IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 23 March 2023, accepted 13 April 2023, date of publication 20 April 2023, date of current version 27 April 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3268775

SURVEY

Information-Centric Mobile Networks: A Survey, Discussion, and Future Research Directions

SANA FAYYAZ[1], MUHAMMAD ATIF UR REHMAN[2], MUHAMMAD SALAH UD DIN[1], (Student Member, IEEE), MD. ISRAFIL BISWAS[2], (Member, IEEE), ALI KASHIF BASHIR[2], (Senior Member, IEEE), AND BYUNG-SEO KIM[3], (Senior Member, IEEE)

[1]Department of Electronics and Computer Engineering, Hongik University, Sejong 30016, South Korea
[2]Department of Computing and Mathematics, Manchester Metropolitan University, M15 6BH Manchester, U.K.
[3]Department of Software and Communications Engineering, Hongik University, Sejong 30016, South Korea

Corresponding author: Byung-Seo Kim (jsnbs@hongik.ac.kr)

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korean Government (MSIT) under Grant 2022R1A2C1003549.

ABSTRACT Information-centric networking (ICN) and its fruition, the named data networking (NDN) is a paradigm shift from host-centric address-based communication architecture to the content-centric name-based one. ICN intends to resolve various major issues faced by today's internet architecture such as privacy, security, consistent routing, and mobility, to name a few. With the massive increase of mobile data traffic in today's era, mobility is one of the major concerns in networking. On the one hand, ICN realization i.e., the NDN follows a pull-based communication model and natively supports the consumer (end-user) mobility in wired networks by maintaining the forwarding states on intermediate nodes. Nevertheless, the mobile consumer nodes confront issues in wireless networking environments such as excessive energy consumption as a result of request flooding, content retrieval delays due to intermittent connectivity, and bandwidth consumption due to the broadcasting nature of the wireless medium, among others. The producer (content-generator) mobility, on the other hand, was not initially supported in the original architectural design of NDN for both wired and wireless networks. Therefore, to efficiently address the degradation issues incurred by mobile consumer/producer nodes, a plethora of mobility management schemes have been proposed over the recent few years. In this paper, we provided a detailed survey on the existing research efforts—in the context of producer, consumer, and hybrid mobility, that have been proposed in the literature. Moreover, we outlined various research directions considering the role of mobility in futuristic technologies such as artificial intelligence-enabled smart networks, software-defined networking, edge computing, vehicular-fog computing, autonomous driving, semantic communication, and resource-constrained Internet of Things.

INDEX TERMS Named data networking, mobility management, producer mobility, wireless networking, artificial intelligence, edge computing, vehicular fog computing, autonomous driving.

I. INTRODUCTION

The 21st century is experiencing immense growth in the production of data[1] as the result of the adaptation of the Internet of Things (IoT) vision in almost every walk of life [1], [2], [3], [4]. The produced data is shared by enabling communication between two parties: 1) the producer node, which could be a resource-rich server device on the Internet or resource-constrained sensor node in wireless sensor networks (WSNs), among others, and 2) the consumer node, which could be an end-user using a mobile application on a smartphone, browsing a website on a laptop, or a base station in the WSNs environment. Due to the heavy data production in real-time scenarios, the current internet architecture

The associate editor coordinating the review of this manuscript and approving it for publication was Barbara Masini.

[1]We use Data with a uppercase "D" to refer to ICN/NDN Data packet whereas data with lowercase "d" refer to general data.

and other existing wireless networking environments such as mobile ad hoc networks (MANETs), vehicular ad hoc networks (VANETs), and WSNs, are facing significant challenges specifically when the communicating nodes follow the mobile patterns [5], and therefore, require efficient mobility management schemes. In the current location-dependent Internet Protocol (IP) based internet architecture, the management of both consumer and producer mobility is a cumbersome task. The reason is that in the IP based networks, a one-to-one connection is required to transmit the data, however, when a mobile producer (MP) moves from one point of attachment (PoA) to another in the network, it needs to change its physical IP address and establish a new connection with the consumer nodes for the data transmission. In doing so, the consumer may experience a delay in receiving the Data which ultimately decreases the performance of the network. To efficiently deal with mobility management in IP-based network architecture, various research efforts have been achieved in the past two decades [6], [7], [8], [9], however, the proposed solutions are either too complex or difficult to adopt in real-life scenarios. Overlay solutions such as Mobile IP [10] and Content Delivery Networks (CDN) [11], among others, may have the potential to resolve the mobility issues, however, these solutions are not scalable enough owing to the explosive increase in the number of smart devices.

A. INFORMATION CENTRIC NETWORKING: A POTENTIAL ALTERNATIVE

ICN [12], [13], [14], on the other hand, has emerged as a potential alternative to IP-based networking, focusing on the content rather than its physical location [15], [16]. The realizations of ICN, such as NDN [17] or content-centric networking (CCN) [18], data-oriented network architecture (DONA) [19], publish-subscribe internet routing protocol (PSIRP) [20], network of information (NETINF) [21], content mediator architecture for content-aware networks (COMET) [22], content network (CONET) [23], and MobilityFirst [24], utilize application layer content names assigned by producer node, for routing and forwarding purposes, and as a result, decoupling the content from its physical location. The name-oriented philosophy of ICN has already paved the way for the development and the emergence of other in-networking technologies or features such as on-path/off-path caching, requests aggregation, innate multicasting, and content-based security. Among these features, the in-network caching and requests aggregation significantly empower the network to deal with issues that may occur due to the presence of mobile nodes [25].

Although several realizations of ICN have been proposed by different organizations and researchers, the NDN [26], an improved version of CCN [18], has gained a lot of attention from both academia and industry. NDN provides a revolutionary paradigm that revolves around the content and treats it as a first-class object. In NDN, content can be accessed by employing the hierarchical and semantically meaningful

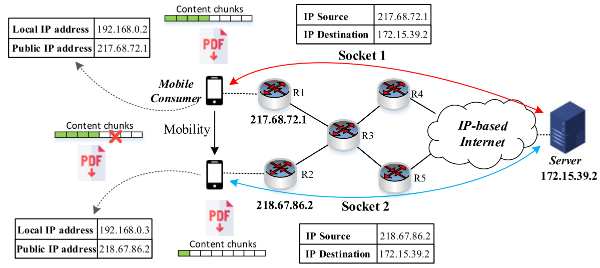


FIGURE 1. IP-based communication model.

name, rather than the IP address indicating the physical location of a producer node in the network. Comparing NDN to the conventional IP-based architecture, the NDN provides several beneficial features such as in-network caching, scalability, content level security, innate-multicasting support, and consumer mobility. The pull-based communication architecture of NDN, to some extent, by default supports consumer mobility in the network. When disconnecting from one PoA, in NDN, the consumer node can simply retransmit the request with the same name to retrieve the Data packet from the network. The retransmitted request may fetch the Data from the in-network caches—if the previous request already reached the old PoA and the Data has been cached somewhere on the intermediate nodes—or through request aggregation—if the previous request has yet to bring back the Data—which helps in reducing the delays in the network. In so doing, the NDN tries to provide mobility transparency in the network. Meaning that the NDN to a certain degree allows the movement of consumer nodes within the network without affecting the application performance and consequently improves the end-user quality of service (QoS) requirements. To further demonstrate the aforementioned scenario and to provide a clear comparison between IP- and NDN-based communication architecture, let us consider a simple file downloading example with the help of the given Figure 1 and Figure 2.

Figure 1 illustrates an IP-based communication scenario in which a mobile consumer on the top-left side is downloading a PDF file and is connected with a router R1 whose public IP address is 217.68.72.1. As shown in the figure, the PDF file is being downloaded from a server whose IP address is 172.15.39.2. As soon the downloading request arrives at the server for the first time, a unique socket—combining the consumer IP and server IP addresses—is formed and a connection is established between the mobile consumer and server. Once the connection is established, the mobile consumer starts downloading the file in the form of chunks. While downloading the file, the mobile consumer disconnects from R1 and relocates to the new location and connects with the router R2 whose IP address is 218.67.86.2. At this point in time, 50% of the file chunks are downloaded whereas 50% of chunks are remaining. However, since the mobile consumer is now connected to the new router which in turn creates a new socket, therefore, the file downloading starts from scratch. Following such protocol, the mobile consumer experiences delay, and the network bandwidth consumption increases, which is one of the major drawbacks of the IP-based internet architecture.

In contrast to the traditional IP-based mobile networking scenario presented in Figure 1, Figure 2 illustrates the mobile consumer scenario that follows NDN as an underlying communication model (a comprehensive discussion on NDN communication procedure is presented in Section III). To ease the reader's understanding, we showed the same file downloading use case to elaborate on the effectiveness of NDN in terms of consumer mobility. As shown in the figure, the mobile consumer interested in downloading a file forwards an Interest packet in the network. The network i.e., the intermediate nodes on receiving the Interest[2] packet, locate the named content by following FIB entries (a detail about FIB is presented in Section III), and consequently, the Interest packet reaches at the producer node. The producer node on receiving the Interest packet prepares and forwards the Data packet back to the consumer node by following the breadcrumb path maintained in PIT (a detail about PIT and aggregation is presented in Section III) at each intermediate router (IR). By doing so the mobile consumer node starts downloading the PDF file. While downloading the file, similar to the previous IP-based scenario, the mobile consumer disconnects from R1 and relocates to the new location and connects with the router R2. Likewise, at this point in time, 50% of the file chunks are downloaded whereas 50% of chunks are remaining. However, since the mobile consumer is now following the NDN-based communication model, it can simply request the remaining chunks (by Name) from the network, which can either be retrieved from the intermediate nodes—if the same request was already issued previously from the old location and the corresponding Data packet is cached somewhere at intermediate nodes—or directly from producer node. In either case, the mobile consumer does not need to download the file from scratch but rather only download the remaining chunks, which in turn decreases the downloading delay compared to the IP-based communication architecture.

B. WHY MOBILITY MANAGEMENT IS IMPORTANT?

Mobility management in NDN is a major concern for both the consumer and the producer of the Data. Even though consumer mobility is natively supported in the NDN architecture as explained earlier, still it faces various challenges, especially in wireless networking scenarios such as excessive energy consumption as a result of request flooding, content retrieval delays due to intermittent connectivity, and bandwidth consumption due to the broadcasting nature of the wireless medium, among others, and required efficient solutions specifically targeting the wireless nature of a communication medium. In addition to the aforementioned issues caused by consumer mobility, the content retrieval delay may increase

[2]We use Interest with an uppercase "I" to refer to ICN/NDN Interest packet whereas interest with a lowercase "i" refer to a general word.

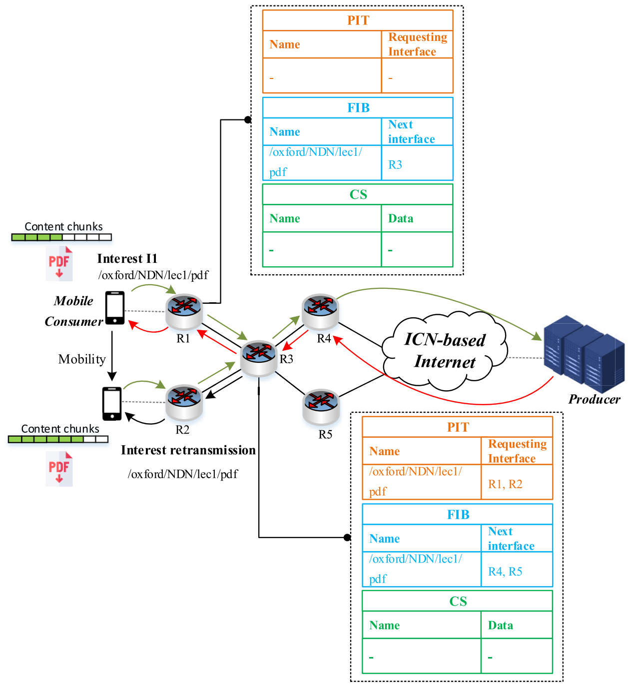


FIGURE 2. **ICN (NDN) based communication model.**

even if the consumer retransmits the request. For instance, what if the retransmitted request does not cross the path with the old request path, causing the network to forward the request to the original content provider, consequently, increasing the content retrieval delay.

In addition to consumer mobility, the efficient handling of producer mobility in NDN is an even more challenging task. The reason is that when a producer node moves from one PoA to another, the routing path pointing towards it must have to be updated with the new information. As a result, the request packets that are in transit should follow the updated path pointing toward the new PoA. One of the major issues in producer mobility is that the consumer or the intermediate nodes cannot be aware of the new location of the producer node unless the producer announces it in the network in a broadcasting manner or via some other advertisement-based approaches. The broadcasting of announcement packets may have an adverse effect on the performance of the network as congestion may increase.

C. PAPER MOTIVATION AND OUTLINE

To resolve mobility management issues in NDN as presented in the previous section, various research works have been proposed in the context of consumer mobility, producer mobility as well as both consumer and producer (hybrid) mobility. In this paper, we shed light on these research efforts by classifying them into various categories. Producer mobility classification includes 1) tracing-based, 2) caching-based, 3) mapping-based, 4) broadcast control based, 5) location-based, and 6) adaptive forwarding-based mobility management schemes. Consumer mobility is classified into 1) hop count-based 2) caching-based 3) control messages-based and 4) location-based mobility management schemes. Finally, hybrid mobility is classified into 1) FIB based 2) PIT based, and 3) storage-point-based mobility management schemes. A comprehensive explanation of the underlying working mechanism of these categories along with a detailed survey of existing schemes in each category are presented in Section IV. We provided a critical analysis of these schemes and highlighted both the contributions as well the limitations. In addition to surveying the NDN-based mobility management schemes, we also discussed mobility support in other ICN projects such as DONA, NETINF, COMET, etc. Moreover, we added a dedicated section that further consists of various sub-sections highlighting the unresolved research challenges and future directions, considering the importance of mobility management schemes in futuristic technologies. In summary, the contributions of our survey paper are as follows:

- At first, this paper outlines the native mobility support provided by the various ICN realizations and describes how each realization tries to consumer and/or producer mobility in the network.
- Second, this paper provides a brief overview of NDN and its underlying communication mechanism.
- Third, this paper provides a detailed survey on existing research efforts in the domain of mobile NDN by classifying them into various categories. A critical discussion highlighting the contributions and limitations of each surveyed scheme is presented in this paper.
- Finally, several research challenges and future directions considering the role of mobility in futuristic technologies are presented in this paper.

To the best of our knowledge, this paper is a detailed and comprehensive survey that covers consumer, producer as well as hybrid mobility management schemes, and also provides insights on the role of mobility in the domain of futuristic networking paradigms following the NDN principles. In the following subsection, we presented a detailed comparison of our survey paper with the state-of-the-art survey papers related to ICN mobility published in the recent past.

D. REVIEW OF RELATED SURVEYS

As efficient mobility management plays a pivotal role in futuristic mobile networks, a plethora of research works—aiming to effectively deliver content to mobile users, have been proposed under the umbrella of ICN. Researchers from both academia and industry [27] have investigated the challenges associated with mobility management in ICN, including consumer node mobility, producer node mobility, and hybrid mobility, and proposed various solutions. Subsequently, several surveyed articles intending to provide an overview of the mobility schemes with different focuses such as congestion avoidance, delay minimization, reducing the signaling overhead, minimizing the bandwidth consumption, and improving packet delivery ratio, have been published. The main theme of these survey papers is briefly described as follows.

To the best of our knowledge, the first comprehensive survey article in the domain of mobile ICN was published in 2012 [28]. The authors of [28] surveyed the mobility support in various realizations of ICN including DONA [19], PSIRP [20], NETINF [21] and CCN [29]. They also identified the research challenges and future directions to resolve mobility issues in different research areas. Since this survey paper was published in the early stages of ICN research, the schemes presented in it are to some extent obsolete. The survey in [30] primarily focused on the mobility management schemes in NDN. The authors of this paper first provided a brief survey on mobility support in IP-based networks, they then presented a discussion on different schemes proposed to handle consumer and producer mobility. The producer mobility schemes are further classified into two categories i.e., 1) MP chasing, and 2) Data rendezvous. Based on the diversity of surveyed schemes, the authors briefly discussed the design tradeoff in terms of 1) signaling overhead, 2) involvement of rendezvous points, 3) packet processing, and 3) security requirements. In [31], Feng et al. reviewed the mobility support in NDN by dividing the proposed solutions into two categories 1) consumer mobility and 2) producer mobility, which further classified into two subcategories i.e., partial separation-based mobility management schemes and total separation-based mobility management schemes. The survey in [32] reviewed the proposed solutions for producer mobility in NDN only. Similarly, in [33], the authors thoroughly discussed the mobility management approaches proposed to tackle the mobility of producer nodes. Finally, in [34], the authors presented a detailed survey on mobile information-centric networking, covering the schemes proposed for consumer and producer mobility. Furthermore, they also discussed the research issues and challenges specifically targeting mobile networks such as MANETs, VANETs, WSNs, and satellite networks, among others.

Given existing works, there still lacks a survey paper that provides concrete and comprehensive discussions on mobility management schemes and at the same time provides insight into the role of mobility management in futuristic networking technologies, which motivates the current work. This survey paper varies from the existing surveys on mobility management in ICN, in the following aspects. First, the current survey paper summarizes the support for mobility management by the various realizations of ICN and provides a quick reference for both researchers and industry experts. Next, we present a comprehensive literature review on various research efforts, in the context of consumer mobility, producer mobility, and hybrid mobility. We further classified these research efforts into the following categories 1) tracing-based, 2) caching-based, 3) mapping-based, 4) broadcast control based, 5) location-based, and 6) adaptive forwarding-based, mobility management schemes, which is a key theme

TABLE 1. Comparison of related surveys.

Survey Paper	Year	Related work	Mobility in ICN approaches	Producer Mobility	Consumer Mobility	Hybrid Mobility	In the context of mobile NDN						Comments
							Artificial Intelligence	Semantic Communication	Edge Computing	Vehicular Fog Computing	Software Defined Networking	Autonomous Driving	
[28]	2012	X	✓	X	X	X	X	X	X	X	X	X	• Discuss only the mobility support in ICN approaches. • Missing mobility support in consumer and producer mobility
[30]	2016	X	X	✓	X	X	X	X	X	X	X	X	• Focus on Producer mobility and discussions. • Not surveyed the consumer mobility
[31]	2016	X	X	✓	✓	✓	X	X	X	X	X	X	• Discussion on both producer and consumer mobility • Missing recent relevant work and research challenges
[32]	2018	X	X	✓	X	X	X	X	X	X	X	X	• Discuss producer mobility support only. • No discussion on consumer mobility
[34]	2018	X	✓	✓	✓	✓	X	X	X	X	X	X	• Discuss both producer and consumer mobility thoroughly. • Missing recent relevant work
[33]	2019	✓	✓	✓	X	X	X	X	X	X	X	X	• Missing research challenges and future directions • Did not discuss consumer and hybrid mobility
Our	2023	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	• Comprehensive discussion on mobility support in producer, consumer as well as other ICN approaches.

of our paper. In addition, we also classified consumer mobility into 4 categories: 1) Hop-count based Consumer Mobility, 2) Caching-based Consumer Mobility, 3) Control messages-based Consumer Mobility, and 4) Location-based Consumer Mobility. Moreover, the Hybrid consumer and producer mobility is further divided into 1) PIT-based hybrid mobility, 2) FIB-based hybrid mobility, and 3) Storage point-based Hybrid Mobility. The literature review in our paper provides a thorough explanation of the underlying working mechanism of these aforementioned subcategories, and therefore, will be a valuable addition to the existing survey literature. The readers can greatly benefit from our survey paper, as this section mostly covers the recent state-of-the-art schemes. Furthermore, we discuss and identify several research opportunities and challenges by exploring the role of futuristic technologies including artificial intelligence, edge computing, vehicular fog computing, software-defined networking (SDN), in-network computations, and autonomous driving, in mobile NDN. To the best of our knowledge, we for the first time are providing such futuristic insights in the domain of mobile NDN, which lacks in almost all of the prior related works. Table 1 provides a summarized comparison of our paper with the existing surveyed articles in terms of the year in which the survey paper is published, related work i.e., the comparison of the survey with the existing surveys, the mobility support provided by the ICN realizations, the producer mobility schemes, the consumer mobility schemes, and the hybrid mobility schemes. Other than that, for the very first time, our survey paper discussed the role of various emerging futuristic technologies in the context of mobile NDN such as artificial intelligence, edge computing, fog computing, in-network computations, semantic communication, and autonomous driving.

The rest of this paper is organized as follows. Section II describes the mobility support in the various ICN realizations. In section III, a brief overview of NDN in terms of its underlying working mechanism is presented. A detailed and comprehensive survey of various mobility management schemes in NDN is presented in Section IV. Section V presents the discussion, future directions, and research challenges and finally, Section VI concludes our survey paper. Moreover, a complete list of acronyms used in our survey paper is provided in Table 2.

II. MOBILITY SUPPORT IN ICN REALIZATIONS

Various ICN realizations, as mentioned in the previous sections, generally provide basic mobility management support as compared to its predecessor the host-centric networking

TABLE 2. List of Acronyms.

Acronyms	Definitions	Acronyms	Definitions
AS	Autonomous systems	MNC	Mobile node consumer
AR	Access router	ML	Machine learning
AI	Artificial intelligence	MU	Mobility update
AN	Anchor node	ML	Mapping list
ASF	Adaptive SRTT based forwarding	NDN	Named data networking
AFS	Auxiliary forwarding set	NETINF	Network of information
AP	Access point	NRS	Name resolution server
AZ	Anchor zone	NDG	NDN default gateway
CCN	Content-centric networking	NAR	New access router
CS	Content store	PS	Proxy server
CDN	Content delivery networks	PIT	Pending interest table
CONET	Content network	PSIRP	Publish subscribe internet routing protocol
COMET	Content mediator architecture for content-aware networks	PoA	Point of attachment
CRS	Content resolution system	PURSUIT	Publish-subscribe internet technology
CR	Connected router	PAR	Previous access router
CMP	Content mediation plane	RV	Rendezvous server
DONA	Data-oriented network architecture	RSU	Roadside unit
DNS	Domain name system	RH	Resolution handler
DP	Domain proxy	RN	Rendezvous node
DDL	Data dissemination limit	RENE	Rendezvous network
DR	Data router	RD	Rendezvous domain
EC	Edge computing	RIB	Routing information base
FIB	Forwarding information base	RP	Rendezvous point
FL	Federated learning	RTT	Round trip time
GUID	Global unique identifier	RPP	Reverse-path partitioning problem
HR	Home router	SDN	Software-defined networking
ICN	Information-centric networking	SDC	Software-defined controller
IoT	Internet of things	SRTT	Smoothed Round trip time
IP	Internet protocol	TI	Trace interest
IR	Intermediate router	TD	Trace data
IU	Interest update	TTL	Time to live
MP	Mobile producer	VANET	Vehicular networks
MANET	Mobile ad hoc networks	VNDN	Vehicular NDN
MLS	Mobility link service	VFC	Vehicular fod computing
MS	Mapping server	WSN	Wireless sensor networks

architecture. However, to meet today's mobility requirements of complex networks, various research challenges in ICN realizations are being addressed as of date by researchers from both academia and industry. These research works, in addition to the ICN realization, employ diverse approaches such as resolution handlers, rendezvous points, and name-based routing planes, to name a few, to efficiently manage and support mobility. As the research efforts, either from academia or industry, are initially evolved by following the fundamental principles of different ICN realizations, we first provide a detailed underlying working mechanism of these realizations in the context of both consumer and producer mobility. Consumer mobility is natively supported by the following ICN realizations: DONA, NDN, PSIRP, and NetInf, however, to efficiently resolve the producer mobility these projects provide different solutions. A detailed description of mobility management mechanisms including consumer and producer mobility is presented in the following subsections. Figure 3 illustrates the timeline of ICN realizations when they were first introduced to the research community.

A. DONA

DONA [19] presented in 2007 provides efficient support for both consumer and producer mobility, by dividing the network into multiple tiers, where each tier is further portioned into various autonomous systems (AS). DONA employs the concept of name resolution by utilizing dedicated nodes named resolution handlers (RH) in each AS to support consumer mobility, whereas, for producer mobility support, a registration process by forwarding the "register" message with the content name is used in the network.

B. PSIRP

PSIRP [20] and its successor, publish-subscribe internet technology (PURSUIT) [35], are also clean slate ICN architectures and provide a publisher-subscriber based communication model consequently replacing the existing host-centric IP networking communication. The term publisher and subscriber may refer to producer and consumer respectively, and therefore onward we use producer and consumer to maintain consistent terms in the paper.

Similar to DONA, the PURSUIT also partitions the network into multiple hierarchical tiers consisting of various ASs where each AS contains several rendezvous nodes (RN) called rendezvous network (RENE). Initially, the producer node publishes the content by sending a "publish message" to the RN residing in its local AS RENE. The consumer node when wishes to subscribe to the content, issues the "subscribe message" into its local RENE which is then forwarded to the upper tier (if the producer is not located in the local RENE) and finally reaches the producer located in another AS. On the one hand, subscriber mobility is achieved by utilizing the caching and multicasting features.

C. NetInf

The NetInf [21] proposes a name-based ICN communication architecture by utilizing a hash-based naming scheme consisting of A:L where A refers to authority or in other words producer node and L refers to the locator part. The content publication procedure of NetInf is similar to PURSUIT. NetInf utilizes a name resolution server (NRS) to maintain name-to-locator mapping. The mobile producer, when wishes to publish the content, forwards the "publish message" containing the name and locator information to the local NRS. The local NRS on receiving the "publish message" store the information and then forwards it to the global NRS. The global NRS store the mapping information as well as the identity of the local NRS. The consumer node when interested in fetching the content from the network issues the "get message" to the local NRS which then contacts the global NRS, and finally the "get message" is delivered to the producer node. The producer node on receiving the "get message" simply responds with the Data packet. The NetInf handles the producer mobility by maintaining the topological information in NRS. Therefore, when the mobile producer moves from one PoA to another, issues the "update location" message and renews the topological information in NRS. Moreover, to notify location modification of the producer node to the currently connected consumers, an appropriate "notification message" is disseminated in the network.

