تقييم فعاليّة سياسة استبدال ذاكرة التخزين المؤقت ICCP مقابل LRFU في شبكات البيانات المسماة

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ملخّص

شبكات البيانات المسماة Named Data Networking (NDN) هي إحدى معماريّات شبكات المعلومات المركزية Information Centric Networking (ICN)، وهي مصممة لتكون بنية متقدّمة جديدة في أنظمة الاتصالات. تركّز شبكات البيانات المسماة على اسم المحتوى بدلاً من عنوان مصدر المحتوى. في بحث سابق، تم اقتراح ICCP كسياسة استبدال ذاكرة التخزين المؤقت المحسّنة المعتمدة على شعبية المحتوى. تتمثل مساهمة هذا البحث من خلال تقييم أداء سياسة استبدال ذاكرة التخزين المؤقت ICCP مقابل سياسة LRFU المدمجة حديثاً وذلك عبر سيناريوهات محاكاة مختلفة باستخدام محاكي ndnSIM. بالإضافة إلى ذلك، يدعو هذا البحث إلى التبني الدائم لسياسات الاستبدال القائمة على شعبية المحتوى، مثل ICCP. يتم إجراء عمليات المحاكاة على طوبولوجيا شبكة GÉANT في سيناريوهين. في السيناريو (أ)، يرسل المستهلك رزم الاهتمام بمعدل 100 رزمة في الثانية. تم إعداد سبع تكوينات مختلفة، مع أجهزة توجيه مجهزة بـ مخزن محتوى بمستويات 100% و80% و50% و40% و30% و20% و5%. في السيناريو (ب)، يرسل المستهلك رزم الاهتمام بمعدل 500 رزمة في الثانية، مع ضبط مستويات ذاكرة التخزين المؤقت على 100% و80% و50%. تُظهر نتائج المحاكاة وتقييم الأداء أن ICCP تتفوق على LRFU من حيث معدل الوصول إلى ذاكرة التخزين المؤقت (CHR) بنسبة 4.4٪ في السيناريو (أ) و 5.4٪ في السيناريو (ب). هناك نتيجة أخرى وهي أن ICCP تقلّل من متوسط تأخير الاسترداد بمقدار 1 مللي ثانية مقارنة بـ LRFU في السيناريو (أ) وبمقدار 0.5 مللي ثانية في السيناريو (ب). أخيراً، فإن متوسط حركة المرور على الشبكة

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في ICCP أقل بمقدار 1.3 رزمة في الثانية مما هو عليه في LRFU في السيناريو (أ) وأقل بمقدار 5.7 رزمة في الثانية في السيناريو (ب).

الكلمات المفتاحية: شبكات البيانات المسمّاة، التخزين المؤقت داخل الشبكة، سياسة استبدال ذاكرة التخزين المؤقت المحسّنة المعتمدة على شعبية المحتوى، سياسة الأقل تكراراً واستخداماً مؤخراً.

Evaluating the Effectiveness of ICCP vs. LRFU Cache Replacement Policies in Named Data Networking (NDN)

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ABSTRACT

Named Data Networking (NDN) is one of the Information-Centric Networking (ICN) architectures, designed to be an advanced new architecture in communication systems. NDN focuses on the content name rather than the source address of the content. In previous work, ICCP was proposed as an Improved Cache replacement policy based on Content Popularity. The contribution of this paper is to evaluate the performance of the ICCP cache replacement policy against the newly integrated LRFU policy across various simulation scenarios using the ndnSIM simulator. Additionally, this paper advocates for the permanent adoption of content popularity-based replacement policies, such as ICCP. Simulations are conducted on the GÉANT network topology under two scenarios. In scenario (a), the consumer sends Interest packets at a rate of 100 packets per second. Seven different configurations are set up, with routers equipped with Content Store (CS) at levels of 100%, 80%, 50%, 40%, 30%, 20%, and 5%. In scenario (b), the consumer sends Interest packets at a rate of 500 packets per second, with cache levels set at 100%, 80%, and 50%. Simulation and

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performance evaluation results show that ICCP outperforms LRFU in terms of Cache Hit Rate (CHR) by 4.4% in scenario (a) and 5.4% in scenario (b). Another finding is that ICCP decreases the average retrieval delay by 1 ms compared to LRFU in scenario (a) and by 0.5 ms in scenario (b). Finally, the average network traffic under ICCP is 1.3 packets per second lower than under LRFU in scenario (a) and 5.7 packets per second lower in scenario (b).

Keywords: Named Data Networking (NDN), In-network Caching, ICCP policy, LRFU policy.

