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A METHOD OF DYNAMICALLY CHANGING MOBILE SWITCHING PATHS TO ENHANCE ICN MOBILITY SUPPORT

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Abstract. *Information-Centric Network (ICN) makes up for the shortcomings of the current TCP/IP network, separates names and addresses, and has inherent advantages in supporting mobility. These current ICN mobility support methods use a single fixed switching path to transmit mobile packets after routing optimization. When the fixed switching path is congested, the transmission delay and loss rate of mobile packets will increase significantly, which will greatly affect mobile users' Quality of Experience (QoE). Therefore, how to detect the congestion of the switching path during route optimization, and how to dynamically change the switching path when congestion occurs are problems to be solved urgently in ICN mobility support. In this paper, we first propose a mobility support method for dynamically changing mobile switching paths based on congestion detection. Then, we propose a late-binding node switching mechanism, which uses Late-Binding Packets (LBPs) to detect mobile switching paths congestion in time and switches mobile packets to a non-congested candidate path. The mechanism includes two stages: congestion detection and late-binding node switching. Finally, experimental results show that our method can enhance mobility support and outperform other methods in terms of average packet delay, packet loss rate, handover delay, and throughput.*

Keywords: Information-Centric Network, Mobility, Route optimization, Congestion detection

1. **Introduction.** According to the prediction of Cisco's annual report [1], the total number of global mobile phone users will increase from 5.1 billion (about 66% of the population) in 2018 to 5.7 billion (about 71% of the population) by 2023. Recent technological advances have made handheld/portable devices dominate the market. These devices introduce mobility, which in turn poses challenges for the support of the underlying network. Therefore, how to provide mobility support will be one of the most important and challenging issues in the future network.

At the beginning of the design of traditional TCP/IP network architecture, mobility support was not considered. The IP address was given dual semantics. On the one hand, it was used as the identity identification of the mobile device to uniquely identify the device. On the other hand, it was used as the location identification of the mobile device to provide routing, addressing and other functions. The dual semantics of IP addresses has seriously restricted the development of mobility management technology. In order to solve the problems of mobility, security and scalability brought about by IP semantic

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overload, Information-Centric Network (ICN) [2] was proposed. Unlike host-to-host communication in traditional IP networks, ICN focuses on the content object itself rather than location. ICN names information by separating identity and location, and replaces IP addresses with corresponding names as identifiers in network transmission [3]. By naming content at the network layer, ICN supports intra-network caching, multicasting, and mobility mechanisms for more efficient and timely delivery of content to users [2,4]. ICN has two types of content discovery mechanisms, routing by name and lookup by name. Content-Centric Networking (CCN) [5] and Named Data Networking (NDN) [6] mainly use hierarchical and aggregated names, and the name resolution process is coupled with the routing process. This paradigm is difficult to be compatible with traditional IP networks, and deployment costs are high. MobilityFirst [7] and On-Site, Elastic, Autonomous Network (SEANet) [8] use flat names, and the name resolution process is decoupled from the routing process. This type of ICN paradigm is more compatible with the existing IP infrastructure and relatively easy to deploy. Note that our proposed mobility support method is based on the latter ICN paradigm.

In recent years, many ICN mobility support methods have been proposed. ICN mobility support methods [9-14] mostly use preset fixed anchor nodes or central mobility management entities to process mobility related information and redirect packets. The use of anchors brings problems such as switching path extension and single point of failure. Anchorless methods [15-26] remove the anchor nodes, thus realizing optimization of the forwarding path to a certain extent and bringing better performance to the handover. [15-20] use special interest packets to update the FIB of the intermediate router, thus optimizing the switching path. [21-23] use a resolution handler server on the transmission path to make the packet forwarding path hop-by-hop optimal, but this mechanism is not applicable to low-latency applications. [24,25] minimize the handover delay using connection attributes connecting mobile users, but do not consider mobile route optimization. DAFM [26] realizes the dynamic allocation of switching paths for multiple mobile data flows in combination with the real network environment. However, after the allocation is completed, the switching path is single and fixed. For AR/VR and other large data volume delay sensitive applications, the current mobility methods without anchor do not consider the dynamic changes of the real-time network environment, making the switching path fixed. If the bandwidth of a fixed switching path cannot meet the transmission of mobile packets, it will lead to network congestion, which will seriously affect mobile users' QoE. Therefore, how to quickly detect the congestion of the switching path and how to dynamically change the switching path when the congestion occurs are the focus of this paper.

Aiming at the above-mentioned problems faced by mobility support in ICN, we are committed to designing a mobility support method that dynamically changes the switching path after detecting congestion to ensure the performance of mobile users. The main content of this article is as follows.

1) Referring to DAFM [26], we propose a mobility support method for dynamically changing mobile switching paths based on congestion detection (we call it CDMM). Through directional propagation and processing Mobile Path Notifications (MPNs), Mobile Congestion Acknowledgments (MCAs) and Mobile Path Switchings (MPSs), the dynamic change of the switching path is realized when the network is congested. The dynamic change of switching paths will improve packet forwarding and ultimately improve mobile users' QoE.

2) We propose a late-binding node switching mechanism. The mechanism includes two phases of congestion detection and late-binding node switching. In the congestion detection phase, Late-Binding Packets (LBPs) are used to detect the congestion of the switching path, and MCAs are fed back to late-binding nodes with a certain probability, thereby triggering late-binding nodes to change. In the late-binding node switching phase, the congestion status of the Candidate Switching Path (CSP) is measured in advance to avoid directly handing over the switching path to the congested link.
3) We conduct a series of experiments to verify the performance of our mobility support method. The experimental results show that our proposed method has a significant improvement in terms of average packet delay, packet loss rate, handover delay, and throughput.

The rest of this paper is organized as follows. In Section 2, we review the related studies on mobility support in ICN and congestion detection in ICN, respectively. In Section 3, we describe the proposed ICN mobility support method. In Section 4, the late-binding node switching mechanism is described in detail. Then, we conduct simulation experiments on the proposed mobility support method, and discuss the experimental results in Section 5. Finally, in Section 6, we conclude this paper and discuss our plans for future work.

