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A Comparative Performance Analysis of Popularity-Based Caching Strategies in Named Data Networking

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ABSTRACT Data communication in the present Internet paradigm is dependent on fixed locations that disseminate similar data several times. As a result, the number of problems has been generated in which location dependency is the most crucial for communication. Therefore, Named Data Networking (NDN) is a new network architecture that revolutionized the handling gigantic amount of data generated from diverse locations. The NDN offers in-network cache which is the most beneficial feature to reduce the difficulties of location-based Internet paradigms. Moreover, it mitigates network congestion and provides a short stretch path in the data downloading procedure. The current study explores a new comparative analysis of popularity-based cache management strategies for NDN to find the optimal caching scheme to enhance the overall network performance. Therefore, the content popularity-based caching strategies are comparatively and extensively studied in an NDN-based simulation environment in terms of most significant metrics such as hit ratio, content diversity ratio, content redundancy, and stretch ratio. In this analysis, the Compound Popular Content Caching Strategy (CPCCS) has performed better in terms to enhance the overall NDN-based caching performance. Therefore, it is suggested that the CPCCS will perform better to achieve enhanced performance in emerging environments such as, Internet of Things (IoT), Fog computing, Edge computing, 5G, and Software Defined Network (SDN).

INDEX TERMS Content centric networking, information-centric networking, named data networking, caching.

I. INTRODUCTION

The unbelievable growth of data traffic in the present Internet requires a high quality of information dissemination services with heterogeneous nature to reduce in-network congestion that is increasing exponentially. In addition, the present IP location-based Internet paradigm continuously is facing several issues of network traffic. For instance, location-based data communication needs extra time (delay) to disseminate data from remote locations and it consumes more bandwidth. Consequently, the consumption of power, energy, and resources had been increasing with high usage frequency [1]–[4]. In fact, the present Internet architecture keeps up the old-fashioned prototype. In addition, IP-addresses are used to connect the Internet with each device. These IP-addresses assigns to indicate the particular location of a device. However, the current Internet- architecture having a plethora of problems in which delays, content fetching overhead because of high congestion of a network, and identical content placement at multiple remote locations are most significant [5]. Therefore, the IP-addresses based Internet-architecture will be inadequate to implement the efficient data dissemination services using addresses since addresses-based data dissemination requires a huge quantity of resources and energy that is the fundamental restrictions of IP-based Internet architecture. Besides, the novel applications

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with heterogeneous data are expected to deliver the massive volume of information that will be very difficult for the location-based Internet to disseminate through restricted network channels [6], [7]. Several projects have been designed to handle the critical problems of the Internet architecture in which, the Information-Centric Networking (ICN) paradigm is considered as the most significant because of its elastic nature to overcome the incurable issues of IP-based network paradigm [8], [9]. In ICN, content is considered an important component than location during data communication procedure. ICN decouples the contents from their physical locations by deploying the in-network cache [10].

ICN provides a number of advantages over the IP-based Internet such as; data dissemination with low latency, easy data access, content level security, and the most advantageous is in-network caching [11], as illustrated in Figure 1. Consequently, the cached content is used to retrieve as the subsequent response, which in result decreases the communication and searching overhead. Furthermore, it has the ability to minimize the latency in the content retrieval process and increases the availability of diverse content. Additionally, the in-network caching decreases the usage of resources, power, and provides chunk-level data dissemination to reduce network congestion. Therefore, ICN architecture is the most beneficial to implement the basic goals of end-consumers [12], [13].

Several ICN-based developments have been made to implement the basic aim of location-independent data dissemination services. As a result, a number of ICN-based architectures were developed. For example, 4WARD project [14], Comet project [15], COMBO project [16], [17], Content Centric Networking (CCN) [18], Network of Information (NetInf) [19], and Named Data Networking (NDN) [20]. NDN has the ability to provide complete functionalities of ICN.

According to literature, several surveys have been written on ICN caching, such as [1], [5], [9], [21]–[23]. However, all of these surveys have explored limited knowledge about contents' popularity based on NDN caching strategies. Moreover, these surveys have restricted scope, and the caching strategies are explained moderately. Conversely, our study provides the limitations and contributions of most recently proposed popularity-based on-path caching strategies within the NDN domain.

The performance of NDN-based on-path caching cannot be detected by only analyzing the cache hit ratio. The rationale is that, some caching strategies can produce efficient cache hit ratio but disturb the performance in terms of other metrics such as diversity and stretch ratio. Therefore, in our study, these strategies are comparatively and extensively evaluated in a simulation environment to find the optimal popularity-based caching strategy in terms of most significant metrics such as cache hit ratio, content diversity ratio, stretch, and content redundancy [24].

The rest of the paper is organized as follows. Section II describes the effectiveness and advantages of NDN-based caching strategies. Section III presents the most recent related work. A comparative analysis of popularity-based caching strategies is presented in section IV. In section V, we discuss the limitations and advantages of popularity-based caching strategies. Subsequently, section VI describes some open research challenges and future directions and finally, we conclude the study in section VII.

II. THE NEED FOR NDN-BASED CAHING STRATEGIES

In NDN, the content is the most important component in the communication process and it decouples communications from their physical locations by the implementation of in-network cache [13]. NDN architecture offers several benefits over the IP-based Internet such as; data dissemination with low latency, easy data access, content level security, and the most advantageous is in-network cache. The in-network cache provides storage to the contents during their dissemination between distant locations. Moreover, it offers transmission services to the content at intermediate locations to be cached for the subsequent responses within a short time that causes less communication overhead. In addition, it reduces the content retrieval latency and increases the diverse communication by sending the heterogeneous contents across the Internet [25]. Therefore, the NDN architecture is the most beneficial to implement the basic goals of ICN because the focus of NDN is to deliver the data without having addresses of the physical locations. Therefore, NDN-based caching architecture is beneficial to achieve the efficient performance of ICN-based environments [26].

Figure 1 illustrates the IP-based Internet architecture and trending problems, which are expected to be uncontrollable in the future. The nature of the current Internet is to send similar objects over the Internet multiple times that result in an increase in the delay in response because every time the user sends a request, the request has to traverse to the remote server. Therefore, the path length between the user and server increases causing a delay and increase in resource usability. Moreover, Internet channels have lower capacity when compared to the amount of data transmitted, the congestion is uncontrollable. In addition, multiple similar requests generated by different users increase the redundancy in requests [27]. Consequently, all the requests consume extra energy (power consumption). The Internet in near future demands a conversion from the host-centric to an information-centric paradigm [28]. Therefore, The NDN may reduce the expected flooding of the global data through cache implementation as elucidated in Figure 1.

On-path caching is the basic approach that is used to cache content within the network routers for a specific time span. In this approach, the node responds to the consumers using locally cached content. The router transmits the corresponding content to the consumer when it receives an Interest. All the NDN routers have the ability to perform a matching operation between the received Interest and the cached contents [29]. In on-path caching, data communication is performed considering two primitives as Interests and content.

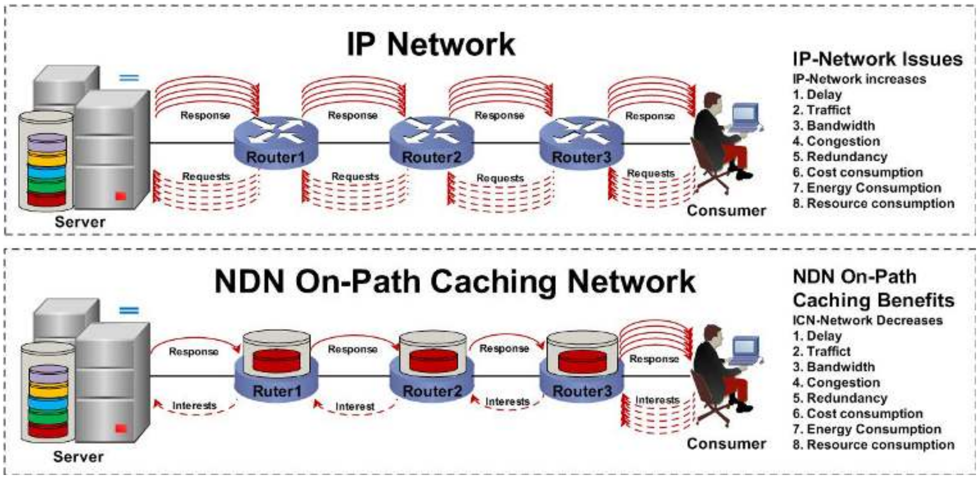


FIGURE 1. IP-Internet architecture versus ICN-Internet architecture.

The Interest carries the name of the required content in the prefix manner. A consumer broadcasts the Interest to the network and the Interest is forwarded by using the forwarding information base (FIB) record to identify a suitable content container. A router having the required content can respond directly to the consumer by transmitting the corresponding content and the content is known as a data packet [30].

In Figure 2, Consumer B sends the Interests to retrieve the desired Content C1 and Content C2. As the Interest1 arrives at router R1, the required content (content C1) is obtained. The router R1 becomes provider and sends the desired content C1 and C2 to the appropriate Consumer B. However, the R1 forwards the received Interest towards a suitable source (content Publisher P1) if the content does not found at R1 and an entry will be created in the PIT. The PIT entry will be deleted when it is identified that the required content is cached in its own CS. For the first Interest of consumer B, the Interest traverses to router R1, where it is satisfied by obtaining the required content C1 and C1 is cached at the intermediate router R2 and R3 to minimize the path length between the provider and the consumer for the subsequent Interests received at R2 from consumer B. Consequently, the consumers located around consumer B will receive the content C1 from router R2 and not from router R1.

On-path caching is the most significant module because of its flexible approach to caching the contents during their transmissions. However, the enhanced caching performance can be achieved by deploying an efficient NDN-based caching strategy [31]. Basically, the caching strategies are used to handle the overall caching services that provide best location for the transmitted contents within a network to produce maximum subsequent responses by caching a content at intermediate routers. As a result, the subsequent Interests get the required content from the nearest cached copy of the popular content in short time. Hence, efficient caching performance needs appropriate caching strategy that has the ability to find the best location of caching contents [32], [33].

III. NDN POPULARITY-BASED CACHING STRATEGIES

NDN is a highly scalable, efficient, and reliable information distribution network architecture. Therefore, these advantages have encouraged most of the researchers to modify the current end-to-end sender driven Internet to a receiver-driven information-centric paradigm. The NDN architecture provides on-path caching (storage for data objects) to the entire network and multicast communication can be produced through data replication. The objective of on-path caching in the NDN architecture is to achieve a scalable, effective, and consistent distribution of information and data object is achieved by using a common communication platform that is available in a dedicated system like a content distribution network [34]. However, the main issue which NDN-caching still facing is the selection of an appropriate router to caches the content during its transmission that can deliver minimum latency in data communication with low congestion and minimizes the distance between the consumers and providers. The reason is that, how each router takes a decision to caches the content at what location that can enhance the complete caching performance such as the most popular content is needed to be placed at the node from where it will be retrieved next. Therefore, the researchers have been developed a number of NDN-based caching strategies in which the popularity-based strategies are significant to provide the most efficient results in order to enhance NDN- based caching performance [20], [35].

