Producer mobility support in information-centric networks: research background and open issues

Ahmad Abrar,
Ahmad Suki Che Mohamed Arif and
Khuzairi Mohd Zaini*

InterNetWorks Research Laboratory,
School of Computing,
Universiti Utara Malaysia,
Changlun, Malaysia
Email: ahmadabrar2011@yahoo.com
Email: suki1207@uum.edu.my
Email: khuzairi@uum.edu.my
*Corresponding author

Abstract: In recent times, an interesting innovation of information-centric networking (ICN) architecture has been introduced to replace the old fashion host-centric communication architecture with content-centric architecture. With the instant growth of mobile devices and mobile data traffic, the mobility issue in the current IP-based network is growing rapidly and is facing many inefficiencies such as unsupported mobility and data delivery. The unsupported mobility causes failure of the communication system and inaccessibility in the network services. The unsupported mobility stimulates several complications and issues in the network such as unavailability of content, denial of service, interest packets loss, and excessive burden in the network. Further, unsupported mobility affects the routing and forwarding plane in the network and terminates the content transmission to its consumers. Thus, this paper will critically explore this issue. It will present a strong foundation of the producer mobility support architecture, research challenges, previous solutions, and open research issues. Along with this discussion, a research roadmap will be delineated.

Keywords: information centric networks; named data networking; NDN; producer mobility; consumer mobility; handoff.

Reference to this paper should be made as follows: Abrar, A., Arif, A.S.C.M. and Zaini, K.M. (2022) 'Producer mobility support in information-centric networks: research background and open issues', *Int. J. Communication Networks and Distributed Systems*, Vol. 28, No. 3, pp.312–336.

Biographical notes: Ahmad Abrar received his Master's in Information Technology from the University of Education Lahore, Multan Campus, Pakistan. Currently, he is a PhD candidate at the School of Computing, Universiti Utara Malaysia (UUM), Malaysia. His research interests include future internet architecture, information-centric networks (ICN), named data networking (NDN), mobility management, and internet of things (IoT).

Ahmad Suki Che Mohamed Arif received his Diploma, Bachelor's and Master's in Computer Science from the Universiti Teknologi Malaysia (UTM). He later received his PhD from the Universiti Utara Malaysia (UUM). His doctoral research was on a new shaped video rate algorithm, referred to as slight delay – shaped variable bit rate (SD-SVBR), which is aimed at controlling the video rate for video application transmission over the internet. This new algorithm is capable of producing a high video rate and at the same time a better quantisation parameter (QP) stability video sequence. In addition, the video rate is shaped efficiently in order to prevent unwanted sharp increment or decrement, and to avoid buffer overflow. His research interests are in multi-areas such as video transmission over the internet, network transport protocol, mobile computing, distributed system, and network traffic analysis/engineering.

Khuzairi Mohd Zaini is a Senior Lecturer at the School of Computing, Universiti Utara Malaysia. He received his PhD in the field of Wireless Computing from the Universiti Sains Malaysia. His research interests include performance modelling and analysis of computer networks, mobile data offloading, network resource allocation, and network economics.

1 Introduction

The idea of internet architecture was developed and established in the 1960s and 1970s when the key objective was resource sharing. Owed to the pertinent objective, certain computing resources were used to communicate by connecting them in a network and commence for exchange information (Bari et al., 2012; Jacobson et al., 2009). Currently, the consumption of the internet is rising exponentially and it is playing an essential role in our daily life (Ahlgren et al., 2012). The internet was introduced to meet the desires of an information communication system (Morley et al., 2018). With the instant and explosive growth in mobile devices, the present internet is replaced from immobile computing system to mobile computing system.

Moreover, the advancement in technology and the internet application push more mobile devices into the internet. Currently, internet users are rising continuously that produced a high usage of computing resources. In fact, the internet provides personal, academic, and social advantages to its consumers. In addition, the internet distributes the number of services for web pages, real-time streaming, user-generated content, video data, voice data, local, global network connectivity, multimedia traffic, etc. Recently, demand for the internet is rapidly increasing day by day because of its advanced services and applications to support the consumers' applications and their requirements.

According to the Cisco Visual Networking Index (VNI) (Jung, 2019) estimation, from 2017 to the year 2022, the consumption in data traffic and users connection will be highly exceeded on the internet. According to the VNI report, the total global mobile data traffic has increased 71% in 2017. It was reached 11.5 exabytes (EB) per month at the end of the year 2017 that was recorded as 6.7 EB per month at the end of the year 2016. In 2016, the global mobile connections and devices were recorded at 7.9 billion. However, in 2017 this amount grew up to 8.6 billion.

Consequently, about 650 million connection and mobile were added during 2017. From 2017 to 2022, the total mobile data traffic will increase up to 77 EB per month and the total mobile data traffic will reach one zettabyte annually. In addition, global mobile data traffic will grow up to seven-fold. According to compound annual growth rate (CAGR), the mobile data traffic will increase 46% and it will reach 77.5 EB per month by 2022. Moreover, in 2017 as per year VNI statistic shows the usage of global mobile devices and connection has been increased from 7.9 to 8.6 billion as compared to the previous year 2016. By 2022 global mobile devices and connection will be increased up to 12.3 billion at 7.5% in CAGR.

Under the significance analysis of VNI (Jung, 2019) from 2017 to the next upcoming five years, the utilisation for non-smartphones will be declined from 34 to 10%. In contrast, the consumption of smartphones will accelerate from 42 to 44%. Moreover, growth in other devices like M2M mobile connections will increase from 11 to 31%. For tablet devices, they increase from 2 to 3% and in phablets devices, they increase from 8 to 10%. However, according to VNI statistic, it shows the excessive demand for the internet services and data that induce a lot of issues such as: creating unnecessary bandwidth consumption does not support proper device mobility, unsupported multicasting, unassisted location-independent naming, data availability issue, content scalability trouble, inefficient content distributive problem, does not serve good caching capabilities; moreover, authentication and security were more challenging (Hossain and Atiquzzaman, 2011). The present location-based (TCP/IP) internet architecture will be insufficient to meet the user requirements because of high congestion that will be difficult to achieve multidimensional users' requirements related to the desired information. Therefore, advanced developments in smart devices and their excessive usage leads to high data traffic due to the connectivity of these devices over the internet. Hence, it requires intensifying demand for the efficient, distributive, scalable and cost-effective network architecture. For this reason, the content delivery network (CDN) was introduced for the betterment of the current internet architecture as a cost-effective distribution and scalability (Xylomenos et al., 2013).

To enhance communication services, bandwidth utilisation, and content distribution across the internet, researchers developed an efficient CDN technology (Peng, 2004). In fact, CDN contains multiple servers situated at different locations or it can be near the user that caches a copy of requested content to fulfil the subsequent responses. These servers install at every edge of the network that belongs to CDN and use to distribute the content to its clients (Pallis and Vakali, 2006).

CDN provides quick delivery of static content from edge cache servers to its data requesting users that are geographically closest in the network. Moreover, its result reduces bandwidth consumption and decreases traffic load in the network that implies an efficient architecture. However, in CDN architecture, identical copies for content with enormous traffic use by access consumers induce deep-rooted issues and complexity in the network. According to the yearly VNI report, it shows an increase in the internet clients that demands to upgrade CDN servers in the sense of handling the immense amount of content. However, to overcome the CDN issues and upgrading, it requires high management cost (Inaba et al., 2015). As a result, researchers were introduced with a new internet architecture referred to as information-centric networking (ICN) as a replacement of the current IP-based architecture. ICN was introduced to solve the complex issues in the CDN and TCP/IP (peer-to-peer) architecture.

2 Information-centric networks

The current internet communication architecture basically relies on the overlay system (peer-to-peer network) and CDNs (Ahlgren et al., 2011). According to recent years, the usage of the internet is gradually increasing because of the increase in the demand for video on demand (VoD), social media applications and online gaming (Dias et al., 2020). Therefore, the consumption of global IP addresses is also increased. During a recent research report, the global IP traffic will accomplish more than 1,000 EB in 2021 (Naeem et al., 2018), and most of the traffic belongs to IP and peer-to-peer infrastructure. It is expected that the IP traffic will increase exponentially in the future under the IP-based architecture. Thus, the current internet will be highly burden (Cisco Jose, 2019).

The current host-to-host internet paradigm is insufficient to support content distribution and sharing information, in recent years, the internet community is facing many complications such as poor security, congestion, mobility and scalability in the current internet architecture (Fang et al., 2018; Zhang et al., 2015). Therefore, the ICN is inaugurated to support the internet based on naming content and placing the information independently instead of controlling the IP host and end-to-end communication system (peer-to-peer networks) (Mars et al., 2019). Fundamentally, ICN architecture is the public-subscriber internet (PSI), where consumers are interested in content and do not concerned about where the content retrieved (Fang et al., 2018). As compared with the current host-based communication model of IP architecture, the content transmission in ICN follows the receiver driven approach. Once the consumer demand for content, the requested content is searched and matched in ICN, the required content is transferred to the receivers along with the reverse path. Therefore, the ICN aims are to find, deliver and disseminate network content instead of the maintenance of host-to-host communication and reachability of end hosts. For mobile hosts, it is difficult to deploy on multiple networks because host-centric networks address a specific network interface. Still, ICN supports the request-reply model and easily be multiplexed over multiple interfaces. ICN utilises content-centric information instead of the location-oriented one to route between a consumer and content provider (Fang et al., 2018).

