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Advancing producer mobility management in Named Data Networking: A comprehensive analytical model

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ABSTRACT

This paper introduces a transformative approach to managing producer mobility in Named Data Networking (NDN). It presents a novel analytical model known as Producer Mobility Management Model (PMMM) that significantly improves handoff latency, signalling cost, and packet delivery efficiency, overcoming limitations of traditional static anchor-based methods. This model serves as an extension of well-established theories drawn from existing literature, thus offering an advanced approach towards managing producer mobility. The model provides the dynamic mobility management solution to adapt to efficiently manage producer movements, ensuring optimal routing and efficient network performance. Comparative evaluations demonstrate marked advancements over existing solutions, establishing the model as a scalable and robust solution for NDN environments that solves high handoff latency, excessive signalling and long packet delivery issues. This work not only addresses current challenges in producer mobility but also sets a new direction for future research and practical applications in NDN architecture.

1. Introduction

The current Internet paradigm has endured significant transformation due to the revolutionary surge in cutting-edge technologies and digital applications in the digital society. The cutting-edge technologies involve the Internet of Everything (IoE), Internet of Medical Things (IoMT), and Internet of Things (IoT). While the digital society refers to the community or a country where the majority of individuals connected to the Internet by using the cutting-edge technologies. These technologies support the civic activities that plays the vital role in various sectors such as business, education, and health sector. All these sectors monitor by the smart devices that uses the multiple digital applications and deal with the high data traffic over the host-centric network (Abrar et al., (2023c)).

As the Internet increasingly becomes a cornerstone for modern communication and information dissemination, its underlying host-centric algorithm presents significant limitations such as lack of content caching routers, unsupported content-oriented communication, unsubstantiated location-based content dissemination, high latency and inefficient content delivery (Zukri, Arif, AlSamman, & Abrar, 2023). These limitations are particularly evident in scenarios involving high mobility and dynamic content access, necessitating a shift towards more adaptive and efficient network architectures. Named Data Networking (NDN), as one of the emerging Information-Centric Networks (ICN), offers a promising solution (Alsamman, Hassan, Mohammed, & Fazea, 2023; NAITO and SUZUKI, 2023; Negara, Syambas, & Mulyana, 2023). Its unique features, including name-based routing, receiver-driven communication, in-network caching, and location-independent naming strategies, position it as a forward-looking alternative to traditional Internet architecture (Abrar et al., (2023a)).

2. Motivation

In NDN, the communication between users and providers is based on content-centric nature rather than the location-based communication. The user firmly interested in to obtain content without knowing its location that increase the scalability and availability of the content. However, the burgeoning use of mobile devices as content providers

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introduces new challenges in maintaining seamless connectivity during mobility. The mobility refers to the physically change in the location of the network devices during communication that can change its position by moving within or around the different networks. This aspect of mobility, crucial in the NDN paradigm, is categorized into consumer and producer mobility. While consumer mobility, involving the relocation of consumers to new access points, is reasonably supported by the network's caching capabilities, producer mobility presents a more complex challenge (Negara et al., 2023). It involves the mobility of content producers, requiring them to frequently transition between access points, a process known as handoff. This mobility not only creates high handoff latency but also leads to increased signalling costs and inefficiencies in packet delivery, posing significant hurdles in the operation of communication networks (Alsamman et al., 2023).

The longer in the handoff leads to high loss of Interest packets and unnecessary Interest packets loss that result in the high signalling and inefficient network performance. During the long handoff process the consumer keep sending the Interest packets towards the producer location. while the unavailability of producer in the network leads to Interest packets lost. Furthermore, prolong in producer handoff latency impact the availability and the scalability of new contents, resulting in decreased in the efficient content delivery. The overall network performance is affected by the long handoff latency, high signalling cost and inefficient content delivery. Therefore, the objective of this research work is to address the aforementioned performance metrics and proposed a solution.

3. Contribution

In order to tackle these complex challenges, our paper presents the Producer Mobility Management Mechanism (PMMM), a groundbreaking solution aimed at transforming producer mobility management in NDN. Our innovative PMMM stands out for its remarkable features and contributions, which include:

- A mechanism to effectively manage mobility, reducing packet loss and signalling costs.
- A strategy to minimize handoff latency and establish optimal paths post-handoff, enhancing overall network efficiency.
- An approach that not only focuses on reducing handoff latency but also ensures a high packet delivery ratio with lower signalling costs.

4. Organization

This paper is structured into several sections, each serving a specific purpose in presenting the study as shown in Fig. 1. The first section is the introduction, which provides a comprehensive background of the research topic. It sets the context and lays the foundation for the subsequent sections. Moving on, the second section focuses on highlighting the importance and encouragement towards producer mobility. The third section describes the significant achievements and objectives related to the enhancement of producer mobility in NDN. This section emphasizes the importance of the study's goals and the potential impact on NDN. To facilitate understanding of the study's flow, the fourth section provides clear and concise guidelines. These guidelines serve as a roadmap for readers to navigate through the paper and grasp the overall structure and organization of the work. Section five delves into the fundamental aspects of the NDN paradigm, providing a deep understanding of its core principles and mechanisms. Following that, section six addresses the related issues specifically related to producer mobility. It explores the challenges and limitations that exist in producer mobility. In section seven, the paper introduces a proposed mechanism aimed at addressing the aforementioned issues in producer mobility. Section eight elaborates on the message exchange process during communication within the proposed mechanism. It elucidates the intricate details and steps involved in the exchange of messages within the NDN

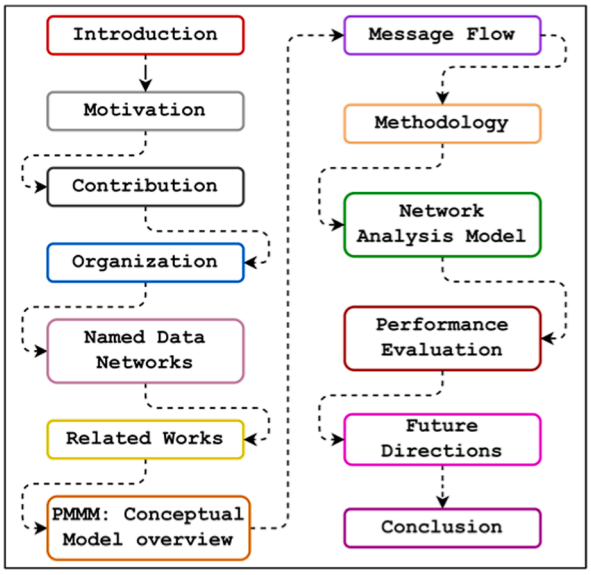


Fig. 1. Organization of work.

framework. Moving on to the next sections explain the selection of the most appropriate methodology. The next sections explain the utilization of network analytical modelling as the chosen methodology to develop and formulate the proposed mechanism and analysis the performance evaluation with the benchmarking studies. Additionally, the subsequent sections offer valuable research guidelines for future investigations, highlighting potential areas of exploration and improvement. Finally, the paper concludes by summarizing the key findings and contributions, providing a comprehensive overview of the entire research endeavour. The Table 1. shows the list of abbreviations of this paper.

5. Named data networking in a nutshell

The NDN is the leading project of ICN, which aims to enhance the current Internet paradigm by switching from a host-centric to a content-centric approach (Ahed, Benamar, Lahcen, & El Ouazzani, 2022). It offers content dissemination by using content unique name based, regardless of content location (Gupta et al., 2023). The content dissemination is regulated by the Interest and Data packets. Furthermore, the packets handled by the NDN data structure that consists of Content Store (CS), Pending Interest Table (PIT), and Forwarding

Table 1
List of acronyms and abbreviations.

Acronyms	Abbreviations
PMMM	Producer Mobility Management Model
IoE	Internet of Everything
IoMT	Internet of Medical Things
IoT	Internet of Things
NDN	Named Data Networking
ICN	Information-Centric Networks
CS	Content Store
PIT	Pending Interest Table
FIB	Forwarding Information Base
MI	Mobility Interest
HA	Home Agent
CR	Content Router
MNP	Mobility Notification Packet
MUP	Mobility Update Packet
IBM	Indirection-based Mobility
PMSS	Producer Mobility Management Scheme
MANET	Mobile Ad hoc Network
VANET	Vehicular Ad hoc Network
6G	Six-generation

Information Base (FIB) as shown in Fig. 2. In NDN data structure the CS uses to store the incoming contents along with the content name. while the PIT manages the incoming interface of incoming Interest corresponding to the name of the content. The FIB keeps the record of the outgoing interface of the respective content provider known as name prefix.

The consumer and producer play a vital role in order to exchange the content between them. The consumer refers to content requester while the producer refers to content provider. The consumer content communication is supported by the CS. When a consumer sends an Interest packet (*Lab.com/s.mp4/v3/s2*) in NDN, the CS in the router assess the availability of the requested content. The content is forwarded to the consumer immediately on its availability otherwise, the Interest packet is transferred to the PIT.

