Code Rate Maximization of Cooperative Caching in Ultra-Dense Networks

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PIMRC 2019

Abstract

Cooperative Caching in Ultra-Dense Networks Using

- Maximum Distance Separable (MDS) Code.
- Repetition Code.

Our Objective

- **Maximize the code rate** while ensuring that end users within certain clusters can restore the file from the associating small base stations (SBSs) without the use of the backhaul link.

Overview

Background

- Video-on-demand is driving wireless traffic growth.
- Predicted to increase 1000 times from 4G to 5G.

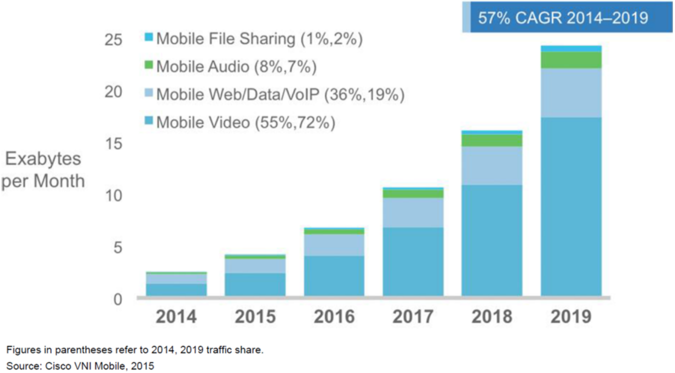

Figure: The Rise of Content: Wireless

Motivation

1. Traditional Wireless Networks

   Most Popular Files Caching

2. Ultra-Dense Networks

   Cooperative Caching

3. Utilize the Cache Memory

$$\left.\begin{array}{c}\text{Cooperative Caching}\\ \text{File splitting}\end{array}\right\} \Rightarrow \text{increase content diversity.}$$

Motivation

1. Prior studies

$$\text{Uncoded Caching} \Rightarrow \begin{cases} \text{Whole file is cached or not} \\ \text{Random Caching} \end{cases}$$

$$\text{Coded Caching} \Rightarrow \begin{cases} \text{Random Caching} \\ \text{Rateless Codes} \end{cases}$$

2. Our Objective

Code Rate Maximization

System Model

1. Collection of L clusters is pre-determined and K_c be the minimum cluster size.
2. Popular files are cached in the same manner and the problem of caching one single file of size B bits is considered.
3. Packets stored in each cluster should contain enough information for decoding the original file.

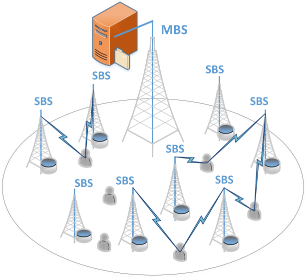

Figure: Two-tier Heterogeneous Cellular Network.

Problem Statement

- To store the file into the caches of the SBSs, a concatenated code is used to encode the file.
- Each SBS stores $\alpha \triangleq T/M$ coded packets.
- The concatenated code rate is given by

$$R = \frac{K}{T} = \frac{K}{\alpha M}. \quad (1)$$

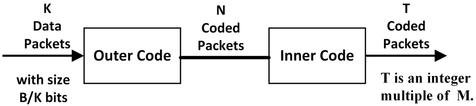

Figure: Concatenated Code.

- **Problem : Code Rate Maximization**
- Example

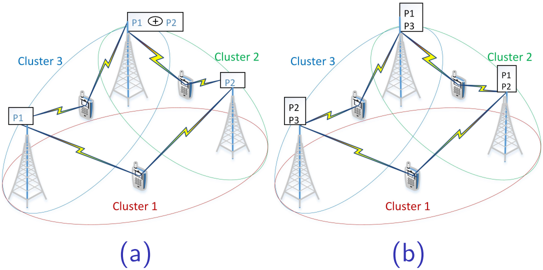

Figure: An example of coded and repetition caching (a) coded caching (b) repetition caching.

Code Rate Maximization

Theorem

Given any network with minimum cluster size K_c, the code rate of any feasible caching scheme is bounded above by

$$R \leq \frac{K_c}{M}. \tag{2}$$

Equality holds only if $\alpha = K/K_c$.

Theorem

Given any network with minimum cluster size K_c, there exists a feasible MDS-coded caching scheme with $K = K_c$ which achieves the maximum code rate

$$R^* \triangleq \frac{K_c}{M}. \tag{3}$$

Repetition Caching

Theorem

Given any network with minimum cluster size K_c and that a file is partitioned into K packets of equal size, the rate R of repetition caching is bounded above as follows:

$$R \leq \frac{K}{\left\lceil \frac{K}{K_c} \right\rceil M}. \tag{4}$$

Repetition Caching

Corollary

In general, repetition caching is not rate optimal.

