**End semester report on R & D Project (NU 302)**

**Academic Year- 2020-21**

on

**Content Popularity Prediction for Caching in Information Centric Networking**

A dissertation

Submitted in partial fulfillment of the requirements for the award of the degree

Bachelor of Technology

by

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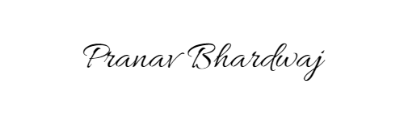
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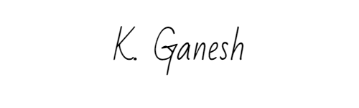


**DECLARATION BY STUDENT(S)**

I/We hereby declare that the project report entitled **Content Popularity Prediction for Caching in Information Centric Networking** which is being submitted for the partial fulfilment of the Degree of Bachelor of Technology, at NIIT University, Neemrana, is an authentic record of my/our original work under the guidance of **Prof. Supratik Banerjee**. Due acknowledgements have been given in the project report to all other related work used. This has previously not formed the basis for the award of any degree, diploma, associate/fellowship or any other similar title or recognition in NIIT University or elsewhere.

Place: NIIT University, Neemrana - Rajasthan

Date: 16/05/2021

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**CERTIFICATE BY SUPERVISOR(S)**

This is to certify that the present R&D project entitled **Content Popularity Prediction for Caching in Information Centric Networking** being submitted to NIIT University, Neemrana, in partial fulfilment of the requirements for the award of the Degree of Bachelor of Technology, in the area of CSE, embodies faithful record of original research carried out by **Mr.** **Pranav Bhardwaj, Mr. Kolavennu Sai Sri Ganesh and Mr. Pranav Kishor Kshirsagar**. They have worked under my guidance and supervision and that this work has not been submitted, in part or full, for any other degree or diploma of NIIT or any other University.

Place: NIIT University, Neemrana-Rajasthan

Supratik Banerjee

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Date: 16/05/2021



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We would like to express our special thanks of gratitude to the **panel members** who gave us this golden opportunity do this wonderful project on the topic “**Content popularity prediction for caching in Information Centric Networking**”, which helped us to increase our knowledge and skills. Also we would like to thank our project supervisor **Prof. Supratik Banerjee** for being such a good resource person and for guiding us at every step in our project.

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**Introduction:**

The Internet has been providing the world excellent services by addressing the communication demands right from the period when a network was required to share expensive and rare resources like long distance communication links and mainframe computers. Its ability to connect different systems around the world allowed a remarkable growth in its size. However, its inspiring growth in size demanded a new design with requirements like content dissemination and storage resources. Implementation of the new design brought various limitations to the internet architecture which were not there in the original design.

A few years back it was noticed that the information-centric usage of the internet has gained popularity, which brought up many new design challenges which gave rise to a question that whether the internet needs a new clean-slate design method or it can keep patching or patches. Thus, to solve this issue a new research group was formed which identified the implementation of existing internet and discussed the major internet objectives. Further, considering the growth and future requirements ***Information-Centric Network*** (ICN) turned into a favorable nominee for the future internet architecture. But further problems with TCP/IP internet came up as it made the architecture centralized and as well as made it complex to do the certificate management [3] as they need to be stored separately so the concept of Named Data Networking [4] came into picture. NDN made it easier to access data over the internet as in NDN the data is cached depending upon the interest show by the audience or data client and remove the security issues as the data gets cached in the data pits and on the requester or provider side.

The data tsunami which was predicated in the mid-1990s considering the growth and increasing volume of data on the internet fortunately did not come. However, due to the increasing number of internet users and the user interest in multimedia applications, the alarm of data tsunami is returning. The Cisco Visual Networking Index [2] reported that the usage of multimedia applications on the internet has become extremely popular on the internet. It is expected that the global IP traffic will be 194 Exabyte per month by 2021. This means that the internet multimedia traffic will reach 82 percent of all users’ internet traffic, which was nearly 70 percent in 2015. Surprisingly, in addition, it was also predicted that the communication devices will be three times the world population by 2021. This can be clearly noticed by finding out what happens in an internet minute. It is interesting to note that in one internet minute [6] there are nearly 4.1 million searches on Google, approximately 10 million advertisements displayed over the internet as well as an approximate of 34.7 million messages are sent over the internet.