The PIT serves to verifies the Interest duplication in order to prevent the Interest looping in the network. The PIT adds the Interest interface if it is duplicated and does not further forwards to the FIB to avoid unnecessary network traffic. While if the PIT receives the Interest packet first time, it stores the Interest incoming interface corresponding to requested content name and further forwards to the FIB. The FIB contains the list of content provider name prefix corresponding to the outgoing interface. The FIB finds the best matching entry and forwards the Interest to the most appropriate provider path as shown in Fig. 3.

When the request content reaches to the router, it searches for the related Interest in the PIT. If the related Interest found in the PIT, the content is acknowledged by the PIT which is known as loop hit. The content is cached in CS and forwarded to the consumer. If the related Interest for incoming content is not found in the PIT which is known as loop miss. The content is dropped at the router level and content is tagged as an unsolicited content. However, the content availability and content distribution challenging task due the producer mobility.

6. Producer mobility

In NDN, the producer operates as a content source that provides the related content to its consumer. When a consumer requests a content in form of Interest, the Interest follows the NDN data structure in order to get content. The content is efficiently retrieved by the nearest NDN consumer router cache. However, due to the limited cache storage size, the content is unable at the router CS. In such a case, the Interest is forwarded to the next router or forwarded to content producer location by following the FIB.

By referring to Fig. 4, the shows the communication between consumer and producer. The consumer sends an Interest (*ILab.my/video*) from Content Router (CR1), the CR1 forwards the Interest packet to its consecutive router CR2 determines by the FIB. The CR2 forwards the Interest packet, and the producer receives the Interest packet from the CR3. The producer generates requested content and forwards the content by following the Interest path inversely. During the communication, when the producer disconnected from the old location CR3 and connected to new location CR4, the incoming Interest still follows the producer old location at CR4. However, the physically change in location impacts the incoming Interest and the Interest experiences loss due to inaccessibility of the producer at CR3. On the other hand, the producer mobility is not fully supported in NDN environment (Fayyaz et al., 2023; Hang, Leau, Park, Yan, & Praptodiyono, 2022).

Content Store (CS)

Content Name	Cached Content
IrLab.com/ndn.mp4/v2/s1	----------

Pending Interest Table (PIT)

Incoming Interface	Content Name
0	*IrLab.com/ndn.mp4/v2/s3*

Forwarding Information Base (FIB)

Outgoing Interface	Name Prefix
0,1	*IrLab.com*

Fig. 2. Data structure in NDN.

The producer relocation in the NDN paradigm cause the inaccessibility towards the content providers, and it also results in the FIB becoming outdated. However, the producer not fully capable to provides the contents in the network that causes several issues such as Interest packet loss, unnecessary Interest packet loss, high handoff latency, and high signalling cost (Abrar et al., (2023b); Abrar et al., (2023c); Azamuddin, Aman, Hassan, & Mansor, 2022).

7. Related works

Several studies have been conducted to overcome the producer mobility concerns such as long handoff latency, high signalling cost and non-optimal packet delivery (Do & Kim, 2015; Hussaini, Nor, & Ahmad, 2019). The solution uses an immobile anchor or Home Agent (HA) in network to monitors the association and dissociation of mobile producer. The HA refers to a static router that locates the producer most recent location. Whenever, the producer disconnected and connected again in network it notifies its location towards the HA. The HA stores the producer location information corresponding to the producer content prefix.

By referring to Fig. 5, shows the producer mobility between different CRs. When producer moves through CR3 and associated with CR4, it sends the binding information packet to CR4 that contains the producer's name prefix and location. The HA stores the binding information with the acknowledgement. Thereafter, incoming consumer requests to HA redirected towards the producer most recent location.

In this way the producer mobility handle through indirection of HA which refers to Indirection-Based Mobility (IBM) (Abrar et al., (2023b)). However, during the mobile producer transition between CR3 to CR4, the incoming consumer Interest experience losses. Additionally, the producer long handoff latency tends to higher the packets loss and increases the signalling cost. Furthermore, in a larger network, the frequent relocation and updating the HA leads to excessive loss of packets and causes high signalling cost.

In study (Hussaini et al., 2019) Producer Mobility Management Scheme (PMSS) which adapted the IBM HA as an anchor router to support producer mobility. The PMSS placed an anchor router to notify the network about the producer location. when the producer reaches to new location, it broadcast its new location prefixes via using Mobility Interest (MI) packet. When MI packet reaches the anchor router, it broadcasts the location towards the whole network and updates the routing path. In result, the new consumer Interest packets moves to producer new location. However, it creates single point of failure issue as well as high signalling cost. Moreover, the frequent producer mobility among the different access points in the network leads the packets to producer old location that cause inaccessibility and interruption in the real-time content communication.

In study (Zhang, Zhang, & Zhang, 2014) producer mobility support in NDN which is known as KITE. The solution uses the immobile anchor to handle producer mobility. It proposed two different packets traced and tracing Interest to manage the consumer and producer communication. However, it does not use the optimal routing path and cause the excessive signalling.

In study (Abrar et al., (2023c)) provides a solution in order to

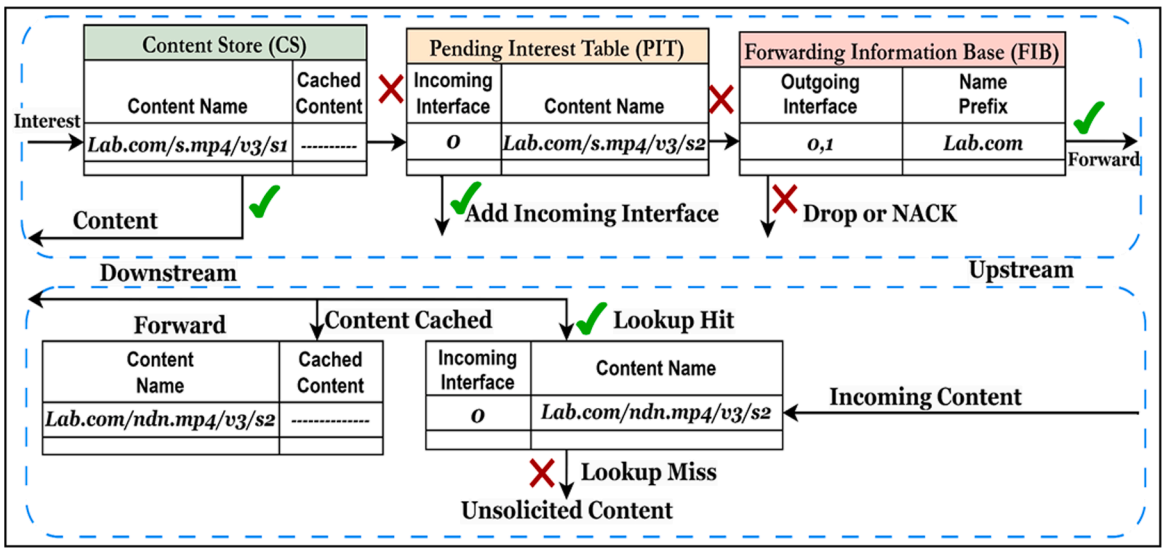


Fig. 3. Content dissemination in NDN data structure.

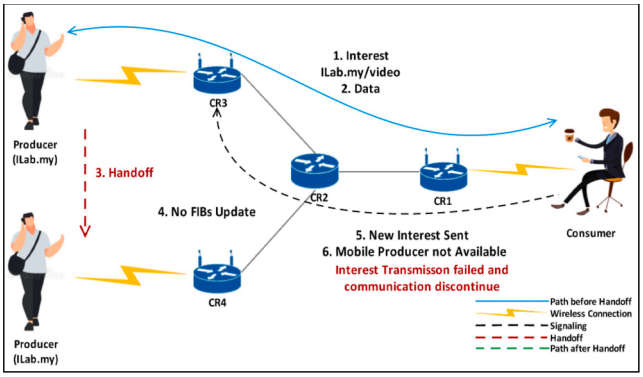


Fig. 4. Producer mobility in NDN.

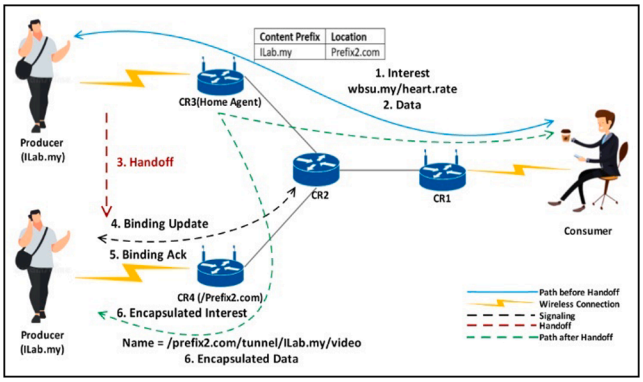


Fig. 5. Indirection-based Mobility in NDN.

improve the associated issues in the producer mobility by using edge nodes and immobile anchor. The immobile anchor is place in the strategic location in order to reduce the path stretch ratio and less hop count between the consumer and producer. Furthermore, the solution uses the edge router to redirects the Interest packets towards the immobile anchor router during the unavailability of mobile producer due handoff. The anchor router caches the incoming Interest packets from the edge router. When the producer associate in the network and updates its location to immobile anchor, the immobile anchor redirects the Interest packets towards the producer new location. The solutions efficiently overcome the Interest packet loss issue. However, it creates the excessive signalling cost in the network and increases the path stretch ratio that cause the high latency in the content delivery. Further, in real world implementation the solution is more complex and less dynamic in the mobile network.

