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Highlights

- ICN is a realistic solution to content delivery between the publisher and subscribers in IoT
- ICN has different key modules for IoT due to the nature of energy constrained devices
- Caching is the most crucial module of ICN-based IoT network

PUC: Packet Update Caching for Energy Efficient IoT-based Information-Centric Networking

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Abstract

The future Internet, known as Information-Centric Networking (ICN), is a realistic solution to content delivery between the content request generators (subscribers) and the server (publisher) in the Internet of Things (IoT) environment due to caching contents by in-network nodes. However, significant redundant copies of contents can be cached in this kind of network which, besides numerous advantages, introduces some undesirable features, such as security issues, content redundancy, access control, and cache overflow among others. ICN has different modules, such as mobility, routing, and caching, which are utmost important for the IoT network due to the nature of energy-constrained IoT devices. While numerous attempts are presently being made to institutionalize this emerging paradigm, careful considerations are needed to caching module at the early stage of this architecture. This is important instead of holding up until the innovation gets used and experienced. In this article, we first list some of the important features and limitations of the ICN-based IoT caching and then propose an ICN caching strategy that fits well in the energy efficient and secure IoT environment. The proposed strategy is simulated and compared with the ProbCache mechanism with regards

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to energy consumption and bandwidth utilization. Preliminary experimental analyses demonstrate that the proposed strategy produces better results than the ProbCache as long as the cache size of network nodes is increased.

Keywords: Probabilistic caching, ICN-based IoT, energy efficiency, Internet architecture, Future Internet, Security, Privacy

1. Introduction

In the past few years, the evolution in network technology caused exponential growth in data access over the Internet [1]. The dramatic growth of sensing devices, i.e., cameras, iPads, smartphones, etc., has succeeded the range of sensing applications way beyond its creators on the Internet of things (IoT) [2, 3], such as healthcare [4, 5], smart homes [6], natural disaster relief [7], and industries [8], gathering information from public infrastructures [9, 10]. People are connected to the Internet by using various networks and can access audios, pictures or videos through sensing devices [11]. These devices change the way users communicate or interact and lead towards a new network. The main inference for huge data traffic on the Internet is higher demands for these media files, i.e., video streaming on Youtube, Vimeo, and Netflix [1, 12]. This higher progression in video streaming may cause data traffic overhead, which directly affects user-perceived data such as video quality.

In the early 1970s, the idea of remote resource sharing (i.e., the current Internet) was introduced because long distance communication was being developed as it was the demand of that time. Thus, the current Internet allows to connect various systems located at different places. However, the Internet size is growing unpredictably, as indicated by the Cisco Visual Networking Index [1], where worldwide Internet traffic will gain 396 exabytes/month or 4.8 zettabytes/year by 2022. In addition, the existing Internet architecture has several limitations in many aspects, such as storage limitations, transmission limitations, control limitations, operational limitations, etc. [13]. In other words, the Internet was not designed for the mentioned protocols as they violate the initial architecture [14]. To surmount this problem, a research community [15] was formed to tackle the Internet issues and consider the main goals together with prerequisites of the future Internet design. Therefore, numerous projects were setup for coupling the ongoing and forthcoming desires of the users in an improved form than what the current Internet offers

[16]. As a result, Information-Centric Network (ICN) was familiarized in a conference in 2009. [17].

Subscribers in ICN request diverse contents, which are stored on publishers, and replicas of these (accessed) contents are cached by different nodes somewhere local in the network [18]. This content caching depends on the caching policy and size of the nodeâs cache. That is, if the size of the nodeâs content store (CS) is free, then contents can be cached for a long time and thus cache-hit– the most important feature of ICN, can be improved [19].

On the other hand, if the CS is occupied by other contents, then on the arrival of a new one, one of the cached contents is removed from the CS in order to create space for the incoming one. This replacement is based on the deployed caching strategy.

2. Related Work

In this section, the existing studies are diagrammatically represented in terms of caching, its types, benefits, pitfalls, and ICN-based IoT caching.

2.1. ICN Caching and its types

ICN caching is the most important module among others and therefore has received a careful consideration from the research community [20]. In ICN caching, every network node is capable of storing contents locally. However, local caching involves several issues, which are discussed later in this article. The ICN caching, which is also called in-network caching, can be categorized into off-path and on-path caching approaches. In the earlier approach, contents are not cached on the subscriber-publisher path but somewhere else in the network. While in the later one, contents are stored by network node(s) on the subscriber-publisher path. Apart from the mentioned two approaches, four other important caching types are cooperative, non-cooperative, homogeneous, and heterogeneous caching [21], for which various strategies have been proposed in the literature [22].

In the cooperative approach, network nodes share content information with neighbors. Thus, if new requests arrive for the cached content, through the shared information it is known that which node has cached the content and therefore the requests are satisfied locally. Instead, in the non-cooperative method, information about the cached content is not shared with neighbors and hence caching decisions are made by all individual nodes [21]. The example of cooperative caching can be seen in Fig. 1 where node