Therefore, the research about the caching strategies is still in its early stage and it needs to find the optimal location to cache a transmitted content that can deliver the most efficient results to achieve the high performance in terms of content retrieval latency with low bandwidth consumption and small stretch. Consequently, the NDN caching mechanism has most of the benefits over the IP-based Internet paradigms and it has the ability to overcome the arising issues related to new Internet architectures such as IoT [36]. In the following subsection, detail descriptions of the most popular NDN on-path caching strategies are presented.

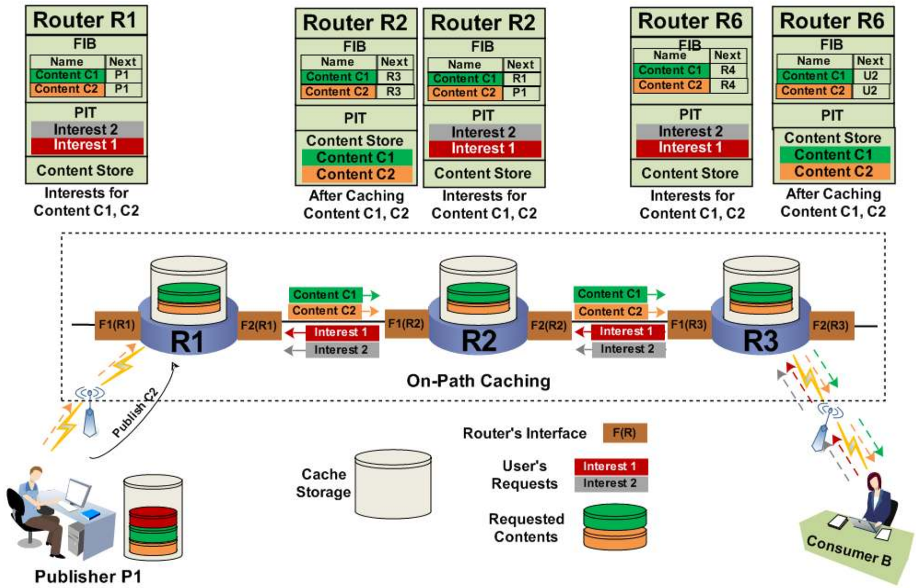


FIGURE 2. On-path caching architecture.

TABLE 1. Acronyms and corresponding notations.

Acronym	Notations
NDN	Named Data Networking
CPCCS	Compound Popular Content Caching Strategy
IoT	Internet of Things
SDN	Software Defined Network
ICN	Information-Centric Networking
CCN	Content Centric Networking
NetInf	Network of Information
FIB	Forwarding Information Base
MAGIC	Max-Gain In-network Caching
HPC	Hop-based Probabilistic Caching
MPC	Most Popular Cache
CCAC	Cache Capacity Aware Caching
DFGPC	Dynamic Fine-Grained Popularity-based Caching
LRU	Least Recently Used
OPC	Optimal Popular Content
LPC	Least Popular Content
PIT	Pending Interest Table
VoD	Video on Demand
UGC	User Generated Content
TSI	Time Since Inception
TSB	Time Since Birth
WSN	Wireless Sensor Network
UDHN	Ultra-Dense Heterogeneous Network

A. MAX-GAIN IN-NETWORK CACHING (MAGIC)

Max-Gain In-network Caching (MAGIC) [37] was proposed to minimize the overall usage of bandwidth as well as the amount of caching operations. In MAGIC, content caching employs two procedures. In first procedure, content is cached in the Content Store (CS) and in the second procedure; the content replacement operation is performed to delete the content from the router's cache so that the new content can be accommodated. The caching operation is dependent on the contents' popularities and the hop reduction count. In MAGIC, two primitives, local cache gain, and Max-gain values are used to calculate the popularities of the requested contents. Each router locally calculates the local cache gain in which the numbers of placement and replacement operations are measured.

MAGIC uses local information (content name, Interest count, popularity count) related to contents to calculate the local gain. The local gain helps to find the appropriate router to caches the incoming contents alongside the content delivery path. To find the router having maximum local gain, the MAGIC requires extra entity named as Max-local gain to compute at each router, and embeds it into the consumer Interest. When the Interest is generated for some content, the counter for Max-gain value is initialized to 0. As the Interest is received at any router, the MAGIC compares the values of Max-gain of Interest with a local gain of the router. If the value of local gain is higher as compared to the value of Max-gain, the router updates the Max-gain value. As the Interest along with its Max-gain reaches the content provider, the Max gain value is delivered to content and embed it into the content. Therefore, the content is cached at multiple routers alongside the content downloading path if the Max-gain value of the transmitted content and the local gain value of the router are equal. Thus, the content with more Interests gets more chance to be cached at intermediate routers.

Figure 3 illustrates the caching concept of MAGIC. According to the given scenario, three Interests (Interest1, Interest2, and Interest3) are generated to download content C1 from router R1. To respond to the received Interests, the routers R1 behaves as a content provider and instantly send the requested content C1 to the appropriate consumers A and B.

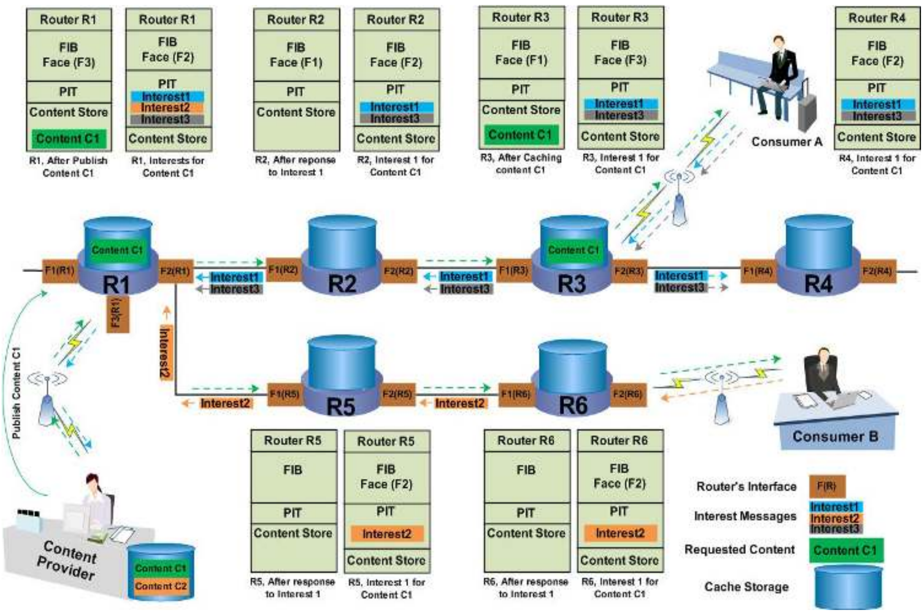


FIGURE 3. Max-gain In-network caching.

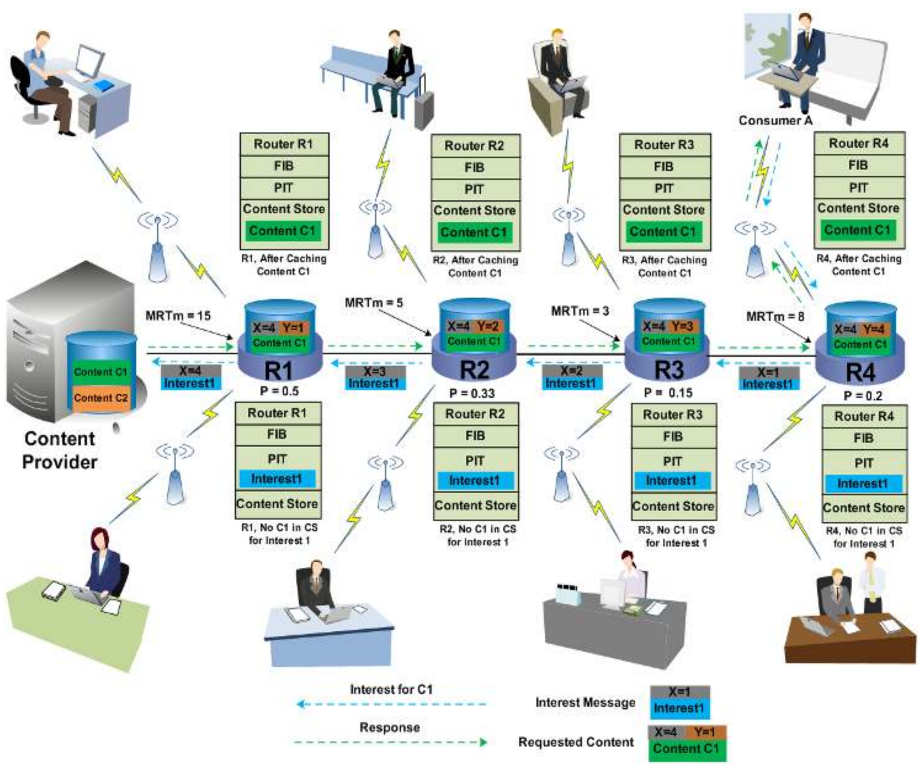


FIGURE 4. Hop-based probabilistic caching.

According to MAGIC, the local gain and Max-gain are measured for all the received Interests. Therefore, the local gain and Max-gain are higher at router R4 as compared to other routers. Therefore, the content C1will be cached at router R3 which is near the Consumer A because it sent more (two) Interests as compared to Consumer B to download Content C1 as shown in Figure 3.

