A Survey of Mobile Information-Centric Networking: Research Issues and Challenges

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***Abstract*—Recently, a series of innovative information-centric networking (ICN) architectures have been designed to better address the shift from host-centric end-to-end communication to requester-driven content retrieval. With the explosive increase of mobile data traffic, the mobility issue in ICN is a growing concern and a number of approaches have been proposed to deal with the mobility problem in ICN. Despite the potential advantages of ICN in mobile wireless environments, several significant research challenges remain to be addressed before its widespread deployment, including consistent routing, local cached content discovery, energy efficiency, privacy, security and trust, and practical deployment. In this paper, we present a brief survey on some of the works that have already been done to achieve mobile ICN, and discuss some research issues and challenges. We identify several important aspects of mobile ICN: overview, mobility enabling technologies, information-centric wireless mobile networks, and research challenges.**

***Index Terms*—Information-centric networking, mobility, in-network caching.**

I. Introduction

With the explosive growth of the mobile data traffic, mobile hosts will exceed wired ones in terms of numbers and traffic load, which makes host mobility a long-standing challenge in the existing Internet architecture [1]. As reported in [2], global mobile data traffic will increase 11-fold from 2013 to 2018. By 2018, fixed devices will contribute to 39 percent of IP traffic, while the rest of IP traffic will be brought about by WiFi and mobile devices. Therefore, the increasingly mobile traffic has led to an emerging trend of addressing "mobility" problem of the Internet.

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One of the main reasons for this challenge lies in its choice of what to name [3]. Traditionally, hosts are named by the Internet Protocol (IP) based on their topological network locations, which intrinsically binds the name with the address. When changing the physical location, a mobile host is often required to alter its corresponding name. Therefore, it is expected that the growing number of mobile devices will overwhelm the Internet, because IP networks need a hard time to accommodate them [4].

To overcome the problem, a plethora of overlay solutions are proposed, e.g., Mobile IP (MIP) [4], peer-to-peer (P2P) networks [5] and content delivery networks (CDNs) [6], which can patch the existing Internet architecture but only superficially bridge the gap between the limited network service capabilities and increasing user needs [1], [7]–[9]. For example, MIP can use tunnels and triangular routing to support the mobility of hosts without changing the IP address, while causing frequent handover and not ensuring quality of service (QoS) [4], [10]. CDNs proactively push content to network edge servers, and user requests can be redirected to nearby nodes and served by manipulating Domain Name System (DNS), which prevents DNS caching and causes network scalability problems [11]. In P2P overlays, mobile nodes are encouraged to cache contents and exchange data with each other by the designed application-level routing and forwarding logic, which suffers from traffic asymmetries and routing policy violations caused by peer churn [8], [12].

Recognizing these limitations of the Internet and current solutions, many research groups have proposed *information-centric networking* (ICN) to better deal with the Internet usage shift from host-centric end-to-end communication model to receiver-driven content retrieval model [13]–[15]. In ICN, users pay more attention to the content itself rather than where it is physically located [16], [17]. The core of ICN is replacing the host-based IP address of existing Internet with an information-based naming scheme [1], [8]. Through this principle, ICN provides uniquely identified network content to consumers by name-based naming routing rather than the routing of data between device pairs [18]. Therefore, by using information-centric naming, it is possible to support seamlessly mobility without performing complex network management required in IP networks, when physical and topological location of a mobile node changes [4], [10].

Although some excellent works have been done in ICN, most of them focus on architectural issues including caching [19], naming and addressing [20], energy efficiency [21] as well as flow control [22]. Therefore,

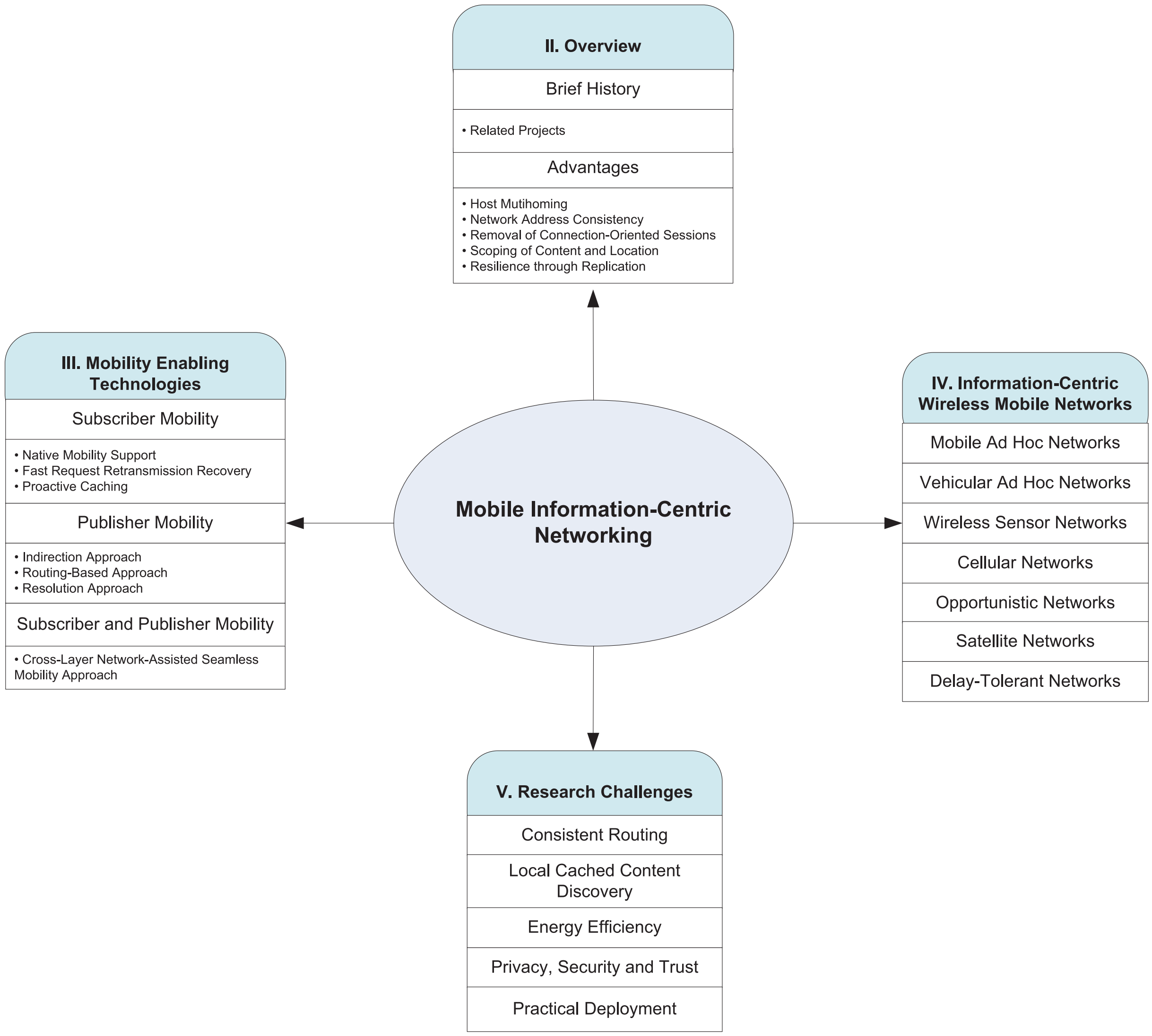


Fig. 1. Road map of mobile information-centric networking.

the mobility issue, especially publisher mobility, has drawn increasing attention [18], [23], [24]. Recently, many approaches have just been proposed to address the mobility issue in ICN from the perspectives of subscriber mobility, publisher mobility, as well as subscriber and publisher mobility. The approaches to enable subscriber mobility in ICN mainly include architectural mobility support [18], [23]–[25], fast request retransmission recovery [26]–[28] and proactive caching [1], [29]–[32]. Indirection [33]–[38], routing-based [33]–[35], [39], [40] and resolution [41] techniques are considered to support publisher mobility in ICN. Moreover, point of attachment (PoA) based, rendezvous point based, and multicast based solutions [42] can be used to enable simultaneous mobility of subscriber and publisher. Although these technologies have addressed the node mobility issue in ICN, many significant research challenges remain to be resolved, e.g., consistent routing, local cached content discovery, energy efficiency, privacy, security and trust, and practical deployment.

In this paper, different from the works in [18] and [43], we provide a brief survey on some works that have already been done to achieve mobile ICN, introduce information-centric mobile wireless networks, and discuss some research challenges. A taxonomy graph of our approach towards the design of mobile ICN is given in Fig. 1. As shown in the figure, we identify four important aspects of mobile ICN where we would like to focus: overview, mobility enabling technologies, information-centric wireless mobile networks, and research challenges.

In the following sections, we elaborate on each such aspect and discuss the related issues. Section II presents a brief history of ICN. Then the main advantages of deploying ICN in mobile networks are summarized. Section III discusses some enabling technologies for mobile ICN. Section IV explores some information-centric mobile wireless networks. Section V presents some research challenges. Finally, conclusions are drawn in Section VI.

II. Overview of Information-Centric Networking

In this section, we first present a brief history by introducing the projects related to ICN. Then, compared with traditional IP-based networks, advantages of ICN in mobile wireless networks are summarized.

