Maximizing Producer-Driven Cache Valuation in Information-Centric Networks

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***Abstract*—In Information-Centric Networks (ICNs), caching decisions are mostly driven by request-centric mechanisms. Fluctuations in request rates and cache capacities typically have the most impact on where content would be cached. However, as ICNs expand in scale, producers may prefer certain nodes to cache their contents based on favorable properties, such as topological centrality, closeness of cache locations with respect to consumers, security measures, and service up-time. These factors would impact the *valuation* of caching nodes. Nevertheless, maximizing cache utilization via dynamic cache valuation is a challenging task in ICNs, largely due to inter-dependencies in model parameters. In this paper, we propose a novel caching model where content producers aim to dynamically valuate cache nodes to optimize caching. The model is built on a value-based utility function that considers dynamic and topological attributes of cache nodes, enabling a dynamic novel caching scheme named *Max-Node Utility* that aims to maximize caching utility. Simulation results demonstrate that *Max-Node Utility* outperforms current state-of-the art caching schemes by providing better caching utility, reducing access delay and increasing cache hit ratios across varying cache sizes and popularity skewness values. An outlook on the premise of producer-driven caching schemes is presented in the conclusion, to emphasize future directions in similar caching models.**

Index Terms*—*ICN caching, In-network caching, Producer-Driven Cache Node Valuation, Caching heuristic, Utility Value of Cache Node.

I. Introduction

The Internet has become a global infrastructure for information distribution with billions of connected users and devices, and Zettabytes (ZB) of yearly transferred data [1]. Internet usage patterns have become increasingly bandwidth-intensive and users are mainly interested in fast and reliable retrieval of information, instead of identifying the host where the information is stored. Information-Centric Networks (ICNs) have evolved as promising candidates for future Internet architectures as the current host-centric Internet architecture is struggling to scale with the projected traffic demand and usage pattern of today's Internet [2].

Content caching is a fundamental component in ICNs, as caching and retrieval schemes play a pivotal role in providing fast, reliable, and scalable content distribution and delivery, especially as the network scales [2]. Despite substantial developments in cache placement and replacement in ICNs [2]–[8], the problem is often addressed under consumer/content driven mechanisms. Devising a cache node valuation and selection scheme where the content producer plays a role in valuating cache nodes for efficiency (aiming to maximize caching utility) is seldom explored. As ICNs scale, it is imperative to investigate the impact of producer-driven caching on overall network performance. Being a key stake-holder, and often aware of varying dynamics of request patterns, the producers can leverage their insights and predictions to improve cache performance.

The main objective of this work is to investigate the impact of producer-driven caching. Thus, we propose a model where producers aim to maximize cache utilization along content delivery paths. This novel caching model enables producers to consider a set of dynamic and topological attributes in assessing and selecting cache nodes.

We address two central research questions in this paper, first whether content producers can achieve higher exposure for their contents if they drive their valuation and selection. If so, what attributes have the highest impact on determining the value of caching nodes? To address these research questions, our contributions in this paper are:

1) We devise producer-centric caching attributes that build towards a cache-valuation model.
2) We propose a novel utility-based caching model that producers utilize to optimize caching decisions, named as *Max-Node Utility*, for maximizing caching utility.

The remainder of this paper is organized as follows. Section II overviews some related research papers of ICN caching. Section III elaborates on our proposed system of node value-based caching, describes the design principles of the proposed node value-based utility function based on which the content producers determine the cache node value and explains the *Max-Node Utility* caching scheme which aims to select the most valuable cache nodes to maximize caching utility. Section IV consists of the performance evaluation results of *Max-Node Utility* scheme comparing to other well known caching schemes and Section V consists of our final discussions and our plan for future work.

II. Literature Review

The proposed mainstream caching schemes in ICN literature are designed based on four major classifiers: popularity

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of content, locations of cache nodes in the network topology, existing collaboration approach among the cache nodes and the content delivery path between the content source and consumer [2]. Content popularity has been considered as the most crucial factor for designing efficient caching schemes [3], [4], [9], [10]. Location-based schemes select some specific subsets of cache nodes while considering topological attributes as the allocation criteria such as standard centrality metrics [4]–[6], [9] and also propose neighborhood-based schemes where the cache nodes utilize the neighbor cache spaces [7], [9]. In collaborative schemes, cache nodes explicitly or implicitly collaborate with one another aiming to achieve reduced content redundancy, improved caching diversity and resource utilization while incurring additional communication overhead [9], [11]. Path-based schemes either cache contents along the content delivery paths or deviating from the paths [4], [8], [10].