B. HOP-BASED PROBABILISTIC CACHING (HPC)

The Hop-based Probabilistic Caching (HCP) [38], [39] was developed to mitigate the problems of probabilistic caching mechanisms. It was developed by using the enhanced version of CacheWeighty factor and CacheWeightMRT. The CacheWeighty was developed to reduce the similar content replications and the parameter y is selected to measure the number of hops between a content provider and

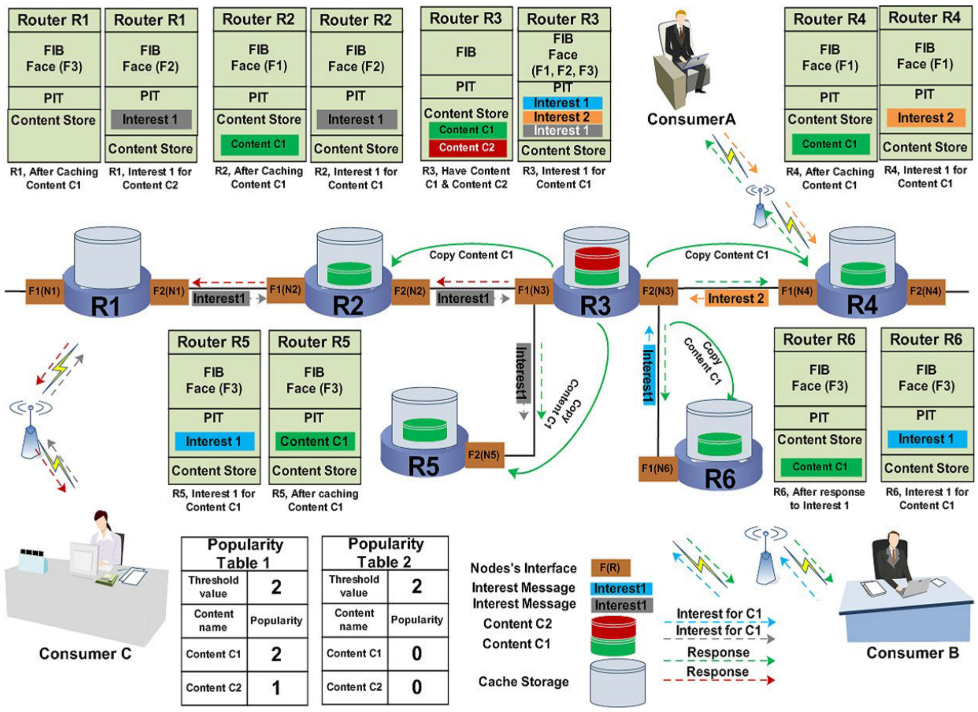


FIGURE 5. Most popular cache.

a consumer. CacheWeighty also helps to minimize the stretch length between consumers and the locally cached content by pushing the appropriate content towards the required consumer to reduce the path length for subsequent Interests.

$$\text{HPC} = \text{CacheWeighty} + \text{CacheWeight}_{\text{MRT}} \quad (1)$$

$$\text{CacheWeighty} = \frac{1}{y+\alpha} \quad \alpha \geq 0 \quad (2)$$

$$\text{CacheWeight}_{\text{MRT}} = \text{MRT}_{\text{m}} + \text{MRT}_{\text{exp}} \quad (3)$$

The $CacheWeight_y$ factor can be explained as; it is the distance between the provider and the consumers. In equation 1, α shows the distance in hop-count and it is selected as a constant integer in which the value of cache capacity of a path link is stored. The $\text{CacheWeight}_{\text{MRT}}$ refers to the duration that identifies for how long a transmitted content can stay at a nodes' cache. $\text{CacheWeight}_{\text{MRT}}$ is derived from two factors as expected Mean Residence Time (MRT_{exp}) and Mean Residence Time (MRT_m). Suppose the value is selected as $MRT_{exp} = 5$ seconds, $\alpha = 1$, and the value of the y parameter is selected as 1, 2, 3, and 4 with routers R1, R2, R3, and R4 respectively. The value of MRT_m factor is derived as 8, 3, 5, and 15 along the routers R1, R2, R3, and R4, respectively. Therefore, CacheWeighty factor will be calculated as 0.5, 0.33, 0.15, 0.2 and this value is dispersed along the data routing path with each router as R1 = 0.5, R2 = 0.33, R3 = 0.15, and R4 = 0.2 as shown in Figure 4. In response to Interest1 (received from Consumer A), the content C1 will be cached at all the routers according to the given probabilistic values.

C. MOST POPULAR CACHE (MPC)

In Most Popular Cache (MPC) [35], each node is associated with a special entity known as a popularity table in which three types of information such as the content name, the popularity count, and the threshold is needed to be stored about the cached content. All the routers need to calculate the number of incoming Interests for each content-name to measures the popularity of a content. The threshold is the maximum value according to which the content is considered as popular, and this value is suggested by the content caching mechanism.

When the popularity count for a particular content-name becomes equal to the threshold value, the content is labeled as popular. If a router holds that popular content, it recommends its neighbor routers to caches the content by sending a suggestion message. The suggestion message may or may not be acknowledged, depending on the resources (i.e., the caches) availability. As the popular content is cached at neighbor routers, its popularity is reinitiated to avoid the flooding of similar content to be cached at unwanted locations.

Figure 5 elucidates the MPC caching mechanism in which two Interests are sent by consumers A and B from the routers R4 and R6 to retrieve the content C1. At the same time, another Interest (Interest1) is received from consumer C to retrieve the content C2 from router R3. According to MPC, content C1 is labeled as popular content because it has received two Interests that were equal to the threshold value, as shown in Popularity Table 1 (see Figure 5). Therefore, router R3 sends suggestion messages to its neighbor routers (e.g., R2, R4, R4, and R6) to be cached the content C1, and the popularity of content C1 is reinitialized to 0, as shown in Popularity Table 2 (see Figure 5).

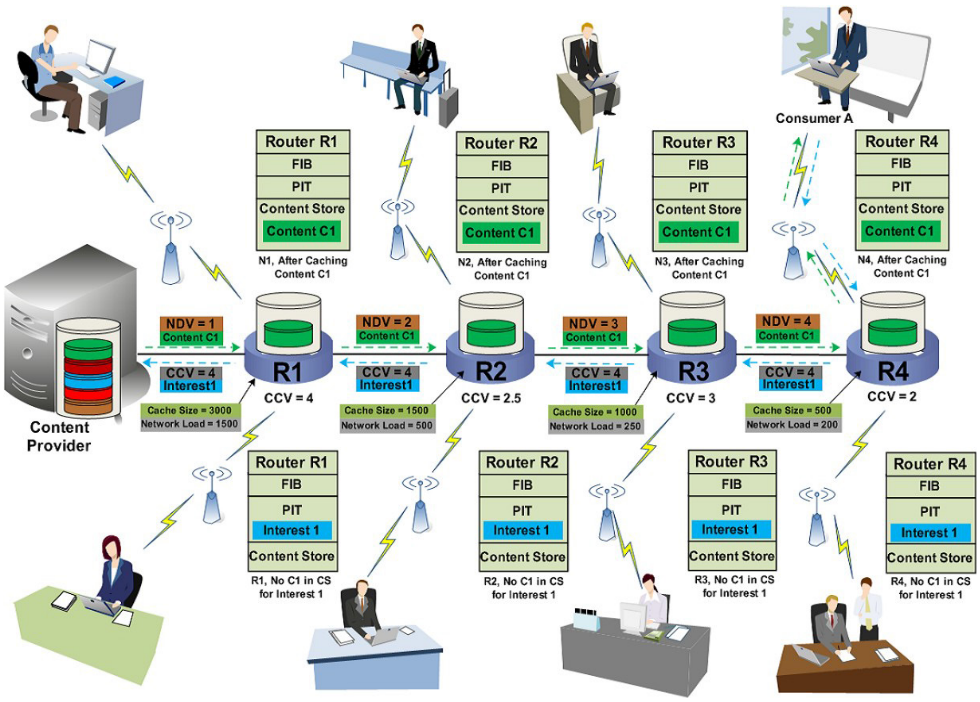


FIGURE 6. Cache capacity aware cache.

D. CACHE CAPACITY AWARE CACHING (CCAC)

Cache Capacity Aware Caching (CCAC) was proposed by combining the cache-aware routing and selective caching mechanisms. The aim of CCAC was to minimize the data traffic load on a network link. CCAC measures the recent usage of cache to obtain the available cache capacity to be cached the newly arriving contents along the data routing path. In CCAC, the consumers' Interests disseminates with the help of extra FIB that is used to transmit the arriving Interests toward the appropriate source router. The available cache is measured with the help of an inverse function that tells about the recent usage of cache capacity. According to the usage of cache, each router show diverse size of free cache capacity. Thus, the free cache capacity for particular content is measured by the following equation:

$$CCV(i) = \frac{c}{L(i)} \times Cache_{size}(i) \tag{4}$$

where c shows the compensation value to handle network caching load, L represents the distortion between the routers. In addition, two primitives CCV (i) and network distance are assigned to all the Interests that is used to measure the distance between the consumer and the provider router and free cache capacity. When a cache hit occurs, the required content is transmitted using the following equation:

$$w_r = \frac{\log r}{logN_{total}} = \log_{N_{total}} r \tag{5}$$

In equation 5, the N_{total} represents the number of content and r shows the ranking of popular contents. The popularity of a particular content is measured using the recent record of Interests which was generated for that content. To rank the popular content regarding their popularities, a weight is assigned to each content that is used to list up the content with higher to low popularity value. As the Interest is matched with the required content, the CCV (i) value is assigned to the content during its transmission from the provider to the consumer. For each content, the threshold is calculated individually by integrating the w_r value and CCV (i) value at all the network routers between consumer and provider as given by the following equation:

$$CCV_{th} = CCV_{highest} \times w_r \tag{6}$$

where CCV_{th} represents threshold value, which is used to make a content popular. Figure 6 illustrates the CCAC content caching mechanism. In given Figure 6, Consumer A sends out an Interest to download the required content named as C1. At content provider, the Interest matches with the required content C1 and consequently, the provider sends the requested content C1 to the appropriate consumer A. During the transmission of C1, a copy of C1 is cached between the consumer A and content provider according to the CCAC content caching mechanisms as shown in Figure 6.

E. WAVE: POPULARITY-BASED CACHING STRATEGY

This caching strategy was designed to achieve data dissemination in chunks form [25]. The objective of WAVE is the efficient distribution of contents as well as reducing the average cache management cost. In WAVE, the content is cached in the form of chunks based on the consumer's requirements. All the chunks are associated with a relation known as inter-chunk relation which is used to keep the record about all

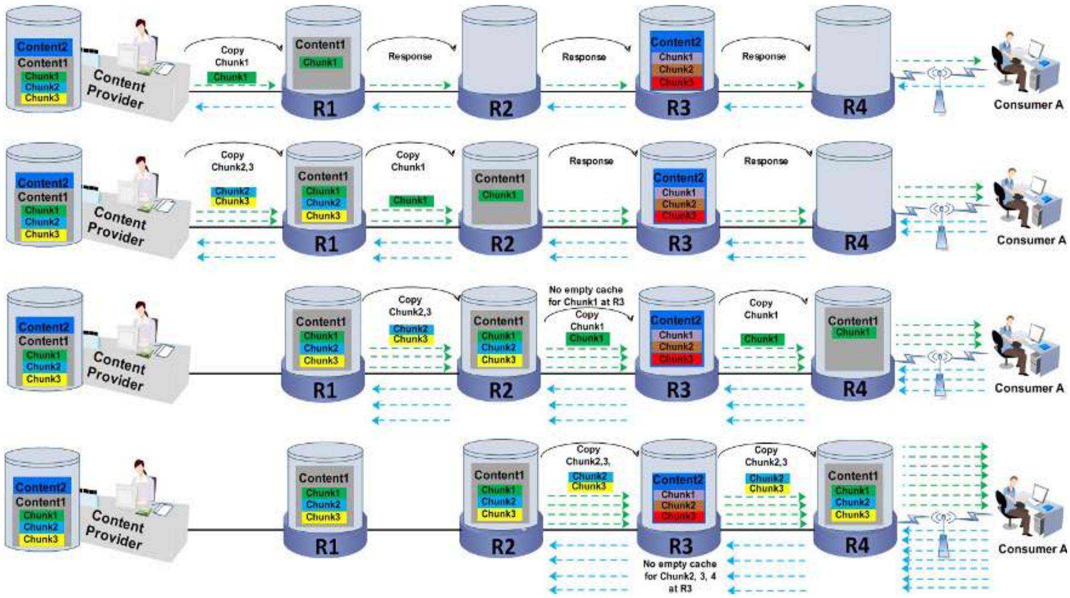


FIGURE 7. WAVE: Popularity-based caching strategy.

the chunks of a content. The WAVE distributes the number of chunks to the network according to the popularity of a content (the number of Interests received by a specific content). It exponentially increases the number of chunks to be cached and gradually forwards these chunks towards the consumers. All the routers individually decide whether the received chunk needs to cache or not. In this strategy, the upstream routers recommend to its down-stream routers to caches the coming chunks, and the router can ignore this recommendation, if the cache storage of the down-stream router is full. If the downstream router does not have free cache to store the coming chunk, the chunk is stored at the subsequent down-stream router. When the content provider receives an Interest for specific content or file, it divides the content into chunks to disseminate the content in chunk form. For instance, the requested content is divided into 50 chunks, and the provider will send that content in the form of chunks to the consumer. All the chunks of a content have a specific type of index, which is used in collaboration with the routers to avoid caching of disorganized chunks because each router individually decides to caches the chunk regarding the caching operation. Moreover, a cache flag bit (e.g., a data packet header) is associated with each chunk for organized data delivery.