2. Related Work.

2.1. Mobility support in ICN.

Compared with anchor-based mobility support methods, anchorless mobility support methods automatically avoid problems such as triangular routing and single-point failure. In this paper, we focus on anchorless mobility support methods in ICN.

MAP-ME [15,16] is an anchorless producer mobility method, which allows producers to send Interest Update (IU) messages from the new location to the previous location to update the inter-mediate routers' FIB, so as to redirect the matched interests to the latest location of the producer. This approach can minimize the cost of path update, because the new entry is only temporarily added to the router between the old PoA and the new PoA. However, the performance of this method depends on the network topology. When implemented on some topologies, the packet forwarding path of MAP-ME is not optimal. In addition, it aims to manage that micro mobility is not suitable for future large-scale mobile networks. [17] proposes a producer mobility support method based on the optimal broadcast strategy. The mobile producer sends a Mobile Interest (MI) packet carrying new location information to the New location Access Router (N-AR), N-AR broadcasts MI packets to update the FIB of the intermediate routers, so that the packet forwarding path between the consumer and the producer is optimal. For further development of the broadcast-based mobility support method, OPMSS [18] was proposed. OPMSS [18] provides a data path optimization solution using mobility update, broadcast, and optimal routing strategies. Although the broadcast-based mobility scheme optimizes interest and data forwarding paths, broadcast mobility signaling brings large network overhead, which is not conducive to network scalability. [19] uses location prediction technology to manage the mobility of producers in real-time multimedia communication. When the Received Signal Strength (RSS) of the producer falls below a certain threshold, the producer sends an interest path update message to the old Access Point (oAP) to inform it of its mobility. The oAP predicts the new Access Point (nAP) of the mobile producer, and sends an interest redirection message to its nAP, updates the forwarding entry of the intermediate router, and redirects the interest to the nAP. If the nAP prediction fails, the mobile producer broadcasts its new name prefix. The acquisition of nAP in this method depends on the accuracy of mobile prediction. If it fails, the method will fall back to the routing update of the whole network. In [20], the producer notifies the consumer and the network about the mobility by using a Mobility Notification Packet (MNP) after initiating the handoff event. As soon as the consumer receives the MNP, it stops forwarding the interest packets. After arriving at the new location, the producer forwards the Mobility Update Packet (MUP) toward the consumer. On receiving the update packet, the consumer restarts the interest forwarding mechanism toward the new location of mobile producer. However, the method does not provide any suitable solution for the interest packets that are arrived during the handoff mechanism, hence increasing the overall content retrieval delay.

MobilityFirst [21] uses GUID to identify the identity information of the device or data, and NA represents the current location information of the device or content. GUID to NA mapping is done through the Global Name Resolution System (GNRS). When the NA is unreachable, the router caches the data packet and continues to forward the data packet after querying the global resolution system to obtain a valid NA to achieve the optimal hop-by-hop forwarding path. MobilityFirst is not suitable for the needs of improving user experience in modern life, such as in high-reliability, low-latency scenarios. An architecture called On-Path Resolver Architecture (OPRA) [22] is proposed to support the mobility of consumers and producers while maintaining scalability. OPRA leverages hierarchical name-based routing semantics and places route resolvers at multiple nodes along the path to content to redirect packets. However, this approach does not consider the impact of resolution query delay on handover performance. Kang et al. [23] proposed an enhanced programmable data plane supporting ICN mobility. Combined with SDN, by offloading mobility-related control plane functions from the controller to the data plane, the data plane can handle mobility signaling locally without interacting with the controller. By improving the flow table matching algorithm, mobile signaling processing capability is enhanced and the delay is reduced. The proposal does not focus on mobile route optimization.

Kar et al. [24] proposed an efficient producer mobility management technology. This method not only registers the mobile producer with the nearest Access Point (AP), but also registers it with multiple adjacent APs. Delays caused by AP handover and packet loss rates can be effectively reduced. When a named data network loses track of the producer, it uses a flooding strategy to transmit packets. [25] uses a dual-connectivity strategy that can be expressed as a soft handover. Whenever a producer changes its NDN Access Router (NAR), the new mobility link service located on the mobile producer's old NDN face repairs the old link so that the connectivity with the pNAR can be maintained for a while. The old NDN face is removed after the new location information on the contents of the producer is disseminated over the NDN network by the Named-data Link State Routing (NLSR) protocol at the nNAR. The new mobility link service decouples connection and transaction to hide the collapse of the link. None of these mobility support methods consider switching path optimization.

DAFM [26] pays attention to the switching path assignment problem and realizes the dynamic allocation of switching paths for multiple mobile data flows in combination with the real network environment. However, after the allocation is completed, the switching path is single and fixed. Therefore, the switching path cannot change with changes in the network environment.

