Journal of Network and Computer Applications 56 (2015) 48–59

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Survey on caching approaches in Information Centric Networking

Ibrahim Abdullahi [a,b,*], Suki Arif [a], Suhaidi Hassan [a]

[a] InterNetWorks Research Laboratory, School of Computing, Universiti Utara Malaysia, 06010 UUM Sintok, Malaysia
[b] Department of Mathematics/Computer Science, Ibrahim Badamasi Babangida University, Lapai, Niger State, Nigeria

ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form
18 April 2015
Accepted 2 June 2015
Available online 10 July 2015

Keywords:
Information Centric-Networks
Cache strategies
In-network caching
Off-path caching
Network communication

ABSTRACT

Information Centric Network (ICN) is increasingly becoming the alternative paradigm to the traditional Internet through improving information (content) dissemination on the Internet with names. The need to reduce redundancy and frequent access to a host (provider of information) has raised an alternative of a man-in-middle concept of ICN. This has necessitated the introduction of some ICN popular architectures (such as Named Data Network (NDN), Content Centric Network (CCN), to name a few) to manage the salient advantages incorporated in ICN. Despite all efforts and issues in naming, security, routing and mobility, power consumption; caching has become the leading variable to fully actualize the future Internet dream by carefully solving the problems in frequency and recency (in objects). Determining what part of the content is to be cached? When is the most appropriate time for caching? How would the object be cached (placed and replaced) and also what path would the object be cached? Thus, this paper span through some selected ICN architectures and projects to investigate and suggest forms of caching in minimizing the total bandwidth consumption, enhanced Delivery of Service (DoS), reduced upwards and downward streaming. In conclusion, pointing out some of the future probable ways to improve caching in ICN. This survey also highlighted the top sensitive issues that influence the active deployment of caches in ICN through recency, frequency, content size, cost of retrieval and coordination, update in caches and replacements. Several cache characteristics were further presented in ways that would improve cache techniques, deployments as research suggestions for content placement, replacement and quick scan on nodes on and off-path of the network.

1. Introduction

Information Centric Network (ICN) aims at achieving the possibilities of bringing new dimension and improved information dissemination platform on the Internet. Its major targeted distinction between the current Internet will be its ability to use names and not the host content addressing like the traditional Internet Protocol (IP) Internet. Several researches and studies conducted previously, have proven that the aspiration will soon be a success (Jacobson et al., 2009; Xylomenos et al., 2013). The advantages of this new paradigm cannot be over emphasized as bandwidth consumption will be reduced, through neighbor node information/interest distribution. In the paper Jacobson et al. (2009, 2012), it was argued that the advantages of dissociating host and Internet Protocol (IP) will also improve fast delivery of services, better scalability among others. However, achieving these advantages like any other concepts has its pros and cons. Studies conducted in the area have proven that users have grown not to be so concerned about where to get information, but rather what to get at the most demanding time (Xylomenos et al., 2013; Ahlgren et al., 2012; Bari et al., 2012). Answering this vital issue of interest (needed data) spans through challenges such as the availability of what is demanded for, the security of what has been found and the authenticity of trusting the location the resulted interest is coming from. ICN has become an attractive subject as researchers identified many issues in designing architectures, frameworks and algorithms to drive the quest to the dream land of content centric networking. A strong motivation behind the paradigm can be based on the report by Gantz et al. (2007) and Cisco (2014) on the rapid growth of contents on the Internet of about 500 exabytes in 2008. IP traffic will be increasing exponentially, thus causing aggregation from 2009 to 2016 which could be a big problem as the years pass on. It further opens the need to find an alternative to the current information dissemination platform that the Internet community benefits.

However, the studies described in Xylomenos et al. (2013) and Ahlgren et al. (2012) identified other issues that would need quick attention to have an acceptable framework which include confidentiality, data integrity, accountability (owner/publisher authentication

* Corresponding author at: InterNetWorks Research Laboratory, School of Computing, Universiti Utara Malaysia, 06010 UUM Sintok, Malaysia. Tel.: +60 169290804.
E-mail address: ibrahim@internetworks.my (I. Abdullahi).

http://dx.doi.org/10.1016/j.jnca.2015.06.011
1084-8045/

and identification), availability and control access (read, write, execute) and storage (Jacobson et al., 2009). This paper is posed at clearly reviewing some selected studies in ICN particularly focusing our attention towards caching as an open area of great importance.

The paper further selected some popular ICN architectures, projects and approaches namely Content Centric Network (CCN) (Jacobson et al., 2009), Named Data Networking (NDN) (Jacobson et al., 2009), Publish-Subscribe Internet Routing Paradigm (PSIRP)/PURSUIT) (Dimitrov and Koptchev, 2010; Dominguez et al., 2011), Network of Information (NetInf) (Ahlgren et al., 2008; Dannewitz et al., 2012), Data-Oriented Network Architecture (DONA) (Koponen et al., 2007), as the test bed comparison in relation to how it intends and implements the caching on nodes, in-network and off-network (in-path and off-path). Good surveys and highly analytical papers have explained ICN in wider perspectives. Examples were also described in Jacobson et al. (2009), Xylomenos et al. (2013), Ahlgren et al. (2012) and Tyson et al. (2013). Cache is mostly influence to achieving some of its advantages which include good use of the bandwidth by reducing wastage. Thus enhancing the prompt delivery of information (reduced delay) and reducing the overall loads on the main source (host). The caching influencing factors can further be elaborated as:

(a) Frequency – in number terms, how many requests are posted or how frequent is an object requested for?
(b) Recency – the time an object or content was referred to or demanded for
(c) Size – the size of a content
(d) Cost of retrieval – the cost incurred to retrieve the content or object
(e) Time of update – a modification in the cache
(f) Replacement – the best time a content becomes less relevant

The structure of this paper is as follows: Section 2 carefully looked at the issues in ICN related to caching, mentioning the challenges and efforts by researchers in the areas of naming, name resolution, mobility and security. Section 3 presented some selected ICN architectures describing their approaches and relating the framework to each cache practices. Section 4 on the other hand presented the generality of caching mentioning cache frameworks and architectural builds in ICN. Section 5 presents the open research issues in ICN caching looking at the in-path and off-path caching. Section 6 concludes the paper.

2. Issues of caching in ICN

This highlights the major issues in ICN design and architectures. The issues explain the principles in naming, name resolution, mobility and security. The four listed issues would be better achieved when an optimal cache description and form is in place. However, the caching in ICN now becomes so relevant and important as to aid the future implementation of the future Internet. ICN concepts generally has predicted the step-by-step manifestation of the current Internet by its wide advantage of enabling the closest nodes specifying and granting request that are similar when interests are sent. The earlier mentioned issues as explained in (Jacobson et al., 2009) can be depicted and illustrated in Fig. 1.

Note that the advantages through caching are that any time a request is posed by client 2 (see Fig. 1), for a similar interest, the closer nodes that has previously initiated such request offer the data requested. This practice is only possible when a chunk of the data is cached in the content store (CS) of the former thus enhanced delivery of service alongside lower upstream and downstream is also incurred (Jacobson et al., 2009). From Fig. 1, client 1 initiates the request channeled through its closest router node B. The routers in some ICN approaches have incorporated the content store (CS), forwarding information base (FIB) and the pending interest table (PIT) as seen on router A. Router B caches the data obtained from Router A and thus passes it onto Router C when it request similar data. To actualize the positive contribution of ICN deployment, one would notice that all information (content) needed (interest) are referred by name, which only can be served after caching. Name resolution therefore becomes paramount because when an interest is sent, there has to be a resolve operation from the content store as in the case of the figure above when client 2 sent out its interest. Mobility and security that will be discussed in the next subsection requires an effective caching mechanism to actualize the goals of ICN (Jacobson et al., 2009, 2012).

(a) Naming
(b) Name resolution
(c) Mobility
(d) Security.

2.1. Naming

Naming in ICN has given the ideas of trying to answer the questions related to the huge amount of information on the traditional Internet. This is due to the fact that in ICN, the clients and nodes are less concerned about the host location address but rather the request of their interest. ICN as a thread process of the current Internet and will have to borrow some ideas of information retrieval and naming like IP. Naming now becomes a vital point of the underlying design of ICN. Hierarchical naming and Distributed Hash Tables (DHTs) are suggested forms of naming in Jacobson et al. (2009); Tyson et al. (2013); Zhang et al. (2011); Kubiatowicz et al. (2000). Naming is thus seen as the way the requester (client 1 and 2) sends an interest. The information is then received by the closest node/router A or station (as depicted in Fig. 2) which, if it has in its Content Store (CS), it forwards through the functions defined in the Forwarding Information Base (FIB) otherwise the interest is placed in a special table known as the Pending Interest Table (PIT) as presented in Jacobson et al. (2009). The motivation here is that the content is cached alongside the interest for further request of similar data. For the purpose of this survey, the paper shall discuss the caching in the remaining sections. An advantage also incurred in ICN is that information are not automatically deleted like in the IP forwarding, thus decreasing the upward streaming of bandwidth and making information fast available for users that subsequently send interests of the same information.