Figure 7 illustrates the content caching mechanism of WAVE. In the given scenario, the Content Provider receives an Interest (Interest1) that is generated by consumer A to retrieve the content C1. In response to the Interest1, the Content Provider sends the content C1 to Consumer A and Chunk1 is cached at router R1 during the first transmission of content C1 from provider to consumer. Later on, Interest2 is sent by consumer A to download the same content C1 again. Consequently, the content C1 is sent to consumer A and the chunks (Chunk2, Chunk3) belonging to C1 are exponentially cached at router R1 and Chunk1 is cached at router R2 in the second transmission of content C1. This process is continuously performed, and the chunks are gradually forwards towards the consumers as shown in the given scenario (Figure 7). In response to Interest4, the entire chunk reaches at the edge router R4 and all the subsequent Interests is accomplished from router R4.

F. DYNAMIC FINE-GRAINED POPULARITY BASED CACHING (D-FGPC)

Dynamic Fine-Grained Popularity-based Caching (D-FGPC) defines a dynamic-based threshold to calculate the contents' popularities [40]. In D-FGPC all the incoming contents are cached at intermediate routers during the contents' transmission from provider to consumers. Moreover, when the cache of a router becomes full, the D-FGPC starts assigning the popularities to the cached contents. To measures the popularities for contents, the content-name, content counter, and the time stamp are required to update continuously. Whenever content arrives at a router's cache, the popularity of that content is compared with a threshold value and the content is cached using the Least Recently Used (LRU) policy [41], only if the content has greater popularity value than the threshold value. The threshold value is set by the strategy's algorithm that is used to evaluate the popular content. If the arriving content has popularity value smaller than the threshold value, it will not recommend to be cached at intermediate routers. However, if the content has more popularity value than the threshold, the content is suggested to be cached at downstream router. Moreover, the content is deleted using LRU content replacement policy whenever the new content with higher popularity value is arrived.

Figure 8 illustrates the content caching mechanism in D-FGPC. In the given figure, initially, the content C3 and C2 are cached already along the data routing path because D-FGPC caches all the incoming contents until the cache storage will be overflowed. Three Interests are sent to download the content C1 from Publisher. After receiving three Interests, the content C1 becomes popular and it is suggested to be cached at intermediate routers. However, the cache storage is full at all the routers along the data routing path. Therefore, the content C3 is evicted using LRU content replacement policy to accommodate the arriving content C1 because the content C1 has grater popularity value than C2 and it is already recommended as popular. Thus, content C1 will be cached at all the routers along the data routing path as shown in Figure 8. In D-FGPC, the threshold value is dynamically changed whenever the content gets more popularity to caches the content that is associated with the highest popularity values.

G. COMPOUND POPULAR CONTENT CACHING STRATEGY

The Compound Popular Content Caching Strategy (CPCCS) was proposed to implement the basic idea of dynamic threshold value [24]. Therefore, the content is divided into two kinds such as Optimal Popular Content (OPC) and Least Popular Content (LPC). In CPCCS, the OPC and LPC are selected by calculating the total number of received Interests for a particular content name. All routers calculates the number of received Interests for each content-name using the PIT record and categorize the content into the OPC (the content that received most of the consumer Interests) and LPC (the content that received least consumer Interests) based on the received Interests. The threshold value is taken by the average of the total number of received Interests for all contents and it is changed whenever a new Interest is generated. The threshold value shows the average of the total number of received Interests for all contents. If the number of received Interests for a particular content-name is greater than the average of the total number of received Interests for all contents, the content is selected as OPC.

Meanwhile, if the total number of received Interests for a particular content-name is less than the average of the total number of received Interests for all contents, then the content is selected as LPC. According to the content selection algorithm, all the LPC contents are sorted as ascending order in a list, and then one-fourth of the total contents from that list are selected as OPC that were most frequently fetched recently. Therefore, the most popular content from that list is selected to increase the cache hit ratio. Thus, a copy of OPC is cached at the all mutually connected routers along the data routing path to reduce the computational overhead and the high bandwidth cost for the dissemination of subsequent Interests and the caching state of mutually connected router is shared with its neighbor routers via a broadcast message to inform them about the location of OPC.

In CPCCS, LPC is cached only at one mutual router that occurs near the requested consumers. To avoid the unnecessary usage of cache, the LPC caches only at one router because there is less chance to regenerate the Interests for LPC. Hence, most of the cache is used to accommodate the OPC content. Figure 9 illustrates the basic content caching mechanism of CPCCS. In the given scenario, router R10 receives four Interests from consumers A, B, and C. To respond, router R10 becomes a provider and sends content C1 to consumers A, B, and C. In Figure 9, the consumers Interests are indicated by dotted line arrows. The solid-line arrows indicate the responses from the provider. Simultaneously, two Interests for content C2 are received from consumer D and consumer E at router R10. In response, R10 sends content C2 to consumer D and consumer E.

According to the CPCCS caching mechanism, the total number of received Interests for content C1 is 6. Subsequently, content C1 is selected as OPC since it has an extra Interest over the average of the total number of Interests that were received for both content C1 and content C2. Therefore, the caching operations during the transmission of content C1 as OPC are done at mutually connected routers R4 and R6 because both routers R4 and R6 are mutually connected with interested consumers A, B and C. Therefore, the subsequent Interests from consumer A, B and C will be satisfied from these mutually connected routers (R4 and R6). Secondly, the content C2 is selected as the LPC because it has fewer Interests than the average of the total number of received Interests for content C1 and content C2 at provider router R10. Therefore, content C2 will only be cached at one mutual router as R11 that indicating lest distance from the interested consumers D and E, as shown in Figure 9.

IV. PERFORMANCE EVALUATION

The performance of popularity-based caching strategies is evaluated in an NDN-based simulation environment to check the effectiveness of all caching strategies to find the optimal solution on the bases of evaluation metrics. For the present study, four significant metrics such as cache hit ratio, content diversity, content redundancy, and stretch are selected to be evaluated the overall caching performance. The SocialCCNSim [7], [21], [24], [39], [42] simulator is selected as a simulation platform and Least Recently Used (LRU) content replacement policy is adopted to release the cache storage and make room for new contents to be cached at intermediate routers. In addition, four types of content categories such as Video on Demand (VoD) content, Web content, User Generated Content (UGC), and File sharing content are selected to extensively and comparatively study the popularity-based caching algorithms. The popularity of the aforementioned traffic categories is defined through Zipf distribution. Table 2 shows the basic parameters which are selected for the current simulation. Various topologies such as GEANT, Abilene, DTeleKom, and Tiger are used to test the effectiveness of cache management strategies. For the traffic source, the SocialCCNSim-Master has emerged

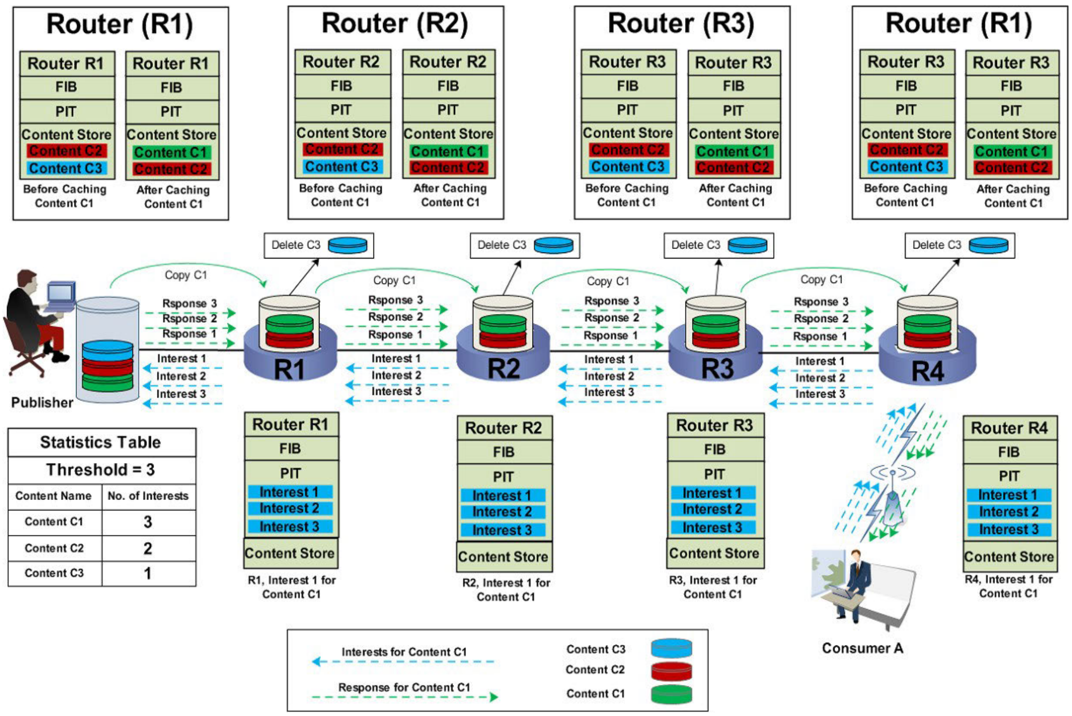


FIGURE 8. Dynamic fine-grained popularity-based caching.