TABLE I
COMPARISONS BETWEEN ICN AND TRADITIONAL IP NETWORKS ON MOBILITY

Features	ICN	Traditional IP Networks
Host Multi-homing	request-reply model [24]	host-to-host connections
Network Address Consistency	content-centric information [44]	host-centric information [23]
Removal of Connection-Oriented Sessions	receiver-driven communications model [45]	re-establishing connection-oriented sessions [18]
Scoping of Content and Location	separation between content and location [23], [33]	location-based IP addresses
Resilience through Replication	in-network caching [46]	binding content to specific locations using host identifiers [47], [48]

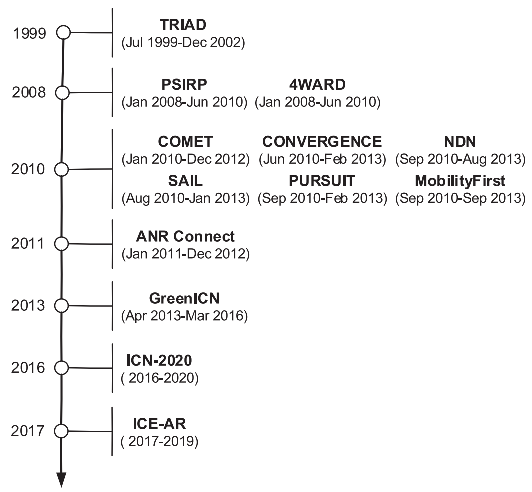


Fig. 2. Timeline of key ICN-related projects.

A. Brief History of Information-Centric Networking

Currently, ICN has been becoming an increasingly hot field for researchers from both academia and industry, which provides users with named contents, instead of host-centric model [49]. In essence, ICN is the publish-subscribe Internet (PSI) architecture, where users are primarily interested in network contents and do not care where they retrieve the contents from [1]. Compared with traditional host-centric end to end connectivity in IP networks, ICN focuses on information delivery to allow a user to obtain the requested content from anywhere in the network [50]. Therefore, ICN has the potential to solve many issues prevalent in current IP networks, such as mobility, energy efficiency, congestion, security and so on.

In 1999, the concept of ICN is first proposed by Cheriton *et al.* when introducing name-based routing in Translating Relaying Internet Architecture integrating Active Directories (TRIAD) [51], [52]. Then, Data-Oriented Network Architecture (DONA) [53] was presented as one of the first clean-slate ICN architectures in 2007. Subsequently, as shown in Fig. 2, many research efforts have been dedicated to ICN [49], including the U.S. funded projects Named Data Networking (NDN) [54], MobilityFirst [55] and ICE-AR [56], the EU funded projects Publish-Subscribe Internet Technology (PURSUIT) [57], Scalable & Adaptive Internet soLutions (SAIL) [58], COntent Mediator architecture for contentaware nETworks (COMET) [59] and CONVERGENCE [60], the French funded project ANR Connect [61], the collaborative EU-Japan project called GreenICN [50], and the International cooperation project named ICN-2020 [62]. As the most promising architecture of ICN paradigms, CCN performs communication by using two specialized kinds of packets: *Interest Packet* and *Data Packet*, which carry a name to uniquely identify the requested content. The former is used to issue a user's request to obtain its interested data while the latter is used to return the corresponded content to the user.

Except for COMET and MobilityFirst, these research projects support subscriber mobility by designing new requests and publisher mobility by using different schemes [24]. For example, DONA uses additional registrations for publisher mobility, NDN designs an Interest flooding protocol to achieve the function. However, subscriber and publisher mobility can be realized in one way used in COMET and MobilityFirst. In COMET, specialized mobility-aware content routers at access network are designed to exchange mobile context state information, while MobilityFirst adopts late binding to first arrive at the mobile's region and then find the mobile user [24], [63].

B. Advantages of Information-Centric Networking in Wireless Networks

Compared with the host-based conversation model of current IP architectures, the content delivery in ICN follows a receiver-driven approach. Once the requested content is matched in ICN, the data is transferred to the receivers along with the reverse path. Therefore, the aim of ICN is to find, disseminate and deliver network contents rather than the reachability of end hosts and the maintenance of host-to-host conversations between them [13], [24], [64]. To achieve these objectives, novel network components are required, such as information naming, routing, caching, security and management [64], [65], which makes it have some key benefits when deploying ICN in mobile wireless environments. Comparisons between ICN and traditional IP networks on mobility are presented in Table I, which gives the main advantages of ICN in mobile wireless networks from the following five perspectives of host multi-homing, network address consistency, removal of connection-oriented sessions, scoping of content and location, and resilience through replication [18], [23].

(1) Host Multi-homing: Host-centric networks bind an address to a specific network interface, which makes it difficult for mobile hosts to use multiple network interfaces. By contrast, due to the request-reply model, requests in ICN can easily be multiplexed over multiple interfaces.

(2) Network Address Consistency: Host-centric networks route between hosts by using pairs of topological identifiers (e.g., IP addresses), and utilize a node's IP address for long-term usage in most applications. By

contrast, ICN uses content-centric information rather than location-oriented one to route between a content consumer and optimal content provider.

(3) Removal of Connection-Oriented Sessions: Host-centric networks often re-establish connection-oriented sessions to maintain the communication between mobile hosts. By contrast, ICN adopts the receiver-driven communication model, where a consumer exactly knows what to receive in return when sending a content request.

(4) Scoping of Content and Location: Host-centric networks identify the mobile hosts by their locations (IP addresses). Once a mobile node changes its location, a new IP address will be assigned, which makes it difficult to support its mobile communication. By contrast, ICN realizes the separation between content and location by using content names to route, and supports seamless mobility of mobile users.

(5) Resilience through Replication: Host-centric networks utilize some concept of location (e.g., a URL) to exchange information, where the content service will be interrupted if a host along the delivery path fails. By contrast, ICN can fast recover the content delivery on basis of increased content redundancy realized by in-network caching ability of ICN.

III. Mobility Enabling Technologies in Information-Centric Networking

Due to the decoupling of time and space between request resolution and data transfer, the publish/subscribe communication model used in the context of ICN fundamentally realizes the seamless mobility of mobile nodes (MNs) [1], [24], [66], [67]. Regarding time, it is unnecessary for subscribers and publishers to simultaneously connect to the network. Whenever information publications are issued, the subscribed contents will be momentarily transferred. Regarding space, they do not usually have references to each other, neither do they know how many users are receiving contents from a particular publisher or how many publishers are providing contents for a subscriber. In this section, we summarize the existing mobility enabling technologies in ICN from the perspectives of subscriber mobility, publisher mobility, subscriber and publisher mobility, respectively, which are shown in Table II.

A. Subscriber Mobility

This subsection presents the current mobility enabling approaches in ICN from the subscriber mobility perspective.

1) Native Mobility Support: Compared with IP networks having implications to mobility of the MNs, ICN has two key differences [24], [25]. Firstly, ICN works by adopting a receiver-driven model where subscribers use the content name to request data from the publishers, while the sender fully controls the content transfer in the current Internet communication model. Secondly, in comparison to TCP's connection-oriented (statefull) control method, ICN uses a connectionless (stateless) manner to realize the content transport from publishers to subscribers. Therefore, when mobile receivers move to a new place, the two characteristics allow them to resend requests to obtain the data they did not receive at their previous PoA, without reestablishing a TCP connection or using cumbersome and costly overlay solutions such as MIP [18], [23], [24], [30].

Supporting subscriber mobility in ICN is generally simpler [24]. The worst scenario is that the receiver sends new requests to get the lost content, which will waste some resources consumed by pending transmissions. According to [24], when MNs move in the decoupled versions of DONA and SAIL, the name resolution system can fast obtain the network addresses of the publishers caching the requested content after reissuing requests. In NDN and COMET, however, the resent requests can be redirected to the current location of the moving subscriber on the basis of the state information, which is recorded in the Pending Interest Table (PIT) of content routers (CRs) generated by the previous same requests. For ICN architectures based on source routing, it may be easy but inefficient, because the routes must be patched after MNs moves to a new position. In PURSUIT, a Bloom filter is used to encode the link information, so it is smarter to support the mobility of subscribers but harder to remove the links. In MobilityFirst, only the locations of MNs need to be locally updated, as the resolution process can delay binding a moving user's identity with its existing address as far as possible.

2) Fast Request Retransmission Recovery: In ICN, a subscriber retransmits the Interest packet if the corresponding Data packet is not received within a retransmission timeout (RTO) interval [28]. Like the calculation method of RTO in IP networks, it relies on the predicted Round Trip Time (RTT), which is the time interval between the transmission of the Interest packet and arrival of the corresponded content [28]. However, because of in-network caching, the transmission delay can vary significantly, which makes it harder to exactly estimate RTT [26]. Moreover, due to the shared and lossy features of the wireless channel, the situation is worsened, as Interest or Data packets may be lost in the request-reply process [26], [27]. To provide reliable delivery, a timer is encoded in each unsatisfied Interest packet, and requests are retransmitted when the timer expires [27], [28]. Although some techniques have been proposed to address Interest retransmission problem, they mainly work in wired networks [72], [73]. Therefore, in order to quick recovery from packet loss status and avoid unnecessary retransmissions, it is of great concern to set the proper Interest retransmission time in mobile ICN [3], [26], [27], [74]. In the following, we summarize the request retransmission recovery approaches to enable subscriber mobility in ICN.