1. Introduction

Named Data Networking (NDN) represents a shift from the host-centric architecture of IP towards a content centric architecture, where the primary function of the network is not delivering packets to specific addresses, but fetching data identified by unique names [1]. And thus, data delivery depends on data names rather than data addresses. NDN provides many benefits such as in-network caching, multipath forwarding, built-in data security, and fast data retrieval [2]. There are three main components in NDN communication system: Consumer, Producer, and NDN router. NDN uses two fundamental types of packets in its communication: Interest packet and Data packet [3]. When a consumer wants to request content, it puts the unique name of that content into an Interest packet and sends it to the network. Routers in the network then forward the Interest towards the producer. Once the Interest packet reaches a node that has the named data, the node returns a Data packet carrying the data to the consumer [4]. An NDN router (NDN node) contains three main structures: Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB), as illustrated in Figure 1.

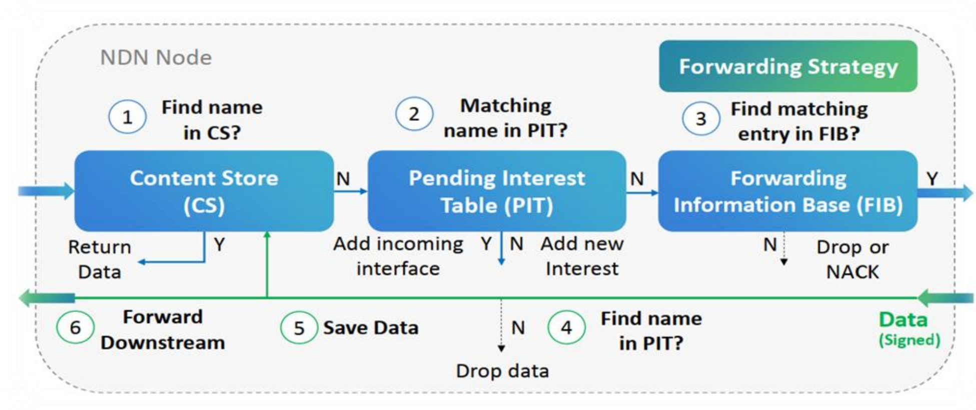

Figure 1: forwarding Interest/Data packets between the components of the NDN node [5].

CS is a cache memory that stores the Data packets temporarily. PIT is a table that contains the name of the data and the faces on which the Interest packet was received. The PIT keeps Interest packets until they are satisfied or expire. FIB is a table that stores the path information about the face from which each Interest packet came and forwards it to the next hop [6].

The goal is to identify the superior cache replacement policy through various simulation scenarios, offering insights into their efficiency and addressing the challenge of content store management in NDN architecture. Previous studies indicate that the LRFU policy outperforms traditional replacement policies like LRU and Priority-FIFO. However, its performance in comparison to ICCP has not been explored.

2. Research Motivation

Cache replacement policies play a crucial role in determining which data to keep and which to evict, directly impacting network performance. However, a cache is not able to keep the entire requested data because of its limited size. Therefore, a competent caching policy has become one of the crucial directions in NDN research domain and affects the efficiency of content distribution [7].

This research strives to evaluate and compare the performance of the ICCP policy proposed in previous work [8] with the LRFU policy [9] which recently included in the ndnSIM simulator to reach a definitive decision on whether content popularity-based policies are superior to traditional policies.

3. Related Work

Existing studies often assume ideal network conditions, ignoring factors such as network congestion and node failure. Existing replacement policies rarely prioritize content popularity, potentially discarding other important factors like content popularity tables and cache hit rates. However, this research examines scenarios where network congestion occurs, and some content stores are configured to have zero size. Additionally, this research focuses on the concept of popularity in comparison to traditional approaches.

Past findings indicate that in LRFU, more recent and frequently accessed content will have higher scores. In contrast, the ICCP assigns higher scores to more popular content. LRFU calculates the weighting function using the time difference between referenced Interest packets and the importance of recency and frequency. On the other hand, ICCP calculates the popularity function using the congestion factor, the Archived Content Popularity Table factor, and the number of times the cache was hit in the current counting cycle. Both ICCP and LRFU can adapt better than static policies like LRU or LFU. ICCP performs better than LRFU in environments with limited cache storage [8][9].

Nana et al. [9] proposed the Least Recently Frequently Used (LRFU) policy, and then compared the performance of the proposed policy with both LRU and Priority-FIFO policies. The LRFU is a combination of LRU and LFU and relies on making the replacement decision by combining two parameters: frequency of content requests and the content usage time. Consequently, a Combined Recency Frequency (CRF) value is assigned to each data packet requested by the consumer. The metric used to evaluate the performance is Cache Hit Rate (CHR). Simulation results showed that the proposed LRFU policy outperforms both traditional replacement policies LRU and Priority-FIFO regarding CHR.

Antonio et al. [10] studied and evaluated the performance of cache replacement policies in network topologies with variable cache levels. Specifically, the performance of the Least Recently Used (LRU), Least Frequently Used (LFU), First in First Out (FIFO), and Random Replacement (RR) policies were evaluated. The metrics used to evaluate the performance are: CHR, retrieval delay, number of upstream hops, network traffic, and interest re-transmissions. The simulation scenarios were performed on a first topology known as the Abilene network, which is a network of 11 nodes, and on a second topology known as the GÉANT network, which is a network of 42 nodes. The researchers concluded that the LFU policy performed the best among the studied policies.