2.2. Name resolution

Name Resolution action normally occurs at a router-like station for SAIL (Xylomenos et al., 2013), 4WARD (Ahlgren et al., 2012), NetInf (Ahlgren et al., 2008,Dannewitz2012), DONA (Koponen et al., 2007), and the rendezvous as in the case in PSIRP/PURSUIT (Xylomenos et al., 2013). The rendezvous in PSIRP architecture work in a fashion of a negotiator and a settler by receiving the interest from the subscriber. The rendezvous finds a match through an opposite provider (Publisher) of the said interest and data. A good number of algorithms have been proposed and discussed in Jacobson et al. (2009) and Xylomenos et al. (2013), which are yielding results in different ICN project and research implemented tests (Ahlgren et al., 2012; Karila and Team, 2008). It will be good to mention that unlike IP, the request and resolution could be settled by a node that has the information that belongs to a close name resolution station. This flexible advantage of retrieving information from multiple span Name Resolution System

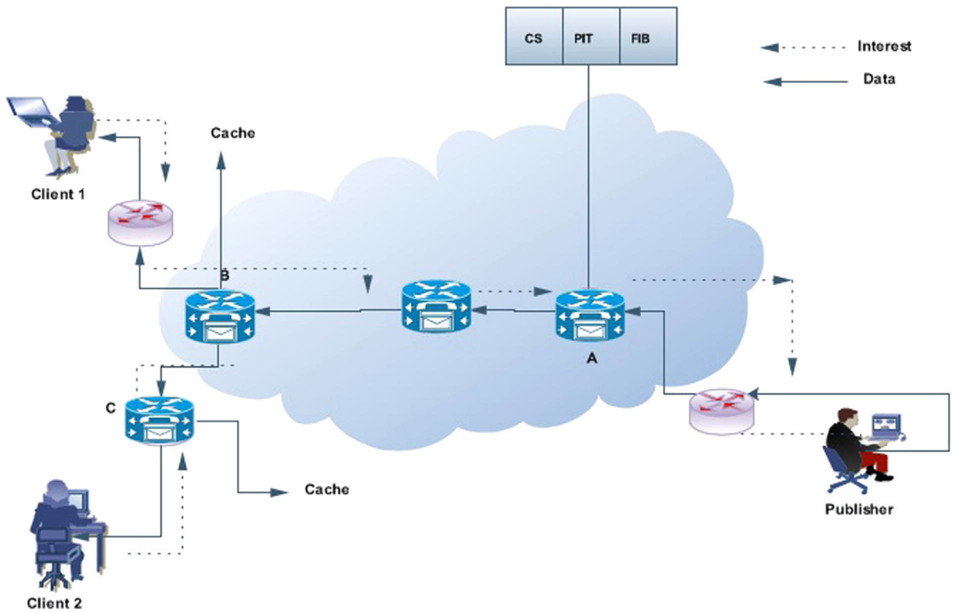

Fig. 1. ICN concept diagram.

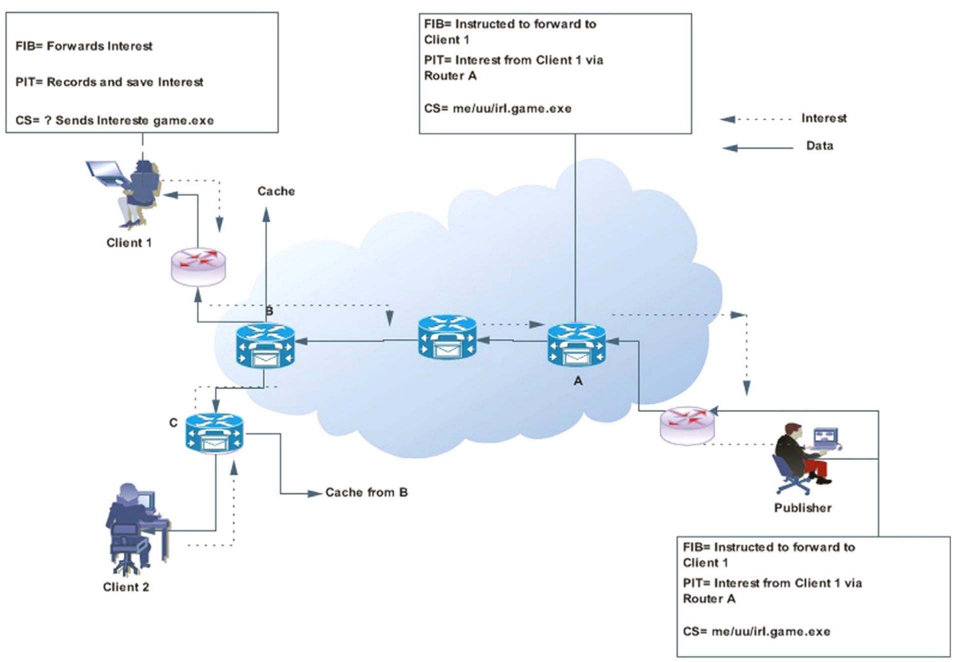

Fig. 2. Naming in ICN.

(NRS) add the advantage of high speed delivery and thus reducing the congestion bottleneck in scheduling. A resolution of name will also prove tough without accurately providing a chunk memory handler at the Name Resolution System (NRS).

This makes ICN challenging in dealing with the large data expected either through subscription or publishing. Name resolution, then becomes the main department in ICN that handles how the routing will be achieved. Since the absence of routing table is felt, the new medium of reactive, proactive and hybrid routing are introduced. In the reactive routing, a subscriber sends interest as the initiator of the operation; thus making the operation possible and successful through caching. This interest is further routed to an appropriate router or node. Thereby getting a publisher or repository that could serve the request. Therefore, adequate caching medium becomes so paramount and highly efficient. The paper further suggests ways to inculcate the caching part into the ICN architectures as mentioned in Xylomenos et al. (2013); Ahlgren et al. (2012). In the proactive routing technique, the subscriber sends interest into the network without necessarily having the Interest requested. This is more or less like broadcasting what the publisher advertises. The name is then cached and copied into locations for further forwarding when requests are made of similar object. In the hybrid, just as the name implies, it combines the both approaches.

2.3. Mobility

ICN solidly claims the mobility of the host and publisher gives an edge over the usual IP networks. Advantages are that when a mobile node moves in and out of the network, there is always a node that has a copy of the information. This therefore reduces disruption and providing ideas on scalability (Ahlgren et al., 2012). Our major concern remains that when mobility is fully in practice, how genuine can a replica station be? Could the content be trusted? These questions are still not clearly answered by researches to gain authority or the best framework to tackle these issues. Mobility also will reduce the cases of information monopoly, censorship and mitigate the privacy right. One may argue that of what benefit would the ICN mobility add to usability if the questions of content reliability are not fully answered? In a way to tackle such assertion, ICN provide a high advantage for disaster areas that cannot normally retrieve information from its original home (i.e. multi-homing is an advantage (Ahlgren et al., 2012)).

2.4. Security

Information on the Internet needs to be trusted thereby providing adequate security measures are issues in ICN. Looking at the Internet from this perspective would create the gap between why do we have firewalls, and other security features like encryption? As such, ICN will also not be excluded from having to provide high security mechanism to control the menace of misuse and unguided information. A major advantage ICN yearn to have in terms of security would be the fact that no information is given unless asked. This to a certain extent could reduce the trouble of bad data transmission and a good way to have security holding responsibility of the node or publisher against bad data publication (Xylomenos et al., 2013). However, since ICN has lots of forwarding nodes, an intruder could as well be a forwarding node for some time and decide to be a nuisance at the next iteration. These problems suggest open and holistic forms of checking and prevention against such. Secure Socket Layer (SSL) as in the normal Internet tends to disappear in ICN. However, other effective means of data security has been established such as key distribution, encryption, digital signing, stale timing, binding, designed strong key hash computations using trees etc. (Xylomenos et al., 2013; Ahlgren et al., 2012; Zhang et al., 2011). This paper therefore itemized these key contentions, but not limited to other serious research unanswered cases in section 4 since the above areas now serves as the universal sets of other challenges. The challenges include caching, data placement and replacement policies, authorization (Read/Write), access control, routing and the main host memory.

3. Popular ICN architectures considered

In the studied popular architectures in Ahlgren et al. (2012), the advantages of scalability, routing, naming and data retrieval cannot be maximally attained without better caching options. However, for the Publish Subscribe Information Routing Paradigm (PSIRP) architecture, a server-based known as autonomous systems (AS) included in the design needs a chunk or copies of the said interest and also the data (requested) before other functions of forwarding, and granting the request would be possible. This section therefore, presents the various popular ICN architectures, projects and proposals by identifying their distinct functionalities and other open areas of research as related to caching. Every node in ICN holds a chunk of information through caching and this serves as a base to the selection of the popular ICN architectures.

