A POPULARITY BASED CACHING STRATEGY FOR THE FUTURE INTERNET

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ABSTRACT

Information-Centric Networking (ICN) is an attractive network model receiving increasing consideration by the research community because of its inspiring features. To better manage the Internet usage move from host-centric communication to receiver-driven content retrieval, revolutionary ICN architectures have been proposed. A distinguished characteristic of these innovative architectures is to provide ubiquitous and transparent in-network caching to enhance network resource utilization and accelerate content dissemination. With the exponential increase of Internet traffic, the issue of content storage is a growing concern in ICN. In this paper, we present a caching strategy that considerably increases cache hit rate and reduces stretch ratio, which are the most important metrics in the evaluation of ICN caching. Through extensive simulations, it is shown that our proposed work is a favorable and realistic contribution for the standardization exercise of data caching for achieving accurate and valid network performance in the future Internet.

Keywords— Future Internet, ICN, CPCE, caching, content popularity

1. INTRODUCTION

Toward the start of the Internet, clients were scholastic in nature, for the most part inspired by mail trade and document exchanges [1]. Moreover, sharing of resources was a vital issue that forced significant difficulties with respect to correspondence among end hosts [2]. However, since the last decade the Internet popularity has brought about the activity on the Internet to become significantly reliable [3]. Information sharing and dissemination, for example, scholastic, social, and business, over the Internet is the major cause of the Internet growth. Distribution of named data is a noteworthy application in the existing Internet. Along with online content dissemination, other distribution technologies, for instance, Content Distribution Network (CDN) and Peer-to-Peer (P2P) communication have been well developed and are advancing the communication framework for getting contents by name, regardless of the location of the main server [3,4]. Keeping in mind the end goal to react to expanding activity volume in the existing Internet for applications are utilized that use caching and content distribution and replication in various particular ways [1].

It is therefore important to deduce that the existing Internet architecture can be considered as a restricting factor of the current Internet growth and the design of new applications. To add more, several studies, for example, [5,6] have shown that the advancement of the Internet design is driven by incremental and responsive increases and therefore change in the architecture is indispensable. In this manner, globally the research community is working towards understanding the architectural challenges to decide the rule that will drive the future Internet design. Numerous research projects (e.g., US NSF GENI [7], EU-FIA [8], and AsiaFI [9]) have been funded in the last few years to define the existing limitations and future needs for the Internet architecture, and therefore Information-Centric Networking (ICN) [1,10–12]] is one of the considerable results of these research activities. ICN has different modules, such as naming, routing, mobility, security, and caching. However, the majority of our research community is attracted by the caching module because of the limited cache size of network nodes. In ICN caching, the network nodes have the ability to cache a content locally once it is downloaded by the end users. Therefore, if new requests arrive for the same content, they are satisfied locally rather than contacting the original server.

2. PROBLEM DEFINITION

In ICN, the contents are cached locally by network nodes (e.g., routers). These routers may pose strict constraints with respect to cache management. Thus management becomes a critical issue for content caching and caching strategies. When the network becomes stable and the router's cache overflows, a replacement policy, such as Least Recently Used (LRU), Least Frequently Used (LFU), or Random policy is used to evict one of the cached contents to make room for the new arrived one. However, besides the replacement policy, content caching is the main issue, i.e., which content should be cached and at which location it needs to be stored so that to efficiently utilize memory and bandwidth consumption. For that, many strategies have been proposed, for example, Cache Everything Everywhere (CEE) [2] - the default ICN strategy, Cache Less for More [13] – caches contents at a node which has the maximum betweenness centrality, Probabilistic Caching (ProbCache) [14] – stores contents near the users, Cooperative In-network Caching (CIC) [15] - where the content is divided into different chunks and cached at more than one node, Cache Aware Target Identification (CATT) [16,17]- where the content is cached at a single node on the publisher-

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This research is supported by the Ministry of Higher Education Malaysia Research Grant Scheme with reference number FRGS/UUM/13258.

subscriber path, Optimal Cache Placement based on Content Popularity (OCPCP) [18] - where the popularity of incoming content is calculated on the basis of cached contents and the new content is cached based on its popularity value, Network Coding based Cache Management (NCCM) [19] - jointly considers content routing and caching strategy through Linear Network Coding (LNC), WAVE [20] - caches contents based on their access count, Most Popular Caching (MPC) [21] – caches contents based on their popularity values, Dynamic Fine-Grained Popularity-based Caching (D-FGPC) [22] – the modification of MPC, however, unlike MPC in FGPC the threshold value for content caching is changed dynamically based on content popularity values. Moreover, some experimental assessment of cache management in ICN are presented in [23]. Some other research on caching has been proposed in [24–31].