8. PMMM: An overview of conceptual model

In order to improve the aforementioned challenges in the previous section, this section provides an overview of the proposed mechanism. By referring to Fig. 6, that shows the working mechanism of PMMM, where the consumer generates the Interest packets and producer responses the Interest packet via data packets. When producer initiate to move from CR3, it sends Mobility Notification Packet (MNP) until the consumer to pause scheduling next Interest packet for content producer prefix. When producer completes the relocation and attached to stable router CR4, it broadcasts the Mobility Update Packet (MUP) to notify the consumer about its availability and resume the transmission through optimal path.

8.1. Basic elements: Packets format and data structure

To effectively handle producer mobility, a proposed mechanism involves the design of special mobility management packets based on the MNP and MUP. These packets are created by modifying regular NDN packets and introducing additional fields, such as mobility status and

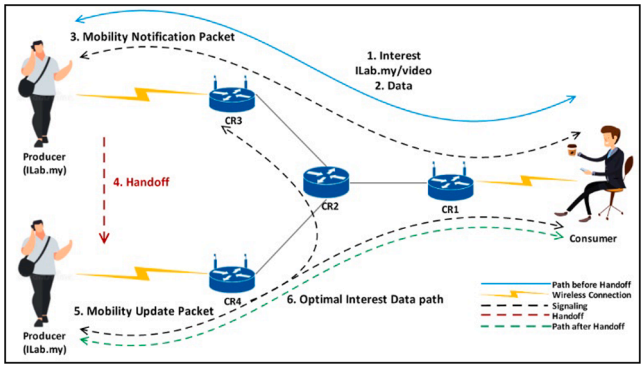


Fig. 6. Producer mobility management model.

packet value as shown in Fig. 7. By incorporating these extra fields, the mechanism enables better management and tracking of producer mobility within the network. This approach enhances the ability to handle and respond to changes in producer location and availability, facilitating efficient data delivery and seamless connectivity in dynamic network environments.

8.1.1. Mobility management packets

The newly added MNP (Mobility Notification Packet) in the proposed model follows a specific format, as depicted in Fig. 7. The MNP includes several fields, such as name, content, nonce, and guider. The definitions of nonce and guider are consistent with those found in normal data packets, as previously explained in the NDN architecture packet format specification. However, in PMMM, the MNP is purposed to serve as a means to notify the network about producer mobility events. To accommodate this functionality, modifications and additional fields are introduced in the MNP by leveraging the capabilities of the NDN module.

One of the added fields in the MNP is the "mobility status" field. This field is used to differentiate between different types of mobility management packets. Specifically, the mobility status field can have a value of either 0 or 1. A status value of 0 indicates that the MNP is notifying the forwarding pipeline about the detachment or unavailability of a producer in the network. This information is crucial for the network to adjust its routing and forwarding behaviour accordingly. When the forwarding pipeline receives an MNP with a status value of 0, it triggers the MNP forwarding function to proceed with forwarding the MNP until it reaches the consumer or consumers. Additionally, the MNP includes a "packet type" field, which indicates the type of packet it is. In this case, the packet type is set to indicate that it is an MNP. This field helps in identifying and processing the MNP correctly within the network. The "mobile" packet type field ensures that the consumer is informed of the producer's unavailability and can pauses the Interest packets generation in the network.

The MUP (Mobility Update Packet) in PMMM follows a specific format, which is illustrated in Fig. 7. Several fields in the MUP, such as content, nonce, and guider, are identical to those found in data packets, as defined in the NDN packet format specification. The MUP shares a similar structure to the MNP, with the key difference lying in the values of the "mobility status" and "packet type" fields. The MUP is triggered when it receives a status value of 1. This status value indicates that the producer has connected or become reachable within the network. Upon receiving a status value of 1, the forwarding pipeline triggers specific functions that assist the MUP in reaching the next router or, ultimately, the consumer.

Similar to the MNP, the MUP also includes the "packet type" field. In the case of the MUP, the packet type is set to "active." This value serves to notify the consumer about the reachability or attachment of the producer to a new router within the network. The "active" packet type field ensures that the consumer is informed of the producer's availability and can initiate Interest packets to retrieve the desired content from the producer.

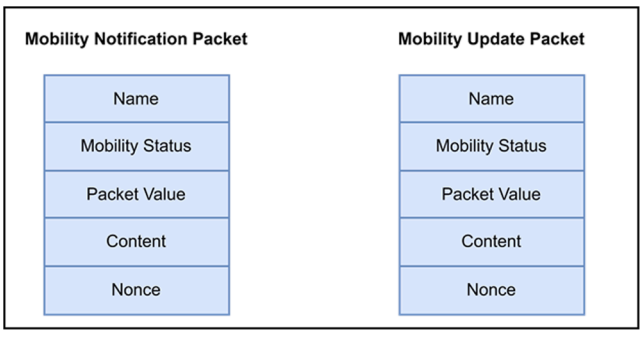


Fig. 7. Mobility management packets in PMMM.

By referring to Fig. 8, that shows the working mechanism of PMMM and the extend data structure of NDN on each router. To notify the consumer about the producer's accessibility or presence in the network, the producer sends an MNP packet with a status value of 0 and a packet type of "mobile" when it detects a weak signal strength. This packet is then forwarded to the consumer. When the forwarding layer encounters a packet with a status value of 0, it follows additional functions specific to handling such packets. Upon receiving an MNP packet with a packet type of "mobile," the consumer temporarily suspends the generation of Interest packets for the corresponding producer prefix.

On the other hand, when the producer finds a strong signal and attaches to a new access point, it broadcasts an MUP packet with a status value of 1 and a packet type of "active." This packet notifies the forwarding layer about the producer's new location. Upon receiving a packet with a packet type of "active" and a status value of 1, the forwarding layer executes additional functions to update the producer's new location information in the network. Furthermore, when the consumer receives a packet with a packet type of "active," it resumes communication for the specific producer prefix.

This mechanism enables efficient communication between producers and consumers in dynamic network environments. It allows producers to inform consumers about changes in their accessibility and triggers appropriate actions in the network to ensure seamless connectivity and data delivery.

8.2. Mobility management packets transmission pipeline

The normal forwarding process for Incoming Data has been modified to include additional functions that support the handling of special mobility management packets. These new functions introduce separate streams for forwarding the mobility management packets, namely "On Mobility Notification Packet," "On Mobility Update Packet," and "Forward Mobility Management Packet," as depicted in the Fig. 9.

When a packet enters the forwarder in the PMMM architecture, it undergoes analysis. If the packet's status value is determined to be 0, it is identified as an MNP packet. The status value is typically set by the application. The forwarder then stores the MNP packet as data in the CS and retrieves the FIBs associated with the next hops. Next, the forwarder iterates through the FIBs to identify similar Interest packets based on the prefixes of the MNP packet. If a matching Interest name is found, the forwarder forwards the MNP packet along the same path as the incoming Interest packet. However, if no matching Interest is found, indicating a lack of pending Interests for the corresponding content, the forwarder declines further processing of the MNP packet. This decision helps avoid unnecessary signalling cost.

On the other hand, if the forwarder encounters a packet with a status value of 1, it identifies it as an MUP packet. Similar to the MNP packet,

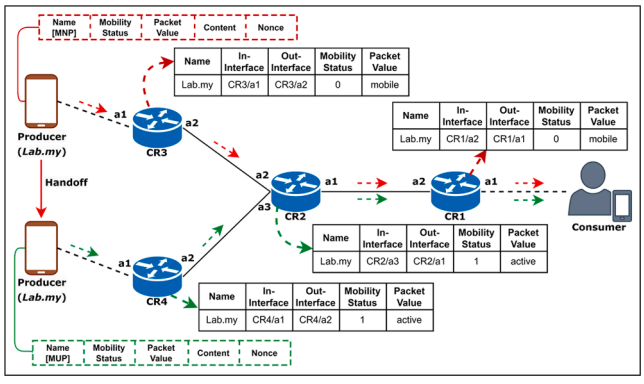


Fig. 8. Producer mobility management mechanism in forwarding data structure.