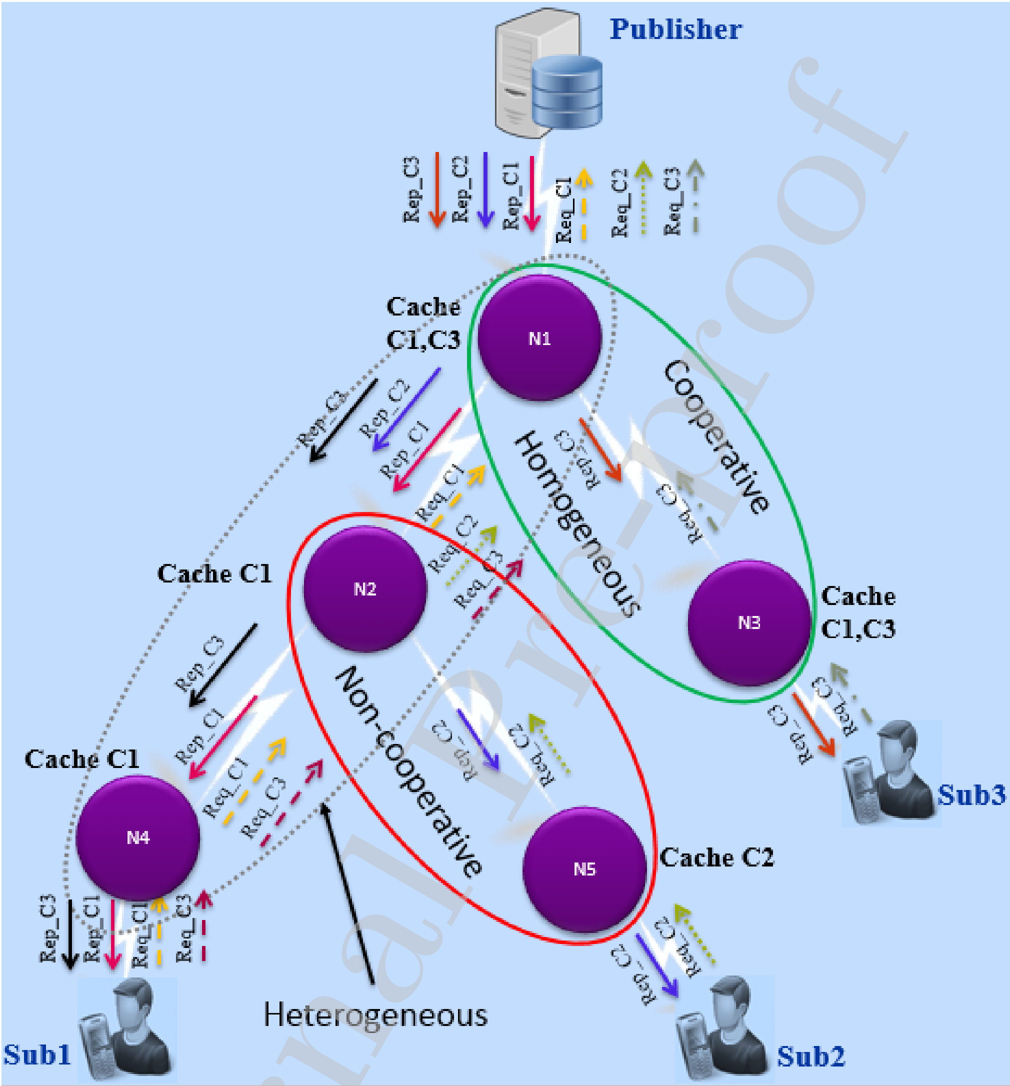

Figure 1: Content network with caching nodes

N1 and *N3* share their information and thereby hold similar cache provisions. In contrast, nodes *N2* and *N5* are non-cooperative as they do not share their caching information with each other and hence embrace different cache provisions.

In homogeneous caching approach, as a content passes through on-path nodes, they store its copy locally. Whereas the idea of heterogeneous ap-

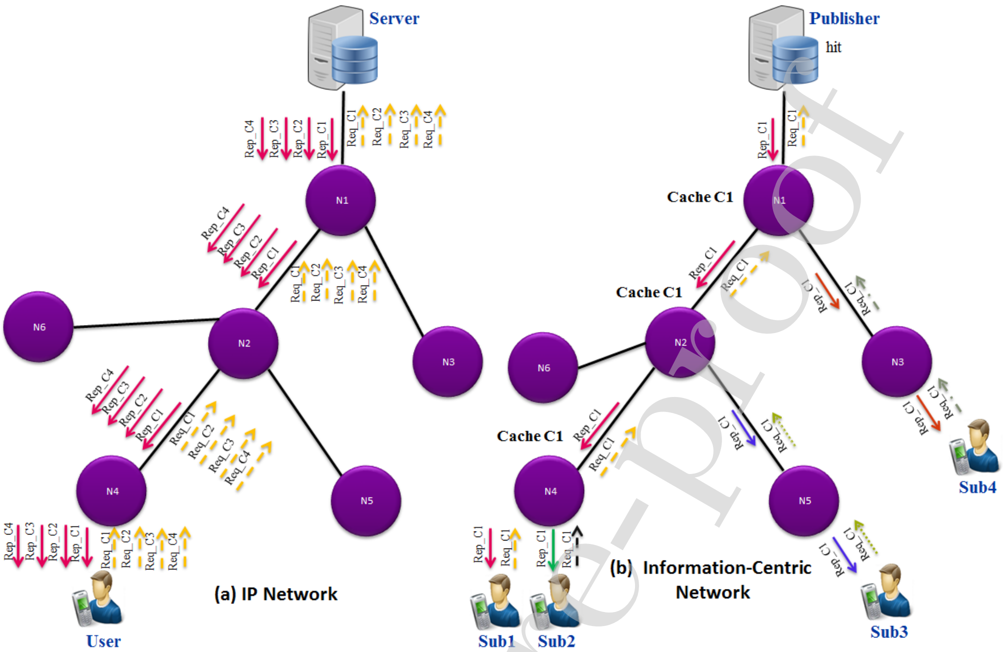

Figure 2: IP network vs. ICN

proach is opposite from the homogeneous caching. Consider Fig. 1 where *N1* and *N3* are homogeneous as they are available on the subscriber-publisher path and thus store similar contents. Whereas, *Sub1* requests content *C3* which is available at node *N1*. During downloading, neither *N2* nor *N4* cache *C3*, and therefore known as heterogeneous.

2.2. Caching Benefits

One of the important features of ICN caching is the *bandwidth*, which is the number of bits transmitted from subscriber(s) to the publisher in one second time. To better understand the utilization of bandwidth in the current Internet and ICN, consider Fig. 2, i.e., in the current Internet architecture (Fig. 2(a)), the entire user's requests must reach the server for the requested data. Thus, each request must pass through the whole network nodes that lie in the *User-Server* path. In the given figure, a network consists of five nodes: *N1* through *N5*, one server, and a user. If five different users request a particular content at the same time, then the entire requests utilize the whole path and thereby a maximum bandwidth is used. On the other hand, in the ICN architecture because of the in-network caching, if a subscriber requests a specific content, a copy of the requested content is stored by local network node(s). Therefore, subsequent requests for the same content may be satisfied locally, as shown in Fig. 2(b), and thus the bandwidth utilization is reduced up to a great extent.