2.2. Congestion detection in ICN.

To sense switching path congestion in a timely manner, we need to detect congestion at the router, not at the receiver. Below, we discuss the mechanism of congestion detection using routers in ICN. Related congestion detection mechanisms mostly exist in ICN congestion control. In the congestion control algorithm based on the receiver, Explicit Control Protocol (ECP) [27] divides the degree of network congestion into three levels, and judges the degree of network congestion by detecting the average length of the transmission queue in the intermediate node. The specific congestion level information is fed back to the content requester through Negative Acknowledgment (NACK), and then the content requester adjusts its interest sending rate accordingly through the Multiplicative Increase Additive Increase Multiplicative Decrease (MIAIMD) algorithm. PCON [28] proposes that each node monitors the queuing delay of each packet on its outbound link to detect congestion. After the congestion is detected, the congestion signal is fed back to the content requester through the data packet, and the content requester adjusts the size of the congestion window after receiving the congestion mark. In the hop-by-hop congestion control algorithm, HoBHIS [29] detects congestion by monitoring the chunk queue length, and adjusts the interest forwarding rate according to the queue length and available resources of nodes. In [30,31], routers detect network problems by observing bi-directional traffic, and mark the congestion level of forwarding ports with red, yellow, and green colors, which respectively indicate that the port is not congested, may be congested, and congested. When congestion occurs, the congested node will generate a NACK signal and forward it to the downstream node. The NACK mechanism enables routers to respond to changes in link status in a timely manner. Although the hop-by-hop method can adjust the forwarding rate according to the real-time congestion state, it also greatly increases the calculation pressure of the router. In a hybrid scheme based on receiver and hop-by-hop control, CHoPCoP [32,33] uses content-requester-based control as the main control and uses hop-by-hop control as a secondary means of control. When the queue length of the intermediate node exceeds the set threshold, CHoPCoP starts the hop-by-hop control mechanism, and the content requester uses the AIMD mechanism to adjust the window size, and the intermediate node adopts the Random Early Mark (REM) mechanism. The REM mechanism detects congestion by monitoring the size of the output data queue, and when congestion occurs, marks the data packet to feed back the congestion information to the content requester. [34] presents an early congestion detection mechanism applied on ICN routers based on an improved Active Queue Management (AQM) algorithm. By detecting early congestion and permanent congestion at intermediate nodes, the receiver can make the correct response according to the network status.

3. **CDMM.**

In Section 3.1, we first present an overview of CDMM's mobility support architecture. We describe the specific handover process of the proposed CDMM in Section 3.2.

3.1. **Architecture overview.**

Referring to DAFM [26], the network architecture used in CDMM is SEANet [8], which can coexist with existing IP networks for incremental deployment. According to the main principle of the separation of identity and location in ICN, elements such as content, equipment, and services can be regarded as entities in the network. Each entity is assigned an Entity-ID (EID) as an identifier (or name), and a Network Address (NA) as a locator. In order to be compatible with the existing IP network, the IP address is used as NA. Therefore, identifiers are completely separated from locators, and they are dynamically bound together through the Name Resolution System (NRS). Referring to the concept in DAFM, we identify the function of the router modifying the destination address of the packets according to the identification (destination EID) as a late-binding function, we label the router that performs late-binding processing as a Late-Binding Node (LBN) and we label a packet that is processed by a late-binding node as a Late-Binding Packet (LBP).

As shown in Figure 1, we consider a mobile communication system, including a producer, routers, Name Resolution System (NRS), wireless Access Points (APs) and a consumer. NRS maintains the latest mapping relationship between EID and NA. A consumer request content is published by a producer. The content will be split into a set of packets for transmission. In order to realize switching path congestion perception, packets need to carry source EID (the identifier of content), destination EID (the identifier of consumer), destination network address (consumer's network address), packet type and late-binding node address. The packet type mainly includes two types, which are the original type and the late-binding type. The late-binding node address indicates the network address of the router that is a late-binding node to process the packet. When the consumer moves, the destination NA in the packet sent to the consumer will become invalid. The router can find the valid network address of the mobile entity in the NRS according to the identifier of the mobile entity. To support packet redirection, each router needs to maintain a Mobility Entity Table (MET), which consists of a set of Mobility Entity Table Entries (METEs). Each METE includes the destination EID and the latest network address of the destination EID. After receiving a packet, the router can support finding the MET according to the destination EID carried in the packet. If there is a matching METE, replace the packet's packet type with late-binding type, replace the late-binding node address with the router's address, replace the destination network address with the corresponding NA in the METE, and then match the FIB table for data forwarding. If the match fails, the router will directly match the FIB for forwarding. Access routers can sense the movement of mobile entities in some way.