To resolve video packet loss problem in information-centric wireless networks, Han *et al.* [26] develop a new and efficient retransmission method including two algorithms: lifetime estimation and retransmission control. In the lifetime estimation algorithm, the sequential hypothesis testing methodology [75] is used to accurately detect RTT variation, and theoretical bounds on the probabilities of detection rates can be obtained on basis of the observed transmission outcomes. Therefore, it is curial to properly tune the lifetime of request packet to timely reissue the lost packets. By analyzing the causes

TABLE II
MOBILITY ENABLING TECHNOLOGIES IN INFORMATION-CENTRIC NETWORKING

Scenario	Technology		Reference	Contributions
Subscriber Mobility	Native Mobility Support		Tyson *et al.* [18], [23]	Introducing two key differences of ICN compared to IP networks to enable subscriber mobility.
			Xylomenos *et al.* [24]	Arguing that supporting subscriber mobility is generally simpler in ICN architectures.
	Fast Request Retransmission Recovery		Han *et al.* [26]	Proposing a retransmission scheme incorporating lifetime estimation and retransmission control algorithm to overcome video packet losses in content-centric wireless networks.
			Amadeo *et al.* [27]	Estimating the average RTT to manage retransmissions of lost content packets in wireless CCN.
			Amadeo *et al.* [28]	Designing a transport routine to address both Interest retransmissions and flow control in case of packet losses in CCN.
	Proactive Caching		Xylomenos *et al.* [1]	Analyzing subscriber mobility problem in ICN from micro-mobility and macro-mobility perspectives, and only selecting some neighbors for caching by considering the subscriber's mobility probability.
			Vasilakos *et al.* [30]	Proactively caching request information and corresponding contents to a subset of proxies with one hop away from the proxy that a subscriber currently connects.
			Siris *et al.* [31]	Exploiting user mobility knowledge to decide where to proactively cache content to realize seamless mobility, while using a congestion pricing scheme to efficiently utilize cache storage.
			Jiang *et al.* [32]	Estimating the time disconnecting from network and prefetching the content that a user is expected to access in the near future.
	Others		Kim *et al.* [34], [35]	Proposing to use a persistent Interest to efficiently request each Data packet in a CCN streaming service, and applying concurrent WiFi connections to select the optimal AP.
			Anastsasiades *et al.* [25]	Desiging a rendezvous-based scheme to enhance user mobility support in ICN.
			Lee *et al.* [68], [69]	Proposing a proxy-based mobility management scheme to enable user-side mobility in CCN with the help of a proxy server.
			Zhang *et al.* [37]	Fully exploiting NDN's forwarding states to keep track of moving nodes and then supporting subscriber mobility.
Publisher Mobility	Indirection Approach	Rendezvous Point	Kim *et al.* [34], [35]	Exploiting a rendezvous server to provide naming resolution service between contents name and locator after publisher mobility in ICN.
		Indirection Point	Hermans *et al.* [36]	Using a rendezvous point as a relay server can be more strongly engaged in publisher mobility enabling of ICN.
		Tunnel-Based Redirection	Lee *et al.* [38]	Presenting a tunnel-based solution to content source mobility in CCN environments.
	Routing-Based Approach	Flooding	Kim *et al.* [34], [35]	Suggesting a scheme called 'zone flooding' to prevent broadcast storm and implement more seamless handoffs.
		Interest Forwarding	Kim *et al.* [34], [35]	Transmitting a virtual Interest to the previous router, which update the forwarding entries of Intermediate routers to seamlessly support the provider mobility.
		Indirection Point-Based Interest Forwarding	Han *et al.* [39], [40]	Using FIB update mechanism to establish a path between home router and the new location of the provider.
		Others	Lee *et al.* [70]	Presenting a partial path extension (PPx) scheme to compensate for the effects of content sources' movement.
			Wang *et al.* [71]	Proposing a greeding routing protocol called MobiCCN to enable publisher mobility, while coexisting with the standard CCN routing protocol.
	Resolution Approach		Hermans *et al.* [41]	Based on the location-dependent name or address in the first response Data packet after a publisher handoff, a customer can send the following Interest packets directly to the new location of the publisher.
Subscriber and Publisher Mobility	Cross-Layer Network-Assisted Seamless Mobility Approach		Ravindran *et al.* [42]	Pproposing three seamless mobility schemes in NDN: PoA based, rendezvous point based, and multicast based to simultaneously support subscriber and publisher mobility.

of packet losses, the retransmission window size is adaptively tuned by the retransmission control algorithm to efficient recovery from packet loss state.

Amadeo *et al.* [27] propose a policy to manage retransmissions of lost content packets in wireless Content-Centric Networking (CCN). Similarly, Jacobson [76] design a simple routine for Interest retransmissions in case of missing Data under their implementation of CCN. When the Interest packet is forwarded, the time information is tracked in each CCN node. When receiving the corresponded data, the nodes record a RTT sample. Therefore, the average RTT is estimated as a moving average of RTT samples and the RTO is dynamically tuned to track the average RTT variations [77]. Moreover, to avoid multi-packet chunks, the requested packet retransmission to obtain the whole chunk is triggered if the Interest packet is lost. To solve this problem, selective retransmission of lost packets is allowed in the proposed scheme. In addition, they also design a transport routine to address both Interest retransmissions and flow control in case of packet losses [28]. If no content is received after a number of times of retransmitting the requested Interest, the user eventually announces the content unreachable. Once receiving each non-duplicated Data packet, the subscriber uses an Exponential Weighted Moving Average (EWMA) method to update the estimate of the RTT. Therefore, by adaptively adjusting the counter parameter, a satisfactory trade-off between efficiency and effectiveness can be achieved.

3) Proactive Caching: In spite of the aforementioned support for subscriber mobility, the delay to receive requested data will be increased when a mobile consumer moves to a new location before receiving the requested content. It is significant for delay-sensitive applications to reduce this delay, such as streaming multimedia services, online gaming, teleconferencing and so on [30]. Therefore, efficient schemes must be designed to support both delay tolerant and delay sensitive traffic when a consumer moves in ICN.

When a mobile user moves from an old to a new PoA in publish/subscribe networks, Siris *et al.* [29] and Vasilakos *et al*. [30] argue that approaches for enabling its mobility can be categorized as follows: reactive approaches [78]–[81], durable subscriptions [82], and proactive (or prefetching) approaches [83], [84]. Among them, compared with obtaining the data from the original content source, proactive caching policies can obviously reduce the delay for transferring the content when the subscriber changes its location [31]. The reason is that the requested content is immediately available because of the pervasive in-network caching capacity. Therefore, proactive approaches can make a trade-off between buffer space and delay in transmitting data objects to subscribers [29], [30].

To proactively cache the mobile subscriber's interested contents near the attachment points it may move to, necessary information or prediction of mobility behaviors and content requests is needed, e.g., the probability transferring to future PoAs [85], [86]. By exploiting the mobility information of a mobile user, proactive actions have been undertaken to reduce the transmission delay in ICN architectures [29], [84] for vehicular WiFi access [87] and cellular networks [85], [86], [88]–[90]. In the following, we focus on proactive caching solutions to address the problem of subscriber mobility in ICN.

Xylomenos *et al.* [1] analyze the subscriber mobility problem in ICN from micro-mobility (i.e., mobility within the same access network) and macro-mobility (i.e., mobility between different access networks) perspectives, and then propose to only choose some neighbors for buffering the requested data to achieve the minimal network cost. In the selection process, several factors should be considered, e.g., moving probability of the mobile consumer, storage costs, and bandwidth/delay caused by obtaining content from a local cache or a remote publisher [29].

To enhance seamless subscriber mobility in ICN architectures, Vasilakos *et al.* [30] present a Selective Neighbor Caching (SNC) approach. In SNC, information requests and the corresponding indexes are proactively cached by a subset of proxies, which are one hop away from the one currently connected by the mobile node. The preliminary ideas of the target cost function used in SNC are introduced in an extended abstract [29], which captures the tradeoff between delay and cache cost. As an extension work of [30], a distributed proactive caching algorithm is proposed by using the node mobility information to decide where to proactively cache content to realize seamless mobility [31]. Moreover, a congestion pricing scheme is designed to efficiently utilize buffer resources.

Based on the application of CCN in wireless mobile environments, Jiang *et al.* [32] present a caching and prefetching mechanism. The main idea is to predict disconnection situations and prefetch the user's interested content in the near future. Thus, the core part of the scheme is to decide when to trigger the caching and prefetching process. To trigger the prefetcher, a disconnection predictor is designed. According the estimated time when the mobile node disconnects from the current PoA, the prefetching process is triggered to obtain the previously requested content cached near to the current mobile user. Then, they design and implement a disconnection predictor algorithm, which can anticipate the time before a user disconnects from an access point (AP) by monitoring Received Signal Strength Indicator (RSSI) [32].

4) Others: In this part, we present some other approaches to enable subscriber mobility in ICN.

Kim *et al.* [34], [35] propose to use a different kind of Interest packet called persistent Interest packet to efficiently request each Data packet in a CCN streaming service (e.g., Live TV). The difference between persistent Interest and regular Interest is the way that PIT deals with the lifetime parameter after being successfully matched in the reply process. Thus, compared with normal Interest packet, it is more efficient for persistent Interest to transfer the applications with real-time and loss-tolerant properties. However, to address the problem of constant path during the lifetime after handoff, a signaling message or a bit embedding solution is used to eliminate the expired persistent Interest packets recorded in the PIT of the intermediate CRs. Moreover, they also argue that the location of the content must be considered except for the common signal strength and the number metrics of attached nodes to obtain high throughput in CCN [34], [35]. To obtain the higher throughput, a mobile user should move to the AP closer to the duplicate of the interested content. To choose the optimal AP, concurrent WiFi connection method is recommended. Due to the multicast characteristic of CCN, the duplicated Interest packets can be delivered to the available paths that a mobile node concurrently connects. Based on the arrival rate of corresponding Data packets, a per-flow optimal AP is chosen when the mobile user moves to a new location.