In addition, ICN aims to make the content retrieval process simple and efficient via in-network caching. That is, a request is made for the desired content and during downloading, a copy of that content may be cached by any network node. Thus, upon the arrival of a new content request, as shown in Fig. 2(b), it is satisfied by one of the local nodes instead of forwarding it to the original publisher, which efficiently utilizes the bandwidth and consequently the content retrieval delay may be noticeably reduced.

Moreover, in the existing Internet architecture, the data communication is not possible without IP addresses. Even for reliable communications, the sender contacts the receiver for authentication. Every individual user and servers are associated with particular IP addresses representing their physical locations and therefore the communication is known as source-driven approach. Thus, all user requests must reach the server(s) to meet their requirements. In the last decade, the retrieval of multimedia contents has gained significant popularity on the Internet where hundreds of thousands of requests arrive at server(s) in seconds. For this reason, a server needs to handle all received requests individually regardless of their nature, i.e., even if a request arrives 100 times, each time the server entertains it. This huge amount of request management overburdens the server and therefore severely degrades the Internet performance. Because of this immense number of user requests, it is indispensable to improve the network capabilities, which is only possible by changing the architecture of the existing Internet. In that situation, to cope with this unavoidable circumstance, ICN is the only solution. This fact can be illustrated by Fig. 2(b) where all subscribers' requests are fulfilled by any IoT node, *N2*, having a replica of the required content.

Furthermore, path reduction is another serious issue in the current Internet architecture. As mentioned earlier that all users' requests, which are based on IP addresses, are forwarded to the main server. As a result, during buffer overflows, encoding/decoding delays, and long path travel of data requests, data objects may get delayed more than desired. This can pose serious issues, especially for multimedia and real time applications. Quite the opposite, the ICN architecture is built on the basis of content rather than its location, i.e., the name of information and its location are separated and thereby the content may travel without knowing the content's physical location. This experience complies with the user requirements as they are only interested in the actual content and not in its location where it is placed. Once the content is downloaded and its copy is cached locally, the path is reduced up to a great extent and hence subsequent requests are entertained by local network nodes having a stored replica of the needed content.

As shown in Fig. 2(b), *Sub1* requests its desired content available at the *Publisher*. The requested content is cached at each node on the delivery path according to the ICN default caching strategy [17]. Next time, when other subscribers, i.e., *Sub2, Sub3*, and *Sub4*, request the same content, their requests are satisfied by local in-network nodes. This improves the network performance with respect to bandwidth utilization, stretch ratio, and hop decrement, which are considered prominent metrics for the network improvement.

Besides, the current Internet envisioned smoothing the progress of communications among different computer systems, it did not encourage content distribution. This fundamental discrepancy has significant effects on network performance in terms of bandwidth utilization, content retrieval delay, and most importantly energy usage [23, 24]. Due to immense increase in the Internet traffic, the energy cost is rapidly increasing. According to [25], currently 2% power electricity is being used in the field of information communication technologies (ICT). In the last five years, the overall worldwide energy consumption of mobile networks was approximately 120 TWh, whereas its cost of energy was 13 billion US dollars [25].

To reduce the cost and usage of energy, ICN is a suitable choice. In ICN, the energy related issues, in terms of cost and usage, can be considerably reduced by implementing caches within the network. In other words, having a local copy of the requested content, local machines satisfy requests without contacting the main server and thus the energy consumption is reduced up to a significant level.

Likewise, in data transmission, ICN meets users' expectations as it delivers contents without any external affirmation of the content source or its validity. One of the main features of ICN-IoT is content distribution by caching at different IoT nodes so that the contents are secure from any kind of attacks, as possible in the IP network, even at the time of insecure communication path. The reason of ICN-IoT security is due to the embedded information enclosed in the content as it follows *named data communication* rather than *IP address-based communication*.

2.3. Caching Pitfalls

The main caching contribution of ICN is to provide subscribers with local cached content upon their made requests. This feature increases the cache hit ratio, minimizes the content retrieval delay, and utilizes the network bandwidth effectively. However, due to a rapid increase in the Internet connected devices and the network node cache size constraints, the CS becomes full and some of the cached contents are replaced accordingly to accommodate the incoming ones. In addition, any subscriber may request several unpopular contents randomly, which drastically affect the CS of the network node and is called cache pollution. Several schemes have been proposed to resolve such a problem, as suggested in [26]. However, this is yet to-be-resolved and still poses a challenging problem for the ICN-IoT research community.

Moreover, Pending Interest Table (PIT) is the basic data structure that is used for content forwarding practices [27, 28]. The PIT performs a vital role in content caching as it records the information of requested objects in network nodes. Nevertheless, the arrangement of requested objects in the PIT is primarily important for efficient cache management. Due to excessive use of the Internet and exponential increase in the number of Internet connected nodes, the size of PIT may overflow [29]. Thus, the management of PIT entries in the future Internet is a challenging and addressable issue. This issue occurs due to substantial usage of prolonged duration of the requested objects in the PIT, specifically due to the unavailability of intelligent replacement schemes.

The majority of caching mechanisms uses the least recently used (LRU) strategy for eviction operations when the PIT overflows [30]. Since the LRU performs unnecessary evictions of PIT entries, it is ineffective in busy Internet hours. As a consequence, the research community is motivated to design an efficient and flexible replacement policy for the arrangement of requested content entries in the PIT.

In addition, the Internet's shift from *host-centrism to content-driven paradigm* has prompted a significant number of essential network designs getting to be noticeably superseded. Refer to Cisco VNI [1] where the number of Internet connected nodes will exceed 28 billions by 2022, the amount of caching contents on the in-network nodes will also increase exponentially. Due to unavailability of a specific content duplication avoidance scheme, the number of caching redundant contents is also expected to increase dramatically. Therefore, a flexible and lightweight strategy is needed for addressing the issues of content redundancy before the ICN deployment.