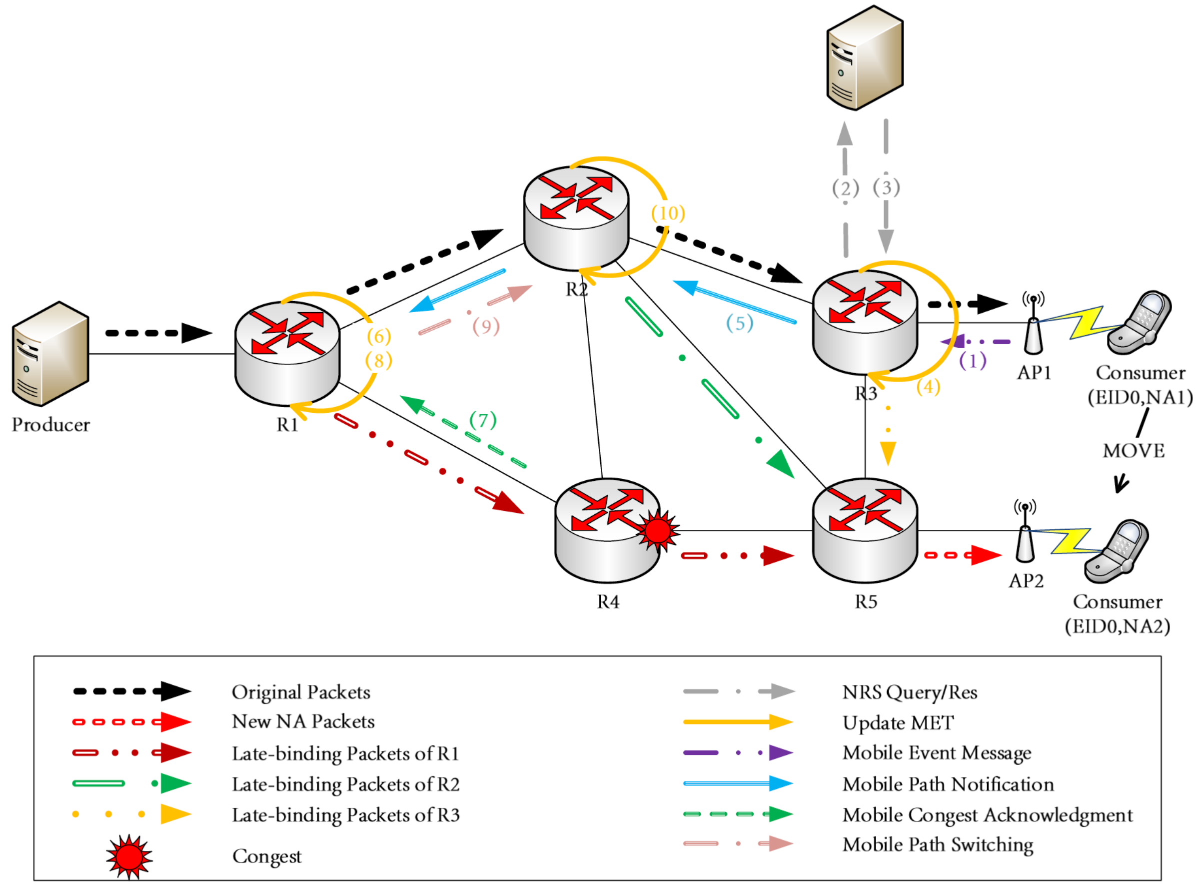


FIGURE 1. CDMM's architecture and handover process

3.2. **Handover process.** Figure 1 shows the operation of mobility support and dynamically changing handover paths based on network congestion. As shown in Figure 1, a consumer requests content published by a producer, so a set of packets is generated between the producer and the consumer. The forwarding path of original packets is Producer→R1→R2→R3→AP1→Consumer. When a consumer moves from the area of the initial access router (R3) to the area of the new access router (R4), the original AP (AP1) will send a Mobile Event Message to the initial access router, which carries the consumer's identifier (EID0) (step 1). After the initial access router (R3) receives the Mobile Event Message, it will query the NRS for the latest network address (NA2) of the consumer based on the consumer's identifier (EID0) (step 2). The initial access router (R3) receives the response from the NRS and learns the consumer's latest network address (NA2) (step 3). Next, the original access router (R3) updates the local MET to redirect the packet (step 4). At this time, the forwarding path of the packet is Producer→R1→R2→R3→R5→AP2→Consumer. Simultaneously, the initial access router (R3) constructs a Mobile Path Notification (MPN) to propagate to the producer's access router (R1) in the opposite direction of the original packet (step 5). In addition to announcing the latest EID-NA mapping relationship (EID0-NA2) of the consumer, MPN also needs to notify the "fork node" router information (e.g., the router's network address) on the MPN propagation path and the priority corresponding to the "fork node". We define routers that forward original packets and late-binding packets using different ports as "fork node", and we refer to these fork nodes on the MPN propagation path as candidate late-binding nodes. The priority of a candidate late-binding node increases hop by hop as the MPN propagates. After the producer's access router (R1) receives the MPN, it updates the local MET (step 6), and records these candidate late-binding nodes information. Up to this step, we have completed the preliminary routing optimization, and the forwarding path of packets is Producer→R1→R4→R5→AP2→Consumer.

As the network traffic changes, it is assumed that the link between R4 and R5 is congested. If R4 detects congestion (see Section 4.1 for the specific congestion detection method), R4 will send a Mobile Congestion Acknowledgment (MCA) to the late-binding node (R1) (step 7). After the current late-binding node (R1) receives the MCA, it updates/deletes the local MET-related entries (step 8). The current late-binding node (R1) sends a Mobile Path Switching (MPS) to the candidate late-binding node (R2) with the highest priority (step 9). The router (R2) selected by using the late-binding node switching algorithm (see Section 4.2) becomes the new late-binding node, updates the local MET (step 10), and records the remaining candidate late-binding node information. At this time, the forwarding path of the packet is Producer→R1→R2→R5→AP2→Consumer. Similarly, if the switching path formed by the current late-binding node (R2) cannot meet the transmission requirements of mobile data, it will continue to switch to subsequent candidate late-binding nodes until the switching path can meet the transmission requirements of mobile data or switch to the mobile user's initial access router. Our method realizes the dynamic change of the switching path by detecting the switching path congestion and triggering the binding node switching. Therefore, our method helps to improve packet forwarding, and improve mobile users' QoE.

4. Late-Binding Node Switching Mechanism.

In order to ensure the mobile handover performance, we need to quickly detect the handover path congestion, and quickly change the late-binding node when the handover path is congested. To this end, we describe a late-binding node switching mechanism in detail in this section. The mechanism includes two phases of congestion detection and late-binding node switching.

4.1. Congestion detection.

We found that by observing the queuing situation at the output port of the router, we can predict whether the network is congested in advance. Random Early Detection (RED) [35] detects congestion by monitoring the average length of router output port queues. Once the congestion is found to be approaching, RED randomly selects connections to notify the congestion, so that they can reduce the congestion window and reduce the speed of sending data before the queue overflow causes packet loss, thus alleviating the network congestion. When the average queue length is between the minimum and maximum thresholds, queued packets will be dropped with variable probability. Therefore, RED can control the average queue length to avoid congestion even in the absence of effective coordination of transport layer protocols.

Referring to congestion control algorithms such as RED and ECP, we detect congestion by calculating the average queue length. Different from RED which calculates the average queue length for all arriving packets and ECP which calculates the average queue length by regular sampling, our congestion detection only occurs when the Late-Binding Packets (LBPs) enter the router output port queue. Different from congestion control mechanisms such as RED and ECP, which send marked packets or congestion feedback to the receiver or content requester, our method sends Mobile Congestion Acknowledgments (MCAs) to late-binding nodes, so as to trigger the late-binding node to switch, change the switching path, and avoid congestion.

When forwarding an LBP, each router decides whether to feed back the MCA with a certain probability, which is related to the degree of congestion. We use the average queue length to evaluate the degree of congestion. When the ith LBP enters the router output port queue, the router knows the length q_i of the current queue length. When calculating the average queue length, due to the burst of network data, if a queue is empty for many times, then quickly filled, and then quickly emptied, it cannot be said that the router is congested and needs to be fed back. Therefore, we use a Low Pass Filter (LPF) with Exponential Weighted Moving Average (EWMA) [36] to calculate the average queue length Q_i, as shown in Equation (1).

$$Q_i = (1 - \mu) * Q_{i-1} + \mu * q_i \tag{1}$$

where μ $(0 < \mu < 1)$ is a weighting coefficient, and q_i is the current queue length.