3.1. Content centric networking ccn

CCN (Jacobson et al., 2009) a popular and easily understandable ICN architecture. Its operations is in the form of client making a request into the network without necessarily specifying the address of who gives what information and how? This is solved by routing the request/interest sent by client 1 from Fig. 3 (CCN) through a router/node that communicates with its neighbors (client 2 and 3) in search of an answer to that request. Subsequently, if the requested interest is identified at the first router, it is then routed back to the requester; see Fig. 3. A good point to mention in CCN operation, all forwarding nodes cache the data being asked in their memory for the future related request for on-path caching while the off-path does the caching at the main repository. Unlike the IP networks, ICN does not need the Uniform Resource Locator (URL) to locate the information, nor the file structure to name the file and the IP to name the interface of the storage node (Ahlgren et al., 2012). Independent object identifiers are used to name information objects.

3.2. Data Oriented Networking Architecture DONA

Data Oriented Network Architecture (DONA) (Koponen et al., 2007) also a popular ICN-driven platform uses the flat names instead of the hierarchical names. This architecture could be viewed as a structure with added advantages which include the ability to cache information at the network layer using the Autonomous System (AS) and Leave Copy Down (LCD) introduced in its design. The inclusion of the AS allows information to be easily retrievable even when the nodes are not available (mobility). Since the information is cached in a node added to the AS. Its strict cryptography ability enables users to authenticate the genuine state of their request. However, this architecture uses IP and routing address which are exhibited locally and globally (Xylomenos et al., 2013). The inclusions of unique servers known as Resolution Handlers (RH) are charged with resolving names as operations unfold on the network as shown in Fig. 4. RH and routers are enclosed into the AS thereby functioning according to the routing policies enforced on the network. DONA operation functions in a mode similar to the above discussed CCN with its major differences in operation via sending a REGISTER message alongside its object to an in-network RH. The RH caches data and stores a pointer so as to enable easy re-broadcast to other tiers housing RHs. This operation of caching continues as mapping takes place in each RH in the AS. Subsequently, a publisher node also issues REGISTER on to the network informing all RH hierarchy that the request can be provided. DONA engages in its operation using two approaches, namely the coupled and de-coupled operational approach. DONA caching remains most interesting as further discussion on its caching will be presented in the subsequent sections.

3.3. Publish-subscribe internet routing paradigm PSIRP

In PSIRP (Dimitrov and Koptchev, 2010), information Objects are retrieved by subscribers after the information objects are fully published into the network by the producing node. A new matcher and negotiator known the rendezvous system handles the matching. Topology management and forwarding are also involved in PSIRP. PSIRP initiates its operation by the subscriber sending interest/request to a rendezvous handler at the client side as shown in Fig. 5. The operation is then followed by a subscription through the closest router station. This is however possible if the resulted interest has been met as a result of either a cache hit or published. Topology manager, provides a route for the delivery of the required interest. A follow-up of an opposite operation is usually performed by an origin node of the object requested by the forwarding manager handling the data. It follows similar fashion of operation by registering its data/ information to its rendezvous handler/site in the publisher closed area. In PSIRP, the server-based rendezvous handler resolves with the client registered rendezvous handler at the publisher side to obtain a match. When these operations are made, the data can

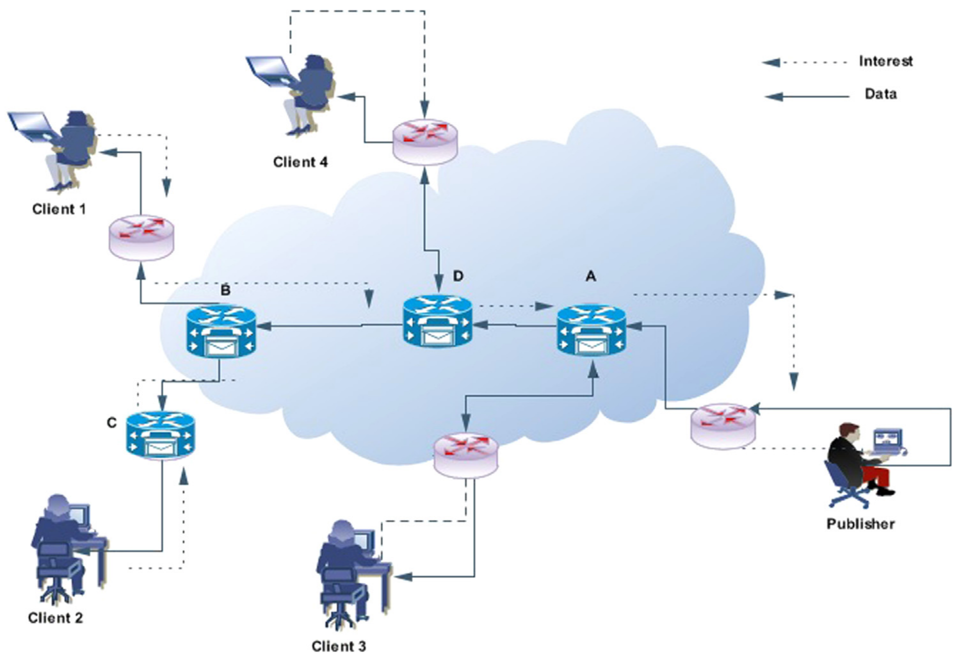

Fig. 3. CCN architecture.

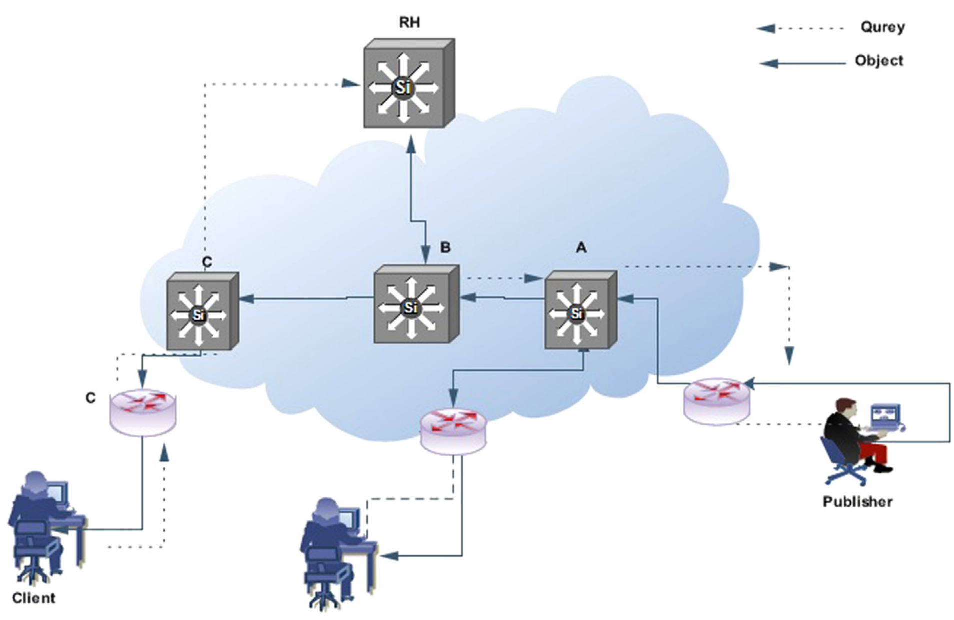

Fig. 4. DONA architecture.

then be routed through the inner router using the same registered path to supply the request to the client (with the aid of the forwarding manager). The PSIRP is also known as a continuation research work by the EU Framework 7 as Publish Subscribe Internet Technology (PURSUIT). Naming in this architecture is done uniquely by some statistical identities in pair. PURSUIT share the same naming structure as DONA (flat names) but managed by the rendezvous and further routed by the Distribution Harsh Table (Rajahalme et al., 2011; Katsaros et al., 2010, 2012). For the quest about our survey, rendezvous is our concern as it relates to how caching is done on the PSIRP / PURSUIT.

The study in Xylomenos et al. (2013) states the possibility of on-path and off-path caching in PSIRP. The off-path operations will necessitate the cooperation of rendezvous network and the publishers through advertisement. Whereas in on-path caching, packets are cached at the forwarding nodes in the PSIRP design in order to mitigate high delays of serving requests similar to the earlier served data.