D. COMET

In COMET [22], a content mediation plane (CMP) is used that acts as a mediator between the content location information and the network infrastructure information for the content transmission. The content resolution system (CRS) in COMET is responsible to manage and maintain the content publication and mapping information. The content resolution and mobility management in COMET are to some extent similar to the ICN realizations described in the previous subsections.

E. MobilityFirst

The MobilityFirst [24] architecture utilizes the global unique identifier (GUID) and global NRS (GNRS) for content resolution and deals with both producer as well as network mobility. In MobilityFirst, the producer node that wishes to publish the content in the network, first obtain the GUID from the naming service and then registers it with its network address in the GNRS. The consumer node when interested in certain content, adds the GUID in the "request message" and utilizes the GNRS to fetch the content from the network. The MobilityFirst realization resolves the mobility issue by using inter-domain and intra-domain routing. For inter-domain routing, edge-aware routing is used, whereas, for intra-domain routing, storage-aware routing is implemented. Moreover, a late-binding algorithm implementation is employed with the help of GUID routing which allows updating the new network addresses, generated as the result of producer mobility.

F. CONET

CONET [23] utilizes the convergence middleware (COMID) that further employs versatile digital items (VDI) containing the content information to publish it in the network. The content resolution process in CONET differs from previously discussed ICN realizations. In CONET, the producer node advertises the content information in the network, whereas the consumer node forwards the Interest message expressing the Interest in certain content that was made available by the

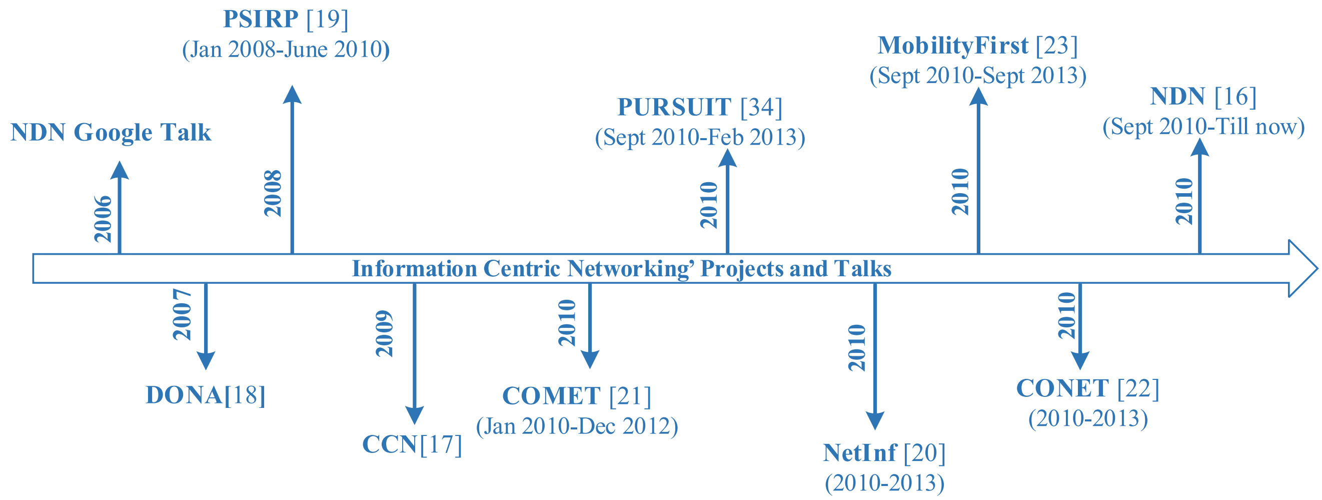


FIGURE 3. Timeline of ICN realizations.

producer node. The Interest message is forwarded hop by hop passing through border nodes (BN) and finally reaches the producer node. The producer node responds with the Data packet which follows the reverse breadcrumb path and finally reaches the consumer node. In terms of mobility, CONET confronts significant performance degradation issues when the mobile consumer changes the location from one PoA to another. The reason is that the IRs do not maintain the state of each incoming Interest message and therefore when the mobile consumer issues a new request of the same Interest message, it is forwarded all the way to the producer (if not available in the IR caches) which then generates a new content response, ultimately increasing the network traffic and the chance of congestion. Producer mobility in CONET is slightly similar to the previously discussed ICN realization and requires updating the COMID. When the producer node moves from one PoA to another, it utilizes the CONET node to cache the content and publish it in the network and at the same time advertises this information on the CONET routing plane. Hence, whenever the subscriber requests for the named data item following CONET principles, the request is routed by name toward the best serving node containing the required content.

G. NDN

CCN [18] and its continuation, the NDN [17], funded by the US Internet architecture program, is an emerging internet architecture in the field of ICN. The NDN follows the pull-based communication model in which the consumer node issues the "Interest" message to fetch the content from the network. Three different types of data structures named 1) pending Interest table (PIT), 2) forwarding information base (FIB), and 3) content store (CS) are utilized by IR to forward the request to the content provider. Each IR while forwarding the "Interest" first checks the CS for the requested content. In the absence of content in the CS, the IR utilizes PIT to aggregate the "Interest" messages to form the breadcrumb path and finally forwards the "Interest" to the next potential IR with the help of FIB. It is worth noting here that in contrast to the CONET, the NDN stores the state of "Interest" message on each IR to create the breadcrumb path and therefore fully leverage from aggregating the multiple requests feature. A detailed description of the NDN request-response mechanism is outlined in the next section and therefore, in this subsection, we mainly describe NDN in the context of consumer and producer mobility. The consumer mobility in NDN is natively supported as when the consumer node changes the location and detaches from one PoA to another, it retransmits the request in the network. The new request on the way to the producer node may aggregate in the PIT of IR and as a result, the overall network overhead decreases significantly. Moreover, as the IR caches the content, the chances are that the new request is fulfilled from the IR rather than from the original producer node which further decreases the network overhead. In contrast to consumer mobility, producer mobility in NDN creates significant networking overhead as a result of broadcasting the content advertisement information in the network.

Summary and Insight: In this section, we discussed various realizations of ICN in the context of consumer as well as producer mobility. From the discussion, we can see that almost all ICN realizations provide basic support for consumer mobility, however, when it comes to producer mobility, either all or some of these realizations support the producer mobility at the cost of network performance overhead. Compared to NDN, although, other ICN realizations somehow support producer mobility in a sophisticated manner, the NDN gained a huge interest from the research community due to its other promising features such as Interest aggregation, in-network caching, content security, and innate multicasting. Owing to these features, NDN emerges as a potential future networking architecture beating all of its counterparts. However, in the context of mobility and specifically producer mobility, since an efficient producer mobility solution was not provided in the original design of NDN, a significant amount of research was carried out in both academia and industry, which eventually resulted in the form of research papers. The existing proposed mobility schemes in the literature specifically focused on the following networking issues; 1) congestion avoidance, 2) delay minimization, 3) reducing the signaling overhead, 4) minimizing the bandwidth consumption, and 5) improving the packet delivery ratio. In the following sections, we first briefly describe the underlying working mechanism of NDN and then dedicated a section extensively detailing the existing research efforts is presented—in the context of consumer, producer, and hybrid mobility.

III. NAMED DATA NETWORKING: A BRIEF OVERVIEW

Van Jacobson et al [36] presented the idea of NDN in his Google talk for the first time in 2006. Since then, a lot of research efforts have been made in this direction and therefore currently the NDN is the most advanced and widely used architecture of ICN in both academia and industry. In the original idea of Van Jacobson, NDN utilizes a hierarchical and semantically meaningful collection of name components to fetch the content from the network. These name components are often separated by the "/" character. One of the potential benefits of hierarchal names is that it reduces the size of routing entries on intermediate nodes by aggregating the incoming requests of the same names. In NDN, the producer node is responsible to assign a name to the content which is being produced under its administration. Once the name is assigned to the content, the producer node disseminates the name in the network so that future requests can be fulfilled. The IRs utilize these names to cache the content–subject to the caching policy. The format of the NDN names shows a strong resemblance to the current structure of the URLs. For instance, the following URL: "hongik.ac.kr/admission/guide.pdf/" in IP-based networking can be represented as "ndn:hongik/ac/kr/admission/guide.pdf/" in NDN. The underlying working difference among these URLs and names is that in NDN these application-layer names are directly forwarded to the network layer, whereas the URLs are first transformed into an IP address by using Domain Name System (DNS), and then an IP address is forwarded on the network layer. In NDN, the consumer node inserts the content name into an Interest packet (request) and forwards it to the network whereas the producer node responds with a Data packet (response).

The nodes such as consumer, producer, and IR in NDN utilize three different types of data structures. These data structures include 1) PIT which is used to keep a record of outstanding Interest packets, 2) CS which is used to store data for future use, and 3) FIB which is used to forward the Interest packet to the next node in the direction of the producer. In addition to these data structures, the nodes also employ different forwarding strategies in conjunction with the FIB to forward the Interest packet to the potentially optimal interface. Such forwarding strategies include, 1) best route strategy, used to forward the Interest to the lowest cost interface in the direction of the producer, 2) multicast strategy, used when the Interest packet needs to be forwarded on all available interfaces pointing towards the producer node, 3) client control strategy enables the consumer node to control the flow of an Interest packet, 4) adaptive smoothed RTT-based forwarding (ASF) strategy periodically probes all available next hops to measure RTTs and then selects the next-hop with the lowest RTT value to forward the packet to the producer node, and so forth.

Figure 4 depicts the overall working flow of communication in NDN and is briefly described as follows. When a consumer node requires certain Data, it forwards the Interest packet in the network. When an Interest packet arrives at the IR, it first searches the CS to check whether a cached copy of the required Data is available. If Data is available, the IR simply fetches the Data from the cache and forwards it to the interface from where the Interest was received. In the absence of the Data in CS, the PIT is checked whether there is a request for the same name is pending. If the Interest message for the same content has already been forwarded, then the Interest message is suppressed, and its incoming face is stored in the PIT in-bound entries. However, if the matching name is not present in the PIT, then the IR creates a new PIT entry and forwards the Interest packet toward the producer node by performing the longest-prefix match on FIB and selecting the associated forwarding strategy with the Interest packet name. The producer node—on receiving the Interest packet, responds with the Data packet. When a Data packet is received at an IR, it checks the PIT table and if PIT entry is available, it forwards the Data on all downstream interfaces. The IR also removes the corresponding entry from the PIT to create storage space for future requests. Furthermore, the IR may store the Data packets in its CS– subject to the caching policy.

As mentioned in the previous sections, NDN supports consumer mobility to some extent whereas producer mobility is not supported by its original architectural design, therefore, a plethora of NDN mobility management schemes have been proposed in the literature and are comprehensively discussed in the following section.

IV. MOBILITY SUPPORT IN NAMED DATA NETWORKING

The pull-based content-centric nature of NDN enables the consumers to initiate the request in the form of an Interest packet to fetch the Data packet from the producer. From the mobility perspective, the consumer and producer both can be mobile and may change their PoAs. Therefore, we classified mobility into three categories: 1) consumer mobility, 2) producer mobility, and 3) hybrid (consumer and producer both are mobile) mobility. Among them, we first surveyed numerous producer mobility schemes by dividing them into various approaches for instance 1) tracing-based, 2) caching-based, 3) mapping-based, 4) broadcast control-based, 5) adaptive forwarding-based, and 6) location-based. After that, we surveyed different consumer mobility-related schemes proposed

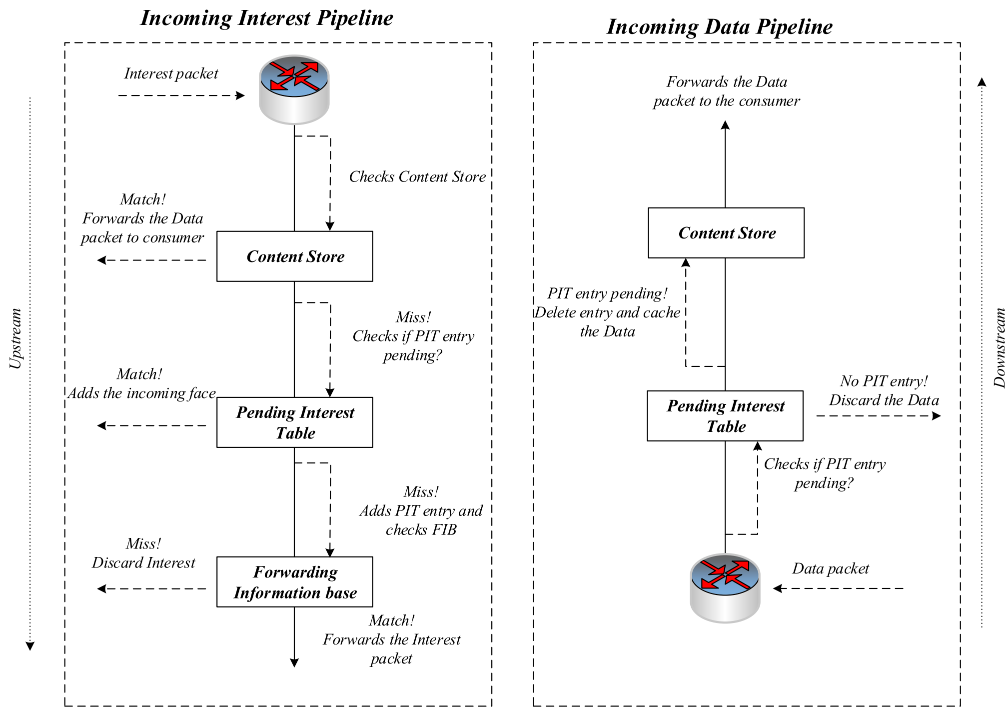


FIGURE 4. NDN communication working flow.

in the literature and categorized them into 1) hop count-based 2) caching-based 3) control messages-based and 4) location-based mobility management schemes. We finally conclude this section by surveying the hybrid mobility management schemes proposed in the NDN literature by classifying them into 1) FIB based 2) PIT based, and 3) storage-point-based mobility management schemes. All of the surveyed schemes are not only critically analyzed, but to avoid the pitfalls, contributions and limitations of each scheme are also presented. Our critical analysis is based on the following factors: 1) deployment strategies i.e., random or fixed, 2) network type for instance pure wireless ad hoc or partial wireless networking scenarios, 3) networking traffic rate, for example, light or dense traffic generation rate, 4) mobility patterns of the nodes i.e., based on speed and direction and the 5) mobility transparency i.e., the effect of mobile nodes movement in the network on end-user QoS requirements.

A. PRODUCER MOBILITY

The producer mobility in NDN is a challenging task as when the producer node changes its PoA, the network needs to update the FIB entries pointing toward the producer node. The updates of FIB entries can either be fulfilled by the advertisement messages or by employing dedicated nodes that keep a record of the traces pointing to the new location of a producer. This section describes the existing proposed producer mobility solutions in the domain of NDN. We classified these schemes into six major categories as shown in Figure 5. Among these categories, the mapping-based schemes are further classified into 1) proxy-based schemes, anchor-based schemes, and controller-based schemes.

FIGURE 5. Classification of producer mobility schemes.

1) TRACING-BASED MOBILITY MANAGEMENT SCHEMES

In tracing-based mobility management schemes, whenever the mobile producer moves from one PoA to another, it leaves traces on the intermediate nodes. These traces are often stored

TABLE 3. Tracing-based producer mobility schemes.

Category	Contributions	Limitations	Ref.
Tracing-based approaches	• Proposing a mobility support scheme in which mobile producer announces its movement using interest update IU message	• IU messages from attacker cause security concerns • Fake IU message may pollute the cache storage	[37]
	• Using fast FIB update mechanism that includes an additional entry that describes the producer's new location	• Extra signaling overhead cost	[39]
	• A tracing-based approach in which a mobile producer keeps the trace setup with a rendezvous server whenever it moves to a new location.	• The optimal path is not guaranteed. • Path signaling overhead cost	[40]
	• Introducing a greedy routing protocol besides the basic NDN protocol	• Increase overhead due to the use of two protocols in case of mobility	[42]
	• Multiple AP updates to reduce AP switching	• Increased overhead	[43]

alongside the existing FIB entries or even new temporary FIB entries have been created that point towards the new location of the mobile producer. A summarized description, highlighting the contribution and limitations of tracing based producer mobility management schemes is presented in Table 3.

In [37] and [38], the authors proposed MAP-ME, tracing-based mobility support for ICN which aims to minimize the unavailability of content due to handoff events. At first, the FIB update mechanism, as a result of producer relocation enables the network to immediately re-route the incoming Interest packets received at an old location toward the new location of the producer, consequently, highly decreasing the chances of packet drop. Second, the MAP-ME protocol reduces the searching delay by proactively updating the new location of the content provider, which in turn enables the network and the consumer to be aware of the producer's new location (even before the producer attaches to the new PoA). The MAP-ME protocol is beneficial for delay-sensitive applications as the Interest packet follows the pre-established path to reach the producer node. Although MAP-ME efficiently handles the producer mobility issues in the networks, it lacks in many perspectives. For instance, the privacy of the consumers and edge routers can be compromised when an Interest update (IU) message arrives from the attacker node. Moreover, the IU messages from the attackers can also pollute the cache storage and as a result, the delay may increase due to fetching the content from the original producer node rather than from intermediate caches.

In [39], the authors proposed publisher mobility support protocol (PMC) in which when the producer node relocates to the new PoA, it updates the routing information on the three main entities in the network i.e., 1) HR, 2) previous PoA, and 3) the IRs. While relocating to the new PoA, the producer employs two different types

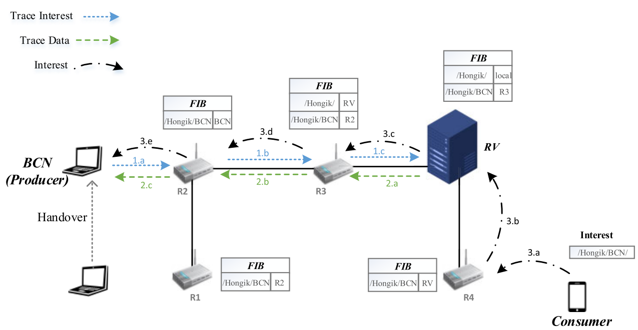


FIGURE 6. Tracing-based mobility solution in Kite.

of preserved names to forward the trace Interest packets. The naming schemes proposed for these Interest packets are as follows 1) publisher-URL/mobilityReport/Home and 3) publisher-URL/mobilityReport/PrevPoA. Among them, the former name is used when the producer moves from HR to the new PoA, whereas the latter is used in the case of mobility from one PoA to another. HR or previous PoA on receiving the aforementioned Interest packets, return the Data Packet to the producer creating the mobility entries in the FIBs of the IRs. The PMC protocol also introduced an additional entry in the FIB named "mobility entry" representing that producer is on the move in the network. When the updates are completed after the producer relocation, the pending interests at the HR or previous PoA are forwarded to the new PoA of the producer.

In [40] and [41] the authors proposed a tracing-based producer mobility solution named KITE, in which whenever the MP moves from one PoA to another, it needs to re-establish its trace setup with a stationary rendezvous server (RV) by employing the Trace Interest (TI) / Trace Data

(TD) packets exchanges. The overall working of the aforementioned tracing-based solution is illustrated in Figure 6 in which an MP issues a TI to the RV after the handover (1.a - 1.c). RV, on receiving the TI verifies it and responds with a TD packet to the MP (2.a-2.c). TD follows the reverse path to the MP, whereas the intermediate nodes, on receiving the TD, create or update FIB entries for the Data name prefix of the MP. These FIB entries point towards the incoming interfaces of TIs, consequently creating a path from RV to the MP. When a consumer requires Data from the mobile producer, it requests the RV, and then RV utilizes the trace setup to retrieve content from the MP (3.a-3.e).

Wang et al. [42], proposed an approach named MobiCCN in which a greedy protocol is used alongside the basic NDN protocol. The only addition in the Interest packet format is the greedy:/ prefix at the start of the Interest packet when using the greedy protocol, whereas ccnx:/ is used for the vanilla CCN protocol. In the proposed solution, a central entity named RV is employed in each domain that maintains and tracks the mobile nodes in the network. When MP relocates to a new PoA, it forwards the greedy update packet to the RV. The greedy update message on the way to the RV modifies the routing paths on the IR by maintaining the traces in the FIB entries that point toward the MP. Consumer, on the other hand, first follows the basic protocol to forward the Interest packet to the producer. However, in the case of producer mobility, greedy Interest is sent toward the RV to retrieve the new location information of the producer node. If the greedy Interest meets the traces kept at the IRs, it can directly access the MP instead of approaching the RV. In so doing the MobiCCN resolves the producer mobility issue in the network. However, the proposed approach increases the overhead in the network as it utilizes vanilla forwarding and greedy forwarding serially. This issue can be avoided if greedy forwarding is selected as a default forwarding mechanism.

Kar et al. [43] proposed a seamless producer mobility management scheme for a real-time communication scenario in NDN-based remote health monitoring. In real-time remote health monitoring systems, high latency and packet loss are major challenges requiring attention from academia and industry. In order to provide seamless communication between doctor and patient during and after the handover, the authors proposed a neighbor registration strategy in which the mobile producer when starts changing the position not only updates the adjacent access point (AP) but also all updates multiple nearest APs to reduce the delay incurred by the AP switching. In so doing the packet loss is decreased. Apart from the benefits, the proposed work may fail to handle unpredictable or sudden mobility events, which may highly affect the quality of healthcare services.

Summary and Insight: In this subsection, we discussed the tracing-based schemes that effectively handle producer mobility in the network. From the description of surveyed schemes, we can see that these approaches employ Interest/Data packet announcements in the network to generate the traces when the producer moves from old PoA to new PoA. Employing these schemes, the Interest packet from the consumer node can simply take the updated path on encountering the matching trace entries at the intermediate nodes. However, the solutions presented in a few approaches such as [39], [40], and [42] come at the cost of following networking overheads. At first, the tracing solutions induce signaling overhead and increase the exchange of additional Interest and Data packets. Second, these traces are usually associated with an expiry timer to invalidate the trace setup in case the producer node further changes the location. To keep these entries alive, a trace refresh packet is periodically forwarded in the network which further enhances the networking overhead and also increases the chances of congestion in the network. A simple solution to tackle this issue is to keep the entries alive for a longer period to reduce the signaling overhead. However, keeping entries alive for a longer duration increases the chances that the consumer Interest may be sent to the producer's old PoA following the expired trace entry. Considering the aforementioned issues, it is of utmost importance to devise novel solutions aiming to decrease the signaling overhead and at the same time, intelligently select the optimal value of the expiry time for trace entry.

2) MAPPING-BASED MOBILITY MANAGEMENT SCHEMES

Mapping based approach is used to track the producer's mobility by using an RV or an HR, which acts as a mapping server. The role of the mapping server is to keep the binding information of the mobile producer's name prefix with the content identifier. When a MP changes its location, it sends the prefix update message to the mapping server to update its location information. After the producer handover, when a consumer requests the mapping server, it sends the updated mapping information to the consumer, which then requests the MP directly. In other words, the mapping server maps the consumer to the MP's new point of attachment. The mapping server also updates the binding information after the producer handover, and when the consumer requests the mapping server, it may tunnel the Interest messages to the MP by itself and sends back the received Data message to the consumer, acting as a kind of redirection handler. In the literature, researchers proposed various schemes in which either the mapping server is used to resolve the producer mobility or the mapping server-based redirection approach is used [44]. A brief description, pointing out the contribution and limitations of mapping-based producer mobility management schemes are presented in Table 4.

In [44], the authors proposed a scheme in which the HR keeps the name prefix information of the MP. All the Interests for the producer first arrive at the HR and then the HR further processes the Interest/Data exchange. When the MP changes its location in the network, its new PoA sends the prefix update message to the HR, which in return sends the acknowledgment message. In this way, the HR keeps the information of the current PoA of the MP, and when it

TABLE 4. Mapping-based producer mobility schemes.

Category	Subcategory	Contributions	Limitations	Ref.
Mapping-based approaches	Home router/ Anchor-based	• Includes a mapping server that encapsulates and decapsulates the Interest and Data from consumer to producer and vice versa	• Encapsulation and decapsulation between consumer and mobile producer increase overhead	[44]
		• Introducing a scalable producer mobility management by distributing multiple mapping servers in the network on a global scale	• High overhead due to binding update mechanism on global scale	[45]
		• Introducing a forwarding hint field in the Interest packet which helps to locate the current location of producer	• Mangement overhead due to the local DNS server in each domain • Single point of failure	[46]
		• Proposing an approach that includes the locator using which Interests can access producer directly otherwise consumer access the home router that redirects to producer	• Double lookup increases the delay and cost	[47]
		• A decentralized approach in which the distributed controllers track producer mobility.	• Extra overhead • Modifies the basic architecture to support mobility	[48]
		• Using an immobile anchor node that keeps the tracks of the mobile producer node and redirects interest to the new PoA	• Causes signaling overhead due to the handover process	[49]
		• Employs an immobile anchor node that updates the FIB entries in all the router after a producer relocation.	• Updating all the FIB entries impacts the network performance	[50]
		• Proposing an anchor chain mechanism in which multiple anchors store the mapping lists and neighbor anchor nodes information to reach the updated location of producer	• Update mechanism causes congestion	[51]
	Proxy-based	• Proposing a proxy-based mobility management scheme in which NDN Access router and proxy servers exchange the signaling messages of handoff to resolve producer mobility	• Extra overhead in highly dense scenarios	[52]
		• A proxy-based scheme in which proxies are used to tunnel the Interest and Data packets to resolve the mobility issues during inter and intra-domain handoff	• Request and Data tunneling through domain proxies create network congestion	[53]
	Controller-based	• Proposing data/control plane-based solution in which a rendezvous handler handles all the updates regarding both inter and intra-domain mobility	• High handoff latency during inter-domain mobility	[54]
		• A software define controller-based scheme in which controllers are responsible for the flexible forwarding and seamless source mobility	• Single point of failure	[55]
		• An SDN based approach in which mobile producer informs the SDN of its mobility and then SDN makes either the local FIB updates or global FIB updates based on few parameters	• Does not resolve stale path issue • Single point of failure	[56]

receives the Interest message from the consumer after the producer handover event, it tunnels the encapsulated Interest message to the new PoA of the producer and in return, it sends back the decapsulated Data message to the consumer all by itself. However, this scheme suffers from an increased network delay, as relaying the Interest and Data packet on behalf of the consumer increases the chances of taking a longer path compared to direct consumer-producer communication. On the contrary, if the path information of the MP is provided to the consumer, it can directly access the producer using the shortest path.