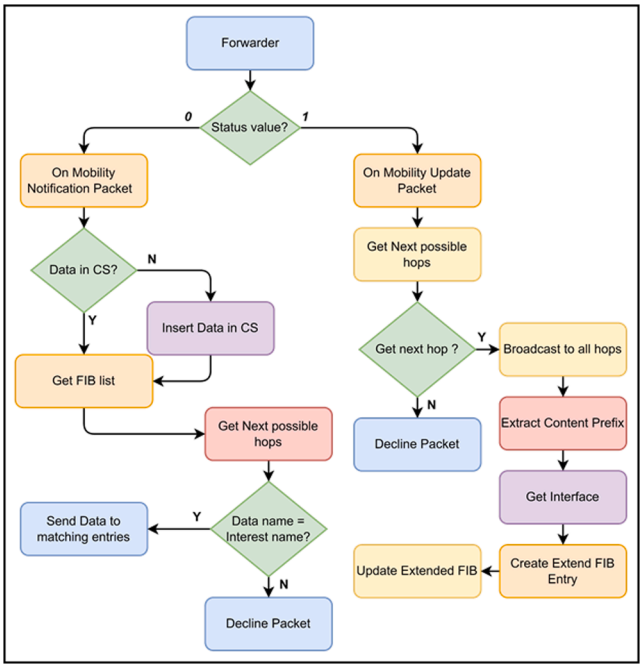


Fig. 9. Mobility management packet flow chart.

the status value for MUP packets is set by the application. When the forwarder identifies an MUP packet, it broadcasts the packet to the next hop lists, ensuring that all relevant nodes in the network receive the update. During this process, the forwarder extracts the incoming packet's prefix and interface information. Subsequently, it creates an extended FIB and updates it with the new interface path. This update ensures that the extended FIB reflects the latest network topology and availability of resources.

Furthermore, to address the issue of excessive signalling costs, both the consumer and producer applications have been modified. These modifications aim to optimize the signalling process and reduce unnecessary signalling overhead. By streamlining the signalling procedures, the system can achieve more efficient communication between consumers and producers while minimizing the associated costs.

Overall, these enhancements to the forwarding process and application design contribute to improving the management of special mobility management packets, enabling smoother mobility transitions for producers and consumers and reducing the signalling burden on the network.

9. Message flow

The proposed mechanism for communication between the consumer and producer is depicted in illustrated Fig. 10. To effectively achieve the objectives, it is assumed that the consumer and producer engage in communication. The detailed description of the communication flow is as follow:

1. The consumer, located at CR1, initiates the communication by sending an Interest packet (*/ndn.mp4*), which is situated at (*IrLab.com*) attached to the CR3. This Interest packet expresses the consumer request for data.
2. The producer responds to the consumer request by supplying the data in succession of versions and segments, each corresponding to the Interest packets. These packets are recognized as (*IrLab.com/ndn.mp4/v1/sn*). Where '*n*' represents a sequential number (e.g., $n = 1, 2, 3,$ and so on).
3. At a particular point, when producer initiate to change its location, it notifies its mobility by sending MNP from CR3 until the CR1. This packet aware the consumer relating the producer mobility.
4. Upon receiving the MNP, the consumer pauses the Interest scheduling event for the specific producer prefix which is extracted by the MNP.
5. The producer completes the handoff process by relocation from CR3 to CR4. From CR4, it sends MUP to update its location towards the network and consumer.
6. The consumer generates an Interest packet (*/ndn.mp4*) to gets the remaining contents (*IrLab.com/ndn.mp4*).

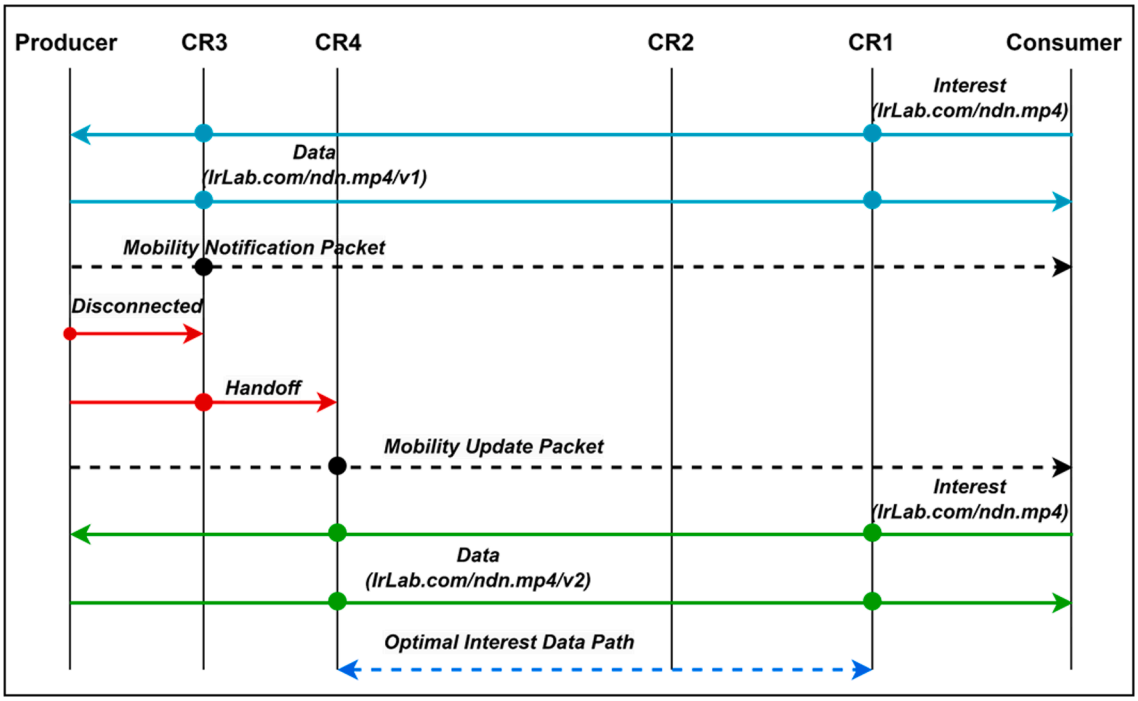


Fig. 10. Message flow in proposed PMMM.

The PMMM ensures the seamless support for producer mobility, eliminating of single point of failure, reduce Interest packet loss, minimize high signalling, less bandwidth usage, and lessen in the Interest retransmission for the same piece of content. In order to measure the performance of the PMMM mechanism, this study evaluates the working mechanism through network analysis modelling.

10. Methodology

The several performance techniques are you used in order to analyse the performance of the network model such as analytical modelling, simulation analysis, and testbed analysis. However, the simulation provides the real-world scenario, but it takes long time in order to implement. Moreover, the testbed analysis is also another efficient way to examine the network performance, but it involves high cost and long time to access the performance. Therefore, this research uses the analytical modelling that measure the performance of network model with minimum time and cost.

10.1. Network analysis model

A network analysis model was developed as in (Abrar et al., (2023b); Do & Kim, 2015; Hussaini et al., 2019) is shown in Fig. 11 for the formulation and the performance evaluation of the conceptual model. For the purpose of validating and performance benchmarking this research, the proposed PMMM, and others benchmarking principal approach IBM, and existing mobility solutions as KITE and PMSS are formulated.

The network analysis model consists of a few nodes, including four CRs, a server (DNS or Mapping or rendezvous), a consumer, and a mobile producer. The four CR are the C-CR that connected to the consumer, the New-CR that connected by the mobile producer after the relocation, the Old-CR that was connected to it before the relocation, and the Anh-CR functioning as the anchor node or immobile anchor. The network link used to transmit data between the nodes is identified by the hop count parameters denoted as a, b, c, and d.

Moreover, Table 2. details the parameters and their values, including their notation, and description. The parameters are as follows: a for latency and cost of packet transmission between consumer to CR (L_{Con_Cr}, C_{Con_Cr}), and a also for latency and cost of packet transmission between producer to CR (L_{Pro_Cr}, C_{Pro_Cr}); b for latency and cost of packet transmission between Old-CR and New-CR (L_{Old_NCr} and C_{Old_NCr}); c for latency and cost of packet transmission between CRs (L_{Cr_Cr} and C_{Cr_Cr}); and d for latency and cost of packet transmission between CR and server (L_{Srv_Cr} and C_{Srv_Cr}).

The S_{Packet_name} in Table 2. provides names or labels for signalling packets that used for various purposes, such as querying, acknowledging, tracing, and creating routes, and so on. These packets have different subscript names to differentiate between them. In the case of modified Interest packets, the size of the packet is increased by 16 bytes from the size of a normal Interest packet. This is due to the additional information contained in the modified Interest packet. Encapsulated packets, such as query update and reply to packets, contain 32 additional bytes of information compared to normal packets.

