Comparative Analysis of Reactive and Proactive Mobility Management in Named Data Networking

Nurul Hidayah Ahmad Zukri, Ahmad Suki Che Mohamed Arif and Mohammed Alsamman

***Abstract*— Massive usage growth in mobile devices and content requires a new Internet architecture. Named Data Networking (NDN) is a prominent solution to this increasing trend of network device mobility by adopting a forwarding philosophy and a data-centric architecture. Thus, managing mobility, especially on the producer side, is of great interest for ensuring network performance and reliability. Despite many existing schemes, a clear understanding of the comparative efficacy of reactive versus proactive mobility management approaches remains elusive. Therefore, this paper aims to fill this gap by critically analyzing and contrasting these two approaches. Specifically, we first present the problem statement for mobile producers in NDN, then classify mechanisms of existing schemes into two approaches: reactive and proactive. Further to this discussion, a comparative analysis of these two approaches is highlighted. Additionally, the study evaluated the performance of both approaches concerning handoff latency and signalling cost using a network analysis model, which led to insightful recommendations based on the findings from the network analysis.**

***Index Terms*— Named Data Networking, producer mobility, proactive, reactive**

I. INTRODUCTION

In an era where Internet users are increasing exponentially through the invention and development of smart devices, the world has undergone significant transformation. Imagine a scenario where thousands of mobile sensors in an intelligent city continuously move and transmit data [1], [2]. In this context, the limitations of the traditional TCP/IP model, particularly in handling mobile data sources efficiently, are glaringly apparent. The Internet's foundation, built upon the Transmission Control Protocol/Internet Protocol (TCP/IP) model, has been the cornerstone of digital communication for decades. Initially designed for connecting a relatively small number of static computers, TCP/IP excelled in establishing robust, end-to-end connections. However, as the digital landscape evolved, several limitations of this model became increasingly apparent, particularly in terms of scalability-efficiency [3] and data-centric requirements [4]. Firstly, the exponential growth in the number of connected devices, especially with the advent of mobile technology and the Internet of Things (IoT), has strained the TCP/IP model. Its infrastructure, primarily designed for fixed endpoints, needs help managing the dynamic nature of mobile communications efficiently. Secondly, users are more concerned with accessing specific data or content rather than connecting to a specific server or IP address. Thus, the modern Internet user's needs have shifted from a connection-centric to a content-centric paradigm.

An emerging and innovative future Internet known as the Information-Centric Network (ICN) has successfully addressed these difficulties by introducing decentralized networks. ICN has replaced IP addressing with content addressing for network communication [5]. This novel idea is examined by Internet architectural research communities, thus introducing some new architectures, namely Data-Oriented Network Architectural (DONA)[6], Content-Centric Networks (CCN) or Named Data Networks (NDN) [7], Publish-Subscribe Internet Technology (PURSUIT) [8], and Network Information (NetInf) [9]. Among these architectures, NDN emerges as a promising solution to these challenges [10], [11] heralding a paradigm shift in how data is handled within a network:

1) Decentralized Approach: Unlike TCP/IP, which is based on a host-centric model by focusing on where the data is, NDN adopts a content-centric approach. This model focuses on what the data is, regardless of its location, which aligns more naturally with current Internet usage patterns.

2) Efficient Data Distribution: NDN uniquely names data instead of data containers (like IP addresses), facilitating more efficient data retrieval and distribution. This approach is particularly beneficial in environments where data sources are highly mobile and dynamic.

3) Network Resilience and Caching: NDN's in-network caching ability allows data to be stored temporarily at various nodes throughout the network. This feature enhances the network's resilience and efficiency, especially in mobile scenarios where network topologies frequently change.

Numerous noteworthy contributions have been made in NDN projects by integrating different elements, with mobility being recognized as the critical factor in achieving effective NDN management. The inclusion of mobility is crucial because the advantages of forwarding, routing, content retrieval, scalability, and caching in NDN can only

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be fully utilized with accommodating mobility [12], [13] especially considering the continuous proliferation of mobile devices [14]. In the context of NDN, mobility enables seamless location switching for mobile nodes across access points with minimal handoff and virtually no interruption due to content availability delays. However, the movement of the content provider is untraceable for the requester of the content. Inefficient management of the mobility specifically for the provider's movement will lead to depraved issues in the network, such as high overhead [15], high packet loss [16], and long handover latency [17]. Accordingly, many mobility deployment strategies have been proposed to attain an appropriate and efficient use of bandwidth by enhancing the proper delivery of information and minimization of handoff, as well as reducing the overall load from the content provider. However, all previous mechanisms still need to be classified into specific approaches based on their conditions and applications.

Thus, this paper delves into how NDN, a paradigm shift in network architecture, rises to these challenges, focusing on the critical aspect of content providers, well known as producer mobility. The primary objective of this paper is to provide a comparative analysis and categorization of producer mobility management schemes in NDN, focusing on two distinct approaches: reactive and proactive. Reactive schemes address mobility management in response to events such as handovers or location changes, whereas proactive schemes anticipate and prepare for such events in advance. By dissecting and comparing these methodologies, the paper aims to elucidate their respective strengths and weaknesses, offering insights into which scenarios each approach is best suited. This comparative analysis is crucial not only for theoretical understanding but also for the design and implementation of more efficient NDN systems. Ultimately, this study contributes to the field of NDN by enhancing understanding of producer mobility in NDN, a critical factor in the network's overall performance, and paving the way for future research and development in this domain.

The rest of the paper is arranged as follows. Section II presents brief information on NDN, including the categorization of mobility. Our goal is to sketch out the differences between both categories and how each category affects the design of the previous works. Thus, recent works based on the reactive approach and proactive approach are present in Sections III and IV, respectively. Followed by a comparative analysis of both approaches with the graphical statistics of the network performance analysis in Section V and Section VI. Lastly, Section VII concludes the paper.

II. NAMED DATA NETWORKING

Named Data Network (NDN) is an emerging novel future Internet that garnered significant attention within the ICN architectural research community. Building upon the foundations of CCN [18], [19] NDN's architectural design and protocol operations closely align with CCN. The NDN architecture maintains the hourglass structure, with modifications centered around the core that place a greater emphasis on content rather than IP, as illustrated in Fig. 1 [20]. The concentration of the content allows the deliverable of a packet by using a given name.

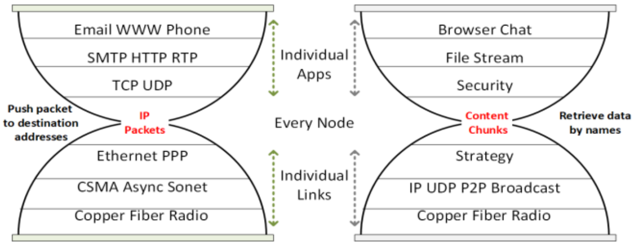


Fig. 1. IP and NDN hourglass architecture.

To meet this requirement, NDNs consist of three key components: the producer, consumer, and NDN router. The producer functions as a content provider, distributing content to consumers through an NDN router. Conversely, the consumer requests specific content from the producer. The NDN router plays a crucial role in facilitating communication between producers and consumers. NDN uses a stateful forwarding plane for the network communication between the producer and consumer [20] by exchanging interest packets and data packets. To fulfil its responsibilities, the NDN router utilizes three data structure tables [21]: Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB). The FIB contains information about publishers and interfaces. The PIT caches all pending interests that have not yet received corresponding data, while the CS serves as a temporary cache for received data packets.

As shown in Fig. 2, the forwarding process begins with the consumer sending an interest packet to retrieve content from the producer. When a router receives an interest packet, the router will check its CS table. If there is any copy of the data, the data will be transferred to the consumer. Otherwise, the router will check the PIT table. Any record of pending interest in the PIT table shows that the interest is already being forwarded to the next router. Thus, the router will only add an incoming interface and wait for the data. If there is no record in PIT, the router will check the FIB table to assess the outgoing interface information. A matched request with the provider information allows FIB to forward the request to the next router and create a new record in the PIT. Alternatively, the router will drop the request and send a Negative Acknowledgment (NACK) packet to the consumer.

