On Maximizing the Value of Cache Contents in ICN

Faria Khandaker
School of Computing
Queen's University
Kingston, ON, Canada
khandake@cs.queensu.ca

Wenjie Li
School of Computing
Queen's University
Kingston, ON, Canada
liwenjie@cs.queensu.ca

Sharief Oteafy
School of Computing
DePaul University
Chicago, IL, USA
soteafy@depaul.edu

Hossam Hassanein
School of Computing
Queen's University
Kingston, ON, Canada
hossam@cs.queensu.ca

***Abstract*—Information-Centric Networks (ICN) are aiming to shift the current host-oriented Internet model towards a content-centric one, by focusing on highly scalable and efficient content distribution and retrieval. Content caching is a fundamental building block in ICN, optimized to enable fast, reliable, and scalable content distribution and delivery. In this paper, we propose a novel utility value-based caching scheme, named *Max-Utility* for maximizing the aggregated utility-value of an *ICN cache service provider*. This novel approach considers attributes of both the content, and its producer, to determine the aggregated value, and builds on a dynamic caching algorithm that aims to maximize the aggregated utility value to guide cache placement and replacement decisions. Simulation results demonstrate that, *Max-Utility* outperforms current state-of-the art caching schemes by providing better caching utility while significantly eliminating caching redundancy and incurring less access delay to retrieve good quality contents across varying cache sizes and popularity skewness values.**

***Index Terms*—ICN caching, In-network caching, Utility Value-Based Caching, Caching heuristic, Value of Content.**

I. INTRODUCTION

The Internet has become a global infrastructure for the distribution of information with billions of connected devices and Exabytes (EB) of transferred data every month [1]. The pattern of Internet usage is increasingly becoming bandwidth intensive and Internet users are mainly interested in fast and reliable retrieval of information instead of identifying the particular host or server where the information is hosted from. Information-Centric Networks (ICN) have evolved into promising candidate for future Internet architecture as the current host-centric Internet architecture is inadequate to scale with the projected traffic demand and usage patterns [2]. Caching has become a fundamental architectural building block in ICN to enable fast, reliable, and scalable content distribution and delivery. Every network router in ICN has the capability to cache named contents and respond to requests for that content. ICN caching is named as in-network caching and ICN are typically considered as networks of caches [3].

While there is a considerable body of research work addressing cache placement and replacement issues in ICN [4]–[6], little attention is given to assigning value to the cache content while designing a caching policy in ICN for efficient cache utilization. Research investigating maximization of the cache utilities by assigning value to the cache contents can play an important role in designing efficient cache decision policies in ICN.

In this paper, our research objective is to maximize the cache utilities of an *ICN cache service provider* by maximizing the value of its cached contents. We define the term *ICN cache service provider* to represent an entity, owning a group of cache nodes or cache routers which aims to maximize its cache utilities by selecting and caching maximum valuable contents. We address two central research questions, first whether an *ICN cache service provider* can benefit from storing high-valued contents and second if yes, what would be the attributes for determining the value of contents? To address these research questions, our contributions from this work are threefold:

(1) We will define the attributes of content and content producer to determine the content value. (2) We will propose a novel utility value-based function that determines the value of content considering our defined attributes. (3) We will design, implement and evaluate a novel utility value-based caching algorithm, named *Max-Utility* that makes cache placement and replacement decisions to maximize the aggregated value of the contents to attain maximum benefits.

The remainder of this paper is organized as follows. Section II overviews the related research papers of ICN caching. Section III elaborates on our proposed system of value-based caching, describes the design principles of the proposed value-based utility function that determines content value and explains the *Max-Utility* caching algorithm which aims to maximize the aggregated caching utility value while making caching decisions. Section IV consists of the experiment set-up and performance evaluation results of *Max-Utility* scheme comparing it to other well-known caching schemes and we conclude in Section V with final discussions and our plans for future work.