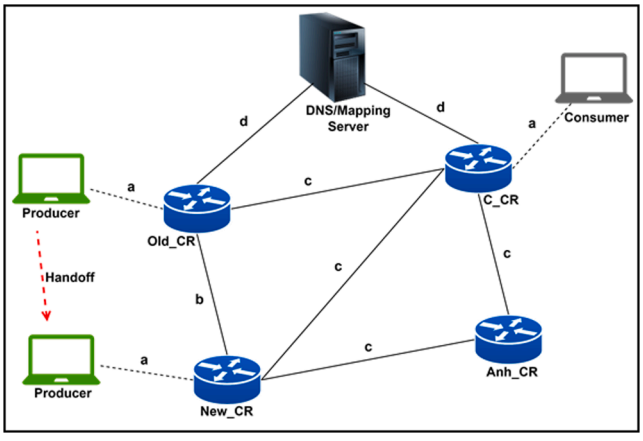


Fig. 11. Network analysis model.

Table 2
Parameter Values of Network Analysis Model.

Category	Notation	Parameter	Value
Packets	S_{Pn}	Size of signalling packet	+16 bytes
	S_{Int}	Size of Interest packet	40 bytes
	S_{Data}	Size of Data packet	2000 bytes
Transmission Latency	L_{Pro_Cr}	Producer to CR	a = 1
	L_{Con_Cr}	Consumer to CR	a = 1
	L_{Srv_Cr}	Server to new CR	d = 9
	L_{Old_NCr}	Old CR to New CR	b = 5
	L_{Anh_Cr}	CRs to Anchor	c = 5
	L_{Cr_Cr}	CR to CR	c = 5
	L_{HF}	Time spans of producer handoff process	l_{hf}
Signalling Cost	C_{Pro_Cr}	Producer to CR	a = 1
	C_{Con_Cr}	Consumer to CR	a = 1
	C_{Srv_Cr}	Server to new CR	d = 9
	C_{Old_NCr}	Old CR to New CR	b = 5
	C_{Anh_Cr}	Anchor to CR	c = 5
	C_{Cr_Cr}	CR to CR	c = 5

The PMMM, IBM, PMSS, and KITE solutions incorporate the network analysis model and hop count parameters into their concept formulation. The hop count formulation is used to identify the performance of the network, which measures the handoff latency, handoff signalling cost, and packet delivery cost.

10.1.1. Handoff latency analysis

The handoff latency is total time that a producer disconnects, reconnect, and arriving of first Interest packet on new connection. To measure the handoff latency, we use the hop count method. It measures the distance between two consecutive nodes. Each content router associated with link delay, queuing delay, and bandwidth for both wired and wireless connection. Therefore, Eq. (1) represents the total delay between two consecutive hops for wired link $L_{wd_packet_name}$ and Eq. (2) shows the total delay between two consecutive hops for wireless link $L_{wls_packet_name}$.

$$L_{wd_packet_name} = \frac{S_{pn}}{B_{wd} + L_{wd} + Q_d} \tag{1}$$

$$L_{wls_packet_name} = \left(\frac{(1+q)}{(1-q)}\right) * \left(\frac{S_{pn}}{B_{wls} + L_{wls}}\right) \tag{2}$$

The packets delay includes the packet size or length S_{pn} per wired bandwidth B_{wd}, the wired link delay L_{wd}, and the routers queuing time Q_d, are added to calculate the total wired link delay $L_{wd_packet_name}$ as expressed in Eq. (1). Also, the packets delay includes the packet size or length S_{pn} per wireless bandwidth B_{wls}, the probability of link failure q, and the wireless link delay L_{wls}, are added to calculate the total wireless link delay $L_{wls_packet_name}$ as expressed in Eq. (2).

The IBM uses the HA to redirects the packets towards the producer or consumer. When the mobile producer disconnects from Old-CR and connected to New-CR, it completes the L_{HF} time Interval. The value of transmission latency of time interval L_{HF} is represented by l_{hf}. The New-CR generates a binding update that consist of forwarding hint about the producer new location and forwards it towards the Old-CR that works as HA with the transmission latency between producer and router L_{Par_Cr}, and between Old-CR and New-CR L_{Old_NCr}. The HA acknowledges the binding update to New-CR and to producer with transmission latency

L_{Old_NCr}, and L_{Pro_Cr} respectively. The consumer sends Interest packet to HA, the HA forwards the Interest packet towards the New-CR to the producer with the transmission latencies L_{Con_Cr}, L_{Cr_Cr}, L_{Old_NCr}, and L_{Pro_Cr}. After integrating the total wired $L_{wd_packet_name}$ and wireless delay $L_{wls_packet_name}$ for a wired and wireless link encountered in the formulation, Eq. (3) is used to calculate the hop count handoff latency for IBM. The calculation took into account the mobile producer's overall handoff latency; it may be used to assess handoff effectiveness and measure how well the IBM technique supports seamless mobility.

By referring to Fig. 12 shows the mobility of producer and messages patterns in IBM. After the producer handoff process, the producer sends message to New_CR, the New_CR forward message to Old_CR. While the Old_CR reply to New_CR, the New_CR further forwards the reply message to producer. The consumer sends new Interest packet to C_CR, the C_CR sends the packet to Old_CR, the Old_CR redirects the packet to New_CR and producer received the packet from New_CR.

$$L_{IBM} = L_{Hf} + L_{Pro_Cr} + L_{Old_NCr} + L_{Old_NCr} + L_{Pro_Cr} + L_{Con_Cr} + L_{Cr_Cr} + L_{Old_NCr} + L_{Pro_Cr}$$

By substituting the total wired and wireless link delay in Eqs. (1) and (2), then:

$$L_{IBM} = l_{hf} + a \times L_{wls_Up} + b \times L_{wd_Up/Ack} + b \times L_{wd_Up/Ack} + a \times L_{wls_Up} + a \times L_{wls_Int} + c \times L_{wd_Int} + b \times L_{wd_Int} + a \times L_{wls_Int} \quad (3)$$

The Eq. (4) express the handoff latency of PMSS solution through hop count formulation. When mobile producer completes the handoff process by disconnecting form Old-CR and connected to New-CR, it completes the handoff by transmission latency time interval L_{HF} which is represented by the value of l_{hf}. Then producer sends MI to the New-CR, the New-CR update the mobility status and tag the MI packets to indicate the mobile producer content name with transmission latency HL_{Pro_Cr}. Further, the New-CR sends the MI packet to anchor router Anh-CR, the anchor router broadcast the MI packet towards the network to update the routers with transmission latencies L_{Anh_Cr}, and L_{Cr_Cr}. The consumer sends the Interest packet to the producer new location with transmission latencies between consumer to C-CR L_{Con_Cr}, between C-CR to New-CR L_{Cr_Cr}, and New-CR to producer L_{Pro_Cr}. The hop count formulation of PMSS is presented in Eq. (4). Equation took into account the mobile producer's overall handoff latency for the proposed PMSS. It is used to assess the effectiveness of handoffs and estimate the degree of seamless mobility support offered by the PMSS solution.

By referring to Fig. 13 that shows the producer mobility, producer, and consumer messages patterns in the network. After the producer relocation at New_CR, the producer sends packet to New_CR, the New_CR forwards the packet to Anh_CR, the Anh_CR broadcast the packet to C_CR and further it moves from C_CR to Old_CR. Hence, the new Interest packet moves from consumer to C_CR, the C_CR further forwards it to New_CR and from New_CR it reaches to producer.

$$L_{PMSS} = L_{Hf} + L_{Pro_Cr} + L_{Anh_Cr} + L_{Anh_Cr} + L_{Cr_Cr} + L_{Con_Cr} + L_{Cr_Cr} + L_{Pro_Cr}$$

By substituting the total wired and wireless link delay in Eqs. (1) and

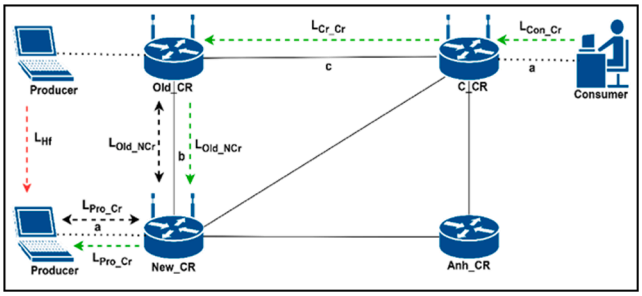


Fig. 12. Handoff latency analysis in IBM.

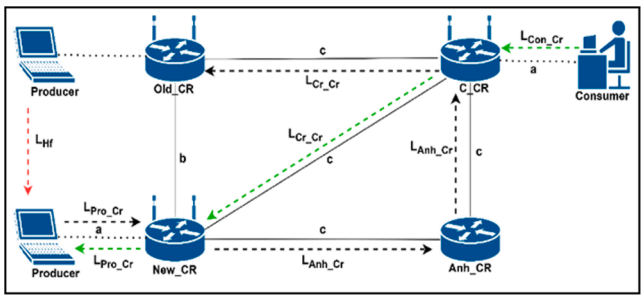


Fig. 13. Handoff analysis in PMSS.