3.4. Network of information netinf

The NetInf (Dannewitz et al., 2012) architecture on the other hand works in a Publisher/Subscriber way. Even though it has a major difference in terms of operation based on the techniques of NRS. Subscribers gets their information through look ups initiated by the publishers as Named Data Objects (NDO) incorporated with some key search aiding attributes see Fig. 6. The look ups are started by engaging the consumer in the closest node search before expanding searches if data are not found. Resolutions are less stressful as Multilevel Distributed Harsh Tables (MDHT) are

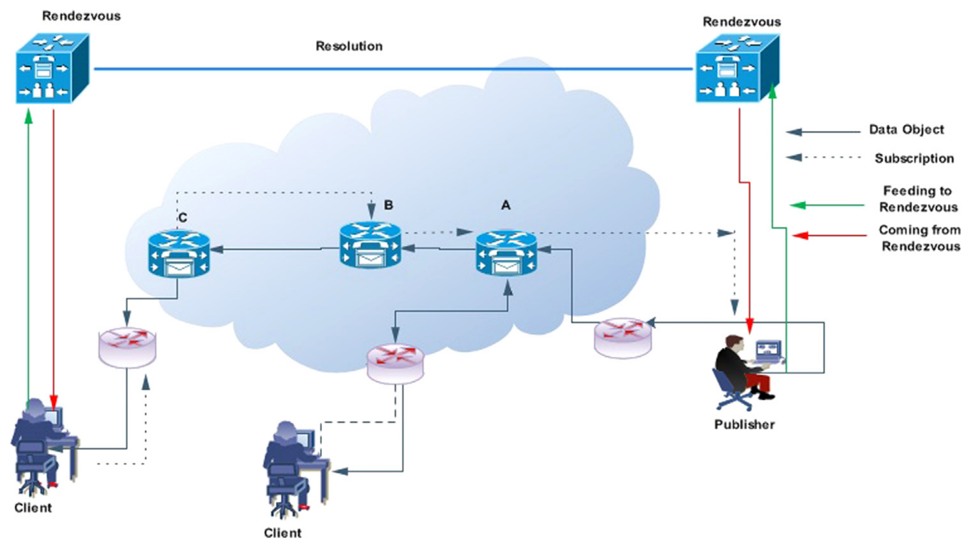

Fig. 5. PSIRP architecture.

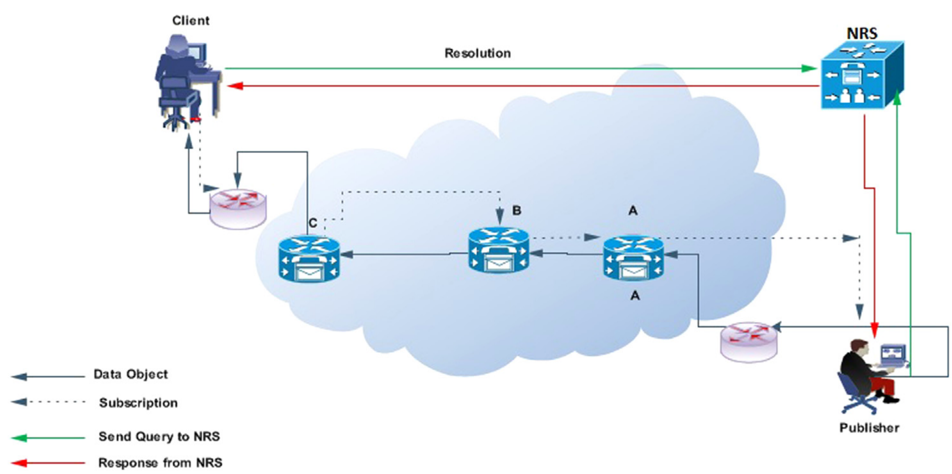

Fig. 6. NetInf architecture.

used. Concurrently, every named object has a self-identifier of a location. NetInf possesses issues of mobility, scalability and naming as seen in all previously mentioned ICN architectures. However, it has the ability to cache on-path even though requester nodes make iterations during the look-up until a match is served by the NR service. NetInf architecture can be said to be intelligent as the consumer nodes are always provided with the list of requests using an indirect approach to send and receive data using MDHT (Tyson et al., 2013). NR stations are mostly the key to fast delivering of the NDO. NetInf make use of the NRS in accessing global requests using the multi-cast. NDO is served by any cast as the resolution completes at several nodes.

For the benefit of the study to examine the caching techniques in the above selected ICN architectures, the paper shall explain some techniques in caching thereby predicting the possibilities of some borrowed caching algorithms and data flow concepts to attain better ICN performance in caching.

4. Caching in ICN

Caching can be defined as having information, data and object temporarily saved in a location for predictive usage on frequent or closely related interval. Content caching as it relates to ICN is our concern in this work. Caching therefore will help in reducing the high cost in up streaming and down streaming of data, information and interest in ICN. Several studies have been conducted in recent times to curb the issues of caching in the web as it can be related to ICN. These include approaches borrowed and enhanced from the previous caching techniques on the web. However, with all the contributions and proposed ideas in ICN popular architectures (Xylomenos et al., 2013; Ahlgren et al., 2012; Tyson et al., 2013), the standardization of in-network and off-network caching is yet to be reached. We therefore aim at exposing the salient features worked upon on this issue (caching). Previously discussed ICN architectures and projects (CCN, DONA, PSIRP and NetInf) itemized the various forms of caching; thereby identifying the on-path off-path node caching. Various studies such as (Hassan et al., 2013; Nagaraj, 2014; Podlipnig and Böszörmenyi, 2003) suggested ways to fulfill the ICN dream of being promising with its advantages but caching being the common issue in all aforementioned ICNs. Major advantages of caching as mentioned earlier will reduce traffic, redundancy of information, bottle neck queuing and competitiveness on frequently accessed or visited domains. Some benefits enjoyed when the cache is in place will include: better utilization of bandwidth, thereby reducing information wastes and high garbage collection (misuse of memory). Bottleneck queue and congestion, improved time of response and bandwidth over head (Podlipnig and Böszörmenyi, 2003).

However, to benefit from the advantages of caching, one may wonder when and how can caching be done? A study in (Sen Wang and Jun, 2013) however, suggested some ways of collaborative approach to propose key additions to caching in ICN architecture. The question still remains very challenging, particularly as it relates to ICN. We are going to expose caching in this section by relating caching in the context of ICN through types and forms of caching in the traditional Internet.

4.1. In-network caching

In this approach, the contents are basically structured and cached based on history of contents frequency which are often referred to as the recency and frequency in some literature (Muscariello et al., 2011; Psaras et al., 2012). In a recent study conducted in Li et al. (2012), in-network caching was used in two distinct forms, namely: Coordinated and non-coordinated with most interest in performance and coordination costs as the metrics. One will agree that as seen in other computer paradigms, a trade-off is always reached to sub-do a factor to enhance performance or vise verse. Coordinated in-network cache according to (Li et al., 2012), described how objects are cautiously picked with the intention of avoiding duplicates in the store. This practice definitely improves the latency and thus makes neighboring node hold non-similar content thereby improving subsequent interest on the path without the need to access the source. In actualizing the above coordinated cache, load on the origin was reduced, routing hop count was minimized, and storage coordination was absent. The load on origin and hop counting was used as the cadence for network performance while storage coordination was used to measure the capability of storage cost in the network.

One may wonder how the coordinated caching could be performed to achieve the objectives mentioned. A mechanism is provided by the designer to check by making sure the nodes don't save same objects using the compare content algorithm. The task, therefore inherit some cost of scanning a wide range topology to check and share the objects. Whereas in non-coordinated in-network cache, this cost of spanning around the topology becomes absent as the need to safely guide and protect against duplicates is not of essence as described in the former. Non-coordinated caching can thus be concluded to have a higher hop counts when the objects subscribed need to be fetched from the main source (Publisher). In submission, we can therefore conclude to say coordinated cache as described in Li et al. (2012) and Psaras et al. (2012, 2014) earns more comfort to the end subscriber through improved time delivery, lesser bandwidth usage and above all lower hop counting. A vital research question now leaves researchers with:

a. How best can the coordinated cache be practiced and archived?
b. At what point and location is it better to be coordinated?
c. What Metrics should we implore between recency and frequency?
d. Would preferred trade-off competition be between the coordination cost and the optimal delivery of service?

Major answers should be channeled towards getting a standard to quantify the overall network performance of routing traffic and cost of coordinating the in-network storage and caching capability. These would be achievable since each router node can have same or similar storage capacity to hold chunks of the content as in Jacobson et al. (2009); Xylomenos et al. (2013); Tyson et al. (2013); Zhang et al. (2011); Zhu and Nakao (2013). In Psaras et al. (2014). However, the design of the in-network differs in its objectives through reducing the cache redundancy and better content flow multiplexing on-path. Probabilistically, the contents are cache and also spaces are reserved for the flow, thereby concluding to say that caches should be performed best to farther distance delivery than longer requesters. Their work was outstanding as it considered both heterogeneous and homogeneous cache environments. Unlike in coordinated in-network caching by Li et al. (2012) concepts used, Psaras et al. (2014) tend to predict the caching favor by calculating the cache based on the number of hops from the publisher to the subscriber. Caching practice as described in Section 4 , the idea is to probabilistically cache content in the nearer node to the source as described in proxy caching so as the farther nodes could have a pick on-path and thus multiplexing depending on the number of caching items on-path.