II. LITERATURE REVIEW

There are many proposed caching schemes in ICN literature to design content placement and replacement policies and model the topologies of cache networks. Many schemes proposed their schemes based on content popularity [4]–[6], some schemes proposed caching policies based on the collaboration approach of the cache routers [5], [6], some schemes used network topology related metrics for selecting cache routers [7], [8] while others proposed schemes based on content delivery path for improving caching efficiency [4]–[6].

978-1-7281-0962-6/19/$31.00

Most of the caching schemes in ICN literature considered only the content popularity for content valuation while designing the cache decision policies [4]–[6]. Popularity of a content is highly correlated with the requesting frequencies for that content made by consumers. One of the most common idea of popularity-based caching schemes is to cache most popular contents at edge routers near consumers and gradually cache less popular contents at intermediate routers near the content producers aiming to increase cache hit rates, and reduce both the delay to retrieve requested content and producer load.

Several caching schemes selected specific routers in the network as cache routers, which have a greater probability of attaining higher number of cache hits compared to the other routers within the network. Several standard graph-centrality metrics are considered as the allocation criteria of the cache routers such as betweenness centrality measured by the number of times a router lies on the content delivery path between all pairs of routers in a network topology [7] or degree centrality (the number of links incident upon a router) [8].

Many studies investigated the effectiveness of collaboration among cache routers for the purpose of making caching decisions to improve caching efficiency [4]–[6]. Collaborative schemes reduce caching redundancy since the same content is not unnecessarily cached at multiple cache routers for collaborative decisions. Moreover, caching diversity is improved as diverse contents are cached by the cache routers resulting into minimized access latency for content retrieval and improved response time. Many studies also proposed Path-based schemes according to the location of cache routers with respect to the content delivery path from content producer to consumer and classified these schemes into two types: On-path or Off-path [4]–[6].

Maximizing caching utilities by cache content valuation has been overlooked in ICN literature. The work in [6] considered the age of content for content valuation, but again content popularity was used to define the content age. More comprehensive attempts were reported in [9], [10] for maximizing the caching utility, where the authors considered the delay, popularity and age parameters to select the content to be dropped while making cache replacement decisions only. But, these papers did not propose any cache content placement scheme for maximizing the caching utilities. Hence, it is very important to give immediate attention to the research investigating valuation of cache contents which can play an important role for maximizing caching benefits in ICN. In this regard, our research specifies the attributes to valuate content, proposes the value-based function that determines content value based on our defined attributes and designs and implements a value-based caching algorithm that makes cache placement and replacement decisions to maximize the caching utilities.

III. UTILITY VALUE-BASED CACHING SYSTEM

We propose our utility value-based caching algorithm *Max-Utility*, upon the most well-known and well-cited ICN architecture in the ICN research community, named Content-Centric Networks (CCN) [11]. In this section, first we describe our proposed system of maximizing value of cache contents, second we define our utility value-based caching function and finally we describe our proposed utility value-based caching scheme which aims to maximize the aggregated utility value of an *ICN cache service provider* while making caching decisions.

A. System Modelling

Our utility value-based caching system mainly focuses on the selection of the most valuable contents to be cached across all the cache routers inside the *ICN cache service* provider so that the aggregated caching utility value can be maximized. Our proposed system consists of three entities: Producers, Consumers and a single *ICN cache service provider.*

Content producers are network nodes that can publish named contents such as servers, tablets, sensors, RFID tags etc. In our system, multiple producers can produce the same content but even if the same content is produced by multiple producers, they are treated differently as the content is tagged and distinguished with its producer's reputation value. Our assumption matches with the settings of CCN architecture because each producer adds a unique prefix to the names of its produced contents. Content consumers are network nodes which subscribe to named content and can be personal computers, smart phones, servers, sensors, etc.

