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, however, there is no widely accepted metric for evaluating savings in intra-ISP traffic. Footprint reduction (FPR) [5] has been proposed as one such metric and is the one we use in this paper. 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 for 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 engenders significantly intra-ISP traffic because requests may be redirected many times. Despite efforts in designing a cooperation policy [7]–[9], 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 [10], [11] 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, \( R_i \), 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 \((M+1)^{th} \) router \((R_{M+1})\). Routers receiving requests directly from users are edge routers. Denote the request probability of file \( i \) by this file’s popularity \( p_i \), and denote the popularity vector by \( p = [p_i] \). When a request for \( f_i \) arrives to an edge router \( R_j \), \( R_j \) first searches \( f_i \) in its cache. If \( R_j \) possesses it, \( R_j \) transmits \( f_i \) to the user; this 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 \( S_j^r \). If \( f_i \) is stored in \( S_j^r \), it is retrieved to \( R_j \) from the closest router (if multiple routers holding \( f_i \) and forwarded to the user. Let \( R_{j,CP} \) be the set of all routers on the path between a leaf router \( R_j \) and the CP (excluding the CP). If no router in \( S_j^r \) stores the item, the request is routed to the next router in \( R_{j,CP} \) 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 \( R_{j,CP} \). 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

The performance of a cooperation policy is determined by the 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. 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. Using these two parameters, we name a cooperation policy with parameters \( K \) and \( r \) as \((K, r)\)-Cooperation Policy which can be 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.

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

Assume a centralized entity deciding which items are stored at each router \( R_i \) when a user requests item \( f_u \) at time \( t \). This entity knows the content distribution \( X^t = [x^t_{i,j}] \) where \( x^t_{i,j} \) is 1 if \( f_u \) is stored at node \( R_i \), and zero otherwise. An optimal caching strategy \( C_{OPT} \) determines whether to cache \( f_u \) in the routers between the edge router \( R_i \) receiving the request and router \( R_{hit} \) storing \( f_u \), and which items to evict in case of full cache occupancy. We refer the set of all these intermediate nodes on the path between \( R_i \) and \( R_{hit} \) as \( S \).

\( C_{OPT} \) minimizes the total cost of serving user requests by exploiting its knowledge of current content distribution \( X^t \), file popularities \( p_i \), and file size \( s_i \) information. Let \( c_{j,k} \) denote the cost of downloading one byte at \( R_j \) from \( R_k \). An item can be served from edge router \( R_j \) or retrieved from another router \( R_k \) including the CP. Let our decision variable \( x_{i,j,k}^{t+1} \) be 1 if \( R_j \) downloads \( f_i \) 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 \( S^t_j \) are not reachable from this edge router, we set \( c_{j,k} = \infty \) if \( R_k \notin S^t_j \). For harmony of notation, we re-define the content distribution by \( X^t = [x^t_{i,j,k}] \) (and drop \( t \) if we do not refer to a specific time). \( C_{OPT} \) is formulated as follows:

\[
C_{OPT} : \min \sum_{i=1}^{N} \sum_{j=1}^{L} \sum_{k=1}^{M+1} s_i p_i f_i x_{i,j,k}^{t+1} + \sum_{j=1}^{L} \sum_{\forall R_k \in S_j \cap R_{hit}} c_{j,k} x_{i,j,k}^{t+1} \\
+ s_n p_u \sum_{j=1}^{L} \sum_{\forall R_j \in S_j \cap R_{hit}} c_{j,k} x_{u,j,k}^{t+1}
\]

s.t. \( x_{i,j,k}^{t+1} \leq C_j, \forall R_j \in S \) (2)

\( s_i x_{i,j,k}^{t+1} + s_u x_{u,j,k}^{t+1} (1-x_{i,j,k}^{t+1}) \leq C_j, \forall R_j \in S \) (3)

Maximum replica constraint: \( \sum_{j=1}^{M} x_{i,j,k}^{t+1} \leq K \) (4)

Feasibility constraint: \( x_{i,j,k}^{t+1} \leq x_{i,j,k}^{t} \) \( \forall i, \forall k \) (5)

Service constraint: \( 1 \leq \sum_{k=1}^{M+1} x_{i,j,k}^{t+1} \) \( \forall i, \forall j, \forall k \in L \) (7)