All of the mentioned strategies investigated only one aspect of the caching (i.e., either content placement or replacement), and none of them covers both aspects. Therefore, a flexible caching strategy is needed so that to place the contents at the best possible position and (on the arrival of a new content) replace one of the cached contents. Actually, the contents are cached in the random access memory (RAM) while the available static random access memory (SRAM) or dynamic random access memory (DRAM) is limited in the size. The DRAM, which is a volatile memory and needs to be refreshed regularly [32] is currently available at 10GB maximum [33, 34]. In other words, cache size is the biggest constraint in ICN caching. However, in most of the existing available strategies, the maximum cache space is occupied. In addition, if the memory of a router becomes full and a new content arrives, none of the existing strategies has any policy for that but simply replaces one of the cached contents by the new arrived content. This is achieved using a replacement policy, i.e., either Least Recently Used (LRU) or Least Frequently Used (LFU). As LRU and LFU replace the content based on the access time, the replaced content may be very popular and therefore the subsequent requests for the same content will be forwarded to the server. In this way, extra content retrieval delay may occur and thus maximum bandwidth is utilized.

To overcome such problems, we propose in this paper a new caching strategy, Cache Popular Content Everywhere (CPCE), which caches popular contents on all network nodes on the publisher-subscriber path. The CPCE strategy is explained in the following section.

3. PROPOSED STRATEGY

The proposed CPCE caches contents at all *on-path* routers available all the way from publisher to subscriber, as in CEE. However, the difference between our proposed caching strategy (CPCE) and the CEE is such that CEE caches every incoming content while CPCE caches contents once their popularity reaches a specified threshold value. In other words, a content is cached when its popularity reaches the threshold value in the Request Table (RT) - a table which locally calculates popularity values based on content requests, that is, if(C$_p$ $>=$ V_t), where C$_p$ is the content popularity and V_t is the threshold value. The V_t is kept 10 in the CPCE to avoid flooding as all incoming contents have the C$_p$ value of 1. Therefore, a content in the CPCE is only considered popular when its C$_p$ reaches 10. Furthermore, if the cache of all *on-path* routers overflows and a new content arrives, the CPCE uses the Least Recently Used (LRU) policy to replace one of the cached contents from each router except that the router which has the maximum outgoing interfaces, denoted by R_{max}, to accommodate the new arrived content. The reason to leave the content at the R_{max} is to avoid maximum bandwidth utilization, as majority of the content requests pass through that router. However, the question arises of how long R_{max} will keep contents as the cache of that may also overflow. Therefore, in case of cache overflows at R_{max}, on the arrival of a new content, LRU policy is used to evict one of the cached contents accessed least recently. The evicted content is cached at the underlying router, denoted by UR_1 (R2 in Figure 1), placed immediately below R_{max}. Furthermore, if the cache of UR_1 is also full then the Random policy is applied here to accommodate the content coming from R_{max}. The purpose of using the Random policy is to avoid searching overhead for content replacement as other replacement policies, e.g., LRU, take some time to find the contents based on their access time. Here the replaced content from UR_1 is moved to the next down cache router, i.e., UR_2, and the same procedure is followed until the content reaches the router placed near the subscriber, i.e., UR_n.