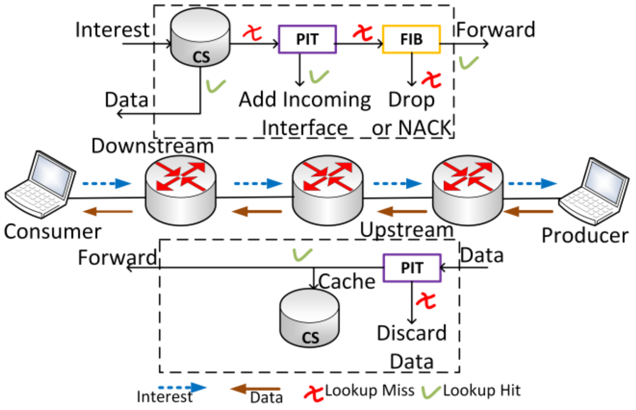


Fig. 2. Node Data forwarding process.

NDN architecture enables network mobility more effectively than the old IP-based model. However, NDN does not naturally solve the mobility problem caused by the producer's movement. With increasing mobile dependencies among the global population [22], solving the mobility problem is compulsory. Hence, this paper describes the mobility in NDN and categorized it into consumer mobility and producer mobility.

A. *Consumer Mobility*

Naturally, the forwarding plane strategy in NDN facilitates consumer mobility. The interest resubmission enables consumers to retrieve the content whenever they are travelling and connected to the new router. NDN uses the receiver-driven concept that defines network communication, which begins with the consumer requesting content. The NDN router that receives the interest will check the data structure tables one by one until the router meets one of these requirements: a) data is found, b) outgoing interface is available, or c) outgoing interface is undefined. On the other hand, the consumer is moving to another access router. After moving, the consumer may resubmit the interest to retrieve the specific data. Here, the communication process proceeded as normal communication.

Fig. 3 illustrates NDN communication for consumer mobility. After the consumer is moved from CR1 to CR4, the consumer may resubmit the interest to get the remaining data. With in-caching functionality, the remaining data is cached in the router CR2. Thus, the consumer can retrieve the data with minimal delay. To conclude, consumer mobility in NDN is supported by retransmitting the interest and the caching functionality [23].

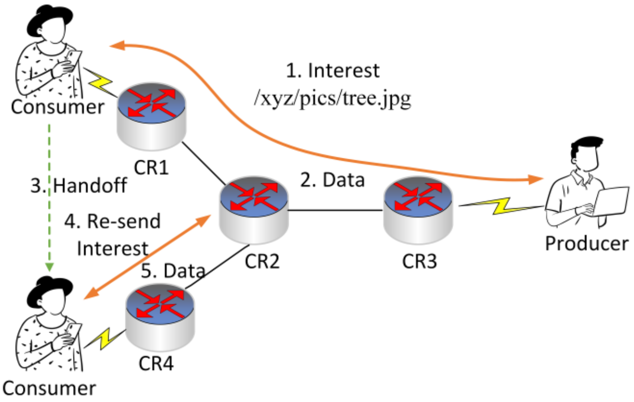


Fig. 3. The circumstances of consumer mobility in NDN.

B. *Producer Mobility*

In NDN architecture, the content name is decoupled from its location but not separated. This information is stored in the FIB table to determine the optimal path of the interest packet. Thus, the FIB must be kept updated for any producer's relocation. The producer mobility problem is triggered by an un-updated FIB that mislead interest submission to the old NDN access router, as shown in Fig. 4.

The consumer sends new interest to CR3. CR3 forwards the interest to CR2, then CR2 forwards the interest to CR1 based on the FIB table. However, the producer is currently attached to CR4, and this situation will cause the router to drop interest. In addition, a failure to update the new producer's location raises several issues, such as high overhead [15], high packet loss [16], and long handover latency [17]. Eventually, network communication services are suspended until the router receives information regarding the producer's new location. Due to these significant problems, researchers are introducing producer mobility schemes. Each scheme is proposed to solve specific challenges in a specific situation. After a thorough analysis, this research has identified that all proposed schemes can significantly reduce the producer mobility problem if the timing to act is fit to the situation. Hence, this study divides the proposed schemes into two groups: the proactive approach and the reactive approach. The categorization was made based on the producer's reaction toward the handoff activity. The following sections elaborate in detail on both approaches.

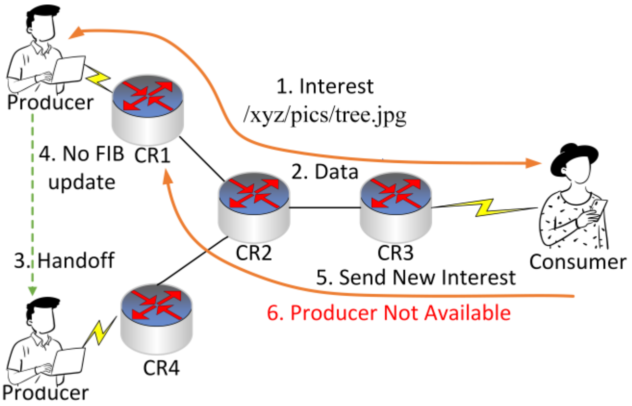


Fig. 4. The circumstances of producer mobility in NDN.

III. EXPLORING REACTIVE MOBILITY MANAGEMENT IN NDN

In the dynamic and ever-evolving world of NDN, the ability to swiftly adapt to changes, particularly in producer mobility, is critical. The reactive approach comes into play precisely in this situation. Defined as the approach that becomes effective only post-handover, the reactive approach springs into action, bridging the communication gap caused by the producer's mobility. It contrasts sharply with proactive strategies that prepare for mobility events in advance. Reactive strategies instead respond to mobility-related changes as they occur, which is particularly useful in scenarios where predicting producer movement is challenging or impractical.

In addition, a diverse range of schemes developed under the reactive approach umbrella is uniquely designed to address specific aspects of the challenges posed by producer mobility in NDN. For example, the MAP-Me scheme stands out as an innovative solution in anchor-less micro-mobility management [24]. However, it confronts potential high signalling costs due to its acknowledgement packet requirement. In contrast, T-Move steers towards cache replacement and proactive content-pushing, emphasizing content trendiness while potentially overlooking less popular content [25].

These examples illustrate the diversity and complexity of reactive strategies in managing producer mobility within NDN. As we explore each scheme's unique contributions and limitations, we unravel the nuanced trade-offs inherent in reactive mobility management. A detailed examination of these schemes, as summarized in the accompanying table, highlights their effectiveness across various network scenarios. This comprehensive overview not only underscores the operational effectiveness of these schemes but also highlights their strategic significance in maintaining seamless producer mobility in the fast-paced NDN environment.

TABLE I
SCHEMES UNDER THE REACTIVE APPROACH

Ref	Contributions	Weaknesses
Map-Me [24]	An anchor-less solution that is designed to access agnostic to manage micro-mobility producers	This mechanism could incur high signalling because each protocol packet sent requires an acknowledgement packet.
T-move [25]	A producer mobility solution that using cache replacement and proactive content-pushing based on trendiness.	Due to its cache replacement policy, this scheme is biased toward unpopular content.
HyNeMo [26]	A hybrid of anchor and anchor-less Producer mobility scheme.	A reactive approach will lead to longer handover latency as compared to the proactive approach.
Opmss [27]	A producer mobility solution that composed of mobility update, broadcasting and best route strategies.	This results in an interest drop because the consumer may forward the interest to the router, yet the FIB still needs to be updated.
Mobility Mechanism [28]	A producer mobility mechanism that informs the consumer and intermediate routers of its moving and current attached router.	Eliminate the triangular problem and reduce the interest drop and excessive bandwidth usage but incur handoff latency.
CBDMM [29]	A cluster-based device mobility management scheme is to locate the producer's current location.	Increases more signalling and handoff latency because of the binding process and updating process of cluster head nodes.
PMSS [30]	The producer mobility scheme that composed of a mobility interest packet, broadcasting strategy and immobile anchor.	The interest retransmission during the handoff process will increase packet drop and utilize more bandwidth.
SCaN-Mob [31]	A seamless mobility mechanism for an NDN wireless network environment by using an Interest forwarding strategy and a cache replacement policy.	Due to its cache replacement policy, this scheme is biased toward unpopular content.