The average queue length is the main indicator to measure the current congestion situation. Based on the queuing situation of the queue, we set two average queue length thresholds, named Q_{th1} and Q_{th2}. According to Equation (2), we calculate the probability P_i of MCA feedback by comparing the relationship between the average queue length and the two queue length thresholds Q_{th1} and Q_{th2} of the router.

$$P_i = \begin{cases} 0, & Q_i < Q_{th1} \\ \sqrt{(Q_{th2}^2 - Q_{th1}^2) * Q_i + Q_{th1}^2}, & Q_{th1} \le Q_i \le Q_{th2} \\ 1, & Q_i > Q_{th2} \end{cases} \tag{2}$$

Then, we use Min-Max scaling to normalize the P_i between the threshold Q_{th1} and Q_{th2} to the range of $[0, 1]$ as shown in Equation (3).

$$P_i = \begin{cases} 0, & Q_i < Q_{th1} \\ \dfrac{\sqrt{\left(Q_{th2}^2 - Q_{th1}^2\right) * Q_i + Q_{th1}^2} - \sqrt{\left(Q_{th2}^2 - Q_{th1}^2\right) * Q_{th1} + Q_{th1}^2}}{\sqrt{\left(Q_{th2}^2 - Q_{th1}^2\right) * Q_{th2} + Q_{th1}^2} - \sqrt{\left(Q_{th2}^2 - Q_{th1}^2\right) * Q_{th1} + Q_{th1}^2}}, & Q_{th1} \le Q_i \le Q_{th2} \\ 1, & Q_i > Q_{th2} \end{cases} \tag{3}$$

If the average queue length is less than Q_{th1}, the degree of congestion is considered light. In this case, the probability of packet loss is very low, and the value of switching late-binding node is not great. In this case, MCA is not fed back. When the average queue length is greater than Q_{th2}, we consider the current congestion situation to be serious. At this time, the probability of packet loss is high, so the probability of feedback is 1. If Q_i is between the thresholds Q_{th1} and Q_{th2}, it is considered to be in moderate congestion, and the probability of feedback increases with the increase of the average queue length. When in moderate congestion, randomly generate a value RV, and make RV uniformly distributed between $[0, 1]$. If RV satisfies the condition (4), MCA will be fed back. The detailed process of MCA feedback is shown in Algorithm 1.

$$RV \leq \frac{\sqrt{(Q_{th2}^2 - Q_{th1}^2) * Q_i + Q_{th1}^2} - \sqrt{(Q_{th2}^2 - Q_{th1}^2) * Q_{th1} + Q_{th1}^2}}{\sqrt{(Q_{th2}^2 - Q_{th1}^2) * Q_{th2} + Q_{th1}^2} - \sqrt{(Q_{th2}^2 - Q_{th1}^2) * Q_{th1} + Q_{th1}^2}} \tag{4}$$

Algorithm 1. Mobile congestion acknowledgment feedback

```
Input: $q_i$, $LBP_i$, $Q_{\max}$
Output: $P_i$
    Initialization: $\mu = 0.9$, $Q_{th1} = 0.25 * Q_{\max}$, $Q_{th2} = 0.75 * Q_{\max}$
    for each Late-Binding Packet (LBP) arrival do
        update the current average queue length $Q_i$ by Equation (1)
        if $Q_i < Q_{th1}$ then
            $P_i = 0$
        else if $Q_{th1} \leq Q_i \leq Q_{th2}$ then
            calculate the probability of MCA feedback $P_i$ by Equation (3)
            $RV = random(0, 1)$
            if $RV \leq P_i$ then
                send mobile congestion acknowledgment
            end if
        else
            $P_i = 1$
            send mobile congestion acknowledgment
        end if
    end for
```

4.2. **Late-binding node switching.** As mentioned before, when the routers on the switching path detect congestion, they will feed back the MCA to the late-binding node. The late-binding node switching process is shown in Figure 2. After receiving the congestion feedback, the late-binding node needs to send a Mobile Path Switching (MPS) to the candidate late-binding node with the highest priority. In order to avoid switching directly to the congested path, we first need to determine whether the Candidate Switching Path (CSP) formed by the candidate late-binding node with the highest priority is a congested path. If the CSP is non-congested, the candidate late-binding node is selected. If the CSP is a congested path, delete the node from the set of candidate late-binding nodes, and continue to send the MPS to the next highest priority candidate late-binding node until a satisfactory late-binding node is found or the set of candidate late-binding nodes is empty. The late-binding node switching algorithm is shown in Algorithm 2.

In this paper, the queue occupancy rate is used to judge whether the CSP is congested. We maintain the congestion state of the CSPs at the candidate late-binding nodes. Please note that if the CSP formed by the candidate late-binding node for different mobile users is the same, the candidate late-binding node only needs to maintain one piece of