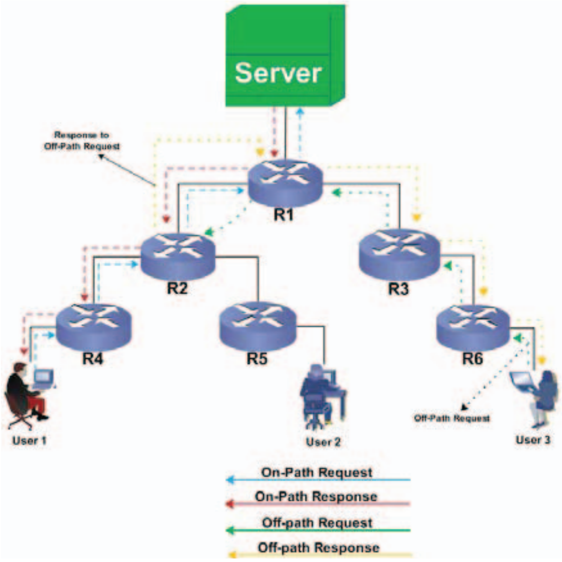

Figure 1. An example topology

As the LRU does not care of content popularity and it is deployed at R_{max}, it may also evict the most popular content. Now, if a new content request arrives for the evicted popular content from *off-path*, it may also go through R_{max}; however, if hit does not occur at R_{max}, it can be found from RT that the requested content is available at the UR_i.

Hence, even the CPCE is designed for *on-path* caching but *off-path* nodes can also benifit from its versatility.

4. SYSTEM MODEL

Cache management in ICN may acquire the Hypergraph [35] characteristics, where an association is obtained between on-path routers and the original server. Our proposed CPCE strategy follows graph theory, called Hypergraph [35–37]. Let a network with routers (V) and connections (E) be represented as a Hypergraph (H) [35–38], such as: H=(V,E), where V=$\{v_1, v_2, ..., v_n\}$, and E=$\{e_1, e_2, ..., e_m\}$. Therefore, the network relationship can be defined as R=$\{r_1, r_2, ..., r_n\}$, where r_i is the i^{th} router and n is the number of total routers. Similarly, the connections denoted by E is such that E=$\{e_1, e_2, ..., e_m\}$, where e_j is the j^{th} connection and m is the number of total connections.

The GEANT topology is used for the validation of the CPCE strategy using Hypergraph, [39]:

A topology T, containing R routers and E connections as

$$T = \{R, E\} \tag{1}$$

with the objective as GEANT maintains the ICN formulation as

$$T^{'} = \{R, E\} \tag{2}$$

as GEANT consists of 22 nodes (see Figure 2), therefore

$$R = \sum_{i=1}^{22} (r_i), \tag{3}$$

where r represents the number of nodes (routers), and as the number of connections (E) in GEANT topology is 38, therefore

$$E = \sum_{j=1}^{38} (e_j). \tag{4}$$

Due to the Internet heterogeneity, each router has a connection pair e_j, such as: [$e_1 = \{r_0, r_1\}$, $e_2 = \{r_1, r_2\}$, $e_3 = \{r_2, r_3\}$, $e_4 = \{r_3, r_4\}$, $e_5 = \{r_3, r_5\}$, $e_6 = \{r_5, r_6\}$, $e_7 = \{r_6, r_7\}$, $e_8 = \{r_7, r_8\}$, $e_9 = \{r_8, r_9\}$, $e_{10} = \{r_9, r_{10}\}$, $e_{11} = \{r_{10}, r_{11}\}$, $e_{12} = \{r_{11}, r_{12}\}$, $e_{13} = \{r_4, r_{12}\}$, $e_{14} = \{r_{12}, r_9\}$, $e_{15} = \{r_{12}, r_5\}$, $e_{16} = \{r_5, r_{13}\}$, $e_{17} = \{r_5, r_{14}\}$, $e_{18} = \{r_{13}, r_{14}\}$, $e_{19} = \{r_{14}, r_{15}\}$, $e_{20} = \{r_{14}, r_{16}\}$, $e_{21} = \{r_{16}, r_{17}\}$, $e_{22} = \{r_{17}, r_1\}$, $e_{23} = \{r_{17}, r_{15}\}$, $e_{24} = \{r_{17}, r_{18}\}$, $e_{25} = \{r_{18}, r_{14}\}$, $e_{26} = \{r_{18}, r_{19}\}$, $e_{27} = \{r_{18}, r_{20}\}$, $e_{28} = \{r_{19}, r_{20}\}$, $e_{29} = \{r_{20}, r_{21}\}$, $e_{30} = \{r_{21}, r_{14}\}$, $e_{31} = \{r_{21}, r_0\}$, $e_{32} = \{r_{21}, r_4\}$, $e_{33} = \{r_4, r_{18}\}$, $e_{34} = \{r_4, r_7\}$, $e_{35} = \{r_4, r_{15}\}$, $e_{36} = \{r_{15}, r_{12}\}$, $e_{37} = \{r_{15}, r_1\}$, $e_{38} = \{r_1, r_3\}$].