(2), then:

$$L_{PMSS} = l_{hf} + a \times L_{wls_MobInt} + c \times L_{wd_MobInt} + c \times L_{wd_MobInt} + c \times L_{wd_MobInt} + a \times L_{wls_Int} + c \times L_{wd_Int} + a \times L_{wls_Int} \quad (4)$$

The hop count formulation of KITE solution is presented in Eq. (5). As the mobile producer completes the handoff process by disconnecting off the Old-CR and connecting to the New-CR, it completes the handoff by the transmission latency time interval L_{HF}, which is indicated by the value of l_{hf}. From the New-CR it exchanges the two different packets form the immobile anchor router to redirects the consumer Interest to the producer new location. Hence, it generates the trace Interest and trace data packets through New-CR to Immobile anchor router. The transmission latency from producer to New-CR L_{Pro_Cr}, New-CR to immobile anchor L_{Anh_Cr} and vice versa (call backs of trace Interest and trace data packet from immobile anchor). The consumer sends Interest packet to the connected router C-CR, the C-CR sends Interest to immobile anchor with transmission latencies L_{Con_Cr} and L_{Anh_Cr}. The immobile anchor redirects the Interest packets to New-CR and New-CR forwards the Interest to the producer with transmission latencies L_{Anh_Cr} and L_{Pro_Cr} respectively.

The Fig. 14 shows that the producer exchanges the number of messages after the handoff process. The producer sends packet TI to New_CR, the New_CR forwards it to Anh_CR. The Anh_CR in response sends TD to New_CR, from New_CR it is received by the producer. While the consumer sends the Interest packet to C_CR, the C_CR forward the packet to Anh_CR. The Anh_CR redirects the packet to New_CR, from New_CR the packet is received by producer.

$$L_{KITE} = L_{Hf} + L_{Pro_Cr} + L_{Pro_Cr} + L_{Anh_Cr} + L_{Anh_Cr} + L_{Con_Cr} + L_{Anh_Cr} + L_{Anh_Cr} + L_{Pro_Cr}$$

By substituting the total wired and wireless link delay in Eqs. (1) and (2), then:

$$L_{KITE} = l_{hf} + a \times L_{wls_TraceIntData} + a \times L_{wls_TraceIntData} + c \times L_{wd_TraceIntData} + c \times L_{wd_TraceIntData} + a \times L_{wls_Int} + c \times L_{wd_Int} + c \times L_{wd_Int} + a \times L_{wls_Int} \quad (5)$$

The hop count formulation of proposed PMMM is expressed in Eq.

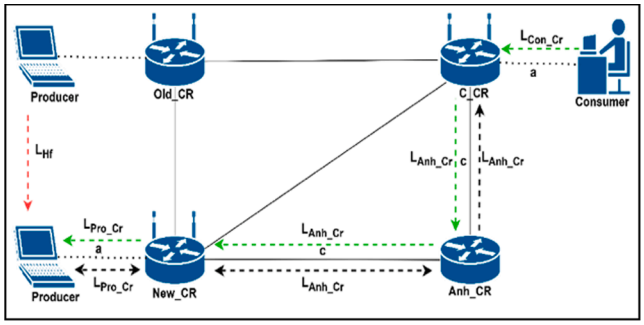


Fig. 14. Handoff analysis in KITE.

(6). When mobile producer completes the handoff process by disconnecting from Old-CR and connected to New-CR, it completes the handoff by transmission latency time interval L_{HF} which is represented by the value of l_{hf}. Then producer sends Mobility Update Packet (MUP) to the New-CR, the New-CR update the mobility status and broadcast the packet to the intermediate's routers with transmission latencies L_{Pro_Cr}, L_{Old_NCr}, and L_{Cr_Cr} respectively. Further, it updates the consumer to resumes its communication towards the producer new location with transmission latency L_{Con_Cr}. The consumer sends the Interest packet from its connected router C-CR, from the C-CR the Interest packet moves to New-CR optimal path and further moves from New-CR to producer with transmission latencies L_{Con_Cr}, L_{Cr_Cr}, and L_{Pro_Cr} respectively.

The Fig. 15 shows the packet exchange between the consumer and producer in network after the producer handoff. The producer sends the packet to New_CR, the New_CR broadcast the packet to Old_CR and also to C_CR. The C_CR further forwards the packets to consumer. The consumer sends an Interest packet to C_CR, the C_CR forwards the packet to New_CR. From New_CR the packet is received by the producer.

$$L_{PMMM} = L_{Hf} + L_{Pro_Cr} + L_{Old_NCr} + L_{Cr_Cr} + L_{Con_Cr} + L_{Con_Cr} + L_{Cr_Cr} + L_{Pro_Cr}$$

By substituting the total wired and wireless link delay in Eqs. (1) and (2), then:

$$L_{PMMM} = l_{hf} + a \times L_{wls_MobInt} + b \times L_{wd_MobInt} + c \times L_{wd_MobInt} + a \times L_{wls_MobInt} + a \times L_{wls_Int} + c \times L_{wd_Int} + a \times L_{wls_Int} \quad (6)$$

10.1.2. Handoff signalling cost

The handoff signalling cost denotes the quantity of data packets or messages exchanged between the initial sender and final recipient, encompassing all successive hops, during the handoff phase. For the formulation of our handoff signalling cost analysis, we employed a similar hop count methodology as previously applied in our handoff delay investigations. The Table 1 shows the signalling packets such as S_{Int}, S_{Data}, and S_{packet_name} and their values also presented in table along with notation. The S_{Int} and S_{Data} represents the Interest and Data packet respectively. The S_{packet_name} refers to any signalling packet such as S_{Up} for binding update, S_{Ack} for acknowledgement, S_{MobInt} for mobility Interest packet, $S_{TraceInt}$ for trace Interest, $S_{TraceData}$ for trace Data, S_{Encp_Int} for encapsulated Interest.

The hop count signalling cost of IBM is expressed when the mobile producer sends two signalling packets S_{Up}, and S_{Ack} to indirection point to maintain communication route. Then, the consumer sends the Interest packet S_{Int} to indirection point and the indirection point tunnelled the Interest packet towards the producer location in form of encapsulated Interest $S_{EncpInt}$. The Eq. (7) shows the handoff signalling cost for IBM. The mobile producer sends binding update to New-CR, the New-CR send binding update to HA with signalling cost SC_{Pro_Cr} and SC_{Old_NCr}. The HA sends back the acknowledgement by following the binding update packet reverse track from indirection point to New-CR and New-CR to producer with signalling cost SC_{Old_NCr} and SC_{Pro_ar}. The consumer sends Interest packet from its connected router C-CR to indirection point

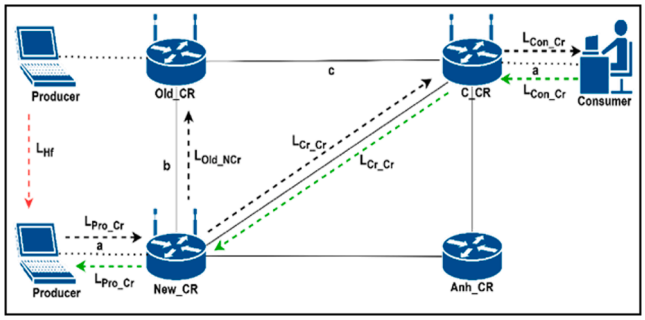


Fig. 15. Handoff analysis in PMMM.

router Old-CR, the indirection point redirects the Interest packet to New-CR and further forwards to producer with signalling costs SC_{Con_Cr}, SC_{Cr_Cr}, SC_{Old_NCr}, and SC_{Pro_Cr} respectively.

$$SC_{IBM} = SC_{Pro_Cr} + SC_{Old_NCr} + SC_{Old_NCr} + SC_{Pro_Cr} + SC_{Con_Cr} + SC_{Cr_Cr} + SC_{Old_NCr} + SC_{Pro_Cr}$$

$$SC_{IBM} = a \times S_{Up/Ack} + b \times S_{Up/Ack} + b \times S_{Up/Ack} + a \times S_{Up/Ack} + a \times S_{Int} + c \times S_{Encp_Int} + b \times S_{Encp_Int} + a \times S_{Int} \quad (7)$$

The handoff signalling cost of PMSS expressed in Eq. (8). The mobile producer sends MI packet to New-CR, the New-CR sends MI packet to anchor router with signalling cost SC_{Pro_Cr} and SC_{Anh_Cr}. The anchor router broadcasts the MI packets to intermediate routers and further in the network to C-CR and Old-CR with signalling cost SC_{Anh_Cr} and SC_{Cr_Cr}. The consumer sends Interest packet from its connected router C-CR to optimal route router New-CR, the New-CR forwards the Interest to producer with signalling costs SC_{Con_Cr}, SC_{Cr_Cr}, and SC_{Pro_Cr} respectively.