Anastsasiades *et al.* [25] propose a rendezvous-based scheme to enhance user mobility support in ICN. In this approach, the moving receiver upon relocation and reattachment to the network can reissue a subscription for the unreceived content. Once receiving this subscription, the rendezvous service computes the new path between the subscriber and a publisher. Depending on the kinds of service, e.g., streaming and file delivery, the system decides whether to recover the lost packets.

Lee *et al.* [68], [69] propose a proxy-based mobility management scheme to support subscriber mobility in CCN, where control messages are delivered to the proxy server by IP address. Before leaving the current position, the mobile user sends a special request message to the proxy server being connected. After receiving the information, the proxy caches the requested content without transferring it to the user. When the mobile node moves to a new location, the acquired new IP address is announced to the proxy server to obtain the content numbers finally received at the previous position. Therefore, when the same requests are retransmitted at the new location, the data stored in the proxy node can be delivered to the mobile device.

Based on NDN's Data forwarding principle, Zhang *et al.* [37] propose a subscriber mobility support scheme called Kite for NDN. In Kite, NDN's PIT entries can be fully used to track the moving users. Except for the advantages of NDN in subscriber mobility, Kite has two features, e.g., locator-freeness and scenario-awareness, which realize the transparent transmission of the mobile nodes and flexible design of application protocols for various scenarios.

B. Publisher Mobility

The identity-location separation and stateless connection of ICN paradigms can potentially facilitate mobility of subscribers and publishers [24]. However, provider mobility is more challenging because of no separation between routing locator and content identifier [18], [23]. To support publisher mobility, there are two key problems needed to be addressed: finding the source's location whenever it moves, and keeping the session continuity.

Unlike subscriber mobility, however, publisher mobility in ICN requires updating the name resolution system through the new location of the mobile publisher to maintain routing consistency during content provider's movement [24], [33]. Unlike off-path caching where related messages are advertised locally, publisher mobility needs the globally available information. This subsection presents the current mobility enabling approaches in ICN from the publisher mobility perspective.

1) Indirection Approach: Similar to MIP, the indirection approach works on basis of home agents, which forward Interest packets to the moving devices and are updated by the PoA being connected [25]. To successfully forward requests to the mobile publisher, however, home agents need to know topological or location information. According to [25] and [33], the obvious benefit of this solution is that there is no overhead in the resolution phase while the drawback is that all Interest and Data packets have to pass the home agent, which can make indirection point be a single point of bottleneck. In the following, three kinds of indirection approaches are presented to enable publisher mobility in ICN.

a) Rendezvous point: In this solution, a rendezvous point uses a location management server called rendezvous server to support publisher mobility. Its key function is to provide naming resolution service between content name and locator after publisher mobility [33]. The operation of a rendezvous point solution is presented in Fig. 3. Because the rendezvous server can keep the track of all the users' locations, a new routable prefix for the data the moving node requests can be obtained by querying the recorded information in the rendezvous point. Therefore, the query to the rendezvous point will be triggered when a device do not obtain its interested content in a predefined period.

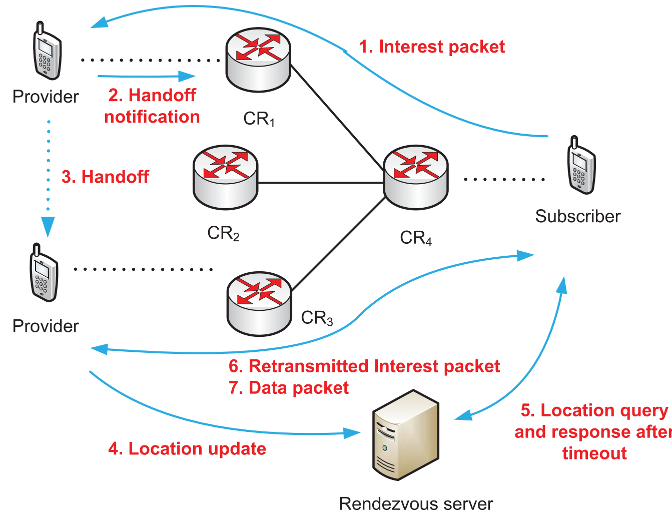


Fig. 3. Operation of a rendezvous point solution.

However, rendezvous point may incur higher latency for new name update/query and Forward Information Base (FIB) establishment, and does not have a good match with the principle of ICN paradigm. Therefore, some schemes should be considered to leverage a rendezvous point to support provider mobility [34], [35].

b) Indirection point: Through supporting mobility as a relay server (indirection server or indirection point), a rendezvous point can minimize handoff latency [33]–[36]. In indirection point solution, all publishers are required to register to a fixed server of an Internet service provider (ISP), and the top-level hierarchical content name of mobile publishers points to this server. This server maintains a set of binding information between target prefix (name) and source prefix (name) [33], [36]. As for a content provider, target prefix is a persistent name used to serve data while source prefix is temporary name used to currently receive Interests. The Interest packet for a publisher firstly reaches the fixed server, which encapsulates the arriving request packet with the source prefix and tunnels it to the new point. In essence, indirection point method can be seen as a home agent, which is a simple emulation of MIP for CCN.

The operation of an indirection point solution is presented in Fig. 4. From Fig. 4, we can find that the indirection point can efficiently reduce handoff latency compared with the rendezvous point scheme [34], [35]. However, the drawback of this solution is that the encapsulation of the original Interest packet is difficult to implement in CCN because of the predefined naming scheme mentioned in [33].

c) Tunnel-based redirection: The principle of tunnel-based redirection is similar to indirection point, but replaces

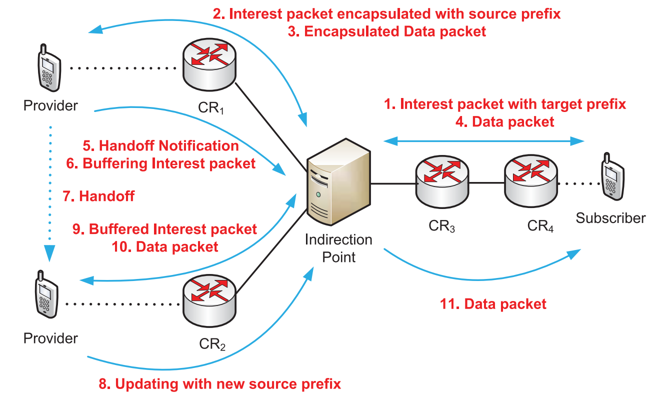


Fig. 4. Operation of an indirection point solution.

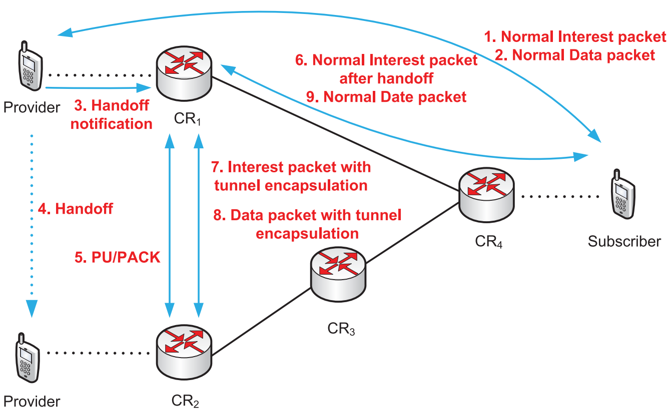


Fig. 5. Operation of tunnel-based redirection solution.

indirection server with a home router [33], [37], [38]. The main idea of this approach is to redirect Interest messages to new location of the provider using tunnel. In tunnel-based redirection solution, two messages and encapsulation formats are used: prefix update (PU) is from new PoA to home router and prefix update acknowledgment (PACK) is from home router to new PoA. When a publisher moves to a new location, a PU message is sent. Then, the home router encapsulates and forwards incoming Interest packets to publishers, and decapsulates the corresponding Data packets and forwards them to subscribers.

Lee *et al.* [38] present a tunnel-based solution to support content source mobility in CCN environments, which results in low network convergence time and service disruption. As shown in Fig. 5, each content provider will register its own name prefixes with home router. Therefore, all Interest requests will be routed to the home router of a publisher. The content will be sent back along the reverse path. When the content provider handovers to another PoA, in order to keep receiving the Interest messages from the content consumer seamlessly, the provider will send a prefix update message to the home router. This message contains the new name prefix advertised by the new CR. From now, when receiving the Interests from the consumer, these Interest packets will be tunneled to the new CR the provider is currently attached to. The proposed scheme is similar to Mobile IPv6 [10] from the perspective of the name binding architecture of the routing table.

However, by adopting in-network cache, the proposed solution can realize seamless reachability and reduce network overhead to support publisher mobility in CCN.