Now, this rapid growth of data is worthy to change the host-centrism of data in Information-Centric architecture by flexibly placing caching nodes in the network through ICN concepts. Caching was intended to reduce the internet traffic but also brought in new challenges like cache storage capacity, expiry of the data over the internet, etc.

Further the article is organized as follows: we discuss the problems statement and the major objectives which are to be accomplished by this research. Then we discuss the literature review. After evaluating and concluding different results from the literature review we discuss our proposed methodology to specific gaps/challenges.

**Problem statement:**

The delivery of data through the multimedia applications on the internet has become extremely popular and this has led to the rise in the internet traffic. This increasing internet traffic has reduced the throughput of the internet and has affected the bandwidth available which has also warned us of the data tsunami.

A group of researchers came up with an idea of introducing in-network caching in ICN which would decrease the internet traffic. However, the increase in transient data over the internet has brought up new design challenges as it increases the complexity of in-network caching. Also the increasing volume of data has questioned the caching capacity of the in-network caching systems. According to a paper on “Router Position-Based Cooperative Caching for Video-on-Demand in Information-Centric Networking” [1] ten per cent of the top videos account for eighty per cent of the requests. Which raised a new question of caching based upon content popularity. Also the dynamic change in popularity of data made it more difficult for the in-network caching systems to cache data based on its popularity. This also introduces the concept of “Data lifetime”.

The objectives of this research which appears as a direct consequence of the problem discussed above are stated below:

* To make an algorithm for in-network caching according to content popularity using Named Data Networking in Information-Centric Network.

**Literature review:**

**Paper*:*** **Caching Transient Data in Internet Content Routers**

**Authors*:*** Serdar Vural, Ning Wang, Member, IEEE, Pirabakaran Navaratnam, and Rahim Tafazolli, Senior Member, IEEE.

This research laid down by the authors explicitly showcases the caching of transient data in the internet content routers. The authors of this paper has introduce the concepts of static data and transient data which is very necessary to be noted as to understand the changing behavior of data. The authors simply state that Static data is data which takes time to change, while transient data has a dynamic nature and changes rapidly. There is also a notable difference in the lifetime of static and transient data. The authors have mainly focused on transient data and the caching of transient data. The authors state a very simple example of IOT data which is a transient data and keeps changing over time, such type of data requires different caching policies. They now explain the traditional technique that avoids unnecessary end to end communications in in-network caching and which reduces the load over the network. These are the push-based and pull based caching techniques. As per the authors it has been significantly noted that these techniques have reduced the in-network traffic in the past few years.

In push-based schemes the data servers push the relevant data into a number of fixed content repositories in the network so that they can be accessed when requested by the data clients. While in pull-based schemes the caching decision is made on a demand basis i.e. based on the incoming request from data clients.

According to the authors push-based schemes can be effective in managing the static networks where the demand and supply trends of data is already known so that update of data in data repositories by the data server can be planned and implemented. While in dynamic environments where transient data is present the push based caching becomes quite rigid as the data changes frequently. The authors suggest that in this case the pull-based schemes appear to be very effective as the network itself needs to adapt according to the changing data request from data clients. In this the network nodes decide which data is to be cached depending upon the interest shown by data clients.

As a result the feasibility of using in-network caching techniques for IoT is being discussed in the Information-Centric Networking Research Group (ICNRG) under the Internet Research Task Force (IRTF). As the authors describe the use cases of in-network caching in a dynamic environment they explain the potential of applying these schemes for monitoring the IOT data. The authors explain these by giving an example. Suppose an IOT device collected the pollution level at different locations which keeps changing every single second. If pull-based in-network caching is applied then the pollution data of a certain location which is popular among certain data providers can be cached so as to reduce the traffic and remove redundant data.