Typically, reactive mobility management schemes in NDN involve strategies that activate when a producer switches from one router to another, ensuring continuous connectivity. Upon disconnecting from an old router, methods such as mobility notification, caching, use of a rendezvous server, or employing an immobile anchor are triggered to manage the transition. Once the handover to a new router is complete, these strategies then work to update the network about the producer's new location. Our analysis reveals that mobility notification is commonly employed to alert the network of the producer's change in status. To facilitate communication with the new location of the producer, schemes typically employ either a broadcasting strategy for systems without a fixed anchor or directly update a stationary anchor. This study focuses on two primary methods, mobility notification and broadcasting strategy, to demonstrate the effectiveness of the reactive approach in managing producer mobility, as illustrated in Fig. 5.

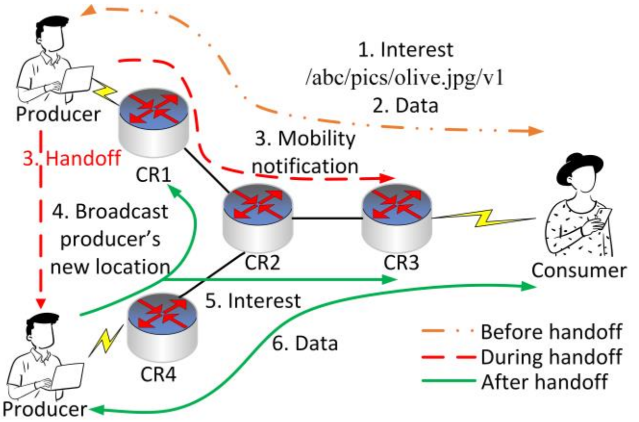


Fig. 5. The general communication of a reactive approach in NDN.

A study by Abrar et al., [28] designs the mobility management packets which comprise the Mobility Update Packet (MUP) and the Mobility Notification Packet (MNP) to manage producer mobility. MUP is employed to communicate the producer's mobility updates to the intermediate routers and the consumer. On the other hand, MNP is utilized post-handover to inform all routers about the producer's new location through the implementation of a broadcasting strategy. Theoretically, this mechanism would reduce the interest packet drop and triangular routing in producer mobility. However, the use of MNP after being connected with a new router will cause a high latency compared to the other schemes in the reactive approach.

Yan et al., [26] introduce a pioneering hybrid approach to managing producer mobility within NDN, skillfully blending the advantages of both anchor and anchor-less methodologies. This approach employs an anchor node to centralize information from mobile nodes while simultaneously dispersing some responsibilities across the network to avoid centralized load and potential failure points. In this context, the study explores the dynamics of Network Mobility (NEMO), which refers to situations where mobile routers, along with their network, change their connectivity points, such as in vehicular networks where a router moves with the vehicle. This concept is crucial in understanding the dynamics of the hybrid approach, as it deals with both intra-NEMO (movement within the same access router area) and inter-NEMO (movement to a new access router area) scenarios. Here, intra-NEMO refers to movements within the same access router's domain. At the same time, inter-NEMO involves transitioning to a new access router, a scenario that presents greater challenges and serves as the primary focus of this research. The study also introduces concepts like Mobile Network Node (MNN) and Home Agent (HA) to illustrate the network's architecture under this hybrid approach. Notably, the proposal includes a Bind Information Table (BIT) that acts as a preliminary FIB, streamlining the packet forwarding process. While this approach effectively reduces table lookup times and limits unnecessary network access, it acknowledges the inherent challenge of a reactive approach: potentially longer handover latencies compared to proactive methods. Such insightful analysis of the hybrid model underlines its potential in enhancing NDN's adaptability to producer mobility, albeit with careful consideration of its trade-offs.

The Producer Mobility Support Scheme (PMSS) is designed to address the mobility issues of producers in NDN by implementing a dual-strategy mechanism [30]. PMSS employs Mobility Interest (MI) packets, which are disseminated throughout the network to announce the producer's mobility status and introduce an immobile anchor for more stable connectivity. This approach ensures that once a producer relocates, its MI packets are received by the immobile anchor, which then broadcasts these packets to update the FIB in intermediate routers. Numerical analysis demonstrates that PMSS effectively reduces handoff latency compared to traditional DNS-like and home agent routing methods. However, PMSS faces challenges during handover, such as the risk of interest packet dropping when the producer becomes unavailable on its old route. Additionally, the necessity for consumers to retransmit interest packets for content retrieval due to unawareness of the producer's mobility can lead to decreased network efficiency and increased bandwidth consumption. A notable concern with PMSS is the high signalling costs associated with broadcasting MI packets network wide.

Hussaini et al., [27] design and implement the mobility update, broadcasting, best route strategies, and Restricted Domain Router (RDR) configuration to address the challenges associated with producer mobility. Each of these methods has distinct purposes and carries out specific functions. As an example, the MI packet updates the producer's new information, while the broadcast method is used to update the FIB of intermediate routers. Then, a best-route strategy works to guarantee data path optimization. So, the pending interest is directly forwarded to the producer's new spot.

Furthermore, the inclusion of an RDR within each domain effectively addresses the issue of broadcasting storms that may arise during intra-domain and inter-domain mobility scenarios. Upon receiving the MI packet, the RDR examines the previous and current prefix data. If the prefix hierarchy includes a neighboring domain, the RDR will rebroadcast the MI packet to that neighboring domain. This mechanism helps mitigate the broadcasting storm concern within and between domains, which ultimately reduces packet losses and average delays. Nonetheless, the MI packet is broadcast to all nodes but never reaches the consumer, which affects the consumer sending pending interest. The router may receive pending interest, yet FIB still needs to be updated. Consequently, the router may send interest to the wrong face.

Following a caching approach, the T-Move scheme proposes the producer mobility solution for NDN with edge caching [25]. The trendiness of a data object is a distinct metric that T-Move utilizes to measure the popularity of related content. T-Move uses proactive content-pushing and cache replacement tactics to improve network performance and Quality of Service (QoS). Both strategies are based on the trendiness of the content, which is determined by prefix matching and trend popularity. In T-Move, each router maintains a trendiness table using a GETT (GET trendiness) message. When a producer undergoes a movement, a GETT message containing the names of the data objects is broadcasted to retrieve the trendiness value. Only the highest trendiness copy for a particular data object is cached at the edge router. Additionally, FIB update messages are sent along the path to notify routers of necessary changes in the FIB. These changes may involve removing or adding FIB entries. By eliminating redundant update messages at attached routers, the scheme effectively reduces the number of FIB updates and optimizes the forwarding of interests to the caching router or producer.

Besides T-Move, Shared Caching in Named Data Networking Mobile (SCaN-Mob) [31] proposes the caching approach on the network edges. The concept of ScaN-Mob is to have a data depot manager manage the local caches from the network devices. The data depot manager could be any central device such as an AP, Base Station, and Road Side Unit (RSU). The data depot manager broadcasts an interest message to all remaining nodes within its domain. Upon receiving the data, the data depot manager assesses whether to store the data or choose an edge node for further processing. In the strategy layer, ScaN-Mob proposes two strategies: (a) the establishment of data priority and (b) the selection of nodes for caching. Data priority for caching is determined by the level of the Received Signal Strength Indicator (RSSI). As RSSI between the data depot manager and a producer decreases, the data is assigned as the higher priority. After determining data priority, this scheme uses round-robin scheduling to locate neighbors in the NIT, which is further used for caching content.

MAP-Me is an anchor-less solution consisting of an update protocol and a notification/discovery protocol to manage the mobility of the producer [24]. The producer transmits an exceptional interest packet known as an Interest Update (IU) to inform the network about its departure status, which includes the producer's prior locations. Each router along the path recognizes the IU for mobility update along with that update the FIB. The producer's frequent movement hampered the propagation of the concurrent FIB updates. As an improvement to Map-Me, Map-Me-IU is developed to maintain a sequence number at the producer's end to prevent inconsistencies. Whenever a handover occurs, the sequence number in the IU packet increases. Only the IU packet with the higher sequence number is updated in the FIB, while propagation is halted for lower sequence numbers. Additionally, a new IU packet with an updated sequence number is transmitted back along the path. There are two enhancements to MAP-Me-IU, which are the Interest Notification (IN) mechanism and a scoped Producer Discovery (PD) mechanism. IN is a breadcrumb left by the producers at every confronted PoA. The mechanism process is the same as IU in terms of the determination of sequence number, FIB lookup, and update process. However, the trace left by IN stays at the first hop router for discovery purposes. In conclusion, this scheme offers a rapid and efficient handover process but results in increased signalling overhead because each IU and IN packet sent requires an acknowledgement packet.