The aim of ICN is to ameliorate the current internet and guarantee superior services in future to vanquish the problems in IP-based architecture. Therefore, the fundamental concept of ICN is to change the current IP-based internet with content-based internet because the intention of the user's in ICN is to retrieve content rather than its physical location in the network (Xylomenos et al., 2013). For this purpose, the design of ICN is based on content-centric nature that identified each content by its unique name rather than IP. In addition, to support seamless mobility in the IP-based network has a need for a high-cost network manager for controlling the mobile nodes because whenever nodes change physically its location topologically, they experience dis-connectivity from the network. Moreover, ICN offers other benefits to support content-centric architecture, such as scalability, robust security, authenticity, secure data integrity, mobility, any-casting, multi-homing, multicasting, and reliability (Akbar et al., 2014).

In ICN, some of its architecture ensures substantial flow control and uses the request and reply method to retrieve content in the hop-to-hop network. However, the ICN architectures still need improvements and experience various challenges such as application design, legal issues, mobility, scalability, deployment, and privacy. The improvements and enhancements have a direct impact on the architecture development that produces robustness in the future network. Generally, ICN is known by different terms such as content-aware, content-centric, data-centric, and ICN. All these terms operating technique follows the content-oriented paradigm of the ICN. Moreover, common ICN architectures are centred on the content name and it has been classified into different naming schemes as hybrid, flat, and hierarchical (Akbar et al., 2014).

In 2012, the Internet Research Task Force (IRTF) introduced a research group that works on ICN. IRTF published a Request for Comments (RFC) 7927 documentation where the focal point in it is ICN emerging challenges such as caching, content placement, mobility management, forwarding, scalability, request staleness, routing, naming, resolution system, data security, data integrity, authentication, etc. (Tyson et al., 2012). Therefore, to strengthen the features of ICN, there is a need to unravel the addresses focal point challenges (Kutscher et al., 2016).

3 ICNs projects

In 1999, the initial ICN idea was proposed by Cheriton et al. (Fang et al., 2018). The European Union Research and Innovation Program (EU FP7) has been introduced to a variety of ICN projects. Multiple EU-based ICN research projects are operating (Hussaini et al., 2018c) such as 4WARD (Brunner et al., 2010), network of information (NetInf) (Dannewitz et al., 2013), publish/subscribe internet routing paradigm (PSRIP) (Fotiou et al., 2010), content mediator architecture for content-aware networks (COMET) (García et al., 2011), public/subscribe internet technology (PURSUIT) (Tcherevik, 2011), scalable and adaptive internet solution (SAIL) (Edwall and Tremblay, 2011), CONVERGENCE (FP7 CONVERGENCE Project, 2013), convergence of fixed and mobile broadband access/aggregation networks (COMBO) (FP7 COMBO Project, 2013), COAST (Sprinkle, 2015) and green ICN (Fang et al., 2015). All these mention projects are moving forward on the path of progress to achieve the superlative version of the internet architecture.

Correspondingly, various prominent US-based ICN research projects have been developed that support the content-based communication instead of the current network architecture, such as translating relaying internetwork architecture integrating active directories (TRIAD) (Cheriton, 2003), data-oriented network architecture (DONA) (Ahlgren et al., 2011; Koponen et al., 2007; Xylomenos et al., 2013), content-centric network (CCN) (Ahlgren et al., 2012), named data networking (NDN) was proposed by National Science Foundation (Ahlgren et al., 2011). An additional ICN-based project that is active content management at internet scale (COMIT), was developed in 2014 at University College London (UCL) (Abdullahi et al., 2015).

Although all these ICN architectures differ with respect to their functionalities, features and architectural properties. In general, the main concern is to develop superior network architecture for content mobility, content placement, content distribution, and the future internet. The ICN-based project objective is to better cope with the effect of flash-crowd attack that is produced due to the numerous service requests. In addition, it also concentrates to support content mobility and steer clear of the disruption in the existing network communication system (Ahlgren et al., 2011). Meanwhile, with the excessive demand for the internet and high data services, the nature of the future network is expected to be highly mobile.

4 Mobility significance in ICN

All ICN projects have been developed by combining various modules in which mobility is considered the most dominant component for actualising the ICN (Naeem et al., 2018).

With the magnificent spread of connected mobile devices, mobility has become the most significant segment of any network communication system as well as an effective feature for next-generation networks (Augé et al., 2015; Palle and Shankar, 2021). The mobility is used for the transmission of content by using an appropriate channel to fulfil the desire and demand of the consumer. In addition, a basic logic behind mobility is determining the appropriate transmission of content without any delay.

Consequently, many mobility deployment strategies have been proposed to attain an appropriate and efficient use of bandwidth by enhancing the proper delivery of information and minimisation of handoff, as well as reducing the overall load from the main server (content provider). Mainly, mobility is categorised into two significant approaches known as consumer mobility and producer mobility. Consumer mobility allows the consumer to relocate or change their location from the current POA to the new POA in the network without any disruption in communication. While provider mobility allows a producer to move in the network or changes its position from current POA to new POA without interruption in content availability.

Although several admirable works have been proposed in ICN projects, most of them focus on architectural issues, including naming, security, forwarding, flow control, addressing, caching, and energy efficiency. Therefore, the mobility problem, especially producer mobility, has to get increasing attention. This paper explains the consumer and producer mobility of several different ICN projects in details and scrutinises the importance of mobility.

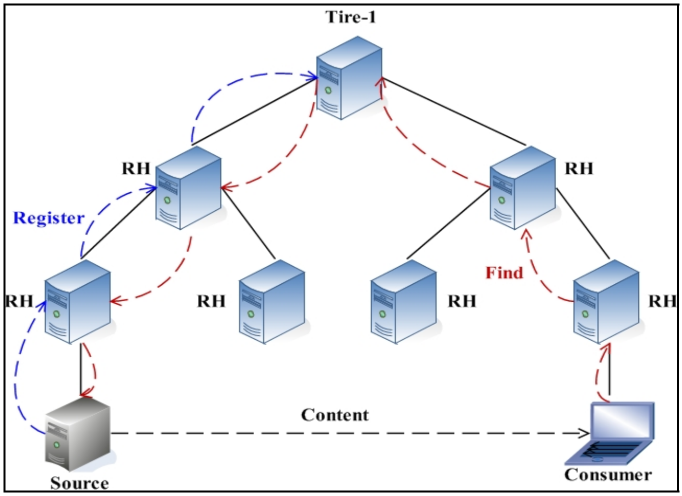
4.1 Mobility support in DONA

DONA proposed by Koponen et al. (2007) is a clean slate paradigm of ICN that prefers to replace the existing IP network from content-centric architecture. DONA introduces flat, self-certifying names in place of DNS name resolution to provide robust content persistence, availability, and authenticity (Koponen et al., 2007).

DONA relies on a cryptographic technique that uses the P:L principal for content names, where P denoted as a cryptographic hash of the producer's public key and L identifies the label of the content (Koponen et al., 2007; Tyson et al., 2012; Xylomenos et al., 2013). DONA supports both consumer and producer mobility by using a special server called resolution handlers (RHs) that is employed to maintain the registration table for the next-hop RH in an autonomous system (AS) which represents the border gateway protocol (BGP) communication system (Bari et al., 2012). In DONA, each AS has a local RH and RHs are in the form of a tree topology having one root parent RH in the network that is interconnected with each other to maintain content index as shown in Figure 1 (Barakabitze et al., 2014; Koponen et al., 2007; Xylomenos et al., 2013).

DONA provides two primitives that are FIND (P:L), use to locate content and REGISTER (P:L) to connecting with local RH. The consumer in DONA is associated with local RH from its location and sends a FIND message to obtain the required content needs to local RH for a copy of the content. In the consumer-producer mobility support scenario, DONA provides REGISTER and UNREGISTER facility in for each mobility (Hussaini et al., 2019).

Figure 1 Mobility support in DONA (see online version for colours)



Source: Koponen et al. (2007)

Whenever the producer mobility occurs, it must be UNREGISTER from its old location RH and REGISTER at new location RH to resume seamless communication. In case of consumer mobility, the remaining content is retrieved by sending the interest packet towards local RH after the completion of handoff process. Hence, the consumer and producer mobility are supported effectively in DONA (Hussaini et al., 2018b; Xylomenos et al., 2013).

4.2 Mobility in publish-subscribe internet technology

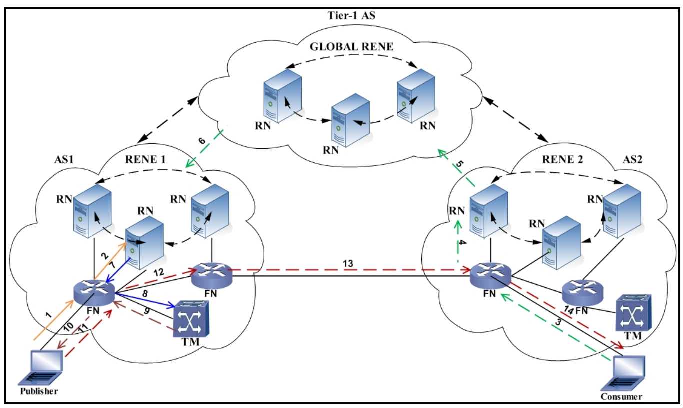
Publish-subscribe internet technology (PURSUIT/PSIRP) (Lagutin et al., 2010) is funded by EU Framework 7. Its main objective is to achieve advancements in the current IP-based internet into the advanced design that is the future receiver-driven network through which the content is retrievable by its name. Moreover, it puts the efficiency in the network and replaces the old-fashioned IP-based network with the content-based network. For this purpose, the core idea of PURSUIT is to research and develop the networks into an ultra-modern efficient internet architecture that publishes/subscribe paradigm (Dimitrov and Koptchev, 2010).