Further the authors make a note of an important point considering the lifetime of transient data as how quickly a data item expires. To solve this problem the authors introduce the concept of selective caching in the Information-Centric network. As in between the content source and content requester there is a generic multihop path in the network. Along this path it is expected to reduce the expected cost (traffic) for accessing the data, so the router modifies the probability of cache for different data items depending upon how many times the data is requested. Thus, it's the popular content which is being requested for more number of times hence popularity based caching. This is how the problem was addressed according to the authors.

As these algorithms work on popularity based caching the majority of content in these popular data files is in-transient as per the author. In-transient means the data which does not expire. This led to a new problem as if the data does not expire the refresh time of the cache data will significantly decrease making it more complex to cache huge amounts of popular data. As per the author, the data with a larger lifetime will remain cached for a longer time once cached. Now collection of such larger lifetime cached data will significantly reduce the size of the cache memory in the network. Thus, the network will get flooded with such files leaving no space for data with smaller lifetime.

Stating these the authors states the future work to be done regarding these issues, as even the benefits of in-network of transient data in ICN are clear, still there has been no potential study been done to improve and discover new transient data caching techniques. Also there is a significant need to work on improving the cache memory size and the storage of in-transient data cache so as to improve the throughput of the network and to significantly reduce the network traffic.

**Paper**: **Content Popularity Prediction and Caching for ICN**

**Authors**: Wai-Xi Liu, IEEE Member, Jie Zhang, Zhong-Wei Liang, Ling-Xi Peng, Jun Cai

In Information-Centric Networking (ICN), prediction of content popularity will increase the performance of caching. Mostly based on Software Defined Network (SDN) from this paper author, wants to bring forward Deep-learning -based Content Popularity Prediction to achieve the popularity prediction. DLCPP adopt the switch’s computing resources and links in the SDN to build an allocated and reconfigurable deep learning network.

ICN can also be known as name-based routing or in-network caching. It will give fast content retrieval, reduce network traffic by modifying a nearby copy of the content and reduce duplicate transmission. There is a limited space to store cache so the popular content must present near the user. SDN software define networking. It is used to show the difference between the control plane and the data plane of the network, which further helps the network to be programmable and centralized control from a global view. Deep learning-based content popularity prediction (DLCPP) is in content popularity prediction. It uses functions into switches/routers.

SDN-ICN is very beneficial for data of the data plane in ICN and for data of the centralized control on the control plane in SDN. Content, not address-bound is routed and pass as an independent entity at the network resources. Cache placement by predicting content popularity:-

The author of our resources proposed WAVE which adjusts the number of cached chunks related to content popularity. The upstream node suggests the number of chunks to be cached, which increases as the demand increases. A mixed-integer program (MIP) with some constraints such as disk space, link bandwidth, and content popularity. They use the request history of similar video, e.g., same TV series show, to predict the demand for a new video. Aiming to store popular content closer to users, Cache-Filter considers content popularity and achieves the goal through a collaboration of on-path nodes. Cache, where some selected nodes cache contents based on the correlation of network topology and content popularity that dynamically varies based on the local content request frequency.

The Most Popular Content (MPC), in which every node counts and caches locally the number of requesting each content item. When the number of a content item reaches a local Threshold, it is regarded as being popular. The node holding the content recommends its neighbor nodes to cache it. However content popularity is time-varying, the content popularity piggybacked by it is expired when data packets return.

Pop Cache allows an individual ICN router to cache content more or less according to its popularity. A cognitive caching approach in Information-Centric Sensor Networks (ICSNs). This approach employs four functional parameters in ICSNs, i.e., age of the data, popularity of on-demand requests, delay to receive the requested information, and data fidelity, to assign a value for the cached data, where the most valuable one is retained in the cache for prolonged time periods.

**Overview of ICN:** In ICN, in-network caching is exploited to temporarily cache forwarded content.There are two message types in ICN: Interest and Data message.

The communication scheme of ICN is consumer-driven. To receive content, a consumer sends out an Interest with the name of desired content.

The Interest is propagated node by node until a matched content block is found from the intermediate node or content servers.

