TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 06/13 pp 419–430
DOI: 10.26599 / TST.2018.9010046
Volume 23, Number 4, August 2018

Broadband Communications for High-Speed Trains via NDN Wireless Mesh Network

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Abstract: With the increasing utilization of High-Speed Trains (HSTs), the need for a reliable and high-bandwidth Internet access under high-speed mobility scenarios has become more demanding. In static, walking, and low mobility environments, TCP/IP (transmission control protocol/Internet protocol) can work well. However, TCP/IP cannot work well in high-speed scenarios because of reliability and handoff delay problems. This is mainly because the mobile node is required to maintain the connection to the corresponding node when it handovers to another access point node. In this paper, we propose a named data networking wireless mesh network architecture for HST wireless communication (NDN-Mesh-T), which combines the advantages of Wireless Mesh Networks (WMNs) and NDN architectures. We attempt to solve the reliability and handoff delay problems to enable high bandwidth and low latency in Internet access in HST scenarios. To further improve reliability and bandwidth utilization, we propose a Direction-Aware Forwarding (DAF) strategy to forward Interest packet along the direction of the running train. The simulation results show that the proposed scheme can significantly reduce the packet loss rate by up to 51% compared to TCP/IP network architecture. Moreover, the proposed mechanism can reduce the network load, handoff delay, and data redundancy.

Key words: named data networking; wireless communications; high-speed trains; mobility; forwarding strategy

1 Introduction

With the fast development of High-Speed Trains (HSTs)[1, 2], the average speed of CRH trains has reached nearly 300 km/h. During transit in high-speed environments, consumers require high-quality user experience, such as wireless communication. Cellular networks adopt 2G/3G/4G technologies to provide fast data access based on TCP/IP (transmission control protocol/Internet protocol); however, this is not efficient under high-speed scenarios. To solve the TCP/IP problems under high-speed environments, some management schemes have been investigated[3, 4]. These schemes add protocols to maintain an IP address under mobile environments (e.g., Mobile-IP[5]). However, these additional protocols result in more complex and less flexible communications, making it infeasible to directly apply TCP/IP in HST networking. Therefore, improvements on mobile communications in HST have not been efficient.

Named Data Networking (NDN)[6] is an innovative network architecture. It can create an Internet infrastructure that directly supports mobile communications in HSTs by introducing a unique named data as a core Internet principle. NDN fundamentally shifts the network communication model from host-centric to data-centric. Data becomes independent from location, application, storage, and means of transportation, enabling in-network caching and replication. In the content-centric

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Manuscript received: 2017-08-04; revised: 2017-09-27; accepted: 2017-12-23

communication mode, the consumer is only concerned with the information.

NDN architecture can handle consumer mobility[7] and security issues more efficiently than the current TCP/IP architecture. However, there are still some open problems regarding the use of NDN in wireless network[8], since original NDN is designed, considering the entire Internet architecture, rather than only HST architecture. Therefore, we consider an underlying innovation architecture to solve the current problems of wireless communication in mobile HSTs.

Wireless Mesh Networks (WMNs)[9] are proposed as a cost-effective technology to provide a citywide Internet access, and generally consist of a Mesh Portal Point (MPP) and Mesh Access Point (MAP). Since WMNs provide multi-hop network and transmission information via IP to access Internet, WMN cannot efficiently solve the problem of unstable IP under HST mobility, except if supported with NDN. Because of the rapid deployment and easy maintenance of WMN, we propose NDN-Mesh-T, a novel HST network architecture that combines WMN and NDN architectures, to improve the throughput, data latency, handover, and consumer mobility of mobile communication in HSTs.

In summary, this paper makes the following contributions:

- We propose NDN-Mesh-T architecture, which combines the advantages of WMN and NDN architectures.
- To reduce the network redundancy and data latency, we propose a Direction-Aware Forwarding (DAF) strategy, which forwards the Interest along the direction of the running train.

The remainder of the paper is organized as follows. In Section 2, we review the related work. In Section 3, we introduce the problem description. In Section 4, we propose the system architecture. In Section 5, we propose a DAF strategy. In Section 6, we report the simulation environment and results. Section 7 concludes the paper.

2 Related Work

With the rapid development of high-speed railway, passengers require high-quality user experience in high-speed environments. The current TCP/IP improves the user experience mainly from schemes that support high mobility and control congestion.

To solve the limitation of TCP/IP in high-speed scenarios, many mobile management protocols have been proposed, such as Mobile-IP, Mobile-IP extensions, Hierarchical Mobile-IP, Proxy Mobile-IP, and Mobile IPv6[4, 10]. Liu et al.[11] proposed an enhanced TCP throughput model to understand TCP in high-speed mobility environment. To minimize handover registration delay and prediction errors, some researchers proposed a predictive handover protocol that combines the Kalman filter and an online hidden Markov model[5]. The underlying cause of the high delay problem is the frequent handover via the triangular routing of the current TCP/IP architecture that exists in the Mobile-IP mechanism[12, 13]. The TCP/IP architecture cannot support high-speed movement because it is based on the connection of end-to-end communication.

Some congestion control schemes for TCP/IP have been proposed to improve network performance in high-speed environments[14–19]. Atxutegi et al.[16] evaluated different Congestion Control Algorithms (CCA) for mobile networks radio resources under challenging conditions and illustrated how the algorithm's features can greatly affect the final mobile performance. Fair-TCP[17] is a novel congestion control algorithm that can achieve a high utilization of network and ensure fairness. However, it does not maintain stability. Application-based TCP control algorithms[18] use the closed-loop control theory to improve congestion control and maintain a stable and constant transmission rate. An adaptive congestion level-based low-priority congestion control protocol[19] can achieve a high throughput in wireless networks. However, the above congestion control schemes for TCP/IP cannot efficiently improve the network performance because of frequent handovers in high-speed environment.