PURSUIT/PSIRP uses the flat name as in DONA. In addition, it contains two identifiers: scope identifier (SId) that defines related multiple scopes of information objects, and rendezvous identifier (RId) that is the identity for a specific part of information (Xylomenos et al., 2013). In PURSUIT/PSIRP paradigm contains three basic functions, which are rendezvous, forwarding, and topology management function. Rendezvous function consists of rendezvous nodes (RNs) that are connected in the form of a hierarchical distributed hash table (DHT) to exchange the information is known as rendezvous network (RENE). All the RENEs are interconnected in the network to enhance the effectiveness of the communication. The role of RN is very significant in PURSUIT/PSIRP used in RENE to exchange the content delivery between the publisher and subscriber by directing the topology manager (TM) (Barakabitze et al., 2014).

By referring to Figure 2 that shows each domain has one TM in its network. The role of TM is to contain the topology information about its domain network. It creates a routing path among the subscribers and publishers for content communication over a global level (Lagutin et al., 2010). For content forwarding in PURSUIT/PSIRP, there is a forwarding node (FN) in each network that supports the subscriber for directing the request for particular content by using bloom filter-based forwarding and also have a capacity to store content (Bari et al., 2012; Xylomenos et al., 2013).

In PURSUIT/PSIRP, when the publisher requires to publish the information, it simply sends a message to its local RN in a network by using identifiers (Sid, Rid) that routes in the RENE. On the other side, when the subscriber requires to retrieve the same published information object, then it sends a message by using the same identifiers (Sid, Rid) to its local RN which routed in RENE. The TM creates a route between the publishers to the subscriber according to instructions of RN then after TM routes the publisher by sending a START PUBLISH query and FN finally serve this route to deliver the information object (Barakabitze et al., 2014; Xylomenos et al., 2013) as shown in Figure 2.

Figure 2 Mobility in PURSUIT (see online version for colours)



Source: Xylomenos et al. (2013)

The subscriber's mobility in PURSUIT/PSIRP is straightforward; when the subscriber relocates, it must be re-subscribed from its new location. The local mobility is handled via multicast and global mobility is handled by modifying the forwarding function (Hussaini et al., 2019, 2018b; Tyson et al., 2013b; Xylomenos et al., 2013). The publisher mobility in PURSUIT/PSIRP is operated by UNREGISTER and RE-REGISTER query whenever the publisher change location it experiences higher overhead and harder to handle mobility to control this issue after every relocation of publisher it immediately updates the name prefixes to rendezvous system (Hussaini et al., 2019, 2018b; Tyson et al., 2013b).

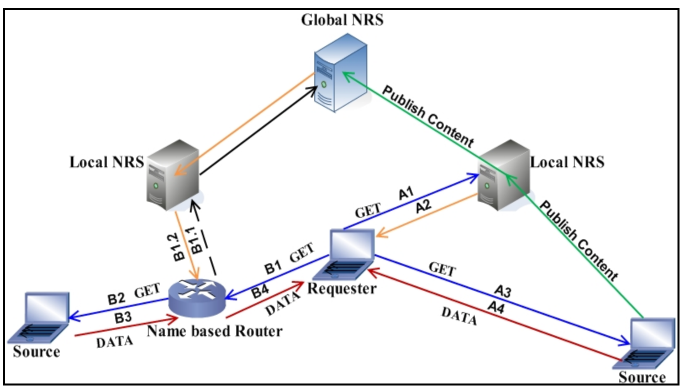
4.3 Mobility in NetInf

The NetInf proposed by Dannewitz et al. (2013) is typically designed to optimise the contents and continuation in the communication through named data objects (NDOs). NetInf uses a flat namespace and self-certifying names for information objects as in DONA architecture (Bari et al., 2012).

To obtain NDOs in NetInf, it provides name-based routing and name resolution service as well as a combination of both known as hybrid operation (Barakabitze et al., 2014). In name-based routing, the consumer sends a GET query for content retrieval that is forwarded between NetInf nodes in a hop-by-hop manner until it retrieves NDOs or reached the original server. If the content is not found between caches of the NetInf nodes in this condition, name resolution service activated and work in the hybrid mood before forwarding the request in name-based routing; it caches the object in intermediate nodes. In name resolution service, multi-level distributed hash table (MDHT) linking to serves global level content sharing in the presence of BGP as well as to assist for local resolution (Barakabitze et al., 2014; Dannewitz et al., 2013; Tyson et al., 2012).

In the case of mobility, NetInf supports all types of mobility and multi-homing. Consumer mobility is handled through the influence of cached contents in the interconnected routers in the domain. As a result, the consumer sends a GET query after the mobility process and obtains the object from the underlying routers with a copy of NDOs. Further, the consumer may forwards a request to a name resolution service to solve the name and gets the routing hint (Dannewitz et al., 2013) as shown in Figure 3.

Figure 3 Mobility in NetInf (see online version for colours)



Source: Dannewitz et al. (2013)

The producer mobility is supported by frequently updates the routing information and name resolution service that is required to inform the networks about the availability of NDOs and the producer (Dannewitz et al., 2013; Tyson et al., 2013b). In NetInf, the name resolution service pretends like a DNS server that is efficiently used by the mobile producer to publish NDOs for local and global level networking and works in a hybrid mood that makes an acknowledge a routing hint (Dannewitz et al., 2013; Hussaini et al., 2018b). Thus, the producer frequent updates in the network provide the route for the upcoming requests for contents, and the network effortlessly chases the producer to deliver the requests and access the contents. However, the frequent updates cause extra signalling and utilise the excessive bandwidth that affects the network's overall performance.

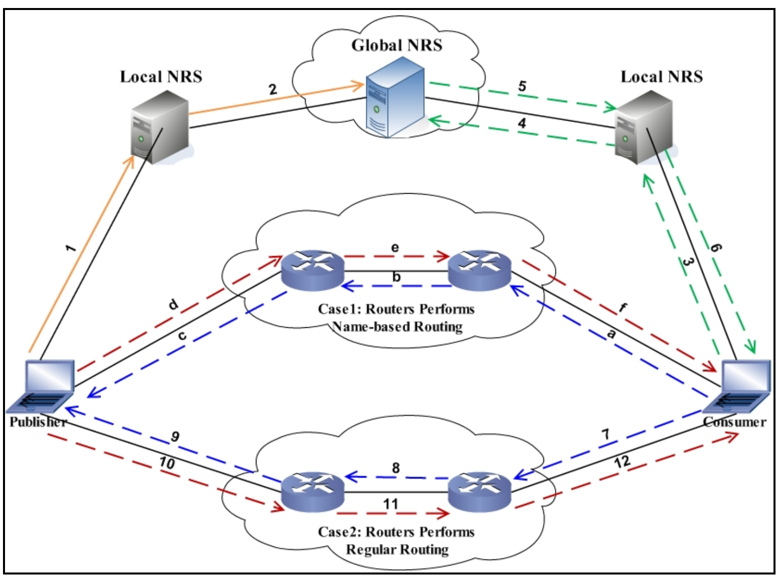
4.4 Mobility in SAIL

SAILs are a substantial and pioneer architecture of ICN. Its designed mechanism ensures the optimisation in the network during content communication. Surprisingly, its adequate design allows the content communication by the content names rather than a specific location that interconnects the IP. Thus, the main consideration of SAIL is to change the current internet architecture and redesign to accelerate the smooth content delivery. The exchange of information objects in SAIL follows the future internet that is based on ICN architecture.

SAIL uses the flat name for information object same as in PURSUIT, and for routing, it also uses the hierarchical name as in NDN for long prefix matching. SAIL uses the name resolution system (NRS) in the form of DHT and MDHT, as shown in Figure 4. However, SAIL uses the ni://A/L scheme for maintains the authority in local NRS, uses the L part resolution and A part resolution for global NRS (Xylomenos et al., 2013).

The publisher in SAIL sends PUBLISH message to local NRS with its locator used to store L part and PUBLISH message with the same authority. Part A is forwarded by aggregation of L from local NRS to the global NRS using bloom filter. Global NRS recorded both the authority A and local NRS mapping (Xylomenos et al., 2013).