2) Routing-Based Approach: Although previous schemes could support the mobile content sources in ICN, some intrinsic problems intrinsic can not be overcome, such as handoff latency and overhead for the encapsulation and decapsulation of packets, which will degrade QoS of network [34], [35]. Therefore, without requiring a new routable content name during the handoff phase, the routing-based approach is designed to improve handoff performance of content sources. By updating the routing tables, the routing-based approach forwards user requests like CCN/NDN. However, publisher mobility leads to some other problems such as frequent routing update and low routing aggregation [70]. That is, publisher mobility makes all relevant CRs update their routing table. Therefore, potential challenges with this method are convergence time and scalability of the routing tables [25]. In the following, we present several kinds of indirection approaches to support provider mobility in ICN.

a) Flooding: The flooding scheme can fully take advantage of the multipath forwarding characteristic of NDN's Interest packet and the ability to announce a name prefix through CRs [42]. Although broadcasting is a common method to cope with mobility and routing issues in a mobile network, it is usually very costly and brings about the broadcast storm problem, which will leads to serious redundancy, contention, and collision [91].

To prevent broadcast storm and implement more seamless handoffs, Kim *et al.* [34], [35] propose a 'zone flooding' scheme, which is shown in Fig. 6. In this solution, multiple copied Interest packets are simultaneously forwarded to the potential access routers that the moving content source may connect to. The set of these candidate access routers is defined as a zone, which is represented by the set of CR_1, CR_2, CR_3 and CR_4 in Fig. 6. Because the formation of a handoff zone depends on the geographical location of permanent access routers, it can be configured in advance or learned from mobile nodes when the access router is installed. Once a publisher attaches to the access router, the related zone information can be transferred from that access router to the content source.

b) Interest forwarding: Interest forwarding approach does not need a new hierarchical name when a provider handoffs [33]–[35]. A scenario for the Interest forwarding scheme is shown in Fig. 7, where this approach begins from the handoff notification process. To seamlessly support the provider mobility, a virtual Interest packet with the same content name is transmitted to the previous router. Once receiving this packet, intermediate routers update their forwarding entries to transfer the incoming packets to a new location. For the Interest packets cached in the previous PoA, a flag parameter is set to indicate retransmission to avoid their loss. Moreover, to prevent radical increment of forwarding entry in FIB, the created forwarding entry by virtual Interest packet has a lifetime.

Based on the outstanding features of ICN, e.g., stateful forwarding, dynamic and distributed Interest load balancing

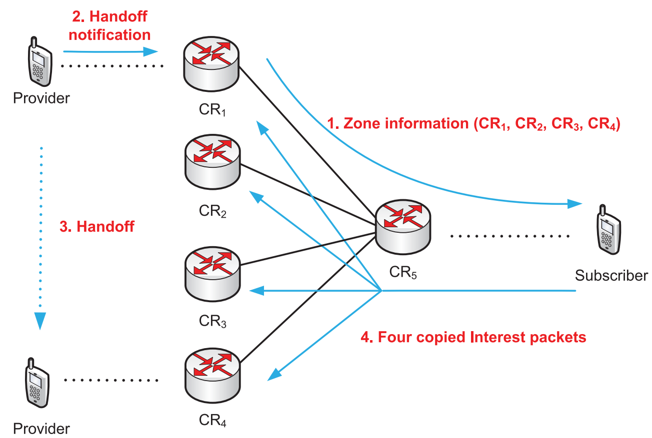
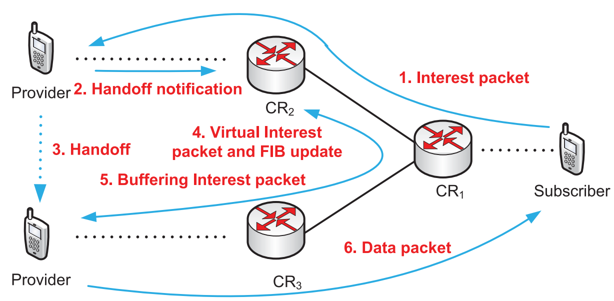


Fig. 6. Zone flooding scheme.

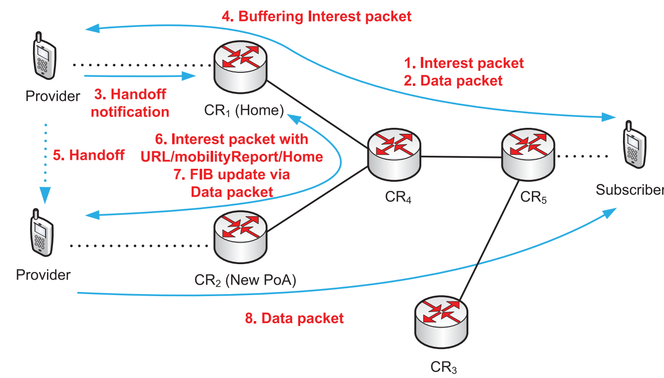


FIB state after receiving virtual Interest packet

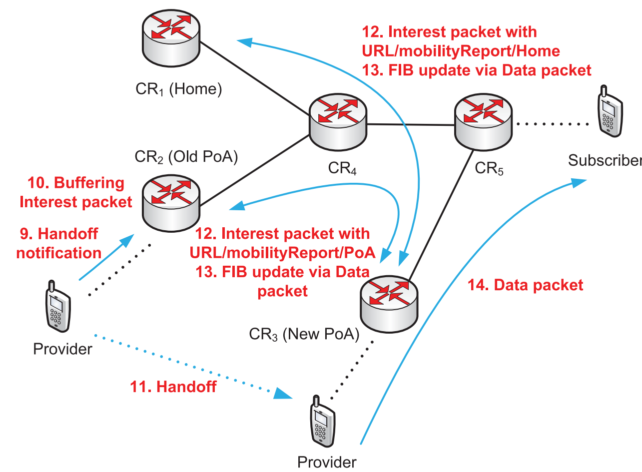
CR$_1$'s FIB	
Name	Next
/CR$_2$/data	CR$_3$

CR$_2$'s FIB	
Name	Next
/CR$_2$/data	CR$_1$

Fig. 7. Interest forwarding scheme.



(a) When the publisher moves from the home to a PoA



(b) When the publisher moves from a PoA to another PoA

Fig. 8. Operation of indirection point-based interest forwarding solution.

and in-network caching, Augé *et al.* [92] design a timely forwarding update mechanism, which populates a Temporary FIB (TFIB) at routers relaying former and current producer location through the Interest Update and Interest Notification operations.

c) Indirection point-based interest forwarding: This solution is a FIB update-based approach [39], [40], which also relies on the MIP concept, but uses FIB update mechanism to establish a path between home router and the new location of the provider. During this process, two reserved names are needed [33], [39], [40]: 'Provider's URL/mobilityReport/Home' is used to update the home on basis of the path information to the provider; 'Provider's URL/mobilityReport/PrevPoA' is used to establish the path from the previous PoA to the new one, and to receive the lost Interest packets reaching the original location when the publisher is moving.

The overall operation of this approach is presented in Fig. 8, which happens in two cases [39], [40]: when the provider moves from the home to a PoA (see Fig. 8(a)) and when the provider moves from a PoA to another one (see Fig. 8(b)). In this approach, the FIB table in each CR will contain two kinds of routing entries: original entry and mobility entry. The original entries will be installed by normal routing protocol. Mobility entries are installed by processing mobility management messages. The mobility entries will have higher priority than original ones for the same name prefixes. When the provider handovers, to create and maintain the mobility entry for the subscribers, it will send an Interest message with the above two reserved names. On receiving this message, the home router and/or previous point will return the data, containing necessary information to install new mobility entries for the name prefixes of provider on the intermediate routers between the home router and the new location of provider. The intermediate router will update their FIBs in order to forward the Interest messages to the new location of provider.

d) Others: Lee *et al.* [70] propose a partial path extension (PPx) policy to eliminate the effects of mobile content source (MCS). A content provider instructs CRs' forwarding behavior by updating the 'Prefix registration (PReg)'. Then CRs transmit this message to the original location. Through exchanging PReg messages, the extended path is configured from the original location to the new one of MCS to support seamless mobility of the provider. Moreover, the range of routing information update along the delivery path is limited to reduce network change and resource consumption of CCN.

By using a greedy routing in CCN, Wang *et al.* [71] design a new routing protocol called MobiCCN to support efficient publisher mobility, which can work with the inherent routing protocol of CCN. In the greedy protocol, prefix greedy:/ is reserved in a greedy packet while the standard one uses prefix ccnx:/. According to the difference of name prefix, a router chooses the corresponding routing protocol to forward the packet. Whenever a publisher changes its position, an 'Update packet' is sent to the previous router, and the corresponding FIB entries related to the publisher are updated among routers the Update passes by. Therefore, the Interest packets routing to the publisher can be transmitted to the new location.

3) Resolution Approach: In the resolution approach, the idea of location-identity split is used to realize a separate resolution, which is similar to Host Identity Protocol (HIP) [25], [93]. If there is a name resolution function in ICN, e.g., SAIL and COMET, this solution can be implemented by updating the content name to locator binding, which can be used for resolution. However, if there is not a resolution system, such as in CCN/NDN, a resolution process can be realized in the following two ways: use content names with location/topology information [42] or add a locator message in Interest packets [41].

By adding a 'Location Name' to the Data packet, Hermans *et al.* [41] solve the detour to obtain contents from mobile publishers. Thus, when receiving the first Data, the user can transmit the Interest packet directly towards the new domain. However, when a content source moves frequently, it might lead to even worse network delay because the user can not be synchronized with the newest domain [34]. For example, when the user sends an Interest packet to request a content with the current domain name, if the content provider moves to another domain before the Interest arrives. Therefore, to obtain the loss data, the user has to resend an Interest packet to the content source's home repository after waiting for a timeout.