To solve this, some Information-Center Networking (ICN) architectures are proposed, such as DONA, 4WARD, PURSUIT, MobilityFirst, and CCN/NDN[20]. ICN[12, 21] is fundamentally different from the traditional IP network and is fundamentally different from the traditional IP network and is not limited by the end-to-end communication mode; therefore, it is a feasible solution to the mobility problem. NDN supports consumer mobility through its data-centric design principles and stateful forwarding plane[7, 22]. Ming et al.[12] analyzed the weakness of Mobile-IP in railway wireless networks and proposed an architecture that leverages NDN to deal with the frequent handoff problem. Some researchers have studied the node movement of ad hoc network and provided some guidelines for ICN research[9, 23].

To improve network performance under the ICN architecture, some related congestion control approaches have been proposed[24–26]. Ren et al.[24] first classified the methods of congestion control for NDN into three categories: receiver-based control, hop-by-hop control, and hybrid method. To realize an equitable and efficient multipath communication in ICN, Remote Adaptive Active Queue management scheme[25] was proposed for window control at the receiver. A practical control scheme[26], which utilizes the stateful hop-by-hop forwarding plane of NDN, was proposed to achieve a higher total throughput. Amadeo et al.[27] proposed bind forwarding and provider-aware forwarding for wireless ad hoc network. Yu et al.[28] provided a neighborhood-aware Interest forwarding scheme based on its *data* retrieval rate for a given name prefix and its distance to the consumer.

Therefore, there is no existing scheme to effectively reduce the frequent handoff delay and improve network throughput in HST environments. We propose the NDN-Mesh-T architecture, which considers both the frequent handoff performance and high bandwidth for high-speed environments.

3 Problem Description

In TCP/IP networks, Mobile-IP is created to enable users maintain the same IP address while traveling to different networks, ensuring that traveling individuals can communicate without a severed session or connection. However, Mobile-IP requires a mobile node to register its current location with the Foreign Agent (FA) and Home Agent (HA). This registration process may lead to data latency, which decreases the application quality of service. Additionally, Mobile-IP requires HA to tunnel the packets to FA (triangular routing) when it receives them from the mobile node, which increases delay. Especially, thousands of consumers will handoff at almost the same time when the HST moves to FA. If this frequently occurs, data latency would occur at FA as well as HA, which further reduces the user experience. The Mobile-IP handoff and data delivery processes are shown in Fig. 1. The poor mobility is mainly because IP networks must know the two endpoints before data transmission, establishing and maintaining a continuous connection for the endpoints. Triangular routing is a well-known problem in Mobile-IP, which further increases the network delay and reduces user experience. To address this problem, we propose NDN-Mesh-T architecture, which combines the advantages of WMN and NDN architectures.

In NDN, once the Interest reaches a node that has the requested data, the returned data packet follows in reverse the path taken by the Interest to return to the requesting consumer. If Interest is forwarded to the opposite direction of a running train, the returned data packet would chase the train. Therefore, the consumer needs to resend the Interest at the next-hop node to pull the data to the current node. Meanwhile, to ensure that the consumer receives the data, the train should stay at the current node within the coverage area. The experiments show that the data hit rate, data return delay time, and packet loss rate increased greatly with an increase in train speed.

In this paper, we propose NDN-Mesh-T architecture as a solution to address these challenges.

4 System Architecture

To address the wireless communication problems in HST environments, we consider the WMN and NDN to construct an HST network architecture. As shown in Fig. 2, the HST network architecture includes three network entities:

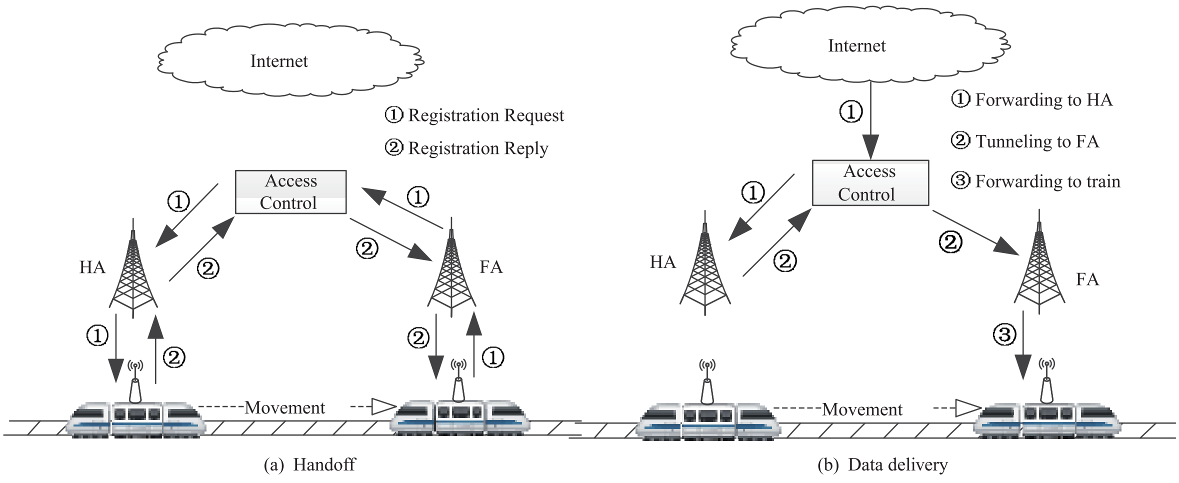


Fig. 1 Mobile-IP handoff and data delivery.