The Cluster-Based Device Mobility Management (CB-DMM) scheme is designed for scenarios where a cluster of NDN routers is present. In this scheme, the cluster heads are selected to identify the location of a producer that has moved to a different access router [32]. A cluster head contains the information of all connected nodes since cluster heads receive information regarding the producer's updated location directly from the producer. In return, the cluster head sends the binding acknowledgement to the producer. Since cluster heads connect, the information of the connected nodes is regularly exchanged and updated. A cluster head updates the routes and redirects the unresolved interest to the node that contains data. The redirection of interest to the producer is quicker, and the interest packet satisfied ratio is also good in CB-DMM. However, the binding update and binding acknowledgement will increase the signalling in the network. In addition, the reactive approach and process of updating cluster head nodes will increase the handoff latency.

IV. DELVING INTO PROACTIVE MOBILITY MANAGEMENT IN NDN

In NDN, proactive mobility management plays a pivotal role in ensuring seamless network functionality, particularly in the context of producer mobility. Unlike the reactive approach that responds to changes post-event, proactive strategies anticipate and prepare for mobility events well in advance. This foresight is essential in scenarios where producer movements can be predicted or are regular, allowing for a more efficient network response.

Proactive approaches offer a strategic advantage by mitigating potential issues before they arise, thus maintaining continuous and efficient network operation. This section explores various proactive schemes in NDN, each uniquely designed to pre-emptively address the challenges of producer mobility. From schemes that optimize routing paths in anticipation of producer movement to strategies that update network information in advance, these proactive methods demonstrate a commitment to network robustness and reliability.

TABLE II uncovers the innovative techniques employed to enhance network performance and the trade-offs they present. The forthcoming analysis and accompanying table will offer a comprehensive view of these proactive strategies, highlighting their contributions to improving network efficiency and the complexities they navigate in the proactive management of producer mobility in NDN, providing a curated overview of key research contributions from 2018 to 2023. This table succinctly captures the essence of various proactive approaches, outlining their primary contributions and identifying their potential weaknesses. By examining these schemes, we gain insights into the innovative methods employed to pre-empt mobility challenges, from real-time multimedia handling to advanced location prediction techniques. However, it is crucial to note the limitations of each approach, such as increased signalling or constraints in dynamic environments, which are pivotal in understanding the trade-offs involved in proactive mobility management. This comparative analysis aids in comprehending the evolving landscape of proactive strategies in NDN, highlighting their applicability and the complexities they navigate.

Our analysis categorizes the proactive approach into four distinct phases: pre-handoff, handoff initiation, during handoff, and post-handoff, as depicted in Fig. 6. This approach uses three key methods: mobility notification, prediction of the next location, and cached interest management. When a producer is expected to exit the wireless range, a mobility notification is sent to its current router (CR1). Unlike reactive approaches that respond to mobility events after they occur, this proactive strategy anticipates the producer’s movement. As a result, any interest intended for the producer, once disconnected from CR1, is rerouted to a router predicted to be the next connection point. This router caches the interests in anticipation of the producer's arrival, contrasting with reactive strategies, which would handle such interests only after detecting the producer's new location. Upon the producer's connection to the new router, cached interests are retrieved, demonstrating a strategic foresight absent in reactive methods.

TABLE II
SCHEMES UNDER THE PROACTIVE APPROACH

Ref	Contributions	Weaknesses
Pro-Pull and Pro-Cache [32]	A producer mobility scheme for real time multimedia in NDN by using two methods which are Pro-Pull and Pro-Cache	The special packets sent before and after handover will cause high signalling.
Location prediction-based scheme [33]	An anchorless mobility management with producer’s future location prediction	This scheme cannot be applied in a real scenario where there is the possibility of having dynamic path losses.
PMLS [34]	A dual connectivity services to both hide the link breakage to the NDN system and support producer mobility.	The buffer interest may store longer than it should be which could lead to an unacceptable delay that affects the performance of especially the stringent time application.
DLPNDN [35]	The producer mobility scheme applies Double-Lead content search algorithm and a location prediction algorithm.	The use of proxy between the consumer and producer path will lead to triangular routing.
HIM [36]	The hybrid indirection method that combines the indirection server and in-caching method	The indirection server causes single link failure and bottleneck issues
OGF [37]	The implementation of rendezvous server and geographic forwarding to choose next AP	The rendezvous server causes single link failure and bottleneck issues

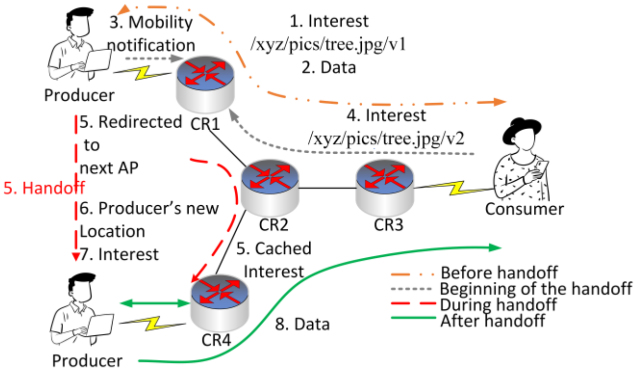


Fig. 6. The general communication of a proactive approach in NDN.

A. *Prediction of Producer’s Future Location*

This section delves into the proactive approach for predicting a producer's future location in NDN. This method proactively monitors the connection between the producer and the router, using the RSSI level as a key metric. When the RSS level falls below a specified threshold, signalling the producer's potential exit from the wireless range, the scheme is activated to calculate the producer's future coordinates. Various predictive techniques are employed, such as Euclidean distance calculations, neural network models, and location analysis, each offering a unique approach to forecasting the producer's following location.

In their study, Ali & Lim [34] apply the Euclidean distance formula to predict the producer's future location in NDN relative to an access point. This prediction is triggered when the RSS level drops below -77 dBm, indicating potential producer mobility. The old Access Point (oAP) then receives an interest message from the producer, including its anticipated future location. The oAP manages interest packets, redirecting them to the new Access Point (nAP) when the producer becomes unreachable. While this method shows low latency and round-trip times, its practical application faces challenges, especially in environments with dynamic path losses, as it relies on a simplified free-space propagation model. Furthermore, inaccuracies in nAP's location prediction can lead to interest packet drops, underscoring a potential limitation of this approach.

Conversely, the author of Rui et al., [36] forecast the producer’s future location by using a neural network model. Every 10 seconds, the Previous-NDN Access Router (P-NAR) checks the producer's connection and collects the information to forecast. When the producer leaves P-NAR, a pre-modified packet is transmitted to the consumer. Pre-modified packets include the location, flag, locator, nonce, and prefix name of the content that the producer gave. Consumer lookups for prefixes, updates the arrival port number and updates the port number of the expected router in the FIB. Then, the pre-modified packet is sent to the predicted router. If the New NDN Access Router (N-NAR) is the predicted location, the scheme directly modifies the FIB in all intermediate routers by using a confirmation packet. Otherwise, this research uses the Double Lead search scheme to search the path and send a cancel packet to the consumer. The Double Lead content search scheme merges the consumer's active search for the producer with the producer's passive notification to the consumer. The search algorithm relies on the distance between neighboring domain and producer. Upon the producer moving within the proximity range of the neighboring domain, the consumer searches for the producer through neighboring nodes. However, if producer is beyond the domain range, the producer employs a proxy to inform the consumer about the new location and path. In cases where the route between the consumer and producer passes through the proxy, triangular routing occurs. It is important to note that this scheme introduces additional packets, leading to increased network overheads.

With constrained overhead, Rui et al. [33] seek to decrease handover delays and enhance customer experience when using multimedia applications. Rui et al. [36] categorize the strategies based on cache state scenarios. The first scenario assumes the subsequent content already exists inside the producer. A solution called ProCache is proposed. ProCache is a proactive cache where an old router caches content in advance. So, interest received at the previous router during the handover time can retrieve content directly. On the other hand, ProPull is applied to retrieve subsequent content in real-time scenarios. The producer gets the router name from the old router before a handover so that the producer can pull interests when it connects with the new router. This scheme applies the location analyst to assess the future producer's location. In comparison to the original NDN and previous solutions, the numerical analysis of this scheme has better results in handover overhead and delay. However, the use of special packets before and after handoff produces high signalling.