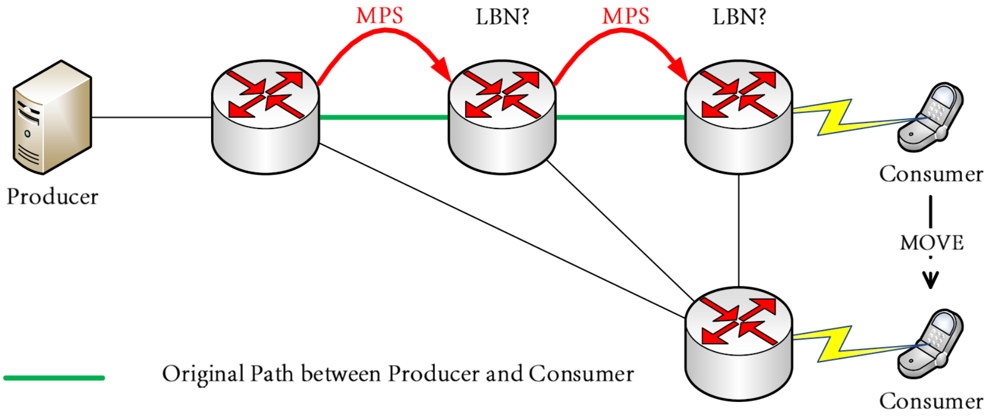


FIGURE 2. Late-binding node switching process

congestion status information. Therefore, the congestion state of the CSPs maintained by the candidate late-binding node is at the level of the path, not at the level of the mobile user. The candidate late-binding node periodically measures the queue occupancy rate of the CSP. Referring to ECP [26], consider a time interval Δt, during which candidate late-binding nodes sample the instantaneous queue lengths of each router on the CSP. The candidate switching path $S = \{R_{candidate}, \dots, R_{N\text{-}AR}\}$ is formed from the candidate late-binding node $R_{candidate}$ to the new access router $R_{N\text{-}AR}$ of the mobile user. At time t, the instantaneous queue length of each router on the candidate switching path S is $\{Q_{R_{candidate}}(t), \dots, Q_{R_{N\text{-}AR}}(t)\}$. Equation (5) is used to calculate the instantaneous queue occupancy rate $\{O_{R_{candidate}}(t), \dots, O_{R_{N\text{-}AR}}(t)\}$ of each router on the candidate switching path.

$$O_R(t) = \frac{Q_R(t)}{Q_{R_{\max}}}, \quad \forall R \in S \tag{5}$$

where $Q_R(t)$ is the instantaneous queue length of router R at time t, and $Q_{R_{\max}}$ is the maximum queue length of router R.

Equation (6) is used to calculate the instantaneous queue occupancy $O_S(t)$ of S, and the instantaneous queue occupancy of S is the maximum of the instantaneous queue occupancy of all routers included in S.

$$O_S(t) = \max\{O_R(t)\}, \quad \forall R \in S \tag{6}$$

In order to avoid misestimation caused by short-term burst traffic, we use a weight factor α $(0 < \alpha < 1)$ to smoothly calculate the average queue occupancy rate $O'_S(t)$ of S, as follows:

$$O'_S(t) = (1 - \alpha) * O'_S(t - \Delta t) + \alpha * O_S(t) \tag{7}$$

We introduce a congestion state threshold O_{thresh}. According to the relationship between $O'_S(t)$ and O_{thresh}, we can judge whether the candidate switching path is in a congested state.

$$congestion\_state = \begin{cases} 0, & 0 < O'_S(t) \le O_{thresh} \\ 1, & O'_S(t) > O_{thresh} \end{cases} \tag{8}$$

The congestion state values of the N candidate switching paths are distributed and maintained on the N candidate late-binding nodes. When the candidate late-binding node receives the MPS, it can immediately determine whether to select it as a late-binding node according to the congestion state value, without waiting for re-detection. Therefore, we can find that the late-binding switching algorithm complexity is $O(1)$. This algorithm

Algorithm 2. Late-binding node switching algorithm

```
Input: $R_{candidate}$, $N$, $MPS$
Output: $LBN_{new}$
Initialization: $Q_{thresh} = 0.75$
for each $\Delta t$ during transmission do
    calculate the average queue occupancy rate $O'_S(t)$ of the CSP by Equation (7)
end for
for each Mobile Path Switching (MPS) arrival do
    if $O'_S(t) \leq Q_{thresh}$ then
        $LBN_{new} = R_{candidate}$
    else
        $N = N \setminus \{R_{candidate}\}$
        if $N = \phi$ then
            $LBN_{new} = R_{candidate}$
        else
            $LBN_{new} = \phi$
            $R_{candidate} = SelectTop(N)$
            send MPS to $R_{candidate}$
        end if
    end if
end for
```

avoids switching the mobile packets directly to the congested path, thereby avoiding the switching of the late-binding node to a certain extent.

5. **Performance Evaluation.** In this section, we conducted a series of experiments to evaluate the impact of our proposed enhanced mobility support method on the performance experience of mobile users. We implemented the proposed mobility support method on Mininet [37], and we also implemented the principle of MAP-ME [16] and OPMSS [18] using special packets to update router forwarding table entries to support mobility.

5.1. **Evaluation metrics.** Average packet delay: The average difference between the time when the consumer receives the packet at the new location and the time when the content producer sends the packet.

Packet loss rate: The ratio of the total number of packets received by the consumer at the new and old locations to the total number of packets sent by the content producer.

Handover delay: [38] defines handover delay as the time between the mobile entity leaving the previous subnet and receiving the first packet in the new subnet. We define handover delay as the difference between the time when the consumer receives the first packet at the new location and the time when the consumer receives the last packet at the old location.

Throughput: [18] defines throughput as the average number of packets received by a consumer per unit of simulation time. The higher the throughput, the better the performance of the mobility support.

5.2. **Experiment setup.** This experiment platform is built on Ubuntu 20.04 system. The experimental platform includes Mininet 2.3.0, OpenvSwitch 2.13.3 and Ryu 4.34 [39] controllers. This section uses Mininet 2.3.0 to create a network topology. We simulate an Abilene [40] topology. The network topology, link bandwidth and link delay settings are shown in Figure 3. We use OpenvSwitch (OvS) 2.13.3 to simulate router to realize data forwarding. Ryu 4.34 is a controller that can connect to OvS through OpenFlow 1.3 protocol. Mininet does not support Layer 3 routing. In order to realize routing in