In our value-based system, *ICN cache service provider* works as a single administrative domain aiming to maximize its aggregated caching utility value. It consists of edge routers, intermediate routers and a central network manager. The consumers send their content requests to the edge routers and receive their requested contents from the edge routers. Consumers have no direct communication with the intermediate cache routers. The central network manager is connected to all cache routers for coordinating the dynamic shared information inside the *ICN cache service provider*. This central network component stores and supplies the necessary information to the cache routers for calculating dynamically updated utility value of contents. Our system uses the shortest-path routing scheme while generating a single content request forwarding path between each pair of edge router and the producer. Fig. 1 shows the framework of our proposed utility value-based caching system.

B. Deriving Utility Value-Based Caching Function

Unlike most of the existing works [4]–[6], along with content popularity, we consider two other key attributes of content and content producer, which can reflect much better prediction about the value of content. Inspired by the research conducted for sensor networks [12], we categorize our design attributes into two categories: cache content attributes and content producer attribute.

1) Attributes of Content to Derive Desirability of Content: Our proposed utility function calculates content desirability in terms of content popularity and number of instances or

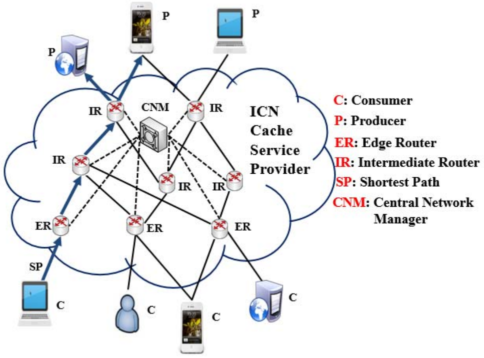


Fig. 1: Proposed framework of utility value-based caching system

replicas of content across all cache routers as follows. We determine the popularity of a content by the consumers requesting frequencies for that content. We define the popularity of a given content k at a cache router j by

$$Pop_{k,j} = \frac{Rq_{k,j}}{\sum\limits_{k \in \mathcal{K}} Rq_{k,j}} \tag{1}$$

where $Rq_{k,j}$ is the total number of requests for the content k received by the cache router j and K is the set of contents to be cached.

To determine the number of replicas of a content in the group or set of cache routers for assessing the content availability, our utility function follows a collaborative approach. We define the replica value of a content k at a cache router j with respect to the whole *ICN cache service provider* consisting of a set of cache routers J by

$$\sum_{j \in \mathcal{J}} Replica_{k,j} = \sum_{j \in \mathcal{J}} NumberofReplica_{k,j} \tag{2}$$

where $\sum\limits_{j \in \mathcal{J}} NumberofReplica_{k,j}$ is the total number of instances or replicas of the content k across the set of cache routers J.

2) Attributes of Content Producer to Derive Quality of Content: Quality of a content producer can significantly influence the value of its produced contents. We consider the reputation of a content producer to determine the quality of the content. The reputation value of content producer reflects the past reputation history of content producers based on the feedback of the consumers. In our utility function, we assume that the reputation values of the content producers are known to us. We rank the reputation values of the producers as *High* and *Low* and considers these two types of reputation values. We define the normalized reputation value of the producer of a content k as

$$RepPR'_k = \frac{RepPR_k}{\max\limits_{k \in \mathcal{K}}(RepPR_k)} \tag{3}$$

where $RepPR_k$ means the reputation value of the producer of content k and $\max\limits_{k \in \mathcal{K}}(RepPR_k)$ means the maximum reputation value among the set of reputation values.

Finally, our value-based utility function defines the utility value of a content k at a cache router j as

$$Value_{k,j} = \lambda.Pop_{k,j} + \beta.\frac{1}{\sum\limits_{j \in \mathcal{J}} Replica_{k,j}} + \gamma.RepPR'_k \tag{4}$$

where λ, β and γ are tuning parameters and sum up to 1. So, the utility value-based caching function determines the content value as a weighted sum of the normalized attribute values determining the desirability and quality of contents. Assigning the values of the tuning parameters is a design decision and depending on our designed system, we adjusted or adapted these tuning parameters.