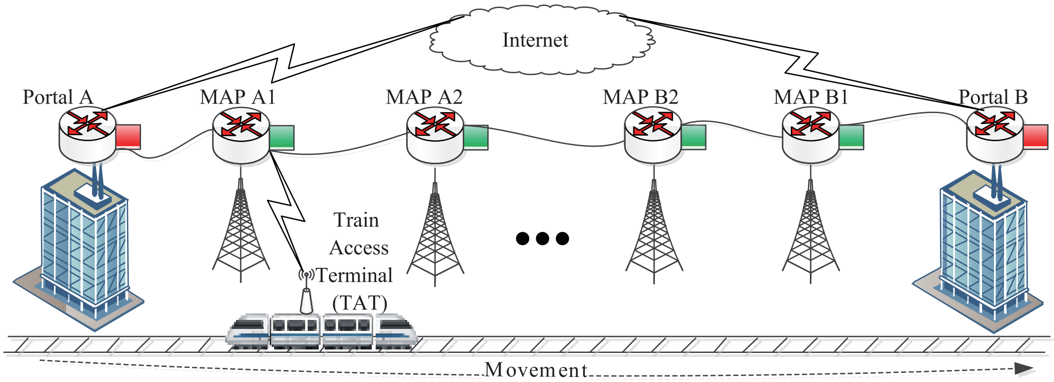


Fig. 2 NDN-Mesh-T communication architecture.

• *MPP*: The MPP forms a mesh of self-configuring, self-healing links among themselves. With gateway/bridge functionality, MPP can be connected to the Internet.

• *MAP*: The MAP also has the necessary functions for mesh networking, and thus can also work as a router in HST. MAP meshing provides peer-to-peer networks among MAP devices. Peer-to-peer network is an efficient solution for information sharing, because it can communicate anytime and anywhere. In this architecture, the MAP nodes which constitute the actual network perform routing and configuration functionalities as well as provide end-user applications to consumers. Consumers can access the network through MAP as well as directly meshing with other mesh nodes.

• Train Access Terminal (*TAT*): The TAT also has the necessary functions for mesh networking. It transmits information to MAP, which further reduces handoff latency.

A WMN is dynamically self-organized and self-configured, and the nodes in the network automatically establish and maintain mesh connectivity among each other, which provides flexibility and reliability of mesh network architecture for HST wireless communication. However, in high-speed environments, WMN cannot efficiently address the problems of triangular routing, network address translator traversal, and address management.

In the HST architecture as shown in Fig. 2, all network devices (including MPP, MAP, and TAT) are equipped with the NDN protocols. In NDN, data and Interest packets are routed and forwarded based on names, without IP addresses, which eliminates some problems caused by IP addresses. There is no triangular routing problem since the NDN uses names to route packets. There is no network address translator traversal problem since NDN does not use addresses when consumers frequently handoff in an HST communication network. Moreover, it is no longer required to assign and manage addresses when a consumer handoffs to different networks.

In the NDN-WMN architecture, we analyzed two different networking modes for MAP and TAT: infrastructure wireless networking (Basic Service Set, BSS) and self-organizing wireless networking (ad hoc).

A BSS is a centralized control network mode which has a wireless Access Point (AP) as the center of communication. In a BSS architecture, an access control is needed to manage the train handovers between the wireless APs; hence, the APs cannot intercommunicate directly. This would increase handoff delay and data latency in HSTs.

Ad hoc network is a continuous self-configuring, self-organizing, and wireless infrastructure-less network of mobile devices. It is composed of individual devices that communicate with each other, and no access control node is required. The nodes coordinate their respective behaviors through hierarchical protocols and distributed algorithms. When the nodes intercommunicate outside their coverage, they need multi-hop forwarding to intermediate nodes. Moreover, the multi-hop route is completed by ordinary network nodes and does not require specialized routing equipment. In addition to strong resistance to destruction and high reliability, ad hoc network has flexible networking features to support the fast access or exit of the mobile nodes.

Ad hoc network can support the dynamic change of network topology that results from increase in the train speed, and can meet the requirement of HST, since mobile nodes are free to join and leave the network. To reduce unnecessary certification and association switch in infrastructure networks, we consider MAP and TAT nodes consisting of ad hoc network, which further decrease handoff delay and improve the user experience, as shown in Fig. 2. In the experimental section, we further verify that the ad hoc network has better application results than the infrastructure network in the NDN-WMN architecture.

The proposed NDN-Mesh-T architecture has some advantages compared to IP networks as follows.

Consumer Mobility. Because data packets are returned by tracing the Interest path back to the consumer, the NDN architecture naturally supports consumer mobility. The additional overhead is that consumer re-expresses an *Interest* packet to retrieve the previously requested data from a router's cache, when the consumer is moving to a new network node.

Frequent Handoff. In our proposed architecture, no change is required on content names and reconfiguration in HST network when the consumer has frequent mobility. The NDN-Mesh-T architecture strongly supports Interest forwarding and data delivery in high-speed environments. We use the MAP to forward the Interest to MPP for Internet access, which improves the network reliability and decreases handoff latency.

Content Caching. Content caching is crucial to support the data delivery model of NDN at low cost. NDN provides high benefits to dynamic contents in case of a multicast or retransmission because of packet loss. It significantly reduces network data dissemination latency and retransmission times in HST. We consider caching content in NDN-Mesh-T local router (MAP), which further reduces the overhead on the producer side and decreases the data delay during the handover process. Furthermore, in-network caching can efficiently reduce the data delivery latency in HSTs.

5 Direction-Aware Forwarding Strategy

To further improve the performance of HST wireless communication, we propose a DAF strategy to forward the Interest in the direction of the running train. We describe the details of the NDN-Mesh-T data communication process in HST, which consists of direction definition, Interest forwarding, and data delivery.