In [45], the authors proposed scalable mobility management (SMM) scheme by providing three separation mechanisms named management/routing separation, Locator/ID

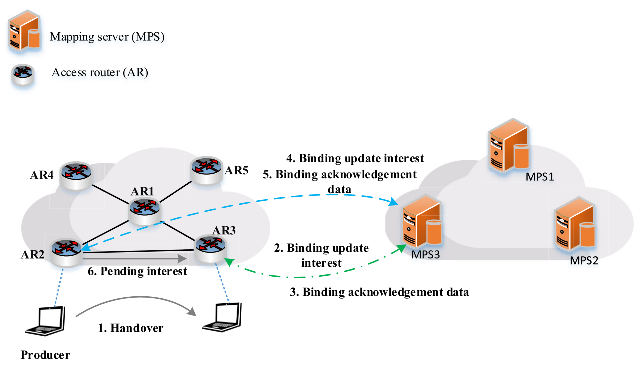


FIGURE 7. Basic producer handover mechanism of a mapping-based approach in SMM scheme.

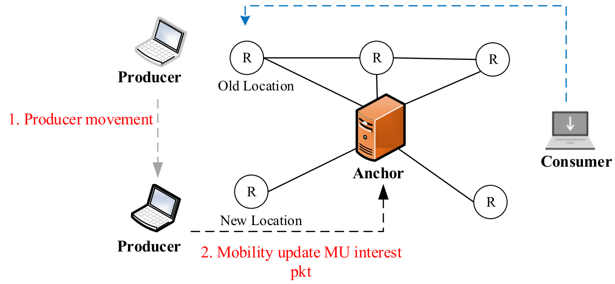
separation, and access/core separation. Figure 7 depicts the basic handover mechanism of the producer in the proposed SMM scheme. In this technique, the MP starts the handover and attaches to the new access router (AR) i.e., AR3 (step 1). After attaching to the AR3, it sends the binding update to the local mapping server (MPS) (step 2). In the given scenario, the local mapping server of the producer is MPS3, which in return acknowledges the newly attached MP by sending an acknowledgment message (step 3). To support seamless mobility, MPS3 forwards the binding update to the previous AR of the producer i.e., AR2 so that it can get access to the new AR of the producer in case it receives a request for the MP (step 4). AR2 sends the acknowledgment message in return to the MPS3 (step 5). Since AR2 knows the updated location of MP, hence, it forwards the pending Interests received during the handover, to the MP (step 6) and forwards the required content to the consumer. However, this mechanism induces high handoff latency in the network. For scalable management, the authors proposed distributed hash tables (DHT) with multiple distributed mapping servers. Inducing the DHT in the basic SMM handover mechanism further increases the handoff latency. Hence, to tackle this issue, another handover procedure is proposed in which when MP attaches to new AR, it sends the binding update (BU) to both the local mapping server and the previous AR at the same time. In this way, the previous AR acknowledges the new location update and forwards the Interest messages to MP without waiting for the location updates of MP through the mapping server's acknowledgment. Moreover, in this scheme, the normal Interest and Data packets are modified using the mobility option extension.

Another approach based on the DNS mapping is proposed by [46], in which the NDN plays its pivotal role to support producer mobility. In this scheme, the authors introduced an additional field in the Interest packet named forwarding hint. This forwarding hint is just being used to give the IR a hint about content availability. When an MP changes its location in the network, it sends the hint to the local DNS server. When the consumer needs to retrieve the content from the MP, it first sends the query to the server and asks for the forwarding hint. On receiving the forwarding hint, the consumer node adds it in the Interest packet which helps to locate the producer. However, this approach suffers from a single point of failure issue, and also each domain requires to have its own local DNS mapping server which ultimately increases the management overhead.

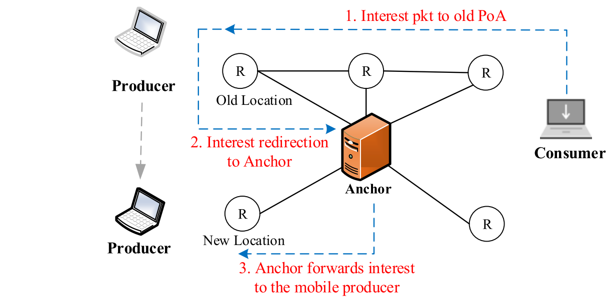
In another mapping-based approach proposed in [47], a locator/id split mechanism is used in which the consumer includes an additional field in the Interest packet i.e., the location name. When an IR receives the Interest packet, it first searches the content name in its cache storage as per the NDN scheme. If the content is not available in the CS, it checks the location name in the Interest packet and matches the location info with the one stored in the FIB table, and forwards the Interest accordingly. Hence, the Interest packets in which the location field is included require two lookups at a router. In the proposed scheme, an HR is deployed in the MP's home domain. MP maps the binding info in the HR, and as a result, when a consumer wants to connect with the MP, it accesses the HR first. The HR on receiving the Interest packet forwards it to the MP according to the binding info. Whenever MP changes its location, it keeps updating the binding in the HR. Consumer node on receiving the content from the MP after the handoff can directly forward the subsequent requests to the MP rather than contacting HR. However, the double lookup mechanism increases the searching cost of this scheme, resulting in increased average delay.

In [48], Azgin et al proposed a mapping-based approach in which producer mobility is handled by the dedicated nodes in the network. Although the use-case scenario in the paper is considering vehicles as mobile nodes, the proposed scheme mainly considers the static and wired connected nodes in the network. In their proposal, the MP nodes are tracked by the distributed controllers such as the local controller and home controller. Multiple domains are assumed based on the AS and each AS consists of the local controller, edge router, and service router. The MPs register their PoA with the local controller and proactively update the location by sending a route-update message. When the consumer node forwards the Interest packet, it is first explored in the service router's local cache either for Data or route. In the absence of a route, the local controller is contacted that performs a lookup on its local cache for the route. If the route is not present, the local controller contacts other AS local controllers to fetch the latest route towards the MP node. Once the route towards the producer node is discovered, the route information is forwarded to the edge routers which then forwards the Interest packet by employing the NDN principles. On receiving the Data packet, the edge router forwards it toward the service router, and eventually, the consumer node receives the Data.

Kim et al [49] proposed a mapping-based approach to resolve the producer mobility issue in which, when a MP moves to the new location, it sends the mobility update (MU) Interest message to an immobile anchor (may refer to as



(a): Mobility update to the anchor due to producer's relocation.



(b): Interest redirection after producer's relocation.

FIGURE 8. Anchor-based mobility solution.

rendezvous) node. The role of the immobile anchor node is to keep track of the MP node as shown in Figure 8(a). When the MP changes its location, it sends the mobility update Interest packet to the anchor node so that it keeps the mapping between the MP and its new location (step 1 & 2). Figure 8(b) illustrates the content retrieval mechanism after the producer handover event. When the Interest packet arrives at the old position of producer after the handover event, it is immediately redirected towards the anchor node instead of being dropped (steps 1 & 2 respectively). The anchor node forwards the Interest packet to the new PoA of the producer tracing the MU sent by the producer (step 3). This approach helps in reducing the content retrieval delay as it does not require Interest retransmissions. Instead, the Interest is seamlessly directed towards the new location of the producer. In so doing, the proposed scheme provides mobility transparency and the end-user's application does not face delay or QoS disruptions. However, this approach causes signaling overhead in the network due to the handover processes.

In [50], the authors proposed a producer mobility support (PPMS) scheme in which a new packet is introduced named mobility Interest (MI). This MI packet contains two fields: 1) mobility flag and 2) anchor tag. Similar to previous schemes described in this subsection, the proposed scheme employs an immobile anchor node (MAN)—a kind of centralized mapping entity, responsible for managing the mobility events that occur in the network. When the MP performs handover from one location to another, it sends an MI packet to the MAN to inform about its mobility. The MAN, on receiving the MI packet updates the FIB entries on all IRs. Consequently, when the consumer transmits the Interest after the producer handover, it chooses the optimal path towards the producer, as the FIB tables are now updated with the new information. Since the FIB entries are updated in advance— even before the consumer ascertains the mobility events in the network—empowers the proposed scheme to provide mobility transparency. Therefore, the end-user i.e., the consumer node does not face any mobility-related issues such as excessive delays in retrieving the remaining chunks of the Data packet. However, updating all IRs' FIB entries is questionable as it may induce a significant performance overhead in the network.

Zheng et al. [51] proposed an extended version of an anchor-based mobility solution in which multiple anchors are placed in the network, responsible for managing the access information of the mobile nodes. These anchor nodes (AN) are also referred to as anchor chains. In the proposed approach, each anchor node maintains the mapping list (ML) storing information such as the prefix of content being produced under the producer, the current location of the producer, and the new location where the producer relocates. Moreover, these anchor nodes also store the information of the neighboring anchor nodes in neighbor AN information (NAI), thus developing an anchor chain in the network. When a producer attaches to AN, the AN sends a control Interest packet to the closest AN to generate the mapping list to reach the producer node. Subsequently, the AN then further forwards this information to the upper-level AN until it forms a complete anchor chain in the network. The consumer nodes utilize the newly formed anchor chain to reach the producer and fetch the required content. Since the mobility-related information is updated in advance—even before the handover event occurs in the network, the consumer node application does not experience any delays or service disturbance. As a result, the proposed scheme provides mobility transparency to the end-user. Moreover, this scheme reduces the handover delay, as the anchor chain updates the network before the producer handover. However, the update mechanism for the whole network can increase network congestion.

a: PROXY-BASED MOBILITY MANAGEMENT SCHEMES

In [52], the authors proposed proxy-based mobility support in named data networking (PMNDN). In the proposed scheme, two functional entities are introduced named 1) NDN AR (NAR) and 2) proxy server (PS). NAR tracks the mobile content source and initiates the handoff signaling to the PS which is responsible for delivering the information of the mobile source. Both the NAR and PS cache the incoming Interests during the handoff event and when the MP attaches to the new NAR or new PS, the cached Interest packets are forwarded from the old PS to the new PS. The new PS, on receiving the outstanding Interest packets immediately responds with the Data packet, hence reducing the handoff delay. Moreover, the authors introduced two new data structures named 1) source location table (SLT) and 2) Interest packet store (IPS), to support the various operations in their proposed scheme. Among them, the SLT keeps the tracks of MPs attached to the

NAR or PS, whereas the IPS stores the outstanding Interest packets.

In [53], Hu et al. proposed a proxy-based scheme in which the network is divided into multiple domains and then each domain is administrated by the domain proxy (DP). The DP has all the topological information of all nodes under its administration and acts as a gateway when required. To resolve the producer mobility issue, DP sets a special bit named flag in the PIT entries. When the MP considers relocating to the new position, it informs the DP about its handoff and the content it owns. DP sets the flag to '1' during the producer's handoff and sets it to '0' otherwise. This approach considers two types of handoffs: 1) intra-domain handoff and 2) inter-domain handoff. Similar to [52], during the handoff, DP buffers the Interest packets destined for the MP, and after receiving the handoff completion message (HOCMP) from the producer, the DP forwards these outstanding Interest packets to the producer. The corresponding Data packets are traversed back from the same path towards the DP and then finally delivered to the consumer. Using this approach, DP does not need to change all the routing information during the intra-domain handoff, hence, reducing the retrieval delay. However, for the inter-domain handoff, it needs to change the gateway information so that Interest can go to the new location of the producer.

b: CONTROLLER-BASED MOBILITY MANAGEMENT SCHEMES

Tang et al. [54], proposed a data/control plane-based solution to support the producer mobility in NDN. In this scheme, the whole network is divided into multiple rendezvous domains (RD). Each RD has a resource handler (RH) which acts as an SDN controller and updates the location information of the attached MP in case if the producer moves from one location to another. RH is also well-aware of the network topology and the information of IRs attached to the same RD. When MP joins the IR, RH assigns a rendezvous point (RP) which keeps the local binding information of MP. This binding of RP to MP, also known as global binding, is then kept at the home repository (HoR). Both the local binding as well as the global binding is stored at the RH. In this scheme, it is assumed that each MP has its own HoR which is placed at its home RD. When a consumer wants to retrieve the content from MP for the first time, it forwards the packet to the HoR of the MP which inserts the global locator of MP i.e., RP in the Interest packet. Once the RP receives the Interest packet, it then forwards it using local binding information towards the MP. Regarding the MP handoff, this scheme considers both the inter and intra-domain handoff. During intradomain handoff, RH just updates the local binding information of MP. In the case of inter-domain, RH updates the global binding information in the HoR as well. This updated binding information is then forwarded to the previous RP also. This approach reduces the handoff latency in the case of intra-domain handoff. However, it increases the handoff latency in the inter-domain handoff. Also, there is a huge signaling overhead since the signaling messages are forwarded among various nodes.

In [55], the authors improved the [54] scheme and proposed a mobility management scheme based on a software-defined controller (SDC). In the proposed scheme, when a content producer moves from one point of attachment to another, it sends a handoff initiation message to the connected router. The router forwards this message to the SDC following SDN principles. During the handoff, SDC receives the Interests targeted for the producer. When the content producer attaches to the new point of attachment, it sends the handoff accomplishment message to the newly attached router, which then forwards it to SDC. After receiving the handoff accomplishment message, SDC rewrites the routing table with the updated path of the content producer and sends these routing table updates to the relevant content routers. The routers, on receiving the updates, modify their FIBs with new routing information. After that, the incoming Interests received during the producer handoff are then forwarded to the new PoA. This scheme reduces the overhead during the producer handoff.

In [56], the authors proposed another SDN controller-based approach in which the SDN performs the mobility management whenever the MP changes its location. This scheme introduces two types of control packets named 1) Move report which is sent by the MP to the controller when it changes its location and 2) Link state packet which is sent by the routing nodes to the controller. SDN controller updates the FIB of NDN nodes when MP changes its location. Based on the number of hops among the original producer node and currently attached NDN nodes, SDN decides to either make local FIB updates or global FIB updates. As the global updates require each node to update its FIB, it creates significant control traffic which leads to congestion in the network. To avoid the huge control traffic, a local FIB update mechanism can be adopted by SDN.

Summary and Insight: This section outlined the mapping-based mobility management schemes proposed in the NDN literature, in which a centralized server is used to keep track of the MP node. Mapping-based schemes include different categories such as using anchor node or home router, controller-based schemes and include the proxy-based servers. Although such schemes resolve the producer mobility management issues, however, most of these schemes suffer the single point of failure issue. These schemes stop working if the mapping server or DNS becomes unavailable due to excessive load or some other unforeseeable reason. Also, utilizing the centralized entity to redirect the Interest or Data packet on behalf of endpoints may increase network delay. For instance, consider a scenario in which the centralized server is located 5 hops away from the consumer node, whereas the mobile producer node relocated to the new location just 2 hops away from the consumer. Following the mapping-based redirection approach, the Interest and

Data packets will take 10 hops rather than the 4 hops if both consumer and producer communicate directly. However, we agree that providing a solution that travels 4 hops is not straightforward and requires further research effort in this direction. Moreover, similar to the tracing-based approaches, a few mapping based schemes presented in [46], [47], and [48] subject to the high network overheads in terms of excessive bandwidth utilization and energy consumption and therefore require efficient solutions.

3) CACHING BASED MOBILITY MANAGEMENT SCHEMES

Caching is one of the most widely used and default NDN features that support producer mobility in the network. By exploiting NDN caching, the content can be proactively stored on the node in the proximity of mobile nodes enabling the consumer nodes to fetch the content from the neighboring nodes even if the mobile node has changed the location in the network. However, the selection of the best caching node, predicting the requested content popularity, and replacing the content in cache requires various modifications in the existing communication flow of NDN. These modifications along with the efficient node selection mechanisms, are presented in the following. Table 5 briefly highlights the contributions and limitations of caching based producer mobility management schemes.

In [57], the authors proposed a proactive data replication scheme named 'OpCacheMob' to resolve the producer mobility issue in the network. This scheme predicts the content to be requested in the near future from the mobile producer and cache it for future use. In addition to the content prediction, the authors try to minimize the network overhead by proposing an optimization scheme subject to constraints such as 1) available CS storage capacity, 2) limiting the distance between caching node and consumer node, and 3) restricting the amount of traffic that is required to support the producer mobility. The main goal of this scheme is twofold: 1) provide the content even when the producer is disconnected and 2) reduce the network overhead as much as possible. However, the scheme lacks support for real-time communication and thus only suitable for static content generated from the mobile producer node.

The use of in-network caching in ICN is beneficial to deal with the producer mobility issues especially in the vehicular environment as it helps the consumer vehicle to access the required content from the nearest convenient cache-store [58].

The authors in [59] proposed a mobility-aware proactive edge caching optimization scheme for information-centric internet of vehicles (IoV) networks aiming to enable delay-sensitive services to IoV networks by adopting the Markov chain to model vehicles' mobility and their connection with corresponding RSUs. The proposed work applied mobility-aware edge caching with the objective enhance the network performance by reducing the transmission delay. The numerical simulation revealed that the proposed work outperformed related caching schemes in terms of latency and cache hit ratio. Apart from the benefits, the proposed scheme requires the deployment of additional edge servers to support proactive caching optimization. This can increase deployment cost and complexity. Moreover, the mechanism relies on mobility prediction in order to proactively cache content at different edge nodes. The mobility prediction may not always be reliable, leading to sub-optimal caching decisions.

In [60], the authors proposed a producer mobility management scheme in NDN for both real-time and non-real-time content named as ProPull and ProCache respectively. For the non-real-time content, a simple caching mechanism is used in which the producer node offloads the content to the current PoA before moving toward the new PoA. In doing so, the subsequent requests for the content can be fulfilled directly from the old PoA cache without forwarding the Interest packet to the new PoA. Contrarily, in real-time scenarios, once the producer node is connected to the new PoA, updates the new location in the network by sending out an Interest packet named propaganda Interest (PI) toward the old PoA. The old PoA then responds with a Propaganda Data packet which updates FIB entries on the way back to the new PoA. In so doing, the old PoA forwards all the subsequent requests towards the new PoA. Although this scheme tries to resolve the producer mobility issues in NDN, nevertheless, both the ProCache and ProPull mechanisms are not effective in certain scenarios. In the former solution, offloading all the content to PoA may overload its CS storage whereas, in the later solution, network overhead may increase due to PI and PD packet exchange.

By exploiting the NDN caching [61] feature, the authors in [62] proposed a cache sharing mechanism that effectively resolves the producer mobility issue in VANETs. In the proposed mechanism, the content is cached at the network edge (a roadside unit) to mitigate the effects of producer mobility or unavailability. As a result, if the producer moves, the Data can still be accessed from the network edge which ultimately improves the Interest satisfaction rate. Similar to this work, in [63], the authors presented the concept of virtual caches in ICN-connected vehicles in which the nodes can exchange the cached content on-demand which can later be used in case if the producer node is unavailable or moved.

Proactive caching, a subtype of caching, is an approach that is used to reduce the Interest retransmissions due to the handover of the mobile producer. In [64], the authors proposed such a scheme in which the future request pattern of a node is predicted, and as a result, the predicted content is proactively cached from MPs to the network caches before the handover event occurs. In doing so, when a consumer requests content after the producer moves to the new location, it can retrieve the required content immediately from the cache without Interest retransmissions. Similarly, Korla et al. [65] improve the producer mobility by exploiting the caching capabilities at the edge routers that are in the proximity of the producer. The popular content is cached at the edge router before the producer node changes its location. For the

TABLE 5. Caching-based producer mobility schemes.

Category	Contributions	Limitations	Ref.
Caching-based approaches	• Predicting the future request content to proactively replicate the data scheme and also minimizing the network overhead by considering various parameters	• Lacks support for real-time content delivery	[57]
	• Mobility-aware proactive edge caching optimization scheme	• Additional edge servers deployment to support caching	[59]
	• Producer node caches the non-real-time content to current PoA before moving to new PoA and for the real-time content, it updates the new location by exchanging special messages with old PoA	• Offloading content proactively may overload CS storage. • Exchanging special messages to update location may increase overhead	[60]
	• A cache sharing mechanism, which caches content at the network edge to mitigate effects of producer mobility or unavailability.	• Requires extra data structures. • Opportunistic caching may not satisfy future demands and lead to wastage of resources.	[62]
	• A concept of virtual cache where data can be exchanged among the nodes on demand.	• Collision may increase as the connecting vehicles are exchanging extra information to enable proactive caching.	[63]
	• Predicting the future request pattern of the user and proactively caching the predicted content at nearby nodes before producer handover	• Not suitable for the real-time communication	[64]
	• Exploiting the caching capabilities of edge content routers that are close to the producer to cache the popular content before the mobile producer relocates	• Only caches the content with high popularity	[65]
	• Proactively caching the data by predicting the next RSU for the vehicle using various parameters such as geo-location, speed, interest frequency of vehicle	• It does not consider variable vehicular node speed. • No V2V communication	[66]
	• Prefetching the data at the roadside units based on its popularity, also considering the content freshness.	• To determine the exact place for content placement is challenging.	[67]
	• Predicting the next RSU of the vehicle to locate a suitable prefetching node to cache the content in advance	• Excessive retrieval delay in the case of inaccurate predictions • Additional overhead for obtaining network information	[68]
	• Using Markov model to predict the next RSUs for vehicle and then comparing the transition probabilities of predicted RSUs to assign the number of chunks to cache accordingly	• Excessive retrieval delay in the case of inaccurate predictions • Inaccurate prediction led to the unused cache storage	[69]
	• Prefetching mechanism to employ vehicular to vehicular communication infrastructure proposing two types of prefetching i-e RapidVFetch and Realtime RapidVFetch.	• Prefetching Interest packet loss due to wireless channel is not handled. • Extra overhead on RSU due to multiple prefetching in dense traffic scenarios	[70]

cache replacement strategy, the content popularity is measured to replace the cached content. Although, this approach is interesting, it fails to take into account the unpopular content.

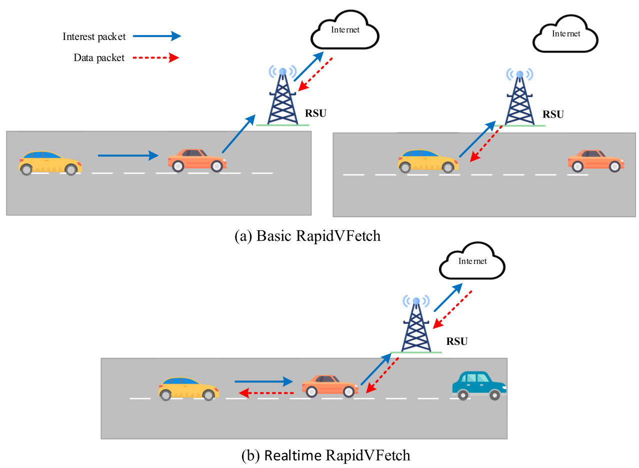


FIGURE 9. Examples of operations of RapidVFetch.

Zhang et al [66] presented a prefetching mechanism by employing vehicular to vehicular communication infrastructure and proposed two different types of prefetching: 1) RapidVFetch for general content and 2) real-time RapidVFetch for video streaming. Initially, when a vehicle is out of the RSU range, it forwards an Interest packet to its neighboring vehicle, which then forwards the packet to the RSU. Once the Interest packet is received at RSU, it prefetches the content from the producer node. Later, when the requesting vehicle enters the RSU range, it retransmits a similar Interest, and eventually, the Data is received directly from RSU. The operations of basic RapidVFetch and real-time RapidVFetch are presented in Figure 9. In Figure 9(a), in the basic RapidVFetch mechanism, the vehicle prefetches, and caches the content at the upcoming RSU using the neighboring vehicles and it retrieves that content by reissuing the Interest to the RSU when it reaches close to the RSU. Whereas Figure 9(b) presents the real-time RapidVFetch scenario, in which the vehicle forwards the request to the RSU using the next neighboring vehicle as a forwarder and that neighboring vehicle fetches the content back to the consumer. This mechanism is used for the retrieval of real-time content.

In [67], Grewe et al. proposed a proactive caching scheme in which the producer nodes proactively cache the Data at the RSU for the future. Authors employed various parameters such as geo-location of a vehicle, speed, and Interest frequency, to predict the next RSU for a vehicle. Once the next RSU is determined, the network downloads the content in advance. This scheme improves the network efficiency by proactively caching the data one hop away from the consumer. In another approach [68], the authors proposed a similar scheme in which data is prefetched at the roadside units based on its popularity. The authors also consider the content freshness to save the storage space at RSU.

Similarly, in [69], the authors proposed a mobility prediction-based proactive caching scheme in the vehicular environment. In this approach, the producer mobility is predicted by predicting the next RSU, by which the vehicle that may pass through, using the Markov base predictors. However, there can be uncertainties in the mobility predictions. Entropy is used to measure the uncertainties in these predictions, which helps to locate the best suitable prefetching node to cache the content. Park et al. [70] also proposed a prediction-based proactive caching scheme in the vehicular network. In this scheme, when a vehicle requests the content from the RSU, it determines that how much content a vehicle can receive from a single RSU. It then downloads that content from the content server and provides the vehicle with as much content as possible. The current RSU then uses the Markov model with the historical information of the vehicle, to calculate the next RSU for the cache allocation. The transition probabilities for the next RSUs are calculated. The RSU with more transition probability is assigned with more content chunks to cache and vice versa. The current RSU then transmits the distributed information containing the identifier of the next RSU with the content chunk numbers to be cached in it. The next allocated RSU then caches the content chunks mentioned in the distributed information. Both [69] and [70] aim to reduce the cache redundancy and the content retrieval delay. However, if these schemes fail to make predictions accurately, it may cause excessive delay in content retrieval and CS storage will be unnecessarily populated.