Figure 4 Mobility in SAIL (see online version for colours)



Source: Xylomenos et al. (2013)

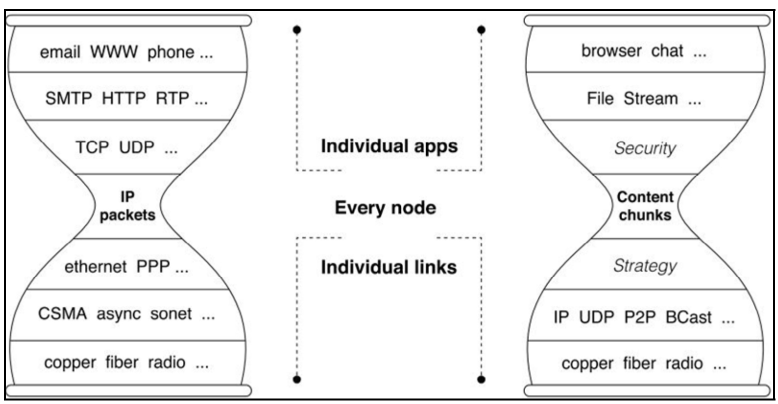
In SAIL, the subscriber sends a GET message to the local NRS to retrieve the information object. The local NRS forwards a message to the global NRS to find the locator for a specific object and get a specific locator for the requested object. Finally, after the subscriber by using a specific locator, send a GET message to the producer and retrieve the information object in the form of a data message (Xylomenos et al., 2013).

In SAIL, NRS plays a worthy role to manage mobility and updates the location information in the network by using late name binding (LNB) that provides the routing hints to get the exact location of the content provider. Thus, the NRS performs a key role to support the producer mobility, and whenever the producer moves within the network, it updates the location information to its local NRS (Hussaini et al., 2018c).

5 Name data networking

The NDN is a proficient project of ICN (Hussain et al., 2021). It is sponsored by the US future internet architecture program, which is an enhanced version of the CCN (Xylomenos et al., 2013). NDN is one of the major ICN projects that induce better impacts on the others ICN architectures. The NDN architecture hourglass holds a similar model as in IP, but the intention of thin waist changes from IP packets to data or content chunks directly without emphasising the location of data or content chunks, as shown in Figure 5. It alters the network communication system from location base packet delivery system to access data or content by its identified name. According to the architectural principles guide, the hourglass of NDN architecture relies on the universal network layer for global connectivity and administrate the security within its architecture. Furthermore, its comprehensive design offers the separation of forwarding and routing plane as well as provision, self-regulation in network traffic and flow-balance during data or content delivery (Zhang et al., 2010).

Figure 5 IP and NDN hourglass architecture

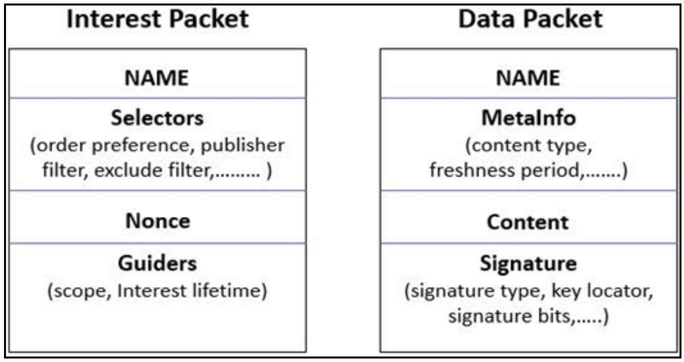


Source: Zhang et al. (2014a)

The NDN, as other common networking protocols, manages all the applications such as VoD and networking environments. It promotes the best-effort packet delivery service through the network layer protocol with physical channels such as Ethernet wires and UDP/TCP tunnels using them as a logical connection over the existing internet.

In NDN, names are hierarchically structured and occasionally assume as the URLs that build a strong relationship between the context and data elements (Zhang et al., 2014a). Therefore, it permits content retrieval services that are easily accessible in the network through unique content names. For content retrieval and communication in NDN, it offers two types of packets as shown in Figure 6. Both interest and data packet has the name to identify the content. The consumer uses the interest packet to access the content. For this purpose, the consumer places the name of the content in the interest packet name field and sends it to the network. The data packets are produced by the producer and send to the consumer in response to the interest packet. The data such as video frames, text file chunks, and sensors reading all forms of data can be retrieved through data packets.

Figure 6 Interest and data packet in NDN architecture

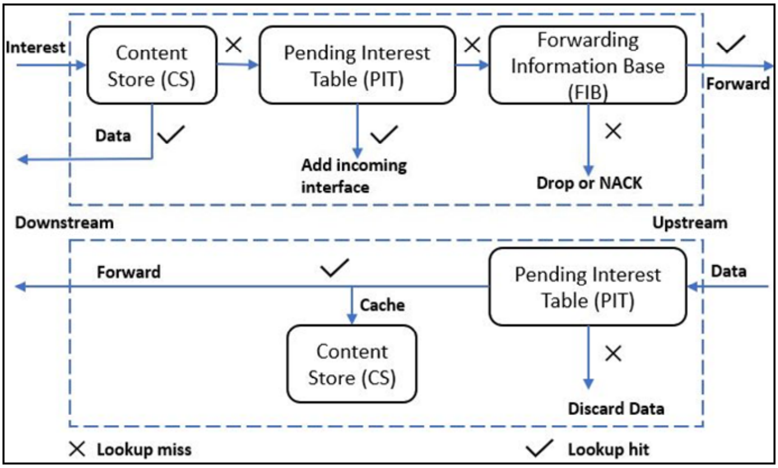


Source: Zhang et al. (2014a)

The interest and data packets are routed for exchanging contents in the NDN network. Therefore, it supports the packets and records all the packets state over the router. The recording mechanism is compulsory to ensure that the contents have been delivered or still is in process. For this purpose, NDN architecture provides various functions over the router to maintain the record of all packets state. The content packets are independent by their location, and freely they can be retrieved and forwarded smoothly. The packets forwarding is managed by the three different types of data structures that have different roles and responsibilities: content store (CS), pending interest table (PIT), and forwarding information base (FIB). The CS is a local cache to store the incoming content at the router space. The PIT is the incoming interface(s) that records the incoming interest packets with their content name and incoming interface. It is also responsible for storing unsatisfied interest packets that are forwarded for retrieving content. The FIB is called output interface(s); it contains the information names through which the incoming interest packets forwarded to the relevant CS or the producer.

In NDN, to benefit from the content retrieval services, the consumer sends an interest packet to the attached content router (CR). The CR searches its own CS for the content; if the requested content is founded in its own CS, the content is sent immediately. Otherwise, the interest packet is forwarded to the PIT. The PIT starts exploring the interest packet in its table; if a similar entry is found, it just stores the interest packet with its incoming face and waits for the data packets. In a scenario, if no entry is found in PIT, then the interest packet moves towards FIB. The FIB checks the name of the interest packet and forwards the packet towards the most appropriate source name, and records the incoming interface in PIT. In case if no similar source or producer name found in FIB, then the interest packet will be dropped, and the consumer receives the negative acknowledgement (NACK) as shown in Figure 7. When the data packet arrives at the router, then it verifies the similar PIT entry and distributes the content to all matching interfaces in PIT. During this process, it removes the matching PIT entries against which the content is delivered and caches the content in CS.

Figure 7 Forwarding process in NDN (see online version for colours)



Source: Zhang et al. (2014a)

6 Mobility in name data networking

NDN is the most eminent clean-slate architecture of ICN. Its pioneer architectural designed mechanism allows attaining data integrity, authenticity, and confidentiality. NDN efficiently supports the named content rather than the networking stack of the IP architecture. Naming becomes the most important segment of application design of NDN that authenticates support for mobility, content distribution, multicast, and delay-tolerant networking (Zhang et al., 2014a). By default, NDN proposes to manage the IP vulnerabilities and control mobility but experiences several challenges in NDN concerning mobility. In NDN, mobility enables the mobile devices to switch their location among the different access points unless any interrupt the minimal hand-off and content availability delay.

In a host-centric communication environment, every point of access for each network interface, devices need an IP address to exchange data and no guarantee the further continuity of an ongoing connection during the mobility. Therefore, after relocating mobile devices, it demands the new IP address to continue the interrupted communication. To handle this issue, several researcher present solutions for mobile IP and host identification protocol (HIP). However, these provided mobility solutions are not effective to directly deals with the current mobility problems. These solutions used an indirection point to control mobility based on topological information to redirect mobile traffic to the source (De Brito et al., 2013). In NDN, contents are accessible by their names instead of IP addresses. Thus, NDN provides a superior facility for mobile devices to get content access without repeatedly acquiring an IP address to continuing their communication. Hence, it is challenging for an IP-based system to continue its interrupted communication using its old IP address.

In an IP-based system, multiple interfaces demand different IP addresses for communication and maintain the TCP connection. Consequently, the NDN has no concern about the application, and the consumer request is smoothly multiplexed over various interfaces (Tyson et al., 2012). On the other side, the progressive thought of NDN enables its users to access contents through their names. Therefore, it magnificently supports multiple network interfaces via sending interest as an alternative of the host-centric network that supports host multi-homing (Mars et al., 2019) where the particular application is needed to establish individual connections as in Bluetooth (Saxena et al., 2016).

The NDN is content-centric in nature; hence, whenever a mobile device moves, it is not compulsory for a mobile device to establish the connection repeatedly to the data source for communication. Although, the current internet develops connection-oriented sessions through which mobile device propagates in-network and further communication demands to re-establish TCP connection (Saxena et al., 2016). Generally, mobility allows the mobile devices to freely moves and connects to different POA without any disruption in the content minimal hand-off and availability delay (Wang and Cai, 2021). However, the current design of the internet is incapable to fully support mobility and still surrounded by many inefficiencies, as mentioned before. Conversely, the architecture of NDN determines better mobility support. Hence, NDN mobility is classified into two categories consumer mobility and producer mobility (Feng et al., 2016; Meddeb et al., 2017).