Availability constraint: \( x_{i,j,k}^{t+1} \geq 1 \) \( \forall i, \forall k \) (8)

Our objective (1) calculates the cost of serving user requests over all the edge routers and minimizes this cost by favoring the most popular files. Note that if \( x_{i,j,k} = 1 \), then \( f_i \) is stored in \( R_j \). 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 \( S \) can consider putting the requested item \( f_i \) into their caches. Maximum replica constraint in (4) ensures that an item can have maximum \( K \) replicas in the network. 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 \( S \) do not change. Service constraint in (7) forces the content to be served from some location (i.e., local cache, another router’s cache, or the CP) while availability constraint in (8) ensures that all items are available from the CP. Decision variables are binary, i.e., \( x_{i,j,k} \in \{0,1\} \). \( C_{OPT} \) is an integer linear programming problem (ILP) which can be solved with optimization software.

Let \( J \) be the list of user requests arriving at leaf router \( R_j \) where \( u_{i,j} \) is the \( i^{th} \) request for a file with size \( s_{u_{i,j}} \). \( R_j \) can retrieve it only from its reachable set \( S^t_j \) which is defined as:

\[
S^t_j = \bigcup_{R_k \in R_j, CP} S^t_k.
\]

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

\[
\delta_{j,i} = \begin{cases} 
1 & \text{if } \sum_{R_k \in S^t_j} x_{i,k,k} \geq 1 \\
0 & \text{o/w.}
\end{cases}
\]
we can compute the FPR as follows:

$$FPR = 1 - \frac{\sum_{j=1}^{L} \sum_{u_{j,i} \in F_j} s_{u_{j,i}} h_{j,i}}{\sum_{j=1}^{L} H_j \sum_{u_{j,i} \in F_j} s_{u_{j,i}}}.$$  (12)

Next, we calculate BHR as follows:

$$BHR = \frac{\sum_{j=1}^{L} \sum_{u_{j,i} \in F_j} s_{u_{j,i}} \delta_{j,i}}{\sum_{j=1}^{L} \sum_{u_{j,i} \in F_j} s_{u_{j,i}}}.$$  (11)

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:

$$FPR = 1 - \frac{\sum_{j=1}^{L} \sum_{u_{j,i} \in F_j} s_{u_{j,i}} h_{j,i}}{\sum_{j=1}^{L} H_j \sum_{u_{j,i} \in F_j} s_{u_{j,i}}}.$$  (12)

**IV. NUMERICAL ANALYSIS**

**A. Setup & Metrics**

We performed numerical evaluation on both realistic and synthetic topologies. Realistic topologies are from [12], and synthetic topologies are scale-free networks. We only present results on synthetic networks: realistic topologies produce similar results. Content popularity is modeled according to [13].

We calculate the betweenness centrality ($C_B$) of each router in order to analyze how it impacts the cached content in this 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. We use CPF as a measure of 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 metrics indicates that content is tightly “coupled” with topology and topological properties have significant impact on 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. 2 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 (12). 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.

**C. Coupling Content and Topology**

The lower plot in Fig. 2 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.

Corresponding to Fig. 2, Fig. 3 shows how cooperation policy influences content placement along the Pareto frontier $BC$. Point $B$ in Fig. 3a, representing Type III cooperation favors BHR and places content in the core. Point $D$ along $BC$ in 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 $C$ in Fig. 3c favors FPR and pushes popular content to the edge.

Fig. 4 shows heatmaps of CPF, BHR, and FPR as function of $K$ and $r$. Lighter values indicate higher values.

**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:

1) Cooperation policy pushes performance to Pareto frontier and couples content popularity and topological prop-
V. CONCLUSION

We modeled cache cooperation policy 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. Our results show when 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 only present results on betweenness centrality. We also experimented with other centrality measures and got similar results. The impact of other properties like diameter or clustering coefficient needs further study.

5) We conjecture that the tight coupling between content popularity and topology comes from them having similar mathematical structures. Both content popularity and network topologies exhibit power-law properties. Were popularity closer to uniform or topology closer to a random network, this tight coupling might disappear. However, this matter requires further study.

REFERENCES