C. Subscriber and Publisher Mobility

To minimize the loss of Interest and Data packets during a handoff scenario, Ravindran *et al.* [42] design three cross-layer network-assisted seamless mobility schemes in NDN from the subscriber and publisher mobility perspective: PoA based, rendezvous point based, and multicast based. In the PoA based solution, anchor-points are used in NDN to support seamless mobility. Compared with the PoA based scheme, the rendezvous point based solution is more flexible when choosing nodes to conduct seamless mobility, and can efficiently reduce the number of points with forwarding states. The multicast based solution makes full use of the multi-path forwarding characteristic of Interest packets in NDN and announces a name prefix in the CRs because of their cache ability.

Moreover, some optimization problems are researched to realize these schemes from the view of practical applications. In the case of PoA based scheme, there are two important components needed to be further researched: transition between the previous PoA and the current one, and reply of pending Interest packets. To solve the optimization problems, handoff methods are designed at layer two of the OSI model, e.g., related information of Data Link Layer and the connectivity status of the mobile subscribers and publishers. In the context of rendezvous point based scheme, a static and dynamic solution is proposed, which tackles with the assignment problem of an rendezvous point during the registration phase of an MN from the perspectives of both global and local optimization. In the multicast based scheme, the complexity of control and forwarding plane is simplified to support seamless mobility. When MNs move, however, its performance largely depends on the accuracy of mobility prediction because of the introduced transient FIB entries, PIT state overhead and data flow copies.

IV. Information-Centric Mobile Wireless Networks

Although most of the current works on ICN are under research in wired environments, based on the native feature of decoupling in space and time between subscribers and publishers, ICN can also be seen a promising networking solution for mobile wireless environments characterized by dynamic topologies, unstable communication channels, the limited and intermittent connectivity [28], [94], [95]. This has been recently demonstrated in several wireless contexts, such as sensors, opportunistic networks, satellite networks and so on [96]–[100]. According to the mentioned five advantages of applying ICN into mobile scenarios in Section II-B, ICN can fundamentally solve the mobility problem in mobile wireless networks. However, to extend the ICN architecture and model to mobile wireless environments, the new forwarding and transport functionalities should be introduced to support node mobility in the disruptive wireless network environments [95]. In this section, we summarize the works that apply the ICN communication paradigm into mobile wireless networks from the perspectives of architecture design (or applications) and enabling technologies.

A. Mobile Ad Hoc Networks

This decoupling in space and time between senders and receivers makes ICN an appealing solution for environments with intermittent connectivity like Mobile Ad Hoc Networks (MANETs) [95], [101]. Although potential beneficial effects of the information-centric paradigm in MANETs are presented in recent works [102]–[104], some necessary and proper procedures should be defined to handle the challenges caused by multihop wireless environments.

1) Architecture Design: To provide reliable and secure content delivery in a hostile network environment, Oh *et al.* [104] design a MANET CCN scheme, which inherits the merits of CCN, e.g., hierarchical name and in-network caching, and the simplicity and scalability of MANET networking. Moreover, some forward and transport functionalities are added in the proposed scheme to accommodate wireless, lossy channels and mobile situations.

To handle the unreliability of the wireless channel and the node mobility, Amadeo *et al.* [101], [105] propose a preliminary content-centric architecture for MANETs, named Content centric fasHion mANET (CHANET). In CHANET, the connectionless content-centric layer is on top of Data Link layer, where each node makes local forwarding decisions by overhearing the receiving packets. Moreover, based on their previous researches in [101] and [105], a CCN-based architecture called Enhanced-Content-centric multiHop wireless NETwork (E-CHANET) is designed, which can be used for distributed wireless environments with the feature of slow mobility [95]. In E-CHANET, a packet suppression mechanism is exploited to avoid the redundancy problem in the process of Interest and Data forwarding and the scalability problem in the network. In addition, ad hoc technique is designed to support node mobility and the Interest transmission rate from mobile users is controlled by the transport module.

Varvello *et al.* [46] identify a set of fundamental approaches, which can be seen as key components in designing a content-centric MANET (CCM) architecture. Then they design analytical models for the identified designs, including reactive and proactive flooding, and geographic hash tables, and evaluate their efficiency for a CCM. Based on the observations in [46], they also present SCALE, a content-centric design for MANETs [106]. SCALE uses name routing to provide local and efficient content delivery, and supports on-path caching to assist potential future retransmission.

2) Enabling Technologies (Caching): Alfano *et al.* [107] analyze throughput-delay scaling laws of MANETs in a content-centric transmission scenario, where users mainly request the contents buffered in other nodes with limited cache capacity. Based on random-walk mobility model, nodes uniformly visiting the network area switch between the quasi-static case and the reshuffling mobility model. In the quasi-static case, the best throughput-delay trade-offs can be made while the performance will get worse as the mobility degree of nodes increases. In the complete reshuffling case, the best throughput-delay trade-offs can be recovered by controlling the transmission range according to the requirements of content delivery.

Routing: Lee *et al.* [108] point out that frequent transmission of popular contents in the same delivery path will exhaust the energy of each node along the way. Thus, the nodes frequently forwarding contents may fail, which will cause energy imbalance in the whole network. To deal with the problem, an energy-efficient routing protocol for CCN-based MANETs is designed to prolong the service life of network nodes, where residual energy and frequency of node usage is used as routing parameters. By using mix of proactive and reactive techniques, Adem *et al.* [109] propose a proactive routing protocol to prevent communication loss that may be interrupted because of movement of intermediate or client nodes. The packet avoidance is transparent to the source node and it is mostly performed by the node that can detect link failure with its next hop.

Forwarding: Meisel *et al.* [102], [103] design a topology-agnostic data-centric forwarding protocol, named Listen First, Broadcast Later (LFBL). In LFBL, the intermediate nodes overhear the receiving packets to overcome the disadvantages caused by broadcasting Interest packets. Therefore, distance-based forwarding decisions are made to avoid collision on basis of the minimal number of state information maintained in each node. Moreover, a Social-Tie based Content Retrieval (STCR) scheme in delay-tolerant MANETs is proposed to overcome the scalable content delivery problem in large-scale sparse MANETs [110]. In STCR, nodes record the essential information when they encounter each other. To compute a social graph of encounter relationships, they use K-mean clustering algorithm to design a hierarchical architecture according to the social-tie between nodes. In the proposed algorithm, the hierarchy is used to improve forwarding strategy's efficiency.

B. Vehicular Ad Hoc Networks

ICN is an promising candidate solution for vehicular networking, where communications are driven by network contents rather than host addresses [94]. The advantages of ICN in vehicular networks were initially discussed in [111] and [112], and additionally investigated in [113]–[118]. As the representative and appealing proposal of ICN paradigm, CCN or NDN may be particularly beneficial in vehicular environments due to their simple and effective communication model [27]. However, the appropriate CCN deployment in vehicular environments encompasses manifold design choices, ranging from forwarding to transport process, which deserve further research efforts.

1) Architecture Design: Amadeo *et al.* [117] design a Content-Centric Vehicular Networking (CCVN) architecture to replace the TCP/IP protocol in Vehicular Ad Hoc Networks (VANETs). CCVN targets non-safety content request and transmission by leveraging both single-hop and multi-hop vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) content-centric communications as a replacement of TCP/IP networking. Moreover, significant adjustments to CCN architecture are implemented in CCVN to make it run in VANETs. A preliminary evaluation of the CCVN architecture is reported in their work in [119], which presents advantages of CCVN over the current Internet based on TCP/IP protocol. They then enhance the previous works [117], [119] by adding an incremental design and evaluation method to achieve the benefits of CCN paradigm in VANETs [28]. Moreover, they also propose a CRoWN framework for CCN to realize the reliable and low-overhead content discovery and delivery in VANETs [118]. In CRoWN, content-centric communications works over the two bottom layers of TCP/IP networking while complying with the Wireless Access in Vehicular Environments (WAVE) standard [120]. It leverages native broadcast feature of the wireless medium, multi-hop V2V communications, and pervasive caching to achieve a more efficient content search and delivery. Moreover, countermeasures are adopted to tackle the problems faced in CRoWN, e.g., the broadcast storm, scalability and mobility issues.

Confronted with unique challenges incurred by VANET applications, Bai and Krishnamachari [111] develop a generic network architecture to support upcoming information-rich VANET applications. Design process of the proposed architecture fully adopts a top-down framework called Information-Centric Networking on Wheels (IC NoW), where distributed protocols are developed and deployed to manage network information. Thus, various kinds of in-network information operations are realized, e.g., information aggregation, storage, dissemination, replication, and query [111]. Based on the locally recorded information, the proposed framework makes local decisions in a distributed manner to adapt to the VANET applications.

Grassi *et al.* [121] apply NDN to networking vehicles on the run, and develop an instantiation of NDN for vehicle networking called Vehicular Named-Data Network (V-NDN). In V-NDN, a unifying architecture is designed to enable the vehicular networking without considering the wired and wireless connected way of all the computing devices. Moreover, a prototype implementation of V-NDN has been designed and developed on basis of all available communication technologies to achieve content search and route.

To realize autonomous driving, Kumar *et al.* [122] design a communication system called CarSpeak, where content-centric approach is adopted and cars query and access sensory information from their local cars. In CarSpeak, road regions are named and accessed by a multi-resolution system to improve the content transmission efficiency under limited bandwidth. Moreover, the MAC protocol of CarSpeak is modified to solve the contention problem between road regions, and the medium allocation and share issue among the cars with the same interest in a region.