6.1 Consumer mobility in NDN

NDN is a receiver-driven content-centric-based (Do and Kim, 2015) communication architecture that follows the request and reply mechanism. It manages communication by using two kinds of message packet: 'INTEREST' and 'DATA' packets (Hussaini et al., 2018a; Ventrella et al., 2017). When the consumer wants to retrieve content, it sends an interest packet from its current location to the connected point of attachment (POA) towards the data source. The POA, after receiving the interest packet, it forwards interest towards the suitable data source that able to deliver the required content.

When the interest reaches at NDN router for content retrieval firstly, the router starts lookup its individual CS. If the related content is available in CS, then, it directly forwards the content to the consumer. Otherwise, the interest is forwarded to the next router depending on FIBs. Additionally, if the interest packet does not satisfy the content, then, it will be stored in the PIT. The PIT is a table, where all the pending interests are mapped along with their incoming interface(s) (Zhang et al., 2014a). When the consumer changes its location before obtaining the requested content is known as a handoff.

In this situation, after the handoff process, the consumer sends an interest packet to acquire the remaining content that is already cached in a common router or intermediate routers. The routers between the path of the old and new locations are nominated as common or intermediate routers. So, the consumer effortlessly gets the remaining content from these router and fulfil its content needs (Xylomenos et al., 2013). Hence, the consumer can efficiently get the remaining data packets by sending interest again for similar content (Mars et al., 2019; Wang et al., 2013), and consumer mobility is effortlessly solvable within the minimum delay (Jiang et al., 2012). In NDN, the consumer mobility issue is inherently solved through the assistance of network routers caching or resend the interest packet towards the intermediate router after the completion of consumer mobility (Chen et al., 2014; Feng et al., 2016).

Figure 8 Consumer mobility in NDN (see online version for colours)

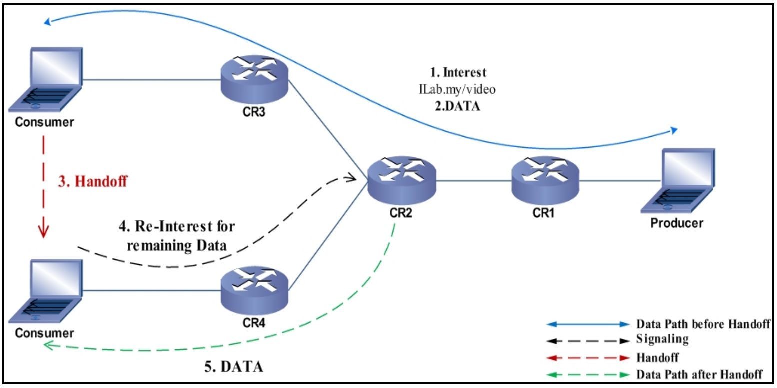


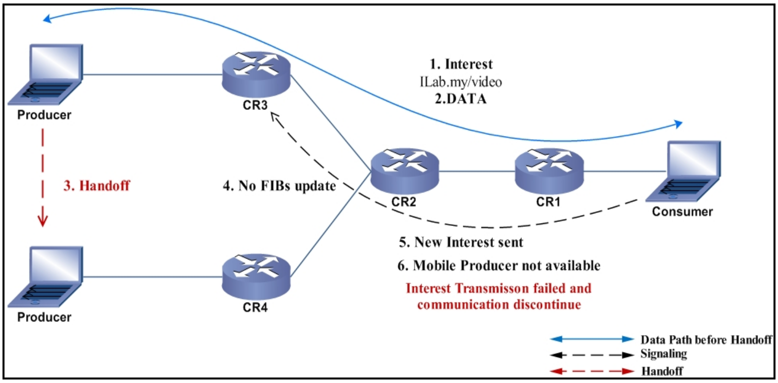
Figure 8 shows a clear scenario of consumer mobility. During the content communication, when the consumer changes its connectivity from CR3 to CR4, the content communication gets interrupted due to handoff. But the NDN architectural design supports the content, and the remaining content has been cached at the common router CR2. Additionally, the CR2 is a common router between CR3 and CR4. When the consumer completes its movement and connects to CR4, the consumer again sends interest for remaining content and easily access content from CR2. In this way, consumer mobility is supported through caching contents between intermediate or junctional routers (Zhang et al., 2014b).

6.2 Producer mobility in NDN

In NDN architecture, the producer is a source to provides content in response to consumer interest. Although in NDN, the name of content is decoupled from the location, its name is not separated from its location. Conversely, the NDN coupled the location with content name directly though adding them to FIB in routing protocol (Feng et al., 2016). Consequently, whenever the consumer sends an interest packet to the connected router, the router determines on the behalf of FIB and evaluates where have to send the interest for a suitable producer (content source). Generally, FIB contains the entries of long prefixes address for the next-hop or content source that allows it to determine the optimal path to access content and forwards the interest packet to the content source or CS.

The producer satisfies the consumer content needs on receiving the interest packet and sends content from its location to the consumer. When the producer moves and connects with the new POA, in this state, it is necessary for the producer to updates the FIB of all CRs in the NDN network (Xylomenos et al., 2013). Otherwise, the interest reaches the old POA and no content is accessible for the consumer due to the unavailability of the producer (Wang and Cai, 2021). The motion of the producer is not traceable for the consumer. As a result, the inefficient management of the producer mobility will suffer from high overhead (Xylomenos et al., 2013), high packet loss, and long handover latency (Chen et al., 2014). Thus, the consumer lost communication until the producer informs its new name prefix in the network (Kim et al., 2015), as shown in Figure 9.

Figure 9 Producer mobility in NDN (see online version for colours)



For further communication, it is compulsory for the producer to updates its new name prefix in the network. Although, NDN uses the listen first broadcast later (LFBL) protocol to control mobility in ad-hoc networks. The main idea of LFBL is to flood the interest packet to the serving routers and decisions for prefix announcements are made according on the results. The most optimal route name prefix is broadcast in the network for further communication among all content provider routers. In NDN, the route is added by the CRs LFBL protocol through flooding interest and broadcasts name prefix across all the serving routers after the producer handoff process is completed (Meisel et al., 2010; Xylomenos et al., 2013). However, this solution protocol generates high signalling and has no mechanism to recover the dropped and incoming interest packet at the old location during the producer mobility.

Table 1 Summary of mobility assistance in ICN projects

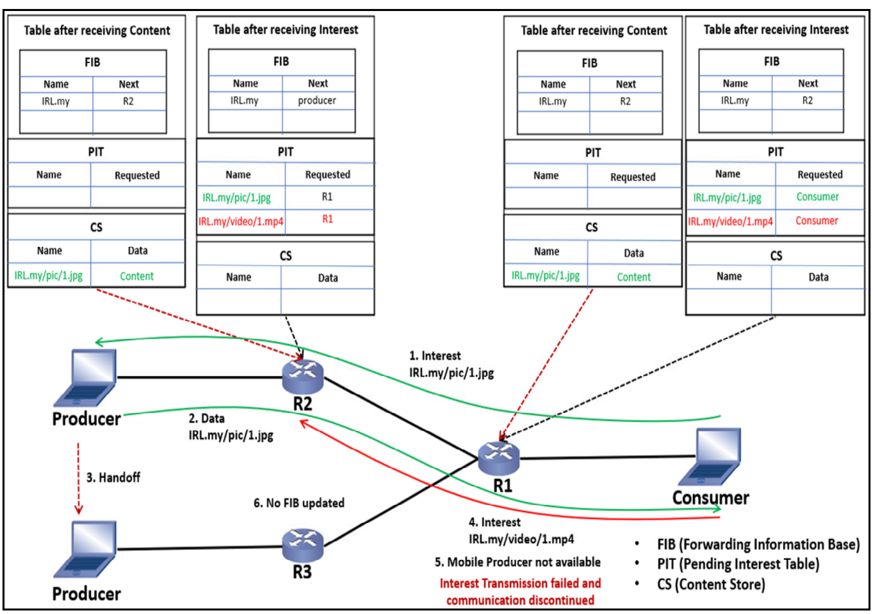
ICN architectures	*DONA*	*PURSUIT*	*PSRIP*	*NetInf*	*SAIL*	*CCN*	*NDN*
Consumer mobility	Supported	Supported	Supported	Supported	Supported	Supported	Supported
Producer mobility	Supported	Undecided	Undecided	Supported	Supported	Unsupported	Unsupported

Table 1 highlights the consumer and producer mobility support in some ICN architectures. The table shows that consumer mobility is well supported in all ICN architecture. However, producer mobility in CCN and NDN is not fully supported. Moreover, the producer mobility in PURSUIT and PSRIP is undecided due to the lack of explanation in their architecture, but its architectural design indicates that the mobility can be supported.