Furthermore, scalable and effective content dissemination is the main goal of ICN, which is possible through in-network caching [31]. As a request is received for a particular content, the in-network node (if it has a cached copy) replies with the required content without verifying its signature. Thus, if the subscriber receives the content copy, the received copy may not be trusted to be authentic [32]. Due to no specific application designed for ICN trust, a subscriber may constantly receive fake contents, which cause cache poisoning. This pitfall may drastically affect the overall communication. Hence, attention from the ICN research community is attracted towards this crucial issue to develop sophisticated techniques for the signature verification.

One of the key modules of ICN is content caching on in-network nodes. In other words, ICN improves content availability through ubiquitous caching. However, the provision of cached content copies at different in-network nodes creates the need for intelligent access control schemes. Most of the access control schemes, as presented in [33], depend on the presence of an online application for the data request authorization. Nevertheless, this online data request authorization noticeably affects the overall communication in terms of communication complexity and computation overhead. Thus, a considerable attention from the ICN-IoT research community for designing a sophisticated access control scheme is indispensable.

2.4. ICN-based IoT Caching

The idea of Internet of Things (IoT) was introduced in 1999 [34], wherein people are allowed to connect things (anything) at any place or time. After that, IoT was linked with different technologies [35] and various techniques were designed to enable IoT perform in any environment [36]. Contents in ICN are delocalized and must not need end-to-end transmission protocols for their retrieval. Therefore, in-network caching accelerates content distribution in the IoT environment and moderates requirements for continuing connections [37]. This perception was revealed as a substitute networking idea for the IoT [38, 39]. In the existing research, the majority of studies on content caching is done in the conventional ICN-based networking models [40, 41], which concentrates on the design of routing schemes and name resolution-based content caching [42]. Most of the available strategies follow heuristic approaches for content caching, thus, unable to provide ideal solutions of centralized administration for subscribers.

Caching protocols that function in an entirely distributed manner are critical in providing scalability, reliability, and robustness to IoT networks

[43, 44]. Contingent to the category of content distribution [45] and the nature of IoT devices as well as networks, various caching strategies, ranging from caching everything to popularity-based caching, have been proposed [46, 47, 48], for example, ICN-IoT caching in ad hoc networks [49], ICN-IoT edge caching [50, 51], etc. Various contents may have the validity for a short time period, hence, do not need to be cached on the publisher-subscriber path, whereas some can serve the rationale of various applications and are therefore recommended for caching [52].

Certain IoT nodes that have appropriate resources may function as content mules and hence forward data objects in an adaptable mode. For instance, moving cars on roads that acquire content from sensors and forward it to other cars on its way. Likewise, in-network caching provides data objects placed at various locations to distinct subscribers/applications, without contacting the original publisher [52, 53]. It may be acceptable to presume that in a building, e.g., house, a specific device is responsible for caching content objects created by a group of nodes and satisfies the requests of distributed applications without contacting the main content publisher [52].

Generally, caching is useful since it accelerates content retrieval and enhances its accessibility. However, it may be quite costly in terms of energy utilization and processing due to excessive content placement and eviction operations [54]. According to [38], ICN caching is highly advantageous even in the IoT environment with tiny devices having small CSs. The reason behind IoT caching efficiency is such that it reduces the number of hops between the publisher and subscribers by restricting the utilization of energy. Contents in the ICN-based IoT environment may be cached by in-network nodes (e.g., switches and routers) and resource-limited nodes by deploying cache placement and eviction mechanisms that constitute the irregularities of IoT data transmission, such as capabilities of nodes in terms of storage and battery life [54].

Various ICN caching strategies have been designed [19] for the effective utilization of space in the CS and consumption of the available bandwidth. ICN caching protocols may also be deployed in the IoT network [55], but these must consider the distribution speed instead of long-term caching due to the transient nature of contents [56]. It is also suggested in [54] that the off-path caching concept– where contents are not cached in the publisher-subscriber path but along alternate paths, may be suitable for the IoT environment due to resource-limited tiny nodes.

Considering the communication cost of IoT devices, i.e., battery life and caching capacity, we have designed an ICN-based IoT caching strategy to make the best use of caching space with respect to bandwidth utilization and energy consumption.

3. Packet Update Caching

The strategy proposed in this study is called Packet Update Caching (PUC), which is, to the best of our knowledge, suitable for the ICN-based IoT environment. The fundamental objective of the PUC is such that it addresses the ICN-based IoT issues with respect to content popularity, hop count reduction, access control, and content retrieval delay. The PUC is based on clustering, circular buffer, data purging, and Incapsula technique to cache, update, and evict contents from a caching node.

3.1. Clustering

A collection of nodes having dissimilar properties and resources that performs as a single and logically collaborated system for better-quality analysis, load balancing, high availability, and parallel and singular processing of data in enhanced and advanced network environment, is known as a cluster. A cluster is based on two main components, i.e., i) cluster head, and ii) cluster member.

3.2. Cluster Head

A node that collects data/requests from different interrelated nodes and forwards these requests as an aggregate to the base station is termed as cluster head (CH). The nodes interconnected to a particular cluster head are cluster members. The CH is selected on three diverse principles, i.e., i) residual energy, ii) number of neighbors, and iii) the distance/length of nodes from the base station.

The purpose of CH selection in a network is to improve the mobility and network performance by utilizing less energy consumption. The CH selection criteria is unique in every clustering strategy. The number of nodes and their workload/weight is used. These nodes and their weight determine the selection of a CH among all nodes. The node power, relative speed or capacity of the node, and node degree, calculate the weight/workload of each node [57].

3.3. *Circular Buffer*

A circular buffer [58] is an array used as a queue or area of memory, or a dedicated circuit that is used to store incoming data. A circular buffer uses two separate pointers for write and reads operations. These pointers mark the positions to write and read from memory locations. The write pointer is used to point the next position in the array where the new element is to be stored/inserted. While the read pointer is used to read the next position of the element from the memory. The write position is set back to 0 when the write position reaches the end of the array, known as "wrapping around". The same is true for the reading position. This mechanism turns an array into a circular buffer. The read and write pointers are not allowed to cross each other so that the unread data cannot be deleted or overwritten by the new data. The circular buffer keeps track the record of the used and free memory. When the write position has not wrapped around, the used space is between the write and read positions. Hence, all the rest is a free space. When the write pointer wraps around all of a sudden, the free space is between the write and read positions.