C. Max-Utility: Utility Value-Based Caching Algorithm

Max-Utility caches and replaces contents based on the objective of maximizing the aggregated caching utilities while reducing the caching redundancy and accommodating as many diverse and high quality contents as possible inside the *ICN cache service provider.*

Algorithm 1 *Max-Utility*

```
Initialize Set of Contents $K$; Set of Cache Routers $J$; Set of Consumers $C$; Set of Content Producers $PR_k$,$k \epsilon K$; Set of Reputation values $RepPR'_k$,$k \epsilon K$.
for all $k \epsilon K$ do
  for all $j \epsilon J$ do
    if $j$ has free space then
      Cache $k$ in $j$ and calculate $Value_{k,j}$
    else if $\sum_{j \in \mathcal{J}} Replica_{k,j} = 0$ then
        Drop $LUVC$ and cache $k$ in $j$
      else
        Calculate $Value_{k,j}$
        if $Value_{k,j}$ >value of $LUVC$ in $j$ then
          Drop $LUVC$ and cache $k$ in $j$
        else
          Do not cache and forward content $k$
        end if
      end if
    end if
  end for
end for
```

Each cache router along the content delivery path makes its caching decision independently based on its own calculated utility values of contents where the utility values of contents are calculated using (4). The central network manager (depicted in Fig.1) keeps track and stores the number of replicas of cached contents whenever any cache placement or replacement inside the *ICN cache service provider* occurs. The cache routers collect these dynamically updated content replica information requiring to calculate the utility values from the central manager. Hence, *Max-Utility* enables the cache routers to coordinate their caching decisions in terms of content availability without explicit information exchange with one another. Because of this coordination, the cache routers are capable of removing caching redundancy by controlling the number of replicas of cache contents while effectively utilizing the available cache spaces.

In the algorithm, lines 4-5 define the cache placement decisions where there is available space in a cache router to cache the requested content. Lines 6-15 define the cache placement and replacement decisions where there is no available space in a cache router to cache the requested content. In this situation, caching decisions are made based on the conditions of whether the requested content has any replica in the *ICN cache service provider* or not. If there is no replica of the requested content, the least utility valued cached content ($LUVC$) in the cache router is replaced to make space to cache the requested content. But if there is at least one replica of the requested content, either the $LUVC$ is replaced to make space and the requested content is cached if the requested content can achieve higher utility value than the utility value of the $LUVC$ or the requested content is not cached either if the requested content has less or has equal utility value to the $LUVC$.

IV. PERFORMANCE ASSESSMENT

In this section, performance of the *Max-Utility* scheme is evaluated under an evaluation environment which resembles the real network scenario. Simulation results show that *Max-Utility* achieves the design objective and performs better compared to other well-known caching schemes for various performance metrics under various experimental settings.

A. Simulation Environment

We use BRITE (Boston university Representative Internet Topology gEnerator) [13] to generate a random realistic network topology and NS-3 based simulator ndnSIM [14] for our simulation. Each producer produces 1000 contents where the size of each content is 1 KB. Arrival of content requests follows a Poisson distribution process and requests are generated according to well-known *Zipf* content popularity distribution law [15]. We evaluate the performance of *Max-Utility* scheme in comparison to baseline scheme Cache Everything Everywhere (*CEE*) [11], the well performing probabilistic scheme *Prob(0.3)* [5] and well-cited popularity-based scheme *ProbCache* [16]. Table I. lists the default parameter values of our simulation environment.

TABLE I: DEFAULT SIMULATION PARAMETERS

Simulation Parameters	Values
Number of Producers	16
Number of Consumers	92
Number of Edge routers	23
Number of Intermediate routers	11
Total Number of Contents	16000
Cache Capacity in Percentage	30%
Popularity Skewness factor α	0.8
Number of requests per second	10

B. Performance Metrics

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

1) Diversity Ratio: We define the diversity ratio as the ratio of the total number of unique or distinct contents stored or cached across all the cache routers without any repetition to the total number of cached contents in the whole network.

