

Effects of Cooperation Policy and Network Topology on Performance of In-Network Caching

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Abstract—In-network caching is a key component in information-centric networking. In this paper we show that there is a tradeoff between two common caching metrics, byte hit rate and footprint reduction, and show that a cooperation policy can adjust this tradeoff. We model the cooperation policy with only two parameters – search radius r and number of copies in the network K . These two parameters represent the range of cooperation and tolerance of duplicates. We show how cooperation policy impacts content distribution, and further illustrate the relation between content popularity and topological properties. Our work leads many implications on how to take advantage of topological properties in in-network caching strategy design.

I. INTRODUCTION

Caching is a key component in information-centric networks (ICN) [1]–[4]. In-network caching not only reduces an ISP’s outgoing traffic, but also reduces traffic within an ISP network. Byte hit rate (BHR) is a common metric for evaluating savings in inter-ISP traffic and footprint reduction (FPR) [5] measures the amount of traffic eliminated by caching (as product of traffic volume and distance it travels in the network) and is the metric we use for intra-ISP traffic savings. We show that BHR by itself is insufficient in capturing the performance of a network of caches; this is often overlooked by existing work. This paper shows that there is a subtle interplay between BHR and FPR and that in some cases these two metrics oppose each other. We argue that a *cooperation policy* among routers can mediate this tradeoff between BHR and FPR and show that two parameters can tune the desired operating region: maximum number of duplicates for each content item (K) and the radius of cooperation (r).

To improve BHR, a cooperation policy covering a large radius enhances network storage utilization by reducing the number of duplicates (*cache diversity* in [6]). However, large-scale cooperation causes communication overheads and increases intra-ISP traffic because requests may be redirected many times. Despite efforts in designing a cooperation policy [7], [8], [10], a proper model for its impact on BHR and FPR is still missing. We characterize cooperation policy by its search strength (r) and capability of reducing duplicates (K). We show how different r and K values lead to different tradeoffs between BHR and FPR, and discuss their implication.

There is considerable interest in exploiting topological properties in cache networks. Initial efforts [11], [12] indicate centrality as a promising metric, but questions like how to measure the topological impact on performance and mechanism of the interplay between topology, and caching strategy still remain open. We use a cache cooperation policy to couple

content with topology and show that this coupling explains how topological properties impact caching performance; the tightness of the coupling indicates degree of topology’s impact.

Our contributions in this paper are as follows:

- 1) We highlight the importance of FPR as a performance metric for in-network caching, and show how BHR and FPR conflict each other at the Pareto frontier.
- 2) We propose a cooperation policy model to show the relationship between cooperation policy, content, and topology. We also categorize different cooperation types.
- 3) We propose a novel way to measure the impact of topology, and perform a thorough numerical analysis to show how it influences system performance.

II. SYSTEM MODEL

Consider a network of M routers, L of which directly receive user requests and are *edge routers*. A router denoted by R_i is equipped with a storage capacity of C_i bytes. We assume N distinct files, denoted by f_i and being s_i bytes in size. All files are stored permanently at the Content Provider (CP) represented as the $(M+1)^{\text{th}}$ router (R_{M+1}). Denote the request probability of f_i by this file’s *popularity* p_i , and denote the popularity vector by $\mathbf{p} = [p_i]$. When a request for f_i arrives to an edge router R_j ($j = \{1, \dots, L\}$), R_j first searches f_i in its cache. If R_j possesses it, R_j transmits f_i to the user; this is a *hit*. Otherwise, in case of a *miss*, R_j contacts routers in its r -hop *neighborhood* to see if any of them has f_i ; this is the *cooperation policy*. We call the set of all routers located at most r -hops away from R_j as the *searchable set* of R_j , denoted by S_j^c . If f_i is stored in S_j^c , it is retrieved to R_j from the closest router (if multiple routers holding f_i) and forwarded to the user. Let $\mathcal{R}_{j,CP}$ be the set of all routers on the path between an edge router R_j and the CP (excluding the CP). If no router in S_j^c stores the item, the request is routed to the next router in $\mathcal{R}_{j,CP}$ and searched there as well as in the new searchable set; there may be overlap between searchable sets of two neighboring routers, depending on r . We define the *reachable set* of a router denoted by S_j^r as the set of all routers in the searchable sets of routers in $\mathcal{R}_{j,CP}$. If no router in S_j^r has f_i , it is downloaded from the CP and routed to the user following the backward path.