In the On-Demand Geographic Forwarding (OGF) mechanism [38], the interest packet is redirected to the producer's following access location via a fixed rendezvous server. To obtain the location information of the access point, each AP and forwarder is associated with a Cartesian coordinate system. The producer chooses the next AP based on the strongest RSS among the available APs. After the producer detects the current RSS is lower than the threshold, a Notification Interest (NI) packet is sent to the Rendezvous Point (RV) containing the coordinate of the following AP. Upon receiving NI, intermediate forwarders and RV update the FIB table. New interest will be forwarded to the producer directly only after the RV updates its FIB. On the other hand, the second scenario uses a slightly different approach whereby the interest is forwarded to the RV by using native NDN forwarding. Consequently, it is possible to reach the producer facing path halfway or at the RV. Through this mechanism, the percentage of packet loss, handoff latency, and signalling overhead is reduced. However, future work should investigate the addition of distributed RV for scalability.

B. Buffer Interest

In the proactive field of NDN, buffer interest schemes play a crucial role in mitigating packet drop issues, particularly during producer mobility. By temporarily storing interests when a producer is unreachable, these schemes ensure continuity in data exchange, effectively bridging gaps in network connectivity. This approach is precious in maintaining seamless transactions in NDN, where even brief disruptions can lead to significant data losses. The study [35] introduces an innovative link-layer detection method specifically designed to recognize a producer's movement in NDN efficiently. This approach facilitates the completion of data transactions, even in the face of disrupted links. It pivots from the traditional perspective of link breakdowns, focusing instead on ensuring uninterrupted data exchanges during mobility-induced disruptions. The concept revolves around a novel NDN link service, namely the Producer Mobility Link Service (PMLS), which adeptly masks link breakages within the NDN system and buffers incoming interests during these transition phases. PMLS adeptly addresses the challenge of broken links by hiding these disruptions from the broader NDN system and buffering interests that arrive during such transitional phases. It ensures that once connectivity is re-established, these buffered interests are promptly forwarded to the producer. Furthermore, PMLS maintains the validity of existing routing information until the network's routing tables are updated with new data about the producer's location. However, a critical consideration in this scheme is the determination of the router's buffer size; if not optimized, it may lead to prolonged storage of interests, potentially causing unacceptable delays and impacting time-sensitive applications.

C. Proactive Caching

Proactive caching stands as a cornerstone in the proactive management of NDN providing a preemptive solution to the challenges of producer mobility. By strategically placing data in anticipation of consumer requests, proactive caching enhances the network's responsiveness and data availability, ensuring that the dynamic nature of producer movement does not impede content retrieval.

In the sphere of proactive caching within NDN, the Hybrid Indirection Method (HIM) [37] introduces in-network caching servers (SR) as a novel element to facilitate the indirection method. HIM proactively engages with handoff triggers to assess the readiness of the producer for mobility, enabling the caching of data packets in advance. This preparedness ensures that content is readily available at strategic network points, reducing latency and enhancing user experience. Once the producer is ready, the producer generates the data package containing the content in advance. During convergence time, the interest request is replied to with the data cached in SR. When the producer moves to a new router, the producer sends an indirect object to update the SR. This object is used as a third party between the consumer and the producer. After handoff and being updated with the producer's new location, the interest package is forwarded to the current producer's location. By combining both the indirection method and the in-network caching elements, HIM offers a balance of responsiveness and efficiency. However, as with any indirection method, the problem always relates to the single point of failure and bottleneck issues.

D. Comparative Analysis of Detection Methods and Post-Action Strategies

The above discussion underscores the diverse strategies employed in proactive caching. We have consolidated these approaches in TABLE III, which provides a comparative analysis of detection methods and post-action strategies. This comparative overview not only highlights the varied detection strategies from RSS-based signals to link-layer indications but also delineates their associated post-detection actions, offering a clear view of how each scheme contributes to the overarching goal of efficient producer mobility. There are three primary methods for detecting a producer's impending departure from the network. The first method utilizes RSS signals, flagging when the producer's signal drops below a critical threshold. The second method involves link-layer indications, which trigger a handoff protocol based on direct signals from the producer. The third detection strategy hinges on explicit handoff triggers communicated by the producer. Upon detection, these methods prompt the network to proactively engage in predictive location tracking and begin either buffering interest packets or caching content, ensuring that network communication remains resilient and uninterrupted despite the mobility of the producer.

TABLE III
COMPARISON OF PRODUCER'S MOBILITY DETECTION METHOD

Ref	Detection method	Post-action after detection	
OGF [37]	RSS	Predict Producer's Future Location by using:	Euclidean Distance
Location prediction-based scheme [33]			
DLPNDN [35]			Neural Network Model
Pro-Pull & Pro-Cache [32]			Location Analyst
PMLS [34]	Link-layer indication	Buffer Interest	
HIM [36]	Trigger handoff	Pro-caching	

V. ANALYSIS AND COMPARATIVE INSIGHTS: REACTIVE VERSUS PROACTIVE APPROACHES

This section embarks on a critical synthesis of the literature surrounding producer mobility in NDN, offering a distilled analysis of the intersecting paradigms of reactive and proactive mobility management. The ensuing discussion navigates the varied landscape of proposed solutions, contextualizing each within its operational framework and anticipated network impact. We dissect these methodologies against real-world constraints, including network topology, application demands, and statistical research conducted, to extract a nuanced understanding of their trade-offs and situational aptitude.

In our literature review, we discern that researchers' methodologies are intricately aligned with their specific study objectives. It becomes imperative, therefore, to contextualize these evaluations within the unique frameworks of each network's topology, the operational applications, and the mobility configurations of nodes [15]. The literature reveals a spectrum of assessment criteria, underscoring that certain strategies may enhance specific performance metrics, albeit at the cost of others, as in TABLE IV.

TABLE IV
COMPARISON OF THE PROACTIVE APPROACH AND REACTIVE APPROACH

Approach	Application	Merits	Demerits
Reactive	Traditional application	Support the applications that doesn't require an immediate response	High handoff latency and high interest packet drop
Proactive	Real-Time application including in an emerging network technology (IoT, vehicle NDN, wireless sensor network)	Support delay tolerant and delay sensitive traffic, low handoff latency and low interest packet drop	High computational processing

A. Application Type

In realm of real-time applications such as streaming multimedia, online gaming, and teleconferencing, where minimal delay is paramount, the choice of mobility management strategy becomes critical [39]. Consistent network connectivity is critical for gaining the benefits of real-time communication. However, such as IoT applications, maintaining internet connectivity to IoT sensors during mobility is difficult [40]. Therefore, the proactive approach, characterized by its ability to diminish content transfer delays during producer location shifts, emerges as more effective in such scenarios.

In contrast, the reactive approach is more suitable for applications where immediacy is not a prerequisite, such as batch-based data processing. This approach aligns with NDN's in-caching capabilities, which offer distinct benefits for content that requires less frequent updating, making it a viable strategy in specific network environments.

B. Performance Metrics

The proactive approach is distinguished by its capacity to reduce handoff latency when the producer's location changes. However, this advantage is often counterbalanced by the need for elevated computational processing at routers, driven by the necessity of predictive mechanisms for anticipating the producer's future location. In addition, the false prediction could lead to unnecessary signalling costs.

In contrast, the reactive approach leads to higher instances of interest packet drops and extended handover latency. This is because the mechanism is activated after a handoff occurs. This approach is particularly suitable for non-real-time applications, which can leverage the caching capabilities of NDN to store content over time. As a result, this method employs simpler processing to help reduce the impact of handoffs.

C. Yearly Trends in Producer Mobility Research

TABLE V and Fig. 7 show the analysis of producer mobility management approaches from 2018 to 2023. The percentage of research conducted is calculated based on the number of papers produced for that particular year.