Corollary

Given any 1D network with minimum cluster size K_c, repetition caching can achieve optimal code rate.

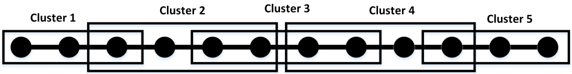

Figure: One-dimensional network.

Repetition Caching

Corollary

Given any 2D regular grid network with square clusters with minimum cluster size K_c, repetition caching can achieve optimal code rate.

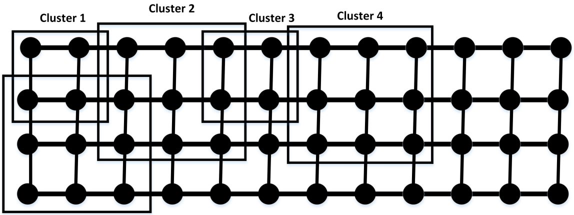

Figure: Two-dimensional regular grid network.

Repetition Caching

- Code Rate Maximization Problem $R = \frac{K}{\alpha M}$ is equivalent to minimizing α/K.
- Given K, the problem of minimizing the storage requirement α is called $\textsc{Repetition}(K)$.

Theorem

$\textsc{Repetition}(K)$ *is NP-hard for* $K \geq 3$.

Proof.

By identifying $\textsc{Repetition}(K)$ with K-$\textsc{Rainbow-Multicolor}$. □

- Heuristic algorithm is proposed.

Optimization for Repetition Caching

How to cluster the SBSs ?

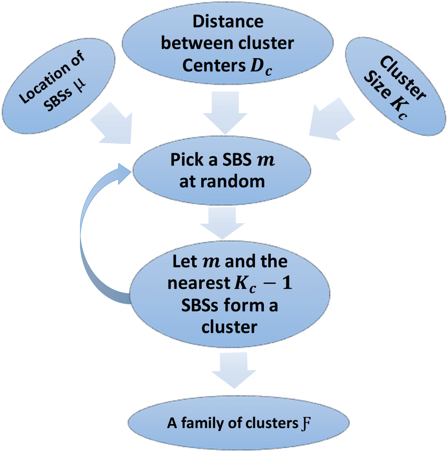

Figure: Distance-Based Clustering

How to assign the subfiles to the SBSs ?

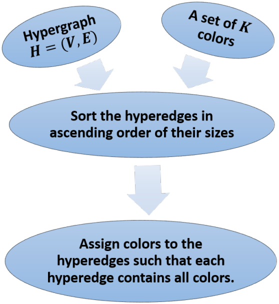

Figure: Multicoloring a hypergraph

How many segments K the file should be divided ?

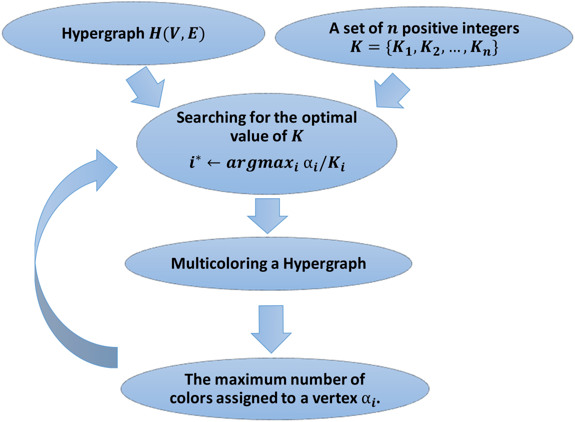

Figure: File Splitting

Simulation Model and Results

- A single macro cell with a large number of SBSs randomly distributed according to homogeneous Poisson Point Process.
- Investigate the effect of the clustering parameters K_c and D_c on the code rate.
- Examine the benefits of MDS-Coded caching in terms of storage efficiency.

$$\text{Coding Gain} = \frac{R_{MDS} - R_{Repetition}}{R_{MDS}} \times 100\%. \tag{5}$$

- **Fix the distance between the clusters centers and observe the effect of cluster size.**

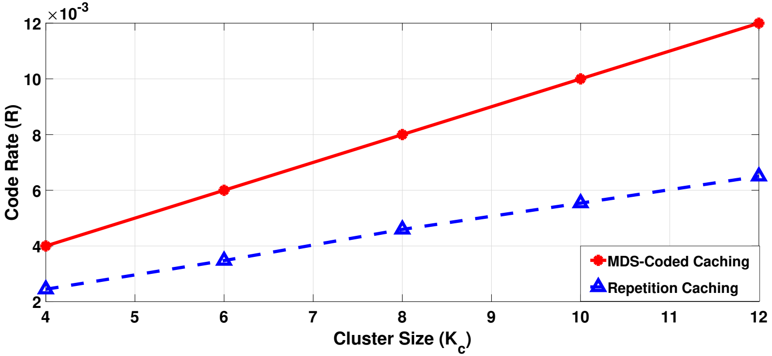

Figure: MDS-Coded Caching verse Repetition Caching with fixed $D_c = 10$ m.