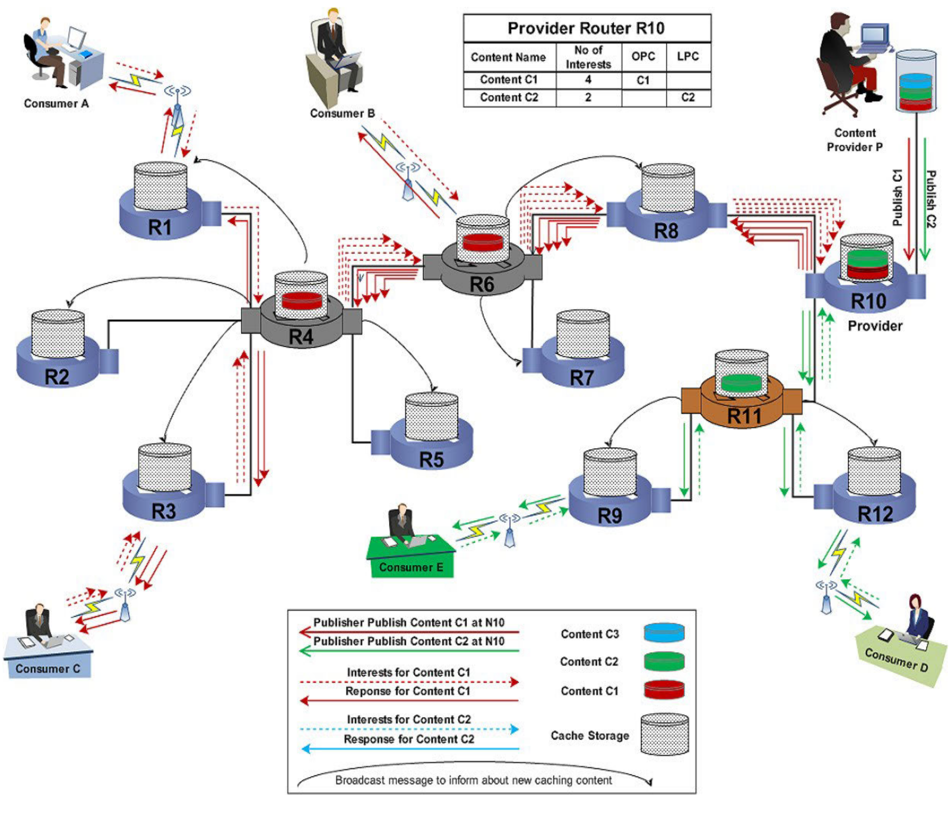
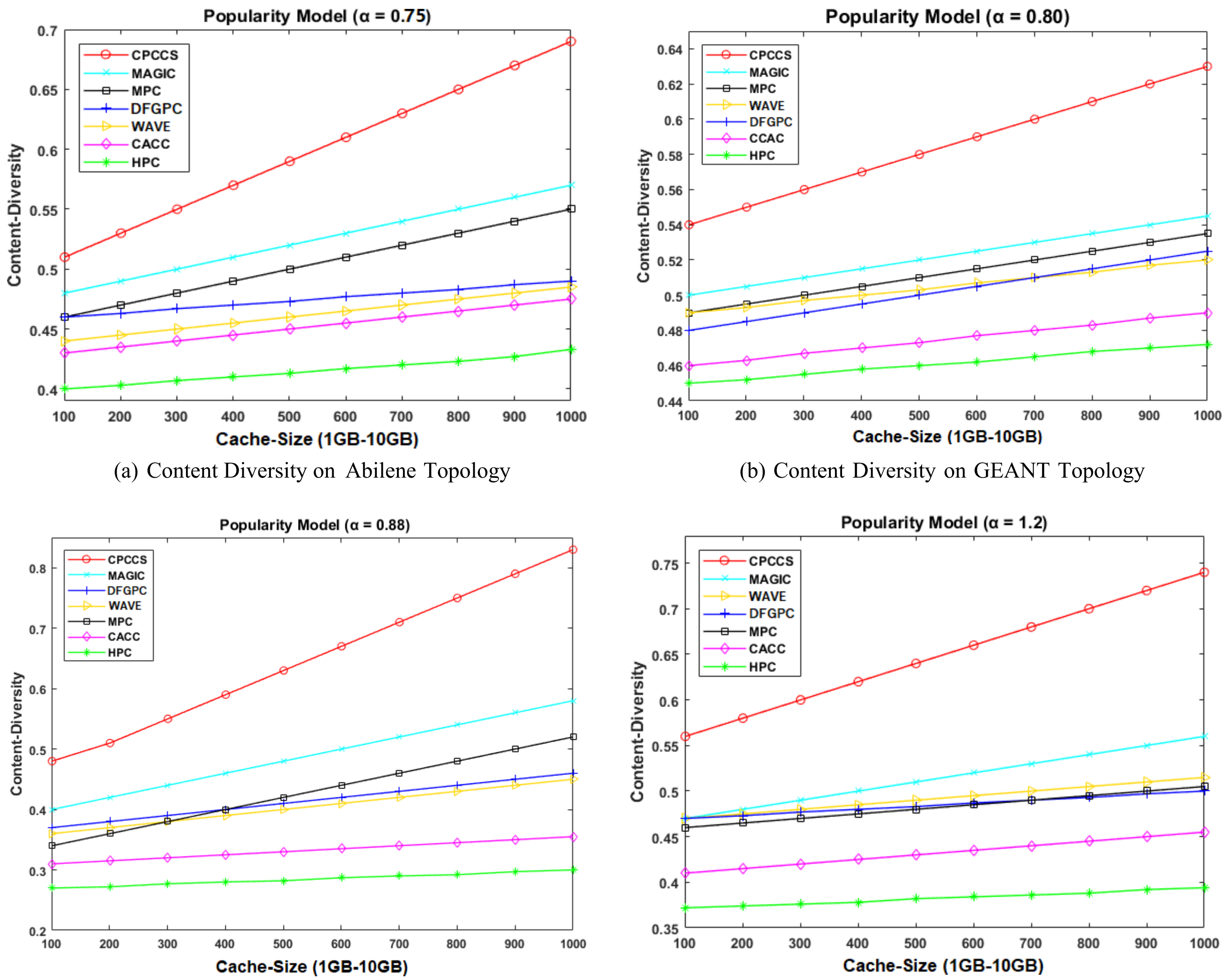


FIGURE 9. Compound popular content caching strategy.

with SONETOR that collects the traffic from the Facebook topology. In each simulation graph, the x-axis is split into 10 equal sections that represent the incremental cache size. Each section represents an increment of 1GB (100 elements) as starting from 100 to 1,000. While the y-axis shows the percentage value of achieved results.



(a) Content Diversity on Abilene Topology

(b) Content Diversity on GEANT Topology

(c) Content Diversity on DTelekom Topology

(d) Content Diversity on Tiger Topology

FIGURE 10. Simulation results on content diversity.

TABLE 2. Simulation description parameters.

Parameter	Value/Description
Simulator	SocialCCNSim-Master
Traffic Source	SONETOR (Facebook)
Content Categories	File, Web, UGC, and VoD
Simulation time	24 hours
Chunk Size	10 MB each
Cache Size	1GB to 10 GB (100-1000 elements)
Catalog Size	10^8
Topology	Abilene, GEANT, DTelekom, Tiger
Replacement Policy	Least Replacement Used (LRU)

A. CONTENT DIVERSITY RATIO

It is the ratio of heterogeneous contents accumulates in-network cache-able routers. Diversity can be defined as follows:

$$Diversity = \frac{\bigcup_{v=1}^{V} X_v}{\sum_{v=1}^{N} C_v} \tag{7}$$

where $\bigcup_{v=1}^{V} X_v$ represents the amount of unique contents within the n number of routers, and $\sum_{v=1}^{N} C_v$ shows the cache storage of all nodes in a network. V represents the total number of nodes.

This study intends to check the high number of diverse-contents' replications and to make room for new incoming content based on the popularity-based caching strategies. The replication of similar contents occupies a large amount of cache storage, which increases the amount of network traffic, congestion and minimizes the amount of diverse content within the network. From the simulation results shown in Figure. 10 (a, b, c, d), we can conclude that the HPC caching strategy is showing less diversity ratio due to its algorithm leaving all the transmitting contents everywhere. Also, the replication of homogeneous contents in HPC is higher than other strategies. Moreover, when we enlarge the cache size from 1GB to 10GB, HPC achieves a slightly better diversity ratio with all content categories and different topologies. The reason is that it cannot reduce the replications that were performed by similar contents within a large cache size.

CCAC is showing a higher diversity ratio than HPC because it reduces the homogeneous contents' replications than HPC. However, it shows little diversity ratio as compare to the MPC due to the higher number of replications that are performed by identical contents. As compared to other strategies, MPC is performing in a different way, because of its procedure to calculate popularity content. Moreover, it has performed better with large cache size than other strategies since it allows to cache content only at neighbor routers and remains the other nodes empty along the data routing path. As a result, with large cache size, supplementary content can be accommodated with diverse nature. DFGPC and WAVE have achieved moderate results due to their nature of algorithms to caches content at partial routers. The reason is that, both strategies allow limited number of replications of a content.

MAGIC has showed better performances in terms of diversity ratio because it allows a content to be cached at limited routers along the data delivery path. CPCCS has boosted the diversity ratio because it does not allow a content to be cached at multiple locations. When we enlarged the cache from 1GB to 10GB, CPCCS still performs better than the other strategies because it does not allow contents to be replicated at numerous locations within large cache sizes. Indeed, CPCCS allows limited copies of a content to be cached along the data delivery path. If the path is associated with a short stretch, the CPCCS caches content only at unique routers. Hence, it is concluded from the given Figure 10, the CPCCS is achieved better performance with all content categories (File, Web, UGC, and VoD) in terms of improving diversity ratio as compared to other strategies.

B. CACHE HIT RATIO

The cache hit ratio is a key metric in evaluating the performance of the NDN-based cache. It refers to the responses by the in-network cache storage in which the content is locally cached for a specific time [30]. It can be calculated as follows:

$$Cache\ Hit\ Ratio = \frac{\sum_{n=1}^{n} Hit_n}{\sum_{n=1}^{n} (Hit + Miss)} \tag{8}$$

The cache hit occurs when a consumer's requested content is found at the network router's cache. The router reacts as a provider by sending the corresponding content to the appropriate consumer [42], [43].

Figure 11 (a, b, c, d) shows the results is achieved using different topologies (Abilene, GEANT, DTelekom, and Tiger). The results show that the CPCCS is performing better with all the cache sizes as compared to other caching strategies. CPCCS shows good quality of cache hit ratio throughout the simulation results with all content categories (i.e., File, Web, VoD, and UGC). The rationale is that the CPCCS caches OPC close to the consumers, which increases the availability of the most desired content to fulfill the requirements for subsequent Interests. Another benefit is that it initializes a time-span for each content, which indicates that how long a content can be cached at a particular location (i.e., router). Therefore, CPCCS decreases the unnecessary usage of cache storage and increases the free cache to accommodate new contents. CPCCS also improves the caching of heterogeneous content by selecting OPC and LPC. Other strategies such as WAVE, MAGIC, DFGPC, and HPC are showing similar performance in terms of cache hit ratio with small and large cache sizes. However, HPC shows a better cache-hit ratio due to its selection of caching content at all on-path routers for a specific time.

Meanwhile, MPC performed better than WAVE and CACC, but its results were not as favorable as those of CPCCS because MPC takes longer to select the popular content. In addition, it uses a popularity table for each content-name, which increases the searching overhead when calculating the most popular content. Moreover, MPC caches the most popular content at all neighbor routers, which increases the unnecessary usage of cache and reduces its chances of accommodating new incoming content. Thus, the overall hit ratio is decreased. CACC performed slightly worse than MPC because it caches all of the content regardless of the consumer's Interest level at the intermediate router that increases the chance of accommodating the least popular content.