5.1 Define direction

In HST wireless communication, consumers can be connected to different MAP nodes, which can forward *Interest* and *data* packets. We define the *Interest* forwarding direction flag as DF. If the *Interest* is forwarded from left to right and is in the same direction with the running train, we define DF = 1 in the Interest packet. At the same time, we define the interface identifier in the MAP node that forwards the *Interest* packet from left to right as *true*. If the *Interest* is forwarded from right to left in the opposite direction of the running train, we define DF = 0, and define the interface identifier in the MAP node that forwards the *Interest* packet from right to left as *false*. The consumers get the direction of the running train from the train devices. We set the current direction as DF= 1 when consumers get the direction of the train.

5.2 Interest forwarding

In NDN, communication is receiver-driven, and two fundamental types of packets are used: *Interest* and *data* packets. *Interest* packets are originally released into the network by nodes aimed to access a particular content, addressing the content with its content name. Data packets include the content itself and a cryptographic signature. An NDN router is composed of three main elements: Forward Information Base (FIB), Pending Interest Table (PIT), and Content Store (CS). When an *Interest* packet arrives, an NDN router matches its CS, PIT, and FIB. When a *data* packet arrives, an NDN router first checks the PIT entry for matching data and forwards the data to the matching interface. If a *data* packet with no matching PIT entries arrives, it is treated as unsolicited and discarded. NDN routers forward *Interest* packets toward data producers based on the names carried in the packets and forward data packets to consumers based on the PIT state information set up by the *Interest* packets at each hop.

To address the direction-aware *Interest* forwarding, we add a DF bit in the Interest packet and FIB table. The NDN *Interest* forwarding process in the NDN-Mesh-T architecture is shown in Fig. 3. When a consumer sends out an Interest packet to an MAP to access Internet, a data packet will be pulled to the MAP node. If the consumer does not receive the data package from the MAP, the MAP would forward the *Interest* packet to subsequent MAP nodes. The first time an *Interest* packet is sent, the FIB table adds an entry with the *Interest* forwarding DF value. First, the *Interest* forwarding direction is checked against the DF value. If the DF value corresponds, the *Interest* would be forwarded to the direction of the running train. If the DF value is different, the *Interest* packet would be discarded. This continues until the *Interest* packet reaches a producer location or a cache hit occurs on intermediate MAP nodes. Both directions of *Interest* package forwarding can be improved for transport reliability; however, this would significantly increase network load and network redundancy. In high-speed environments, if an *Interest* packet is forwarded to the opposite direction of a running train, *data* packet would follow the running train. Moreover, if a consumer switches

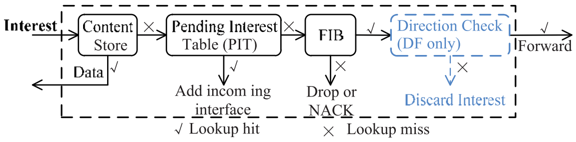


Fig. 3 NDN Interest forwarding process proposed.

to the next-hop MAP, the *data* packet would only reach the last MAP where the *Interest* packet was first received. This leads to unnecessary bandwidth consumption and increases network redundancy in HST wireless communication. In this study, to reduce network redundancy and data latency, we consider an *Interest* forwarding direction that is the same with that of the running train.

The DAF strategy determines the forwarding direction before the Interest packet is forwarded from the FIB. We determine the direction according to Algorithm 1 to ensure that the Interest packet is forwarded along the direction of the running train. Algorithm 1 indicates that when the train runs from left to right, the MAP node forwards the *Interest* packet from the right interface or when the train runs from right to left, the MAP node forwards the *Interest* packet from the left interface. Only in these two cases are *Interest* packets forwarded. Otherwise, they are discarded.

Algorithm 1 Direction-aware forwarding algorithm

Input: *Interest* packets

```
Initialize:
  Define the direction of Interest from left to right is true,
  the forwarding direction is the same as the running train,
  Interest.DF=1.
  Define the direction of Interest from right to left is false,
  the forwarding direction is opposite as the running train,
  Interest.DF=0.
  Define the outface of router forwarding to right is true,
  FIB.DF=1.
  Define the outface of router forwarding to left is false,
  FIB.DF=0.
if (!(Interest.DF) ⊕ (FIB.DF=1)) then
    Forwarding Interest
else
    Drop Interest
end if
```

5.3 Data delivery

NDN architecture effectively supports consumer mobility without additional operations. Data packets return to a consumer through the *Interest* forwarding reverse path. In a running train direction, data packets are cached along the path in a local MAP (consumer connecting MAP). If the *Interest* sent by the consumer is satisfied in a local MAP, data packets directly return to a consumer as shown in Fig. 4a. If a cache miss occurs in a local MAP, the Interest is sent only to the next-hop MAP, as shown in Fig. 4b. Once the consumer retransmits the Interest request in the next-hop MAP, data packets are returned directly from the local MAP or next-hop MAP. In the opposite direction of the running train, data packets chase the running train until they meet the Interest request in the same MAP. In this case, data packets are lost seriously, which increases data latency, especially in high-speed environments. We propose a DAF strategy to forward the *Interest* in the direction of the running train, which further improves the user experience.

The proposed DAF strategy adds a flag in the *Interest* packet and FIB table. However, because NDN protocol has a good scalability, this will not make the DAF deployment in NDN architecture more difficult. Moreover, the DAF scheme does not modify the current NDN-Mesh-T architecture and its mechanism does not require any critical change in current NDN protocols.

6 Evaluation

In this section, we implement the NDN-Mesh-T architecture and evaluate the performance in ndnSIM[29], which is extended to support high-speed network and the proposed DAF strategy.