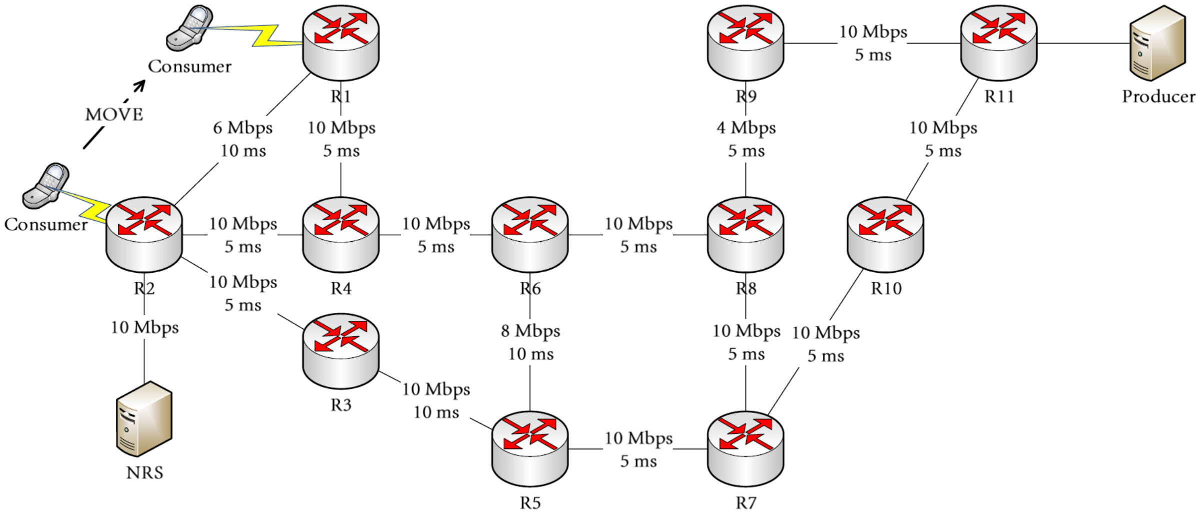


FIGURE 3. Simulation topology

multi-path network topology, we run a routing protocol on the controller. The routing algorithm adopted by the routing protocol is Dijkstra algorithm with bandwidth as the weight.

Table 1 shows the parameter settings of our simulation experiments. We consider a producer sending packets at a rate R_d with an average packet size P. The rate of congested data is R_c and the average packet size is also P. The router's maximum queue length is $Q_{\max}$. The values of μ, α, Q_{th1}, Q_{th2} and Q_{thresh} are set according to [41]. Set the value of the path measurement time interval Δt according to [42]. The time from leaving the old access router to attaching to the new access router is T_{PN}, and the time delay for the NRS to respond to the query request of the access router is T_{RA}. During the simulation, the producer continues to send packets to the consumer, and the sending data packet rate can be adjusted according to different simulations. One second after the simulation starts, simulate consumer movement. The total simulation time is 3 s. For each round of simulation, we calculate the average value of the measured performance metrics.

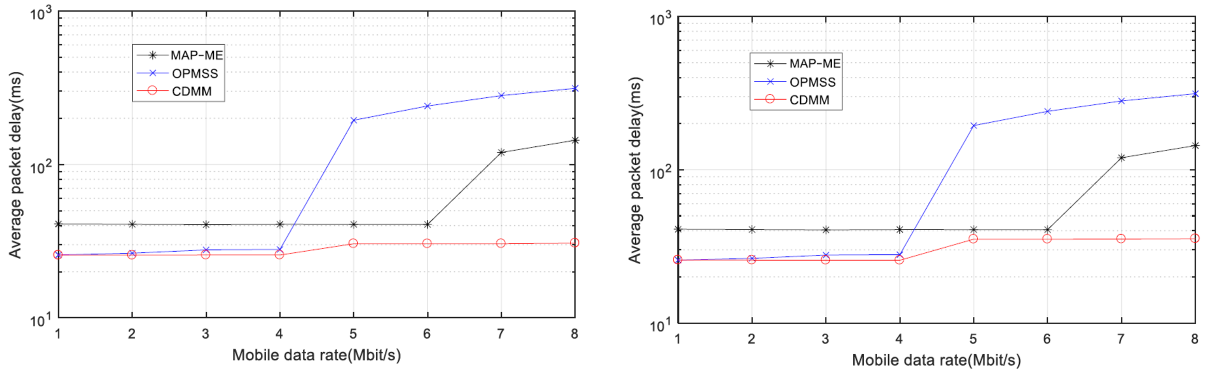
TABLE 1. Experiment parameters and values

Parameter	**Value**
Mobile data rate (R_d)	$[1, 8]$ Mbit/s
Congestion data rate (R_c)	12 Mbit/s
Average packet size (P)	1000 bytes
The maximum queue length ($Q_{\max}$)	100 packets
The lower threshold for queue length (Q_{th1})	$0.25 \times Q_{\max}$
The upper threshold for queue length (Q_{th2})	$0.75 \times Q_{\max}$
Weighting factor of average queue length (μ)	0.9
Path metrics time interval (Δt)	100 ms
Queue occupancy threshold (Q_{thresh})	0.75
Weighting factor of queue occupancy (α)	0.9
Time interval consumer disconnection and reconnection from P-AR to N-AR (T_{PN})	100 ms
Response latency between NRS and ARs (T_{RA})	$[1, 5, 10]$ ms

To evaluate the performance of the mobility method in terms of average packet delay and packet loss rate, we simulate two scenarios. Scenario 1 is the base scenario. We set the latency of NRS responding to R2's query to 1 ms, and adjust the speed of mobile data from 1 Mbit/s to 8 Mbit/s. Scenario 2 is a congestion scenario. In order to simulate link congestion between R7 and R8, we connect external hosts to R7 and R8. One second after the simulation starts, the external host of R7 starts to send congested data packets at a rate of 12 Mbit/s to the external host of R8 continuously. We set the latency of NRS responding to R2's query to 1 ms, and adjust the rate of mobile data from 1 Mbit/s to 8 Mbit/s. Other parameter settings are shown in Table 1. In order to evaluate the performance of the mobility approach in handover delay, we set the delay parameters of the NRS to respond to R2's query as 1 ms, 5 ms and 10 ms respectively on the basis of scenario 1 for simulation. To evaluate the performance of the mobility approach in throughput, we set the rate of data packets to 5 Mbit/s, 6 Mbit/s, 7 Mbit/s, and 8 Mbit/s, respectively. The latency of NRS responding to R2's query is set to 1 ms. We calculate the average number of packets received by the consumer per unit time.