For cache node selection, topological-based schemes consider several standard graph-related centrality metrics as the selection criteria such as the betweenness centrality defining the number of times a cache node lies on the content delivery paths between all pairs of nodes in a network topology [5], [6], [9] or the degree centrality defining the number of links incident upon a cache node [12]. In [4], concept of routing betweenness centrality (RBC) is adopted for cache selection where RBC value of a cache node is the expected number of content Interest packets that pass through the node from the content consumer to content source. The authors in [11] select cache nodes based on content-based centrality (CBC) where CBC value of a cache node is defined as the sum of the ratio of the number of shortest paths from all consumers to all contents that passes through the cache node to the total number of shortest paths between all pairs of consumers and contents. Many caching schemes also consider cache node's available cache capacities [8], [13], maximum number of cache hits [13], and closeness with respect to the requesting consumers [10], [14] for cache node selection.

Despite significant research efforts that address cache node selection, to the best of our knowledge, maximizing producer-driven caching has been seldom explored in ICN literature. Hence, we propose a novel concept of producer-driven cache node valuation and selection scheme to maximize the cache utilities. In our caching scheme, the content producers aim to be benefited by getting higher exposure to their contents by intelligently selecting cache nodes while taking caching decisions. To alleviate the load on some specific high centrality-valued well connected nodes having higher possibilities of being selected as cache nodes, the content producers consider some important dynamic attributes of cache nodes as node value determining attributes along with the topology attributes in our caching system. In our node valuation scheme, the content producers decide and rank the cache node assessment attributes, adjust or adapt the weight values of the attributes for optimizing the caching decisions, and decide the node value assessment and selection methods for maximizing caching utility.

III. Node value-based caching system

Our proposed node value-based caching system and *Max-Node Utility* node valuation and selection scheme work upon the most well known and well cited Content-Centric Network (CCN) architecture [15]. In this section, at first we describe our proposed producer-centric caching system of maximizing value of cache nodes, second we define the proposed utility value-based cache node valuation function and finally we describe our proposed utility value-based cache node valuation and selection scheme which aims to select the maximum valuable cache nodes while making caching decisions.

A. System Model

Our utility-based caching system focuses on selecting the most valuable cache nodes, from the view of content producers, to maximize caching utility. Our proposed system consists of three entities: Producers, Consumers and an *ICN cache service provider*.

Content producers are network nodes that originate, publish and store content, such as servers, tablets, and sensors. Content consumers are network nodes which subscribe-to/request content. An *ICN cache service provider* works as a coherent administrative domain consisting of edge routers, intermediate routers and a network manager (NM). As any cache router in ICN typically has caching capability, a cache router can cache requested content and be the content source while full-filling consumer requests. So, for a requested content, the content source can be the content producer or the cache router caching the requested content.

In our proposed system, the content producers are the decision making entities aiming to benefit by selecting the most valuable cache nodes for caching their contents. Content producers decide and rank cache node attributes. A NM collects caching decision criteria, node valuation and selection schemes from content producers. Thus, whenever the NM receives a request for content interest processing, it carries out the pre-determined assessment and selection steps and reports back the cache node selection decisions to the content producers or to the cache nodes (caching the requested content) so that the requested contents are cached at the "best" or most valuable cache nodes while routed back to the consumers. To remedy security issues in our proposed system, the NM tracks the dynamic conditions of network while valuating and selecting the cache nodes instead of allowing the producers direct access to network status.

Fig. 1 shows the framework of our proposed utility value-based cache node valuation system. Suppose, a content request is forwarded from the consumer C_1 to the content producer P_2 in step 1. In step 2, the producer P_2 sends the request for the corresponding content request processing to NM. In step 3, NM reports back the caching decision to the producer P_2 after executing the cache node assessment and selection scheme and the requested content is cached at the selected cache node, such as at node IR_1 while routed back to the requesting consumer C_1 in step 4. If a content request gets the requested content in a cache node along the request