III. OPTIMAL IN-NETWORK CACHING

A. Cooperation Policy Design

Performance of a cooperation policy is determined by contents in the searchable set which is a function of r . The

diversity of contents cached in this set increases caching efficiency which then calls for a caching scheme avoiding duplicate copies in the set [8], [9]. However, popular content may better be cached in multiple routers to be more accessible from all network edge routers. We model this tradeoff with parameter K which is the maximum number of content replicas in the network. In reality every file would have its own maximum number of copies which emerges automatically if r is fixed; we use a fixed K to illustrate system behavior across the whole parameter range. Using these two parameters, we name a cooperation policy with parameters K and r as (K, r) -Cooperation Policy, classified into four as follows:

- 1) Type I, **small** r , **small** K : Weak cooperation due to limited access to other caches and limited availability of popular content; the system is not using all its resources.
- 2) Type II, **small** r , **large** K : This is en-route caching. The most popular content is pushed to the network edge.
- 3) Type III, **large** r , **small** K : Network storage is effectively a single cache. Popular content is in network core.
- 4) Type IV, **large** r , **large** K : Strong cooperation. BHR and FPR cannot be improved at the same time since caching system is fully-utilized and reaches its Pareto frontier.

The complexity of cooperation can be calculated via communication and computation overhead [8]. Initially, all routers exchange their set of stored contents with routers in their searchable set. Assuming that each content is unit size and dropping the router index, this initialization step requires $O(MC|\mathcal{S}^c|)$ messages and results in $O(M^2C)$ message exchanges in the worst case. Upon a change in the cache of a router, this router informs all its r -hop neighbours about the evicted and admitted items. This per change announcement requires $O(|\mathcal{S}^c|)$ message in the worst case. In terms of computation, the cooperation does not involve any processing rather than discovering which of the replicas is closest to a specific router. Therefore, computation overhead is $O(|\mathcal{S}^c|)$.

B. Optimal Caching under (K, r) -Cooperation Policy

Assume a centralized entity knowing the content distribution at time t , $\mathbf{X}^t = [x_{i,j}]$ where $x_{i,j}$ is 1 if f_i is stored at R_j , and zero otherwise. At time t a user issues a request to R_l for f_u which is stored at R_{hit} . Denote the set of intermediate routers on the path between R_l and R_{hit} by \mathcal{S} , and the extended set $\mathcal{S} \cup R_{M+1}$ by \mathcal{S}^+ . An optimal caching strategy (C_{OPT}) determines whether to cache f_u in the routers in \mathcal{S} , and if to be cached which items to evict in case of full cache occupancy.

A requested item can be served from edge router R_j or retrieved from another router R_k including the CP. Let $c_{j,k}$ denote the cost of downloading one byte at R_j from R_k . The cost function reflects the distance between the two entities and can be calculated using shortest path algorithms. For a (K, r) -Cooperation Policy, as the routers not in \mathcal{S}_j^r are not reachable from R_j , we set $c_{j,k} = \infty$ if $R_k \notin \mathcal{S}_j^r$. Let our decision variables $\mathbf{Y}^t = [y_{i,j,k}] \in \{0, 1\}$ be 1 only if R_j downloads f_i from R_k . Note that if $y_{i,j,j} = 1$, then f_i is stored in R_j . C_{OPT} aims to minimize the total cost of serving all user requests arriving to all edge routers in the long run (first term in (1)) and cost of serving f_u for which user request is just received and

can be cached in one of the routers in \mathcal{S} (second term). C_{OPT} exploits its knowledge of current content distribution \mathbf{X}^t , file popularities (\mathbf{p}) , and file size (s_i) information as follows:

$$\min \sum_{i=1}^N \sum_{j=1}^L \sum_{k=1}^{M+1} s_i p_i c_{j,k} y_{i,j,k} + s_u p_u \sum_{j=1}^L \sum_{R_k \in \mathcal{S}^+} c_{j,k} y_{u,j,k} \quad (1)$$

s.t. Cache capacity constraints:

$$\sum_{i=1}^N s_i x_{i,j} y_{i,j,j} + s_u y_{u,j,j} (1 - x_{u,j}) \leq C_j \quad \forall R_j \in \mathcal{S} \quad (2)$$