Ying et al. [11] proposed a Content-Popularity and Betweenness Based Replacement Scheme (PBRS), which integrates the popularity of cached contents and the betweenness of the node in the network. An intra-domain Resource Adaptation Resolving Server (RARS) has been setup to retain the cache status. The routers inform the RARS with cache information and then the RARS keeps the cache status of the whole intra-domain. The metrics used to evaluate the performance are: CHR and average hops. The simulation results showed that the proposed scheme outperforms LRU and LFU cache replacement polices by increasing CHR and decreasing average hops.

YingQi Li et al. [12] proposed a new cache replacement policy based on hierarchical popularity and compared its performance with FIFO, LRU, and LFU policies. The proposed policy assumes that the popularity factor cannot be simply categorized as popular and unpopular. Instead, it divides content popularity into five levels from PL1 to PL5, so that each content belongs to only one popularity level, allowing multiple contents to belong to the same popularity level. A popularity value is assigned to each content that reaches the cache. When the cache is full, the less popular content is replaced by gradually searching the Popularity Level lists, starting from PL5 (the least popular), and if it is empty, the Popularity Level list PL4 is searched, and so on until reaching the Popularity Level PL1 (the most popular). The performance metric used is CHR. Simulation results showed that the hierarchical popularity-based cache replacement policy outperforms FIFO, LRU and LFU in terms of CHR.

Ding et al. [13] proposed a new cache replacement policy called Cache Replacement Policy Based-on Content Popularity (CCP). The performance of the proposed CCP policy was then compared and evaluated with both LRU and LFU policies. The proposed scheme calculates the content popularity by adding a new data structure called Content Popularity Table (CPT) in addition to the weight factor for content popularity. The content popularity value is updated after each specific counting cycle called cache refresh cycle. The CPT contains the cache hit value, current popularity value, and previous popularity value for each content. When the content cache is full, the less popular content will be replaced. The performance metrics used include Cache Hit Rate (CHR), network traffic, and server load. The researchers concluded that the proposed CCP policy outperforms all the studied policies.

In [8], a new cache replacement policy derived from CCP policy was developed, called the Improved Cache Replacement Policy based-on Content Popularity (ICCP). This policy relies on two important factors that were not previously considered: the congestion factor and the archived content popularity table. The performance of ICCP policy was evaluated against Least Recently Used (LRU), Priority-FIFO, and CCP cache replacement policies. Seven different scenarios were prepared where the routers are equipped with different levels of CS. The performance metrics are: CHR, retrieval delay, number of upstream hops, network traffic, and number of re-transmissions. The simulation scenarios were conducted on Abilene network, which is a network of 11 nodes, and on a second topology known as the GÉANT network, which is a network of 42 nodes. The researchers concluded that the ICCP policy outperforms LRU, Priority-FIFO, and CCP polices in terms of CHR, retrieval delay, and network traffic.

The contribution of this paper is that it evaluates the performance of the ICCP cache replacement policy proposed in [8] against the newly integrated LRFU policy in the ndnSIM simulator. In other words, this study is particularly significant as it assesses the effectiveness of content popularity-based replacement policies against traditional cache replacement policies. By conducting this evaluation, the paper can provide a clear recommendation on which cache replacement policy offers superior performance.

4. Research Background

Cache replacement policies have an important effect on network performance and efficiency. Every cache replacement policy has a replacement decision that determines how to choose the Data packets to be replaced when the CS reaches its top capacity. As a result, the replacement policy decides which Data to keep and which Data to evict, and accordingly the effectiveness of the replacement policy changes [6].

In NDN architecture, there are traditional cache replacement polices based on content arrival time, content accessed time, and content frequency. *LRU* is the most common cache replacement policy because it is simple and easy to implement. *LRU* policy evicts data that has not been used for the longest time. *LFU* replaces the less often requested content. The drawback of this policy is some contents keep their place in cache for a long time even without using them. *FIFO* replaces the content that arrived first to the CS with the content that arrived most recently [10][14]. *Random Replacement (RR)* simply evicts random contents from CS. *Priority-FIFO* like FIFO but with three queues of relative priorities: the unsolicited queue, the stale queue, and the FIFO queue [15]. The above are five traditional cache replacement policies in NDN.

4.1. Improved Cache replacement policy based-on Content Popularity (ICCP)

It is a policy that was proposed, implemented, and evaluated in a previous work [8] to improve in-network caching in NDN [13]. Caching is a key feature of NDN where the NDN router caches contents in the CS to serve incoming content requests. To make the cache replacement decision, the ICCP policy relies on two key factors: the congestion factor and the Archived Content Popularity Table factor.

Based on these two parameters, we can get a new computation formula to calculate the content popularity. This new formula derived from the CCP policy computation method. Then the proposed ICCP will replace the content with less popularity.