Based on the CCN architecture, Arnould *et al.* [115] propose a new network architecture for hybrid VANETs. In the proposed architecture, a new packet is designed to present emergency messages when necessary and prioritization mechanisms are used to support the guaranteed delivery of some types of contents. In addition, Wang *et al.* [112] present a vehicle information collection system via named data, which is designed for manufacturers to provide monitoring and alert functions. In the system, the CCN architecture is used, where Road-Side Units (RSUs) work as subscribers to broadcast Interest packets and collect messages from vehicles play the role of providers in a given region.

2) Enabling Technologies (Caching): To enhance the in-network caching efficiency in V2V, Quan *et al.* [123] focus on investigating the application of ICN in the social cooperation among neighbor vehicles under a highway scenario. Then, a highway-customized ICN-based COoperative Caching solution called ICoC, is proposed to ensure the quality of experience (QoE) of multimedia streaming services [123]. In ICoC, the partner-assisted cooperation and courier-assisted cooperation are designed to improve the utilization of caching resources for Information-Centric Multimedia Streaming (ICMS) in highway VANETs.

Network Coding: To address the issue of message dissemination in vehicular network scenarios, TalebiFard and Leung [116] propose a model and solution by adopting the content-centric idea of CCN. This solution interprets the increase properties of interacting nodes in a cluster as social connection states of these nodes, and works by using a selective random network coding approach. To enhance the reliability and efficiency of information dissemination, they also design a novel selective network coding method, where forwarding decisions are made on basis of the semantics of information and the spectral features of the cluster.

Forwarding: TalebiFard *et al.* [124] present the problem of information transmission under vehicular clouds and propose a novel forwarding and discarding scheme, which adopts the dimensionality reduction principle. The workflow of this proposed solution includes two phases: reduction of topology based on spectral features of information topology and dimensionality reduction by using eigenvectors of the most important characteristics. Therefore, when the nodes in vehicular clouds increases, the system can achieve a lower processing cost and complexity.

Retransmission: To well satisfy the operational requirements on top of the IEEE 802.11p access technology in VANETs, Amadeo *et al.* [27] mainly research the reliability problem at the transport-level of a CCN architecture. After analyzing the benefits of a segmentation and reassembly process in named content delivery, they design an adaptive retransmission scheme to address video packet losses in content-centric wireless networks, because the retransmission window size can be adaptively adjusted according to the reasons of packet losses. Moreover, Wang *et al.* [114] propose and evaluate an application for V2V traffic information dissemination by fully using efficient Interest and Data packet broadcasting of CCN. Moreover, a set of timers are exploited to modify the transmission paths in the network and achieve minimal packet collisions for shared wireless medium.

Content Dissemination: Leal *et al.* [125] design an information-centric opportunistic dissemination protocol to support different vehicle density situations, where content dissemination can adapt to spatial and temporal characteristics of the events. Thus, the density-based method is able to efficiently reduce the number of packets to be rebroadcasted in high density scenarios while maintaining good retransmission latency and number of receptions. Besides, opportunistic dissemination can avoid performance deterioration when working in low density scenarios. Moreover, to address the problem of efficient data dissemination in VANETs, Zhu *et al.* [126] design a novel network layer protocol on basis of distance and time information related to the dissemination approach. In the proposed protocol, the system can efficiently distribute messages accustomed to the changing densities in VANETs.

C. Wireless Sensor Networks

In the publish/subscribe communication networks, tasks are conducted in the way of space, time and synchronous decoupling, which makes it attractive to wireless sensor networks (WSNs) [127]. Besides, the characteristics of ICN, in-network caching and content replication, are beneficial to WSNs [128].

1) Architecture Design: Meijers *et al.* [129] propose a two-tier CCN architecture to manage the heterogeneity resources in WSNs, including sensor nodes, the remote server and so on. In the proposed architecture, the forwarding strategies in CCN is modified to improve data collection. Thus, based on the existing devices, they design and implement a original prototype to present the viability of their solution.

As a replacement of IP protocol to support sensor networks, Ren *et al.* [130] develop, realize and evaluate a variant of CCN protocol for WSNs. Specifically, the key components of CCNx protocol [74] are inherited and finely adjusted to satisfy the related constraints of sensors, links and communication models in WSNs.

Do and Kim [128] and Dinh and Kim [131] propose to apply the ICN architectures to wireless sensor and actor networks (WSANs), and design a information-centric WSANs framework named ICWSANs. In ICWSANs, the idea of content naming is like that in ICN while achieving different purposes. Moreover, to make the proposed framework accustomed to WSANs, new functions of the ICN are introduced for WSANs, such as efficient coordination, interoperability, service discovery, and prioritized routing [128], [131].

Waltari comes up with the idea of combining CCN with the concept of IoT, and looks at different ways on how to make use of the hierarchical CCN content naming, in-network caching and other information-centric networking characteristics in a sensor environment [132]. As a proof of concept, they implement a CCN interface for a home automation system, that supports various sensor devices.

2) Enabling Technologies (Data Aggregation): To address the problem of data aggregation existed in current IP networks, Shim and Kim [133] propose a content aggregation solution for multiple sinks in an information-centric WSN environment, where an ID-based ICN is used to reduce energy consumption of network transmission. Then, the proposed energy-transmission cost is further discussed in the scenario of multiple sinks compared with the previous methods, e.g., Directed Diffusion, Tree-based Data Aggregation, and Data Aggregation [133].

Motivated by the need to further develop CCN-WSN [130] to realize efficient content aggregation in WSNs, Teubler *et al.* [134] extends CCN-WSN by revising the following three key components: unicast faces to prevent broadcast storm, forwarding function to generate overlay networks with a realistic topology, and an intra-node protocol to support communications among different layers in the network.

Energy Efficiency: Jin *et al.* [127] apply the publish/subscribe communication architectures to WSNs and propose an energy-efficient model to address the energy consumption problem. The proposed energy model not only achieves the decoupling of the centralized problem but also reduces energy consumption in WSNs.

D. Cellular Networks

Nowadays, it is rather difficult for current radio access network (RAN) deployments and mobile backhaul networks to meet the increasing demands posed by mobile users to support rich multimedia services. Caching policies may be a potential outlet of the mentioned problem and have been proven to efficiently reduce traffic caused by cellular networks [85], [86], [135]–[137]. Therefore, incorporating ICN paradigms will be a growing important and obvious feature of future cellular networks [137], [138]. The main purpose of ICN in cellular networks is to add the storage function for each network node to provide universal caching ability, which can reduce network traffic and content access delay of mobile devices.

1) Applications: Detti *et al.* [139] demonstrate an application for cooperative video streaming running, which adopts ICN architectures and works on mobile devices without using the cellular radio interface. Then, they present the application in a test-bed environment, which installs the CCNx open source as the software implementation of ICN, and utilizes the VideoLAN player and the Apple HTTP Live Streaming (HLS) protocol. Moreover, they also test a P2P application in ICN to transmit live video streaming encoded with different bit-rates. The application works on basis of main components of ICN and improves the quality of video playback through communication cooperation of local cellular wireless devices [140].

2) Enabling Technologies (Caching): Based on traffic traces from telecom operators, Erman *et al.* [141] discuss the possibility of using forward caching in 3G cellular networks and design a caching cost model to make a tradeoff when deploying its deployment at different network layers. Moreover, Wang *et al.* [137] focus on caching techniques in existing mobile wireless networks, and explore their potential (e.g., core network caching and radio access network caching) in 5G mobile networks to reduce network traffic and delay.

Relay: Anadiotis *et al.* [142] present a novel, content-aware relaying solution, where the mobile stations (MSs) work as active relays on basis of their requested content information and channel quality. To realize content awareness in cellular networks, they design and implement a cross-layer algorithm, where an information-centric networking layer is considered. Simulation results show that this algorithm can obviously reduce transmission power in comparison with the non-relay and non-content-aware cases.

Multi-access: Pentikousis *et al.* [143] present an information-centric cooperative multi-access solution to transfer video contents in an urban scenario. By cooperatively using several WMAN schemes and considering recent achievements in multi-radio resource management and resource abstraction techniques, the requested video data can be delivered to more mobile users while fully utilizing current infrastructure and past investments. Moreover, Han *et al.* [144] explore the effect of NDN on the delivery performance of adaptive video streaming in wireless mobile environments, and propose an corresponding scheme based on NDN to realize adaptive mobile video streaming.

E. Opportunistic Networks

In opportunistic networking, network connectivity and communication durations between mobile devices are varying and not predicted. Its main purpose is to utilize the opportunistic characteristics between mobile users to provide them the best-effort content delivery in mobile wireless environments. Considering the exchanged information, users perceive communication opportunities of neighboring devices, and connect to neighbors individually to conduct content discovery and delivery. ICN can be exploited to provide content service for users in opportunistic networking due to the fact that all communications in opportunistic networks can be carried out locally [25], [145]. Therefore, content service can be satisfied without discovering the mobile devices.

1) Architecture Design: Batista and Mendes [146] propose a new multi-platform information-centric framework named

ICON for opportunistic networking. In ICON, the key components of CCN is adopted to realize interoperability between devices. However, some revisions are performed to better adapt to opportunistic networks with heterogeneous devices owned by any person. Moreover, a software implementation is designed to verify the effectiveness of the proposed framework.