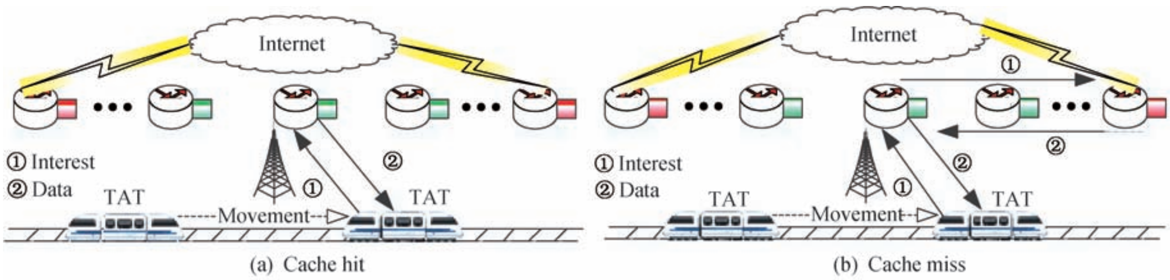


Fig. 4 NDN-Mesh-T data delivery.

6.1 Simulation settings

In NDN-Mesh-T network, all network nodes are enabled with caching functionality and the Leave Copy Everywhere policy is used, which means that all network nodes may cache data packets. In order to work effectively in high-speed environments, we use the log-distance propagation model for channel-induced losses. We use *ConsumerCbr* application to generate *Interest* traffic. We consider different numbers of MAP nodes, in which the nominal coverage radius is 175 m for each node. The main simulation parameters are summarized in Table 1.

To evaluate the performance of NDN-Mesh-T, we define the performance metrics as follows:

Packet Loss Rate: Number of packet loss / total number of packets transmitted.

Interest Packets Forwarding Times: The total times of Interest packets forwarded from consumer to producer.

Data Packets Forwarding Times: The total times of Data packets forwarded from producer to consumer.

Network Load: Actual throughput value / theoretical network bandwidth.

Handoff Delay: Handoff delay is $(T_2 - T_1)$, where T_1 indicates the time when a consumer sends *Interest* to the current MAP, and T_2 indicates the time when a consumer receives the Data packet in next-hop MAP.

Average Request Times: The *Interest* packets retransmission times.

Average Delay Time: This represents the delay between the first Interest sent and the Data packet received (i.e., includes time of Interest retransmissions).

6.2 Simulation results

To explain the performance of our proposed scheme, we did a comparative analysis in the following:

NDN-Mesh-T vs IP. To evaluate the proposed architecture, we compare the performance of the packet loss rate under different speeds. In this simulation, we set 10 MAP nodes and transmit 10 000 packets in the NDN-Mesh-T and IP network architecture. We used DAF strategy in the NDN-Mesh-T architecture and optimized link state routing strategy for the IP architecture. As shown in Fig. 5, the result shows that with an increase in speed, the packet loss rate of IP increases faster than that of DAF. Compared to the Mobile-IP architecture, DAF can reduce packet loss rate by up to 51%. The fundamental reason for the serious packet loss in Mobile-IP architecture is that it cannot efficiently solve the problem of IP address conversion and management, when a consumer frequently handoffs between MAP nodes in high-speed scenarios.

Table 1 Simulation parameters.

Parameter	Value
Data payload	600 bytes
CS size	10 000 packets
Traffic mode	40 Interest packets /s
Propagation model	Log Distance
Nominal radio range	175 m
Technology	IEEE 802.11b
Number of MAP nodes	10, 40
Mobility model	Constant Velocity
Speed of consumer	10–100 m/s

Infrastructure Network (BSS) vs Ad-Hoc. To verify the performance of the network model, we compare the packet loss rate of the infrastructure network mode with ad hoc network mode in the same traffic model. The two network models use the ConsumerCbr application to generate *Interest* traffic following a predefined pattern (send 40 *Interest* packets per second). In Fig. 6, with an increasing in speed, the packet loss rate of the BSS model is significantly higher than that of the ad hoc. In addition, the packet loss rate of the ad hoc model steadily increases with speed and is 25% lower than that of BSS. The high packet loss rate in BSS model is because the switch between different MAPs needs to be reassociated and authenticated.

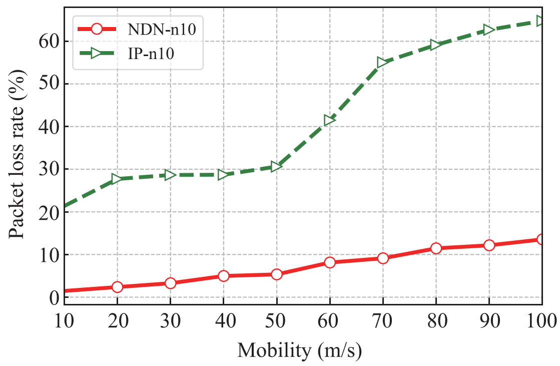


Fig. 5 NDN-Mesh-T vs IP network.