**Paper: Intelligent data cache based on content popularity and user location for Content-Centric Networks**

**Authors:** Hsin‑Te Wu, Hsin‑Hung Cho, Sheng‑Jie Wang and Fan‑Hsun Tseng

Content cache, as well as a data cache, is vital to Content-Centric Network (CCN).The paper presents a data cache scheme, that is content popularity, and user location (CPUL) scheme. It gets the cache problem of CCN routers by pursuing a better hit rate and storage utilization.

In this paper, Two components are newly proposed in CCN, i.e., Forwarding Information Base (FIB) and Pending Interest Table (PIT). As there are many authors and some of them proposed a new method, are as follow:

1 A new FIB approach with dynamically allocated memory. Basically, it’s a name-data forwarding and searching.

2 PIT records the information of request data. The author researched related to PIT entry lifetime and a hop limit-based adaptive PEL.

3 The packet format of data acknowledgment and a forwarding strategy was designed to reduce redundant data transmission.

4 The multi-path routing, caching, and replacement policies are investigated.

5 Zhang introduce a cache replacement scheme called popularity prediction caching (PPC). Which show the most popular chunk and caches in linear complexities.

6 This led us to the concept of collaborative cache scheme based on the concept of dominating set.

The author here also has noted some problems and has proposed a scheme for them as follows.

The cache problem on content popularity and user location. Nowadays people only see content popularity or cache location. Content Popularity and User Location (CPUL) is used to summarize what kind of data we should be cached in which router at the same time. The scheme discussed above in CCN can’t use the cache capacity of routers efficiently. Routers with the routing path, cache the diverted data content without consideration and optimization.

**Paper:** **Caching in Information-Centric Networking: Strategies, Challenges, and Future Research Directions**

**Authors:** Ikram Ud Din Student Member IEEE, Suhaidi Hassan Senior Member IEEE,

Muhammad Khurram Khan Senior Member IEEE, Mohsen Guizani Fellow IEEE, Osman Ghazali Member IEEE, and Adib Habbal Senior Member IEEE**.**

From the research paper, the author wants to convey the message that ICN (Information-Centric Network) is very flexible and handy to use in various projects and provides a better management system for internet usages. Basically, it provides transparent and easy in-network caching to improve the network for better utilization of data distribution.

Data tsunami, it’s a term defined in the late 90s to describe a tremendous amount of requirement for data by users, but at that time it was a false alarm.

Nowadays it’s in very high demand which was not expected. The Cisco Visual Networking, says that multimedia is now a part of every living creature on the planet and which also invites a huge amount of data, according to Cisco, by 2021 ends the global IP traffic will be 194 Exabyte’s or 2.3 Zettabytes per month. So as we know the population is increasing very high in numbers which in turn demands a huge amount of devices we use on daily basis.

The data includes a video on demand, point to point, and television combine holds 86% of world wild user traffic.

**The design scheme of ICN**:

The layout of ICN depends on an end-to-end relation between hosts, which is known as a host-centric network.

As discussed above increasing demands for efficient and highly scalable distribution of contents is enough to motivate people to shift towards Name-Data-objects (NDOs).

**Proposed methodology:**

Over the past few years researchers have been working on various algorithms to improve the throughput of ICN and also to improvise its data traffic handling capacity. However, some common gaps among all the prominent algorithms remain the same and the major problem among these was cache space limitation. Considering the problem that the ICN

Nodes have limited cache space and to cache contain based upon its popularity many IOT-based caching strategies we applied such as:

* Client-Cache strategy
* Tag-based caching strategy
* Sleep based caching strategy

All the mentions above strategies however do not investigate any optimum cache space management based upon popularity based caching in ICN.

**The major challenges are as follows:**

* The dynamically changing popularity of the content.
* Handing the transient data: Data which never expires.

Considering the above mentioned challenges the proposed methodology is as follows:

* The first step is to receive data and calculate the number of data requests to differentiate between popular content and normal content.
* The popular content is cached on a particular node, if a user under the node requests for the popular content and there is adequate cache space. Else the least popular content in the cache is evicted to provide space for the current content.
* The server maintains a field called request number for each content and it is incremented whenever a request arrives for the content.
* Ten percent of the content having highest request number will be popular content and rest of them are normal content.
* Each content will be assigned a lifetime and once the lifetime expires the content is evicted from the ICN node.