$$SC_{PMSS} = SC_{Pro_Cr} + SC_{Anh_Cr} + SC_{Anh_Cr} + SC_{Cr_Cr} + SC_{Con_Cr} + SC_{Cr_Cr} + SC_{Pro_Cr}$$

$$SC_{PMSS} = a \times S_{MobInt} + c \times S_{MobInt} + c \times S_{MobInt} + c \times S_{MobInt} + a \times S_{Int} + c \times S_{Int} + a \times S_{Int} \quad (8)$$

The KITE solution hops count signalling cost presented in Eq. (9). The mobile producer sends trace Interest to New-CR, the New-CR sends trace Interest packet to immobile anchor router Anh-CR, the immobile anchor replies with trace data with signalling cost SC_{Pro_Cr} and SC_{Anh_Cr} twice. The consumer sends Interest packet from its connected router C-CR to the immobile anchor router Anh-CR, the immobile anchor router redirects the consumer Interest packet to New-CR and further forwards to producer with signalling costs SC_{Con_Cr}, SC_{Anh_Cr}, SC_{Anh_Cr}, and SC_{Pro_Cr} respectively.

$$SC_{KITE} = a \times S_{wls_TraceIntData} + a \times S_{wls_TraceIntData} + c \times S_{wd_TraceIntData} + c \times S_{wd_TraceIntData} + a \times S_{wls_Int} + c \times S_{wd_Int} + c \times S_{wd_Int} + a \times S_{wls_Int}$$

$$SC_{KITE} = a \times S_{TraceIntData} + a \times S_{TraceIntData} + c \times S_{TraceIntData} + c \times S_{TraceIntData} + a \times S_{Int} + c \times S_{Int} + c \times S_{Int} + a \times S_{Int} \quad (9)$$

The proposed PMMM solution hop count signalling cost presented in Eq. (10). The mobile producer sends MUP to New-CR, the New-CR broadcasts MUP to the intermediate routers including Old-CR with signalling cost SC_{Cr_Cr}, and SC_{Old_NCr}. The MUP further reaches to the consumer to activate the sending Interest packet event with signalling cost SC_{Con_Cr}. The consumer sends Interest packet from its connected router C-CR to optimal route router New-CR, the New-CR forwards the Interest to producer with signalling costs SC_{Con_Cr}, SC_{Cr_Cr}, and SC_{Pro_Cr} respectively.

$$SC_{PMMM} = SC_{Pro_Cr} + SC_{Old_NCr} + SC_{Cr_Cr} + SC_{Con_Cr} + SC_{Con_Cr} + SC_{Cr_Cr} + SC_{Pro_Cr}$$

$$SC_{PMMM} = a \times S_{MobInt} + b \times S_{MobInt} + c \times S_{MobInt} + a \times S_{MobInt} + a \times S_{Int} + c \times S_{Int} + a \times S_{Int} \quad (10)$$

10.1.3. Packet delivery cost

The packet delivery is measured after the completion of producer handoff process and the packets between consumer to producer moves through the new route of communication. Further, it includes the consumer Interest packet that's moves to producer and in response the data packet reaches to the consumer.

The packet delivery cost of IBM is presented in Eq. (11). After handoff process, the consumer sent Interest packet from C-CR, the C-CR sends the packet to Old-CR, the packet redirects to the producer router New-CR and it moves to producer with transmission hop cost per packet DC_{Con_Cr}, DC_{CR_Cr}, DC_{Old_NCr}, and DC_{Pro_Cr}. The producer forwards the data packet by following the reverse path towards the consumer with transmission hop cost per packet DC_{Pro_Cr}, DC_{Old_NCr}, DC_{Cr_Cr}, and DC_{Con_Cr}.

$$DC_{IBM} = DC_{Con_Cr} + DC_{Cr_Cr} + DC_{Old_NCr} + DC_{Pro_Cr} + DC_{Pro_Cr} + DC_{Old_NCr} + DC_{Cr_Cr} + DC_{Con_Cr}$$

$$DC_{IBM} = a \times S_{Int} + c \times S_{Int} + b \times S_{Int} + a \times S_{Int} + a \times S_{Data} + b \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (11)$$

The Eq. (12) shows the packet delivery cost of PMSS. After the producer handoff process, the consumer sends the Interest packet from C-CR, the C-CR sends the packet to New-CR, the New-CR forwards to producer that covers the transmission hop cost per packet DC_{Con_Cr}, DC_{Cr_Cr}, and DC_{Pro_Cr}. In response the producer forwards the data packet by following the reversal path to consumer with transmission hop cost per packet DC_{Pro_Cr}, DC_{Cr_Cr}, and DC_{Con_Cr}.

$$DC_{PMSS} = DC_{Con_Cr} + DC_{Cr_Cr} + DC_{Pro_Cr} + DC_{Pro_Cr} + DC_{Cr_Cr} + DC_{Con_Cr}$$

$$DC_{PMSS} = a \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (12)$$

The packet delivery cost of KITE is expressed in Eq. (13). The packet delivery cost is calculated after the completion of producer handoff process. After the handoff process, the consumer sends the Interest packet from the connected router C-CR, the C-CR sends the packet to immobile anchor router Anh-CR, the immobile anchor router redirects the packet to the producer connected router New-CR and further forwarded to producer with transmission hop cost per packet DC_{Con_Cr}, DC_{Anh_Cr}, DC_{Anh_Cr}, and DC_{Pro_Cr}. The producer forwards the data packet by following the reverse way towards the consumer with transmission hop cost per packet DC_{Pro_Cr}, DC_{Anh_Cr}, DC_{Anh_Cr}, and DC_{Con_Cr}.

$$DC_{KITE} = DC_{Con_Cr} + DC_{Anh_Cr} + DC_{Anh_Cr} + DC_{Pro_Cr} + DC_{Pro_Cr} + DC_{Anh_Cr} + DC_{Anh_Cr} + DC_{Con_Cr}$$

$$DC_{KITE} = a \times S_{Int} + c \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (13)$$

The Eq. (14) shows the packet delivery cost of PMMM. After the producer handoff process, the consumer sends Interest packet from C-CR, the C-CR sends the packet to New-CR, the New-CR forwards packet to producer that covers the transmission hop cost per packet DC_{Con_Cr}, DC_{Cr_Cr}, and DC_{Pro_Cr}. Thereafter, the producer responds with data packet by following the revers path to the consumer with transmission hop cost per packet DC_{Pro_Cr}, DC_{Cr_Cr}, and DC_{Con_Cr}.

$$DC_{PMMM} = DC_{Con_Cr} + DC_{Cr_Cr} + DC_{Pro_Cr} + DC_{Pro_Cr} + DC_{Cr_Cr} + DC_{Con_Cr}$$

$$DC_{PMMM} = a \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (14)$$

11. Performance evaluation

The performance evaluation refers to the assessing and measuring the effectiveness of network model in solving a specific concern. By referring to Fig. 16 shows the handoff latency impact with respect to wireless link failure probability variation.

The results show the PMMM has the lowest latency as compared to IBM, PMSS and KITE. While, the IBM and KITE has the highest latency caused by the signalling process. KITE uses two types of packets to setup the connectivity and IBM also uses two types of packets to manage connectivity. Additionally, both solutions use the immobile anchor as a centralize controller between consumer and producer that creates non-optimal path between consumer and producer communication. The PMSS uses a MI packet along with immobile anchor to manage and continue the network connectivity. Further, the PMSS solution creates the sub optimal path between consumer and producer that shows the lower in latency as compared to IBM and KITE. Whereas PMMM uses MUP to continue its network connectivity in short period of time and uses the optimal path without involving of any static node or centralize controller or immobile anchor node. Hence, the results reflects that the PMMM outperform in comparison of IBM, PMSS, and KITE.

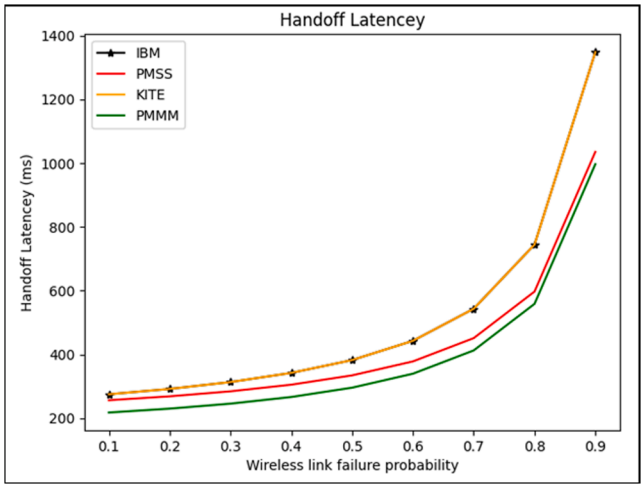


Fig. 16. Handoff latency variation with link failure probability.