Simulation Model and Results

- **Fix the distance between the clusters centers and observe the effect of the amount of overlapping by changing K_c.**

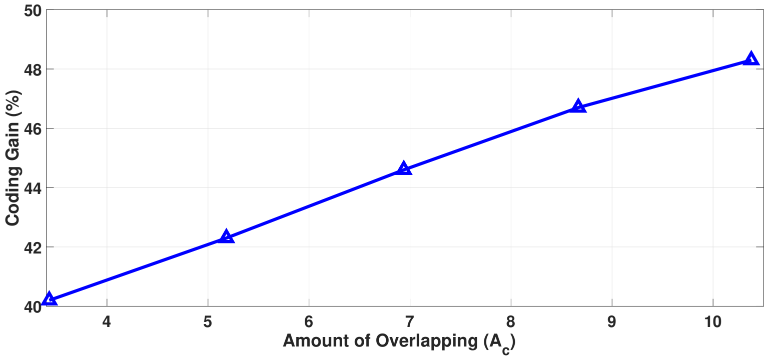

Figure: Coding Gain verses Amount of Overlapping A_c with fixed $D_c = 10$ and variable K_c

Simulation Model and Results

- **Fix the cluster size and observe the effect of the distance between cluster centers.**

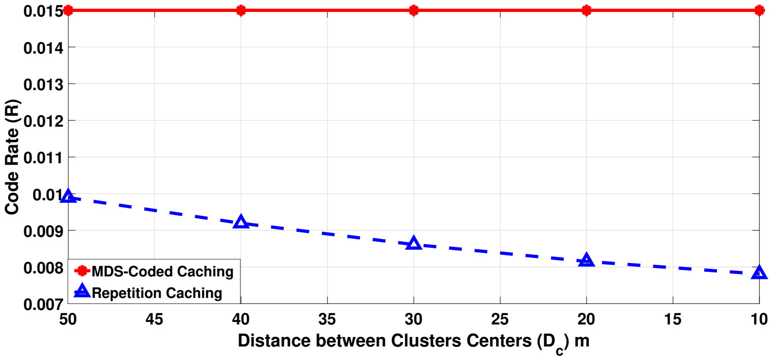

Figure: MDS-Coded Caching verse Repetition Caching with fixed $K_c = 15$.

- **Fix the cluster size and observe the effect of the amount of overlapping by changing D_c.**

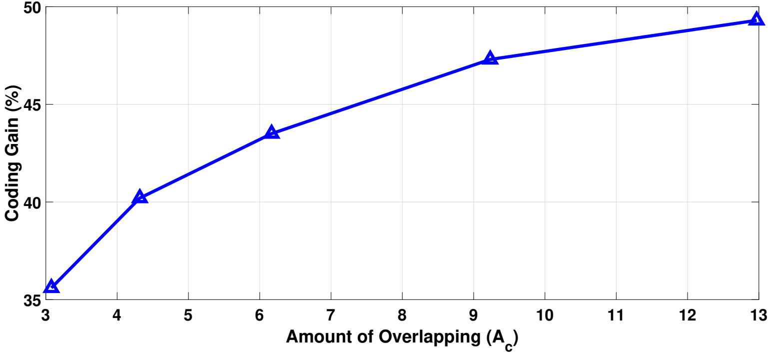

Figure: Coding Gain verse Amount of Overlapping A_c with fixed $K_c = 15$ and variable D_c

- **Fix the Amount of Overlapping.**

Table: Coding Gain for Fixed Amount of Overlapping

$\mathbf{K}_c$	$\mathbf{D}_c$	$\mathbf{A}_c$	$\mathbf{R}_{Repetition}$	$\mathbf{R}_{MDS}$	**Coding Gain**
4	10	3.4284	0.0024	0.0040	40.2%
6	22	3.4176	0.0037	0.0060	39%
8	29	3.4336	0.0050	0.0080	38%
10	35	3.4130	0.0061	0.0100	39%
12	40	3.4464	0.0074	0.0120	38%

Summary

Conclusion

1. MDS-coded caching is rate optimal in general.
2. Repetition caching can achieve optimality only for some special network topologies.
3. Code rate maximization problem for Repetition caching is NP-hard.
4. Coding gain ranging from 35% to 50% and increases when the amount of overlapping between the clusters increases.

Summary

Future Work

1. Design a clustering algorithm, taken into consideration the user distribution.
2. Investigate the scenario where a user may not be able to connect to all SBSs within a cluster.

References

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Thank You