**Workflow:**

There are number of router involved in a communication network which simultaneously work to improve the network performance in Named Data Network. Therefore to apply the above proposed methodology the Caching strategy of CAPIC (Content Based on Popularity and Class) will be used. The steps for the flow of the whole process are as follows:

1. **The consumer requested content will be searched in the NDN router:**

* Every time a consumer request a content the content will be firstly searched in the content store of a downstream router which is one hop away from the host who requested the content. If the content is found then the data is reverted to the consumer.
* If content is not found in content store then it is searched in the Pending Interest Table (PIT) of the router to find an entry for corresponding interest packet. If content is found in the PIT of the router then the entry of interest packet found is aggregated in the list of incoming interfaces in the PIT. If not then the router inserts a new entry for the interest packet to PIT.
* If the content is not found even in the PIT then it is searched in the Forwarding Information Base (FIB). If the corresponding interest packet is found in the FIB then it forwards the interest upstream. If the interest packet is not found then the packet is discarded and the request get forwarded to the Edge router.
* The Edge router checks for the requested interest packet in the similar way. If found then it is being forwarded back to the downstream router near host or else the request is send to the server.

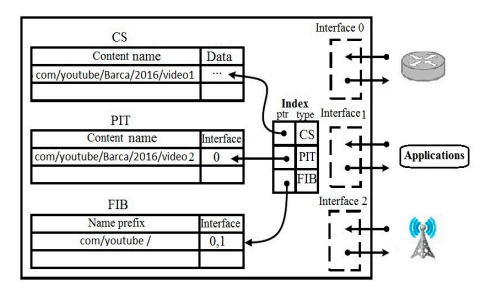
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Figure 1: NDN router and its components [7]

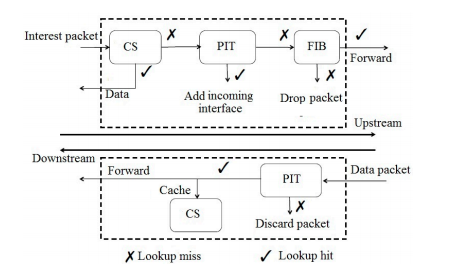
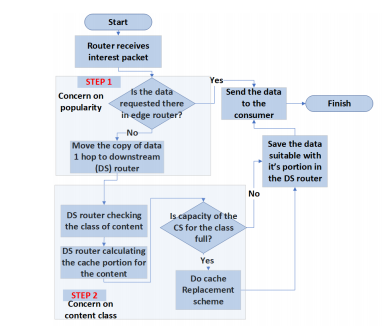


Figure 2: Forwarding process in NDN router [7]

1. **Caching of the consumer requested content based upon its popularity:**
   * While the content is searched in NDN router in the first step, if the requested interest packet is not found then it gets discarded from the router. But is the requested content is found in the content store for the requested interest packet the popularity of the content is checked.
   * The popularity of the content is determined by maintaining a request number field at all the Edge routers as the edge router are connected to a network of router in a particular region.
   * The request number of each interest packet being requested is stored by counting the number of hits for a particular interest packet. If the interest packet is receiving specific number of hits then the interest packet is considered as popular and a copy of its data packet get cached in the router with its request number.
   * Now if an interest packet requested by the consumer is found on the edge router then it is forwarded to a router near the consumer and it popularity is checked. If the interest packet is found popular by looking at the request number table then a copy of its data packet and its request number is cached in the router as then is forwarded to the consumer.
2. **Cache Replacement Scheme:**
   * As the cache storage for each router is limited it is very important to check for the data which is cached in the router before caching new content. To handle the limited space problems a Cache Replacement Scheme will be used.
   * According to the proposed methodology the cached memory of the router will hold a table with the copy of the data packet of the popular content with its request number.
   * Now if a new popular content is found and the cache memory of the router is full then the cache memory of the router is checked.
   * The request number of the cached content is check and is compared with the request number of the new popular content.
   * If the request number of (new popular content > some other cached content) then in these case the list of cached content whose request number is less that the request number of new popular data is considered. Among the list the content which has the least request number is discarded from the cache memory and the new found popular data will be cached in the router.
   * If the request number of (new popular content < all other cached content) then the newly found popular content is not cached in that router but is send to the next one-hop router and if cached is space available otherwise same process is repeated.
   * While if only one cached content is found in the router which has less request number than the new found popular data then it is directly discarded from the cache memory and the new found popular data will get cached in the router.