TABLE V
YEARLY RESEARCH CONDUCTED ON PRODUCER MOBILITY MANAGEMENT APPROACHES

Year	Number of research Proactive	Reactive	Total number of research
2018	3	1	4
2019	2	1	3
2020	1	1	2
2021	1	0	1
2022	1	0	1
2023	0	3	3

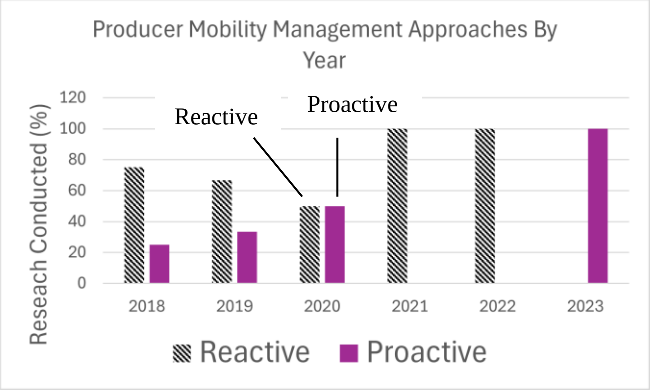


Fig. 7. Yearly research conducted (%) on producer mobility management approaches

From 2018 to 2022, the total research that implemented the reactive approach was higher than the proactive approach since many researchers focused on how to make NDN a promising future Internet by solving the inherent problems of IP. However, the chart also shows that the research on reactive approach is declining year by year. As of last year, the year of 2023, all research has implemented a proactive approach. Currently, researchers are witnessing the emergence of network technologies, such as IoT and Vehicle Named Data Network (VNDN), which alarmingly calls for proactive measures to avoid uninterrupted services. The proactive approach that predicts mobility is a suitable method to provide the data in advance by proactive caching or redirecting the interest to the future location of the producer.

VI. PERFORMANCE ANALYSIS OF REACTIVE AND PROACTIVE APPROACHES

This section delivers a thorough evaluation of network performance for a comparative analysis between proactive and reactive approaches in NDN. This analysis employs a detailed network model to measure handoff latency and signalling cost due to the adverse effects towards interest bandwidth consumption and packet submission. This analysis not only highlights the strengths and weaknesses of proactive and reactive strategies but also provides insights into their applicability in different network scenarios. As shown in Fig. 8, a network model has been designed to measure the handoff latency, which is the overall time taken for a producer to disconnect, reconnect, and wait until the interest packet comes to the new locations of the producer. While signalling cost refers to the total number of messages transmitted across the network during the handoff process. For this analysis, the hop count is determined and denoted as follows: the hop count between a router and the other two nodes, which are a consumer and a producer, is *a*, and the hop count between three routers is *b*, *c*, and *d*.

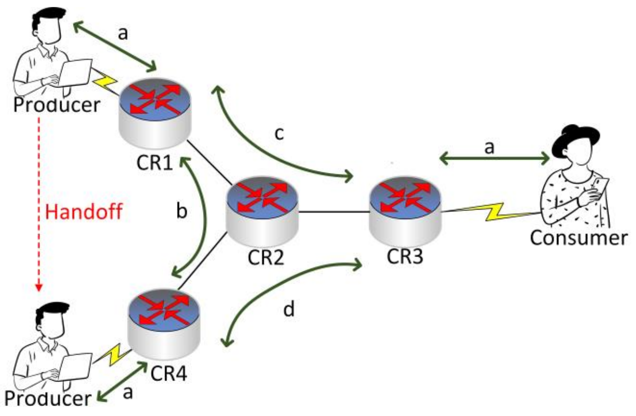


Fig. 8. Network analysis model.

The parameters used for analytical investigation are defined in TABLE VI. S_{name} is used as the abbreviation of variety of packets which are the mobility update packet and the mobility packet. 16 bytes are added for any packets with the additional field. Therefore, $S_{mup} = S_{m} =$ 56 bytes.

With that, the hop delay between wired and wireless link is [41], [42] formulated as in the (1) and (2):

$$L_{w\_name} = \frac{S_{name}}{(B_w + L_w + Q_d)} \tag{1}$$

$$L_{ws\_name} = \frac{(1+q)}{(1-q)} * \frac{S_{name}}{(B_{ws} + L_{ws})} \tag{2}$$

TABLE VI
NETWORK PARAMETER ANALYSIS

Category	Notation	Description	Value
Size of Packet (S)	S_{name}	Name of packet	+16 byte
	S_{int}	Interest packet	40 bytes
Latency (L)	L_w	Wired	2 ms
	L_{ws}	Wireless	10 ms
	L_{hf}	Handoff	50 ms
Bandwidth (B)	B_w	Wired	100 ms
	B_{ws}	Wireless	11 ms
Queue (Q)	Q_d	Delay	5 ms
Hop Count	a	Router – Consumer/Producer	1
	b	Router – Router	5
	c	Router – Router	5
	d	Router – Router	5

In reactive approach, after L_{hf}, the producer broadcast S_{mup} to all attached routers. Upon receiving the packet, routers are updating their FIB table, thus enable the consumer to send interest packet from CR3 to CR4 directly to the producer's new location. Handoff latency equation $(HL_{reactive})$ as in (3) and signalling cost $(SC_{reactive})$ is presented in (4)

$$HL_{reactive} = L_{hf} + a * L_{ws\_mup} + b * L_{w\_mup} + d * L_{w\_mup} + a * L_{ws\_int} + d * L_{w\_int} + a * L_{ws\_int} \quad (3)$$

$$SC_{reactive} = S_{mup} * (a + b + d) + S_{int} * (a + d + a) \quad (4)$$

In proactive approach, once the producer is connected to the new router, the producer sends S_m to the new router. In return, the new router will send the interest that has been cached to the producer. The handoff latency in the proactive $(HL_{proactive})$ is illustrated in (5) signalling cost $(SC_{proative})$ is presented in (6)

$$HL_{proactive} = L_{hf} + a * L_{ws\_m} + a * L_{ws\_int} \quad (5)$$

$$SC_{proactive} = S_m * a + S_{int} * a \quad (6)$$

In this study, the handoff latency is analyzed by varying link failure probability, hop count between the old router and the new router (b), and hop count between the new router and the router that connected to the consumer (d). Fig. 9 shows the handoff latency proportional to wireless link failure probability. When wireless link failure probability increases, the wireless network's stability decreases, and every scheme's latency shows a sign of rise. The result shows that the reactive approach has a high latency compared to the proactive approach. The reactive approach uses the broadcasting strategy to inform about its current location, which takes more time to reach the exact destination of the producer. Upon receiving the mobility update packet from the producer, the routers along the path updated their FIB. Subsequently, the interest packet was forwarded to the producer's new location. In proactive approaches, a wireless link failure has a lower impact on handoff latency because cached content and related packets are sent during the convergence time. Therefore, proactive approaches provide better and more stable handoff latency in the case of an unstable network link.

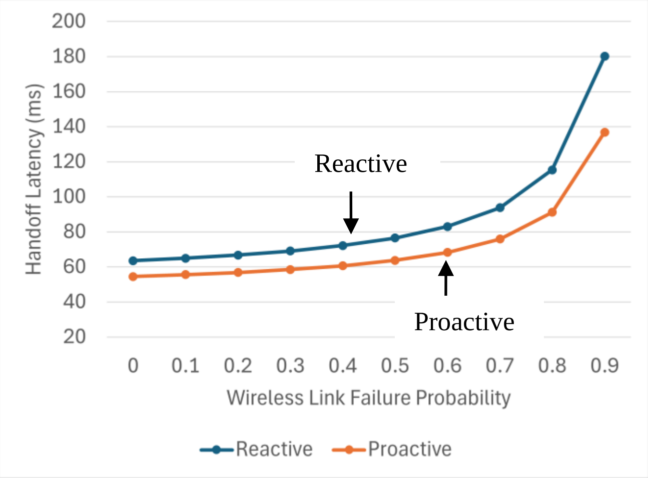
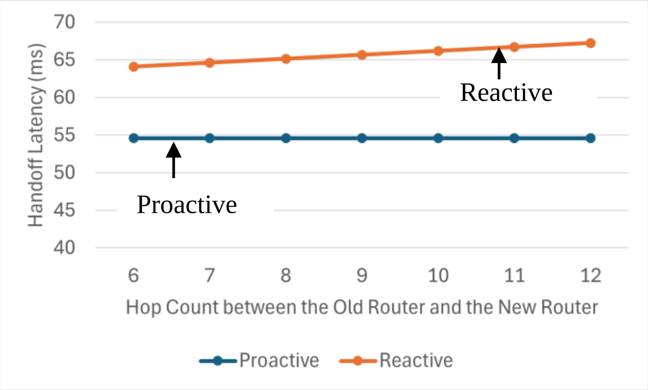