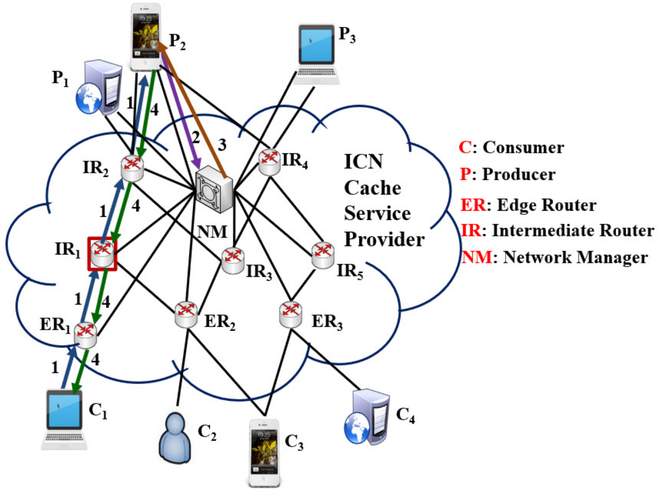


Fig. 1: **Proposed Framework of Node Value-based Caching System**:The 4-step process of cache node selection is highlighted with numbered arrows, and detailed in Section III.A

forwarding path, the NM executes the same assessment and selection scheme and reports back the caching decision to the cache node.

B. Utility Value-based Cache Node Valuation

In our proposed cache node valuation system, content producers determine the utility value of a cache node in terms of some dynamic attributes and topological attributes of the cache node. The proposed utility value-based node valuation function defines the value of the cache node based on the producers decided attributes and the proposed caching scheme aims to select the most valuable cache nodes based on the node valuation function.

1) Topological Attributes of Cache Node: Centrality of the cache nodes determining the cache nodes' relative positions in the network topology effectively measures the importance of the nodes as candidate caching locations [6], [12]. In our scheme, the content producers consider the most widely used centrality measures which are Betweenness [5] and Degree Centrality [12] values of the cache nodes for node valuation.

Betweenness Centrality (BC) is a useful indicator of node importance in a network topology as caching at important nodes having high betweenness centrality values increases the reachability of contents incurring increased cache hits and reduced content retrieval latency. BC value of a cache node j can be defined by Equation(1)

$$BC_j = \sum_{s \neq j \neq t \epsilon J} \frac{\sigma_{s,t}(j)}{\sigma_{s,t}} \tag{1}$$

where $\sigma_{s,t}$ is the total number of content delivery paths between the two cache nodes s and $t (s \neq j \neq t)$ and $\sigma_{s,t}(j)$ is the number of content delivery paths between s and t that pass through cache node j.

Degree Centrality (DC) is based on the concept that having more direct ties results into being more important in the network topology while maintaining increased contacts with numerous other cache nodes. DC value of a cache node j can be defined as

$$DC_j = \frac{degree(j)}{(n-1)} \tag{2}$$

where $degree(j)$ is the number of edges incident upon cache node j and n is the total number of cache nodes.

Content producers determine the topological value of a cache node j, defined as $TopV_j$ using Equation (3), where the BC and DC values of cache node j impact the likelihood of caching at that node.

$$TopV_j = (BC_j)(DC_j) \tag{3}$$

2) Dynamic Attributes of Cache Node: Content producers consider a cache node's distance with respect to a specific requesting consumer and the replacement ratio as dynamic attributes for assessing the utility value of that cache node.

Topological attributes such as BC and DC values do not suffice to determine cache node value. A well connected node having high BC or DC value is not necessarily a closer node to the requesting consumer. Caching content closer to the consumer can increase cache hit and reduce content retrieval delay. To minimize retrieval delay and maximize cache hit, the content producers consider the distance of a cache node in terms of number of hops from the requesting consumer and aim to cache contents closer to the consumers.

The distance of a cache node j is defined as

$$Dist_j(k) = \frac{Hops_{k_{src},j}}{Hops_{k_{cons},k_{src}}} \tag{4}$$

where $Hops_{k_{src},j}$ defines the number of hops between the content source (can be a cache node or the content producer) of the candidate content k and the cache node j and $Hops_{k_{cons}}, k_{src}$ defines the number of hops between the content source and the requesting consumer of the content k. So, Equation (4) dynamically calculates the closeness of a potential cache node from the requesting consumer with respect to a specific content request and gives higher values to the cache nodes closer to the requesting consumers.

The replacement ratio of a cache node defines the ratio between the total number of replaced contents, and the total number of received content requests at that cache node. Cached contents at important central nodes and nodes closer to the consumers can easily be replaced. So, to prevent the exhaustion of these important central and near consumer nodes, the content producers aim to restrict excessive caching tendency of nodes preventing large cache replacement ratio.

The cache replacement ratio of a cache node j is defined as

$$CRR_j = \frac{TotalRpc_j}{TotalInterest_j} \tag{5}$$

where $TotalRpc_j$ is the total number of replaced contents and $TotalInterest_j$ is the total number of content requests that have arrived at cache node j.