By referring to Fig. 17, shows the correlation between the handoff signalling cost and subnet crossing rate among the IBM, PMSS, KITE, and PMMM. The IBM shows the higher level of signalling cost produced by the binding update and binding acknowledgement signalling messages. Additionally, the signalling messages increases the stretch ratio due higher hop count and triangular routing to setup the path. Similarly, the KITE uses the two packets and an immobile anchor to maintain the communication, but it shows the less in signalling cost as compared to KITE due to the strategical placement of the immobile anchor or less in path stretch ratio.

The PMSS shows the lowest signalling cost as compared to IBM and KITE due to use of one type of signalling packet and an immobile anchor to continue the interrupted communication. While the PMMM shows the

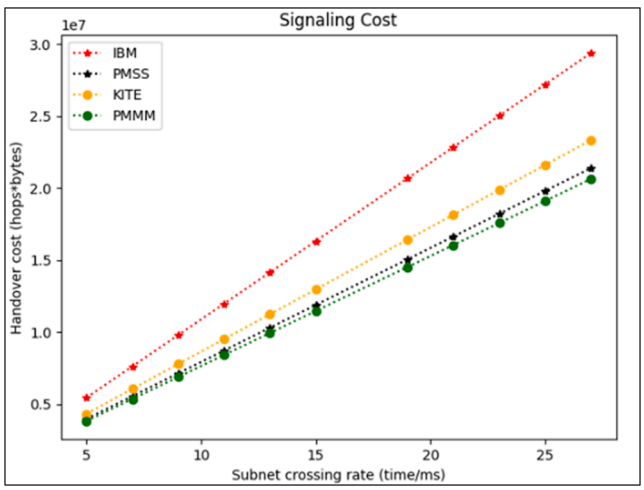


Fig. 17. Signalling cost variation with crossing rate.

lowest level of signalling cost among all the solutions which reflets the better performance of solution. The PMMM creates the optimal path without involving any immobile anchor or centralize controller that improves its signalling costs.

The Fig. 18 represents the data packet delivery cost of all solutions that includes IBM, PMSS, KITE, and PMMM. The results show the overall packet delivery of PMMM is lowest and the PMSS delivery ratio overlaps the PMMM trendline due to same delivery ratio. Both solutions optimise path for the Interest and data packet delivery while eliminating the reliance centralized or immobile anchor node. However, the IBM and KITE solutions exhibits a higher level of packet delivery cost caused by the additional hops such as immobile anchor. This immobile anchor introduces a path stretch ratio, which impacts the efficiency and cost-effectiveness of the delivery process. Therefore, the KITE and IBM solutions trendline overlaps caused by the similar delivery cost.

12. Future directions

This research proposes a mechanism to solve the associated problem in the producer mobility in NDN. The proposed solution, called PMMM (Producer Mobility Management Mechanism), offers the seamless mobility management and creates the optimal path between consumer and producer communication. Furthermore, it solves the challenges associated with the handoff, ensures the seamless transition of producer among the different network areas. However, for further research advancements and practical implementation of PMMM, there are numerous significant aspects to be mindful concerning:

12.1. Deploy cutting-edge technologies

The PMMM solution supports the producer mobility and improves the performance several metrics in the NDN. According to the future prospective, the PMMM solution has ability to improve the content dissemination in several cutting-edge technologies such as Internet of Things (IoT), Internet of Everything (IoE), and Internet of Medical Things (IoMT). Further, its efficient mobility management mechanism amins to ensures the seamless communication among the mobile devices using the different networks such as Mobile Ad hoc Network (MANET), Vehicular Ad hoc Network (VANET), and six-generation (6G) mobile networks.

12.2. Real-time implication

The performance of the producer mobility might significantly demonstrate the different evaluation results during the delay in the real-time content communication. While, in this research, the specific content is not provided such as the audio and video, it is crucial to acknowledge the significant influence content and high proportion of real-time content communication. Further, research is necessary to deal and comprehensively evaluate the impact of the real-time application, particularly in light of increasing demand of cutting-edge technologies such as IoT, IoMT, IoE, and wireless sensor network.

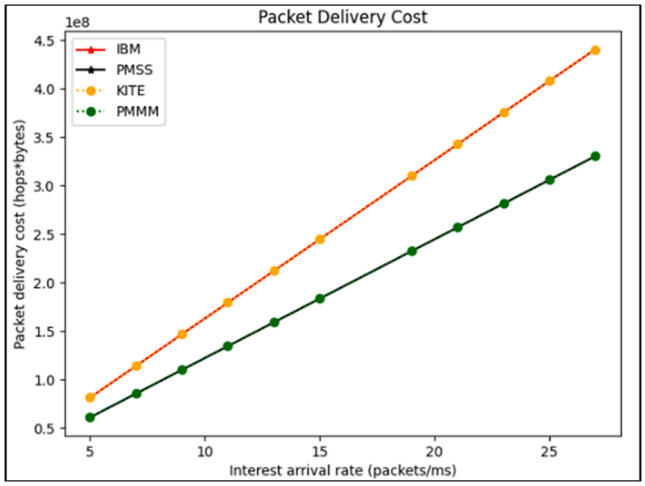


Fig. 18. Packet delivery cost with Interest arrival rate.

12.3. Consumer and producer mobility management

This research presents a solution aimed at addressing the several challenges in producer mobility, supported by existing lecture that demonstrates the lack of producer mobility management in NDN. However, the study recognised that consumer and producer experience distinct challenges that can be addressed together, resulting in a robust network communication system with improved in the several network performance metrics. Notably, any freely moving node without any constrains in the network can function as a consumer and producer. Consequently, proposing a solution that ensures the support for consumer and producer mobility is a worthy of investigation. By exploring this approach, this research aims to thrives in the development of comprehensive solutions that achieve the mobility requirements for consumer and producer. Additionally, it ultimately enhances the overall performance of the real-time NDN-based network communication.

12.4. Security and privacy aspects

This research focuses on the producer mobility management in NDN communication system, highlighting the paramount importance of ensuring the security and privacy of sensitive content during the handoff process. To address these security concerns, it is imperative to implement robust and effective cryptography mechanisms that can effectively safeguard confidential information from unauthorized access by mobile producers. By employing advanced cryptographic techniques, we can establish strong encryption protocols that protect sensitive content from interception or tampering (Cintas-Canto, Mozaffari-Kermani, Azarderakhsh, & Gaj, 2022; Kermani & Azarderakhsh, 2016; Sarker, Kermani, & Azarderakhsh, 2022). These mechanisms should encompass secure key exchange protocols, encryption algorithms, and authentication mechanisms to guarantee the confidentiality, integrity, and authenticity of the data being transmitted. Several studies offer the cryptographic mechanisms to ensure the security and privacy that should be consider in future for the reliability of NDN. By incorporating robust cryptographic mechanisms, NDN can effectively protect against various security threats, such as unauthorized access, data tampering, and eavesdropping.

12.5. Simulation and testbed evaluation

In this research, the PMMM performance evaluation is thoroughly examined via analytical modelling. Although a well-known NDN-based simulator is developed to handle the large-scale network experiments. Due to the several constraints such as limited time and high cost the PMMM is limited to the analytical modelling. The PMMM analytical modelling the significant improvements in NDN. Therefore, the PMMM significant improvements indicates the high potential to get benefits from the simulation and the real testbed implementation that can effectively gains the practical and tangible environment to evaluate the effectiveness of the mechanism.

13. Conclusion

In this paper, we comprehensively explain the effectiveness of NDN and thoroughly describe the operational mechanism of NDN data structure. Also, clearly elaborates communication mechanism of consumer mobility support and producer mobility support. Further, we

delve into previous research on producer mobility support in NDN and critically evaluate the challenges associated with producer mobility from multiple perspectives, including high handoff latency, excessive signalling, and packet delivery cost. In order to handle the mentioned challenges, we proposed the PMMM (Producer Mobility Management Model). The proposed PMMM is briefly explained that contributes to reduce the associated issues such as long handoff latency, signalling cost, and packet delivery cost. Additionally, the performance evaluation is carried out by employing network analysis modelling. The network analysis model is used to formulate the hop count handoff latency, signalling cost, and packet delivery of the IBM, PMSS, KITE and the proposed PMMM. The overall results of PMMM shows the better performance as compared to benchmarking solutions due to the optimal routing path. While, the existing solutions shows the higher handoff latency, signalling cost and higher delivery cost due to uses the static router as immobile anchor. Furthermore, we highlight several significant research directions that can greatly benefit from cooperation with the PMMM.

CRediT authorship contribution statement

Ahmad Abrar: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ahmad Suki Che Mohamed Arif:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Khuzairi Mohd Zaini:** Supervision, Formal analysis. **Mohd Hasbullah Omar:** . **Yahui Meng:** Resources, Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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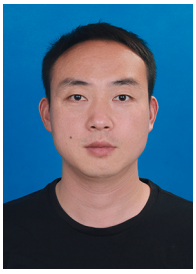
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