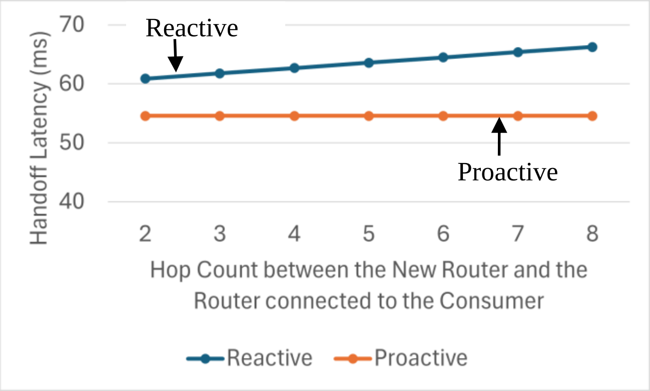
Fig. 9. Impact of link failure probability on handoff latency

The numerical result on handoff latency and signalling cost based on hop count indicates the correlations between them as shown in Fig.10 and Fig.11. When the latency experienced during handoff processes is elevated, the associated signalling costs are also likely to be higher due to the increased number of messages that need to be transmitted across the network during these transitions. In Fig.10, the handoff latency of the reactive approach slightly increases as the value of b and d gets larger, while the handoff latency of the proactive approach remains static. A similar trend is observed in Fig.11, with signalling cost rising as b and d increases. The results indicate that the proactive approach yields more favorable outcomes regarding handoff latency and signalling cost compared to the reactive approach under both conditions.

As illustrated in the general architecture of the proactive approach, the scheme predicts the producer's location to redirect the interest packet to the router before handoff latency occurs. Consequently, the producer can retrieve the interest immediately from the currently attached router. Thus, regardless of the increase in hop count, interest packets are cached at the predicted router before the arrival of the producer.

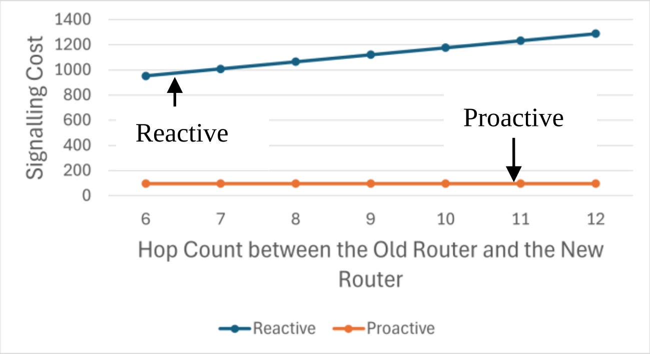


Impact of b on handoff latency.

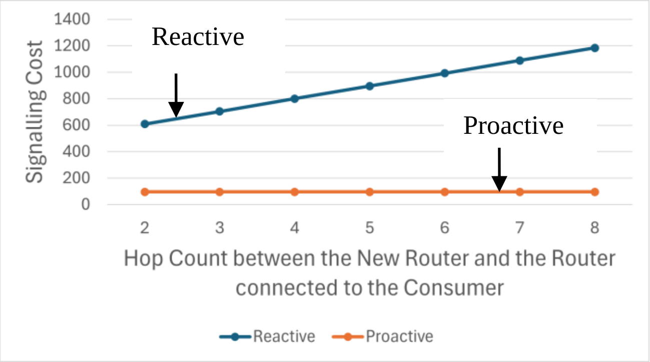


Impact of *d* on handoff latency.

Fig. 10. Impact of hop count on handoff latency.



Impact of *b* on signalling cost.



Impact of *d* on signalling cost.

Fig. 11. Impact of hop count on signalling cost.

Despite the demonstrated advantages of proactive approaches in achieving improved handoff latency and less signalling cost, reactive approaches remain valuable in various applications and environments. Therefore, careful consideration should be justified when proposing a new mechanism for producer mobility. Additionally, the implications of mobility challenges should be factored into future research efforts aimed at enhancing NDN before its commercial deployment.

VII. CONCLUSION

This study delves into the mobility support mechanisms within the NDN architecture, starting from a foundational understanding of NDN and progressing to a detailed examination of reactive and proactive mobility management approaches. By categorizing and critically analyzing these strategies, we uncover the rationale behind existing solutions and their contributions to addressing producer mobility challenges.

The research landscape on producer mobility within NDN is extensive, presenting several unresolved issues and challenges. Despite these hurdles, the academic and research communities are actively seeking innovative solutions to mitigate the effects of producer mobility. Our analysis aims to serve as a valuable resource for future researchers venturing into this field, offering insights into which strategies may offer superior performance. In our future work, we will investigate further in a simulation environment to assess the handoff performance, packet loss, and signalling cost in comparison to established schemes. By managing producer mobility in NDN, offering the potential for substantial advancements and enhancements in network performance amidst the mobility challenges

REFERENCES

[1] I. A. Aboagye *et al.*, “Public Wi-Fi Set-Up to Complement Existing Campus Internet Access Provided by the University of Ghana,” in *Proceedings of the International MultiConference of Engineers and Computer Scientists 2023 IMECS 2023*, Hong Kong, Jul. 2023.

[2] N. Nkorder, A. Ayoola, O. Bankole, O. Oludotun, E. Nwabueze, and O. P. Chidi, “Green Computing: Towards Sustainable 5G Network Deployment,” in *Proceedings of the World Congress on Engineering and Computer Science 2019 WCECS 2019*, N. Nkordeh, A. Ayoola, O. Bankole, O. Oludotun, E. Nwabueze, and O. P. Chidi, Eds., 2019.

[3] D. Mars, S. M. Gammar, and A. Lahmadi, “Using Information Centric Networking in Internet of Things: A Survey.,” vol. 105, no. 1, 2019, doi: 10.1007/s11277-018-6104-8ï.

[4] A. Abrar, A. S. Che, M. Arif, and K. M. Zaini, “Internet of things producer mobility management in named data networks: a survey, outlook, and open issues,” 2023.

[5] S. Fayyaz, M. A. U. Rehman, M. S. ud Din, M. I. Biswas, A. K. Bashir, and B. S. Kim, “Information-Centric Mobile Networks: A Survey, Discussion, and Future Research Directions,” *IEEE Access*, 2023, doi: 10.1109/ACCESS.2023.3268775.

[6] T. Koponen *et al.*, *A Data-Oriented (and Beyond) Network Architecture*. Association for Computing Machinery, 2007.

[7] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, *Networking Named Content*. 2009.

[8] N. Fotiou, P. Nikander, D. Trossen, and G. C. Polyzos, “Developing Information Networking Further: From PSIRP to PURSUIT,” 2012.

[9] C. Dannewitz, D. Kutscher, B. Ohlman, S. Farrell, B. Ahlgren, and H. Karl, “Network of information (NetInf)-An information-centric networking architecture,” *Comput Commun*, vol. 36, no. 7, pp. 721–735, Apr. 2013, doi: 10.1016/j.comcom.2013.01.009.

[10] W. X. Liu, S. Z. Yu, G. Tan, and J. Cai, “Information-centric networking with built-in network coding to achieve multisource transmission at network-layer,” *Computer Networks*, vol. 115, pp. 110–128, Mar. 2017, doi: 10.1016/j.comnet.2015.05.009.

[11] M. Meddeb, A. Dhraief, A. Belghith, T. Monteil, K. Drira, and S. Gannouni, “AFIRM: Adaptive forwarding based link recovery for mobility support in NDN/IoT networks,” *Future Generation Computer Systems*, vol. 87, pp. 351–363, Oct. 2018, doi: 10.1016/j.future.2018.04.087.

[12] A. B. Feroz Khan and G. Anandharaj, “The embedded framework for securing the internet of things,” *Journal of Engineering Research (Kuwait)*, vol. 9, no. 2, pp. 139–148, Jun. 2021, doi: 10.36909/jer.v9i2.9823.