Thus by the definition of Hypergraph, directed and undirected connections are achieved. In Figure 2, r_0 and r_1 have a direct connection, whereas r_0 and r_3 have an undirect connection, therefore, it is generalized in the GEANT order that r_i,r_i+1= direct, otherwise, the connection is undirect .

In the case of ICN, a router represents the overall connectivity, i.e., intersection and inter-connectivity. Hence a router's degree can be represented as [39]:

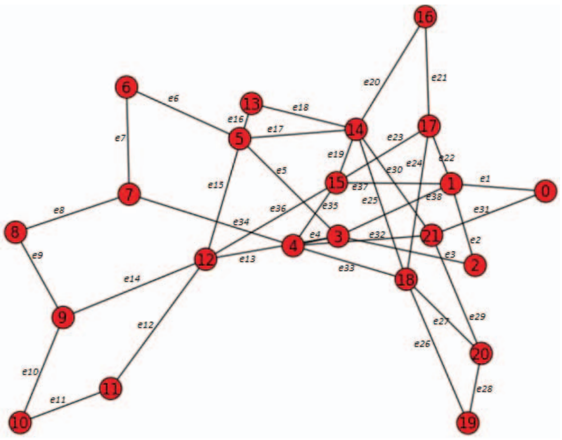

Figure 2. GEANT topology

$$d_r = \{In - degree + Out - degree\} \tag{5}$$

For example, in Figure 2 $d(r_4)$= 6 and $d(r_{14})$= 6 for 6 inter-connected routers on the edge.

According to the definition of the graph, the maximum degree of a network G is represented by ΔG.

To prove our model using GEANT topology, the maximum router degree is ΔT =6.

Therefore, the overall router degree, which is defined as maximum cache capacity of ICN router is given by

$$\Delta T = \sum_{i=1}^{n} (r_i). \tag{6}$$

To know the idea of ICN routers and connections relationship, assume the routers' membership in T, as described in [35, 39], if r_i represents routers and C_i the cache size, it implies that each router r_i can cache a content. Then the cache size of router r_i can be

$$C_{size} = \sum_{i=1}^{n} (C_i). \tag{7}$$

This develops a network topology T with routers and connections as

$$T = \{r_1, r_2, ..., r_n\}, \tag{8}$$

where $r \epsilon C$.

Table 1. Simulation Scenario.

Cache Size	1GB-10GB
Catalog Size	10^8
Zipf probability (α)	0.7, 1.0
Topology	GEANT and DTelekom
Social Network Topology	Facebook [40–42]
Simulator	SocialCCNSim [43, 44]
Simulation Runs	10 times

5. ANALYSIS

To know the accuracy of the system model and the simulation, the simulations are performed in SocialCCNSim [43] - ICN caching simulator, according to the parameters presented in Table 1, while the analysis is done in Maple 18 for cache hit according to the parameters presented in Tables 2 and 3. For the analysis of cache hit, we consider a real Facebook topology [40–42] which consists of 4,039 nodes. We assume that each node in the network is placed at a constant distance: in our assumption, this distance is 25 meters. Each time when a content is downloaded, the hop decrement increases 100 hops. This assumption is made on the basis of our ordinary topology in Figure 1, where initially a subscriber is 4 hops away (on any path) from the node (i.e., Server) having the desired content. As hit occurs and the content popularity reaches the threshold value (i.e., 10), it is cached at all *on-path* routers. However, according to our proposed strategy, the content may be evicted from all routers (UR_1 to UR_n) but it will stay at the router having maximum outgoing interfaces (Router R1 in the given figure), which is 3 hops away from the user(s).