Summary and Insight: In this subsection, we surveyed the existing efforts exploiting the NDN caching feature to resolve the mobility issues in the network. Most of the presented schemes target the particular facets of VANETs such as vehicle to infrastructure (V21) and vehicle to vehicle (V2V), or the general mobility use case scenarios. We observe that majority of these schemes utilize the proactive caching mechanism in which the popular content is fetched in advance on either the neighboring nodes or on the network edge. In terms of mobility transparency, these schemes, in general, provide transparent mobility to the consumer nodes in the network. The obvious rationale is that the MP node before relocating to the new location caches the content on the immediate neighboring nodes. In so doing, the consumer Interest request is immediately fulfilled even in the absence of a producer node, consequently, decreases the delay which may occur otherwise if the consumer node retransmits the Interest packet in the network towards the new location of the producer. Some schemes such as [67], [68], [69], and [70] presented the solution in which the outstanding chunks of the requested content are fetched beforehand on the network edge in the direction of moving nodes. Although these schemes resolve the mobility issues, the prediction mechanism is highly dependent on the estimation which if estimated incorrectly result in excessive resource utilization issues. Furthermore, considering the high speed of moving vehicles on the road, this prefetching of content on the next RSUs may increase the control overhead in the network. The rationale is that each time the vehicle enters into the next RSU range, the RSU initiates a new request–if the content is not available in local caches–to fetch the content from the producer node. To this end, a novel solution that fetches the content by utilizing the previous RSU is required. By doing so, the routing paths established by the previous RSU can be utilized to fetch the desired content from the producer node. In summary, further in-depth analysis is required in the direction of the aforementioned highlighted issues and their possible solution aiming to decrease the networking overhead.

4) BROADCAST CONTROL BASED MOBILITY MANAGEMENT SCHEMES

The broadcast control-based schemes aim to reduce the redundant packets exchanged in the network and at the same ensure successful packet delivery in the network. To this end, various concepts such as time to live (TTL), packet suppression, and restricting hop-count, are utilized to decrease the unnecessary and redundant transmissions of both Interest and Data packets in the network. In the following, we described the working principles of these schemes including their shortcomings. In Table 6, the contributions and limitations of each broadcast control based producer mobility management schemes are presented.

In [71], the authors proposed a hop count-based forwarding strategy to cope with the producer mobility problem. Two fields i.e., the hop count and hop count threshold are introduced in the Interest packet. When an Interest packet arrives at the IR, it makes the forwarding decision based on the hop count and decides whether to forward the Interest packet to the matched interface in the FIB entries or broadcast it to all the available interfaces. If the hop count value is less than the threshold, the IR forwards the Interest packet on the matched interface, thus avoiding the unnecessary broadcast storm in the network. On the contrary, if the hop count threshold is achieved and the producer node is not located yet, the IR broadcast the Interest on all available interfaces.

Similarly in another hop-count-based scheme proposed in [72], the authors control the Data packet storm in the network by adding the hop count limit on the Data dissemination by MP vehicle node. This scheme considers a push-based Data communication scenario in VANET and therefore alters the fundamental communication style that advocates the use of a consumer-initiated pull-based communication model. Since the vehicle nodes in this scheme are equipped with a wireless ad hoc interface, the packet transmission is broadcasted in the radio range of a vehicle, thus creating the broadcast storm if all other neighboring vehicles forward the Data packet again. Although the hop-count limit in such mobile wireless ad hoc scenario reduces the unnecessary packet transmission to some extent, nevertheless, the redundant packets are forwarded due to high node density in the producer vehicle proximity. In [73] authors proposed a Context-aware naming and forwarding for NDN-based VANETs aiming to effectively disseminate the road events such as road works, accident notifications, and traffic jams. In this work, the transmission range of the Interest sender is divided into 8 forwarding angles (FAs) where the 4 FAs correspond to the high-priority forwarding zones (i.e., red forwarding zones (RFZs)) while the remaining four FAs are low-priority forwarding zones i.e., white forwarding zones (WFZ). Nodes in RFZs and those that are far from the most recent Interest sender have a high likelihood of being selected as forwarders. In so doing, the number of hops are decreased that in turn decreases the transmission and chances of congestion. Despite the advantages, the proposed work has limitations such as the assumption that the vehicles have enough storage to record the context information may not always be possible, especially in a resource-constrained environment such as the vehicles with limited storage capacity. Moreover, the proposed scheme may introduce an additional search cost owing to the context information lookup, which can affect real-time communication in VANETs.

The optimal producer mobility support system (OPMSS) [74] was proposed to reduce unnecessary delays and packet loss by offering an optimized path to forward the data when the mobile producer changes its location. Simulation-based results revealed that OPMSS effectively reduced the interest packet losses and delay by maintaining almost equal and tolerable signalling overhead costs. Along with the benefits, there are some limitations such as the proposed work highly depends on producer mobility prediction in order to proactively update routing tables, and any erroneous prediction may lead to false routing decisions. In addition, the proposed work may also require frequent routing updates, which may induce additional network overhead and enhance network latency.

The authors in [75] proposed a novel fuzzy logic scheme for push-based critical data broadcast mitigation in VNDN (FLPDF) to reduce the broadcast storm in the network. This work organized vehicles into clusters via K-means clustering, and fuzzy logic is adopted for Cluster Heads (CHs) selection where each CH is responsible for sharing critical data with its cluster members. In addition, a gateway node is also employed to carry out the inter-CH communication. The evaluation results showed that the proposed work outperformed the naïve mechanisms in terms of data packet transmissions and boosts overall efficiency. The proposed work also has some limitations such as: it is assumed that all nodes have identical resources to execute the fuzzy logic-based operation, which may not be feasible in low-resource environments. In addition, the fuzzy logic computation may induce additional latency, which can affect real-time communication in VNDN. Similarly, another novel broadcast control mechanism named redundancy elimination forwarding (REF) [76] was proposed that mainly targets controlling the redundant packets dissemination by modifying the NDN node architecture and PIT operation. In this scheme, the PIT is searched prior to the CS similar to conventional NDN. The rationale is to minimize the searching overhead and to reduce the duplicated Interest packet transmission. The simulation results showed that REF achieved high throughput,

TABLE 6. Broadcast control mechanism based producer mobility schemes.

Category	Contributions	Limitations	Ref.
Broadcast control mechanisms	• Including hop count in the interest packet and making the forwarding decisions based on it	• Topology dependent	[71]
	• Introducing push-based data dissemination in the VANET scenario in which mobile producer adds the hop count limit to reduce the unnecessary packet transmission	• High node density in producer vehicle proximity increases redundancy	[72]
	• Context-aware naming and forwarding in vehicular named data networking to reduce broadcast storm and network congestion	• Vehicular storage capacity • Additional search cost owing to the context information lookup	[73]
	• Producer mobility support system to reduce signaling overhead and broadcast storm	• Additional network overhead owing to frequent routing updates	[74]
	• Fuzzy logic scheme for push-based critical data broadcast mitigation in VNDN	• Additional delays owing to fuzzy logic computations	[75]
	• Novel broadcast control mechanism to control the redundant packets dissemination	• Additional overhead due to the huge number of Interest packet transmissions for reference discovery and storage	[76]
	• Another push-based data dissemination includes two types of naming schemes that limit the data broadcast within its own RSU coverage.	• Does not consider time validity and angle to avoid Data redundancy	[77]
	• Pushing one-hop beacon message before the critical Data dissemination to create synthetic PIT entries	• Beacon broadcast storm • Lack of suppression of beacon packets causes congestion in the network	[78]
	• Controlled data dissemination scheme for vehicular NDN that includes a hop-count field to avoid the broadcast storm in case of producer mobility.	• The problem of the broadcast storm of Interest packets is not considered. • Low efficiency in cases where the provider and consumer nodes are far from each other.	[79]
	• Introducing a PIT entry lifetime mechanism that helps in supporting producer mobility	• Huge broadcast storm in dense network scenario • Fixed number of hops	[80]
	• Proposed a dual-mode suppression mechanism which avoids broadcast storm in the case of producer relocation	• Not suitable for frequent mobility scenarios in resource-constrained IoTs	[81]

and reduced transmission overhead and resource utilization. Apart from the benefits, REF ignored the mobility pattern and speed in its decision-making progress which may affect the performance in mobile scenarios. Moreover, REF may generate an additional overhead due to the huge number of Interest packet transmissions for reference discovery and storage, which may degrade the network performance.

In [77], authors proposed a hierarchical named-based mechanism for push-based data broadcast control for VANETs. Similar to [72], the authors in [77] also consider push-based data dissemination in the network and avoid the unnecessary packet transmission by proposing two types of naming schemes: 1) content naming scheme and 2) vehicle naming scheme. The structure of the content naming scheme is as follows: "/Vehicle ID/RSUID/Direction/Speed | payload" that includes the vehicle as well as RSU identity, whereas the vehicle naming scheme includes Vehicle ID and RSUID and construct a name as follows: "Vehicle ID/

RSUID''. Following the working principles of [77], when a vehicle receives the Data packet carrying the aforementioned content naming scheme, compares its second component: RSUID with the RSUID of its own vehicle level naming scheme. In case of a successful match, the receiving vehicle further broadcast the Data packet in its radio range or in other words, in the RSU coverage; otherwise suppresses the transmission. Since this scheme avoids unnecessary transmission by only taking into account the RSU coverage area, nevertheless a large number of redundant packets are forwarded in the network which can be avoided if we utilize the other metrics such as angle and time validity.

In [78], authors proposed beacon-enabled push-based data dissemination for VANETs. In the proposed scheme, a beacon packet is transmitted in the network to create the synthetic PIT entries that are consumed by future push-based Data packets. Once the PIT entries are created, the broadcast storm of Data packets can be avoided because the IR selects a limited set of the interface while forwarding the Data packet to the downstream nodes. Although the proposed scheme resolves the Data broadcast issues, it suffers from the beacon broadcast storm in the network. There is no doubt that the size of the beacon packet is small and resource consumption in beacon transmission is comparatively low, nevertheless, it creates congestion in the network due to the lack of any suppression mechanism.

In [79], Ahmed et al proposed a controlled data dissemination scheme for vehicular NDN (VNDN) named CONET. The authors introduced a hop-count field in the Interest packet and a TTL field in the Data packet. The hop count aims to restrict the Interest packet to a specific number of communication hops to avoid the Interest broadcast storm. Similarly, the rationale for including the TTL field is to avoid the Data broadcast storm in case of producer mobility. In another scheme proposed in [80], an adaptive PIT entry lifetime mechanism based on numbers of hops and data link layer parameters, is presented. Further, Zhang et al in [81] proposed a dual-mode packet suppression mechanism to avoid the broadcast storm in the network. Initially, in the absence of FIB entries, the Interest packet is transmitted in a control broadcast manner (flooding mode) following different techniques such as packet suppression and TTL. Once the FIB entries are populated in the initial phase, the Interest is then forwarded in a directive unicast mode. In so doing, the proposed scheme avoids the redundant packet transmission in the network, even when the producer node relocates from one position to another.

Summary and Insight: In this subsection, we presented a comprehensive outline of existing broadcast control-based mobility management schemes proposed for NDN. Based on the underlying working mechanism of these schemes, we can classify them into three categories: 1) hop-count-based, 2) packet suppression, and 3) name-based techniques. A critical overview of these three categories while focusing on the advantages and disadvantages of each proposed scheme is presented. Comparing these schemes with the ones presented in previous subsections, we can see that mobility issues in wireless ad-hoc communication scenarios vary from the wired networks. One obvious difference in wireless communication scenarios is that the mobile nodes are not connected to a certain PoA which on the other hand in wired networks is most common. Rather, these nodes communicate on their own by employing the wireless ad-hoc interface, and when relocating to the new location, the nodes employ the single interface wireless broadcasting techniques to populate the FIB entries on the neighboring nodes. In addition to hop-count, packet suppression, and name-based techniques, we believe that adding angle information in forwarding decisions has the potential to further reduce the redundant packet transmission. For instance, when a node receives an Interest packet, after validating the hop-count, duplication, and name matching, it should check the angle from the previous node. If the node lies in that angle which points towards the producer node, then it should forward the packet and otherwise should drop the packet. However, we agree that the angle calculation is not straight forward and therefore a further research effort is required in this direction. Moreover, a few schemes such as [72] and [80] are not suitable for the highly dense network scenarios because these schemes tend to create high broadcast storm instead of controlling it.

5) ADAPTIVE FORWARDING BASED MOBILITY MANAGEMENT SCHEMES

The adaptive forwarding schemes try to recover the forwarding path, altered by the mobile producer, on the fly by observing the Interest/Data packet exchanges in the network. The main goal in such schemes is to fetch the data from the optimal shortest route, quickly detect the forwarding path failures, and instantaneous recovery of the broken paths to maintain seamless communication [82]. Table 7 briefly describes the contributions and limitations of each adaptive forwarding-based producer mobility management scheme.

Meddeb et al. [83] proposed an adaptive forwarding-based link recovery (AFIRM) strategy to resolve the producer mobility issues and to increase the content availability in dynamic environments. This scheme consists of two phases: 1) FIB construction phase and 2) link recovery phase for producer mobility. In the FIB construction phase, Interest flooding is employed to retrieve the routing information and to populate the FIB entries. In response to the Interest flooding, when a node receives the Data packets, it adds the incoming and outgoing interfaces in the FIB with the name and prefixes of content. The number of hops between the producer and receiver node is added in the FIB entries to select the best next-hop forwarder for future requests. The second phase i.e., the link recovery phase, is used to update the old and new paths to resolve the producer mobility for new Interests. To detect the producer movement, this phase uses a keep-alive mechanism. In this mechanism, the gateway periodically sends the ping messages to check if the producer

TABLE 7. Adaptive forwarding-based producer mobility schemes.

Category	Contributions	Limitations	Ref.
Adaptive forwarding based approaches	• A distributive and adaptive forwarding scheme that uses link recovery phase to handle the producer mobility	• Increased overhead	[83]
	• Forwarding decisions are made based on the node's success in retrieving content and geolocation information.	• Low ISR due to the repeated calculations of content connectivity store and location store values in a highly dynamic environment	[84]
	• An adaptive mobile video streaming and sharing mechanism	• Proposed for the 3G/4G cellular network and thus lacks the support for 5G communication	[85]
	• Producer to consumer notification	• Scalability issues in scenarios where consumers are in abundance	[86]
	• Context-aware adaptive routing and forwarding model for NDN-based VANET	• Constant monitoring of the surroundings to update mobile nodes routing and forwarding tables	[87][88]
	• Software-defined mobility architecture to address mobility issues	• Single point of failure and excessive information collection issues in large scale networks	[89]

is still attached to its PoA. If it does not receive the response from the producer, it sends the recovery message with the content name to delete this path. The producer attached to the new PoA sends the positive recovery message to add the new forwarding information in the FIBs.

In [84], the authors proposed an adaptive forwarding scheme for VANET named content connectivity and location-aware forwarding (CCLF). In CCLF, the nodes broadcast the NDN packets and allow other nodes to make independent decisions. These decisions are based on two factors 1) the success of the node in retrieving content, and 2) geo-location information. More explicitly, the node sets a timer and forwards the packet on the timer expiration. The timer is set in a way that the nodes which have a shorter distance to the data location and better success ratio will forward the Interest first. The neighboring nodes overhear the transmission and suppress their forwarding in case the same packet is forwarded. This density-aware suppression mechanism, in conjunction with the smart forwarding timer, significantly reduces unnecessary packet transmissions and improves the communication mobility scenarios.

The authors in [85] provided an adaptive mobile video streaming and sharing mechanism by leveraging the multi homing feature of NDN and aiming to address the video traffic issue. In this scheme, the mobile nodes first try to fetch the video content from local devices connected with the Wi-Fi. If the content is not available locally, the mobile nodes then switch to the cellular interface and fetch the content from the server by adaptively adjusting the bit rate.

In [86], the authors proposed a producer mobility management scheme where the producer node notifies the consumer node and the network about the mobility by using a mobility notification packet (MNP) after initiating the handoff event. As soon as the consumer node receives the MNP, it stops forwarding the Interest packets to the producer to avoid the packet loss. After arriving at the new location, the producer node forwards the mobility update packet (MUP) toward the consumer node. On receiving the update packet, the consumer node restarts the Interest forwarding mechanism toward the new location of mobile producer. In the proposed scheme, the newly introduced packet i.e., MNP and MUP follow the modified forwarding plane instead of utilizing the FIB routing information. The proposed scheme aims to reduce the packet loss as well as the high bandwidth and signaling cost, however, the scheme does not provide any suitable solution for the Interest packets that arrived during the handoff mechanism, hence increasing the overall content retrieval delay.

The authors in [87] and [88] developed a context-aware routing and forwarding model (CARF-NDN) for NDN-Based VANET. The main motivation behind their approach is to extract position information and create a database of a vehicle's neighbors by utilizing overhead packets rather than beacon broadcast. The interest packets are then sent using a geographical forwarding technique to their final destinations. The downside of the proposed scheme is that the use of context-aware routing and forwarding in NDN-based VANETs may result in additional overhead, as the nodes may require to constantly monitor the surroundings to update their routing and forwarding tables based on the context which may lead to an increased communication latency as well as packet losses.

In [89] Quality of Service (QoS)-aware Software Defined Mobility (SDM) architecture for Named Data Networking (NDN) was proposed. The proposed work utilizes SDM to address the mobility issues in NDN and enhance the QoS of the network. The architecture comprises of two key components: a centralized SDM controller and a distributed NDN forwarding plane. The SDM controller is responsible for managing the mobility of NDN nodes, while the NDN forwarding plane is responsible for forwarding NDN packets. The proposed work utilizes a QoS-aware handoff mechanism to achieve seamless handoff between different access points. In addition, the architecture also utilizes a QoS-aware path selection mechanism, which selects the path that provides the best QoS for data transmission. The proposed architecture also utilizes a QoS-aware caching mechanism, that caches the most frequently accessed data closer to the users, thereby reducing the latency and improving the QoS. The simulation results shown significant improvement in terms of handoff latency, network overhead, and data delivery ratio. Apart from the benefits, the proposed architecture requires a centralized SDM controller, which can introduce a single point of failure and increase network latency. Adding to this, the proposed scheme relies on network-wide knowledge of QoS, which can be difficult to obtain and maintain in large-scale networks.

Summary and Insight: In this subsection, we critically surveyed and presented the adaptive-based producer mobility schemes, and broadly categorized them into 1) mobility management in the wireless networks, and 2) mobility management in wired networks. These schemes detect network failures by constantly observing the Interest and Data packet exchanges in the network which comes at the cost of network overhead. Moreover, the Interest flooding mechanism proposed by some schemes to initially populate the FIB entries may storm the network with multiple packet exchanges subsequently increasing the chances of congestion in the network. To avoid such congestion scenarios, a solution such as the one presented in [84] has the potential to decrease the transmission intensity of the packet. However, choosing the optimal node for packet transmission, specifically in wireless mobile networking, requires a careful and effective selection procedure as the unpredictable contention in the wireless channel and intermittent connectivity due to fast-moving nodes frequently changes the network topology consequently invalidating the existing selection criteria. In terms of mobility transparency, the schemes such as [77] and [78] provide transparent mobility to the consumer nodes in the network. The reason is that these schemes tend to update the routing information immediately after encountering the producer movement employing various mechanisms such as the keep-alive method and Interest timer expiry based on the distance from the MP node.

6) LOCATION-BASED MOBILITY MANAGEMENT SCHEMES

Similar to other producer mobility management schemes, the objective of location-based schemes is to reduce the network traffic overhead. To this end, the geographical location of either the content itself or the original producer is employed to ensure content availability when the producer node moves from one geographical location to another. In the following, we surveyed some of the location-based mobility management schemes and provided our critical insight considering their underlying working mechanisms. A brief overview of each location-based mobility management scheme in terms of contribution and limitation is presented in Table 8

Duarte et al. [90] proposed the solution of source mobility in the vehicular environment by combining the concepts of floating content (FC) and home repository (HRP). The proposed scheme utilizes the concept of FC, according to which when a vehicle node moves from a certain region where initially the content was generated and advertised, it replicates the content to the remaining neighboring vehicle nodes in that certain location. By this means, the content remains in its location even when the mobile vehicle moves away. That certain geographical region where the content is originally produced and advertised is named as anchor zone (AZ). The vehicular nodes that receive the replicas make sure that they are in the same AZ to satisfy future content requests. Later, when these nodes leave the AZ, they also replicate the content to the other available nodes. However, this replication can cause huge overhead specifically in the wireless communication scenarios. To avoid extra overhead, the replications are made according to the density of vehicles within the AZ. In case when there is no vehicle available in the AZ to keep the replicas of content, the proposed scheme uses the concept of HRP combined with the FC to avoid unsatisfied requests. HR is kept in the region to keep the replicas of content.

In [91], the authors proposed a mobile VNDN framework in which a geolocation-based scheme is adopted to resolve the vehicular mobility issues. In this scheme, an advertisement packet is introduced by the authors, which is used by the content producers to disseminate information of available content objects in the network. The proposed scheme employs two content dissemination approaches:1) advertised content and 2) on-demand content. In the first approach, when the content producers generate the content, they send the advertisement messages in the network to advertise available content objects to the consumer vehicles. In the latter approach, content that has not been yet advertised by the producer is requested by the consumer vehicle on demand. To select the forwarders of advertisement messages, the sweet spot concept is introduced. Vehicles within the sweet spot (certain location) are considered to have a high probability of accessing a larger number of vehicles to forward advertisement messages. In this mechanism, each vehicle within the sweet spot selects a timer based on the distance to the destination vehicle. The vehicle closer to the destination sets a small timer and forwards the message as the timer expires. MobiVNDN to improve VANET application's performance in high mobility scenarios, and overcome the broadcast storms, and packet redundancy.

In [92] and [93], Rao et al. proposed a locator-based mobility management approach. In this approach, when a

TABLE 8. Location based producer mobility schemes.

Category	Contributions	Limitations	Ref.
Location-based approaches	• Presenting a VNDN approach by combining both the floating content and home repository schemes to keep the content within its certain original geographical region	• Inefficient global resource optimization	[90]
	• A geolocation based VNDN framework in which producer either advertises its content using timer-based distributed broadcast approach or provides the unadvertised content on demand	• The advertisement of undesired content may lead to network overhead. • Timer-based broadcast strategy causes network delay	[91]
	• Locator-based mobility management approach in which old PoA of mobile producer buffers interests during the producer handoff	• Not suitable for time-sensitive applications • No path optimization	[92], [93]
	• A controller-Based Intelligent Location and Energy Manager protocol	• Excessive network information collection communication workload	[94]
	• A robust location-based forwarding technique for low earth orbit (LEO) satellite networks	• Heavy degree of inter-nodes satellite coordination	[95]

MP changes its location, it sends an update message to its current PoA to inform about its handoff process. When the current PoA receives this handoff initiation message, it starts to buffer the Interest messages for the mobile producer during the producer handoff. When the mobile producer completes its handoff, it updates the old PoA about the completion of the handoff process. After receiving this handoff completion message, the old PoA modifies the Interest packets by updating the new location of the producer and forwards them all towards the producer. This approach reduces the handoff latency and helps to prevent the Interest packet loss on the path towards the old location of the mobile producer by buffering the Interest packets, however, it might not be suitable for time-sensitive applications.

The authors in [94] proposed a controller-based intelligent location and energy-aware protocol to address the consumer, producer, and intermediate mobility issues in wireless mobile ad-hoc networks. The SDN controller with an overall topological view and battery information of each networking node provide updated route information to the nodes in case of mobility events. Moreover, to keep the controller CENTRAL_TABLE updated about the new location, the mobile nodes check and compare their own location by consulting the local NEIGHBOR_TABLE and inform the controller using the Node_Info packet if the location is changed completely. In so doing, the controller provides updated mobility related to any node in the network. Although the proposed solution keeps track of the mobile node changes in the network, it comes at the cost of excessive communication work-load require to update the mobility events, especially in scenarios where mobile nodes frequently change location.

In [95], a robust location-based forwarding technique for low earth orbit (LEO) satellite networks makes use of the inter-satellite links (ISL) grid structure and information on the satellites' relative positions to carry out NDN packet forwarding was proposed. In the proposed work the packet forwarding is performed at each node using only local information (node's location and destination locations). Through extensive software-based simulations, the authors claimed that their proposed forwarding strategy has the potential to support the future efficient and successful deployment of the NDN architecture in LEO satellite networks. Apart from potential benefits, location-based forwarding may require a heavy degree of inter-nodes satellite coordination, which is somewhat difficult to maintain. Moreover, additional resources are required to compute the location of nodes and satellites.

Summary and Insight: In this section, we analyzed geolocation-based mobility management schemes proposed for NDN. From the discussion, we can see that geolocation is either added into the packet header and shared with other nodes in the network to update FIB entries, or a certain geographical location is considered to store the content when the MP moves. In the latter case, the nodes in the geographical location keep on replicating the content on neighboring nodes if the new MPs also change the location. The location-based mobility management approaches provide mobility transparency solutions to the consumer nodes by following a similar approach as described in the caching-based approaches.

As explained earlier, these schemes replicate the content in a certain location before moving to the new location. In so doing, even after mobile producer node's movement, the Data can be retrieved from the old location. These schemes, no doubt, resolve the producer mobility issue in the network, though violates the fundamental principle which advocates that the NDN is location-independent communication architecture.

B. CONSUMER MOBILITY

NDN, due to its content-centric nature, natively supports consumer mobility in the network. To fetch the desired Data, the consumer node transmits an Interest packet in the network. The Interest packet—while searching for the Data, leaves a bread-crumb trail on the IR. Once the Interest packet reaches the producer region, the producer node constructs the Data packet and forwards it back to the consumer. The Data packet follows the bread-crumb trail on the way back to the consumer node. A brief description highlighting the contributions and limitations of each consumer mobility management scheme is presented in Table 9.