4.1.1 ICCP Workflow

According to [8], when an NDN node receives a new content, it checks whether it is already in the CS or not. If it is, the cache hit value is increased by one. If not, it first verifies whether the content name is in the congestion list or not. Congestion list stores the name of each content along with its congestion value. Whenever getCongestionMark() is greater than zero, the congestion value is increased by one. If the content name isn't in the congestion list, it is added with an initial congestion value of zero. Each time the CongestionMark exceeds zero, the congestion value is increased by one. Then Archived_P=0 and Archived_H=0 are defined as the congestion-based popularity of the archived content and the cache hit value, respectively.

Next, we check whether this content exists in the Archived Content Popularity Table. If it does, a copy of this content's information (Archived_P, Archived_H) is kept to be used to calculate the congestion-based content popularity (Con_P), instead of starting with initial values of zero. If this content is not in the Archived Content Popularity Table, we proceed with the following:

Calculating the Con_P where the congestion-based content popularity is defined according to the proposed formula [8] below:

$$Con\_P[i+1] = \frac{(N[i] * \alpha + P[i]) * 0.5}{(\alpha + 1)} + (0.5 * congestion)$$

$P[i]$ indicates popularity of the cached content. $N[i]$ is number of times the cache was hit in the current counting cycle (cache refresh rate). α is the weight coefficient of the content popularity. $congestion$ indicates the number of times getCongestionMark() was greater than zero for the current Data packet. After that, we set the cache hit value to one and store this content in the Content Popularity Table along with its information [8].

If the counting cycle (*T*) ends, we move to the next step. But if *T* does not end, we repeat the above for new content. When *T* ends, Con_P is updated for all contents in the Content Popularity Table and then they are sorted by their popularity value.

Finally, the ICCP checks whether CS is full or not. If it isn't, the content is stored directly in the CS. On the other hand, If the CS is full, then the less popular content is removed from both the CS and the Content Popularity Table and the most recently arrived content is stored instead. Then, the removed content (which was removed earlier) is stored in the Archived Content Popularity Table [8].

4.2. Least Recently Frequently Used (LRFU)

The LRFU cache replacement policy is designed to manage CS by considering both the recency and frequency of content access. The LRFU aims to improve the efficiency of content retrieval in NDN. As a reminder, the LFU policy removes the less often requested content from the cache to make place for new incoming content. LRU removes content that has not been used for the longest time [9].

LRFU keeps track of how recently and how frequently each Data packet has been accessed. A Combined Recency Frequency (CRF) value is assigned to each data packet requested by the consumer. CRF is a combination of how recently and how frequently the content has been accessed. More recent and frequently accessed content will have higher scores. The weighting function of LRFU defined by the following formula [9]:

$F(x) = \left(\frac{1}{2}\right)^{\lambda x}$ Where: $0 < \lambda < 1$

λ balances the importance of recency and frequency. When λ is close to 0, the policy behaves more like LFU, giving more weight to the frequency of access. When λ is close to 1, the policy behaves more like LRU, giving more weight to the recency of access. x indicates the time difference between referenced Interest packets. When the cache is full, the content with the lowest score is replaced first. This approach helps in making better decisions about which Data to keep in the cache and which to evict [9].

5. Performance Evaluation

This paper uses ndnSIM to evaluate the performance of cache replacement policies in NDN. ndnSIM is an effective open-source simulator based on NS-3. It is valuable for researchers interested in conducting NDN studies and simulations. ndnSIM offers the ability to set up simulation topologies, define simulation parameters, model the communication layer protocols, simulate interactions between various NDN nodes, and record simulation events [16].

The limitations of the study include increasing interest packets beyond 500 packets per second or reducing the CS below 50%. In these scenarios, hardware resource exhaustion and unresponsiveness were realized.

5.1. Simulation Setup

ndnSIM was installed and run on Ubuntu 22.04 LTS. The simulations and performance evaluations are conducted on the GÉANT Network topology, which consists of 42 routers. Consumers are installed on 41 routers, while one router is designated for the producer, as shown in Figure 2.

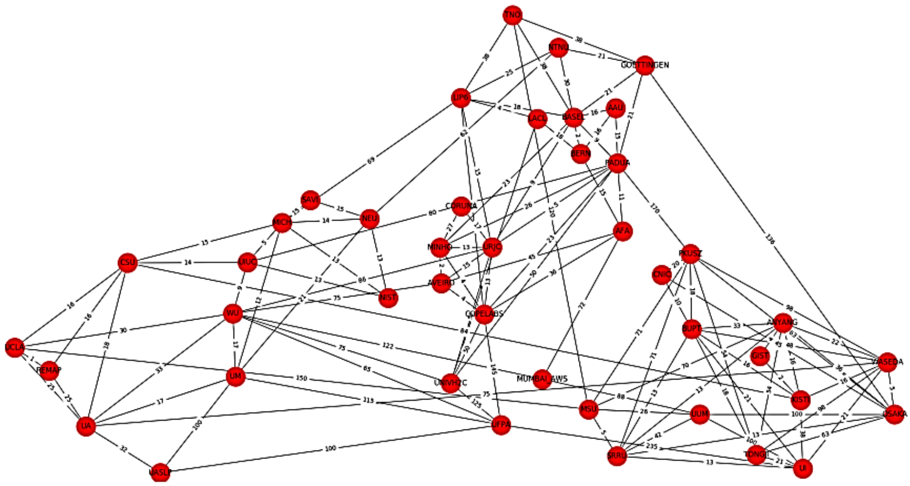

Figure 2: GÉANT Network topology [10].