When $0 < \alpha < 1$, the asymptotic cache hit ratio, H_c, is calculated as [45, 46]:

$$H_c = C^{1-\alpha} \tag{9}$$

where *C* is the cache size that caches chunks (each chunk is of 10MB size) and α=0.7. Looking at the analysis and simulation results, presented in Table 2, the average result of analysis is 16% while it is 14.3% for simulation. The average difference is 1.7% and hence the accuracy is 98.3% . The resultant graph is shown in Figure 3(a). The same variables, i.e., cache size and chunk size, are used for the scenario when α=1.0. Now, if α=1.0, the asymptotic cache hit ratio, H_c, is calculated as [45, 46]:

$$H_c = lnC. \tag{10}$$

The analysis and simulation results are presented in Figure 3(b) and Table 3. The average analysis and simulation results are 37.6% and 36.1% , respectively. The average difference is 1.5% and therefore the accuracy is 98.5% . It is observed that when the cache size is small then the difference of analysis and simulation results (with α=1.0) is high, however, with the increase of cache size this difference approaches 0.

Similarly, for the analysis of stretch results, we consider the same scenario with a real Facebook topology [40–42]. The numerical results can be calculated as [47]:

$$S = \frac{\alpha n}{2\gamma} \tag{11}$$

where *S* represents the stretch, *n* is the total number of network nodes, γ is the distance between two hops, and α is the Zipf probability parameter, such that $0 < \alpha < 1$.

In addition, the numerical results for α=1.0 can be calculated as:

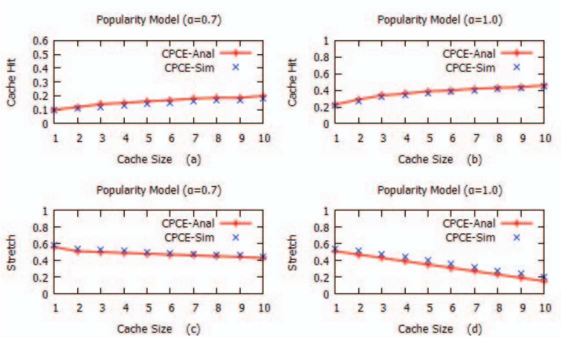

Figure 3. CPCE analysis vs. simulation

Table 2. Cache Hit: Analysis vs. Simulation with $\alpha = 0.7$ and Chunk Size 10MB.

Cache Size	Chunk	Anal	Sim	Difference
1	$1(10^2)$	0.10	0.10	0.00
2	$2(10^2)$	0.12	0.11	0.01
3	$3(10^2)$	0.14	0.12	0.02
4	$4(10^2)$	0.15	0.13	0.02
5	$5(10^2)$	0.16	0.14	0.02
6	$6(10^2)$	0.17	0.15	0.02
7	$7(10^2)$	0.18	0.16	0.02
8	$8(10^2)$	0.19	0.17	0.02
9	$9(10^2)$	0.19	0.17	0.02
10	$10(10^2)$	0.20	0.18	0.02

Table 3. Cache Hit: Analysis vs. Simulation with $\alpha = 1.0$ and Chunk Size 10MB.

Cache Size	Chunk	Anal	Sim	Difference
1	$1(10^2)$	0.23	0.22	0.01
2	$2(10^2)$	0.29	0.27	0.02
3	$3(10^2)$	0.34	0.32	0.02
4	$4(10^2)$	0.36	0.34	0.02
5	$5(10^2)$	0.39	0.37	0.02
6	$6(10^2)$	0.40	0.39	0.01
7	$7(10^2)$	0.42	0.40	0.02
8	$8(10^2)$	0.43	0.42	0.01
9	$9(10^2)$	0.44	0.43	0.01
10	$10(10^2)$	0.46	0.45	0.01

$$S = \frac{\alpha n}{2\gamma} - (D + h) \tag{12}$$

where *n* is the number of total network nodes, γ is the distance between two hops, *D* is the hop decrement, and *h* is a constant. We assume that *D*=γ and the value of *h*=4. This assumption is based on our ordinary proposed topology, shown in Figure 1. The achieved analysis results are presented in Figure 3(c) and Table 4 for α=0.7, and Figure 3(d) and Table 5 for α=1.0. The average difference in α=0.7 is 2.2% while it is 4.8% when α=1.0.