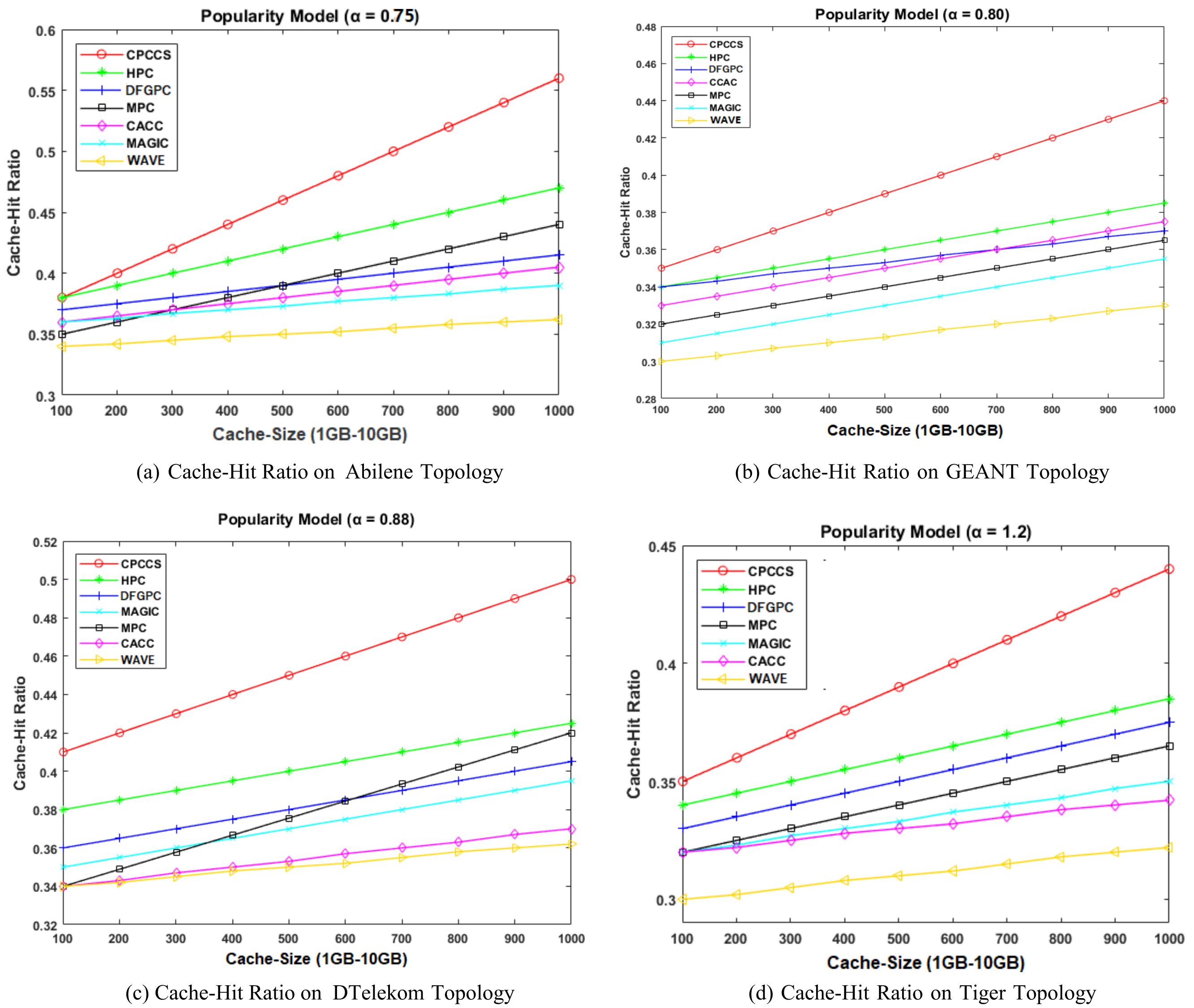
WAVE depicts lower cache hit ratio, because it increases the number of similar contents' replications along the data downloading path and it consumes extra time to bring the required content near the consumers. Therefore, Interests for diverse content needs to forward the Interests to the main provider, which takes a long trip in content downloading. When the cache size is increased, CPCCS still shows better results because of its nature of caching heterogeneous content close to the consumers. We may conclude that CPCCS performs better in terms of the cache hit ratio than the comparing strategies.

C. CONTENT REDUNDANCY

Content-redundancy shows the amount of redundant content caching at multiple locations in the same network [32]. It can be defined using the following equation:

$$\text{Redundancy} = \sum_{i=1}^{n} Rc_i \tag{9}$$

where Rc_i shows the redundancy given by the i^{th} item of the cached contents. Figure 12 (a, b, c, d) illustrates the content-redundancies on Abilene, GEANT, DTelekon, and Tiger topologies. According to the given simulation results in Figure 12, HPC and CACC show higher content-redundancies because both strategies cache all the contents at all the routers on the same path that increases the high amount of similar content duplications. MPC, WAVE, and DFGPC show fewer repetitions of similar contents than HPC and CACC because MPC caches the content at neighbor routers only, and WAVE performs caching operations after receiving a large number of Interests. Moreover, WAVE consumes more time to caches content at all the routers because it delivers the content in distributed chunks form that gradually pushes the content



(a) Cache-Hit Ratio on Abilene Topology

(b) Cache-Hit Ratio on GEANT Topology

(c) Cache-Hit Ratio on DTelekom Topology

(d) Cache-Hit Ratio on Tiger Topology

FIGURE 11. Simulation results on cache-hit ratio.

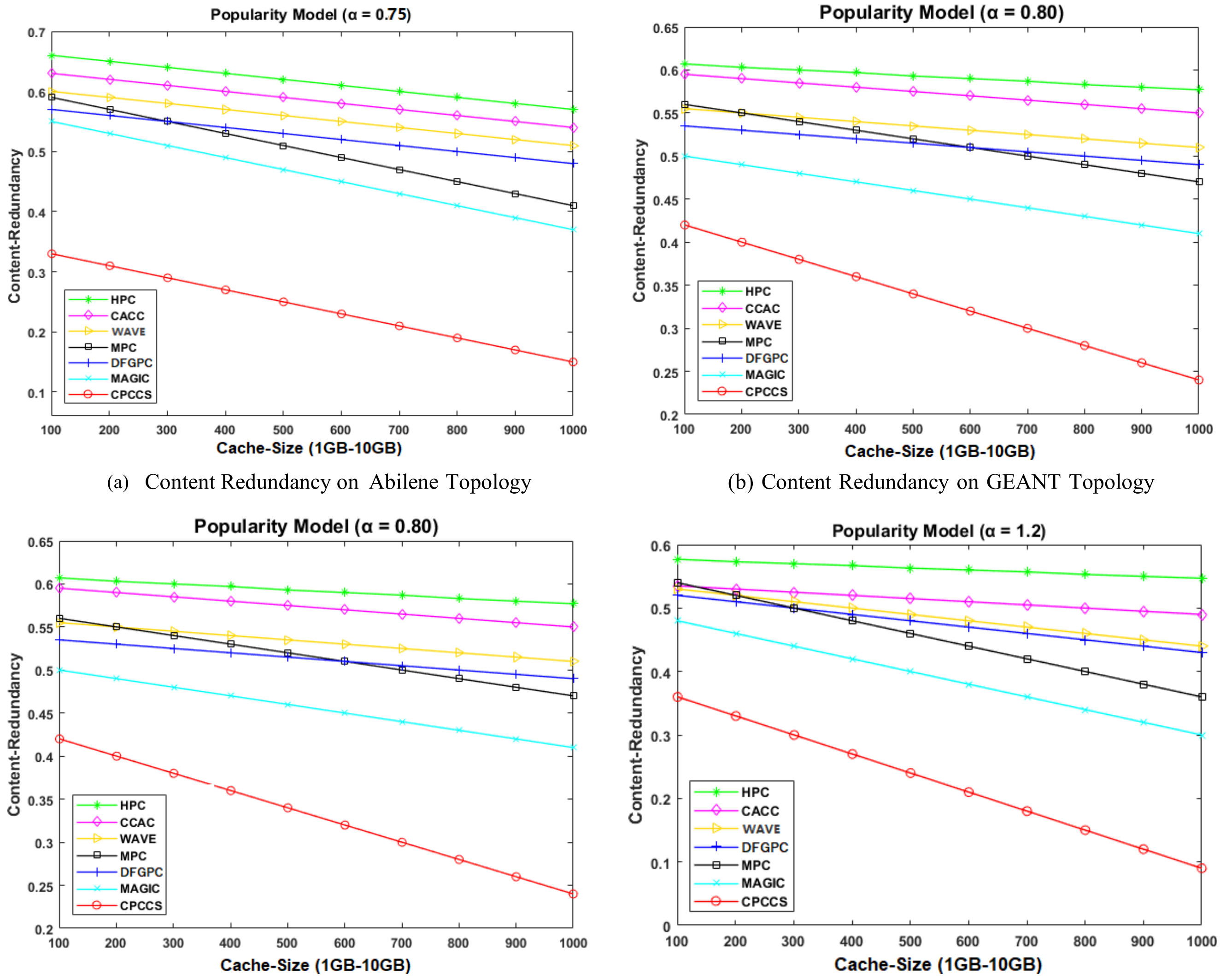
towards the consumers. In addition, DFGPC caches content at several routers for different time-intervals. Therefore, the subsequent Interests are satisfied from these routers to some extent that increases the redundant caching operations by similar contents. MAGIC shows low replications of homogeneous content because it allows the content to be cached at limited routers. Hence, it shows better performance in terms of redundancy. CPCCS performs better in terms of redundant caching operations than the other strategies because of its nature of performing caching at partial locations alongside the data routing path.

D. STRETCH RATIO

The distance traveled by a consumer Interest toward the content provider is known as stretch. The following equation is to calculate the stretch as:

$$\text{Stretch} = \frac{\sum_{i=1}^{R} Hop - traveled}{\sum_{i=1}^{R} Total - Hop} \tag{10}$$

where $\sum_{i=1}^{R} Hop - traveled$ shows the number of hops covered by an Interest between the consumer and the content provider router, $\sum_{i=1}^{R} Total - Hop$ represents the total number of hops between the consumer and provider and I illustrate the total number of generated Interests for specific content-name. CPCCS caches the popular content close to the consumers at the central position (mutual centrality node), from where all the desired consumers can get their required content. Therefore, it makes the distance smaller between consumer and provider. Thus, most of the consumer Interests travel through mutually connected router and satisfies from these router.



(a) Content Redundancy on Abilene Topology
(b) Content Redundancy on GEANT Topology
(c) Content Redundancy on DTelekom Topology
(d) Content Redundancy on Tiger Topology

FIGURE 12. Simulation results on content redundancy.