2) Enabling Technologies (Caching): Anastasiades *et al.* [145] implement a scheme to add caching ability in opportunistic networking to enable content transmission in the intermittent network environment. Then, the CCNx framework is used to install and deploy the proposed scheme, which is evaluated on wireless mesh nodes via multicast and unicast communication models. The evaluation results show that the mechanism can efficiently perform content delivery in opportunistic networks without incurring obvious computing and caching cost.

Content Discovery: Anastsasiades *et al.* [25] propose a content delivery solution in information-centric opportunistic networks, where agent delegation and overhearing techniques are exploited to achieve efficient content delivery and fast recover from the disrupted network environment. Moreover, they also describe two methods to discover contents for mobile communications: Enumeration Request Discovery (ERD) on basis of name enumeration requests and Regular Interest Discovery (RID) on regular Interest packets, which are implemented in the CCNx framework [147]. When not receiving information during a timeout period, a retransmission counter is used to address occasional loss and collisions.

F. Satellite Networks

So far, researchers pay most attention to applying ICN to terrestrial networks, seriously neglecting the advantages of ICN in satellite networks, let alone integrating both networks in a ICN communication paradigm to combines and exploits their superiorities [148]. Specifically, due to the features of wide-area coverage and native broadcast, satellite networks can obtain the maximal benefits when using ICN principle to integrate satellite and terrestrial networks. Meanwhile, some prominent problems faced by satellite networks can be handled by utilizing ICN capabilities, e.g., long transmission delays and fast changing network topology under circumstance of Low Earth orbiting (LEO) satellite constellations [148].

1) Architecture Design: Detti *et al.* [96] firstly explore the potential of ICN in a geostationary satellite network, where users' Internet access can be realized by the communication between a geostationary satellite and a terrestrial gateway station. Then, they propose a ICN-based satellite architecture, present and evaluate its operation mechanism. In the proposed architecture, some techniques (e.g., overhearing, caching) are implemented to satisfy the demands of network services. With respect to plain HTTP or live streaming services, these techniques can efficiently reduce bandwidth consumption on basis of the temporal locality information.

2) Enabling Technologies (Caching): D'Oro *et al.* [149] propose a novel in-network caching approach called SatCache for information-centric satellite networks, which utilizes its inherent broadcast capability, information locality, and the statistical information of user requests and content popularity to decide the caching locations. Research findings show that the similar relation between user requests and content popularity can be used to improve the content delivery, thus saving the satellite bandwidth resources and reducing the propagation delay.

G. Delay-Tolerant Networks

A delay-tolerant network (DTN) can support significant delays or disruptions between data search and data receive phases caused by low density of nodes, network failures, and wireless transmission limitations [110], [150]. Recently, the potentials of applying ICN to DTN have been explored, which can provision highly resilient communications even during disaster scenarios [151].

1) Architecture Design: Tyson *et al.* [48] explore the potential of integrating both ICN and DTN to design an information-centric DTN (ICDTN) architecture. Then, they analyze and evaluate the proposed framework, and describe its main advantages and remaining challenges. Likewise, Sathiaseelan *et al.* [152] propose a novel architecture called I-DTN adopting the merits of ICN and DTN, where various types of networking protocols are supported.

Monticelli *et al.* [153] research the content-driven network model and design an enhanced ICN mechanism to support fast communication recovery in disruption-prone DTN environments. In the proposed scheme, unlike the assumption made by many current ICN efforts, the information exchange is achieved considering the limited available resources, the routing and transmission paths. Besides, the separation of logical and actual interfaces is realized because of the varying network topology.

2) Enabling Technologies (Routing): CCN-based DTN routing mechanisms can be divided into two categories: epidemic routing and knowledge based routing [116]. Through further analysis of spatio-temporal relation between network devices, Nguyen *et al.* [154] propose a routing scheme to build bio-inspired gradient space between content sources and consumers. Moreover, as a key metric, social relation is used to address the routing problem in information-centric DTN, which chooses the optimal node to forward the requested data [155].

H. Comparison of Approaches

In this subsection, we provide a brief analysis and comparison of the proposed approaches when applying ICN into different mobile wireless networks. From the perspective of architecture design, the related works pay more attention to designing a novel ICN-based architecture, especially the CCN-based paradigm, to replace the TCP/IP protocol, where the CCNx open source needs to be properly modified to adapt to different mobile scenarios and the corresponding new equipments (e.g., content router) must be designed. From the perspective of enabling technologies, various schemes are proposed, e.g., caching, routing and forwarding policies, to realize some optimal objective (e.g., energy consumption, delay), which may bring signaling overhead and security problem to ICN.

V. Research Challenges

In spite of the potential advantages of ICN in mobile networks, it is still a new research field full of challenges. Many significant research challenges still need to be addressed before its widespread deployment. In this section, we present some important yet challenging problems in mobile ICN.

A. Consistent Routing

Based on the identity-location separation in ICN, it is possible for ICN to realize pairwise routing: request routing towards a content provider and reverse content transmission to one or more subscribers [18], [23]. Specifically, response routing is performed according to the hop-by-hop information recorded by the routers during the request routing. However, it is challenging to apply ICN to mobile wireless environments because of the frequently varying network topologies, which has an negative effect on consistent routing. Therefore, how to cope with the change of physical paths is an important research issue to address. To ensure reliable content delivery, more information is required in information-centric wireless networks, e.g., the locations of publishers and subscribers, and the network topology knowledge.

B. Local Cached Content Discovery

One outstanding advantage of ICN is the increased resilience attained by deploying ubiquitous caching throughout unreliable networks. However, it will bring about significant content discovery challenges when ICN works in mobile networks, particularly MANETs and DTNs [23]. Compared with host-centric routing, the caching and replacement behavior of network contents leads to frequent routing churn in ICN-based wireless environments. Therefore, an obvious research challenge is to design and implement a efficient name resolution and routing mechanism to address the unpredictable content relocation problem in a mobile network. In the process, the caching of unpopular contents should be properly tackled. Because the potential gains may be unsatisfactory by using more sophisticated structured routing policies (e.g., GHT) to deal with unpopular contents [46].

C. Energy Efficiency

Although considerable efforts from industry and academia are made to realize green ICN, most of the works are performed to deal with the energy efficiency problem in the fixed network scenarios. Therefore, given the rapid development of mobile networks, it is a research challenge to solve the energy consumption problem in information-centric mobile wireless network environments. When addressing the energy efficient issue of mobile ICN, the tradeoff between the performance and the energy consumption should be carefully researched, because most current solutions reduce energy consumption by sacrificing network QoS [156], [157]. Moreover, whether the traditional energy saving solutions (e.g., hardware optimization, shutdown, slowdown) can be used in mobile ICN and what should be modified to adapt to different wireless scenarios are emphasized but still unsolved.

D. Privacy, Security and Trust

Like the current open mobile networks, privacy, security and trust is also a significant research challenge required to be handled in an ICN-based wireless network [18], [23], [24]. In ICN, the content is secured by the global unique name. However, this naming policy may lead to severe privacy problems, because the name of the requested content is visible to the nodes along the transmission path. If the third parties participate in the naming management, the privacy problem will be worsen. Moreover, the security issues in ICN need to be properly investigated. Because the potential publishers can enable malicious devices to manipulate networks routing policies, which is rather ubiquitous in mobile networks with open routing schemes. Finally, efficient mechanisms should be designed to establish trust relationships among various stakeholders, which remain an open issue.

E. Practical Deployment

To gain the advantages of ICN in mobile wireless networks, an urgent challenge is the problem of practical deployment to support mobile ICN [18], [23], [24]. From a practical perspective, it is most likely that the short-term deployments of mobile ICN will adopt the overlay mobile ICN solutions, which can be fast realized and quantify the effectiveness of mobility support in ICN without abandoning the existing mature Internet architecture and realizing clean-state mobile ICN solutions. However, the future deployments of mobile ICN will be towards a network-layer solution rather than an application-lay one. Therefore, based on the deployment experience of short-term solutions, an intelligent deployment method can be designed to avoid and eliminate the potential problems. Moreover, how to choose an ideal ICN architecture to support mobile ICN remains an active research direction.

VI. Conclusion

This paper addresses mobile information-centric networking, which is becoming an important concept that not only can reduce the mobile traffic, but also can improve the QoS of mobile users. We began our discussion with an overview of ICN with a brief history. We then summarize some advantages of deploying ICN in mobile networks. Next, some mobility enabling technologies for mobile ICN were discussed from the perspectives of subscriber mobility, publisher mobility, as well as subscriber and publisher mobility. We also explored some information-centric mobile wireless networks, such as Mobile Ad Hoc Networks, Vehicular Ad Hoc Networks, Wireless Sensor Networks and so on. Finally, we discussed some significant research challenges in mobile ICN, e.g., consistent routing, local cached content discovery, energy efficiency, privacy, security and trust, and practical deployment.

In summary, research on mobile ICN is quite broad and a number of research issues and challenges lay ahead. Nevertheless, nowadays researchers from the research community and the society are making efforts to cope with these challenges to minimize the influence of applying the programming novel ICN architectures in mobile wireless environments.

This article attempts to fully investigate the existing technologies related to mobile ICN and we discuss research challenge that may prove beneficial in realizing mobile ICN.

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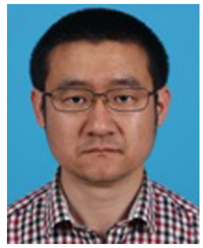

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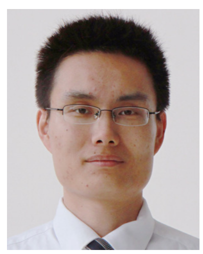

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