The maintenance of the bread-crumb trail in PIT helps in providing the native support to consumer mobility. If the consumer node moves from one PoA to another, it can retransmit the similar Interest packet. In doing so, the new and similar Interest packet may reach the IR that still has a PIT entry from the old Interest packet. In the presence of a PIT entry, the IR simply aggregates the incoming face-id and forwards the Data packet once received. In the absence of a PIT, the IR simply forwards the packet to the next IR and the chances are that the next IR may have the PIT entry. In addition to PIT aggregation, NDN caching at IR may provide the desired Data and in so doing, the new Interest packet will not be forwarded to the original producer node. It is to be noted that the consumer mobility in NDN is highly dependent on the assumption that the paths of the old Interest packet and the retransmitted Interest packet may cross each other at IR's. If the paths cross each other, then re-transmitted Interest packets can be fetched either from the IR's cache or by aggregating the new Interest packet with the old Interest packet in PIT. Contrarily, if these paths never cross each other then the request must have to be forwarded to the original producer of the Data, consequently increasing the network overhead. To cope with such scenarios, various consumer mobility schemes have been proposed in the literature and are described as follows. Figure 10 shows the typical behavior of consumer mobility in NDN. In the given figure, the mobile consumer transmits Interest to the producer node (Step 1). However, the consumer node changes its location before receiving the Data packet (Step 2). After its relocation, the requested Data packet arrives at the previous location of the consumer node (Step 3). To retrieve the content, the consumer node retransmits the Interest packet from the new location as per consumer mobility support provided by NDN (Step 4). On its way to the producer node, this retransmitted Interest packet finds the cached Data at the NAR2 since this router is on the same path where the previous Interest packet passed through and the Data packet was previously cached at this access router. When retransmitted Interest arrives at NAR2, the cached Data packet is returned to the consumer (Step 5) hence reducing the delay even after its relocation.

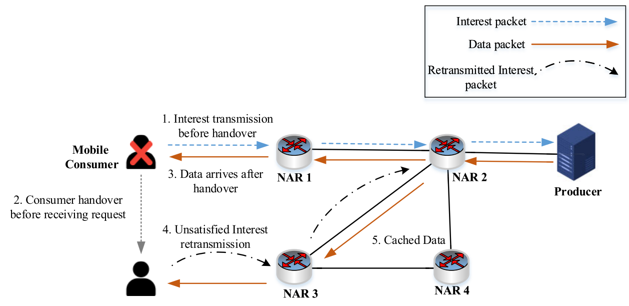


FIGURE 10. Typical behavior of consumer mobility in NDN.

The consumer mobility schemes are organized into different categories and a detailed explanation is provided as follows.

1) HOP COUNT BASED CONSUMER MOBILITY

In addition to native consumer mobility support, Ahmad et al [96], proposed an efficient solution to locate the consumer in case if its location is changed in vehicular communication scenarios. The authors introduced a data dissemination limit (DDL) field in the Data packet and set its limit to slightly higher than the number of hops that an Interest packet traversed. The inclusion of DDL has twofold benefits: 1) the broadcast storm can be avoided since the Data packet can only be traversed back up to the certain number of hop defined in the DDL field and 2) the slight increase in the number of hops comparing to the Interest packet hops, enable the network to locate the consumer even if it has changed the location and currently moved 2-3 hops away.

In [97], Duarte et al. proposed a novel VNDN routing protocol in which the issues of consumer mobility are resolved. Due to consumer mobility, disruptions could occur in the communication links between the forwarders of Data messages causing reverse-path partitioning problems (RPP). Due to RPP, the Data packet cannot be delivered to the content requester, ultimately degrading the application performance. To resolve the RPP issues, the authors proposed an auxiliary forwarding set (AFS) in this paper. In AFS, a set of extra forwarder vehicles are selected to forward the Data message in the case of RPP. AFS considers different input parameters to calculate the probability of RPP among the Interest forwarders. If the RPP occurrence probability rate is high, an extra set of forwarder vehicles are selected to forward the Data packets towards the consumer besides the original forwarders. This scheme maintains high-Interest satisfaction rates, hence, improving the content delivery ratio. However, this approach is not much suitable in scenarios with low vehicular densities.

TABLE 9. Consumer mobility schemes.

Category	Sub-Category	Contributions	Limitations	Ref.
Consumer Mobility Schemes	Hop Count-Based	• Introducing data dissemination limit field in the Data packet and set its limit slightly higher than the number of hops that an Interest packet traversed in case if consumer changed its location.	• It does not consider the high density of a network • This work did not take the mobility in the reverse path into account.	[96]
		• Introducing Auxiliary Forwarding set that includes extra forwarders in case of communication link disruptions occurring due to consumer mobility	• Not a suitable technique in low vehicular densities scenarios	[97]
		• Proposing two mechanisms to deal with low vehicular density problems in VANETs named 1) Agent delegation for VNDN and 2) Store-carry-forward for VNDN	• Huge broadcast problem	[98]
	Caching-Based	• Proposing a proactive caching scheme in which the future location of mobile consumer is predicted to find the optimal routers to cache the required content	• Network complexity • Extra overhead	[99]
		• A cluster-based caching scheme in which vehicles with the same mobility patterns are clustered together and among each cluster, a cluster head is selected, and then data is cached at suitable cluster nodes.	• In highly mobile vehicular scenarios, clustering is performed repeatedly to select cluster head	[100]
		• A prefetching approach in which the consumer notifies the connected router before handoff, at which the router selects some neighboring nodes to prefetch and cache the required data	• Increases cache cost	[101]
		• Prediction based scheme using deep learning algorithm LSTM to predict next RSU to proactively cache the data	• Unnecessary cache utilization in case of false predictions	[102]
	Control Messages-Based	• Introducing a mobile link service-based transaction connection between consumer and the NDN gateway, using the control messages to reestablish the previous connection with old NAR after the consumer handoff	• Having old NAR in different network area increases the retrieval delay	[103] [104]
	Location-Based	• All nodes share their content list to their neighboring nodes available in its vicinity after every predetermined interval which supports the seamless consumer mobility	• This scheme only considers the scenario where new NAR and old NAR of consumer node is one hop away • High overhead	[106]
		• Proposing mobility management and flow control by providing distributed controllers in the network named associated controller and supervisory controller.	• Getting information by communicating with other servers cause overhead	[107]
		• Consumer mobility awareness using mobility manager	• Single point of failure owing to reliance on mobility manager	[108]

Duarte et al. further extended their work in [98] by proposing two solutions to deal with the low densities of vehicles in the VANET. The proposed mechanisms include 1) agent delegation for VNDN (VNDN-RSU) and 2) store-carry-forward for VNDN (VNDN-SCF). The former mechanism relies on infrastructure (RSU) to forward the Interest messages to the producer. However, RSUs are not available frequently worldwide. In the latter mechanism, the subsequent neighbor nodes carry the messages towards the producer vehicle. In this mechanism, when a vehicle transmits the message towards the neighbor vehicle, it overhears the communication medium that either the message is delivered to the next vehicle or not. If the message is not delivered, the forwarder vehicle retransmits the Interest packet after a certain period towards the subsequent vehicle.

2) CACHING BASED CONSUMER MOBILITY

In [99], the authors proposed a proactive caching scheme (OpCCMob) in which the required Data is proactively cached at the optimal routers so that the requests can be fulfilled without any multihop retransmissions in the case of consumer mobility. To find the optimal routers for the Data placement, the future location of mobile consumer is predicted. Also, the future Interest requests are predicted using the request pattern predictors. This scheme is appropriate for the consumer mobility issues since it reduces the Interest retransmissions, however, it increases the network complexity.

Huang et al. [100] proposed a cluster-based caching scheme for mobility issues. In this scheme, the authors proposed two methods: 1) prediction-based clustering algorithm and 2) cooperative caching. In the first method, the mobility predictions for the vehicles are made and the vehicles with the same mobility patterns are grouped into the same clusters. These predictions are made using the Markov Model. The link expiration time is also predicted that helps in choosing the suitable cluster heads for the caching purpose. In the latter method, the cluster heads are selected among all the vehicular clusters, and then the content is cached at the suitable cluster heads. The cached data is also categorized into two types: 1) most popular data (MPD) and 2) least popular data (LPD). MPD is cached at the cluster heads whereas LPD is cached at various cluster members. The proposed scheme with the help of the aforementioned caching mechanism serves the Data to the consumer, even if it relocates to the new position.

In [101], the authors proposed prefetching scheme named proactive multi-level scheme (PMCS) to support consumer mobility. In this scheme, content is prefetched at a predicted neighboring router during the consumer handover event. Before the handover event, the consumer notifies the connected router (CR) about the handover. The CR selects neighboring routers that possess a high probability of consumer connection after handover, to cache the content requested by the consumer. Moreover, CR sends the neighbor packets to the consumer containing the information about the neighboring packets. CR forwards the information about the content to be fetched, to the neighbor routers, which on receiving the content information, fetch the requested content in advance from the producer and cache it for future mobile consumer requests. When the consumer connects to the new router, it sends the request to the neighbor router and retrieves the content without any further delays. This scheme reduces the latency as the consumer does not need to fetch the content by starting the fetching mechanism from the scratch, instead, it can directly retrieve the content from the caches.

In [102], Khelifi et al. proposed a proactive caching-based mobility prediction scheme in which long short-time memory (LSTM) algorithm is used to predict the next roadside unit (RSU) to which vehicle connects in the future. When a vehicle requests the data to an RSU, it provides the consumer vehicle with the required data as much as it can, and then the remaining data is proactively cached at the predicted next RSU. When the vehicle passes through the next RSU, it can retrieve the remaining data without any delay. Hence, this scheme helps to mitigate the latency effects during the data retrieval process.

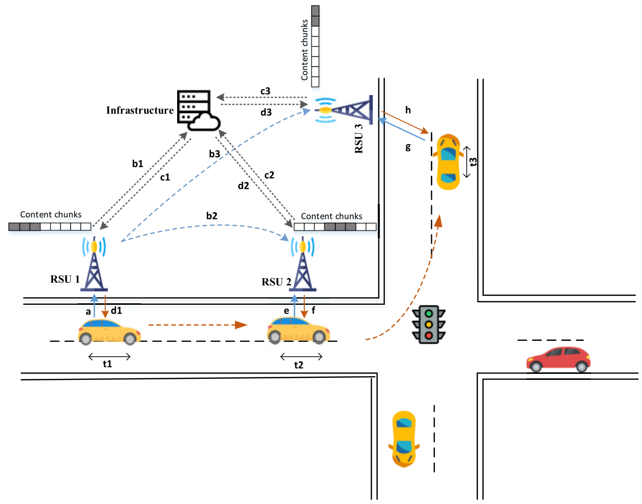


FIGURE 11. Proactive caching-based mobility solution.

Figure 11 presents the proactive caching-based mobility solution. As shown in the figure, when a vehicle requests the data to the RSU1 (arrow a), it forwards the request to the infrastructure to get the required content (arrow b1). At the same time, RSU1 predicts the next RSUs with which the consumer vehicle will connect in the future i.e., RSU2 and RSU3 and it forwards the requests to these RSUs (arrows b2 & b3 respectively). Then, the infrastructure provides the requested content to RSU1 (arrow c1) and at the same time, RSU2 and RSU3 will forward the requests to the infrastructure (arrows c2 & c3 respectively). RSU1 forwards the Data to the consumer vehicle (arrow d1) and on the other side, infrastructure provides the requested Data to the RSU2 and RSU3 which is then cached at these RSUs (arrows d2 & d3 respectively). When the vehicle arrives at RSU2, it sends the request for the Data (arrow e). Since the next Data chunks are already cached at RSU2, it will forward the Data chunks to the consumer vehicle immediately (arrow f). Similarly, the consumer vehicle gets the remaining chunks from RSU3 (arrows g & h). This scheme, however, does not consider the vehicle speed which may cause unnecessary data storage in case if the vehicle does not enter the range of the next predicted RSU.

3) CONTROL MESSAGES BASED CONSUMER MOBILITY

In [89], the authors proposed a mobility link service (MLS) that is used to manage the transaction between the NDN default gateway (NDG) and the mobile node consumer (MNC). This MLS is proposed to support seamless consumer mobility by reestablishing the connection to the previous NDG instead of creating a new transaction. The authors proposed new control messages such as data segment messages, status report messages, and acknowledge messages in this scheme. These control messages are used to support consumer mobility, retransmission, and segmentation purposes. MLS assembles all the received data segment messages during the transaction and sends them to the MNC. However, if a consumer changes its location before the transaction completion, it sends the status report message to retrieve the lost content messages due to the interrupted connection. In the status report message, the consumer informs the NDG about its updated address and the sequence number of the lost messages. In this way, it reestablishes the previous transaction using the MLS for the retrieval of the remaining missing content. After the transaction completion, if the consumer wants to request new content, it establishes a new connection by sending a new Interest packet in the current network by using the anycast address. This scheme helps to maintain a seamless connection after the consumer handover; however, the control messages increase the overhead in the network, and hence, reducing the overall network performance. To reduce the network overhead, the authors proposed an improved version by reducing the control messages [104]. In this proposed work, the authors used two types of control messages named 1) MLS fragment message and 2) status report message. MLS scheme overall reduces the Interest retransmissions and the handoff delay since it does not create a new connection after consumer handover. However, the content retrieval delay is increased in the scenarios where consumer handoffs from one network to another.

4) LOCATION BASED CONSUMER MOBILITY

In [103], authors proposed a vicinity-based approach to fetch the content from the nearby replicas instead of fetching content from a faraway producer. Authors further used this approach in the mobile environments, to support consumer mobility [106]. In the proposed scheme, the authors consider a scenario in which the consumer node forwards an Interest to the attached NAR and handoffs to another NAR before receiving the requested content. The old NAR caches this received content and publishes its content list to the nodes in its vicinity. The content list contains the names of content cached in the CS of the publishing node. All the other nodes that cache the content coming from the producer also forwards the content list to their vicinities. In the proposed scenario, the new NAR is one hop away from the old NAR. When the old NAR publishes its content list, the new NAR also receives this list. It saves the mappings of the content list objects with the receiving interface in its FIB. If a node receives the same content name in the content lists coming from different faces, it saves all the faces with the hop distance (cost). Then the Interest is forwarded to the node at a low cost (nearer to the consumer). When the consumer sends the Interest to the new NAR, it checks the FIB and forwards the Interest to the nearest cache node and fetches the content. Hence, the consumer does not need to fetch the content from the producer which can be far away from the consumer. However, if the producer node is nearer, then the content is fetched from it directly. This scheme reduces the content retrieval delay as it can receive content from the nearest node. However, this increases the network overhead since the nodes publish their content list after every predetermined time interval.

In [107], mobility management and ubiquitous flow control (robust flow scheduling) in a software defined mobile IoT environment are achieved by distributing multiple controllers in various regions of the network. These controllers coordinate with each other for seamless and scalable mobility management (Distributed controllers perform tasks such as managing mobility in coordination with each other, determining the access point, and flow scheduling). There are two classes of controllers in this scheme: 1) associated controller, a kind of management node to which the device is currently attached and 2) supervisory control. The associated controller is the node with which the device is currently attached. Whereas the supervisory controller is assigned to each new IoT device when it enters the network, thus maintain, and manage all the devices under its administration. When the consumer mobile device relocates to the new position and attaches to another associated controller, the new controller gets the information about the previously associated controller from the supervisory controller and in turn, connects with it. In doing so, the new controller fetches all the previous flow information of the mobile consumer and reroutes them through new paths. This approach decreases the delay and increases network efficiency.

In [108], Diego et al. proposed a seamless consumer mobility management approach in the named data networks using a vehicular environment. The proposed scheme introduced a central entity named Mobility Manager (MM), which is responsible to keep track of mobile consumers as well as their next point of attachment i.e., RSU. MM communicates with the current RSUs of the mobile consumer utilizing the newly proposed packets named Interest Switch and Data Switch, aiming to predict the future RSUs in advance of consumer mobility. Moreover, it creates communication paths between future RSUs and content providers.

Summary and Insight: In this sub-section, we surveyed various consumer mobility management schemes proposed in the NDN literature. Although the vanilla NDN claims the innate support for consumer mobility, a plethora of situations occur where default consumer mobility support does not work well. For instance, as discussed earlier, it might be possible that the path followed by the retransmitted Interest may not cross with the path taken by the old Interest packet which in turn forces the retransmitted Interest to fetch from the original producer. Such situations, if occur, increase the Interest satisfaction delay as well as the chances of congestion in the network. Various solutions, aiming to resolve such issues, have been proposed in the literature and among them, as expected, the caching-based solutions gained much attention from the research community. Other than the caching, centralized controller-based solutions have also been proposed which maintain the flow control and reroutes the packet if the consumer node changes the location in the network. In terms of mobility transparency, several consumer mobility management schemes such as [98], [101], [102], [103], [106], and [107], to some extent support mobility transparency. For instance, the scheme proposed in [98] retains a high satisfaction rate even after the mobility event occurs in the network, consequently, improves the end-user QoS. Similarly, the consumer mobility management scheme proposed in [101] offered a caching mechanism that serves the Data to the mobile consumer—even if the consumer itself relocates to the new location—without any delays. Likewise, the scheme presented in [102] provides mobility transparency with the help of prefetching mechanism. However, a few schemes such as [106] and [107] tend to share certain information among the nearby nodes which ultimately increase the network overhead in the resource constrained environments.

C. HYBRID (CONSUMER & PRODUCER) MOBILITY

Hybrid mobility referred to a situation where both the consumer and producer nodes are prone to change the location in the network. Managing networks that incorporate both mobile consumers and producers are even more challenging comparing standalone mobility solutions. In the following, we surveyed various such techniques that resolve the hybrid mobility issues in the network. Moreover, Table 10 highlights the contributions and limitations of each hybrid mobility scheme. The hybrid producer mobility schemes are organized into different categories and a detailed explanation is provided as follows.

1) FIB BASED HYBRID MOBILITY

In [109], authors introduced on-path resolver architecture (OPRA) in which some of the ARs are equipped with a resolver entity that is responsible for the route resolution. The point of attachment of producer and consumer are considered as home resolvers which keep all the routing updates regarding the producer and consumer. Figure 12 (a) and (b) illustrate producer and consumer mobility support mechanisms, respectively. In Figure 12(a), at first, the consumer sends the Interest packet to the producer's original location (arrow 1). At this point, the producer performs the handover and relocates to another location. To provide support for the mobile producer, the OPRA introduces a new packet named binding update packet which is used to inform the movement of the producer. After the relocation, the producer sends the binding update packet to its home resolver (arrow 2). When the home resolver receives the binding update packet, it caches the binding information in the binding information table (BIT). The BIT includes the content name and the routing tag which represent the name of the resolver with which the mobile producer is currently attached. Following the OPRA working mechanism, when the Interest packet intended for the mobile producer arrives at the home resolver, it updates the Interest packet with the name of the new resolver with which the producer is attached. This way the Interest is directed to the new location of the producer (arrow 3). The consumer

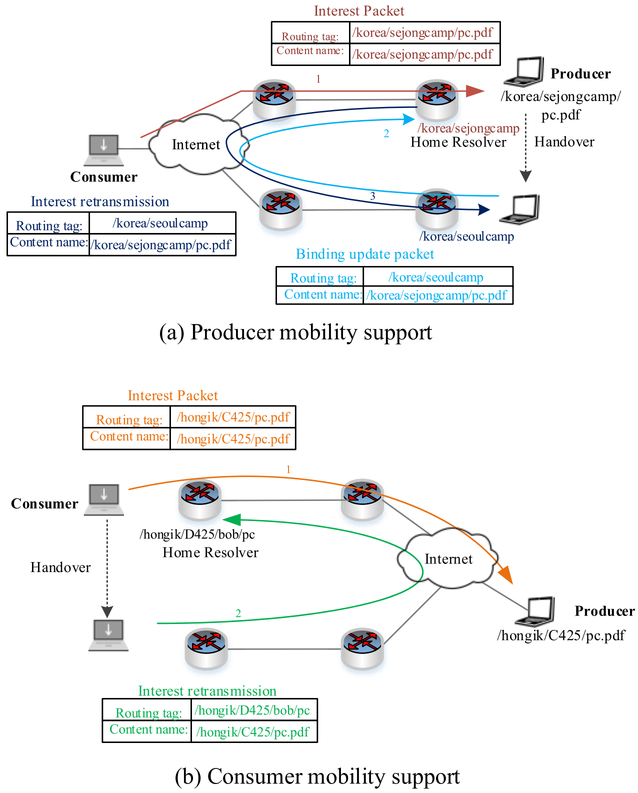


FIGURE 12. Hybrid mobility support in OPRA.

mobility on the other hand is presented in Figure 12(b), in which the consumer node changes the location before the Data packet arrives. When the consumer node is relocated to the new position, it retransmits the Interest packet with the updated routing tag to its home resolver where the previously requested Data might have arrived. Similar to the mobile producer routing tag, the consumer tag also includes the name of the home resolver. The retransmitted Interest packet arrives at the home resolver following the routes in the FIB (arrow 2). Home resolver, on receiving the updated routing tag-based Interest packet, forwards the Data to the new location of the consumer. In this way, the consumer can retrieve the content without any delay.

In [110], the authors proposed a data plane and control plane separation approach in which the controller node is used. In this approach, the network is divided into several AS. Each AS is assigned with one controller node and these controller nodes can exchange topological information with each other. When a producer node relocates in an AS, it updates the controller node, which then updates the FIB tables accordingly in the routers. When a consumer changes its location, it reissues the Interest packets to the controller, which then finds the best optimal path for the consumer. Hence, this approach helps to prevent Interest or Data packet loss. This scheme also reduces the handover latency, since the producer informs the controller about its relocation before the handoff, which seamlessly completes the process. However,

TABLE 10. Hybrid mobility schemes.

Category	Subcategory	Contributions	Limitations	Ref.
Hybrid Mobility Schemes	**FIB-Based**	• Includes additional resolver attached to several ARs to keep the binding updates of mobile producer and mobile consumer	• No recovery mechanism	[109]
		• A distributed mobility management scheme sending control messages to attached routers before the producer or consumer handover to update the routes	• High signaling in the network	[110]
		• A data/control plane-based approach in which the controller is well aware of all topological information of its AS resolving both producer and consumer mobility	• Single point of failure	[111]
		• Introducing a fog computing layer between ICN and vehicular layer which caches the Data to support producer mobility and to support consumer mobility, it stores their address locations in a table	• Limitation of Data storage at fog layer is not considered	[112]
	PIT-Based	• Introducing rendezvous server that can act as a naming server or as a relay server • An interest forwarding scheme in which virtual interest Is sent to the previous router to update the localized routing paths • Using persistent Interest for Data retrieval during live streaming	• The use of a rendezvous point increases the handoff latency • The use of RV acts as a single point of failure	[113] [114]
	Storage -point based	• A location-based content delivery solution that resolves the producer as well as the consumer mobility by using the handover algorithm which is performed in a unicast way	• Forwarding entries are updated using a broadcast mechanism, which is costly	[115]

this scheme fails to take into account the single point of failure issue.

Kim et al. [111] and [112] proposed efficient schemes to resolve both consumer mobility and producer mobility. In the proposed work, the authors adopted three different efficient mechanisms to resolve the producer mobility in the network. In one of the proposed mechanisms, RV acts as a naming server, that keeps the tracks of MP. When a consumer sends Interest to the MP, it waits for a certain amount of time period for the response from MP. If it does not receive the response, it requests the RV for the updated location of MP. RV sends the updated content name to the consumer node so that it can access the MP directly at its new location. This scheme, however, induces high handoff latency which is its major drawback. The authors further introduced another approach in which RV acts as an indirection point or a relay server between consumer node and MP, to minimize the handoff latency. In this proposed approach, before the handoff initiation, MP informs the nearby indirection point. After handoff notification, when RV receives interests for the MP, it keeps buffering the Interest packets. After the completion of MP's handoff, RV forwards the buffered Interests to the MP and forwards the received corresponding Data packets back to the consumer node by encapsulation/decapsulation. This scheme reduces the handoff latency as compared to the previous one, however, the round-trip time (RTT) is much higher than that. Also, this indirection point scheme can cause the single point of failure issue since all the communications in the network take place using this central entity. Authors further proposed routing-based approaches named 1) Interest forwarding and 2) zone flooding. These approaches reduce both the handoff latency as well as the RTT as compared to the other two approaches., in which the name updates are not involved right after the MP handoff. In the former approach, MP informs the previous AR before the handoff initiation so that it buffers the upcoming interests for the

MP. After it connects to the new AR, the current AR sends a virtual Interest packet from the new AR to the previous AR. This Interest creates the FIBs at the IRs as well to direct the Interest towards the updated location of MP. When the previous AR receives this virtual Interest, it forwards all the buffered Interest packets towards the new location of MP. The FIB entries created by the virtual Interest have a lifetime, which expires after the communication is ended. In the latter approach, the copies of Interest packets are forwarded to the multiple routers with which MP can get attached to. In this proposed architecture, to resolve the user-side mobility, the authors considered the scenario for the real-time applications. This scheme introduced the persistent Interest packets for the retrieval of real-time content i-e Tv live streaming. Persistent Interest packets stay in the PITs for the lifetime even after the completion of Data retrieval. However, if the consumer relocates, this persistent Interest remains in the PIT which leads to the wastage of resources. To resolve this issue, the authors introduced two mechanisms named 1) bit embedding and 2) signaling messages. Also, in the proposed scheme, the authors recommend that the user should choose the AP in which the copy of requested content is available, besides considering signal strength and attached nodes, to avail higher throughput. To select the optimal AP for the Data retrieval in CCN, the user can send copies of Interest to multiple APs, and based on the content retrieval rate, it can choose optimal AP. In [113], the authors proposed location-based content delivery approach in vehicular scenarios. In this approach, geo-location addresses are used to perform communications among the vehicles. The proposed work provides solution not only for the producer mobility but for the consumer mobility as well. When either the producer or consumer completes the handover operation, it performs the respective handover algorithm in a unicast way to update the routing entries correctly. In the proposed work, the producer or consumer sends hello message on a regular basis to its nearest access point (AP) so that its paths are always up-to-dated. When the provider detects it change of location, it performs the handover algorithm by sending the Geo-Provider HandOver message to its new AP. The new AP then creates the FIB entry for the newly attached provider. However, the previous AP deletes the FIB entries for the corresponding provider since it does not receive hello message from the provider anymore. For the receiver mobility, if the receiver starts the handover before receiving the requested content, it performs the receiver handover algorithm. In this algorithm, it sends the handover message to the new AP, which then connects with the previous AP of the receiver and hence the previously requested content can be retrieved even after the handover. This scheme however has high network overhead.