As shown in Fig. 3(1), the read/write heads are at initial locations of the buffer, i.e., 00, which wait for the content arrival in the content store. In Fig. 3(2), upon starting content caching, the write pointer is triggered to write/store data in the buffer, moving forward from location 00 to 02 for writing H. Henceforward, the read pointer is initiated to read data, shifting from position 00 to 02 for reading H. In Fig. 3(3), at position 02, the read/write heads wait to receive a fresh copy of the content. At the time a fresh copy of the content is available for caching, the write pointer is triggered for writing at the subsequent buffer location, e.g., when the write pointer shifts from location 02 to 04 to write E (in Fig. 3(4)). To read this content from the buffer, the read pointer is actuated and progressed from position 02 to 04 for reading E. In Fig. 3(5), both read/write heads wait again to receive a fresh copy of the content. In Fig. 3(6), the write pointer is triggered again on the arrival of the fresh copy for caching and L is written at location 06 by the write pointer. This entire practice may be reiterated till the completion of HELLO, as can be seen at position 10 of Fig. 3(8). Afterward, the read pointer starts reading from position 04 to position 10, as depicted in Fig. 4(14). The next content, i.e., W, will be stored at position 10. If the buffer memory gets full, then the old content is purged from the buffer memory and the new one is stored in the same manner at the same memory locations, i.e., 00, 02, 04, 06, 08, and 10.

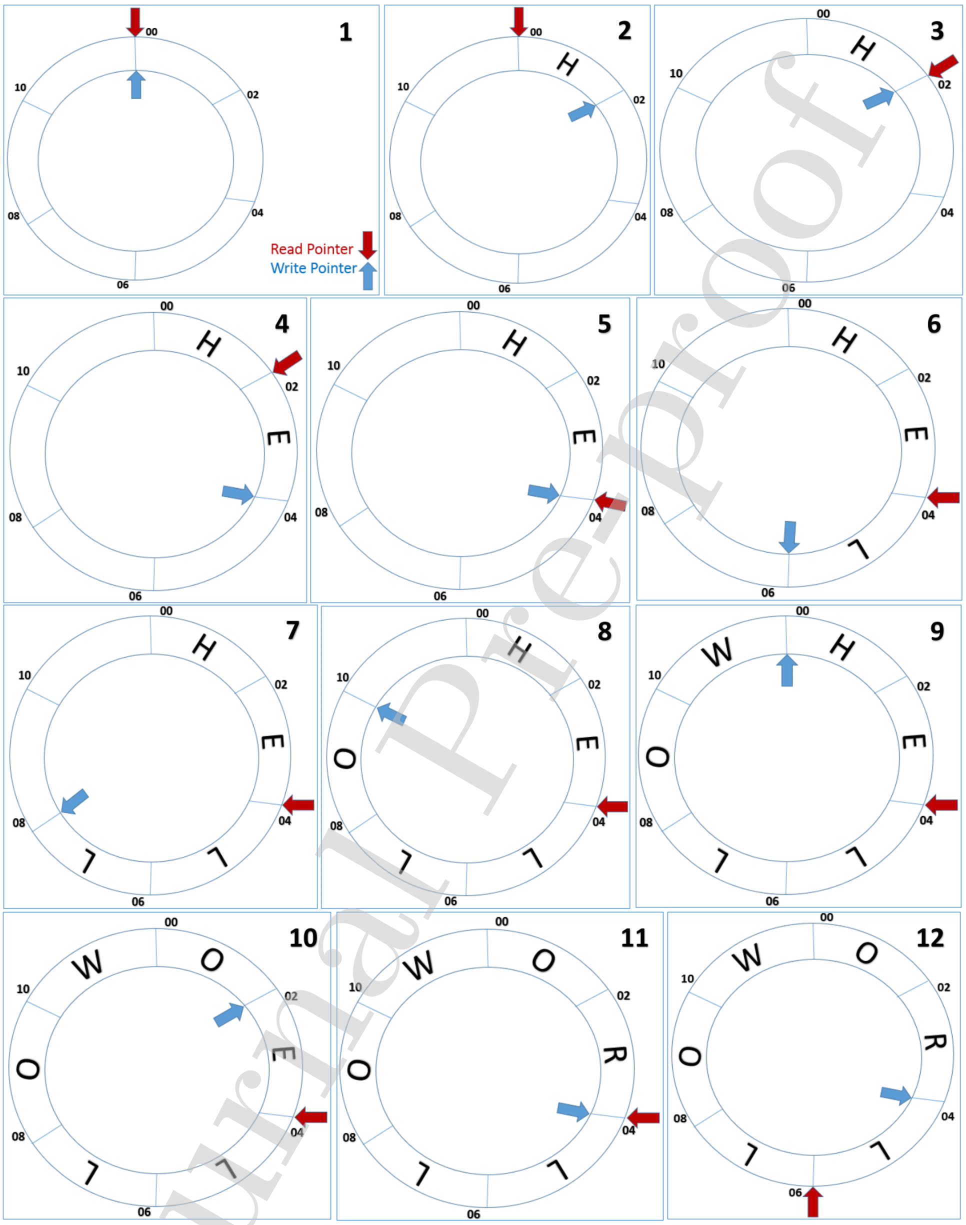

Figure 3: Circular Buffer Part (a)