The idea of Leave Copy Down (LCD) was used in the design of the test, however, the suggestion was that not all router on-path should be cache-enabled. The advantage is to reduce the redundancy as contents travel is very important according to the design. Furthermore, Psaras et al. in Psaras et al. (2014) argued that for better management of the in-network cache, attention must be taken on the cache path capacity and predicted traffic that the cache contents will undergo each time so as to justify caching a contents on route (path).Some factors were introduced to make these measures viz: path cache capacity as related to space in memory, path cache capability related to the amount of paths to cross in relation to traffic, path length monitoring just like in the normal web called Time To Leave (TTL) for packets. In conclusion, studies by Psaras et al. (2014) submitted and justified that in-network caching should be deployed in an uncoordinated fashion as against the concept in Li et al. (2012). The justification for the conclusion was drawn from the fact that resources need to be managed diligently and cache redundancy needs to be eliminated alongside traffic. Some similar issues identified in the study include:

(a) Better probabilistic functions should be investigated to actualize the standard desire for an acceptable caching.
(b) Caching has not been carefully put into practice based on content relevancy.
(c) Popularity and frequency of contents must be defined.
(d) Since multiplexing was used, better security need to be induced to avoid caching bad and unwanted contents.
(e) For How long can we afford to cache contents in a given router? and also for how long do we need to cache contents in a given path in order to minimize redundant traffic and maximize gain? (Psaras et al., 2014).

4.2. Off-path caching

In off-path caching as described and summarized in Xylomenos et al. (2013), CCN/NDN, DONA, PSIRP, NetInf all have the capability of the on-path caching using different techniques. However, the off-path caching in all the mentioned architectures requires additional processes. Registrations are required in DONA and PSIRP while routing information needs upgrade in NDN/CCN. NetInf on the other hand has already got additional advantages through cache-aware transport facility and Name Resolution System (NRS). However, in a recent proposed intra-autonomous caching idea via a cooperative mechanism in Min et al. (2013), it argued that since caching in CCN is inefficient because of its data redundancy, an autonomous system in cooperation needs to tackle this issue. This was submitted by the efforts of the neighboring node in AS to always serve and take care of requests. This unarguably was demonstrated through the collaboration of all nodes in neighboring terms servicing each request concurrently as an AS.

In similar fashion, Wang et al. (2013)) in another work based on collaborative caching using hash-route included an extension in the content store called ingress link. The ideas were based on the issues of limited cache sizes by eliminating the problem of caching via referral. Their algorithm AssignCache was said to have better cache hits. The study in Xie et al. (2012); Wang et al. (2013) further concentrated on the issues of better performance of caching even though the major questions still exist as when would the off-path stations be more reliable? How legitimate can the information be? A recent study by Abdullahi et al. (2015) proposed the deployment of the off-path caching using additional registration as suggested in Xylomenos et al. (2013) through fog computing in the ubiquitous ICN scenario.

4.3. Cache deployment strategies

Strategies in cache deployment have been of high importance for better content retrieval. The positioning of the cache enables routers or nodes predict high cache and content hit ratio. According to (Nagaraj, 2014), the position aid in better hop crossing and time efficiency of the data. Caching as vital as it sound could be classified based on deployment structures into the following viz: proxy, reverse proxy, transparent, adaptive, push and active (Nagaraj, 2014). Each type differs in its operation through some sets of properties and characteristics. For the ICN, one will definitely need to be predicted on the option to implore and the most suitable topology/architecture in question.

4.3.1. Proxy

As the name implies, this deployment architecture serves as an aid in the middle. It is based on the principle of a node/router as seen in Fig. 7 which keeps a content on the path before accessing the main publisher. In that way, response time is enhanced and bandwidth is drastically minimized since the re-interest of the same data set will not require going back to the publisher. On-path as it may seem in this architecture means if cache content is not found, then a forward to the server/publisher is initiated. Great benefits in this architecture places the cache proxy closer to the client nodes.

4.3.2. Reverse proxy

Cache center is positioned closer to the publisher in reverse proxy as against the mode in proxy. For this architecture, we hope and predict its efficacy and better use to reduce the access of malicious information when implored ICN architecture. It has the advantage of making the content almost fully autonomous to the client as the cache center is placed closer to the publisher against the previously mentioned ordinary proxy cache as shown in Fig. 8. As mentioned earlier, the advantage could prevent a client forwarding a malicious content to any neighbor that request same data. However, if the publisher fails the chances of keeping a smooth publish request could be grossly reduced.

4.3.3. Transparent

This offers deployment similar to the entire concept of ICN. Transparent performs its caching based on a cache supervisory system that hold the initial content cached. This reduces and balanced loads in the network through sub routed caches connected. It improves the caching by reducing the overall work force to another routed cache using the cache-to-cache connection. The advantages could be seen that the caching arrangement is similar to the Shared Memory Architecture (SMA) in computer organizational structure. Disadvantage could sometimes be recorded when a node cache attached to a parent cannot re-fetch from the directly routed as presented in Fig. 9.

4.3.4. Adaptive

Figure 10 presents the adaptive deployment scheme of caching. An adaptive cache architectural option works in a way similar to a mesh network topology. The cache information is sent to groups which are created overlapping each other with the intention of serving highly requested data or interest. The intelligence in adaptive deployment of caches is beneficial when it re-organizes the data based on types to form groups. This thus reduces high demand from the main source or publisher. It could also be related to how the Autonomous System in PSIRP and rendezvous network (RENE) systems function.

4.3.5. Active

In active cache deployment strategy, request or interest will be dynamically cached thereby allowing also for personalization of the said request. Users often prefer their request to be personalized. Therefore an intelligent section code need to be added to the caching component to perform the task of personalization. In active deployment, the cache gives the flexibility of the server to move its request to a closer proxy as shown in Fig. 11.

5. Open research issues in ICN caching

5.1. Caching in ccn and unresolved issues

According to (Ahlgren et al., 2012), contents in the CCN architecture are usually cached based on the specification by an administrator. It was articulated that dynamic caching can also be implored based on the popularity and high request of the content (frequency). The concept of the administrative guided and dynamic caching forms a step to achieving ICN. Li et al. (2012) used the form of coordinating and uncoordinated cache to exhibit the caching option flexibility. It was, however noticed that issues of strong retention of competition will exist in the provider of the information as noticed by the research team in Internet Engineering Task Force (IETF) ALTO. Also, the issues of the in-network caching that would minimize the overhead become very obvious to the team IETF DECADE working group in the proposed ICN design. For the aforementioned issues, it is suggested that providing additional caching mechanism would be necessary. However, the survey conducted in Ahlgren et al. (2012) submitted key challenging research issues in the probability of getting the requested content and information by requester/subscribers without necessarily altering the CCN architecture for in-network caching. Delivery and distribution of cache chunks on traversing paths at most stipulated time are issues that need addressing in ccn during interest request. CCN therefore adopts the in-network caching since it has a name based routing and content transport working together (coupled) see Fig. 2. Therefore, unresolved issues include when content is cached, when are they best replaced? Could the entire content be cached?

5.2. Caching in dona and unresolved issues

DONA on the other hand performs its architectural function in a fashion that best required the use of caches at different instances due to its incorporated Resource Handlers (RH) stations. This special inclusion of the RH makes DONA architecture gain flexibility of using on-path caching. In DONA, the RH takes intelligent decisions of caching the data demanded by the subscriber as its address request. This is done by substituting publisher IP of FIND with a RH address prior to the next schedule of finding a RH as forwarded request

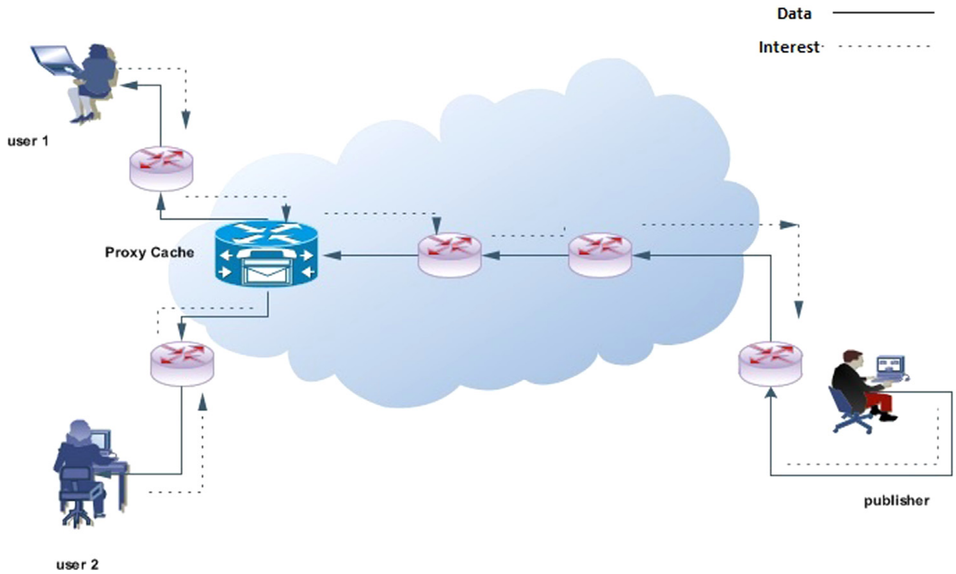

Fig. 7. Proxy cache.