2) PIT BASED HYBRID MOBILITY

Yan et al. [114] proposed a distributed mobility management scheme that is suitable for both the consumer and the producer mobility. This scheme introduces a new signaling message named a control packet which is sent from the old AR to the new AR before the handover of the attached consumer or producer. This control packet contains information about the new AR and the pending content of the moving producer/consumer. In the case of consumer mobility, the control packet helps to update the PIT entries which enables the Data packets to arrive directly at the new AR. While in the case of producer mobility, the control packet updates the routing path information to send the Interest packets directly to the new AR. In this approach, a branching node is selected, which provides transmission paths for both the new and old AR. The branching node helps to update the routing paths accordingly. In this scheme, a handover failure occurs if the consumer/producer does not connect to the new selected AR. To recover from such failure, the proposed scheme uses the timer approach in the control packet to adjust the newly added FIBs or PITs. The proposed scheme helps to minimize the handoff delay in the case of consumer mobility and reduces the routing update costs in the scenario of producer mobility. However, the major drawback of the proposed scheme is that it only considers the scenarios with two terminals involved, which is not practical for real-life scenarios.

3) STORAGE POINT BASED HYBRID MOBILITY

Wang et al. [115], proposed a fog assisted ICN approach to resolve the producer and consumer mobility. The authors introduced a fog computing layer in between the ICN layer and the IoV. In this approach, vehicles do not publish the Data themselves, instead, they offload the Data to the fog layer, where fog nodes further process, store and publish the Data to the ICN layer. The storage of Data at the fog computing layer helps to support producer mobility. When the fog node publishes its Data, it also caches the data for future use. However, the limitation of Data storage is not being discussed in the proposed scheme. To retrieve the content requested by the consumer, fog nodes maintain a random unique name (RUN) table to store the location of the consumer node. When the required Data packet is received at the fog node, it computes the address location of the mobile consumer and directly transmits the Data packet to the consumer. Following this scheme working standards, even if the consumer changes its location during the content retrieval, there is no additional mechanism required to support its mobility, as the fog nodes track the consumer using the location information stored in the RUN table.

Summary and Insight: In this subsection, we described the hybrid mobility management solutions for NDN. The covered solutions mainly utilize the previous PoA and forwards a packet on reaching the new location, aiming to construct a path between the new PoA and old PoA. In doing so, when the Interest or Data in case of consumer or producer movement arrive at the old location, they can seamlessly be redirected to the new location. In terms of mobility transparency, a few hybrid mobility management schemes, to some degree, support mobility transparency. For instance, the scheme proposed in [98] decreases the end-user delay by caching the content on fog nodes, and as a result, provides a transparent mobility solution to the consumer nodes in the network. Although, the covered schemes provided some efficient solutions to cope with the hybrid mobility management issues, almost all of the use-case scenarios presented in the above schemes do not consider the pure wireless MANET consisting of the mobile consumer, mobile producer, and even mobile IRs. In MANETs, as the whole network presents the mobile profile, handling the mobility issues is even more challenging. The following important points are of utmost importance to be considered while designing the solutions to cope with the issues of MANETs. Since the mobile nodes are equipped with the ad-hoc interface, the Interest or Data packet can be forwarded in a broadcasting manner. Considering this fact, the proposed solution should incorporate the controlled broadcast-based solutions that aim to reduce the network overhead. Moreover, as the whole network is mobile including the IRs, it is of utmost importance to consider whether the utilization of PIT and FIB are cost-effective and beneficial. The reason is if mobile IRs are frequently changing the location in the network, their PIT and FIB entries become obsolete in a very short period leading to invalidating the routing and forwarding paths. Such behavior in turn increases the network overhead and congestion due to resource unavailability issues. Concluding our final remarks, we would like to urge the research community to do further research in this direction to resolve the questions/issues we raised and presented in the domain of MANETs.

V. DISCUSSION: MOBILITY CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In this section, we have provided futuristic insights on the challenges associated with nodes mobility in different networking scenarios. Moreover, we also discussed the role of futuristic technologies in mobile NDN. The organization of this section is as follows. At first, we discussed the promising vision of artificial intelligence (AI) to resolve network mobility issues. Here we specifically discussed the machine learning and federated learning approaches that have the potential to address various issues. Secondly, we presented the new emerging paradigm called in-network computations through edge computing (EC) and vehicular fog computing (VFC) and discussed the research challenges that a network may face due to mobile nodes. Thirdly, we discussed the mobility challenges and their potential solution in the domain of resource-constrained IoT. Fourthly, we provided our insights on the integration of software-defined networking (SDN) with NDN in combating the NDN mobility issues. Finally, we concluded this section by providing a detailed discussion, in terms of mobility management, on general VANETs and the rise of autonomous driving networks.

A. MOBILE NODES AND THE PROMISING VISION OF ARTIFICIAL INTELLIGENCE

The increasing amount of mobile data in wireless networks requires sophisticated technologies and additional resources for efficient end-to-end data delivery. To cope with such highly mobile and dynamic data traffic, various AI techniques such as machine learning (ML), deep learning (DL), and federated learning (FL), among others, can be applied to achieve efficient solutions for NDN based producer and consumer mobility.

1) MACHINE LEARNING FOR MOBILE NODES

Most of the traditional wireless mobile networks employ reactive solutions for mobility management which typically comes at the cost of high latency [116]. However, the machine learning-based solutions, on the other hand, if employed, enables proactive decision-making for better mobility management.

Example Scenario: An example in the above case could be the utilization of multiple available interfaces on connected mobile vehicular networks. Typically, a modern vehicle may equip with multiple transmission technologies (interfaces) such as 1) Bluetooth, ultra-wideband (UWB), and ZigBee—generally used for short-range communication, 2) dedicated short-range communication (DSRC) and Wi-Fi used for medium-range communication, 3) cellular-vehicle to everything (C-V2X) and 5G New Radio (5G-NR) used for long-range communication [116], enabling a modern vehicle to select and communicate over different transmission interfaces. These vehicles when utilizing NDN as an underlying communication architecture, greatly leverage from the default multihoming feature of NDN. With the multihoming feature of NDN, a modern vehicle can utilize more than one transmission technology for communication at the same time. Moreover, based on the various parameters such as traffic congestion, wireless channel condition, and data rate requirement, a modern vehicle may also choose the optimal interface—or a set of interfaces—for communication. To this end, a vehicle may employ various ML or DL-based prediction schemes to select the best performing transmission interface, enabling proactive decision making which in turn improves the overall performance of the modern vehicular networks.

2) FEDERATED LEARNING FOR MOBILE NODES

In addition to ML or DL for mobility management, the FL which has gained extensive attention in the recent past from both industry and academia can be utilized to improve the performance of the mobile network. FL enables the mobile communication nodes to learn the networking environment in a collaborative manner and share prediction models aiming to improve the overall network performance. The FL in mobile networking can be envisioned as distributed learning approach where each node initially learns (model training) the flow of the networking traffic on its own based on the incoming and outgoing Interest/Data packets. Once the local model is trained, it can then be shared with network management entities such as RV, HR, and centralize controllers. These entities on the receiving the model trained by each node in the network, combine them all and take the average to improve the shared model. Once the average model is obtained, it can then be reshared with the mobile nodes in the network to make appropriate decisions if mobility events occur in the future. Moreover, the NDN caching mechanism stores the consumer-requested data (comprised of both sensitive and nonsensitive information) at multiple static and mobile entities distributed across the network, securing such data is highly essential to avoid privacy leakage, poisoning, or backdoor attacks. Federated learning-backed frameworks such as multi-tentacle federated learning (MTFL) [117] can be adapted to reduce the chances of aforementioned attacks and ensure the trustiness of stored data on static and mobile nodes across various network nodes.

Example Scenario: To further understand the importance of the aforementioned scenario, let us take an example of a network consisting of various static and mobile nodes. Assume that the network is administrated by RV which has the overall control of the network. In such a network, each node monitors the incoming Interest/Data traffic flow, and in the case when the NDN negative acknowledgment is received– due to the mobile node movement, from any of its immediate neighbors it can learn the local movement pattern of the nodes. Once the local model is trained, the node shares the trained model with the RV, which on receiving the model may combine it with other models from other nodes. It is worth noting here that the nodes are only sharing the trained model rather than sharing the sensitive details of the packet such as content name and/or Data packet signature, which consequently protect the information and is the core requirement of FL. By sharing the models, not only RV learns the overall mobility patterns in the network, but the individual nodes when receiving the updated model from the RV, also learn the mobility pattern of other nodes in their vicinity. As a result, the nodes will be able to make appropriate decisions in case of consumer/producer node mobility in the network.

3) AI FOR GENERAL MOBILITY ISSUES

In addition to the aforementioned discussion, let us now briefly discuss the manifold problems, with the help of various example scenario, in existing mobility management schemes that can be further improved by utilizing AI techniques.

Example Scenarios: The prefetching-based approaches discussed in the previous section can greatly leveraged from the AI. For instance, the request patterns of the mobile client can be tracked by applying the ML algorithms and in doing so, the content can be perfetched and cached at the next nearby node for future consumer requests. Similarly, in vehicular scenarios, when a consumer vehicle requests the required content, it is possible that the complete Data cannot be retrieved during the connection time. In these cases, ML models can be applied in the vehicular networks which can predict the next RSUs and can prefetch the remaining content chunks before. Similar approach is used by the authors in [69] and [70] in which they use the Markov chain model to predict the next RSU of the mobile vehicle and cache the content beforehand. In so doing, applying machine learning-based techniques in a vehicular environment has the potential to reduce the content retrieval delay and ultimately improve the network performance.

Additionally, let's recall the tracing-based mobility management scheme presented in the section IV-A1. As mentioned previously, in tracing-based solutions selecting an optimal expiry timer to invalidate the trace setup is a challenging task and may lead to network performance degradation. To improve the accuracy of expiry timer value, similar to other AI-based solutions, different ML-based techniques can be utilized which basically monitor the trace setup traffic and mobility events in the network. Based on the recorded values of mobility events and trace traffic, the ML algorithms can predict a comparatively better expiry timer value and hence improve the overall network performance.

Discussion & Research Challenges: Although the ML and specifically the FL has the potential to improve the overall network performance, we believe its integration in the networking and specifically in NDN is not straightforward and yield many research challenges. For example, what if the model shared by any node is lost due to hostile networking conditions such as network congestion or unstable wireless channel condition. In this case, the averaged model by the RV will not be as accurate as it could be otherwise. Moreover, as NDN follows a name-based communication model, it is of utmost importance to design an efficient naming scheme that can be utilized in accessing or sharing the models in the network in addition to the content. Finally, the novel design of caching schemes is another challenging task, as model sharing is somewhat different from content sharing in the network, and thus its caching placement and replacement strategies should also be different from the content placement and replacement strategies.

B. IN-NETWORK COMPUTATIONS AND THE ROLE OF MOBILE NODES

In-network computation enables the intermediate nodes, on the path from end-user to cloud node, to perform computations, in order to improve the latency requirements and simultaneously reduce the workload on the cloud node. In the following subsection, we discuss some of the in-network computation-based techniques and presented the research challenges associated with their integration with NDN.

1) EDGE COMPUTING

Edge computing (EC) is a new paradigm that brings the computational and storage resources close to the end-user devices, aiming to reduce the backhaul network traffic, average latency, and overall bandwidth consumption [118], [119], [120]. The benefits of edge computing can be viewed from two different angles i.e., from the cloud perspective and the end devices perspective. However, both of these perspectives serve the common networking goals described as follows. From the cloud perspective, the goal of the EC is to reduce the workload on a single centralized cloud node by filtering out the unnecessary content at the network edge. In so doing, the cloud node only receives the optimized and valuable data for further analysis and storage. On the other hand, from the end device perspective, since the computations and storage resources are now in close proximity—ideally, at one hop distance, the overall communication delay is at the order of less magnitude comparing to the traditional cloud-only solutions. Such communication delay improvement enables the end-devices, specifically the mobile nodes to complete the required task within the deadline time.

Example Scenarios: To realize the aforementioned advantage of EC, let us consider an example, in which a mobile user is connected with the wireless access point (WAP) in AS1 and moving towards another WAP in AS2. Since the end device is mobile, its connection time with WAP1 is limited and may break any time soon. In this case, if the user requests the computations from the cloud node, the chances are when the response will arrive the user will be no longer connected with AS1 WAP. In contrast, if the AS1 is equipped with its own EC node, the communication latency will be reduced and the response will be delivered to the mobile user in a relatively very short span of time.

Another example in the context of mobile nodes and edge computing could be the vehicles connected with RSUs. Since the vehicle speed is usually high, the connection time of a vehicle with RSU is small, thus decreasing the chances to get the requested computations results from the cloud node within the connection time. On the contrary, if each RSU is equipped with a powerful computing node, enables it to perform the computations locally and immediately respond to the requesting vehicle which ultimately receives the result within connection time.

Although edge computing improves the overall performance of mobile networks, it brings extra benefits when utilizes the NDN as an underlying communication model rather than in-efficient address-based communication protocols. With the NDN as an underlying communication model, the RSU in the above example scenario, can aggregate the same computation requests from different vehicles and forwards a single request to the EC node (application). This mechanism further improves the performance of the network by reducing the load on the EC node. Moreover, if the RSU equipped with EC, has to offload the computation request due to excessive load, it can partition the compute request and utilize the NDN multihoming feature to forward the partitioned request on multiple available interfaces for parallel computations execution, which in turn further improves the computation efficiency.

2) VEHICULAR FOG COMPUTING

Vehicular Fog Computing (VFC), which is another type of in-network computing, enables the static as well as mobile nodes to form a cluster of vehicles—acting as computation nodes, to meet the increasing demand for computations from vehicular applications [121]. To this end, parked vehicles and moving vehicles are equipped with embedded computers acting as compute infrastructure and perform the computations offloaded by the nearby vehicles. In terms of computations, the vehicular fog nodes (VFN) are usually responsible for the local processing of data generated by the in-car sensors and offloaded data by the nearby vehicles that cannot perform computations due to excessive workload. To perform computations, monolithic services, as well as microservices, can be deployed on the VFN by employing container-based technologies and in the form of virtual machines [122]. Such deployment strategies enable the VFN to do live migrations and/or downloading the services either from the VFN or from remote cloud nodes.

Example Scenarios: To envision the potential benefits of VFC, let us consider a smart transportation system as a use-case scenario. Today's era smart transportation systems are usually equipped with roadside edge nodes—often termed as a vehicular edge—providing computational and storage resources in the close proximity of end-user consumer vehicles. The vehicular edges, no doubt, are improving the performance of the vehicular networks by decreasing the overall response delays, nevertheless, face excessive workload issues specifically in congested urban traffic scenarios. As a result, vehicular edges yet again are forced to offload the computation to the cloud nodes located far away from end-user consumer vehicles. This phenomenon in turn increases the overall response delays and decreases the vehicular network performance. The VFC in this case appears as a potential savior solution. Since the resource-rich parked vehicles can be found in urban areas such as on the roadside parking lots, they may form a cluster (fog) and communicate with vehicular edge terminals through a dedicated gateway node, alleviating the computation burden on the vehicular edge and providing computation in relatively close proximity comparing to the cloud node. VFC when combining with vehicular edge and utilizing NDN as an underlying communication protocol can further improve the network performance by aggregating multiple requests of the same computations at gateway nodes.

Discussion and Research Challenges:

While NDN and EC intuitively improve the overall performance of the network equipped with mobile nodes, further research efforts are required to practically implement and validate the intuitive solutions. For instance, it can be seen from our discussion in Section V-B1 that the offloaded compute request can be partitioned into multiple requests for parallel transmission and execution, but what if some communication paths are vulnerable and packets may be dropped due to congestion. In this case, the edge node may not be able to receive some of the computed results which ultimately require either local computation (if resources are available) or retransmission on different interfaces, both increasing the overall delay. Therefore, how to cope with the aforementioned parallel execution and efficient offloaded communication path selection are important research issues to address. To ensure reliable computation results delivery, more information is required in terms of NDN, e.g., optimal compute interface selection and resource monitoring of offloaded compute nodes.

In VFC on the other hand, unlike parked vehicles, the communication and computation workload in moving VFC varies due to the spatiotemporal variation of traffic on the road. This poses significant challenges to the development of efficient compute-based communication protocols that effectively handle the frequent offloading of the running computations on vehicles that are moving out of the communication range due to varying speeds. Since modern vehicles are usually equipped with GPS, the vehicle's movement pattern can be predicted to some extent and offloading can be prescheduled to avoid delays [122]. In terms of underlying communication architecture, although NDN is actively being explored for the in-network computations and offloading mechanisms, the NDN research in moving VFC is still in its infancy and require a lot more attention from both academia and industry. The manifold issues that NDN may face in VFC include 1) the named based protocol design to migrate the running containerized instance of computations, 2) namespace design for microservices access management mechanism, 3) name-based optimal compute vehicle selection in moving VFC, and 4) protocol design for proactive or reactive resource monitoring mechanism, to name a few. These challenges require further research effort from the research community to practically adopt the NDN-based VFC in smart cities.

C. SOFTWARE-DEFINED NETWORKING

SDN decouples Data plane functionalities from the control plane, aiming to ease the management and programmability of network resources. NDN on the other hand as we know aims to replace the traditional IP-based Internet architecture with a content-based approach, the integration of these two futuristic architectures re beneficial for mobile wireless networks and has the potential to resolve various mobility issues in the network. In SDN, a logically centralized controller monitors the network in terms of nodes' mobility and route changes and provides extremely flexible network management and resource allocation techniques [123]. The SDN controller exhibits similarities with the anchor node or RV in the network, however, it offers better network performance and reduced overhead. In SDN, the routing path states (control packet) and the information related to mobility events [94] are typically sent proactively and periodically to avoid any issue that may occur due to controller ignorance of recent path updates and mobility. The SDN controller on receiving the routing path and mobility events information —recognized by the packet type, checks for path changes that may occur owing to changes in mobile nodes' location. If the routing paths need to be changed due to the mobility of the nodes, the controller constructs the new flow rules, which in the NDN case would be the FIB update rules, and forward them back to only those nodes where these rules are required to be installed. The forwarding of these control packets may follow the well-defined OpenFlow [124] protocol of SDN. Unlike the proactive approach discussed before, in the reactive approach, when a mobile node changes its location, it contacts the SDN controller to notify its mobility information. The SDN on receiving the notification packet updates the FIB entries on the corresponding intermediate nodes by following the similar procedure described previously in the case of the proactive approach. The reactive approach reduces the routing update overhead as in this approach the controller is only contacted when the mobility event occurs in contrast to periodic exchange of control packet in case of proactive approach. In [55] as discussed earlier in the producer mobility section, the authors proposed a similar scheme in which an SDN controller—acting as a central entity, is accessed by the mobile node before and after the handover process. Moreover, SDN in collaboration with NDN may provide efficient and secure routing. For instance, SDN controllers can monitor network traffic and adjust the forwarding rules to avoid congestion and ensure that data is delivered in a timely manner. In addition to utilizing the SDN concept for routing and forwarding, it can also be utilized to optimize the in-network caching feature of NDN aiming to deal with mobility management [125]. As in-network caching helps to reduce the network latency in the case of producer handover, when a mobile producer node changes its location, it can share its cached content either with nearby nodes or with the SDN controller. In both of these cases, the SDN controller has to be informed about the cached content which in the former case is of utmost importance. Since the SDN controller is well aware of all the topological information of the network and now also knows the cached content location, it can install the flow rules on intermediate nodes to forward the Interest packet to the appropriate cache node rather than the original producer.

1) MOBILITY-RELATED EXAMPLE SCENARIO

Location change is among one of the main problems in mobile networks. The Interest packet forwarded by the consumer reaches the potential provider by creating in-transit PIT entries. While the Interest packet is in transit and the potential provider may change the location resulting in packet loss and wastage of resources. Moreover, if the consumer changes its location, the data packet traversing the chain of PIT entries may never reach the consumer's new location resulting in retransmissions and packet losses. Integrating the NDN with SDN, the updated information dynamics such as speed, location, and neighbours information due to the changes in mobility patterns of the node are made available to the controller. In so doing, the mobile consumer request or mobile provider response can be forwarded to the designated node by consulting the updated route information from the controller. The controller encompassing the global network view and updated paths highly optimizes the frequent packet losses, retransmissions, and packet losses.

2) GENERAL EXAMPLE SCENARIO

To further understand the importance of SDN and specifically its synergy with NDN from the general perspective, let us take an example of a large smart campus consisting of multiple buildings (such as departments) equipped with various research laboratories, classrooms, offices and administrators rooms, all consisting of multiple computing devices. Moreover, various—thousands in number— IoT sensors are also installed in the smart campus for monitoring and controlling purposes. Undoubtedly, in such a smart environment, the devices running on different networking protocols can be greatly leveraged from different promising features of SDN. One obvious benefit of SDN could be the interoperability among different networks i.e., the communication between a network of administrative nodes and a network of sensor devices. The SDN controller in this case can act as a gateway node between these aforementioned networks running on NDN and NDN-Lite protocols respectively, and translate the Interest/Data packets format into the corresponding compatible protocol format. Moreover, as the SDN controller or gateway node when utilizing NDN/NDN-Lite [126] protocol can intercept the content of the request (i.e., the ''Name''), request aggregation can be achieved, decreasing the flow of unnecessary packets in the network.

Discussion & Research Challenges: Although the integration of NDN and SDN further improves the network performance, there are still open research challenges that if not addressed efficiently may cause performance degradation. At first, the open flow protocol of SDN needs a major rewrite for NDN-based communication architecture. As the OpenFlow operates on top of IP protocol, it cannot be directly used in NDN. Therefore, rewriting a name-based OpenFlow communication protocol, that enables the communication between the named-based SDN controller and name-based intermediate nodes, is the first major challenge that the NDN research community may face, if they want to fully leverage from the SDN benefits. Secondly, the proactive and reactive forwarding of control packets has its own pros and cons. In proactive control packet forwarding, a network may face excessive overload resulting in network congestion whereas, in reactive control packet forwarding, a network may face delay in accessing the new path information. Therefore, a further research effort aiming to devise an efficient and adaptive named-based control packet exchange protocol is required.

D. MOBILITY SUPPORT IN RESOURCE-CONSTRAINED INTERNET OF THINGS

Among other issues in wireless networks, one of the major research challenges in resource-contained IoTs such as WSN is to support energy-efficient producer mobility. The WSN nodes are usually equipped with a limited power battery source [127], [128] and deployed in inaccessible areas to monitor the environment. Based on the deployment strategies and networking architecture, the WSN can be broadly classified into three categories: 1) single-tier flat networking architecture, 2) cluster-based networking architecture, and 3) multi-tier networking architecture. In the following subsection, we first discuss the basic working principles of each of these networking architectures, and then we provided the discussion along with the research challenges.

1) SINGLE-TIER FLAT NETWORKING ARCHITECTURE

In single-tier flat architecture, the network consists of various resource-constrained homogeneous nodes equipped with identical computational and storage resources, performing similar types of tasks. In addition to sensor nodes, a powerful sink node is deployed in the network to fetch the sensed information from all nodes in the network. Sensor nodes, after fetching the readings from the environment forward them to the sink either via single-hop communication, if resides in close proximity and the direct communication range, or via multiple hops if the sensing node and sink node are far away from each other. Based on the networking requirements and complexity, the sink node can either be static and located at the same position during the network lifetime or mobile and changing the location to gather the data from the network. In the former case, when all the sensor nodes forward the sensed data towards the sink node, an energy hotspot is created in the neighborhood of the sink node, depleting all of the neighboring node's energy due to frequent data forwarding on behalf of other nodes. To overcome this issue the mobile sink concept was introduced in which the sink node changes the position in the network to avoid an energy hotspot.

Example Scenario: The single-tier flat WSN architecture use case could be a forest fire detection system. In a forest fire detection system, various nodes are deployed—either randomly or on a pre-defined path—in various regions of the forest to monitor any fire abruption events. These nodes monitor the forest and forward collected data towards the sink node and eventually to the base station (reporting center) by following either pull or push-based communication patterns. The NDN, if used as an underlying communication architecture in WSN, may bring various benefits. At first, as WSN exhibits content-centric nature with the main focus on sharing content in the network, the NDN that treats content as a first-class citizen could be naturally fit communication architecture for WSN. Second, since each node is aware of the content passing through it, a large number of request packets can be aggregated which ultimately decreases the flow of unnecessary packets in the network and improve the overall energy consumption. Third, the address-space limitation issue can be resolved —specifically in forest fire detection scenario where thousands of nodes are required to be deployed—by using the lightweight naming schemas.

2) CLUSTER-BASED NETWORKING ARCHITECTURE

As discussed before, the single-tier flat networking architecture requires multiple hops to forward the sensed data from sensor node to sink node and consumes a significant amount of energy. Therefore, to cope with such limitation, a cluster-based approach is also often used in WSNs, in which the sensor nodes either based on geographical location or task type organize themselves into various groups [128], [129], [130]. Once the groups are formed, a head node called cluster head (CH) is nominated which is responsible for tasks, such as data aggregation, filtration, and finally forwarding toward a sink node. In such an architecture, a child sensor node is located at the one-hop distance from the CH and directly forward the sensed information towards CH. In so doing, a substantial amount of energy can be conserved in a cluster-based networking architecture.