2) Access Delay : We measure the access delay as the ratio of the total time lapsed to retrieve the requested contents from the caches to the total number of the contents retrieved from the caches in the unit of Microsecond (µs). We focus on the access delay to retrieve *High* reputed contents only to assess our contribution of considering the quality attribute of content (reputation value of producer) for content valuation.

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

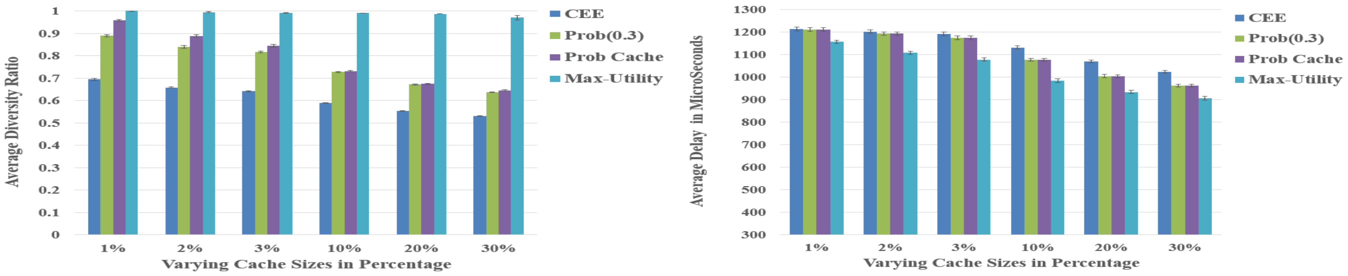
C. Performance Analysis

We evaluate the effect of cache capacity percentage and popularity skewness parameter upon the three performance metrics for performance analysis of the schemes. We consider 95% confidence interval for the performance analysis.

1) The Impact of Cache Capacity Percentage: Cache capacity percentage is defined as the ratio of the total cache size of all cache routers over the total content size in percentage. While varying cache capacity, we consider homogeneous cache allocation settings for performance analysis.

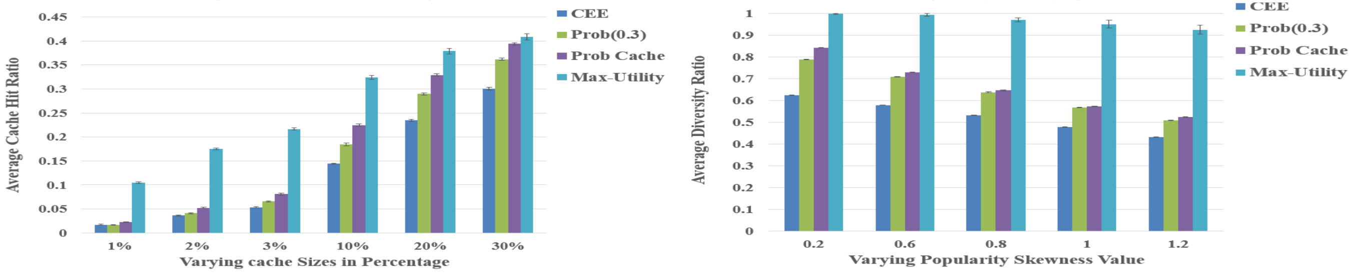
Fig. 2a depicts that, *CEE* produces the least average diversity ratio among all caching schemes as it unnecessarily caches multiple replicas of the same content resulting into huge caching redundancy. *ProbCache* and *Prob (0.3)* achieve much higher diversity ratio comparing to *CEE* as *ProbCache* allocates the available cache capacity fairly among the different content flows and *Prob (0.3)* caches content in a probabilistic way considering content popularity.