Figure 3: Flow chart of popular content caching using CAPIC strategy [8]



**Technology:**

The proposed methodology requires one main techniques for the functioning in Named Data Network. This techniques is the base for the proposed popularity based content caching methodology. This strategy further performs two techniques in two steps. One for searching the interest packet in the NDN router and second for optimizing cache storage.

**Content Based on Popularity and Class (CAPIC) caching strategy:**

* 1. **Search of interest packet and performing popularity check**
     1. CAPIC is a caching strategy technique to cache content in NDN based upon its popularity. Here, the popularity is determined by keeping a record of number of hits for a specific interest packet as a request number at the edge routers.
     2. In this caching strategy the requested interest packet is searched in the on-hop downstream router near the consumer (host) in its content store, pending interest table and forwarding information base.
     3. During the search if the corresponding interest packet is found then its popularity is determined by checking the request number table at the edge router.
     4. If the interest packet is found popular then a copy of its data packet is cached in the router.
  2. **Cache replacement technique:**
     1. When an interest packet is found popular a copy of its data packet get cached in the router.
     2. In case if the router cache memory is full then the cache replacement technique is performed.
     3. In this technique the popularity of the contents cached in the router will be checked and the least popular content will be discarded from the cache memory and new popular content will be cached in the router.
     4. Now in case if the new popular content is less popular i.e. has less request number compared to all the other content cached in the router then the copy of data packet of the new popular content is forwarded to the next one-hop router for caching and the same Cache Replacement Technique is applied on that router in case the cache memory is full.
     5. This process continues till edge router and still if the new content has less popularity then the copy of its data packet is discarded and the content is not cached.

**Result and analysis:**

The CAPIC caching strategy is the backbone for the proper functioning of the methodology proposed. Therefore, some evaluation test in order to test the performance of CAPIC caching strategy in dynamic and static network environments with different frequency limiting factor so that the number of request occurring every second keeps changing. For the test the following simulation parameters were considered.

Table 1: Simulation parameters [8]

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| **Number of routers** | 20 |
| **Number of class** | 3 |
| **Number of content** | 500 (1st class) |
| 700 (2nd class) |
| 1000 (3rd class) |
| **Number of rounds** | 10,000 |
| **Average request rate per round for each class** | 10 (1st class) |
| 20 (2nd class) |
| 30 (3rd class) |

After completion of the simulation the performance of CAPIC in all the three classes in both dynamic and static environment were compared with the LCD (Leave Copy Down) caching strategy which is a simple caching method where every data which is requested gets cached in the router. These simulations were carried out with the changing frequency limit factor for a clearer picture and the graphs below were obtained.

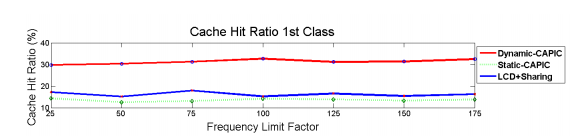


Figure 4: Cache hit ratio for 1st class [8]

The above graph (figure 4) shows the cache hit ratio for the 1st class i.e. the class which hold the top 20% popular contents in the network. The red line show the data of cache hit of CAPIC in dynamic environment which is more that the cache hit ratio of the Leave Copy Down (LCD) caching strategy which is represented by the blue line. While the cache hit ratio of 1st class of CAPIC in static environment is less than that of the LCD caching strategy. Thus, it shows that the CAPIC show good performance in terms of cache hit ratio in 1st class.