7 NDN architecture research direction and mobility challenges

The thought of reshaping the internet architecture is an excellent idea, but as increasing in the number of internet users and mobile devices, mobility support becomes a significant component. The unsupported producer mobility has raised many critical challenges in the network such as interest packet loss, unnecessary bandwidth consumption, flash crowd, interest retransmission, content unavailability, inaccessible routing and forwarding path. Consumer mobility is innately supported in NDN as well as in all projects of ICN by resending the request for content after the mobility process. On the contrary, the mobility of the producer is not fully supported and there are several challenges to NDN. The reason is that the content name does not contain any location information of the content in CS. Besides, the requested content relies on the routing entries in FIBs that are guided to the content source or the producer. Meanwhile, when the producer changes its location, the previous FIBs entries cannot reach the producer-new location. The self-same request for content can retrieve content from the caching of the router but the rest of the requests directed to the producer old location and cause packet loss due to the producer unavailability as illustrated in Figure 10. The figure clearly shows the interest packet loss scenario due to the absence of the producer. When producer completes the handoff process and connects to router R3 and have no connection with R2. Meanwhile, the FIBs are completely unaware of the producer movement behaviour that causes the consumer interest packets loss at R2.

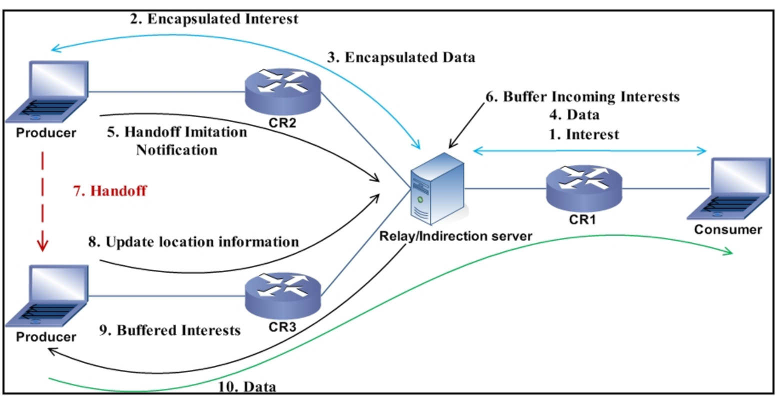
Figure 10 The architectural design of the producer mobility issue in NDN (see online version for colours)



In paper (Tyson et al., 2013a), it has been pointed that consumer mobility is well supported through ICN consumer-driven nature. Similarly, researchers in Xylomenos et al. (2013) stated that consumer mobility is handleable through re-issuing the interest from its current location. In addition, Feng et al. (2016) defined that consumer mobility is solved inherently in NDN through re-request for content and supported by cached contents at router space after the handovers. However, maintaining the routing consistency during producer mobility is more challenging. Because the producer must update its location information in the network after every single relocation. The producer mobility effect can be lessening via caching particular content at the router although, the request for the rest of the contents cannot be satisfied. Nevertheless, producer mobility is not natively supported due to the unavailability of content locators and failures in content access through the routing system.

In Fang et al. (2018) and Kim et al. (2012, 2015), the solutions have been proposed to conquer the influence of producer mobility in the NDN network. In order to support the producer mobility, a rendezvous point is introduced in two ways: rendezvous point as a relay server and rendezvous point as a naming server. The rendezvous point as a relay server maintains the binding between the source prefix and the target prefix. The relay server plays an intermediate role between the consumer and the producer, as shown in Figure 11. When the consumer sends the interest packet to the producer, first, it moves to the relay server, where it is shaped into an encapsulated form. Thereafter, it is forwarded to the producer location. The producer decapsulates the interest packet and sends the requested content to the relay server in encapsulated form. Further, the relay server decapsulates the content and forwards it to the consumer. When the producer needs to move, it sends the handoff imitation notification to the relay server that buffers the incoming interest at server space. When the producer completes its mobility, it updates its location information to the relay server and retrieves the buffered interest and provides the content. The relay server works as an indirection point and performs a major role in decreasing handoff. However, the encapsulation of interest and content is very tricky to manage due to the predefined naming scheme. The relay server creates a point of bottleneck issue, and the failure of the server disconnects the overall communication.

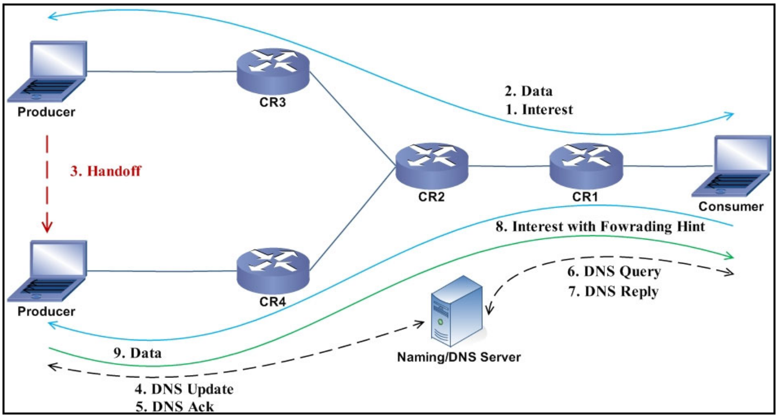
Figure 11 Rendezvous point as relay/indirection server (see online version for colours)



Source: Fang et al. (2018)

Fang et al. (2018) and Kim et al. (2012) proposes a rendezvous point as a naming server to manage the communication during producer mobility. The key function of the naming server is to map the locator and identifier at the server level that works as a mapping server (Zhu et al., 2013). When the producer moves and attaches to the new location, it registers its new location alongside the identifier at the server. When the consumer does not respond from the producer's old location, it passes the query to the naming server and obtains the current location of the producer, as shown in Figure 12. The naming server keeps track of all the producers in the network and maintains their location and content name to support producer mobility. However, during the producer mobility, the interest packets experience losses and frequent movements of the producer increase in the packet loss. Moreover, the producer location updating queries and the consumer location obtaining queries to the server both increase the signalling and incur higher latency.

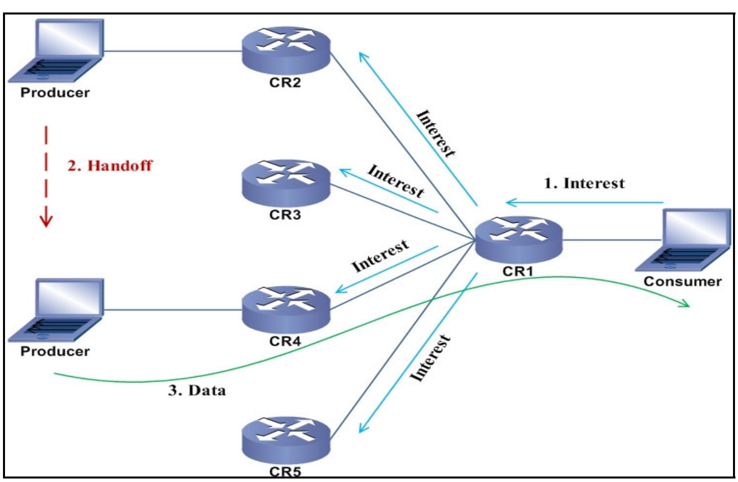
Figure 12 Rendezvous point as naming/DNS server (see online version for colours)



Source: Fang et al. (2018)

Another interesting solution (Fang et al., 2018; Kim et al., 2015; Zhu et al., 2013) is proposed to handle producer mobility, which aims to ensure content delivery in the response of interest. For such purpose, the consumer interest is broadcasted in the network and the producer sends the content from the connected router as shown in Figure 13. The broadcast method effectively fulfils the consumer content needs as well as point out the location of the producer. However, only one interest satisfies the content needs, and the rest of the interest packets are dropped at the routers due to the unavailability of the producer. Moreover, broadcasting is very costly and consumes excessive bandwidth in the network. Further, this technique is merely successful for the small number of nodes in the network.

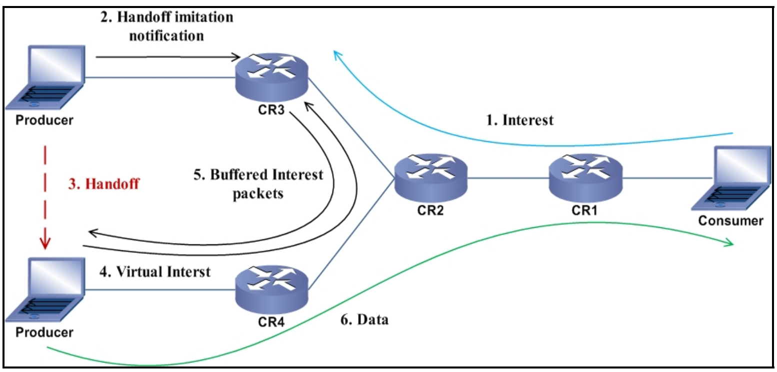
Figure 13 Zone flooding technique (see online version for colours)



Source: Fang et al. (2018)

The interest forwarding technique (Fang et al., 2018; Kim et al., 2012, 2015) is proposed to control the shortcomings during producer mobility. According to this technique, the producer's old location router buffers the incoming interests during the producer mobility and forwards it to the producer after the handoff process. The producer from its new location sends the virtual interest notification to its old location router and claims the buffered interests as shown in Figure 14. On receiving the interest packets, it effectually forwards the content to its appropriate consumers. This particular technique controls the generated effect due to the producer mobility, and to some extent, it minimises the interest packets loss. However, this technique still has inefficient in a scenario of the producer increase in the handoff process that may lead to loss of interest packets. Moreover, the technique does not update the producer location Information in the whole network after the producer handoff.