Simulations and performance evaluations are conducted under two cases. In the first case, the consumer sends Interest packets at a rate of 100 packets per second. Seven different scenarios are set up, with routers equipped with CS at levels of 100%, 80%, 50%, 40%, 30%, 20%, and 5%. These varying CS levels provide a comprehensive view of network performance and help evaluate cache replacement policies under different conditions, such as node failure or limited CS size within a node. In the second case, simulations are conducted with the consumer sending Interest packets at a rate of 500 packets per second. The cache levels are set at 100%, 80%, and 50%. It's important to note that reducing the CS below 50% in this scenario led to hardware resource exhaustion and unresponsiveness, so only these three levels were considered. Additionally, CS size is set to 1000, with 1000 different contents generated by the producer.

Consumers request content based on the Zipf–Mandelbrot model, a discrete probability distribution in probability theory and statistics [17], with a modeling factor of α = 1.1. This means the traffic generated follows the Zipf–Mandelbrot popularity distribution, reflecting the popularity weight of the traffic generated by the nodes [18].

The Best Route strategy [19] is selected as the forwarding strategy. Leave a Copy Down (LCD) policy [20] is used as the default cache placement policy, as this research focuses on studying replacement policies only. The simulation runs for 240 seconds.

Simulation parameters conducted in these experiments [10] are detailed in Table1 below.

Table1: Simulation parameters.

Parameter	Value
Interest Packets	100 packets/s (a), 500 packets/s (b)
Cache level	100%, 80%, 50%, 40%, 30%, 20%, 5%. (a) 100%, 80%, 50% (b).
Cache size	1000 contents
Content name	1000 different names
Content Request Model	Zipf–Mandelbrot
Modeling Factor	α = 1.1
Forwarding Strategy	Best Route
Cache Placement Policy	LCD
Cache Replacement Policy	ICCP, LRFU
Metrics	CHR, Retrieval Delay, Network Traffic
Simulation time	240 seconds

5.2. Results and Discussion

This work uses three performance evaluation metrics [10], which are as follows:

- Cache Hit Rate (CHR) measures the effectiveness of caching by determining how well content requests are satisfied from the CS instead of the original source (producer). This is defined as the ratio of Interest packets successfully satisfied by the CS to the total number of Interest packets sent. CHR can be calculated from the following formula [10]:

$$Cache\ Hit\ Rate\ = \frac{\sum hit}{\sum(hit + miss)} * 100\%$$

$\sum hit$: Total number of cache hits.

$\sum(hit + miss)$: Total number of cache hits and misses.

- Retrieval Delay indicates the time taken from when an Interest packet is sent to when the corresponding Data packet is received (including time for re-transmissions) [14].
- Network Traffic refers to the total amount of interest Packets and Data Packets moving across the network at any time.

5.2.1. Cache Hit Rate

The simulation results presented in Figure 3 indicate that ICCP outperforms LRFU. Additionally, it is evident that the CHR improves as the number of content stores in the network increases. The reason for this behavior is that with more content stores in the network, there is a higher possibility of finding the requested content along the path before reaching the content producer.

It is important to note that when the number of content stores is limited, they fill up quickly, leading to frequent cache replacements. Consequently, the size of CS significantly impacts the results achieved. Another key point is that the performance disparity between cache replacement policies becomes more obvious when there are fewer content stores in the network.

It has been agreed that LRFU policy relies on content arrival time and frequency to make the replacement decision, while ICCP policy considers congestion factor, Archived Content Popularity Table, and content popularity, so it performs better. When content stores are present in 50% of the network nodes, ICCP outperforms LRFU by 4.4% in case (a) and 5.4% in case (b).