Example Scenario: To illustrate the use case scenario of cluster-based WSNs, let us take an example of a battlefield monitoring and surveillance system. The nodes in such a system are responsible to perform functions such as sensitive area monitoring, collaborative target tracking, performing data analysis tasks, and communication. The deployment of these nodes follows a cluster-based hierarchy in which multiple sensor nodes are combined in a specific geographical location and the cluster-head is selected responsible for managing all nodes under its administration. The child nodes in each cluster can be heterogeneous in terms of their functions. For example, a cluster may consist of the nodes responsible for 1) movement tracking, 2) temperature monitoring, and/or 3) object recognition. The cluster-head node collects the information from these child nodes and forwards it either to the base station or to the other cluster head for further analysis and monitoring purposes. Moreover, to further preserve energy, the resource-rich cluster head node can utilize the NDN caching feature along with optimal caching placement and replacement to store high-priority popular content to avoid frequent updates. Moreover, with the optimal caching scheme, the cluster-head if changing the location owing to a mobility event can share the stored content with the new cluster head.

3) MULTI-TIER NETWORKING ARCHITECTURE

In multitier architecture, the network may comprise multiple tiers in which each tier may contain both heterogeneous and homogeneous nodes. Usually, the first tier consists of scalar nodes responsible for the task such as motion detection, pressure sensing, and vibration sensing, among others. The second layer consists of multimedia nodes responsible for audio/video data acquisition, whereas this layer consists of resource-rich nodes responsible for performing compute-intensive tasks on data received from the bottom layers and before forwarding to the sink nodes.

Example Scenario: The smart industry monitoring system could be the potential use case of the multi-tier WSN architecture. In such a system, the scalar nodes such as temperature, pressure, and vibration sensor, among others, can be deployed in tier 1, and multimedia mobile nodes such as robotic cameras can be deployed in tier 2. The scalar nodes initially monitor the machines and report either to the sink node or base station in a normal fashion. However, if any abnormal event such as a fault in the machine occurs, the scalar node may contact the multimedia nodes to capture the video frame and forward it towards the base station for better analysis of the faulty machine. Since the above use case may require different commands such as ''turning on the camera'', the NDN could be the best fit to efficiently execute the required commands on the appropriate node [127].

Discussion and Research Challenges: To aid better understanding and provide an in-depth analysis, we divided our discussion into the same hierarchy in which the types of WSNs are presented above. Therefore, we start our discussion with the research challenges in NDN based single tier WSNs.

As it is evident from the literature, the NDN has attracted attention in the context of resource-constrained IoT and a few research efforts have been devoted in this direction [131]. However, a comprehensive performance analysis of NDN when utilizing the mobile sink nodes in the single-tier flat networking architecture has yet to be explored. The following are some of the research challenges that we believe, require extensive attention from the NDN research community. Among them, the first issue is populating the name-based routing information on intermediate sensing nodes FIB. As the sensing nodes are often equipped with limited storage capacity, saving the name-based routing information may utilize much of the storage capacity, leaving little storage for other operations such as PIT entries storage, and CS Data storage. The second question or the research challenge is whether there is a need for the routing information base (RIB) that is used to populate the FIB entries on the Internet either through the NLSR protocol or via network administrators. In our opinion, the use of RIB depends on the networking resources, and if the resources are scarce then the FIB should directly be populated through adaptive and novel routing protocol for WSNs. Moreover, we also believe that the structure of FIB should be modified as in WSNs the nodes are usually equipped with a single radio interface, enabling them to forward the Interest/Data packet on the same physical interface. Therefore, in WSN the FIB shouldn't be storing the interfaces but rather it should store the information of the neighboring node that can participate in forwarding the Interest packet and resides in the direction of the producer node.

The challenges presented above are related to the single-tier WSN, whereas moving forward, we now shed light on the challenges and possible research directions in cluster based WSN. In cluster-based WSN and specifically the collaborative targeting scenarios, the nodes from various clusters collaborate with each other to detect the specific object. Therefore, to this end, the participating CH shares the child node's information with each other and maintains a named-based member information table that stores the node and data name to access the information in the future [131]. In this case, if for any reason, the child node moves from one cluster to another cluster, the old CH and other CHs participating in the collaborative target tracking must have to be informed, so that the new name of the sensor node can be used to access the information. One approach to share this information among other CHs is to utilize simple flooding-based solutions. However, flooding-based approaches come at the cost of excessive energy consumption. Therefore, to address such limitation, a new named information sharing schemes are of utmost importance in the domain of NDN and cluster-based WSN.

Finally, the multi-tier NDN-based WSNs have certain similarities with both single-tier flat architecture and cluster-based networking architecture, and therefore to some extent share similar research challenges. For instance, if the nodes move within the same tier, it faces challenges similar to single-tier flat architecture whereas when moved between the different tier, confronts with challenges that a node may face in cluster-based networking architecture.

E. VEHICULAR NETWORKS AND THE RISE OF AUTONOMOUS DRIVING

Autonomous Driving: The vision of self-driving autonomous vehicles is becoming a reality with each passing day. A vast amount of research is being conducted in both academia and industry to improve the safety requirements for autonomous vehicles. Among other research areas, efficient visual perception is critical for autonomous vehicles as autonomous vehicles need to detect various objects in a road environment, such as traffic signs, obstacles, and road markings. A complete realization of autonomous vehicles not only require the real-time acquisition of multimodal visual data using various in-car sensors such as light detection and ranging (LiDAR) and cameras but also need an efficient collaborative communication mechanism to share such useful visual information with other autonomous or simple vehicles on the road as well as with RSU. Collaborative communication among autonomous vehicles and with the roadside edge units is a key enabler technology that may lead to an overall improvement in the flow of traffic and prevent fatal crashes [132], which may occur otherwise. The following example scenario discusses the real-life accident that occurred due to the absence of collaborative communication.

Example Scenario: A real-life fatal crash occurred in 2016 when an autonomous car Tesla Model S running on autopilot mode with moving a speed of 68 mph on the highway struck a trailer that pulled out from the private driveway and intending to take the left turn. This unfortunate accident costed a human life. Such fatal crashes bring forth various core issues in the autonomous driving system. The first and foremost issue is, taking the driving decision solely based on the images captured by the autonomous vehicle itself. A single autonomous vehicle, although identifying the objects on the roads, cannot guarantee 100% reliability, especially in the scenario when the object is not in the observing view of the camera, as happened in the Tesla Model S crash. Therefore, employing collaborative communication in these scenarios may avoid fatal crashes. For example, if the Tesla Model S car in the previous accidental example collaborated with RSU and then RSU, in turn, collaborated with the truck on completely another side of the road, the accident could have been avoided [132].

Discussion & Research Challenges: From our previous discussion, it can be envisioned that most of the communications in vehicular networks and specifically the autonomous driving networks exhibit a content-centric approach. For instance, an autonomous car is usually interested in fetching the recent road conditions, no matter which node is providing this information i.e. road-side fixed edge camera or mobile-edge camera mounted on another vehicle. Thus, efforts have been made to check the feasibility of employing ICN (and favorably its particular implementation, NDN) as the underlying communication architecture for VANET [133], [134], [135]. Different self-driving communication scenarios can be modeled through ICN as a communication architecture using the Interest-Data exchange model. In such an architecture, autonomous vehicles can act as consumers, providers, and/or data forwarders. At the same time, RSUs and core network elements can serve as intermediate forwarders with caching capabilities. The following are some of the potential benefits of employing ICN in vehicular networks. Through named data and routing by name, ICN matches the above-described vehicular pattern and requirements, better than the current address-based communication model such as IEEE802.11p [136] and WAVE architecture [137]. Content (both multimedia or scalar) discovery is simpler because ICN does not need name-to-IP-address resolution and does not ask for the producer to always be connected. In addition, ICN simplifies content retrieval from multiple consumers (e.g., requesting the status in the form of images from the road-side fixed camera in the collaborative communication manners) by aggregating requests for the same-named content in the PIT; it is sufficient to keep track of the Interest incoming interfaces for later Data delivery. In regard to mobility, as detailed discussed in the previous sections, the IP-based host-centric protocols work awkwardly in mobile environments. In both the highway scenario, where autonomous vehicles move at very high speeds and the urban scenario, with signal propagation typically obstructed by buildings, the quality and duration of communication links can be adversely affected. In such topologies, classic IP networking operations, like address assignment and path maintenance, become difficult to achieve. Consequently, networking solutions alternative or complementary to IP are also encouraged by standardization bodies in the vehicular application/technology domain. With ICN, the use of named data simplifies mobility support. The anycasting and in-network caching properties of ICN allow vehicles to retrieve content from the most convenient (typically nearest to the consumer) producer/storage point. This reduces data latency and network traffic. Moreover, a store-carry-and-forward mechanism can be supported by ICN, through which a vehicle can serve as a link (''data mule'') between disconnected areas and enable communications even under intermittent connectivity.

In addition to the discussion presented above, we would also like to shed light on flooding-based data transmission schemes and their solutions in general VANETS. As various flooding and broadcasting techniques are often used—attributed to the fast-changing and dynamic nature of vehicular typologies, to disseminate the messages among vehicles, these techniques create broadcast storm problems and degrade the performance of the network in terms of increased overhead, collision, and dissemination delay. To cope with such issues, numerous broadcast storm avoidance techniques have been proposed in the domain of information centric VANETs [138]. These techniques often consider either one or all of the following parameters in conjunction: 1) Interest packet suppression, 2) Data packet suppression, 3) Interest transmission limit, 4) Data transmission limit, and 5) farthest forwarder selection, to reduce the broadcast storm in the network. In addition to the aforementioned techniques, we believe that the inclusion of the following two parameters: 1) the number of current contacts and 2) the angle of transmission can further reduce the chances of the broadcast storm. In the former approach, all the vehicles first calculate the current number of contacts (neighboring vehicles), and then only that vehicle will be selected as a forwarder that has more neighboring nodes as compared to others. In doing so, the chances of reaching a producer node (in case of Interest packet transmission) or consumer node (in case of Data packet transmission) will be increased. This technique can further be integrated with the angle of transmission technique, in which after calculating the current number of contacts, the selected vehicle computes the angle of transmission (dense area selection) with respect to its current location coordinates. Once the angle is computed, the Interest or Data packet will be forwarded within that specific angle to further limit the number of potential forwarders and to increase the chances of locating the consumer or producer vehicle.

F. INTEGRATING SEMANTIC IN NDN

As discussed previously, the NDN communication philosophy is mainly built on ''content Names'' rather than IP addresses that effectively promote scalable and efficient delivery of requested content. Apart from the intrinsic benefits of named base communication, there may exist the occurrence of false positives in the delivered data. Meaning that the user may not get the actual content against the interest packet. Semantic communication can effectively handle the problem due to its ability to understand the meaning of the data being transmitted, as opposed to simply transmitting and receiving packets based on their names. Semantic communication may help NDN routers to make intelligent forwarding, and mobility-related decisions and avoid the occurrence of false positives. Incorporating Natural language processing in NDN forwarding and mobility may help to enable semantic communication.

1) GENERAL EXAMPLE SCENARIO

In order to understand the concept more clearly, consider the following example: if a user requests a named data packet containing the word ''APPLE'' the NDN router may never identify whether the user is looking for APPLE fruit or APPLE company's information. By understanding the context and meaning of the data being transmitted, NDN can provide more intelligent content delivery and enable new applications with effective content delivery by comprehending the context and meaning of the data being transferred.

2) MOBILITY-RELATED EXAMPLE SCENARIO AND RESEARCH CHALLENGES

Semantic communication can also improve mobility management in the mobile network. For instance, various mobility management protocols utilize different packets to share the mobility events with for instance network controllers or rendezvous points. These information-sharing packets if utilise semantic-less information may also result in false mobility updates. For instance, if location information only contains direction information without specifying the reference point for the direction may lead to incorrect updates in routing updates. To handle such scenarios and false updates, there is a need for further research in this direction that focuses on developing efficient mobility information protocols following semantic information principles.

VI. CONCLUSION

ICN and specifically its realization; the NDN, is an emerging research field that intends to resolve the issues faced by the current IP-based internet architecture such as intermittent connectivity, in-efficient routing, and network overhead caused by consumer mobility, among others. However, in the context of wireless nodes' mobility and specifically the producer mobility, since an efficient mobility solution was not provided in the original design of NDN, a significant amount of research was carried out in both academia and industry, which eventually resulted in the form of research papers. In this survey paper, therefore, we provided a comprehensive survey of the producer, consumer, and hybrid mobility schemes in NDN which is currently a growing concern to practically adopt the NDN. The position of this paper is manifold. At first, we provided a brief introduction to ICN and shed light on how ICN mitigates the challenges of data transmission in mobile networks. Second, we provided a detailed survey covering the mobility management issues in various ICN realizations and provided a quick reference for both researchers and industry experts. Third, we described the basic components of the NDN and its working mechanism. Next, we comprehensively surveyed the various producer, consumer, and hybrid mobility schemes proposed under the umbrella of NDN aiming to efficiently address the mobility issues in the network. Here, we classified these research efforts into various categories such as 1) tracing-based, 2) caching-based, 3) mapping-based, 4) broadcast control based, 5) location-based, and 6) adaptive forwarding based mobility management schemes. We critically discussed these schemes considering the various factors including 1) deployment strategies i.e., random, or fixed, 2) network type for instance pure wireless ad hoc or partial wireless networking scenarios, 3) networking traffic rate, for example, light or dense traffic generation rate, 4) mobility transparency i.e., the effect of mobile nodes movement in the network on end-user QoS requirements and the 5) mobility patterns of the nodes i.e., based on speed and direction, among others, and presented both contributions as well as the limitations of these schemes. Finally, several research challenges and future directions considering the role of mobility are presented in futuristic technologies such as artificial intelligence-enabled smart networks, edge computing, software-defined networking, vehicular-fog computing, autonomous driving, and resource-constrained internet of things.

ACKNOWLEDGMENT

(Sana Fayyaz and Muhammad Atif Ur Rehman are co-first authors.)

REFERENCES

[1] S. Arshad, M. A. Azam, M. H. Rehmani, and J. Loo, "Recent advances in information-centric networking-based Internet of Things (ICN-IoT)," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2128–2158, Apr. 2019.

[2] B. Nour, H. Ibn-Khedher, H. Moungla, H. Afifi, F. Li, K. Sharif, H. Khelifi, and M. Guizani, "Internet of Things mobility over information-centric/named-data networking," *IEEE Internet Comput.*, vol. 24, no. 1, pp. 14–24, Jan. 2020.

[3] D. Mars, S. Mettali Gammar, A. Lahmadi, and L. Azouz Saidane, "Using information centric networking in Internet of Things: A survey," *Wireless Pers. Commun.*, vol. 105, no. 1, pp. 87–103, Mar. 2019, doi: 10.1007/s11277-018-6104-8.

[4] M. Amadeo, C. Campolo, J. Quevedo, D. Corujo, A. Molinaro, A. Iera, R. L. Aguiar, and A. V. Vasilakos, "Information-centric networking for the Internet of Things: Challenges and opportunities," *IEEE Netw.*, vol. 30, no. 2, pp. 92–100, Mar. 2016.

[5] G. Li, M. Dong, K. Ota, J. Wu, J. Li, and T. Ye, "Towards QoE named content-centric wireless multimedia sensor networks with mobile sinks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[6] Z. Zhu, R. Wakikawa, and L. Zhang, "A survey of mobility support in the internet," RFC, 2011. [Online]. Available: https://www.rfc-editor.org/rfc/rfc6301.html

[7] Y. Bi, H. Zhou, W. Xu, X. S. Shen, and H. Zhao, "An efficient PMIPv6-based handoff scheme for urban vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 12, pp. 3613–3628, Dec. 2016.

[8] K.-H. Lee, H.-W. Lee, W. Ryu, and Y.-H. Han, "A scalable network-based mobility management framework in heterogeneous IP-based networks," *Telecommun. Syst.*, vol. 52, no. 4, pp. 1989–2002, Apr. 2013, doi: 10.1007/s11235-011-9479-3.

[9] C. Makaya and S. Pierre, "An analytical framework for performance evaluation of IPv6-based mobility management protocols," *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 972–983, Mar. 2008.

[10] C. E. Perkins, "Mobile networking through mobile IP," *IEEE Internet Comput.*, vol. 2, no. 1, pp. 58–69, Jan./Feb. 1998.

[11] A.-M. Pathan et al., "A taxonomy and survey of content delivery networks," Grid Comput. Distrib. Syst. Lab., Univ. Melbourne, Melbourne, VIC, Australia, Tech. Rep. GRIDS-TR-2007-4, 2007, p. 70, vol. 4, no. 2007. [Online]. Available: https://www.bibsonomy.org/bibtex/2f3dfe239f506b802f75e2611db9aaf12/chesteve

[12] *IRTF Information-Centric Networking Research Group (ICNRG)*. Accessed: Nov. 14, 2022. [Online]. Available: https://irtf.org/icnrg

[13] K. Yu, S. Eum, T. Kurita, Q. Hua, T. Sato, H. Nakazato, T. Asami, and V. P. Kafle, "Information-centric networking: Research and standardization status," *IEEE Access*, vol. 7, pp. 126164–126176, 2019.

[14] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, and B. Ohlman, "A survey of information-centric networking," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 26–36, Jul. 2012.

[15] G. Xylomenos, "A survey of information-centric networking research," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 1024–1049, 2nd Quart., 2014.

[16] A. V. Vasilakos, Z. Li, G. Simon, and W. You, "Information centric network: Research challenges and opportunities," *J. Netw. Comput. Appl.*, vol. 52, pp. 1–10, Jun. 2015.

[17] L. Zhang, A. Afanasyev, J. Burke, V. Jacobson, K. Claffy, P. Crowley, C. Papadopoulos, L. Wang, and B. Zhang, "Named data networking," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 66–73, Jul. 2014, doi: 10.1145/2656877.2656887.

[18] V. Jacobson M. Mosko, D. Smetters, and J. J. Garcia-Luna-Aceves, "Content-centric networking: Whitepaper describing future assurable global networks," Response DARPA RFI SN07-12, 2007. [Online]. Available: http://mmlab.snu.ac.kr/courses/2007_advanced_internet/papers/20071010_1.pdf and https://www.bibsonomy.org/bibtex/7f704918cca2b3d07940f216e218f6f4

[19] T. Koponen, M. Chawla, B.-G. Chun, A. Ermolinskiy, K. H. Kim, S. Shenker, and I. Stoica, "A data-oriented (and beyond) network architecture," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 37, no. 4, pp. 181–192, Oct. 2007.

[20] N. Fotiou, D. Trossen, and G. C. Polyzos, "Illustrating a publish-subscribe internet architecture," *Telecommun. Syst.*, vol. 51, no. 4, pp. 233–245, Dec. 2012.

[21] 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.

[22] G. García, "COMET: Content mediator architecture for content-aware networks," in *Proc. Future Netw. Mobile Summit*, Jun. 2011, pp. 1–8.

[23] A. Detti, N. B. Melazzi, S. Salsano, and M. Pomposini, "CONET: A content centric inter-networking architecture," in *Proc. ACM SIGCOMM Workshop Inf.-Centric Netw.*, Aug. 2011, pp. 50–55.

[24] D. Raychaudhuri, K. Nagaraja, and A. Venkataramani, "MobilityFirst: A robust and trustworthy mobility-centric architecture for the future internet," *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 16, no. 3, pp. 2–13, Dec. 2012.

[25] C. Anastasiades, T. Braun, and V. A. Siris, "Information-centric networking in mobile and opportunistic networks," in *Wireless Networking for Moving Objects*. Cham, Switzerland: Springer, 2014, pp. 14–30.

[26] A. Afanasyev, J. Burke, T. Refaei, L. Wang, B. Zhang, and L. Zhang, "A brief introduction to named data networking," in *Proc. MILCOM IEEE Mil. Commun. Conf. (MILCOM)*, Oct. 2018, pp. 1–6.

[27] *Mobile Video Delivery With Hybrid ICN IP-Integrated ICN Solution for 5G*. Accessed: Jun. 3, 2021. [Online]. Available: https://www.cisco.com/c/dam/en/us/soluti ons/collateral/service-provider/ultra-services-platform/mwc17-hicn-video-wp.pdf

[28] G. Tyson, N. Sastry, I. Rimac, R. Cuevas, and A. Mauthe, "A survey of mobility in information-centric networks: Challenges and research directions," in *Proc. 1st ACM Workshop Emerg. Name-Oriented Mobile Netw. Design Archit., Algorithms, Appl.*, Jun. 2012, pp. 1–6.

[29] D. Perino and M. Varvello, "A reality check for content centric networking," in *Proc. ACM SIGCOMM Workshop Inf.-Centric Netw.*, Aug. 2011, pp. 44–49, doi: 10.1145/2018584.2018596.

[30] Y. Zhang, A. Afanasyev, J. Burke, and L. Zhang, "A survey of mobility support in named data networking," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2016, pp. 83–88.

[31] B. Feng, H. Zhou, and Q. Xu, "Mobility support in named data networking: A survey," *EURASIP J. Wireless Commun. Netw.*, vol. 2016, no. 1, pp. 1–9, Dec. 2016.

[32] M. Hussaini, S. A. Nor, and A. Ahmad, "Producer mobility support schemes for named data networking: A survey," *Int. J. Electr. Comput. Eng. (IJECE)*, vol. 8, no. 6, p. 5432, Dec. 2018.

[33] M. Hussaini, M. A. Naeem, B.-S. Kim, and I. S. Maijama'a, "Efficient producer mobility management model in information-centric networking," *IEEE Access*, vol. 7, pp. 42032–42051, 2019.

[34] 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 Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2353–2371, 3rd Quart., 2018.

[35] N. Fotiou, P. Nikander, D. Trossen, and G. C. Polyzos, "Developing information networking further: From PSIRP to pursuit," in *Proc. Int. Conf. Broadband Commun., Netw. Syst.*, 2010, pp. 1–13.

[36] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, "Networking named content," in *Proc. 5th Int. Conf. Emerg. Netw. Exp. Technol.*, Dec. 2009, pp. 1–12.

[37] 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 Trans. Netw. Service Manage.*, vol. 15, no. 2, pp. 596–610, Jun. 2018.

[38] J. Augé, G. Carofiglio, G. Grassi, L. Muscariello, G. Pau, and X. Zeng, "Anchor-less producer mobility in ICN," in *Proc. 2nd ACM Conf. Inf.-Centric Netw.*, Sep. 2015, pp. 189–190.

[39] D. Han, M. Lee, K. Cho, T. Kwon, and Y. Choi, "Publisher mobility support in content centric networks," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Feb. 2014, pp. 214–219.

[40] Y. Zhang, Z. Xia, S. Mastorakis, and L. Zhang, "KITE: Producer mobility support in named data networking," in *Proc. 5th ACM Conf. Inf.-Centric Netw.*, Sep. 2018, pp. 125–136.

[41] Y. Zhang, H. Zhang, and L. Zhang, "Kite: A mobility support scheme for NDN," in *Proc. 1st ACM Conf. Inf.-Centric Netw.*, Sep. 2014, pp. 179–180.

[42] L. Wang, O. Waltari, and J. Kangasharju, "MobiCCN: Mobility support with greedy routing in content-centric networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 2069–2075.

[43] P. Kar, R. Chen, and Y. Qian, "An efficient producer mobility management technique for real-time communication in NDN-based remote health monitoring systems," *Smart Health*, vol. 26, Dec. 2022, Art. no. 100309. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352648322000435

[44] J. Lee, S. Cho, and D. Kim, "Device mobility management in content-centric networking," *IEEE Commun. Mag.*, vol. 50, no. 12, pp. 28–34, Dec. 2012.

[45] S. Gao and H. Zhang, "Scalable mobility management for content sources in named data networking," in *Proc. 13th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2016, pp. 79–84.

[46] X. Jiang, J. Bi, and Y. Wang, "What benefits does NDN have in supporting mobility," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jun. 2014, pp. 1–6.

[47] F. Hermans, E. Ngai, and P. Gunningberg, "Global source mobility in the content-centric networking architecture," in *Proc. 1st ACM Workshop Emerg. Name-Oriented Mobile Netw. Design Archit., Algorithms, Appl.*, Jun. 2012, pp. 13–18.

[48] A. Azgin, R. Ravindran, and G. Wang, "A scalable mobility-centric architecture for named data networking," 2014, *arXiv:1406.7049*.

[49] D. Kim and Y.-B. Ko, "On-demand anchor-based mobility support method for named data networking," in *Proc. 19th Int. Conf. Adv. Commun. Technol. (ICACT)*, 2017, pp. 19–23.

[50] M. Hussaini, S. A. Nor, and A. Ahmad, "PMSS: Producer mobility support scheme optimization with RWP mobility model in named data networking," *Int. J. Commun. Netw. Inf. Secur. (IJCNIS)*, vol. 10, no. 2, pp. 329–338, Apr. 2022.

[51] Y. Zheng, X. Piao, and K. Lei, "Anchor-chain: A seamless producer mobility support scheme in NDN," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–6.

[52] D. Gao, Y. Rao, C. H. Foh, H. Zhang, and A. V. Vasilakos, "PMNDN: Proxy based mobility support approach in mobile NDN environment," *IEEE Trans. Netw. Service Manage.*, vol. 14, no. 1, pp. 191–203, Mar. 2017.

[53] B. Hu, Z. Li, and S. Zou, "Provider mobility management based on domain proxies in content centric networks," in *Proc. 14th Int. Symp. Commun. Inf. Technol. (ISCIT)*, Sep. 2014, pp. 393–397.

[54] J. Tang, H. Zhou, Y. Liu, H. Zhang, and D. Gao, "A source mobility management scheme in content-centric networking," in *Proc. IEEE 11th Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2014, pp. 176–181.

[55] F. Ren, Y. Qin, H. Zhou, and Y. Xu, "Mobility management scheme based on software defined controller for content-centric networking," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2016, pp. 193–198.