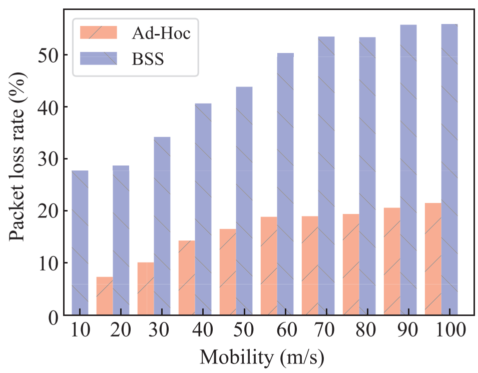


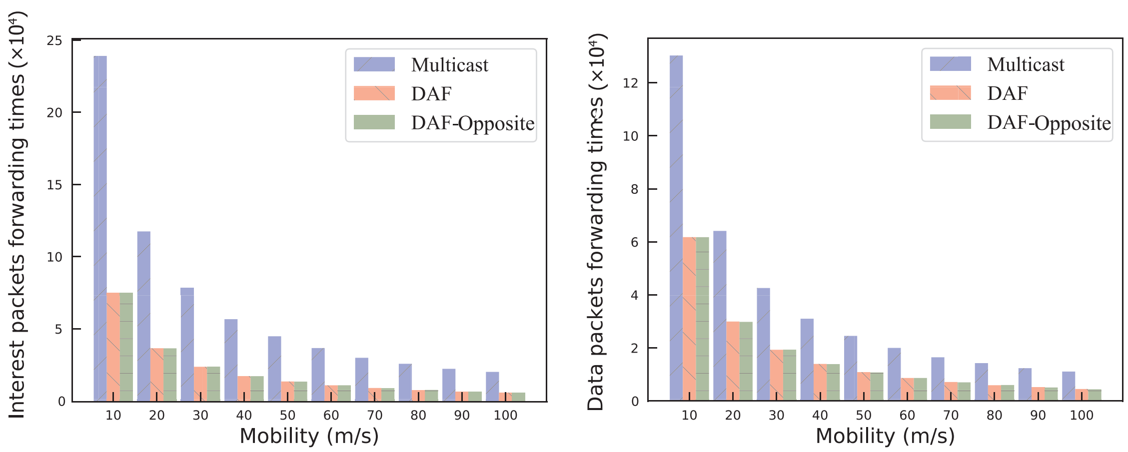
Fig. 6 BSS vs Ad-Hoc.

Interest and Data Packets Forwarding Times. Figures 7a and 7b show the Interest and Data packets forwarding times in different forwarding strategies. Because in the multicast strategy, Interest packets are forwarded in two directions, the number of Interest packets sent by this strategy is much larger than that sent by the DAF and DAF-Opposite strategies. In Fig. 7a, the number of Interest packets forwarded by the multicast strategy is three times as mush as that forwarded by the other two strategies. Interest retransmission and packet loss also increase the number of Interest packets forwarded.

Because data packets are returned back to the consumer by tracing the Interest path, the basic NDN communication is one-Interest-one-Data. However, the returned data packets are not the same as the Interest packets in Figs. 7a and 7b. If multiple Interests request the same content, only one Interest will be forwarded because of the Interest aggregation on NDN PIT. Therefore, the number of returned packets is less than the number of forwarded Interests. In the simulation, the number of packets returned using the multicast strategy is about twice as much as that returned using DAF or DAF-Opposite strategies, which increases network redundancy and bandwidth consumption.

Network Load. To verify the impact of forwarding policies on network load, we calculate the network load between different forwarding strategies as shown in Fig. 8. Compared to the multicast strategy, the DAF strategy can reduce the network load by up to 50%. The fundamental reason is that the DAF only uses the train in front of the network for data transmission, and the train behind the network is not used. That is, data packets only return to the consumer from the direction of train by tracing the Interest path. However, the multicast strategy sends Interests both along the same and opposite directions of the train, and the data will be returned from the two directions. So its network load is larger than that of the DAF strategy.

Impact of Forwarding Strategies. We consider DAF strategy to forward the *Interest* along the direction of the running train. In Fig. 9, we compare the packet loss rate of different forwarding strategies. Because the multicast strategy forwards the Interest along the same and opposite directions of the train, the packet loss rate is lower than that of other strategies. Despite that the packet loss rate



(a) Interest packets forwarding times (b) Data packets forwarding times

Fig. 7 Interest and data packets forwarding times.

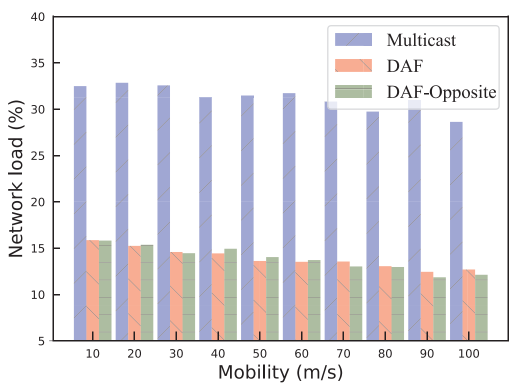


Fig. 8 Network load.

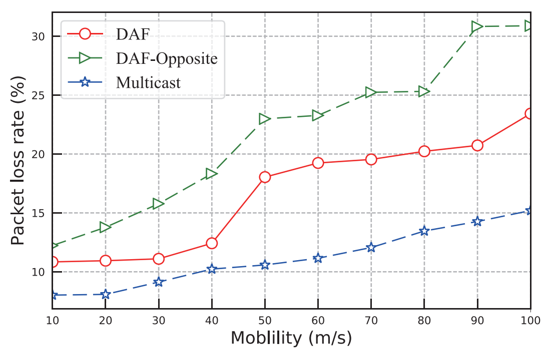


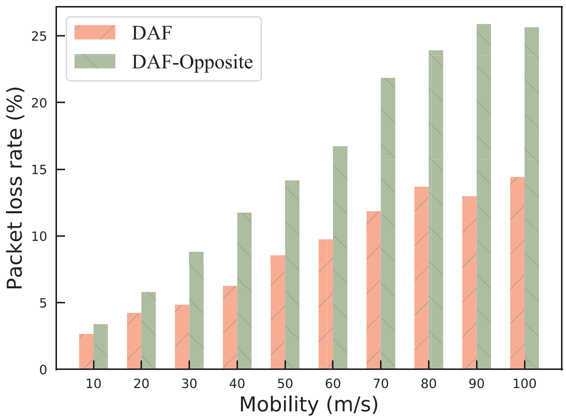
Fig. 9 Different forwarding strategies.

of NDN multicast forwarding strategy is lower than that of the proposed DAF strategy, we can reduce the number of *Interest* packets by half and reduce data redundancy in the opposite direction. If *Interest* packets are forwarded along the opposite direction of the running train, data packets would cache in MAP nodes. The packet loss rate of the DAF-Opposite strategy significantly increases compared to that of other strategies. Here, consumer received the data packets from the opposite direction of running train, however, data redundancy and bandwidth consumption are increased. Moreover, compared to multicast strategy, the packet loss rate of DAF is only increased 7% maximum, even when the consumer moves at 100 m/s.