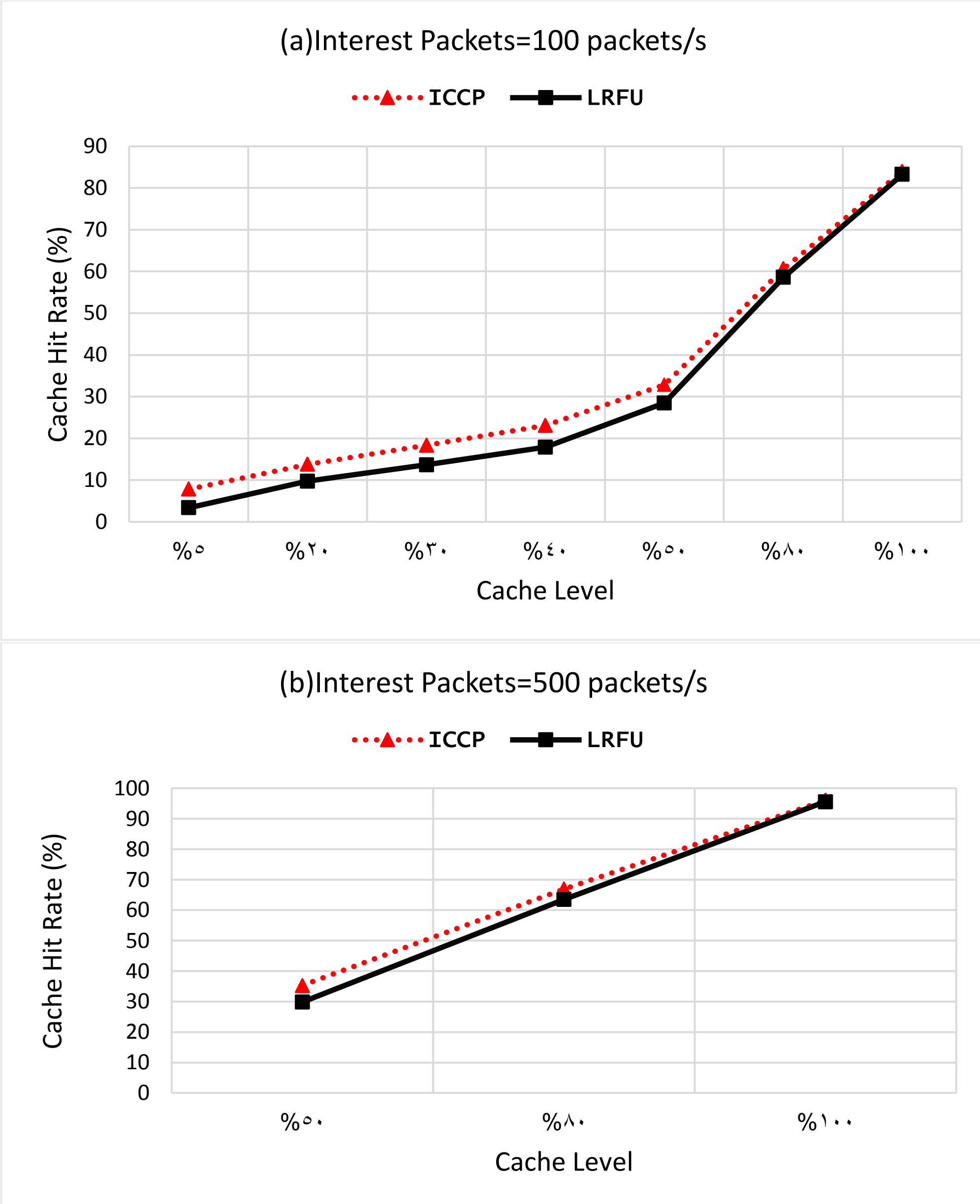

Figure 3: CHR with variable number of CS.

5.2.2. Retrieval Delay

The results in Figure 4 demonstrate that ICCP outperforms LRFU in terms of average retrieval delay. The observed delay in milliseconds represents the total delay, including content retrieval delay during retransmissions.