Max-Utility achieves the highest average diversity ratio among all for all test cache sizes while having significant performance improvements compared to others. This is because, *Max-Utility* not only considers popular contents but also considers less popular scarce contents and contents having a *High* reputation value while caching to maximize the aggregated caching utility value. As a result, *Max-Utility* prioritizes to cache diverse contents in the whole *ICN Cache Service Provider* while greatly reducing caching redundancy by limiting the number of replicas of cached contents. Fig. 2a shows that, for 30% cache size, *Max-Utility* achieves 50% and 52% higher diversity ratio compared to *ProbCache* and *Prob(0.3)*. All schemes demonstrate the same trend of producing lower diversity ratio with increasing cache size because multiple replicas of same content get cached with larger cache sizes. Although the diversity ratio deteriorates significantly for all other schemes, *Max-Utility* remains almost stable with the increasing cache sizes ensuring caching redundancy elimination. For example, the diversity ratio for *ProbCache* and *Prob(0.3)* reduce to 13% and 14% when the cache size increases from 10% to 30%. However, *Max-Utility* demonstrates steady performance such as diversity ratio decreases to only 2% when cache size increases from 10% to



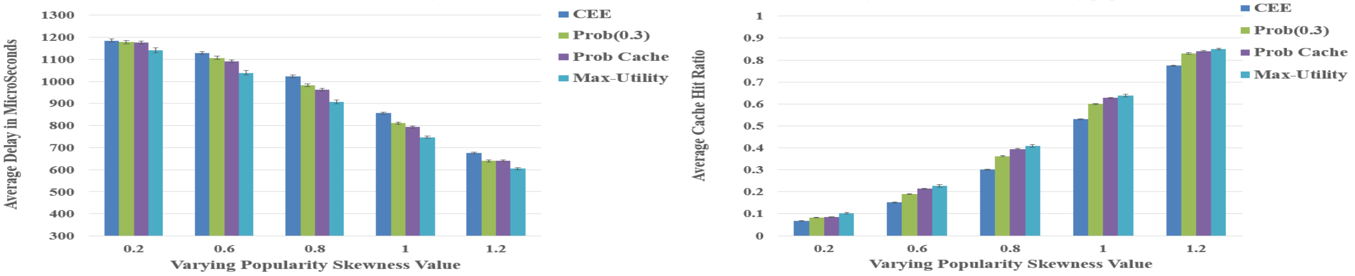
(a) Average diversity ratio for varying cache sizes

(b) Average delay for varying cache sizes



(c) Average cache hit ratio for varying cache sizes

(d) Average diversity ratio for varying popularity skewness



(e) Average delay for varying popularity skewness

(f) Average cache hit ratio for varying popularity skewness

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

30%. The reason behind of this steadiness is, *Max-Utility* enables the cache routers to limit the number of replicas of cached contents in the whole network in a coordinated way even for popular contents and larger cache capacities.

We evaluate the average delay to access *High* reputed contents only as our interest focuses only on the required delay to retrieve good quality contents. Fig. 2b demonstrates that, *CEE* incurs the largest average delay to access *High* reputed contents as it caches contents indiscriminately without considering any content attribute. *ProbCache* and *Prob(0.3)* both outperform *CEE* as *ProbCache* and *Prob(0.3)* consider content popularity to cache contents and *ProbCache* ensures fair multiplexing among different content flows while sharing the cache capacity resulting in a reduced number of hops to retrieve contents. *Max-Utility* not only prioritizes caching popular and unpopular scarce contents, but also caches good quality contents having *High* reputation. As a result, *Max-Utility* incurs the least delay to access *High* reputed contents among all schemes such as it outperforms *ProbCache* and *Prob (0.3)* by 6% for 30% cache size. The average delay for all schemes is reduced with the increment of cache size because the increased available cache spaces can cache a higher number of contents incurring lower access delay.