The content producers determine the dynamic attribute value $DynV_j$ of a cache node j using Equation (6) where the distance of cache node j from the content source is proportional to caching probability, whereas the replacement ratio of node j is inversely proportional to caching probability.

$$DynV_j = (Dist_j(k))(1 - CRR_j) \quad (6)$$

3) Utility Value-Based Caching Function: The content producers define the utility value of a cache node j by the utility function defined in Equation (7), where $UtilityVj$ is a Weighted Sum Value (WSV) of the topological and dynamic attributes of the cache node j.

$$UtilityVj = \beta(TopV_j) + \gamma(DynV_j) \quad (7)$$

To get the optimal results for node valuation and selection, content producers adjust or adapt the weight values of the attributes (β and γ) where β and γ sum up to 1.

4) Max-Node Utility: Producer-Driven Cache Node Valuation and Selection Scheme: Given that our dynamic cache node valuation scheme is producer driven, content producers decide and rank the cache decision attributes, adjust the weight values of the decision attributes, and design the cache node valuation and selection scheme. The NM collects these producers' selected decision criteria, attributes, weight values, node valuation and selection scheme, computes the utility values of the cache nodes based on the designed scheme, selects the cache nodes based on the selection criteria and finally reports back the cache nodes selection decisions to the content producers or the cache nodes caching the requested contents. Though all caching decisions are made by the content producers, the NM executes the cache valuation and selection scheme to prevent any security or exposure concern that can be raised if the producers are allowed to directly collect the network status for calculating the node values.

In the *Max-Node Utility* scheme, the inputs are initialized in the first iteration. $TopV_j$ and $DynV_j$ of the cache nodes $j \in J$, along the content request forwarding paths are calculated using Equations (3) and (6) in Steps 3 and 4. The utility

Algorithm 1 *Max-Node Utility: Producer-Driven Cache Node Valuation and Selection Scheme*

Input:
K: Set of Contents
J: Set of Cache Routers
C: Set of Consumers
$PR_k, k \in K$: Set of Content Producers
M: Percentage of top cache node selection

```
1: for all k ∈ K do
2:    for all j ∈ J do
3:       TopV_j ← (BC_j)(DC_j)
4:       DynV_j ← (Dist_j(k))(1 − CRR_j)
5:       UtilityVj ← β(TopV_j) + γ(DynV_j)
6:    end for
7:    S_{j,j∈J} ← Rank nodes based on UtilityVj
8:    Return top M% nodes of S_{j,j∈J} to cache content k
9: end for
```

TABLE I: DEFAULT SIMULATION PARAMETERS

Simulation Parameters	Values
Number of producers	3
Number of consumers	92
Number of edge routers	23
Number of intermediate routers	24
Total number of contents	30000
Cache capacity in percentage	30%
Popularity skewness factor α	1.2
Percentage of selected top cache nodes	20%

values $UtilityV_j$, $j \in J$ of the cache nodes are calculated using Equation (7) in Step 5. In Step 7, cache nodes are ranked in the descending order based on their utility values. Finally, in Step 8, the top $M\%$ cache nodes are selected for caching contents.

IV. Performance Assessment

This section presents a detailed simulation of our *Max-Node Utility* scheme, building on realistic topologies. Simulation results demonstrate the gains of *Max-Node Utility* in leveraging producer-driven caching, while contrasting to well known caching schemes.

A. Simulation Environment

We use ndnSIM for our simulation and BRITE [16] for generating a realistic random network topology. Without loss of generality, and to demonstrate the scale of our proposed scheme, we consider 3 content producers where each producer generates 10000 contents, each 1KB in size. Content requests arrive following a Poisson distribution process, and requests are generated according to a *Zipf*-popularity based distribution. We evaluate the performance of *Max-Node Utility* scheme in comparison to baseline scheme Cache Everything Everywhere (*CEE*) [15], well cited probabilistic scheme *ProbCache* [14], well performing scheme Leave Copy Down*(LCD)* [17] and the popular Betweenness Centrality-based scheme, which we refer to hereafter as *Betw* [5]. All caching schemes use a Least Recently Used (*LRU*) policy for cache replacements. The default parameter values of our simulation environment are listed in Table I.

B. Performance Metrics

For assessing performance, we consider the following three performance metrics:

1) Node Utility Value: We consider the utility value of a cache node to quantify the *value* that the cache node brings while selected for caching.