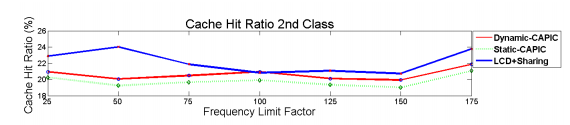


Figure 5: Cache hit ration 2nd class [8]

The graph above (figure 5) show the performance of CAPIC in terms of cache hit ratio in 2nd class which hold the top 30% popular content in the network. Here, it is clearly visible that the cache hit ratio of the CAPIC in 2nd class in dynamic environment shown in red line is less than that of the cache hit ration of LCD caching strategy in the same class. It also show that at a frequency limit factor of 100 the cache hit ratio data of CAPIC in dynamic and LCD caching strategy coincide with each other which is an anomaly. The graph show that CAPIC even in 2nd class has a good performance as the cache hit ratio is less which is theoretically right as it has less popular data than 1st class and thus has less cache ratio hit, which is also practically proved showing good performance of CAPIC.

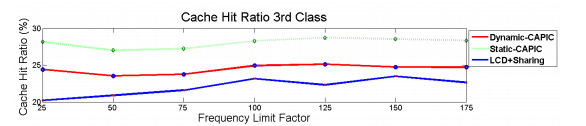


Figure 6: Cache hit ratio 3rd class [8]

The above graph (figure 6) show CAPIC performance in terms of cache hit ratio in 3rd class which hold remaining 50% of popular content which is the least popular content as compared to 1st class and 2nd class. The graphs shows that the cache hit ratio of CAPIC in dynamic environment shown with red line lies in between the cache hit ratios of CAPIC in static environment shown with green line and LCD caching strategy cache ratio shown in blue line. It is also seen that the cache hit ratio of CAPIC in 3rd class in dynamic environment is less than the cache hit ratio of CAPIC in static environment and is greater than that of the cache hit ratio shown by LCD caching strategy.

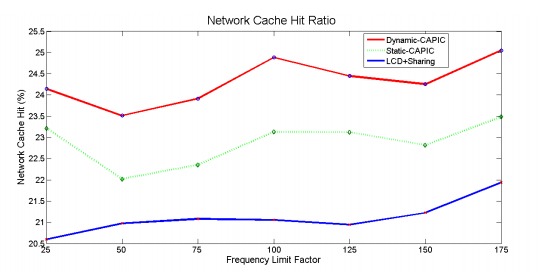


Figure 7: Network Cache Hit Ratio [8]

The figure 7 graphs show the cache hit ratio of the whole network used in the whole simulation process. The graphs clearly shows that the cache hit ratio of CAPIC in dynamic environment shown in red line and CAPIC in static environment show with green line is way more than that of the LCD caching strategy shown by blue line.

Therefore, as a result it is seen that the CAPIC in static and dynamic environments shown different performance in each class. Also it was noticed that the greater the Frequency limit factor the amount of top content considered in determining the proportion of cache in the content store. CAPIC gives great performance in terms of cache hit ratio in dynamic as well as static environments in Named Data Network and thus shows that the proposed methodology for popularity based content caching will give good result after implementation in NDN.

**Conclusion and future scope:**

In conclusion, this research explains the basic idea of popularity based content caching in Named Data Networking. It also discusses the problems occurred in a period of years due to the constant increasing demand of internet facilities and the demand of multimedia resources available online. It also then brief about the proposed methodology for solving the various problems and how Named Data Network is the best for implementing such methods. It also then briefly discusses about different content caching techniques and then explains the working of the proposed methodology using the CAPIC caching strategy. Finally, it discusses the network simulation test result and shows that the methodology on implementation will have much better results. Thus, the research concluded that the Popularity Based Content Caching in Named Data Network can be successfully achieved by following the proposed methodology using the CAPIC caching strategy.

The research also opens a future scope of designing an algorithm which works as per the proposed methodology for implement popularity based content caching in Named Data Network. Also shows to work on the limited cache memory space so as to improve the performance in term of space complexity. It also open and end of implementing Machine Learning in the network so as to use the data already available to train the network for adapting to the changing nature of popular content in real time.

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