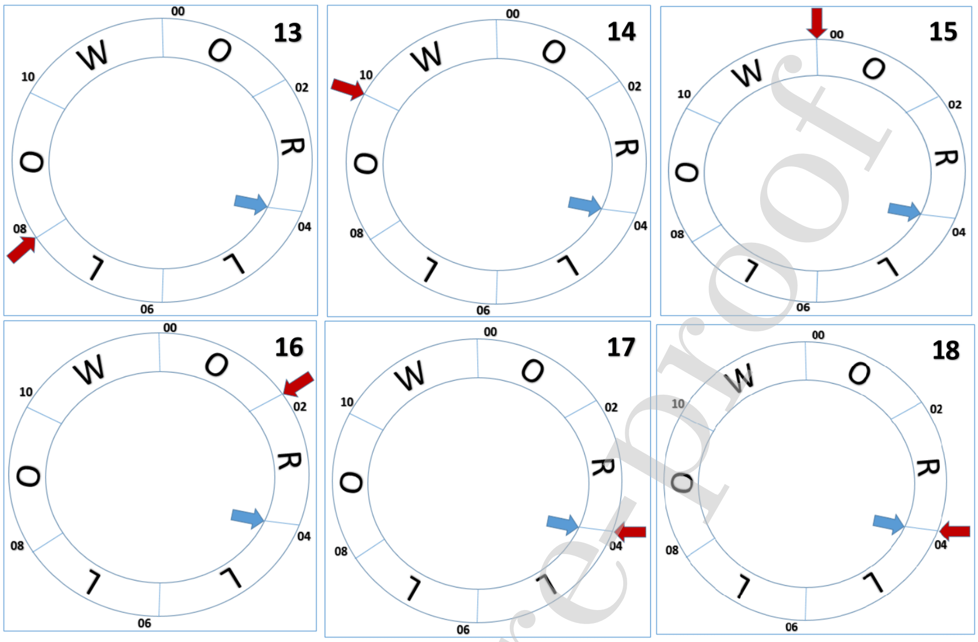

Figure 4: Circular Buffer Part (b)

3.4. Data Purging [59]

The term data purging describes the methods for permanent deletion of older data/content from a storage location and opens up the storage or memory space for the newer content to be stored. The purge is stronger than the delete as the deleted contents can be retrieved by un-deleting them, while the purged content cannot be recovered. For example, in some Database techniques, automatic data purging is being used to delete older data. Although an organization wants to keep all of its data for analysis and data mining, due to a fixed amount of storage, data is purged repeatedly. If data is not purged on a regular basis, the table in a database grows so larger that the performance begins to decline.

3.5. Incapsula [59]

Incapsula is a cloud-based delivery application, which is being used in Content Delivery Networks (CDN). It provides a great protection against the Distributed Denial of Service (DDoS) attacks over the Internet. Incapsula protected one of the largest Internet attacks on a website in October 2013, which lasted for nine hours with 100 Gbit/sec of traffic against the

BTU (Bitcoin) China [60]. Beside security, Incapsula provides a sophisticated caching policy by identifying the resources that switch their contents constantly. It also offers the provision to automatically fix the policies consistent with the requirements of caching. This provides an ideal default refresh strategy wherein a content may always stay updated, which is an elegant way for instantaneous purging.

Incapsula deals with two types of content caching, i.e., i) Static Content Caching such as Java resources, images, and HTML files, and ii) Dynamic Content Caching consisting weather reports, newspapers, and stock exchange rates by making a dynamic purge request to check the resources that frequently change the contents and update the cached content to improve the performance without affecting the freshness of content [59]. In PUC, time-stamp expiration and new content generation are two crucial terms for keeping the cached content updated.

3.5.1. Time-stamp Expiration

A time-stamp is a set of encoded information or characters for the identification of a certain event to happen, generally assigning time and date, and sometimes precise to a minor fraction of a second. In present times, the term time-stamp is being used to refer to the digital date and time information attached to digital data. For instance, computer files have time-stamps that tell when a file was most recently altered/modified. In ICN, each content may have a time-stamp assigned by the publisher. On the expiration of this time-stamp of a cached content, an automatic purge request is generated from a CH to the publisher for updating the older content with an updated/fresh one.

3.5.2. Copy Update

In this case, it may be possible that the time-stamp of a content is not expired but the publisher produces an updated/fresh copy of the same content, which was cached on a CH. By setting the purging rules, this mechanism regularly checks the publisher for an updated/fresh copy of the content. Even though the time-stamp of the cached content is not expired and if an updated copy is found on the publisher or on any on-path CH, the *Incapusla intelligent in-network caching functionality* purges the old content with a copy of the fresh/updated one.