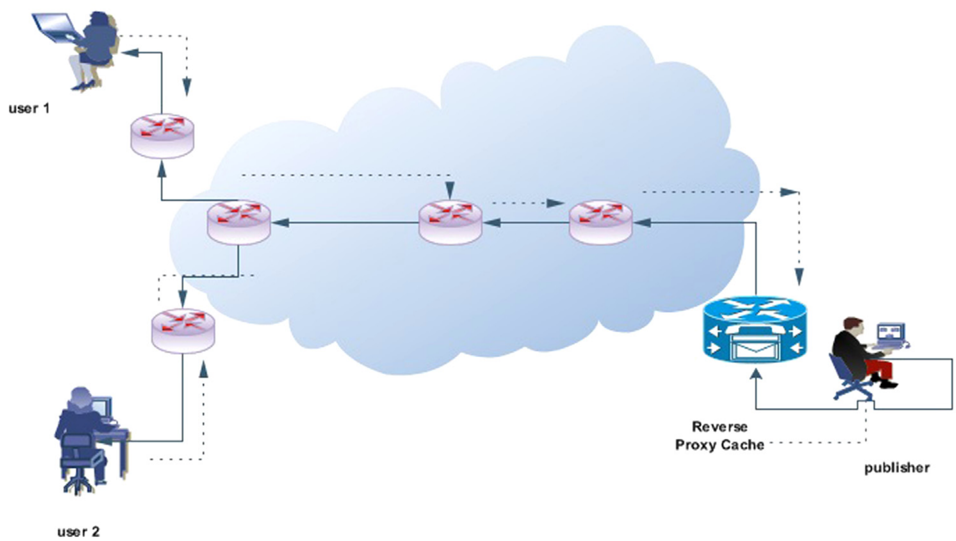

Fig. 8. Reverse proxy.

(Xylomenos et al., 2013) see Fig. 4. This new path of communication in searching to fulfill the demanded data, create the path; thus on finding the data, the resulting data is channeled through the same path thereby caching in every RH it crossed. This advantage, then makes the data available to a subsequent request of the same FIND interest. Major problems faced in this architecture are the size of the data cached by the RH as it progresses. Each RH has a Time To Leave (TTL) for the data as it caches through the paths. It has thus become very challenging for researchers to find the best way to design for the TTL as vital information or data (interest) could be negatively set to leave may be as a result of malicious cache hits. It therefore becomes an open issue to document the acceptable form of cache to be incorporated in DONA.

5.3. *Caching in pursuit/psirp and unresolved issues*

Publisher/Subscriber Information Paradigm is an architecture that operates and move content in and out of the nodes through the special content housing called Rendezvous as described in Section 3. An advantage incorporated in PSIRP is the flexibility of its caching ability. PSIRP has the mechanism of the on-path and off-path caching. Since the PSIRP as described in Xylomenos et al. (2013) separates its function based on three subroutine viz. Rendezvous, Topology Management and Forwarding. Each performing a distinct function of subscriber publisher matching, route creation and forwarding respectively as presented in Fig. 5. However, an acceptable standard is yet to be documented on the series of caching that will definitely exists in these subroutines. The mentioned caching issues become critically unresolved in the ICN research community.

5.4. *Caching in netinf and unresolved issues*

Unlike the CCN/NDN, the NetInf performs its caching using the in-network form of caching. As described by Xylomenos et al. (2013) and Li et al. (2012), NetInf is said to be opportunistic as compared to other architectures (NDN, DONA, PURSUIT). NetInf performs its caching following two rules: in one category, the subscribed information is obtained from a NRS directly if the copy exists as registered. Sometimes the operation is initiated via a broadcast using the local search. The other approach by NetInf uses cache-aware transport facilities provided in the architecture

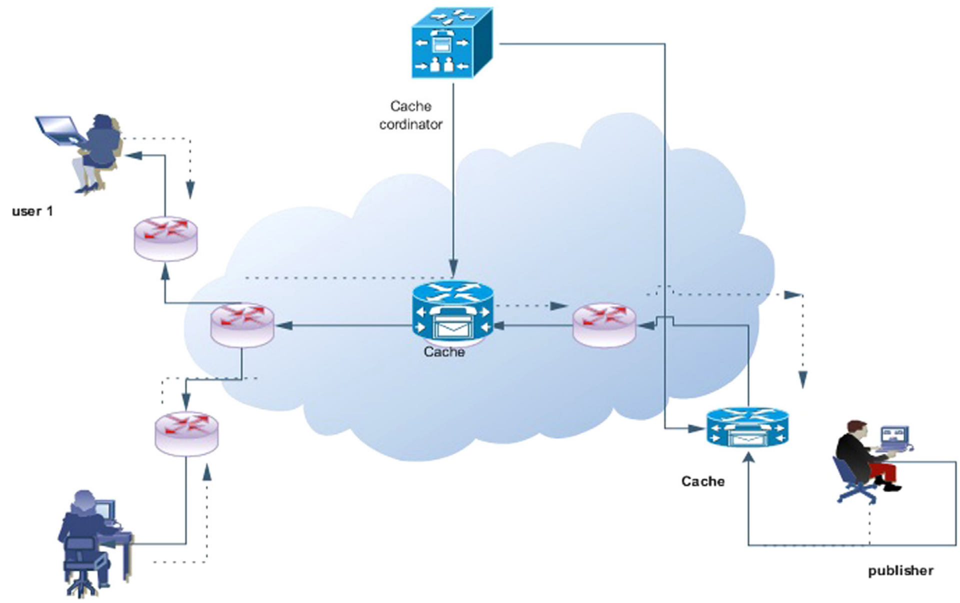

Fig. 9. Transparent.

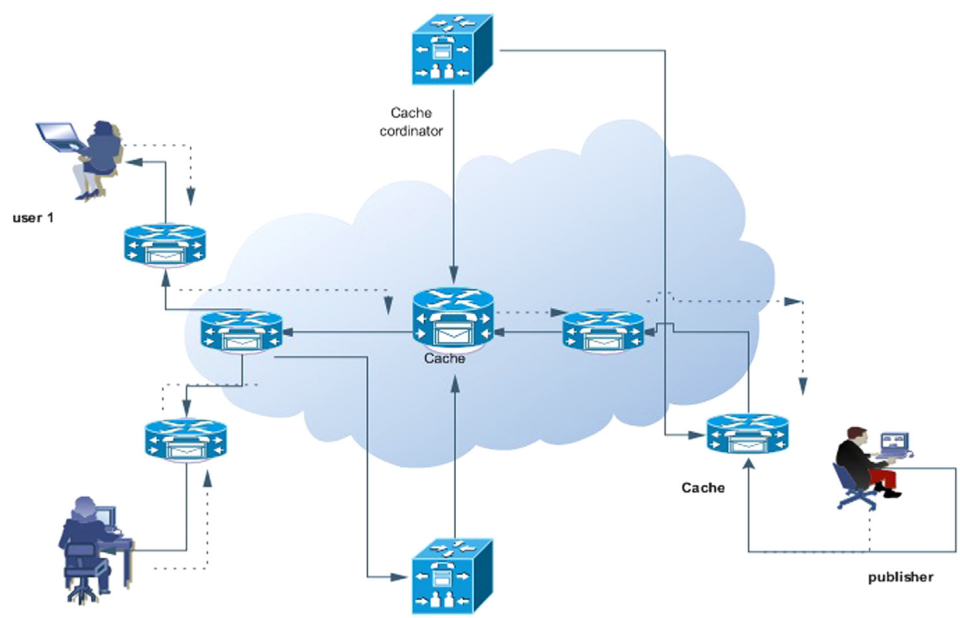

Fig. 10. Adaptive.

which makes it possible to point to a location where the copy exists with the help of an NRS. This therefore places NetInf ahead in terms of caching as it provides two distinct operations for caching. With high security advantages in NetInf, researchers will ponder and figure out better and more suiting ideas of the best cache form as described in Section 4 to be designed for NetInf. Doing this still remain an issue as genuine-state of information is not to be compromised and therefore coordinated and non-coordinated caching needs to be carefully designed so as to attain an acceptable optimization (Wang et al., 2011).