Table 4. Stretch: Analysis vs. Simulation with $\alpha = 0.7$ and Chunk Size 10MB.

Cache Size	Chunk	Anal	Sim	Difference
1	$1(10^2)$	0.56	0.58	0.02
2	$2(10^2)$	0.51	0.54	0.03
3	$3(10^2)$	0.50	0.53	0.03
4	$4(10^2)$	0.49	0.52	0.03
5	$5(10^2)$	0.48	0.50	0.02
6	$6(10^2)$	0.47	0.49	0.02
7	$7(10^2)$	0.46	0.48	0.02
8	$8(10^2)$	0.45	0.47	0.02
9	$9(10^2)$	0.44	0.46	0.02
10	$10(10^2)$	0.43	0.44	0.01

Table 5. Stretch: Analysis vs. Simulation with $\alpha = 1.0$ and Chunk Size 10MB.

Cache Size	Chunk	Anal	Sim	Difference
1	$1(10^2)$	0.51	0.54	0.03
2	$2(10^2)$	0.47	0.52	0.05
3	$3(10^2)$	0.43	0.48	0.05
4	$4(10^2)$	0.39	0.44	0.05
5	$5(10^2)$	0.35	0.40	0.05
6	$6(10^2)$	0.31	0.36	0.05
7	$7(10^2)$	0.27	0.32	0.05
8	$8(10^2)$	0.23	0.28	0.05
9	$9(10^2)$	0.19	0.24	0.05
10	$10(10^2)$	0.15	0.20	0.05

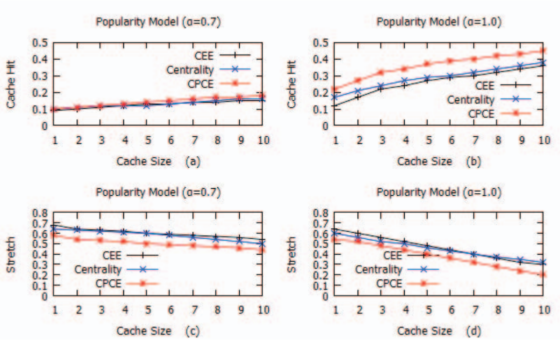

Figure 4. Result on GEANT topology

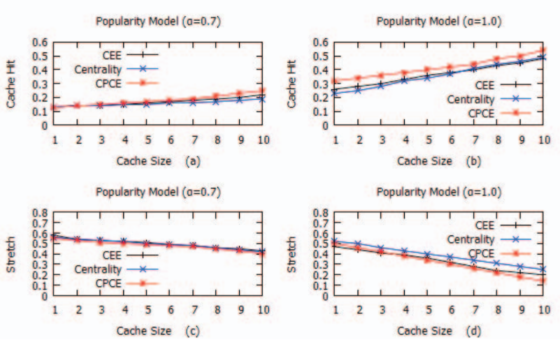

Figure 5. Result on DTelekom topology

6. TOPOLOGICAL EFFECT ON RESULTS

Topology has a direct impact on the simulation results [48] and according to the ICN baseline scenarios [49, 50], there is no general agreement on the topology selection. Therefore, for a fair evaluation, apart from the GEANT topology, we have also simulated all the strategies on the DTelekom topology. To evaluate the performance of ICN caching, we believe that cache hit and stretch ratio are considered the most prominent metrics because cache hit combines the properties of other metrics, such as content eviction rate, cached element rate, and cached miss rate, while the stretch ratio also affects the hop decrement as well as the content retrieval delay. Therefore, we present the simulation results for cache hit and stretch ratio on the mentioned two topologies in the following subsections.

