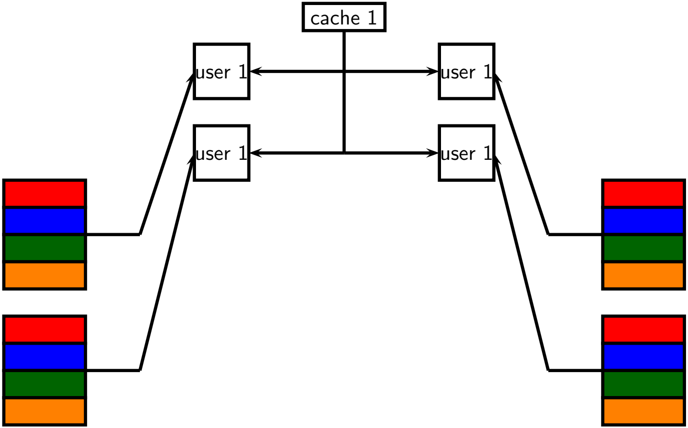

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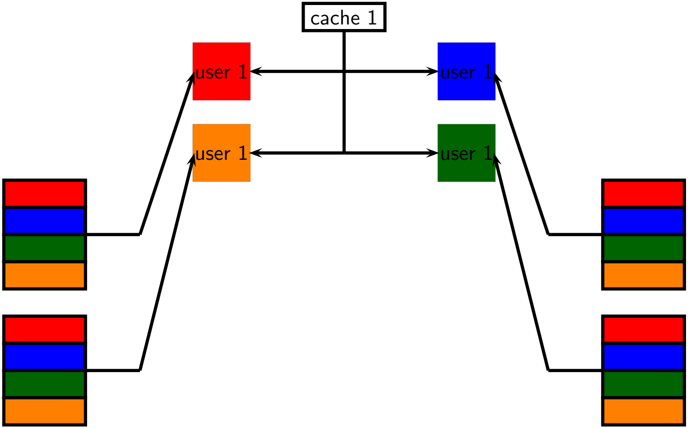

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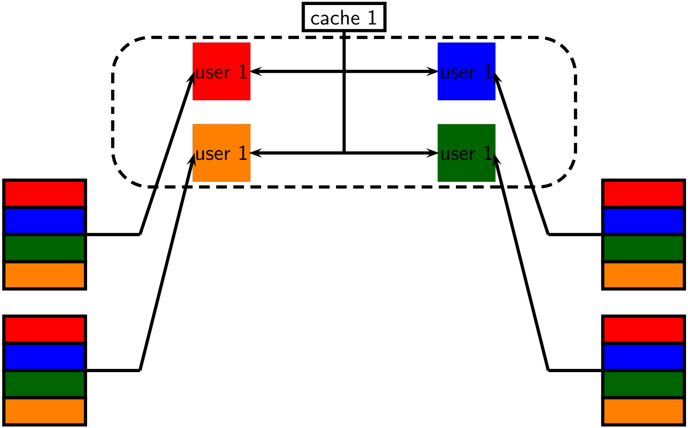

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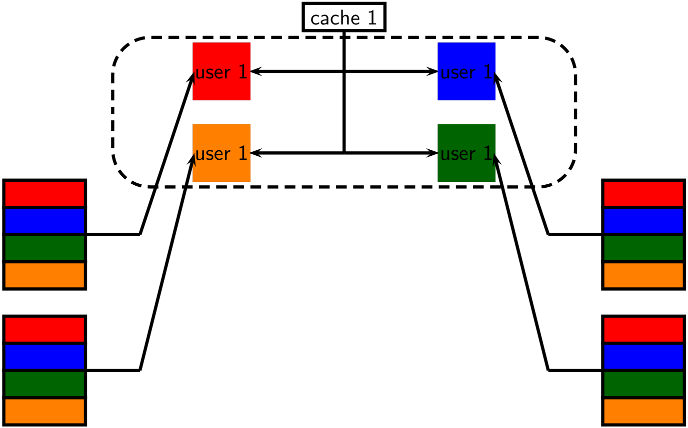

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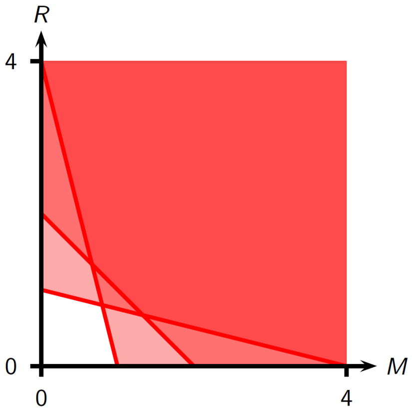

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- For general N and K

$$R \geq \max_s \left(s - \frac{s}{\lfloor N/s \rfloor} M \right)$$

- Comparing with achievable rate yields the theorem