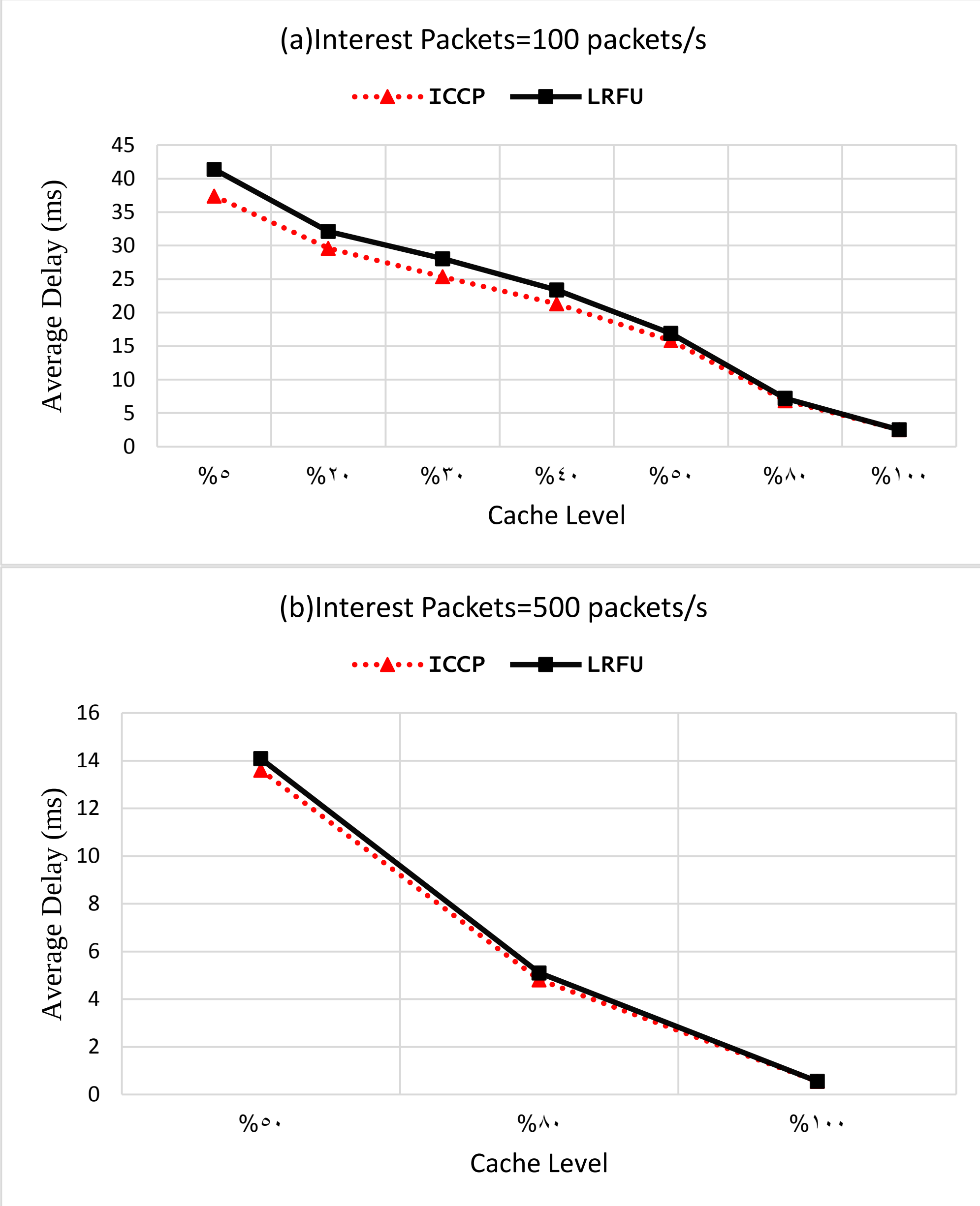

Figure 4: Average Retrival Delay with variable number of CS.

It also shows that with fewer content stores, the delay is significantly larger. This is because Interest packets are forwarded to distant nodes, requiring more hops. Thus, the response time is longer as the Interest packet traverses more nodes to retrieve the content.

When the number of content stores is greater, the probability of retrieving the content with fewer hops is high, meaning the content is likely retrieved from a nearby CS. However, when the content is not retrieved, then the retransmission process will occur, and the producer will send a negative acknowledgment (NACK). When content stores are present in 50% of the network nodes, the ICCP reduces the average retrieval delay by 1 ms compared to the LRFU in case (a) and by 0.5 ms in case (b).

5.2.3. Network Traffic

Regarding network traffic, Figure 5 shows that ICCP outperforms LRFU in terms of average network traffic. Additionally, the results indicate that with fewer content stores, the network traffic is high. As the number of content stores increases, the network traffic decreases. The reason behind this behavior is that with fewer content stores in the network, each node that receives an Interest packet forwards it to a more distant node towards the producer. Similarly, each node that receives a Data packet forwards it back towards the node that requested the content (consumer), which increases the network traffic. As the number of content stores in the network increases, the possibility of the requested content being in a node close to the consumer is higher. Consequently, Interest packets and Data packets travel shorter paths, reducing the network traffic.

When content stores are present in 50% of the network nodes, the average network traffic under ICCP is 1.3 packets/s lower than under LRFU in case (a) and 5.7 packets/s lower in case (b).