Figure 14 Interest forwarding technique (see online version for colours)



Source: Fang et al. (2018)

Regardless of the potential benefits of NDN in mobility, it is assuredly new research in the field of networks with full of challenges. Presently, several substantial research challenges need to be addressed before its actual implementation in the network of the world. The most important aspect of mobility is producer mobility that is not fully endorsed and still is in the field of research. From the research as mentioned earlier works, it has been concluded that the research in producer mobility is still required to under process and needs further research to handle the issues. The presented producer mobility solutions suffer from the different key issues such as a single point of failure, interest packet loss, less scalability, signalling, high handoff latency, and unnecessary use of bandwidth. The rendezvous as relay server is a virtuous concept to control the interest packets, but it creates delays in delivering content and invokes the single point of failure issue. The encapsulation of the interest at the relay server is especially tricky and increases the complexity in the large network. On the contrary, interest forwarding is a better solution to solve the single point of failure, but it creates triangular routing. Moreover, it is not feasible for the large network where it creates more delays in the delivery of packets due to an increase in the number of hops. To mitigate this issue, the flooding zone is another alternative solution, but unfortunately, it increases the packet loss and consumes extra bandwidth. Hence, there is a need for a flexible solution that lessens the produced issues by producer mobility. Further, it is better to maintain the routing entries by adding extra functions in the routing and forwarding plane that remains in touch with the network regarding the producer movement. Moreover, modifying the interest by adding the producer identified a unique name that may forwards it to the producer location. Mainly, the consumer concern about the content; it is a smart idea if the producer cached the popular content on the router space near the consumers. The popular cached content fulfil the needs of upcoming interest packets that may decrease the packets loss for the cached content.

Table 2 Summary of producer mobility support schemes in NDN

Method	*Routing path*	*Merits*	*Demerits*
Rendezvous point as relay/indirection server	Triangular	Reduce interest packet loss Forward interests to producer location	Single point of failure Delays in content delivery
Rendezvous point as naming/DNS server	Optimal	Track the producer location	High signalling Packet loss
Zone flooding/ broadcast	Optimal	Makes possible the content delivery	High bandwidth usage High packet loss
Interest forwarding	Triangular	Reduce interest packet loss	High signalling Inefficient for large network

Table 2 highlights the several producer mobility support schemes in NDN. Additionally, it shows the different schemes analysis and illustrates the method, delivery path, merits, and demerits of each scheme.

8 Conclusions

This paper demonstrates the deep-rooted survey in ICN's most prominent projects related to consumer and producer mobility. Also, explain issues surrounded by the current internet in terms of mobility. The current internet architecture suffers from various limitations and not completely able to support mobility. Currently, the host-centric paradigm is not fully capable of supporting mobility and is enclosed by many inefficiencies. Therefore, in NDN, the host-centric paradigm is replaced by a content-centric paradigm that supports mobility and reduces the mobility shortcomings in IP-based architecture. Consumer mobility is effortlessly supported in NDN; rather, producer mobility is still unsupported and produces several challenges as in IP. Several research works have been conducted to minimise unsupported mobility. In this paper, we examine several existing research works geared towards NDN mobility support. From the critical analysis, it has been concluded that the rendezvous point as a relay server is supporting mobility, but it is suffering bottleneck issues. Also, it is a bit tricky solution in terms of encapsulation of interest and data packet. On the contrary, the rendezvous as a naming server prevents the encapsulation of packets, but it experiences interest packet loss, high latency, and signalling issues. To ensure content delivery, the flooding zone broadcasts the interest packet that leads to excessive use of bandwidth and unnecessary drop of the interest packets. The interest forwarding technique is determined to conquer the effect of packet loss due to the broadcast, but this technique applicable to the small network. Additionally, it does not update the producer location information in the network. Hence, it has been clear that future research must be considered producer mobility in NDN. Moreover, an efficient solution needs to be inaugurated to overcome the mentioned challenges or issues.

Acknowledgements

This research has been carried out under Centre of Excellence Research Grant (S/O Code: 13726) provided by Universiti Utara Malaysia.

References

Abdullahi, I., Arif, S. and Hassan, S. (2015) 'Cache-less redundancy using hypergraph in information-centric network', *Advanced Science Letters*, Vol. 21, No. 11, pp.3546–3549 [online] https://doi.org/10.1166/asl.2015.6582.

Ahlgren, B., Dannewitz, C., Imbrenda, C., Kutscher, D. and Ohlman, B. (2011) 'A survey of information-centric networking (draft)', Paper presented at the *Dagstuhl Seminar Proceedings*.

Ahlgren, B., Dannewitz, C., Imbrenda, C., Kutscher, D. and Ohlman, B. (2012) 'A survey of information-centric networking', *IEEE Communications Magazine*, Vol. 50, No. 7, pp.26–36, DOI: 10.1109/MCOM.2012.6231276.

Akbar, M.S., Khaliq, K.A., Rais, R.N.B. and Qayyum, A. (2014) 'Information-centric networks: categorizations, challenges, and classifications', Paper presented at the *2014 23rd Wireless and Optical Communication Conference (WOCC)*.

Augé, J., Carofiglio, G., Grassi, G., Muscariello, L., Pau, G. and Zeng, X. (2015) 'Anchor-less producer mobility in ICN', Paper presented at the *Proceedings of the 2nd ACM Conference on Information-Centric Networking*.

Barakabitze, A.A., Xiaoheng, T. and Tan, G. (2014) 'A survey on naming, name resolution and data routing in information centric networking (ICN)', *Int. J. Adv. Res. Comput. Commun. Eng.*, Vol. 3, No. 10, pp.8322–8330.

Bari, M.F., Chowdhury, S.R., Ahmed, R., Boutaba, R. and Mathieu, B. (2012) 'A survey of naming and routing in information-centric networks', *IEEE Communications Magazine*, Vol. 50, No. 12, pp.44–53.

Brunner, M., Abramowicz, H., Niebert, N. and Correia, L.M. (2010) '4WARD: a European perspective towards the future internet', *IEICE transactions on communications*, Vol. 93, No. 3, pp.442–445.

Chen, Y-S., Hsu, C-S. and Huang, D-Y. (2014) 'A pipe-assisted mobility management in named data networking networks', Paper presented at the *16th Asia-Pacific Network Operations and Management Symposium*.

Cheriton, D.R. (2003) *TRIAD: Translating Relaying Internetwork Architecture Integrating Active Directories*, Dept. of Computer Science, Stanford Univ., CA.

Cisco Jose, S. (2019) *Cisco Visual Networking Index (VNI) Global Mobile Data Traffic Forecast Update*, 2017–2022 White Paper. CA, USA [online] https://twiki.cern.ch/twiki/pub/HEPIX/TechwatchNetwork/HtwNetworkDocuments/white-paper-c11-741490.pdf.

Dannewitz, C., Kutscher, D., Ohlman, B., Farrell, S., Ahlgren, B. and Karl, H. (2013) 'Network of information (NetInf) – an information-centric networking architecture', *Computer Communications*, Vol. 36, No. 7, pp.721–735.

De Brito, G.M., Velloso, P.B. and Moraes, I.M. (2013) *Information-centric Networks: A New Paradigm for the Internet*, John Wiley & Sons, New York, USA.

Dias, P., Cadime, I., García, D.C.J.A., Marzo, C.J., García, D.C-L.Á. and López-Sánchez, C. (2020) 'Problematic Internet and Facebook use and online gaming among university students: an exploratory study', *Psihologija*, Vol. 53, No. 4, pp.12–12.

Dimitrov, V. and Koptchev, V. (2010) 'PSIRP project – publish-subscribe internet routing paradigm: new ideas for future internet', Paper presented at the *Proceedings of the 11th International Conference on Computer Systems and Technologies and Workshop for PhD Students in Computing on International Conference on Computer Systems and Technologies*.

Do, T-X. and Kim, Y. (2015) 'Optimal provider mobility in large-scale named-data networking', *KSII Transactions on Internet & Information Systems*, Vol. 9, No. 10, pp.4054–4071.

Edwall, T. and Tremblay, B. (2011) *Scalable and Adaptive Internet Solutions (SAIL) Project*, No. 4 [online] https://sail-project.eu/.

Fang, C., Yao, H., Wang, Z., Wu, W., Jin, X. and Yu, F.R. (2018) 'A survey of mobile information-centric networking: research issues and challenges', *IEEE Communications Surveys & Tutorials*, Vol. 20, No. 3, pp.2353–2371.

Fang, C., Yu, F.R., Huang, T., Liu, J. and Liu, Y. (2015) 'A survey of green information-centric networking: research issues and challenges', *IEEE Communications Surveys & Tutorials*, Vol. 17, No. 3, pp.1455–1472.

Feng, B., Zhou, H. and Xu, Q. (2016) 'Mobility support in named data networking: a survey', *EURASIP Journal on Wireless Communications and Networking*, Vol. 2016, No. 1, pp.220–228.

Fotiou, N., Nikander, P., Trossen, D. and Polyzos, G.C. (2010) 'Developing information networking further: from PSIRP to PURSUIT', Paper presented at the *International Conference on Broadband Communications, Networks and Systems*.

FP7 COMBO Project (2013) [online] http://www.ict-combo.eu/.