$$\sum_{i=1}^N s_i y_{i,j,j} \leq C_j \quad \forall R_j \notin \mathcal{S} \quad (3)$$

$$\text{Maximum replica constraint: } \sum_{j=1}^M y_{i,j,j} \leq K \quad \forall i \quad (4)$$

$$\text{Feasibility constraints: } y_{i,j,k} \leq y_{i,k,k} \quad \forall i, \forall j, \forall k \quad (5)$$

$$y_{i,j,j} = x_{i,j} \quad \forall i, \forall R_j \notin \mathcal{S} \quad (6)$$

$$\text{Service constraint: } 1 \leq \sum_{k=1}^{M+1} y_{i,j,k} \quad \forall i, \forall j \quad (7)$$

$$\text{Availability constraint: } y_{i,M+1,M+1} = 1 \quad \forall i. \quad (8)$$

Our objective (1) aims to minimize the serving cost by favoring the most popular files. *Cache capacity constraints* in (2) and (3) ensure the total size of items to be stored in a router's cache cannot exceed cache capacity. Only routers in \mathcal{S} can consider putting the requested item f_u into their caches. *Maximum replica constraint* in (4) ensures that an item can have maximum K replicas in the network. Note that by removing this constraint, system can figure out optimal K for each neighborhood automatically. *Feasibility constraint* in (5) reflects f_i being retrievable from R_k only if R_k stores f_i whereas (6) states that contents cached by routers not in \mathcal{S} do not change. *Service constraint* (7) forces the requests received at edge routers to be served from some location (i.e., local cache, another router's cache, or the CP), while *availability constraint* in (8) ensures all items are available from the CP. After C_{OPT} determines \mathbf{Y}^t , we update the new content distribution as $\mathbf{X}^{t+1} = \mathbf{Y}^t$ for the next decision instant. C_{OPT} is an integer linear programming problem which can be solved with optimization software for small instances of the problem but requires low-complexity distributed schemes for large scale networks. We leave distributed solutions for future work.

Let $\mathcal{F}_j = \{u_{j,1}, u_{j,2}, u_{j,3}, \dots\}$ be the list of user requests arriving at edge router R_j where $u_{j,i}$ is the i^{th} request for a file with size $s_{u_{j,i}}$. R_j can retrieve it only from its reachable set \mathcal{S}_j^r which is defined as follow:

$$\mathcal{S}_j^r = \bigcup_{R_k \in \mathcal{R}_{j,CP}} \mathcal{S}_k^c. \quad (9)$$

A request will be counted as hit if at least one of the routers in \mathcal{S}_j^r stores it. More formally, we define hit function $\delta_{j,i}$ for request $u_{j,i}$ (assuming $u_{j,i}$ is a request for f_i) as follows:

$$\delta_{j,i} = \begin{cases} 1 & \text{if } \sum_{R_k \in \mathcal{S}_j^r} y_{i,k,k} \geq 1 \\ 0 & \text{o/w.} \end{cases}$$

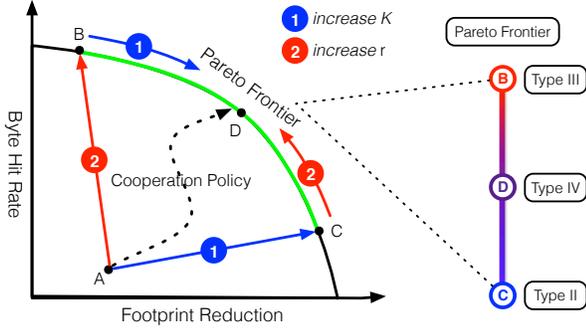


Fig. 1: Conflicting BHR and FPR at the Pareto frontier. Type of cooperation at different points shown on right.