[56] J. Ge, S. Wang, Y. Wu, H. Tang, and Y. E, "Performance improvement for source mobility in named data networking based on global–local FIB updates," *Peer Peer Netw. Appl.*, vol. 9, no. 4, pp. 670–680, Jul. 2016.

[57] H. Farahat and H. S. Hassanein, "Proactive caching for producer mobility management in named data networks," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2017, pp. 171–176.

[58] C. Chen, C. Wang, T. Qiu, M. Atiquzzaman, and D. O. Wu, "Caching in vehicular named data networking: Architecture, schemes and future directions," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2378–2407, 4th Quart., 2020.

[59] S. S. Musa, M. Zennaro, M. Libsie, and E. Pietrosemoli, "Mobility-aware proactive edge caching optimization scheme in information-centric IoV networks," *Sensors*, vol. 22, no. 4, p. 1387, Feb. 2022.

[60] L. Rui, S. Yang, and H. Huang, "A producer mobility support scheme for real-time multimedia delivery in named data networking," *Multimedia Tools Appl.*, vol. 77, no. 4, pp. 4811–4826, Feb. 2018.

[61] M. A. Hail, M. Amadeo, A. Molinaro, and S. Fischer, "Caching in named data networking for the wireless Internet of Things," in *Proc. Int. Conf. Recent Adv. Internet Things (RIoT)*, Apr. 2015, pp. 1–6.

[62] 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," *Comput. Netw.*, vol. 156, pp. 62–74, Jun. 2019.

[63] D. Grewe, M. Wagner, S. Schildt, M. Arumaithurai, and H. Frey, "Caching-as-a-service in virtualized caches for information-centric connected vehicle environments," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2018, pp. 1–8.

[64] H. Farahat and H. Hassanein, "Optimal caching for producer mobility support in named data networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.

[65] 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, p. 28, Jan. 2019.

[66] Z. Zhang, T. Li, J. Dellaverson, and L. Zhang, "RapidVFetch: Rapid downloading of named data via distributed V2V communication," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2019, pp. 1–8.

[67] D. Grewe, M. Wagner, and H. Frey, "PeRCeIVE: Proactive caching in ICN-based VANETs," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2016, pp. 1–8.

[68] D. Grewe, S. Schildt, M. Wagner, and H. Frey, "ADePt: Adaptive distributed content prefetching for information-centric connected vehicles," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–5.

[69] N. Abani, T. Braun, and M. Gerla, "Proactive caching with mobility prediction under uncertainty in information-centric networks," in *Proc. 4th ACM Conf. Inf.-Centric Netw.*, Sep. 2017, pp. 88–97.

[70] S. Park, S. Oh, Y. Nam, J. Bang, and E. Lee, "Mobility-aware distributed proactive caching in content-centric vehicular networks," in *Proc. 12th IFIP Wireless Mobile Netw. Conf. (WMNC)*, Sep. 2019, pp. 175–180.

[71] V. Sivaraman and B. Sikdar, "Hop-count based forwarding for seamless producer mobility in NDN," in *Proc. GLOBECOM IEEE Global Commun. Conf.*, Dec. 2017, pp. 1–6.

[72] A. K. Niari, R. Berangi, and M. Fathy, "ECCN: An extended CCN architecture to improve data access in vehicular content-centric network," *J. Supercomput.*, vol. 74, no. 1, pp. 205–221, Jan. 2018, doi: 10.1007/s11227-017-2126-3.

[73] W. U. I. Zafar, M. A. U. Rehman, F. Jabeen, B.-S. Kim, and Z. Rehman, "Context-aware naming and forwarding in NDN-based VANETs," *Sensors*, vol. 21, no. 14, p. 4629, Jul. 2021.

[74] M. Hussaini, M. A. Naeem, and B.-S. Kim, "OPMSS: Optimal producer mobility support solution for named data networking," *Appl. Sci.*, vol. 11, no. 9, p. 4064, Apr. 2021, doi: 10.3390/app11094064.

[75] S. A. Khan and H. Lim, "Novel fuzzy logic scheme for push-based critical data broadcast mitigation in VNDN," *Sensors*, vol. 22, no. 20, p. 8078, Oct. 2022, doi: 10.3390/s22208078.

[76] N. N. Dehaghani, R. Sadeghi, and S. M. F. Imani, "REF: A novel forwarding strategy in wireless NDN," *Wireless Pers. Commun.*, vol. 117, no. 2, pp. 1025–1042, Mar. 2021.

[77] R. Ullah, M. A. U. Rehman, and B. S. Kim, "Hierarchical name-based mechanism for push-data broadcast control in information-centric multihop wireless networks," *Sensors*, vol. 19, no. 14, p. 3034, Jul. 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/14/3034

[78] M. F. Majeed, S. H. Ahmed, and M. N. Dailey, "Enabling push-based critical data forwarding in vehicular named data networks," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 873–876, Apr. 2017.

[79] S. H. Ahmed, S. H. Bouk, M. A. Yaqub, D. Kim, and M. Gerla, "CONET: Controlled data packets propagation in vehicular named data networks," in *Proc. 13th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2016, pp. 620–625.

[80] S. H. Bouk, S. H. Ahmed, D. Kim, K.-J. Park, Y. Eun, and J. Lloret, "LAPEL: Hop limit based adaptive PIT entry lifetime for vehicular named data networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 5546–5557, Jul. 2018.

[81] S. Gao, H. Zhang, and B. Zhang, "Energy efficient interest forwarding in NDN-based wireless sensor networks," *Mobile Inf. Syst.*, vol. 2016, pp. 1–15, Apr. 2016, doi: 10.1155/2016/3127029.

[82] C. Yi, A. Afanasyev, L. Wang, B. Zhang, and L. Zhang, "Adaptive forwarding in named data networking," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 42, no. 3, pp. 62–67, Jun. 2012, doi: 10.1145/2317307.2317319.

[83] 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 Gener. Comput. Syst.*, vol. 87, pp. 351–363, Oct. 2018.

[84] M. Chowdhury, J. A. Khan, and L. Wang, "Leveraging content connectivity and location awareness for adaptive forwarding in NDN-based mobile ad hoc networks," in *Proc. 7th ACM Conf. Inf.-Centric Netw.*, Sep. 2020, pp. 59–69.

[85] B. Han, X. Wang, N. Choi, T. Kwon, and Y. Choi, "AMVS-NDN: Adaptive mobile video streaming and sharing in wireless named data networking," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2013, pp. 375–380.

[86] A. Abrar, A. S. C. M. Arif, and K. M. Zaini, "A mobility mechanism to manage producer mobility in named data networking," in *Proc. IEEE Region 10 Symp. (TENSYMP)*, Jul. 2022, pp. 1–6.

[87] E. da Silva, J. Macedo, and A. Costa, "Context-aware routing and forwarding model for NDN-based VANET," in *Proc. Int. Conf. Ad Hoc Netw.* Cham, Switzerland: Springer, Nov. 2021, pp. 18–32.

[88] E. T. da Silva, J. M. H. de Macedo, and A. L. D. Costa, "Design of a context-aware routing system model with mobility prediction for NDN-based VANET," in *Proc. DCE Symp. Electr. Comput. Eng., Book Abstr.*, 2021, p. 21.

[89] J. Ali, M. Adnan, T. R. Gadekallu, R. H. Jhaveri, and B.-H. Roh, "A QoS-aware software defined mobility architecture for named data networking," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2022, pp. 444–449.

[90] J. M. Duarte, T. Braun, and L. A. Villas, "Source mobility in vehicular named-data networking: An overview," in *Proc. Ad Hoc Netw., 9th Int. Conf., (AdHocNets)*, 2018, pp. 83–93.

[91] J. M. Duarte, T. Braun, and L. A. Villas, "MobiVNDN: A distributed framework to support mobility in vehicular named-data networking," *Ad Hoc Netw.*, vol. 82, pp. 77–90, Jan. 2019.

[92] R. Ying, L. Hongbin, G. Deyun, Z. Huachun, and Z. Hongke, "LBMA: A novel locator based mobility support approach in named data networking," *China Commun.*, vol. 11, no. 4, pp. 111–120, Apr. 2014.

[93] Y. Rao, D. Gao, and H. Luo, "NLBA: A novel provider mobility support approach in mobile NDN environment," in *Proc. IEEE 11th Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2014, pp. 188–193.

[94] A. Khalid, R. A. Rehman, and M. Burhan, "CBILEM: A novel energy aware mobility handling protocol for SDN based NDN-MANETs," *Ad Hoc Netw.*, vol. 140, Mar. 2023, Art. no. 103049. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1570870522002219

[95] P. Iglesias-Sanuy, J. C. López-Ardao, M. Rodríguez-Pérez, S. Herrería-Alonso, A. Suárez-González, and R. F. Rodríguez-Rubio, "An efficient location-based forwarding strategy for named data networking and LEO satellite communications," *Future Internet*, vol. 14, no. 10, p. 285, Sep. 2022.

[96] S. H. Ahmed, S. H. Bouk, M. A. Yaqub, D. Kim, H. Song, and J. Lloret, "CODIE: Controlled data and interest evaluation in vehicular named data networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3954–3963, Jun. 2016.

[97] J. M. Duarte, T. Braun, and L. A. Villas, "Receiver mobility in vehicular named data networking," in *Proc. Workshop Mobility Evolving Internet Archit.*, Aug. 2017, pp. 43–48.

[98] J. M. Duarte, T. Braun, and L. A. Villas, "Addressing the effects of low vehicle density in highly mobile vehicular named-data networks," in *Proc. 6th ACM Symp. Develop. Anal. Intell. Veh. Netw. Appl.*, Nov. 2017, pp. 117–124.

[99] H. Farahat and H. S. Hassanein, "Supporting consumer mobility using proactive caching in named data networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[100] 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.

[101] L. Rui, S. Yang, and H. Huang, "A proactive multi-level cache selection scheme to enhance consumer mobility support in named data networking," *Int. J. Distrib. Sensor Netw.*, vol. 13, no. 4, 2017, Art. no. 1550147717700897.

[102] H. Khelifi, S. Luo, B. Nour, A. Sellami, H. Moungla, and F. Nait-Abdesselam, "An optimized proactive caching scheme based on mobility prediction for vehicular networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[103] J.-H. Cha, J.-H. Choi, J.-Y. Kim, S.-G. Min, and Y.-H. Han, "A mobility link service in NDN face to support consumer mobility service," in *Proc. 9th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2017, pp. 444–449.

[104] J.-H. Cha, J.-H. Choi, J.-Y. Kim, Y.-H. Han, and S.-G. Min, "A mobility link service for NDN consumer mobility," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–8, Jul. 2018.

[105] A. Suwannasa, M. Broadbent, and A. Mauthe, "Vicinity-based replica finding in named data networking," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Jan. 2020, pp. 146–151.

[106] A. Suwannasa, M. Broadbent, and A. Mauthe, "Effectiveness of vicinity-based content finding in mobile NDN environments," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Jan. 2021, pp. 343–348.

[107] D. Wu, X. Nie, E. Asmare, D. I. Arkhipov, Z. Qin, R. Li, J. A. McCann, and K. Li, "Towards distributed SDN: Mobility management and flow scheduling in software defined urban IoT," *IEEE Trans. Parallel Distrib. Syst.*, vol. 31, no. 6, pp. 1400–1418, Jun. 2020.

[108] D. Hernandez, M. Luis, and S. Sargento, "Consumer mobility awareness in named data networks," *IEEE Access*, vol. 10, pp. 18156–18168, 2022.

[109] H. Nakazato, S. Zhang, Y. J. Park, A. Detti, D. Bursztynowski, Z. Kopertowski, and I. Psaras, "On-path resolver architecture for mobility support in information centric networking," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2015, pp. 1–6.

[110] Z. Zhou, X. Tan, H. Li, Z. Zhao, and D. Ma, "MobiNDN: A mobility support architecture for NDN," in *Proc. 33rd Chin. Control Conf.*, Jul. 2014, pp. 5515–5520.

[111] D.-H. Kim, J.-H. Kim, Y.-S. Kim, H.-S. Yoon, and I. Yeom, "Mobility support in content centric networks," in *Proc. 2nd Ed., ICN Workshop Inf.-Centric Netw.*, 2012, pp. 13–18.

[112] D.-H. Kim, J.-H. Kim, Y.-S. Kim, H.-S. Yoon, and I. Yeom, "End-to-end mobility support in content centric networks," *Int. J. Commun. Syst.*, vol. 28, no. 6, pp. 1151–1167, Apr. 2015.

[113] X. Wang, Y. Li, and X. Wang, "Location-related content communications with mobility support in vehicular scenarios," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 4, pp. 918–930, Dec. 2018.

[114] Z. Yan, S. Zeadally, S. Zhang, R. Guo, and Y.-J. Park, "Distributed mobility management in named data networking," *Wireless Commun. Mobile Comput.*, vol. 16, no. 13, pp. 1773–1783, Sep. 2016.

[115] M. Wang, J. Wu, G. Li, J. Li, Q. Li, and S. Wang, "Toward mobility support for information-centric IoV in smart city using fog computing," in *Proc. IEEE Int. Conf. Smart Energy Grid Eng. (SEGE)*, Aug. 2017, pp. 357–361.

[116] M. N. Ahangar, Q. Z. Ahmed, F. A. Khan, and M. Hafeez, "A survey of autonomous vehicles: Enabling communication technologies and challenges," *Sensors*, vol. 21, no. 3, p. 706, Jan. 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/3/706

[117] G. Li, J. Wu, S. Li, W. Yang, and C. Li, "Multitentacle federated learning over software-defined industrial Internet of Things against adaptive poisoning attacks," *IEEE Trans. Ind. Informat.*, vol. 19, no. 2, pp. 1260–1269, Feb. 2023.

[118] W. Z. Khan, E. Ahmed, S. Hakak, I. Yaqoob, and A. Ahmed, "Edge computing: A survey," *Future Gener. Comput. Syst.*, vol. 97, pp. 219–235, Aug. 2019.

[119] E. Ahmed and M. H. Rehmani, "Mobile edge computing: Opportunities, solutions, and challenges," *Future Gener. Comput. Syst.*, vol. 70, pp. 59–63, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167739X16303260, doi: 10.1016/j.future.2016.09.015.

[120] N. Abbas, Y. Zhang, A. Taherkordi, and T. Skeie, "Mobile edge computing: A survey," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 450–465, Feb. 2017.
[121] X. Hou, Y. Li, M. Chen, D. Wu, D. Jin, and S. Chen, "Vehicular fog computing: A viewpoint of vehicles as the infrastructures," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3860–3873, Jun. 2016.
[122] Y. Xiao and C. Zhu, "Vehicular fog computing: Vision and challenges," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PerCom Workshops)*, Mar. 2017, pp. 6–9.
[123] Q.-Y. Zhang, X.-W. Wang, M. Huang, K.-Q. Li, and S. K. Das, "Software defined networking meets information centric networking: A survey," *IEEE Access*, vol. 6, pp. 39547–39563, 2018.
[124] *Openflow Switch Specification*. Accessed: Sep. 30, 2010. [Online]. Available: https://opennetworking.org/wp-content/uploads/2014/10/openflow-switch-v1.5.1.pdf
[125] K. Tantayakul, R. Dhaou, and B. Paillassa, "Mobility management with caching policy over SDN architecture," in *Proc. IEEE Conf. Netw. Function Virtualization Softw. Defined Netw. (NFV-SDN)*, Nov. 2017, pp. 1–7.
[126] Z. Zhang, E. Lu, Y. Li, L. Zhang, T. Yu, D. Pesavento, J. Shi, and L. Benmohamed, "NDNoT: A framework for named data network of things," in *Proc. 5th ACM Conf. Inf.-Centric Netw.*, Sep. 2018, pp. 200–201.
[127] M. A. U. Rehman, R. Ullah, and B.-S. Kim, "NINQ: Name-integrated query framework for named-data networking of things," *Sensors*, vol. 19, no. 13, p. 2906, Jun. 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/13/2906
[128] M. S. U. Din, M. A. U. Rehman, R. Ullah, C.-W. Park, and B. S. Kim, "Towards network lifetime enhancement of resource constrained IoT devices in heterogeneous wireless sensor networks," *Sensors*, vol. 20, no. 15, p. 4156, Jul. 2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/15/4156
[129] H. Lu, J. Li, and M. Guizani, "Secure and efficient data transmission for cluster-based wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 3, pp. 750–761, Mar. 2014.
[130] T. M. Behera, S. K. Mohapatra, U. C. Samal, M. S. Khan, M. Daneshmand, and A. H. Gandomi, "Residual energy-based cluster-head selection in WSNs for IoT application," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 5132–5139, Jun. 2019.
[131] M. A. U. Rehman, R. Ullah, B.-S. Kim, B. Nour, and S. Mastorakis, "CCIC-WSN: An architecture for single-channel cluster-based information-centric wireless sensor networks," *IEEE Internet Things J.*, vol. 8, no. 9, pp. 7661–7675, May 2021.
[132] Z. Dong, W. Shi, G. Tong, and K. Yang, "Collaborative autonomous driving: Vision and challenges," in *Proc. Int. Conf. Connected Auto. Driving (MetroCAD)*, Feb. 2020, pp. 17–26.
[133] M. Amadeo, C. Campolo, and A. Molinaro, "Information-centric networking for connected vehicles: A survey and future perspectives," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 98–104, Feb. 2016.
[134] G. Grassi, D. Pesavento, G. Pau, R. Vuyyuru, R. Wakikawa, and L. Zhang, "VANET via named data networking," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2014, pp. 410–415.
[135] I. Din, B.-S. Kim, S. Hassan, M. Guizani, M. Atiquzzaman, and J. Rodrigues, "Information-centric network-based vehicular communications: Overview and research opportunities," *Sensors*, vol. 18, no. 11, p. 3957, Nov. 2018.
[136] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," in *Proc. VTC Spring IEEE Veh. Technol. Conf.*, May 2008, pp. 2036–2040.
[137] *IEEE Guide for Wireless Access in Vehicular Environments (WAVE) Architecture*, Standard 1609.0-2019 (Revision IEEE Std 1609.0-2013), 2019, pp. 1–106.
[138] H. Khelifi, S. Luo, B. Nour, H. Moungla, Y. Faheem, R. Hussain, and A. Ksentini, "Named data networking in vehicular ad hoc networks: State-of-the-Art and challenges," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 320–351, 4th Quart., 2020.

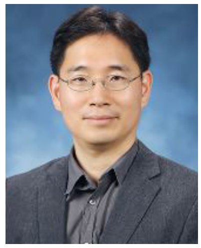
SANA FAYYAZ received the B.S. degree in computer science from Bahauddin Zakariya University (BZU), Multan, Pakistan, in 2019, and the M.S. degree in electronics and computer engineering from Hongik University, Republic of Korea, in 2022. Her major research interests include information-centric networking (mobile/wireless named data networking) and the Internet of Things.

MUHAMMAD ATIF UR REHMAN received the B.S. degree in electronics and communication from the University of Lahore, Lahore, Pakistan, in 2013, the M.S. degree in computer science from the COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2016, and the Ph.D. degree in electronics and computer engineering from Hongik University, South Korea, in 2022. He is currently a Lecturer (Assistant Professor) with Manchester Metropolitan University, Manchester, U.K., with both research and teaching responsibilities. His research interests include edge cloud computing, network protocol design, application-centric networking, microservice-centric networking, information-centric networking, future vertical communication networks, integration of ICN with edge computing, the Internet of Things, and beyond 5th-generation communication. His work has appeared in more than 50 publications, including journals, conferences, and patents. Moreover, he is the Unit Leader of the Advanced Computer Networks Unit, Manchester Metropolitan University. In addition to his academic background, he also has industry experience, and from 2013 to 2018, he was a software engineer and an architect in leading IT companies in Pakistan. He has more than six years of software and application development experience in modern application development technologies, such as C/C++, C#, Angular, TypeScript, JavaScript, Swift, Java, ASP.NET, Entity Framework, Dapper, SQL, and MongoDB. He is a Founding Member of the IEEE SIG on Metaverse. He serves as a Reviewer and/or a TPC Member for various international conferences and workshops, including IEEE ICC, and ICWMC 2020, 2021, 2022, and 2023. He serves as a regular Reviewer for journals, such as IEEE Internet of Things Journal, IEEE Transaction of Wireless Communication, IEEE Access, *Future Generation Computer Systems* journal (Elsevier), and *Digital Communications and Networks* (KeAi/Elsevier). He is also serving as the General Chair for the IEEE ICC 2023 Metaverse-Based Networking and Computing Workshop. Furthermore, he serves as the Guest Editor for the *Electronics* journal (MDPI).

MUHAMMAD SALAH UD DIN (Student Member, IEEE) received the Bachelor of Engineering degree in information technology (majors in software engineering) from KICSIT (University of Engineering and Technology Taxila), Pakistan, in 2013, and the M.S. degree in computer science (major in wireless communication) from the COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2016. He is currently pursuing the Ph.D. degree in computer engineering with the Department of Electronics and Computer Engineering, Graduate School, Hongik University, South Korea. From 2013 to 2019, he was a software engineer in leading IT companies in Pakistan. His major research interests include wireless sensor networks, the Internet of Things, and underwater wireless sensor networks.

MD. ISRAFIL BISWAS (Member, IEEE) received the Ph.D. degree in communication engineering from the University of Aberdeen, U.K., which, among other research outputs, has led to an Internet-Draft with IETF. He is currently a Lecturer (equivalent to an Assistant Professor in the USA) with the Department of Computing and Mathematics, Computing Subject Group, Manchester Metropolitan University (Manmet). He is teaching both undergraduate and postgraduate units. He is the Unit Leader of an M.Sc. Moodle and an M.Sc. Apprenticeship Program Lead for cybersecurity. He is also leading several academic and industrial research projects. He is an active member of Greater Manchester Cyber Foundry and works as a trained independent assessor in the U.K. degree apprenticeship program. He is supervising several Ph.D.s, including many B.Sc. and M.Sc. projects in the field of cybersecurity, the IoT, AI, machine learning, data science, and communications networks. He is an active and renowned personnel in networks and security, has initiated and is currently leading the advanced cybersecurity testbed with Manmet, has published several high-impact papers in top journals and conferences, contributed to IETF standardization, and published patents in collaboration with academic and industrial partners. He has obtained funding from Digital Futures 2010 at Horizon Digital Economy Research, U.K., and led as an innovator and project lead for several international projects. Previously, he worked with the EPSRC-funded large ''SPHERE IRC'' for the ''Internet of Things (IoT) Networking'' project at the University of Bristol and was involved in designing, developing, debugging, and maintaining two large projects simultaneously. In 2018, he was a Research Engineer for the development of the ''Data to Action'' Project with British Telecom (BT) for an end-to-end IoT management framework and published patents with BT. He was a Research Associate for several multimillion projects at Ulster University. He was also a Research Fellow with the City University London for multimillion value projects, in collaboration with many industrial partners, including The European Microsoft Innovation Center. He was also a Visiting Lecturer for undergraduate and postgraduate students with the School of Informatics, City University London. He is a member of the Bangladesh Computer Society (BCS) and the Institute of Engineers Bangladesh (IEB). He has chaired several international conferences and workshops and has delivered many invited and keynote talks across the globe. He is also a reviewer and an editor of many well-reputed journals and conferences.

ALI KASHIF BASHIR (Senior Member, IEEE) is currently a Reader with the Department of Computing and Mathematics, Manchester Metropolitan University, U.K. He is also the Leader of the Future Networks Laboratory and the Head of Advanced Cybersecurity Testbed. He is supervising/co-supervising many Ph.D.'s, postdoctorals, and research associates. Along with his students and colleagues, he has published over 250 high-impact articles in top venues. He has obtained over €4 million in external funding from U.K., South Korean, Japanese, European, Asian, and Middle Eastern agencies. He is also a Co-I of GM AI and GM Cyber Foundry, each having €6 million in funding. He is a member of more than ten IEEE technical societies, and a Distinguished Speaker of ACM. He has chaired several international conferences and workshops and has delivered over 40 invited and keynote talks across the globe. He also enjoys several honorary and adjunct professorship in many countries, such as China, Canada, Lebanon, United Arab Emirates, India, and Pakistan. He is serving as the Editor-in-Chief for IEEE Technology, Policy and Ethics and *Journal of Autonomous Intelligence*, and an Editor of over ten international journals, including *Scientific Reports*, *Nature*, and IEEE Transactions on Network Science and Engineering.



BYUNG-SEO KIM (Senior Member, IEEE) received the B.S. degree in electrical engineering from In-Ha University, In-Chon, South Korea, in 1998, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Florida, in 2001 and 2004, respectively. His Ph.D. study was supervised by Dr. Y. Fang. From 1997 to 1999, he was with Motorola Korea Ltd., Paju, South Korea, as a Computer Integrated Manufacturing (CIM) Engineer in advanced technology research and development (ATR&D). From 2005 to 2007, he was with Motorola Inc., Schaumburg, IL, USA, as a Senior Software Engineer in networks and enterprises. His research focus at Motorola Inc. were designing the protocol and network architecture of wireless broadband mission-critical communications. From 2012 to 2014, he was the Chairperson of the Department of Software and Communications Engineering, Hongik University, South Korea, where he is currently a Professor. His work has appeared in around 242 publications and 24 patents. His research interests include the design and development of efficient wireless/wired networks, including link adaptable/cross-layer-based protocols, multi-protocol structures, wireless CCNs/NDNs, mobile edge computing, physical layer design for broadband PLC, and resource allocation algorithms for wireless networks. He served as a member of the Sejong-City Construction Review Committee and the Ansan-City Design Advisory Board. He is a TPC Member of the IEEE VTC 2014-Spring and the EAI FUTURE2016, and ICGHIC 2016 and 2019 conferences. He served as the General Chair for the Third IWWCN 2017. He served as the Guest Editor for Special Issues of the international IEEE Internet of Things Journal, *International Journal of Distributed Sensor Networks* (SAGE), IEEE Access, and the *Journal of the Institute of Electrics and Information Engineers*. He is an Editor of *Telecommunications Systems* and an Associate Editor of IEEE Access.