FP7 CONVERGENCE Project (2013) [online] http://www.ictconvergence.eu/.

García, G., Beben, A., Ramón, F.J., Maeso, A., Psaras, I., Pavlou, G. and Soursos, S. (2011) 'COMET: content mediator architecture for content-aware networks', Paper presented at the *2011 Future Network & Mobile Summit*.

Hossain, M.S. and Atiquzzaman, M. (2011) 'Asymptotic scalability analysis of mobility protocols based on signalling overhead', *International Journal of Communication Networks and Distributed Systems*, Vol. 7, Nos. 1–2, pp.119–134.

Hussain, S., Ullah, S.S., Gumaei, A., Al-Rakhami, M., Ahmad, I. and Arif, S.M. (2021) 'A novel efficient certificateless signature scheme for the prevention of content poisoning attack in named data networking-based internet of things', *IEEE Access*, Vol. 9, No. 2, pp.40198–40215.

Hussaini, M., Naeem, M.A., Kim, B-S. and Maijama'a, I.S. (2019) 'Efficient producer mobility management model in information-centric networking', *IEEE Access*, Vol. 7, No. 1, pp.42032–42051.

Hussaini, M., Nor, S. and Ahmad, A. (2018a) 'PMSS: producer mobility support scheme optimization with RWP mobility model in named data networking', *International Journal of Communication Networks and Information Security*, Vol. 10, No. 2, pp.329–339.

Hussaini, M., Nor, S.A. and Ahmad, A. (2018b) 'Producer mobility support for information centric networking approaches: a review', *Int. J. Appl. Eng. Res.*, Vol. 13, No. 6, pp.3272–3280.

Hussaini, M., Nor, S.A., Ahmad, A., Maijama'a, I.S., Isah, A. and Aminu, A. (2018c) 'Mobility support and operation of information centric networking approach', *International Journal of Computer Network and Information Security*, Vol. 9, No. 10, p.18.

Inaba, Y., Tanigawa, Y. and Tode, H. (2015) 'Content retrieval method in cooperation with CDN and ICN-based in-network guidance over IP network', Paper presented at the *2015 IEEE 40th Conference on Local Computer Networks (LCN)*.

Jacobson, V., Smetters, D.K., Thornton, J.D., Plass, M.F., Briggs, N.H. and Braynard, R.L. (2009) 'Networking named content', Paper presented at the *Proceedings of the 5th International Conference on Emerging Networking Experiments and Technologies*.

Jiang, X., Bi, J., Wang, Y., Lin, P. and Li, Z. (2012) 'A content provider mobility solution of named data networking', Paper presented at the *2012 20th IEEE International Conference on Network Protocols (ICNP)*.

Jung, H. (2019) *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2017–2022 White Paper*, Technical Report, Cisco Systems Inc.

Kim, D-h., Kim, J-h., Kim, Y-s., Yoon, H-s. and Yeom, I. (2012) 'Mobility support in content centric networks', Paper presented at the *Proceedings of the Second Edition of the ICN Workshop on Information-Centric Networking*.

Kim, D-h., Kim, J-h., Kim, Y-s., Yoon, H-s. and Yeom, I. (2015) 'End-to-end mobility support in content centric networks', *International Journal of Communication Systems*, Vol. 28, No. 6, pp.1151–1167.

Koponen, T., Chawla, M., Chun, B-G., Ermolinskiy, A., Kim, K.H., Shenker, S. and Stoica, I. (2007) 'A data-oriented (and beyond) network architecture', *ACM SIGCOMM Computer Communication Review*, Vol. 37, No. 4, pp.181–192.

Kutscher, D., Eum, S., Pentikousis, K., Psaras, I., Corujo, D., Saucez, D. and Schmidt, T.C. (2016) 'Information-centric networking (ICN) research challenges', *Internet Research Task Force (IRTF)*, Article RFC 7927 [online] https://discovery.ucl.ac.uk/id/eprint/10087578.

Lagutin, D., Visala, K. and Tarkoma, S. (2010) 'Publish/subscribe for internet: Psirp perspective', in *Towards the Future Internet*, pp.75–84, IosPress [online] https://ebooks.iospress.nl/doi/10.3233/978-1-60750-539-6-75.

Mars, D., Gammar, S.M., Lahmadi, A. and Saidane, L.A. (2019) 'Using information centric networking in internet of things: a survey', *Wireless Personal Communications*, Vol. 105, No. 1, pp.87–103.

Meddeb, M., Dhraief, A., Belghith, A., Monteil, T. and Drira, K. (2017) 'Producer mobility support in named data internet of things network', *Procedia Computer Science*, Vol. 109, pp.1067–1073.

Meisel, M., Pappas, V. and Zhang, L. (2010) 'Listen first, broadcast later: topology-agnostic forwarding under high dynamics', Paper presented at the *Annual Conference of International Technology Alliance in Network and Information Science*.

Morley, J., Widdicks, K. and Hazas, M. (2018) 'Digitalisation, energy and data demand: the impact of internet traffic on overall and peak electricity consumption', *Energy Research & Social Science*, Vol. 38, No. 4, pp.128–137.

Naeem, M.A., Nor, S.A., Hassan, S. and Kim, B-S. (2018) 'Performances of probabilistic caching strategies in content centric networking', *IEEE Access*, Vol. 6, No. 3, pp.58807–58825.

Palle, S. and Shankar, S. (2021) 'Mobility prediction assisted call admission control model for mobile heterogeneous cellular network', *International Journal of Communication Networks and Distributed Systems*, Vol. 26, No. 2, pp.219–244.

Pallis, G. and Vakali, A. (2006) 'Insight and perspectives for content delivery networks', *Communications of the ACM*, Vol. 49, No. 1, pp.101–106.

Peng, G. (2004) *CDN: Content Distribution Network*, arXiv preprint cs/0411069.

Saxena, D., Raychoudhury, V., Suri, N., Becker, C. and Cao, J. (2016) 'Named data networking: a survey', *Computer Science Review*, Vol. 19, No. 1, pp.15–55.

Sprinkle, T. (2015) *Screw the Valley: A Coast-to-Coast Tour of Americas New Tech Startup Culture*, BenBella Books, Inc., New York, Boulder, Austin, Raleigh, Detroit, Las Vegas, Kansas City.

Tcherevik, D. (2011) *Publish/Subscribe Mechanism for Web Services*, Google Patents.

Tyson, G., Sastry, N., Cuevas, R., Rimac, I. and Mauthe, A. (2013a) 'A survey of mobility in information-centric networks', *Communications of the ACM*, Vol. 56, No. 12, pp.90–98.

Tyson, G., Sastry, N., Cuevas, R., Rimac, I. and Mauthe, A. (2013b) 'Where is in a name? A survey of mobility in information-centric networks', *Communications of the ACM (CACM)*, Vol. 56, No. 12, pp.90–98.

Tyson, G., Sastry, N., Rimac, I., Cuevas, R. and Mauthe, A. (2012) 'A survey of mobility in information-centric networks: challenges and research directions', Paper presented at the *Proceedings of the 1st ACM workshop on Emerging Name-Oriented Mobile Networking Design-Architecture, Algorithms, and Applications*.

Ventrella, A.V., Piro, G. and Grieco, L.A. (2017) 'Publish-subscribe in mobile information centric networks: modeling and performance evaluation', *Computer Networks*, Vol. 127, No. 7, pp.317–339.

Wang, L., Waltari, O. and Kangasharju, J. (2013) 'MOBICCN: mobility support with greedy routing in content-centric networks', Paper presented at the *2013 IEEE Global Communications Conference (GLOBECOM)*.

Wang, X. and Cai, S. (2021) 'Mobility management in vehicular named data networking', *IEEE Sensors Letters*, Vol. 5, No. 8, pp.1–4.

Xylomenos, G., Ververidis, C.N., Siris, V.A., Fotiou, N., Tsilopoulos, C., Vasilakos, X. and Polyzos, G.C. (2013) 'A survey of information-centric networking research', *IEEE Communications Surveys & Tutorials*, Vol. 16, No. 2, pp.1024–1049.

Zhang, L., Afanasyev, A., Burke, J., Jacobson, V., Crowley, P., Papadopoulos, C. and Zhang, B. (2014a) 'Named data networking', *ACM SIGCOMM Computer Communication Review*, Vol. 44, No. 3, pp.66–73.

Zhang, Y., Zhang, H. and Zhang, L. (2014b) 'Kite: a mobility support scheme for NDN', Paper presented at the *Proceedings of the 1st ACM Conference on Information-Centric Networking*.

Zhang, L., Estrin, D., Burke, J., Jacobson, V., Thornton, J.D., Smetters, D.K. and Papadopoulos, C. (2010) *Named Data Networking (NDN) Project*, Relatório Técnico NDN-0001, Nos. 157/158, Xerox Palo Alto Research Center-PARC.

Zhang, M., Luo, H. and Zhang, H. (2015) 'A survey of caching mechanisms in information-centric networking', *IEEE Communications Surveys & Tutorials*, Vol. 17, No. 3, pp.1473–1499.

Zhu, Z., Afanasyev, A. and Zhang, L. (2013) *A New Perspective on Mobility Support*, Named-Data Networking Project, Tech. Rep [online] https://named-data.net/publications/techreports/.