Next, we calculate BHR as follows:

$$BHR = \frac{\sum_{j=1}^L \sum_{u_{j,i} \in \mathcal{F}_j} s_{u_{j,i}} \delta_{j,i}}{\sum_{j=1}^L \sum_{u_{j,i} \in \mathcal{F}_j} s_{u_{j,i}}}. \quad (10)$$

If request $u_{j,i}$ is served from a router that is $h_{j,i}$ hops away from the user, and the path from R_j to the CP is H_j hops long, we can compute the FPR as follows:

$$FPR = 1 - \frac{\sum_{j=1}^L \sum_{u_{j,i} \in \mathcal{F}_j} s_{u_{j,i}} h_{j,i}}{\sum_{j=1}^L H_j \sum_{u_{j,i} \in \mathcal{F}_j} s_{u_{j,i}}}. \quad (11)$$

IV. NUMERICAL ANALYSIS

A. Setup and Metrics

We performed numerical evaluation on realistic and synthetic topologies. Realistic topologies are from [13], and synthetic topologies are scale-free networks of 50 nodes. Each node can store 25 objects. We present results on synthetic networks; realistic topologies produce similar results. Content popularity is modeled according to [14], and content set contains 5000 objects. We calculate the betweenness centrality (C_B) of each router in order to analyze its impact on cached content in a specific router under various (K, r) pairs. We define *coupling factor* (CPF) as the Pearson correlation between C_B and average popularity per bit in a node's cache; it measures topological impact on system performance. The rationale is that optimal system performance is achieved by placing content at specific locations in a network according to its popularity and that C_B is a good metric to characterize a node's position in a graph. Strong correlation between the two indicates that content is tightly "coupled" with topology and topological properties influence system performance.

In the simulations, 30% of the edge routers are randomly selected and connected with client, and the server randomly connects to one of the 5 core nodes with highest C_B . Experiments were repeated at least 50 times.

B. Pareto Frontier

Fig. 1 shows how K and r impact caching performance. The solution to C_{OPT} provides the optimal cache profiles for given K and r (e.g., point A in Fig. 1), but it does not indicate the best values for these two parameters, i.e., we can improve performance by tuning K and r , because the system may be

underutilized. However, our optimization model can be used to find Pareto frontier of the performance (green arc BC in Fig. 1). When we reach the Pareto frontier, we cannot improve BHR or FPR without hurting the other. The fan-shaped area defined by ABC is the area which a cooperation policy can explore to find the best tradeoff between K and r . Point D where we eventually reach the Pareto frontier depends on how cooperation policy balances BHR and FPR. Lines AB and AC are not parallel to the x- and y-axis, since changing either of r or K affects both BHR and FPR, as we show below.

The upper graph in Fig. 2a shows how BHR and FPR vary as we move along the segments AB , BC , and CA , by varying r and K . Starting from A and moving clockwise (left to right in the figure), we increase the search radius which improves BHR, but decreases FPR due to additional search traffic or letting content be cached at routers with higher $h_{j,i}$ in (11). From B to C , along the Pareto frontier, we observe the tradeoff between BHR and FPR, with FPR reaching its maximum at C . From C to A , r is 0 so the system reduces to en-route caching where larger number of copies (near C) is beneficial, hence as we move towards A , both BHR and FPR decrease. Fig. 2b shows heatmaps of CPF, BHR, and FPR as function of K and r . Lighter values indicate higher values. It shows how BHR and FPR conflict each other, i.e., one achieving the highest performance while the other has the worst, in regions corresponding to the Pareto frontier.

C. Coupling Content and Topology

The lower plot in Fig. 2a shows how CPF evolves along the same path. Values close to -1 or 1 indicate strong dependence between popularity and betweenness. A router with a high C_B is in or close to the core of the network whereas a router with low C_B is close to the network edge. At B , where CPF is close to 1, popular content is in nodes with high C_B , i.e., the core, whereas at C , where CPF is close to -1, it is at the edge where C_B is low. Along the Pareto frontier BC , we observe a "migration" of content from core to edge. At D where CPF is 0, both BHR and FPR are close to halfway point between their respective minima and maxima at B and C . We have observed this phenomenon across a wide range of experimental settings, but its full investigation is left for further study.

Fig. 3 shows cooperation policy's impact on content placement along the Pareto frontier BC . Point B (Fig. 3a), representing Type III cooperation favors BHR and places content in the core. Point D along BC (Fig. 3b) strikes a tradeoff between BHR and FPR and the content is neither in the core nor on the edge; this is Type IV cooperation. Finally, point C (Fig. 3c) favors FPR and pushes popular content to the edge.