5.5. Cache size vs cache location

From the summaries presented in Table 1, several researches in ICN have shown that cache sizes are relatively small as compared to the predictive requests that move in and out of nodes or stations. As explained in Li et al. (2012), cache type (C-Type) is on-path. Meaning that the location of the cache-enabled router is within the route/path of interest and data access. Xylomenos et al. (2013) in their work exposed the need to have additional mechanism for off-path caching in ICN. Therefore, for closer node and information to the user, proxy strategy was adopted by four (4) authors on the summary table. From the traditional Internet perspective, caches are meant to hold few information for some limited duration. Placement and cache location deployment has gained a lot of attention in the ICN research community. The deployment and location can be an influencing factor for bandwidth utilization, mitigating high hop crosses, minimizing traffic and overall network delay. Studies by Psaras et al. (2014), Sourlas et al. (2013) and Ren et al. (2014) have identified the need for proxy, reverse proxy, active deployments of caches with each related to the localization of the cache-enabled node/router. Therefore, cache size would be efficiently utilized based on the deployment scheme and algorithm of placement, eviction or replacement of contents in ICN.

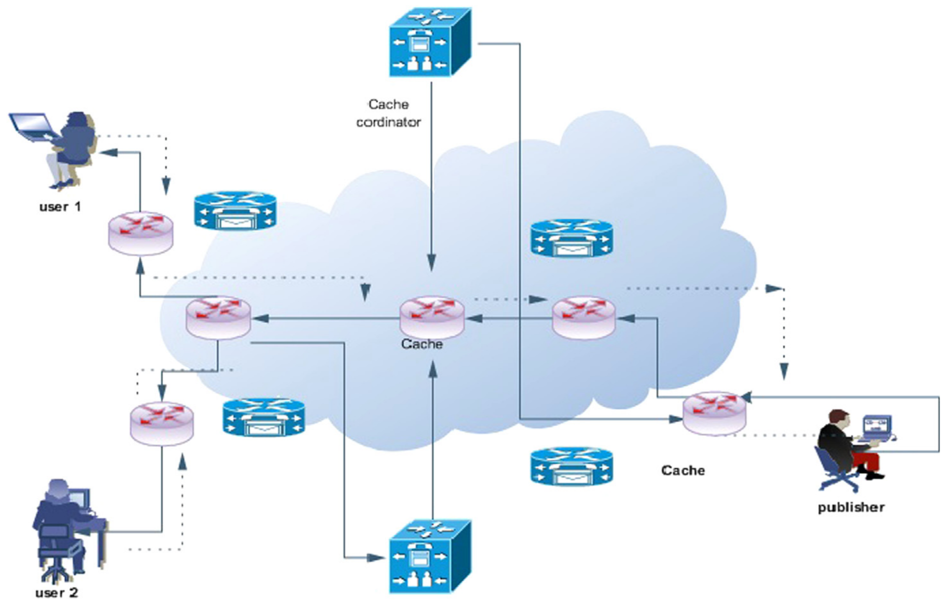

Fig. 11. Active.

Table 1
Summaries of selected ICN strategies and researches Summary of Caching strategies in ICN.

Title	Authors	C-type	Gains	Issues	Algorithm	Strategy	Issues
Coordinating in-network caching in CCN	Li et al. (2012)	On-path	Mitigate excess Bandwidth	cost of Coordination	Popularity based concept	data loss	Coordination cost
Age-based cooperative caching in ICN	Ming et al. (2012)	On-path	Mitigate delay	Manual config.	Age calculation	Age	FIFO,LRU
MultiCache: an incrementally deployable	Katsaros et al. (2010)	On-path, off-path	Mitigate cache misses	Cache redundancy	Multi, Cache	Proxy	Cache fed by others
Proactive selective neighbor cache	Vasilakos et al. (2012)	On-path	Mitigate delay,cost	Cost and delay	Selective neighbor	Reactive	Coordination cost and delay
Autonomic cache management in ICN	Sourlas et al. (2012)	On-path	Complex, execution time	optimality	Greedy	Active	Coordination cost
Probablistic in-network caching for ICN	Psaras et al. (2012)	On-path	hit ratio	AS caching	Popularity	Reverse Proxy	Cost
Caching in ICN satellite networks	Galluccio et al. (2012)	On-path	Mitigate excess Bandwidth	Distance	SatCache	Selective	Coordination cost
Collaborative caching based on hash-routing	Wang et al. (2013)	On-path	Byte hit ratio	Hit Ratio	Assign Cache	Adaptive, Transparent	Forwarding
PropCache: cache more or less based	Suksomboon et al. (2013)	On-path	Time, Distribution	RTT	Popularity	Proxy	Averaging download time
Cooperative caching through routing in ICN	Saha et al. (2013)	On-path	Mitigate content redundancy	cooperate cache	WaxMan	Proxy	Redundancy
Intra-AS cooperative caching for CCN	Min et al. (2013)	On-path	Duplicate elimination	Traffic	G-Heuristic	Proxy, active	Ubiquitous LRU
Distributed cache management in ICN	Sourlas et al. (2013)	On-path	Minimize network traffic cost	Overhead, complexity	Coperative, holistic, myopic	Active, Transparent	Extended AutoCache, Message complexity
MAGIC:A distributed max-gain in-network caching	Ren et al. (2014)	On-path	Mitigate excess Bandwidth, cache penalty	Hop counts	LCE, RAC, MFU	Cache Distributed	Extended PropCache

6. Conclusion

The study has demonstrated an in depth survey in ICN as it relates to caching. Part of the issues presented were general overview of the ICN technology. Motivations through the need to provide a flexible paradigm to meet the demand of today's Internet was presented. However, ICN is still in its developmental stages. Several researches are proving and yielding inspiring results of actualizing ICN as a shift for traditional Internet. Standards are discussed and proposed through several research groups. Issues related to Naming, Name resolution, mobility, security, confidentiality and caching have received high attention. This was a drive to the authors intention of involving such sections. Caching in ICN has been one of the very active studies nowadays; we have therefore comprehensively discussed the research issues in its design and frameworks. We covered the issues in CCN, DONA, PSIRP and NetInf architectures and how caching could be placed using the proxy, reverse-proxy, adaptive, reactive caching models. We have also summarized and compared some key studies in the area for suggestions on how to improve ICN paradigm caching practice.

Acknowledgement

This research is one of the Malaysian Government funded projects under Ministry of Higher Education (MOHE) Long-Term

Research Grant (LRGS) with reference number LRGS/TD/2011/UKM/ICT/02.

Appendix A. Supplementary data

Supplementary data associated with this paper can be found in the online version at http://dx.doi.org/10.1016/j.jnca.2015.06.011.

References

Abdullahi I, Arif S, Hassan S. Ubiquitous shift with information centric network caching using fog computing. In: Computational intelligence in information systems, advances in intelligent systems and computing, vol. 331. Switzerland: Springer International Publishing; 2015. p. 327–35.

Ahlgren B, D'Ambrosio M, Marchisio M, Marsh I, Dannewitz C, Ohlman B, et al. Design considerations for a network of information. in: Proceedings of the 2008 ACM CoNEXT conference, CoNEXT'08. New York, NY, USA: ACM; 2008. p. 66:1-6. http://dx.doi.org/10.1145/1544012.1544078 ⟨http://doi.acm.org/10.1145/1544012.1544078⟩.

Ahlgren B, Dannewitz C, Imbrenda C, Kutscher D, Ohlman B. A survey of information-centric networking. IEEE Commun Mag 2012;50(7):26–36. http://dx.doi.org/10.1109/MCOM.2012.6231276.

Bari M, Chowdhury S, Ahmed R, Boutaba R, Mathieu B. A survey of naming and routing in information-centric networks. IEEE Commun Mag 2012;50(12):44–53. http://dx.doi.org/10.1109/MCOM.2012.6384450.

Cisco. Cisco visual networking index:global mobile data traffic forecast update, 2013–2018. Technical Report. Cisco; 2014.

Dannewitz C, Herlich M, Karl H. Opennetinf – prototyping an information-centric network architecture. In: 2012 IEEE 37th conference on local computer networks workshops (LCN Workshops); 2012. p. 1061–9. http://dx.doi.org/10.1109/LCNW.2012.6424044.

Dimitrov V, Koptchev V. Psirp project-publish-subscribe internet routing paradigm: new ideas for future internet. In: Proceedings of the 11th international conference on computer systems and technologies, CompSysTech'10. New York, NY, USA: ACM; 2010. p. 167–71.

Dominguez A, Novo O, Wong W, Valladares T. Publish/subscribe communication mechanisms over psirp. In: 2011 7th international conference on next generation web services practices (NWeSP); 2011. p. 268–73. ⟨http://dx.doi.org/10.1109/NWeSP.2011.6088189⟩.