Fig. 2c depicts that, *ProbCache* and *Prob(0.3)* attain higher cache hit ratio compared to *CEE*. This is because *Prob(0.3)* caches contents based on content popularity and *ProbCache* manages cache resources efficiently by assigning cache weight factors to increase the probability of cache hits. *Max-Utility* produces the highest cache hit ratio among all such as producing 44% and 76% more cache hit ratio than *ProbCache* and *Prob(0.3)* for 10% cache size. The significance of performance variances between *Max-Utility* with *ProbCache* and *Prob(0.3)* decreases as the cache size increases. This is due to the fact that, popularity-based schemes get the opportunity to cache more replicas of popular contents along with increased cache capacities but at the expense of having less diverse and good quality contents. Even though, *Max-Utility* considers content popularity, it also caches diverse and good quality contents that reduces the cache hit ratio for larger cache sizes. Therefore, *Max-Utility* efficiently utilizes caching resources by greatly ensuring caching diversity and availability of high quality contents as well as demonstrates acceptable cache hit ratio even for larger cache sizes.

2) The Impact of Popularity Skewness: We evaluate the performance of the caching schemes by controlling the popularuty skewness parameter α in the *Zipf* popularity distribution where α captures the degree of concentration of content requests.

Fig. 2d reveals that, *Max-Utility* produces the highest average diversity ratio while generating significant performance variances compared to all other schemes across all α values such as 66% and 68% over *ProbCache* and *Prob(0.3)* respectively for α=1. This significant superior performance is attributed to the fact that; *Max-Utility* is capable of restricting the number of replicas of cached contents even when it receives highly skewed content requests. A similar trend of reducing diversity ratio because of the increasing α can be observed for all schemes.This is because, users requests concentrate on a smaller set of popular contents for larger values of α. When α increases to 1.2 from 0.2, the diversity ratio of *CEE*, *ProbCache* and *Prob(0.3)* significantly decrease to 44%, 55% and 60% because of caching multiple replicas of the highly skewed popular contents. However, *Max-Utility* shows robust performance against varying α such as maximum 8% performance degradation among all test cases. This is because, *Max-Utility* ensures caching diversity by limiting the number of replicas of cached contents even for the smaller set of highly popular contents as well as caching scarce and high quality contents.

With the increment of α value, all schemes tend to incur less average delay to access contents. This is because, for larger α, maximum users' requests focus only on small number of *High* reputed contents which generates more cache hits and eventually incurs less access delay. Fig. 2e shows that, *Max-Utility* incurs the least delay among all schemes across all test cases such as 8% and 6% less delay over popularity-based *Prob(0.3)* and *ProbCache* respectively even for high α value (α=1). This is bacause, *Max-Utility* ensures a well balanced caching of high quality, popular and diverse contents to maximize aggregated utility value.

Fig. 2f depicts that, *Max-Utility* generates the highest cache hit ratio among all schemes across all α values. Even for large α value such as 1, *Max-Utility* outperforms the popularity-based schemes *ProbCache* and *Prob(0.3)* by 2% and 6% respectively. Although the performance improvement of *Max-Utility* in comparison to the popularity-based schemes is not significant as popularity-based schemes prioritize to cache frequently requested contents, *Max-Utility* is able to produce acceptable cache hit ratio while maintaining diversity and caching high quality contents across all α values.

V. CONCLUSION

In this paper, our proposed *Max-Utility* scheme fulfills the main research objective of maximizing aggregated caching utility value because of its caching criteria based on content popularity, diversity and reputation. *Max-Utility* demonstrates significant performance superiority and robustness while removing caching redundancy compared to very well-known caching schemes as it can strictly limit the number of replicas of cached contents even for very skewed content popularity distribution having large cache capacity. In addition, *Max-Utility* requires the least delay to retrieve *High* reputed contents as it prioritizes caching high quality contents. Although *Max-Utility* efficiently utilizes the caching resources by ensuring caching diversity and availability of good quality contents, it also demonstrates acceptable cache hit ratio even for large cache sizes and large popularity skewness value.