D. Implications

Our results have profound implications on relationship between cooperation policies, content popularity, and network topology. They also give us hints on when and how topological properties should be taken into account in caching strategy design. We summarize the main implications as follows:

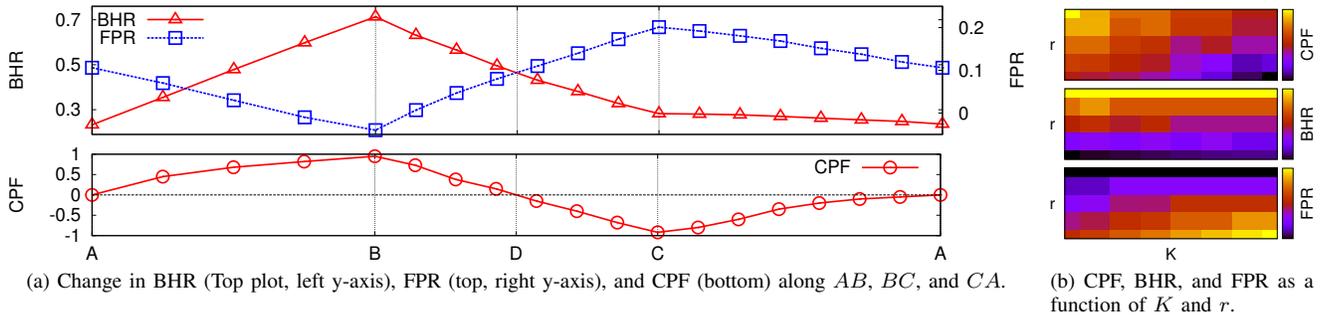


Fig. 2: Performance of (K, r) -Cooperation along the boundary defined by ABC (a), and for all (K, r) pairs (b).

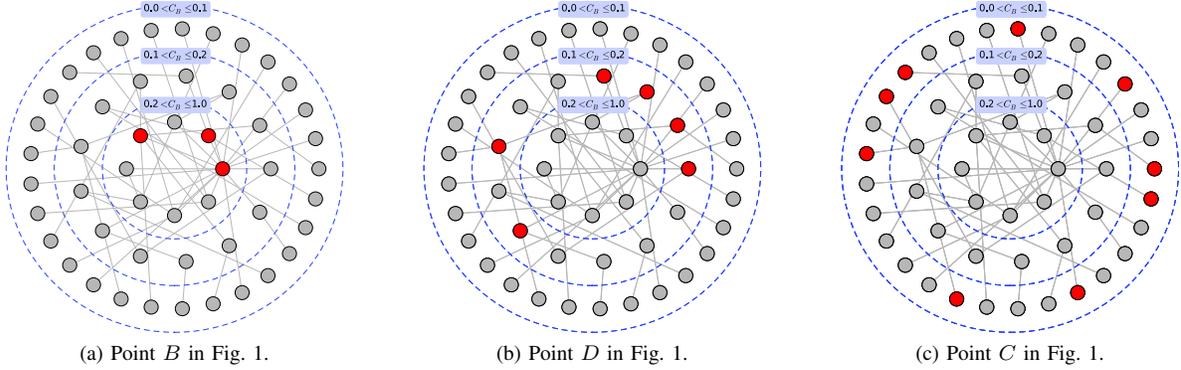


Fig. 3: Content placement at points B , D , and C . Red color (dark dots) marks the most popular content. Nodes are grouped in circles according to C_B . Content migrates from core to edge as we move from B to C .

- 1) Cooperation policy pushes performance to Pareto frontier and couples content popularity and topological properties together. How and where it falls on the frontier depends on how it balances BHR and FPR.
- 2) Content popularity and topology strongly correlate with each other only close to the Pareto frontier. Whether the correlation is positive or negative depends on how the cooperation policy favors one of the two metrics.
- 3) The optimization model implies that C_B has more influence on performance when we get closer to points A or B in Fig. 1; only Type II and III cooperation policies can fully utilize C_B to enhance performance.
- 4) We conjecture that tight coupling between content popularity and topology comes similar mathematical structures as both exhibit power-law properties. Were popularity closer to uniform or topology closer to a random network, this tight coupling might disappear.

V. CONCLUSION

We modeled cache cooperation by its search radius and tolerance of duplicates. We performed a thorough numerical analysis and showed that cooperation policy pushes system performance to its Pareto frontier, and how it couples content with topology. We proposed a way to measure impact of topology on system performance. We show when and how topological information should be taken into account in in-network caching strategy design.

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