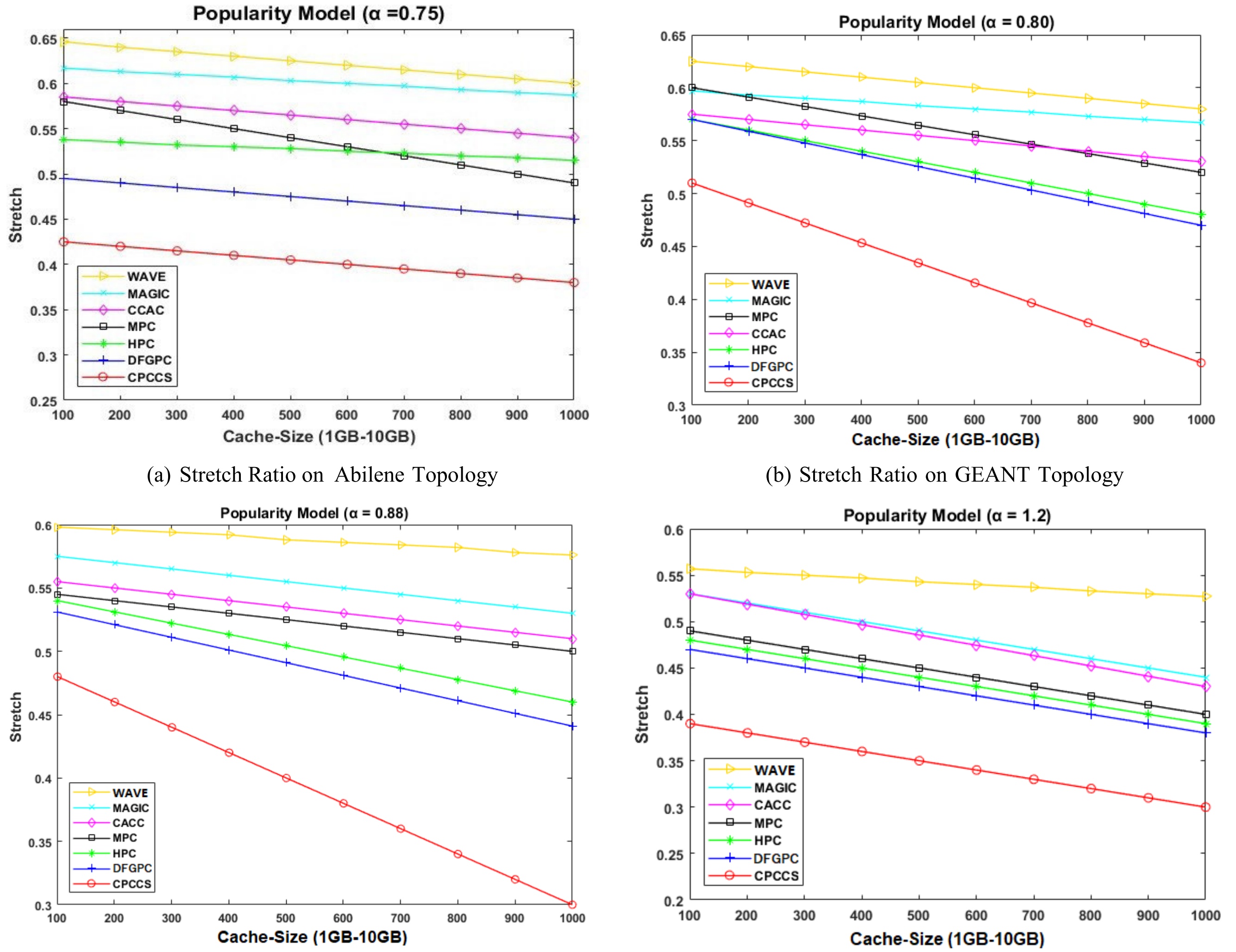
Moreover, CPCCS selects diverse popular content to be cached close to the consumers that increase the overall stretch ratio.

The results on stretch ratio are shown in Figure 13 (a, b, c, d). WAVE shows the lager path stretch with all cache sizes because it caches the popular content only at next router from the provider router that increases the length between consumer and provider. However, WAVE brings the content close to the consumer, but it takes a long time because of its nature of caching the contents in distributed chunk form. As compared to MAGIC and CACC, HPC performs better with small and large cache sizes because it caches a copy of the transmitted content at all on-path routers. As a result, the subsequent Interests are satisfied with the nearer cached copy of the required content. However, MPC and DFGPC produce better results in terms of reducing the stretch because these strategies cache the required contents close to the consumers.

V. CONTRIBUTIONS AND LIMITATIONS

NDN caching is a revolution in modern network architectural requirements. It can overcome the issues related to Internet Traffic. Moreover, it can reduce communication overhead, resource, and bandwidth consumption, through caching popular content at multiple locations. However, it is difficult to decide which content needed to be cached at a location to produce optimal solutions. Cache-management strategies [9], [44], [21] have been developed to achieve efficient results. Still, it is not clear which caching mechanism is the most ideal for each situation. Table 3 illustrates the contributions and limitations of the popularity-based caching strategies.

The DFGPC was proposed to reduce the content redundancy by the selection of popular content using a dynamic threshold value. However, in DFGPC strategy, the content caching mechanism increases the number of homogeneous content's replications, which reduces the amount of cache storage which is required to accommodate the large number



(a) Stretch Ratio on Abilene Topology

(b) Stretch Ratio on GEANT Topology

(c) Stretch Ratio on DTelekom Topology

(d) Stretch Ratio on Tiger Topology

FIGURE 13. Simulation results on stretch ratio.

of diverse content. It also increases the resource (cache) utilization and bandwidth consumption by caching analogous content at different locations. In particular, it decreases the content diversity ratio because it increases the amount of identical content within the network cache, which reduces the amount of memory space available for less-popular contents. Consequently, most of the Interests for less-popular content have to be forwarded to the remote content providers to be satisfied.

The WAVE caching strategy was developed to implement the chunk level caching to reduce the usage of resources and increase the number of diverse content to be cached at a particular location. However, it requires more time for caching entire chunks that belongs to the same content and thus, the cache hit ratio is decreased. Consequently, the WAVE strategy delivers moderate performance in terms of stretch ratio. Further-more, WAVE strategy provides fast content dissemination. However, it distributes redundant and replicates content at multiple locations, exhibits higher resource consumption, no content distinction, and the content has to be continuously updated, resulting in computational overhead.

MAGIC was developed to reduce the bandwidth consumption and stretch (hop reduction). It also provides a solution for the issue of the least recently used contents in the different strategies. While caching contents locally, the best possible position of cache is required. The efficient caching performance can be achieved by caching the transmitted contents at the optimal routers, which will minimize the average cost, usage of resources, bandwidth consumption, and manage the cache efficiently. MAGIC demonstrates a high cost and requires more resources to execute the max gain and local gain values. Consequently, it increases the content retrieval time and decreases the cache hit ratio.

CCAC claims to provide content caching with content routing services. For both services, it employs several entities such as CCV_i, CCV_{th}, additional FIB, w_r (content ranking),

TABLE 3. Contributions and limitations.

Caching Strategies	Caching Category	Aim/Goal	Contributions	Limitations
Cache Capacity Aware Cache	On-Path	Cache content at different locations near the consumers	High cache hit ratio and Less stretch ratio	No distinction for low popular contents, High redundancy ratio, Less diversity ratio, and High memory consumption
Hop-based Probabilistic Caching (HPC)	On-Path	Pushes content towards the consumer for a particular period	High cache hit ratio and Short stretch ratio	No distinction for less popular contents, High redundancy ratio, Less diversity ratio, and High memory consumption
Most Popular Cache	On-Path	Cache popular content at neighbor routers	High cache hit ratio and Low stretch ratio	High redundancy ratio, Less diversity ratio, and High delay due to calculation of content popularities
Dynamic Fine Grind Popularity-based Caching	On-Path	Cache popular content at content dissemination path for a specific time	High cache hit ratio and Short stretch ratio	Less diversity ratio, High redundancy ratio and High memory consumption
WAVE: Popularity-based Caching Strategy	On-Path	Cache content in chunks form and gradually pushes content towards consumers	High cache hit ratio, Less delay, and Short stretch ratio	Less diversity ratio, High redundancy ratio, High memory consumption, and High bandwidth
MAx-Gain In-network Caching (MAGIC)	On-Path	Minimize bandwidth and cache popular content	Low bandwidth, and Less memory consumption	High delay, Low cache hit ratio, and Diversity ratio
Compound Popular Content Caching Strategy	On-Path	Cache optimal popular and least popular contents at restricted locations along data dissemination path for a specific time	High cache hit ratio, Less delay, Low diversity ratio, and High redundancy ratio	Difficult to separate the content regarding their popularities.

and popularity for contents. All these entities execute at all the routers separately whenever an Interest is generated, or a router responds with a Data packet. This process increases the overhead to keep the cache hit ratio at its minimum level since millions of Interests are generated, and correspondingly contents are transmitted in a very short interval. Moreover, CCAC shows the content redundancy because it distributes cache capacity along the data routing path within all routers, and all the contents are replicated wherever they found free-cache. Hence, similar types of popular content are cached at multiple routers that decrease the overall diversity ratio.

MPC utilizes extra space in NDN router' cache because it generates popularity tables for all content, and caches millions of entries for similar content-names and popularity count in popularity tables. MPC leads to some drawbacks that decrease overall caching performance [9], [24]. Usually, MPC generates homogeneous content's replications by caching the same content at all neighbor routers. If the content provider and the consumer are associated with a small-stretch path, MPC keeps diversity at its minimum level because of multiple redundant caching operations along data routing path. Therefore, the diversity ratio cannot satisfy its effiient level. However, if the content becomes popular again, there is no any criterion to stop the flooding of similar content in the network, which increases the utility of the resource (cache). Moreover, the caching of similar content at multiple locations increases the usage of cache storage to manage the popularity table for each content-name at all routers, which increases the communication overhead to decide which popular content needed to be cached at the neighbor routers while multiple contents indicating the same popularity within the limited cache size. HPC was introduced to improve the content caching mechanism in terms of reducing content redundancy. It associates a specific time to all the contents during their dissemination from a provider to a consumer. The caching duration increases with decreasing in distance from the desired consumer. Nevertheless, HPC also increases the homogeneous content replications at multiple locations. However, it does not explain any criteria to cache content when there is no free cache for the accommodation of new content. Therefore, it increases the retrieval latency because there is a possibility of caching contents far from the consumer that increases the stretch [45]. This strategy needs additional computational cost and resource consumption because it requires extra parameters (TSI and TSB) to computed for all the contents at all routers [21].

CPCCS performs better than other strategies in terms of content diversity, cache hit ratio, content redundancy, and stretch ratio. The rationale is the CPCCS strategy caches the optimal popular content near the consumer as well as less popular content at restricted locations. Also, the CPCCS caches the content near the desired consumers, and all the subsequent Interests are satisfied with the cached content that increases the cache hit and stretch ratios. Moreover, CPCCS allows limited content replications that increases the content diversity ratio and reduces the content redundancy. Therefore, CPCCS has performed better in simulation environment to achieve enhanced caching performance [24]. All caching strategies try to reduce the difficulties of the NDN-based caching module. However, it seems that the dynamic threshold gives enhanced performance because the dynamic threshold selects most popular and desired contents to be cached at intermediate routers. Thus, the overall caching performance is increased. Therefore, CPCCS and DFGPC implements dynamic thresholds to select popular content, but CPCCS provides better performance in terms of content diversity and redundancy. The reason is that, the DFGPC caches all the contents along the data routing path that increases the content redundancy ratio and decreases the content diversity ratio.