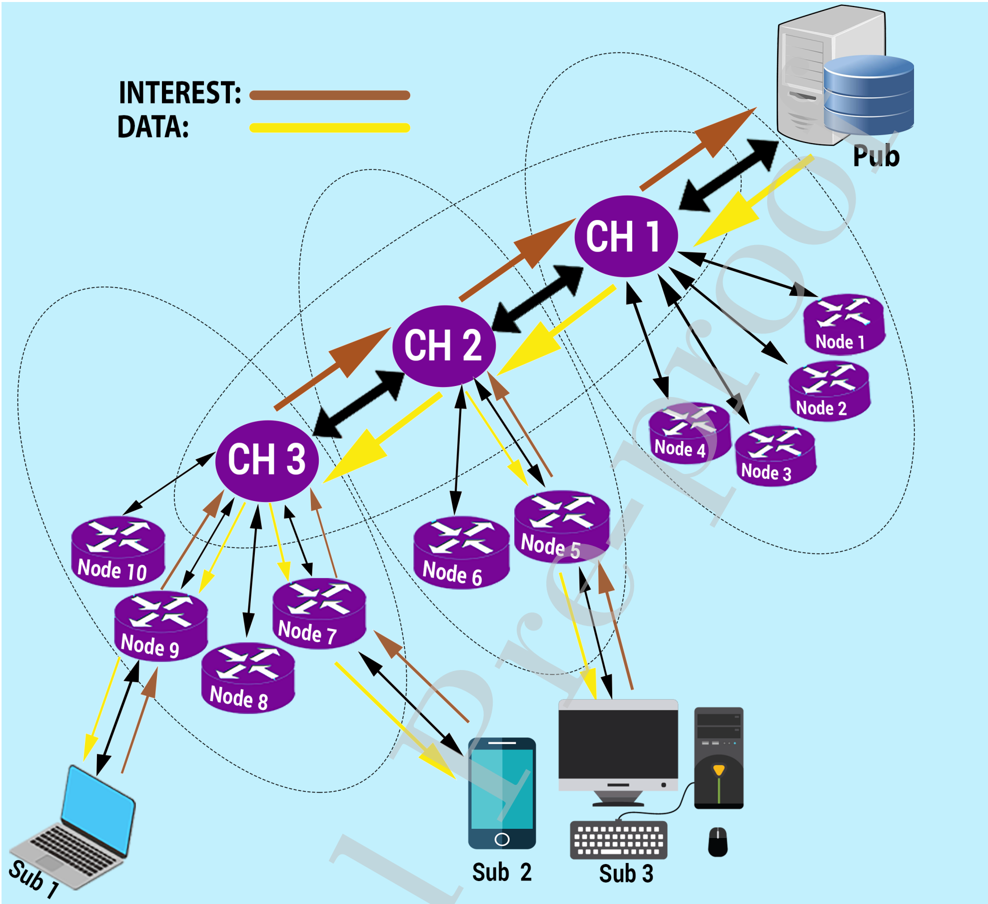

Figure 5: Caching on cluster heads

3.6. Cache Placement

Inspired by [61], the proposed mechanism is based on clustering. That is, the contents are cached on a cluster head using the concept of circular buffer. Fig. 5 depicts three different cluster zones having cluster heads, i.e., CH1, CH2, and CH3, along with several member nodes having a lot of consumers. As a subscriber generates an interest, it is forwarded to the CH through the member nodes of that particular zone. For instance, if two or more consumers are connected to different member nodes of a cluster zone 3 and generate request for a content, say abc.jpeg, their requests are forwarded combined by the member nodes to the CH of that particular zone. If the said content is locally cached on the CH of that zone, the interest packet is entertained by the data packet and the content is delivered to the consumers of different member nodes without any delay by saving the bandwidth and enhancing the user experience. Moreover, the content redundancy is reduced as the content is not being cached on the member nodes of a zone.

If a requested content is not cached locally on a CH, then the interest packet is forwarded to other on-path CH(s). The interest packet is forwarded to the publisher in case the content is not cached at any on-path CH. Whenever a content is accessed from a publisher, the requested content is delivered to the consumer and is cached locally on the CH of that zone and not on other CHs by using the reverse path from where the request message was generated. Whenever a cached content gets an update or it is replaced by a new copy on the publisher (or the memory of a CH gets full), the Incapsula and circular buffer techniques are used to update the content and purge the old content to provide a fresh and most recent content to users without their requests.

4. Experiment Environment and Results

The ndnSIM, which is a library of ns-3 simulator, is used to simulate the PUC strategy. The simulator is installed on a machine that is running Ubuntu 16.04 operating system. The topology consists of 40 ICN nodes, which are randomly placed in an area of 100m x 100m. In the simulation setup, one node is designated as the publisher that runs IEEE802.15.4 ZigBee protocol, whereas the remaining 39 nodes function as subscribers that run the IEEE802.11a WiFi standard [62]. The cache size of every node is set to accommodate 5 chunks in one scenario and 10 chunks in the second scenario that are simulated in 100 different runs. The Zipf popularity model is selected with the α value ranging from 0.5 to 1. Every time the topology is simulated for 120 seconds wherein the average of all 100 runs is combined as a final result. The remaining parameters about the simulation setup is presented in Table 1.

The simulations are run to investigate the performance of the PUC in comparison with probabilistic caching (ProbCache) [63]– which grabs contents near the subscribers, in terms of energy consumption and bandwidth utilization.

In Fig. 6 and 7, the x axis shows different values of α, while the y axis depicts the average ratio of energy consumption (in millijoules) by all IoT

Table 1: Experiment environment: parameters and values

Parameter	Description
Popularity model	Zipf
α	0.5, 0.6, 0.7, 0.8, 1
Simulation area	100 x 100m
Wireless connectivity	Zig-Bee, Wifi
Publisher	1
Subscribers	39
Cache size	5; 10 chunks
File size	1 chunk
frequency/sec on individual messages	8-10/sec
Mobility model	Random-direction
No. of simulation runs	100
Simulation time/run	120 sec