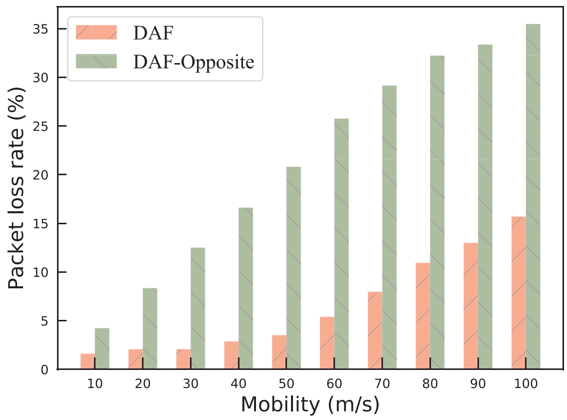
Impact of Speed. In high-speed environments, we consider the impact of the forwarding directions and numbers of MAP nodes at different speeds. In DAF strategy, the *Interest* packets are forwarded along the direction of the running train and in DAF-Opposite strategy, *Interest* packets are forwarded along the opposite direction of the running train. In Fig. 10a, the packet loss rate of the proposed DAF is lower than that of the DAF-Opposite, since the *Interest* packet is forwarded along the direction of the running train, which means the consumer will receive *Data* packets in the next-hop MAP on the direction of the running train. The Interests may be satisfied by the intermediate MAP nodes rather than by the content providers, which further reduces packet loss rate because of the caching functions in the NDN-Mesh-T architecture. With an increase in the number of the MAP nodes, the packet loss rate when using the DAF-Opposite with 40 MAP nodes is higher than that with 10 MAP nodes. Moreover, compared to DAF-Opposite, DAF can reduce the packet loss rate up to 20% as shown in Fig. 10b, because the consumer switching time increases with the number of MAP nodes; the data retransmission also increases as the speed increases, which also increases the packet loss rate. In addition, as the number of the MAP nodes increases, the packet loss rate of DAF remains stable. This is because the returned data is cached on MAP nodes in front of the running train. As the number of MAP nodes increases, the DAF strategy can cache more data packets for subsequent consumers.

Overlap Areas of Two MAP Nodes. To reduce the blind spots of radio network coverage, Mobile-IP increases overlap areas of two MAP nodes for HST environments, which increases the number of MAP nodes deployed as well as cost. The MAP nominal radio range is 175 m. We decrease the overlap areas to reduce the number of MAP nodes. In Fig. 11, we reduce the overlap areas of two MAP nodes from 100 m to 10 m, and the results show that the packet loss rate of DAF is lower than that of DAF-Opposite. This is because NDN can support a seamless consumer handoff between MAP nodes in overlap areas. For another reason, in the current 802.11, CSMA/CA dictates the half-duplex communications, only one radio can transmit on the same channel at any given time. In the overlap areas of MAPs, if the MAPs are on the same channel, unnecessary medium contention overhead occurs. Therefore, to avoid co-channel interference and adjacent channel interference in overlap areas, we use the NDN-Mesh-T architecture to connect the next-hop MAP as soon as possible. In summary, DAF can reduce the packet loss rate as well as the number of MAP node deployed in HSTs.

Impact of Handoff Delay. There is currently no measuring method to calculate the handoff delay for existing NDN networks. To calculate the handoff delay, we use a simple measuring method, in which we calculate the time interval between when the consumer sends the

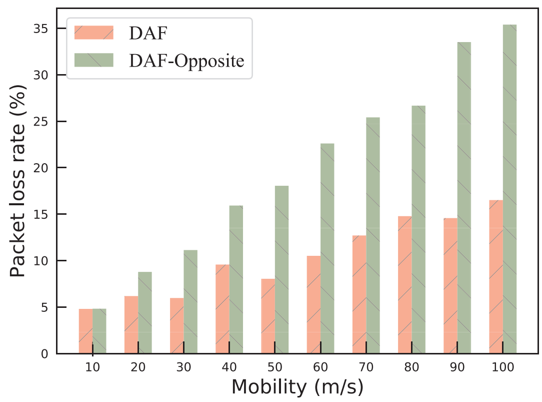


(a) 10 MAP nodes

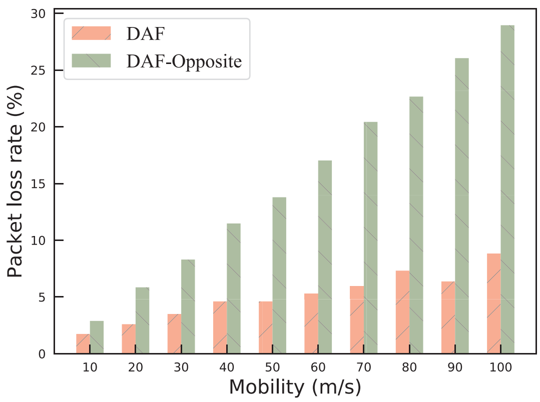


(b) 40 MAP nodes

Fig. 10 Packet loss rate in different numbers of MAP nodes.