In the future, we plan to propose an actual reputation calculation scheme and also to consider valuation of cache nodes for achieving further improved cache utilization.

REFERENCES

[1] *Cisco visual networking index: forecast and methodology, 2017-2022*, CISCO White papers, February 27, 2019.

[2] J. Pan, S. Paul, and R. Jain, "A survey of the research on future Internet architecture," *IEEE Communications Magazine*, vol. 49, no. 7, pp. 26–36, July, 2011.

[3] G. Carofiglio, M. Gallo, L. Muscariello, and D. Perino, "Modeling data transfer in content-centric networking," in *Proceedings of the 23rd International Teletraffic Congress (ITC 23)*, San Francisco, USA, September 6, 2011, pp. 111–118.

[4] S. Guo, H. Xie, and G. Shi, "Collaborative forwarding and caching in content centric networks," in *Proceedings of the 11th International IFIP TC 6 Networking Conference*, Prague, Czech Republic, May, 2012, pp. 41–55.

[5] K. Cho, M. Lee, K. Park, T. T. Kwon, Y. Choi, and S. Pack, "Wave: Popularity-based and collaborative in-network caching for content oriented networks," in *IEEE International Conference on Computer Communications Workshops(INFOCOM WKSHPS)*, Orlando, FL, March, 2012, pp. 316–321.

[6] Z. Ming, M. Xu, and D. Wang, "Age-based cooperative caching in information-centric networks," in *Workshop on Emerging Design Choices in Name-Oriented Networking*, China, Shanghai, August, 2012, pp. 1–8.

[7] W. K. Chai, D. He, I. Psaras, and G. Pavlou, "Cache "less for more" in information-centric networks (extended version)," *Computer Communications*, vol. 36, no. 7, pp. 758–770, April, 2013.

[8] S. Eum, K. Nakauchi, Y. Shoji, N. Nishinaga, and M. Murata, "CATT: Cache aware target identification for ICN," *IEEE Communications Magazine*, vol. 50, no. 12, pp. 60–67, December, 2012.

[9] F. M. Al-Turjman, A. E. Al-Fagih, and H. S. Hassanein, "A value-based cache replacement approach for ICN," in *IEEE 38th Conference on Local Computer Networks Workshops (LCN Workshops)*, Sydney, NSW, Australia, October, 2013, pp. 874–881.

[10] F. M. Al-Turjman, M. Imran, and A.V.Vasilakos, "Value-based caching in information-centric wireless body area networks," *SENSORS*, vol. 17, no. 1, p. 181, 2017.

[11] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, "Networking named content," in *Proceedings of the 5th ACM International Conference on Emerging Networking Experiments and Technologies (CoNEXT 2009)*, Rome, Italy, December, 2009, pp. 1–12.

[12] C. Bisdikian, L. M. Kaplan, and M. B. Srivastava, "On the quality and value of information in sensor networks," *ACM Transactions on Sensor Networks*, vol. 9, no. 4, July, 2013.

[13] A. Medina, A. Lakhina, I. Matta, and J. Byers, "Brite: An approach to universal topology generation," in *9th IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems*, Cincinnati, OH, USA, August, 2001, pp. 346—-353.

[14] A. Afanasyev, I. Moiseenko, and L. Zhang, "ndnSIM: NDN simulator for NS-3," NDN, Technical Report, NDN-0005, 2012, October, 2012.

[15] L. Breslau, P. Cao, L. Fan, G. Phillips, and S. Shenker, "Web caching and zipf-like distributions: evidence and implications," in *IEEE International Conference on Computer Communications (INFOCOM)*, New York, NY, USA, March, 1999, pp. 126–134.

[16] I. Psaras, W. K. Chai, and G. Pavlou, "Probabilistic in-network caching for information-centric networks," in *Proceedings of the second edition of the ICN workshop on Information-centric networking*, Helsinki, Finland, August, 2012, pp. 55–60.