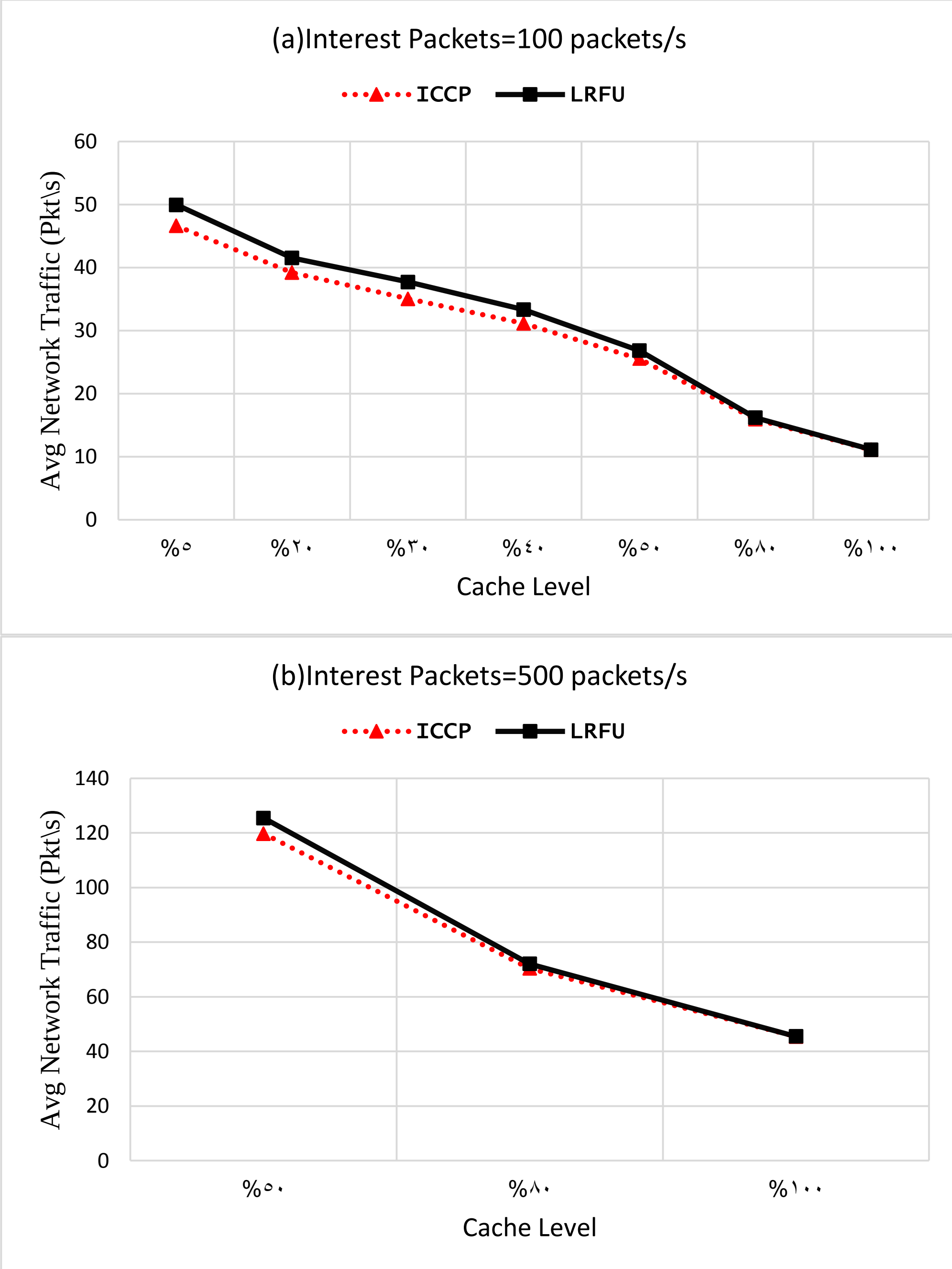

Figure 5: Average Network Traffic with variable number of CS.

6. Conclusion and Future Work

The ICCP policy can speed up the data retrieval process and increase the CHR. This research aimed to evaluate the performance of the ICCP cache replacement policy versus the LRFU policy across multiple simulation scenarios. Using ndnSIM for simulations and performance evaluations, the results demonstrated that ICCP outperforms LRFU in terms of CHR by 4.4% in scenario (a) and 5.4% in scenario (b). The ICCP decreases the average retrieval delay by 1 ms compared to LRFU in scenario (a) and by 0.5 ms in scenario (b). Finally, the average network traffic under ICCP is 1.3 packets/s lower than under LRFU in scenario (a) and 5.7 packets/s lower in scenario (b).

ICCP manages limited cache storage more effectively than LRFU, which is essential in resource-constrained environments. Additionally, ICCP improves cache hit rates and reduces delays compared to traditional policies like LRFU and LRU.

The ICCP policy maintained its superior performance even as the number of Interest packets increased. Our previous findings showed that ICCP outperforms CCP, LRU, and Priority-FIFO. This research further concludes that ICCP also outperforms LRFU. Our literature review revealed that cache replacement policies based on content popularity consistently outperform traditional replacement policies. Therefore, this study recommends the permanent adoption of content popularity-based replacement policies, such as ICCP. For future work, it would be interesting to evaluate the performance of content popularity-based replacement policies, such as CCP, ICCP, PBRS, and hierarchical popularity-based cache replacement policies, in IoT environments.

7. Abbreviations

CCP	Cache replacement policy based-on Content Popularity
CHR	Cache Hit Rate
CPT	Content Popularity Table
CRF	Combined Recency Frequency
CS	Content Store
FIB	Forwarding Information Base
FIFO	First In First Out
ICCP	Improved Cache replacement policy based-on Content Popularity
ICN	Information Centric Networking
LCD	Leave a Copy Down
LCE	Leave a Copy Everywhere
LFU	Least Frequently Used
LRFU	Least Recently Frequently Used
LRU	Least Recently Used
NDN	Named Data Networking
PBRS	Content-Popularity and Betweenness Based Replacement Scheme
PIT	Pending Interest Table
RARS	Resource Adaptation Resolving Server
RR	Random Replacement

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