2) Hop Reduction Ratio: We define the hop reduction ratio as the ratio between the hop count from the requesting consumer to the first cache node where a cache hit occurs, and the length of the content delivery path (in terms of number of hops from the requesting consumer to the content producer).

3) Cache Hit Ratio: We define the cache hit ratio as the ratio between the total number of cache hits, and the sum of cache hits and cache misses.

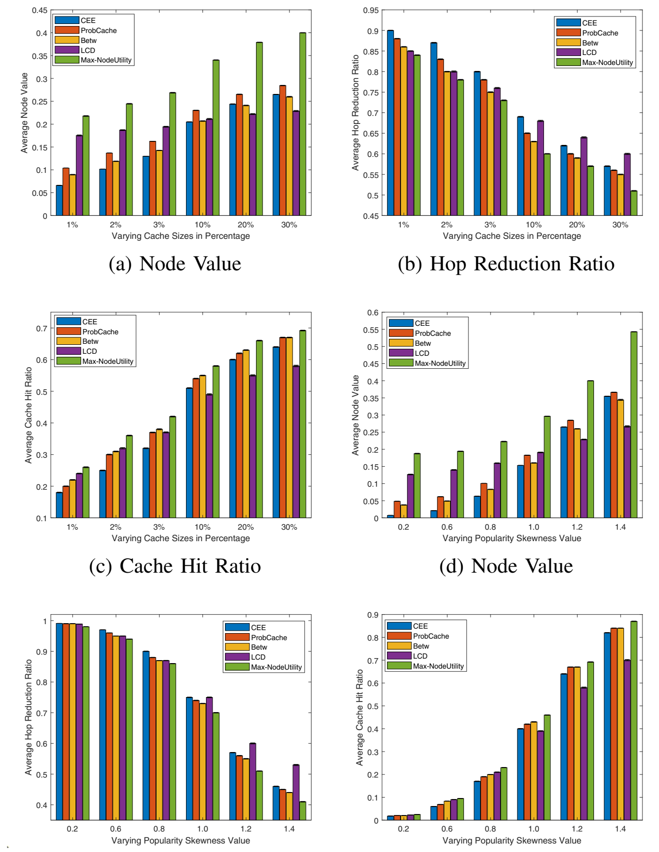
C. Performance Analysis

The effects of varying cache capacity percentages and popularity skewness values are presented with 95% confidence intervals in our performance analysis.

Fig. 2a depicts that *CEE* attains the least utility value for lower cache sizes, as it selects cache nodes indiscriminately, evidently without considering any node attribute. *ProbCache*, *LCD* and *Betw* outperform *CEE*. Specifically, *ProbCache* increases its caching probability for nodes closer to the requesting consumers, *LCD* selects cache nodes near consumers for caching frequently requested contents and reduce replacement errors and *Betw* selects the high BC valued nodes for efficient caching. For higher cache sizes, the performances of *LCD* and *Betw* degrade because *LCD* mainly caters to cache exclusivity by reducing replicas and *Betw* restricts itself by considering only BC values of nodes, while both schemes fail to utilize the increased cache capacity efficiently. However, *Max-Node Utility* performs the best among all schemes for all test cache sizes while producing the highest node utility value. This is because, *Max-Node Utility* selects high valued *quality* cache nodes by considering cache node's distance from the consumers, cache replacement ratio of nodes and also topological connectivity such as BC and DC values of nodes. *Max-Node Utility* achieves significantly greater utility value comparing to all other schemes specifically for high cache sizes such as it outperforms *ProbCache* by 41% for 30% cache capacity. This significant performance improvement of *Max-Node Utility* occurs because, with the increment of the cache capacity, increased number of high valued cache nodes are selected for caching resulting into higher node utility value.

In fig. 2b, we evaluate the average hop reduction ratio to demonstrate the performance improvement of the caching schemes achieved by lessening the traversed number of hops to retrieve requested contents. The hop reduction ratio is incrementally improved for all schemes with the increment of cache size because the increased available cache spaces can cache a higher number of contents resulting into reduced number of required hops to retrieve contents. *ProbCache* performs better than *CEE* as it considers caching path as a shared pool of resources while ensuring a fair multiplexing of the resources among all the incoming requests resulting into reduced number of traversed hops to retrieve contents. *Betw* performs better than *ProbCache* as high BC valued nodes ensure efficient contents retrieval while reducing number of hops. *Max-Node Utility* outperforms all schemes requiring the least number of hops to retrieve contents for all cache sizes as it selects *quality* cache nodes considering both cache node's centrality values and distance from the consumers. The significance of performance improvement of *Max-Node Utility* increments along with the increment of cache size such as it outperforms *ProbCache* by 9.8% for 30% cache size as more cache capacity gives the opportunity of selecting more high valued cache nodes.