6.1. Cache Hit on GEANT and DTelekom

Figure 4(a,b) and Figure 5(a,b) represent the cache hit ratio on GEANT and DTelekom topologies, respectively. In a low popularity scenario, i.e., when α is 0.7, the ratio of cache hit is low on both GEANT and DTelekom topologies with cache sizes 1GB to 10GB, but with the increase of cache size as well as the increase of popularity value, i.e., α=1.0, a higher hit ratio was achieved. On the other hand and for the GEANT topology, the recorded hit ratio was 15%, 16%, and 18% for CEE, Betweenness-Centrality, and CPCE, respectively, with popularity value of 0.7. However, with the increase of popularity model, the hit ratio reached 45% with α = 1.0 in CPCE as compared to 38% of Betweenness-Centrality and 36% of CEE. Similarly, on the DTelekom topology, the achieved simulated results for α=0.7 were as follows: CEE = 22%, Betweenness-Centrality = 19%, and CPCE = 25%. While with the increase of popularity model, the hit ratio reached 54% with α = 1.0 in CPCE as compared to 49% of Betweenness-Centrality and 48% of CEE. In all figures, Betweenness-Centrality is represented by *Centrality*.

6.2. Stretch on GEANT and DTelekom

Figure 4(c,d) and Figure 5(c,d) show the stretch ratio exhibited by CEE, Betweenness-Centrality, and CPCE on GEANT and DTelekom topologies, respectively. The stretch was almost the same for all strategies with low popularity model and lower cache size on DTelekom topology, however, there was some difference on the GEANT topology. When the popularity model α was increased from 0.7 to 1.0, the recorded stretch ratio was as follows: on the GEANT topology it ws 64%-30% in CEE with cache size 1GB-10 GB, 60%-32% in Betweenness-Centrality, and 54%-20% in CPCE. While on the DTelekom topology the recorded stretch with the same parameters was as follows: CEE = 47%-20%, Betweenness-Centrality = 52%-25%, and CPCE = 50%-14%, respectively.

7. DISCUSSION

Throughout this study, the performance of CPCE is assessed with respect to different parameters, such as popularity model variation, cache size, metrics measurement, and topological impact, i.e., cache deployment. The CPCE caches popular contents, and according to Cisco visula networing index [51] multimedia applications are popular contents because video on demand (VoD) only from YouTube and Netflex attract more than half of the overall traffic, therefore, when the skewness of the distribution (which is measured through α) increases, popular contents attain maximum portion of the Internet traffic.

In addition, the current available DRAM is 10GB (maximum), therefore, after some times the memory becomes full and content eviction starts for the accommodation of new arrived contents. Consequently, the cache hit rate is reduced and subsequent requests for the evicted contents are forwarded to the server, which increases the content retrieval delay. To add more, with the eviction of contents, the hop decrement is affected and thus stretch ratio increases. Similarity, CEE and Betweenness-Centrality also cache diverse kinds of contents (as they are not particularly designed for popular contents) and the popular ones (i.e., VoD) will not have enough space to be cached. Moreover, in case of memory overflow, there is no eviction policy in CEE and Betweenness-Centrality but they simply delete the contents which affect the mentioned metrics.

The Cache size is another factor of the CPCE result supremacy, i.e., when the network becomes stable then CEE and Betweenness-Centrality cache sizes overflow and thus eviction operation starts. On the other hand, unlike CEE, the CPCE does not cache every content and hence still has space for accommodating new contents rather than deleting the cached ones. Besides, Betweenness-Centrality stores lesser contents than the CEE but because of having no eviction policy for Betweenness-Centrality, the popular contents are evicted and subsequent requests for those contents are forwarded to the original server. This leads to reduce the performance of Betweenness-Centrality. While in the CPCE the contents are not deleted but cached at other routers, as discussed earlier.

8. CONCLUSION

In the modified draft of ITU - T recommendation [52] it is requested that every network segment in data aware networking (DAN) is recommended to support a caching component and be additionally ready to assess subscriber requests that pass through it with the goal that it can make a decision on subscriber requests and respond using the cached data objects. To address the ITU-T recommendations, this paper proposes a flexible caching strategy, named CPCE, for popular content caching to improve the performance of ICN caching in terms of cache hit rate and stretch ratio during content downloading. The performance of CPCE is compared with two other strategies, i.e., the default ICN strategy, known as Cache Everything Everywhere (CEE), and Betweenness-Centrality. In simulations, the CPCE strategy outperformed both CEE and Betweenness-Centrality in terms of cache hit rate and stretch ratio.

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