Galluccio L, Morabito G, Palazzo S. Caching in information-centric satellite networks. In: 2012 IEEE international conference on communications (ICC); 2012. p. 3306–10. http://dx.doi.org/10.1109/ICC.2012.6363993.

Gantz JF, Reinsel D, Chute C, Schlichting W, McArthur J, Minton S, et al. The expanding digital universe: a forecast of worldwide information growth through 2010. Technical Report. An IDC White Paper- Sponsored by EMC; March 2007.

Hassan S, Aziz Z, Nisar K. On the cache performance of the information centric network. In: 2013 International conference on computing, electrical and electronics engineering (ICCEEE); 2013. p. 477–81.

Jacobson V, Smetters DK, Thornton JD, Plass M, Briggs N, Braynard R. Networking named content. In: Proceedings of the 5th international conference on emerging networking experiments and technologies, CoNEXT'09. New York, NY, USA: ACM; 2009. p. 1–12.

Jacobson V, Smetters DK, Thornton JD, Plass M, Briggs N, Braynard R. Networking named content. Commun ACM 2012;55(1):117–24.

Karila A, Team PP. Psrip project; 2008. URL ⟨http://www.psirp.org/home.html⟩.

Katsaros K, Xylomenos G, Polyzos G. Multicache: an incrementally deployable overlay architecture for information-centric networking. In: INFOCOM IEEE conference on computer communications workshops; 2010. p. 1–5. http://dx.doi.org/10.1109/INFCOMW.2010.5466639.

Katsaros, K. Fotiou, N. Vasilakos, X. Ververidis, C. Tsilopoulos, C. Xylomenos, G. et al. On inter-domain name resolution for information-centric networks, in: NETWORKING 2012, Vol. 7289 of Lecture Notes in Computer Science, Springer Berlin Heidelberg; 2012. p. 13–26.

Koponen T, Chawla M, Chun BG, Ermolinskiy A, Kim KH, Shenker S, et al. A data-oriented (and beyond) network architecture. SIGCOMM Comput Commun Rev 2007;37(4):181–92. http://dx.doi.org/10.1145/1282427.1282402.

Kubiatowicz J, Bindel D, Chen Y, Czerwinski S, Eaton P, Geels D, et al. Oceanstore: an architecture for global-scale persistent storage. SIGPLAN Not 2000;35(11):190–201. http://dx.doi.org/10.1145/356989.357007.

Li Y, Xie H, Wen Y, Zhang ZL. Coordinating in-network caching in content-centric networks: model and analysis. URL ⟨http://www.ntu.edu.sg/home/ygwen/Paper/LXW-ICDCS-13.pdf⟩.

Min WJ, Jun Z, Brahim B. Intra-as cooperative caching for content-centric networks. In: Proceedings of the 3rd ACM SIGCOMM workshop on information-centric networking, ICN'13. New York, NY, USA: ACM; 2013. p. 61–6.

Ming Z, Xu M, Wang D. Age-based cooperative caching in information-centric networks. In: 2012 IEEE conference on computer communications workshops (INFOCOM WKSHPS); 2012. p. 268–73. http://dx.doi.org/10.1109/INFCOMW.2012.6193504.

Muscariello L, Carofiglio G, Gallo M. Bandwidth and storage sharing performance in information centric networking. In: Proceedings of the ACM SIGCOMM workshop on information-centric networking, ICN'11. New York, NY, USA: ACM; 2011. p. 26–31. URL ⟨http://doi.acm.org/10.1145/2018584.2018593⟩.

Nagaraj SV. Web caching and its application, no. 1-4020-8050-6. Kluwer Academic Publishers: New York, Boston, Dordrecht, London; 2004. URL ⟨http://ebooks.kluweronline.com⟩.

Podlipnig S, Böszörmenyi L. A survey of web cache replacement strategies. ACM Comput Surv 2003;35(4):374–98. http://dx.doi.org/10.1145/954339.954341.

Psaras I, Chai WK, Pavlou G. Probabilistic in-network caching for information-centric networks. In: Proceedings of the second edition of the ICN workshop on information-centric networking, ICN'12. ACM: New York, NY, USA; 2012. p. 55–60. http://dx.doi.org/10.1145/2342488.2342501⟨http://doi.acm.org/10.1145/2342488.2342501⟩.

Psaras I, Chai W, Pavlou G. In-network cache management and resource allocation for information-centric networks. IEEE Trans Parallel Distrib Syst 2014;PP(99):0–1. http://dx.doi.org/10.1109/TPDS.2013.304.

Rajahalme MJ, Sarela KV, Riihijarvi J. On name-based inter-domain routing. Comput Netw 2011;55:975–86.

Ren J, Qi W, Westphal C, Wang J, Lu K, Liu S. et al., Magic: a distributed max-gain in-network caching strategy in information-centric networks. In: 2014 IEEE conference on computer communications workshops (INFOCOM WKSHPS); 2014. p. 470–5. http://dx.doi.org/10.1109/INFCOMW.2014.6849277.

Saha S, Lukyanenko A, Yla-Jaaski A. Cooperative caching through routing control in information-centric networks. In: 2013 Proceedings on INFOCOM. IEEE; 2013, p. 100–4. http://dx.doi.org/10.1109/INFCOM.2013.6566743.

Sen Wang JW, Jun Bi. Collaborative caching based on hash -routing for information-centric networking. In: SIGCOMM'13. ACM: Hong Kong, China; 2013. p. 535–6.

Sourlas V. Flegkas P, Gkatzikis L, Tassiulas L. Autonomic cache management in information-centric networks. In: 2012 IEEE network operations and management symposium (NOMS); 2012. p. 121–9. http://dx.doi.org/10.1109/NOMS.2012.6211890.

Sourlas V, Gkatzikis L, Flegkas P, Tassiulas L. Distributed cache management in information-centric networks. IEEE Trans Netw Serv Manag 2013;10(3):286–99. http://dx.doi.org/10.1109/TNSM.2013.052113.120382.

Suksomboon K, Tarnoi S, Ji Y, Koibuchi M, Fukuda K. Abe S, et al. Popcache: cache more or less based on content popularity for information-centric networking. In: 2013 IEEE 38th conference on local computer networks (LCN); 2013. p. 236–43. http://dx.doi.org/10.1109/LCN.2013.6761239.

Tyson G, Sastry N, Cuevas R, Rimac I, Mauthe A. A survey of mobility in information-centric networks. Commun ACM 2013; 56 (12): 9098. http://dx.doi.org/10.1145/2500501.

Vasilakos X, Siris VA, Polyzos GC, Pomonis M. Proactive selective neighbor caching for enhancing mobility support in information-centric networks. In: Proceedings of the second edition of the ICN workshop on information-centric networking, ICN'12. ACM: New York, NY, USA; 2012. p. 61–6.

Wang S, Bi J, Wu J, Li Z, Zhang W, Yang X. Could in-network caching benefit information-centric networking? In: Proceedings of the 7th Asian Internet engineering conference, AINTEC'11. ACM: New York, NY, USA; 2011. p. 112–5.

Wang Y, Li Z, Tyson G, Uhlig S, Xie G. Optimal cache allocation for content-centric networking. In: IEEE international conference on network protocols; 2013.

Wang S, Bi J, Wu J. Collaborative caching based on hash-routing for information-centric networking. SIGCOMM Comput Commun Rev 2013;43(4):535–6. http://dx.doi.org/10.1145/2534169.2491727.

Wang S, Bi J, Wu J. Collaborative caching based on hash-routing for information-centric networking. In: ACM SIGCOMM 2013 conference on SIGCOMM, SIGCOMM'13. ACM: Hong Kong, China; 2013. p. 535–6.

Xie M, Widjaja I, Wang H. Enhancing cache robustness for content-centric networking. In: 2012 Proceedings on INFOCOM. IEEE; 2012. p. 2426–34. http://dx.doi.org/10.1109/INFCOM.2012.6195632.

Xylomenos G, Ververidis C, Siris V, Fotiou N, Tsilopoulos C, Vasilakos X, et al. A survey of information-centric networking research. IEEE Commun Surv Tutor 2013;99:1–26. http://dx.doi.org/10.1109/SURV.2013.070813.00063.

Zhang X, Chang K, Xiong H, Wen Y, Shi G, Wang G. Towards name-based trust and security for content-centric network. In: 2011 19th IEEE international conference on network protocols (ICNP); 2011. p. 1–6. http://dx.doi.org/10.1109/ICNP.2011.6089053.

Zhu Y, Nakao A. A deployable and scalable information-centric network architecture. In: 2013 IEEE international conference on communications (ICC); 2013. p. 3753–3758. http://dx.doi.org/10.1109/ICC.2013.6655139.