(a) Overlap areas are 100 m



(b) Overlap areas are 10 m

Fig. 11 Overlap areas of two MAP nodes.

last *Interest* packet to the MAP and then receives the first *Data* packet from the next-hop MAP and when the consumer handoffs to the next-hop MAP node. We define the time interval as the handoff delay in our simulation. This interval will be higher than the actual handoff delay because of data latency. We calculate the average handoff delay with different numbers of MAP nodes at different speeds. From Fig. 12, we found out that in our simulation we reduced the handoff delay around three orders of magnitude compared to the Mobile-IP[30]. It can also be observed that all handoff delays are almost the same for a consumer even in high-speed environments. The experimental results show that the proposed scheme significantly reduces handoff delay, which further improves the user experience in HST environments.

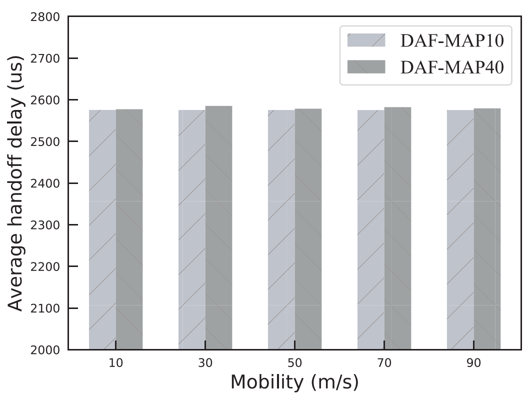


Fig. 12 Handoff delay.

Average Request Times with Cache. To verify the DAF strategy for the cache utilization, we calculate the average request times on DAF and DAF-Opposite. Direction-aware forwarding caches the returned data packets on an MAP node in front of the train, which can directly get data in a local MAP or next-hop MAP node. The consumer only needs to send one request to get the content in MAP node. Contrarily, in the DAF-Opposite strategy, the returned data packets are cached on an MAP node in back of the train. When the consumer requests the content and changes to the next-hop MAP node, another request needs to be sent for data packets from the last MAP node. In this case, the consumer sends at least two requests for data packets. As the speed increases, the consumer frequently handoffs between MAP nodes, which needs to resend more requests to the network, as shown in Fig. 13.

Average Delay. To verify the DAF performance with caching, we added a train to the simulation experiment, designating the first train as TAT1 and the second as TAT2. We set TAT1 to start first and sent an Interest packet, and set TAT2 to start at the interval time and sent the same Interest packet, so that TAT2 hits in the cache. Figure 14 shows how the mobility affects the average delay for DAF-Cache and DAF-NoCache. The average delay of DAF-NoCache significantly increases with speed, whereas that of DAF-Cache declines. This is because TAT2 can get data from the cache when the requested content has been cached. Thus, caching can effectively reduce network delay in HST scenarios.

7 Conclusion

High-speed trains are developing very quickly around the

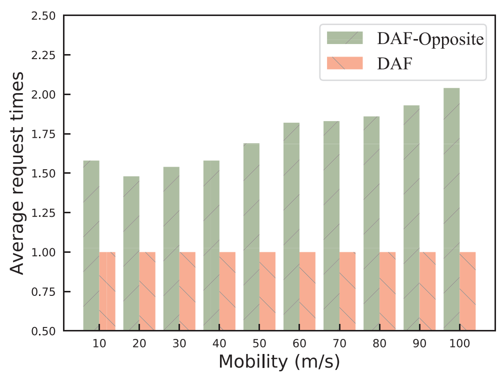


Fig. 13 Average request times with cache.

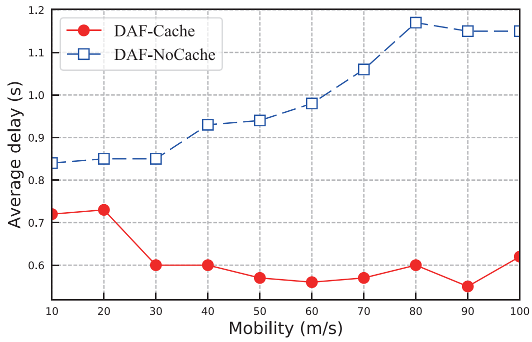


Fig. 14 Average delay.

world, particularly in Asia and Europe. However, they possess TCP/IP network challenges. We use the NDN wireless mesh network architecture to solve some key problems on wireless communications for HST scenarios. We propose an NDN-Mesh-T architecture that utilizes NDN architecture to handle the frequent handover that occurs when a consumer is moving. We consider the advantage of WMN for NDN development in HST. The proposed NDN-Mesh-T combines the advantages of WMN and NDN architectures, which significantly reduces handoff delay and network load in high-speed scenarios. To further improve the performance of HST networking, we propose a DAF strategy, in which the Interest packet is forwarded along the direction of the running train. The results show that the packet loss rate of DAF was slightly higher than that of the NDN multicast forwarding strategy, and we can reduce the number of *Interest* packets by half and reduce data redundancy in the opposite direction. In addition, we reduce the overlap areas of two MAP nodes, which decreases the number of MAP node deployments. Therefore, the proposed schemes can significantly improve user experience in high-speed scenarios.

In future work, we plan to conduct theoretical analyses and real experiments to evaluate the proposed schemes in real-world HST environments.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 61309025), the Hunan Provincial Natural Science Foundation of China (No. 2017JJ2332), the National Key Technology R&D Program (No. 2015BAH05F02), and the Fundamental Research Funds for the Central Universities of Central South University (No. 2017zzts146).

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