VI. FUTURE RESEARCH DIRECTIONS

On-path caching is beneficial because of its flexible approach to caching the contents during their transmissions. It delivers several advantages for the Internet technologies such as Internet of Things (IoT) [46]–[48] edge cloud computing [48], [49], Blockchain [50], [51], fog computing [51], [52], Software-Defined Networking (SDN) [53], and fifth-generation (5G) [54] mobile-cellular networks. These technologies can employ on-path caching to enhance their architectural design to implement the most efficient, flexible, and scalable network services.

A. NDN CACHING TO SUPPORT ULTRA-DENSE HETEROGENEOUS NETWORK (UDHN)

The usage of radio frequency powered cognitive network has been increasing in which the data transmission capacity is exceeding that makes difficulties to transmit data from one network to another network [55]. On the other hand, the exponential increment in demands of mobile data traffic is challenging for the current cellular network (4G and 5G). As a result, network densification and Ultra-Dense Heterogeneous Network (UDHN) are the favorable technologies to reduce the high congestion by data traffic in mobile cellular networks [56]. Basically, in UDHN the base stations were deployed near the user using small cells that are densely distributed and consequently the energy is used in efficient manner. Currently, the demands of the consumers for high definition multimedia applications over the mobile Internet are increasing significantly. It is to be noted that the current cellular network delivers a centralized architecture. Therefore, the current mobile technologies cannot satisfy the modern demands using the present backhaul network, link capacity, and bandwidth of the radio access network owing to the large-scale growth of mobile traffic [57], [58].

Therefore, several drawbacks were identified, of which the content retrieval latency owing to the high congested path is crucial to the dissemination process. However, a huge effort is being expended to manage the mobile network equipment, and several operators are being used to enhance the bandwidth in wireless links using modern technologies inside the modern access control layer. Moreover, through long term evaluation of advanced systems it was determined that in the physical layer, the carrier aggregation, coordinated multipoint transmission, and massive multiple-input multiple-output are the most significant. Another important drawback related to mobile multimedia traffic is the multiple downloading of a few popular content (such as a popular song) that is associated with a large size [59]. Therefore, the research community attempted to determine an effective approach that should be flexible for decreasing the amount of homogeneous duplications in the overall network transmissions.

In these situations, NDN offers considerable services by deploying in-network cache, which can reduce the overall network traffic load. Moreover, it can decrease the content retrieval latency by caching a copy of the disseminated popular content at intermediate locations to respond to the successive requirements. In addition, on-path caching can reduce the usage of energy, resources, and a large amount of mobile traffic that will be handled within a small capacity link and bandwidth [21]. Therefore, a consumer sends an Interest to any caching [60] router and the required content will be delivered to the consumer by any router holding the corresponding content. Conversely, if the content is not found at one place, the router forwards the Interest towards the appropriate provider source router. [45]. To respond to the received Interests, each caching router can send a copy of the corresponding content to the mobile network devices and the subsequent response will be delivered from the caching routers; thus, it is not required to forward the Interests to the remote server. Consequently, to enhance the quality of service for all consumers, it is crucial to design a suitable caching strategy for on-path caching-based 5G networks [7], [61].

B. SOFTWARE-DEFINED BASED CACHING

Software-Defined Networking (SDN) has earned extensive attention in both academia and industry. SDN, ease the burden on forwarding devices by implementing control functionalities in the logically centralized external entity, called controller. The key concepts of SDN can be utilized to fulfill the network requirements such as network management, network function virtualization, resource utilization, security and privacy, energy management, and interoperability. SDN may improve the caching and in particularly, popularity-based caching in NDN by moving the caching decisions to the controller. The rationale of moving caching decisions to the controller is the controller usually has the complete knowledge of forwarding devices and also has more computational resources. Therefore, the controller may precisely decide the location and node for caching the popular content. However, relying only on the single centralized controller may cause the load-balancing and single point of failure issues. The plausible solution to avoid these issues is to employ the concept of distributed controllers in the network. Dedicated research in this direction may greatly improve the decisions of caching popular content.

In SDN, the failure of the controller can be disturbed to the specific flow of the network because the controller is in charge of all the configurations, operations, and validations of the network resources and topologies. Moreover, it is unsafe for those environments where only one controller is performing because if the controller breaks down, the network flow will be stopped completely as there is no available backup facility [62], [63]. Therefore, on-path caching is useful to manage these critical problems and it can deliver better performance by caching the transmitted content at intermediate locations for subsequent interests [64]. Moreover, SDN can be integrated with on-path caching to create a more beneficial network architecture in which the controller of SDN will manage by NDN network [65]. Consequently, the network will be managed through the SDN control plane in which protocols and diverse policies will be merged. The contents within the caching nodes will be controlled by using the data plane and the network devices such as the routers and switches, which will work together on the data plane.

C. NDN CACHING FOR INTERNET OF THINGS

The Internet of Things (IoT) is a new promising architecture that integrates several technologies and communication developments. It provides several benefits using identification and tracking technologies for both wired and wireless networks. Moreover, it offers distributed intelligence for smart objects [66]. The IoT technology delivers benefits to almost all fields, such as informatics, telecommunication, social science, and electronics. However, IoT still faces several complications owing to the large amount of data that is produced from heterogeneous smart devices. Numerous diverse sensors are required in IoT that increases the power and resource consumption. Furthermore, IoT devices transmit huge amount of contents that are difficult to manage using the current Internet architecture. In these situations, on-path caching introduces an enhanced architecture of the Internet, which can overcome the current challenges of the IP-based Internet and IoT.

The extensive number of smart devices generates a significant amount of content that can be managed easily by the implementation of on-path caching. On-path caching provides content availability to the network routers and all the routers can stores the disseminated contents during their transmission. Consequently, they can fulfill the requirements of subsequent Interests in a shorter time span when compared to the retrieval of content from remote servers. Moreover, on-path caching can reduce the power and resource consumption; thus, if a source node in the IoT is in a sleeping mode, the consumers can still retrieve their desired content from any other caching node. The integration of ICN within the IoT can increase the reliability of IoT architecture by deploying the content near the end consumers. Furthermore, on-path caching provides efficient content distribution with enhanced transmission efficiency and low latency in content dissemination.

D. NDN CACHING FOR BLOCKCHAIN

The blockchain growth is still facing restrictions and bottlenecks in content routing using the present IP location-based Internet architecture. It delivers irregular connectivity with unsuitable protocols that increases the content retrieval latency, which causes the inconsistency in the blockchain. Moreover, the TCP/IP protocols are insufficient to provide multicasts, which increases the data dissemination overhead [50]. However, on-path caching is an ideal candidate for the future Internet in which the content selection is based on a primary component rather than the physical locations. The on-path caching provides the ability of cacheable nodes that are used to reduce the data transmission problems in a network by caching a copy of the disseminated contents at intermediate nodes for subsequent data transmission.

E. NDN CACHING FOR FOG COMPUTING

The main advantage of fog computing is distributed storage that is used to reduce the content retrieval latency. However, it cannot be fully profitable because of the limited storage capacity and processing speed. In this situation, the integration of on-path caching with fog computing promises to achieve better results in terms of enhancement of the storage capacity for content retrieval in a short time [67], [68]. It offers an in-network cache between the global network and the underlying networks that links the IoT connected devices with distributed fogs. Several cache management mechanisms were designed (e.g., probabilistic caching and popularity-based caching) to increase the efficiency of transmission of contents within a limited resource (cache) [51]. Moreover, in-network cache delivers several benefits over the fog computing, such as low retrieval latency, low congestion of network traffic, low power consumption, and low computational overhead in the content routing process [69]. In addition, on-path caching is used to increase the amount of diverse contents and deliver contents near the end consumer, which decreases the total network traffic whereas it provides faster responses for subsequent content retrieval processes within a short time period.

F. INTELLIGENT CACHING

Artificial Intelligence and specifically machine learning techniques have made a breakthrough in the field of networking in recent years. Various machine learning techniques such as supervised learning, unsupervised learning, reinforcement learning, and federated learning can be used to improve the network performance from various perspectives such as congestion control, intrusion detection, and routing decisions [70]. These techniques can be employed in the decision making of caching and specifically popularity-based caching in the NDN domain to locate the precise location of the content. However, to select the appropriate machine learning algorithm that can optimize the caching decision may require further research effort in this direction.

G. CACHING IN HIGHLY MOBILE ENVIRONMENTS

Mobility is a very important factor in the domain wireless sensor network (WSN), mobile AdHoc networks [71], and cellular communication. A mobile producer or mobile cache node may greatly affect the performance of NDN caching in terms of data unreachability when a mobility event occurs. In node mobility, especially in the case of mobile WSN, the location of cached content change constantly. For example, if a particular node (node-A) fetched content chunk (content-chunk-A), and it is cached someplace in the network at mobile node (mobile-node-B), the next request for another chunk (content-chunk-B) of same content from node-A may not reach to the mobile-node-B because it is highly likely that the node is at different location. Consequently, it affects the overall performance of a network. Future research in this direction can further improve the popularity-based caching decision in NDN.

H. NDN CACHING SUPPORT FOR 5G AND BEYOND

In the 5G communication and beyond, demand for low latency services is expected to increase. In low latency services, especially in the case of 5G, real-time feedback for the end-user is required and, to fulfill this requirement, there is a need to process large amounts of data near to the end-user. Edge computing is a promising concept in which resource-full devices are positioned near the end-user to store and process large data quickly. Caching the most popular content near to the end-user, i.e., on the edge devices (base-station), may further improve the key requirement of ultra-low-latency. However, to handle the dynamic traffic requirements of the end-users at base-station may further require more research effort in this direction.

I. CACHING IN WIRELESS SENSOR NETWORK

Wireless Sensor Network (WSN) may comprise heterogeneous nodes with limited resources such as low computational power, short communication range, small size battery source and limited storage capacity. These nodes sense the environment and store the acquired information into their small memory for a very short time and then forward the information toward the sink node. The nodes in WSN are content centric in nature and thus NDN could be a best fit for WSN [72]. NDN caching can improve the performance of WSN in terms of latency reduction and energy consumption by considering the resource contained nature of the WSN nodes.

VII. CONCLUSION

In this paper, on-path popularity-based NDN caching strategies are comparatively and extensively explained to overcome the intensifying concerns of the current Internet. The position of this paper is manifold. First, certain basic caching aspects and their caching strategies are explained, which are essential for achieving efficient results in NDN data communication. Second, we critically analyzed and described the contributions and limitations of popularity-based caching strategies. The CPCCS and DFGPC performed better in terms of achieving enhanced content diversity ratio, cache hit ratio, content redundancy ratio, and stretch ratio because of their flexible nature to select the content OPC and LPC content using dynamic threshold and cache the contents at appropriate locations. Fourth, we presented future directions and open research challenges of integrating on-path caching with other networking fields such as radio frequency powered cognitive network, Ultra-Dense Heterogeneous Network, IoT, fog computing, edge computing, and 5G.

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