Fig. 2c depicts that *Max-Node Utility* produces the highest cache hit ratio among all for all cache sizes as it efficiently



(a) Node Value (b) Hop Reduction Ratio

(c) Cache Hit Ratio (d) Node Value

(e) Hop Reduction Ratio (f) Cache Hit Ratio

Fig. 2: Performance comparison of the caching schemes for varying cache capacity percentage and popularity skewness value

selects cache nodes considering hop count, replacement ratio and topological location of nodes. *LCD* performs better under a low availability of cache capacity. Usually popular contents closer to consumers get replaced by non popular ones in low cache availability. But *LCD* avoids such replacement errors near consumers as *LCD* requires multiple requests of a content to replace an already cached popular content. On the other hand, *LCD* restricts redundant caching for maintaining cache exclusivity which degrades its performance for the large cache sizes attaining less cache hits while not utilizing the larger cache spaces. *CEE* produces the least cache hits among all but for high cache availability, its indiscriminate redundant caching attains better cache hits while performing better than *LCD*. *Betw* and *ProbCache* perform better than *CEE* as *ProbCache* utilizes cache resources efficiently by fair multiplexing among different content flows and *Betw* selects the cache nodes those lie along a high number of content delivery paths while attaining increased cache hits.

Fig. 2d shows that *Max-Node Utility* produces the largest utility value among all schemes demonstrating significant performance improvement comparing to all other schemes across all skewness values as it only selects *quality* cache nodes while considering distance of cache nodes in terms of hop count, cache node's relative position in the network topology and replacement ratio of nodes. For example, *Max-*

Node Utility achieves higher utility value comparing to *ProbCache* by 48.19% for α=1.4. The utility values of all schemes increase with the increment of the popularity skewness value. This is because, users requests concentrate on a smaller set of popular contents for larger α values. As a result, multiple replicas of this smaller set of popular contents are redundantly cached achieving increased hop reduction ratio and decreased cache replacement ratio while resulting into higher utility value. For high skewness value, the performances of *LCD* and *Betw* degrade because *LCD* behaves conservatively aiming to maintain cache exclusivity by reducing repetitious caching of the highly skewed popular contents and *Betw* restrictively caches only at high BC valued nodes.

All schemes tend to require traversing less number of hops to retrieve contents with the increment of α value. For larger α value, only a small number of contents are requested by the maximum consumers while generating more cache hits and eventually requiring less number of hops for contents retrieval. Fig. 2e shows that *Max-Node Utility* requires the least number of hops to traverse among all schemes across all skewness values such as 9.76% less hops over *ProbCache* for α=1.4 because of its consideration of node's hop distance and topological location. For high skewness value, *LCD* is unable to perform well because of its design objective of maintaining strict cache exclusivity by reducing redundant caching resulting into requiring high number of hops to be traversed to get cache hits even for high skewness value.

Fig. 2f reveals that *Max-Node Utility* attains the highest cache hit ratio among all schemes across all α values because of its selection of *quality* cache nodes. *LCD* is unable to capture high skewness value as it restricts itself from redundant caching of the smaller set of popular contents while producing less cache hits. *CEE* attains better cache hits than *LCD* for high skewness values as it caches multiple replicas of the smaller set of popular contents.

V. Conclusions and Future Work

Producer-driven caching introduces many potential gains in future caching techniques. In this paper, *Max-Node Utility* presents a scheme that aims to maximize caching utility by selecting the most valuable cache nodes, factoring in hop distance, replacement ratio and topological location of nodes. The superior performance of *Max-Node Utility* compared to some well performing caching schemes, while requiring the least number of traversed hops to retrieve contents, and achieving the highest cache hit ratio reveal that producers can get higher exposures by driving the cache selection problem.

Future developments in this domain necessitate dynamic caching and pricing models which jointly focus on improving cache utilization. This will enable dynamic caching models that cater for non-periodic fluctuations in request patterns, changes in user activity, predictable patterns in popularity changes (for example higher-bitrate content being requested at specific periods), and topological changes.

It is critical to asses the impact of producer-driven caching schemes under macro and micro fluctuations of content request patterns, as well as non Zipf popularity distributions. Ultimately, considering caching from the perspective of producers, and how they value topological, security and monetary factors in caching networks, is an important dimension in the domain of ICN caching evolution.

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