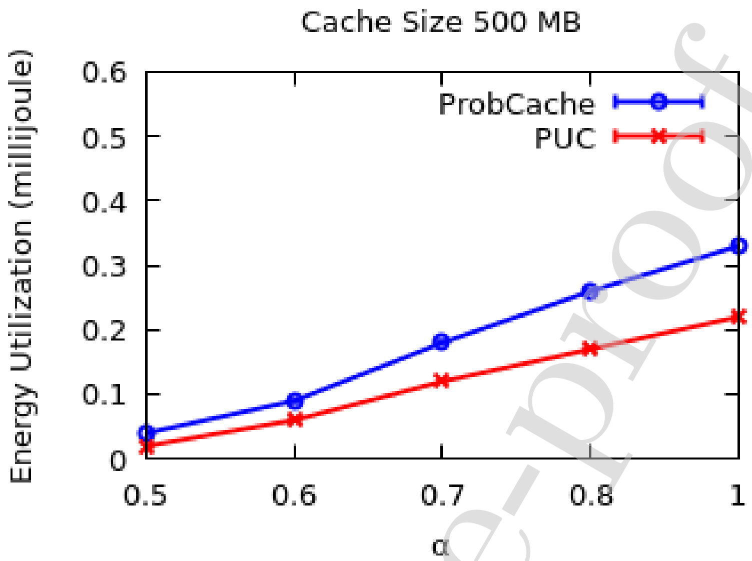

Figure 6: Energy utilization with cache size 500 MB

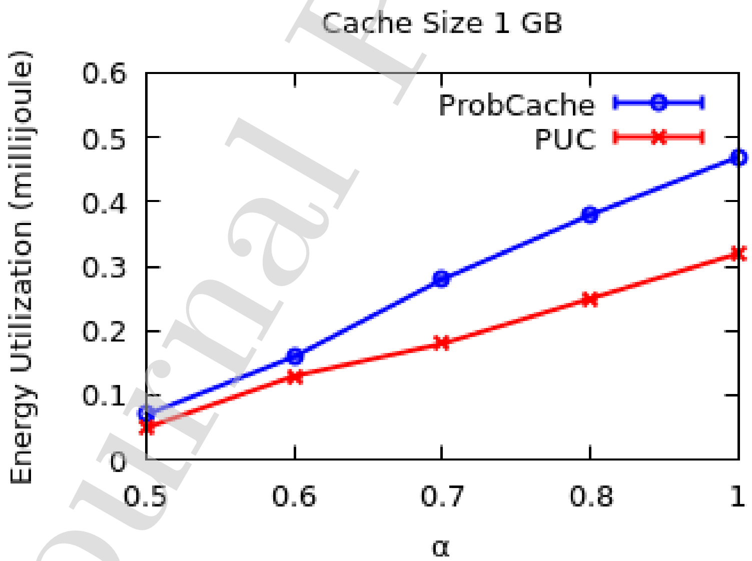

Figure 7: Energy utilization with cache size 1 GB

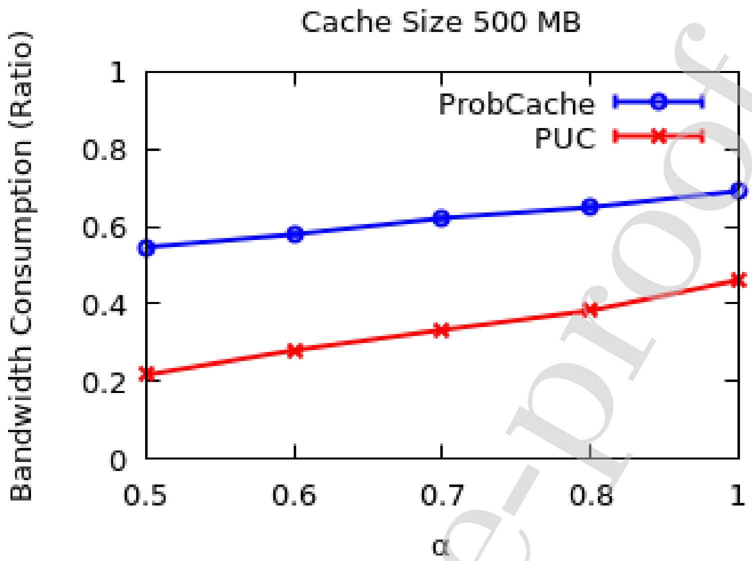

Figure 8: Bandwidth consumption with cache size 500 MB

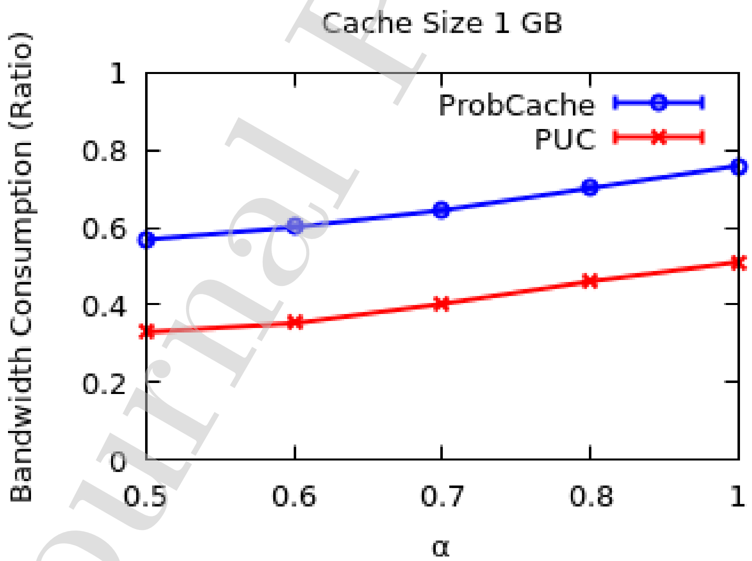

Figure 9: Bandwidth consumption with cache size 1 GB

devices. These values are calculated on 500 MB and 1 GB cache sizes, each for a specified period which is mentioned in Table 1.

Looking at Fig. 6, there was a slight difference in the utilization of energy between the two strategies when the cache size was 500 MB. However, when the cache size was increased from 500 MB to 1 GB (see Fig. 7), the proposed PUC strategy beat the ProbChache as its maximum utilization was 0.32 in comparison with 0.47 of the ProbCache. Similarly, the maximum bandwidth consumption was 0.46 with $\alpha = 1$ and 500 MB cache size in the PUC, whereas this ratio was 0.69 in the ProbCache as an average value (see Fig. 8). As far as the utilization is concerned, the less the better. Furthermore, when the cache size was changed from 500 MB to 1 GB, the minimum bandwidth utilization ratio in the ProbCache was observed as 0.56 with $\alpha = 0.5$, and the maximum value was 0.76 with $\alpha = 1$. Whereas in the PUC strategy, these values were as follows: 0.33 with $\alpha = 0.5$ and 0.51 with $\alpha = 1$, as shown in Fig. 9. Thus, as long as the cache size and α values are increased, the PUC strategy performs better than the ProbCahce both in the energy consumption and bandwidth utilization.

5. Conclusion

Combining Information-Centric Network (ICN) with the Internet of Things (IoT) is a sophisticated solution to data transmission between the subscriber(s) and the publisher because of the in-network caching concept. However, besides numerous contributions, ICN-based IoT caching faces different challenges. This article provides a summary of the caching issues that happen in the ICN-based IoT environment. First, we introduced the main ICN-based IoT caching contributions, i.e., bandwidth utilization, content retrieval delay, server load, path reduction, energy saving, and data privacy. Second, we described the basic caching limitations in terms of cache pollution, PIT overflow, content redundancy, cache poisoning, and access control. Last, we proposed a caching strategy, named Packet Update Caching (PUC), to overcome the critical limitations of the ICN-based IoT environment. The proposed strategy is also compared with the ProbCache in terms of energy consumption and bandwidth utilization, and observed that PUC performed better than the ProbCache, especially when the cache size is large enough to accommodate maximum contents.

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The Editor-in-Chief

Future Generation Computer Systems

Prof. Peter Sloot

Subject: Submission to Future Generation Computer Systems

Dear Prof. Peter Sloot,

Please find the attached revised version of manuscript entitled "PUC: Packet Update Caching for Energy Efficient IoT-based Information-Centric Networking" Manuscript ID: FGCS_2019_2445_R1 Submitted to Future Generation Computer Systems. We would like to state that this is an original paper which is not under review in any other journal or conference. We also confirm that there is no conflict of interest including any financial, personal or other relationships with other organizations or people.

Thank you.

Prof. Ahmad Almogren