[13] M. Hussaini, S. Awang Nor, and A. Ahmad, “Producer Mobility Support for Information Centric Networking Approaches: A Review,” 2018. [Online]. Available: http://www.ripublication.com

[14] CISCO, “Cisco Visual Networking Index: Forecast and Trends, 2017–2022,” 2019.

[15] L. Alkwai, A. Belghith, A. Gazdar, and S. Al-Ahmadi, “Comparative Analysis of Producer Mobility Management Approaches in Named Data Networking,” *Applied Sciences (Switzerland)*, vol. 12, no. 24, Dec. 2022, doi: 10.3390/app122412581.

[16] W. M. H. Azamuddin, A. H. M. Aman, H. Sallehuddin, and Z. Wenhua, “Producer Mobility in Named Data Networking: Handoff Latency and Packet Arrival Rate,” in *2023 International Conference on Electrical Engineering and Informatics (ICEEI)*, IEEE, Oct. 2023, pp. 1–6. doi: 10.1109/ICEEI59426.2023.10346641.

[17] M. Toaha *et al.*, "PoP-VNDN: Proactive On-path Content Prefetching in Vehicular Named Data Networks," 2022. [Online]. Available: https://ssrn.com/abstract=4058929

[18] A. Chaabane, E. De Cristofaro, M. A. Kaafar, and E. Uzun, "Privacy in Content-Oriented Networking: Threats and Countermeasures," 2013.

[19] G. White and G. Rutz, "Content Delivery with Content-Centric Networking," 2016.

[20] A. A. Fiu, J. Burke, T. Refaei, L. Wang, B. Zhang, and L. Zhang, "A Brief Introduction to Named Data Networking," in *MILCOM 2018–2018 IEEE Military Communications Conference (MILCOM)*, 2018, pp. 1–6. [Online]. Available: http://cnn.com

[21] N. H. A. Zukri, A. S. C. M. Arif, M. AlSamman, and A. Abrar, "Enabling a Sustainable and Inclusive Digital Future with Proactive Producer Mobility Management Mechanism in Named Data Networking," in *Communications in Computer and Information Science*, N. H. Ahmad Zukri, A. S. Che Mohamed Arif, M. AlSamman, and A. Abrar, Eds., Springer Science and Business Media Deutschland GmbH, 2024, pp. 343–354. doi: 10.1007/978-981-99-9589-9_26.

[22] CISCO, "Cisco Annual Internet Report (2018–2023)," 2018. Accessed: Dec. 05, 2022. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf

[23] A. Abrar, A. S. Mohamed Arif, and K. Mohad Zaini, "A systematic analysis and review on producer mobility management in named data networks: Research background and challenges," Apr. 15, 2023, *Elsevier B.V.* doi: 10.1016/j.aej.2023.02.022.

[24] J. Auge, G. Carofiglio, G. Grassi, L. Muscariello, G. Pau, and X. Zeng, "MAP-Me: Managing Anchor-Less Producer Mobility in Content-Centric Networks," *IEEE Transactions on Network and Service Management*, vol. 15, no. 2, pp. 596–610, Jun. 2018, doi: 10.1109/TNSM.2018.2796720.

[25] S. Korla and S. Chilukuri, "T-move: A light-weight protocol for improved QoS in content-centric networks with producer mobility," *Future Internet*, vol. 11, no. 2, Jan. 2019, doi: 10.3390/fi11020028.

[26] Z. Yan, Y.-J. Park, Y.-B. Leau, L. Ren-Ting, and R. Hassan, "Hybrid Network Mobility Support in Named Data Networking," in *2020 International Conference on Information Networking (ICOIN)*, Barcelona, Spain, 2020. doi: 10.1109/ICOIN48656.2020.9016516.

[27] M. Hussaini, M. A. Naeem, and B. S. Kim, "Opmss: Optimal producer mobility support solution for named data networking," *Applied Sciences (Switzerland)*, vol. 11, no. 9, May 2021, doi: 10.3390/app11094064.

[28] A. Abrar, A. S. Che Mohamed Arif, and K. Mohd Zaini, "A Mobility Mechanism to Manage Producer Mobility in Named Data Networking," in *2022 IEEE Region 10 Symposium (TENSYMP)*, Mumbai, India, 2022, pp. 1–6. doi: 10.1109/TENSYMP54529.2022.9864454.

[29] M. Gohar, N. Khan, A. Ahmad, M. Najam-Ul-Islam, S. Sarwar, and S. J. Koh, "Cluster-Based Device Mobility Management in Named Data Networking for Vehicular Networks," *Mobile Information Systems*, vol. 2018, 2018, doi: 10.1155/2018/1710591.

[30] A. Ahmad, M. Hussaini, S. A. Nor, and A. Ahmad, "PMSS: Producer Mobility Support Scheme Optimization with RWP Mobility Model in Named Data Networking," *Article in International Journal of Communication Networks and Information Security*, vol. 10, no. 2, 2018, [Online]. Available: https://www.researchgate.net/publication/327426506

[31] F. R. C. Araújo, A. M. de Sousa, and L. N. Sampaio, "SCaN-Mob: An opportunistic caching strategy to support producer mobility in named data wireless networking," *Computer Networks*, vol. 156, pp. 62–74, Jun. 2019, doi: 10.1016/j.comnet.2019.04.008.

[32] W. Huang, T. Song, Y. Yang, and Y. Zhang, "Cluster-Based Cooperative Caching With Mobility Prediction in Vehicular Named Data Networking," *IEEE Access*, vol. 7, pp. 23442–23458, 2019, doi: 10.1109/ACCESS.2019.2897747.

[33] L. Rui, S. Yang, and H. Huang, "A producer mobility support scheme for real-time multimedia delivery in named data networking," *Multimed Tools Appl*, vol. 77, no. 4, pp. 4811–4826, Feb. 2018, doi: 10.1007/s11042-017-5601-1.

[34] I. Ali and H. Lim, "Anchor-Less Producer Mobility Management in Named Data Networking for Real-Time Multimedia," *Mobile Information Systems*, vol. 2019, 2019, doi: 10.1155/2019/3531567.

[35] J. H. Choi, J. H. Cha, Y. H. Han, and S. G. Min, "A dual-connectivity mobility link service for producer mobility in the named data networking," *Sensors (Switzerland)*, vol. 20, no. 17, pp. 1–16, Sep. 2020, doi: 10.3390/s20174859.

[36] L. Rui, S. Dai, Z. Gao, X. Qiu, and X. Chen, "Double-Lead Content Search And Producer Location Prediction Scheme For Producer Mobility In Named Data Networking," *Comput J*, Sep. 2022, doi: 10.1093/comjnl/bxac125.

[37] W. Muhd, H. Azamuddin, A. Hafizah, M. Aman, H. Sallehudin, and E. Yadegaridehkordi, "HIM: Hybrid Indirection Method for Producer Mobility Handoff in Named Data Networking," 2023, [Online]. Available: https://ssrn.com/abstract=4656651

[38] M. Bellaj, N. Naja, and A. Jamali, "On-demand Geographic Forwarding for producer mobility support in Named Data Networking," Association for Computing Machinery (ACM), May 2023, pp. 1–7. doi: 10.1145/3607720.3607755.

[39] C. Fang, H. Yao, Z. Wang, W. Wu, X. Jin, and F. R. Yu, "A survey of mobile information-centric networking: Research issues and challenges," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 2353–2371, Jul. 2018, doi: 10.1109/COMST.2018.2809670.

[40] M. A. Hail, "IoT-NDN: An IoT architecture via named data netwoking (NDN)," in *Proceedings - 2019 IEEE International Conference on Industry 4.0, Artificial Intelligence, and Communications Technology, IAICT 2019*, Institute of Electrical and Electronics Engineers Inc., Jul. 2019, pp. 74–80. doi: 10.1109/ICIAICT.2019.8784859.

[41] T. X. Do and Y. Kim, "Optimal provider mobility in large-scale Named- Data networking," *KSII Transactions on Internet and Information Systems*, vol. 9, no. 10, pp. 4054–4071, Oct. 2015, doi: 10.3837/tiis.2015.10.016.

[42] C. Makaya and S. Pierre, "An analytical framework for performance evaluation of IPv6-based mobility management protocols," *IEEE Trans Wirel Commun*, vol. 7, no. 3, pp. 972–983, Mar. 2008, doi: 10.1109/TWC.2008.060725.