5.3. **Results and discussions.** In this section, we present the most important results pertaining to our evaluation of CDMM through simulations.

5.3.1. *Average packet delay.* Figure 4(a) shows the comparison between the average packet delay and mobile data rate for different mobility support methods in base scenario. We can find that our proposal performs better than MAP-ME and OPMSS in terms of average packet delay at the same mobile data rate. We noticed that when the mobile data rate is lower than 4 Mbit/s, the average packet delay of OPMSS and CDMM is the same as and lower than that of MAP-ME, because the switching paths of both OPMSS and MAP-ME will converge to the shortest path. OPMSS broadcasts special data packets through the new location access router (R1), so that the switching path converges to the shortest path calculated by the routing plane (Producer→R11→R9→R8→R6→R5→R4→R1→Consumer). CDMM first selects R11 as the late-binding node through propagation processing MPN to form the shortest handover path. Since the bandwidth of the shortest switching path can satisfy the transmission of mobile data whose rate is lower than 4 Mbit/s, CDMM no longer performs late-binding node switching. The final switching path of CDMM is the same as that of OPMSS. MAP-ME converges the handover path to Producer→R11→R10→R7→R5→R3→R2→R1→Consumer by sending an Interest



(a) (b)

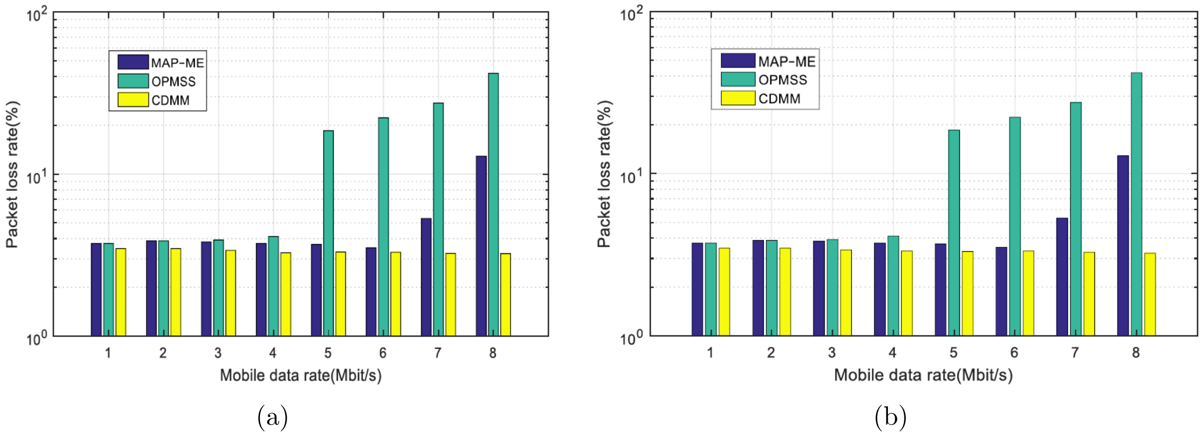
FIGURE 4. Comparison of average packet delay in different scenarios: (a) Base scenario; (b) congestion scenario

Update (IU) message to the old location. However, when the mobile data rate is higher than 4 Mbit/s, the bandwidth of the shortest switching path used by OPMSS cannot meet the data transmission, resulting in a large delay. When the mobile data rate is higher than 4 Mbit/s, the average packet delay of CDMM is lower than that of MAP-ME. Since CDMM detects that the shortest path cannot satisfy mobile data transmission, it switches the late-binding node from R11 to R7 and forms a switching path (Producer→R11→R10→R7→R8→R6→R4→R1→Consumer) with lower latency. When the mobile data rate is higher than 6 Mbit/s, the average packet delay of MPE-ME increases significantly, because the bandwidth of the switching path used by MAP-ME cannot meet the transmission of mobile data with a rate exceeding 6 Mbit/s.

Figure 4(b) shows the comparison between the average packet delay and mobile data rate for different mobility support methods in congestion scenario. We can find that, at the same mobile data flow rate, our proposal performs better than MAP-ME and OPMSS in terms of average packet delay. Comparing Figure 4(a) and Figure 4(b), we found that when the mobile data flow rate is higher than 4 Mbit/s, the average packet delay of CDMM in congestion scenario is higher than that in base scenario. In congestion scenario, we make the link (R7→R8) congested, so the switching path formed by R7 as the late-binding node is a congested path. Therefore, CDMM continues to select R5 as the late-binding node to redirect the packet. The transmission delay of the switching path (Producer→R11→R10→R7→R5→R6→R4→R1→Consumer) formed by the late-binding node R5 is slightly higher than the transmission delay of the switching path formed by the late-binding node R7 under non-congested state. The non-congested state means that the switching path formed by the late-binding node R7 is non-congested in base scenario.

Both MAP-ME and OPMSS use fixed switching paths to transmit data. Therefore, when the mobile data rate exceeds the bandwidth of the bottleneck link, the average packet delay will increase significantly. CDMM can dynamically change the switching path according to the link congestion situation. Therefore, our proposal can reduce the average packet delay to some extent compared with the mobility support method with fixed handover path.

5.3.2. *Packet loss rate.* Figure 5(a) shows the comparison of packet loss rate and mobile data rate for different mobility support methods in base scenario. We find that our proposal outperforms MAP-ME and OPMSS in terms of packet loss at the same mobile data rate. We found that when the mobile data rate is lower than 4 Mbit/s, the average packet



(a) (b)

FIGURE 5. Comparison of packet loss rate in different scenarios: (a) Base scenario; (b) congestion scenario

loss rate is not much different because the bandwidth of the switching path formed by the three mobile support methods can meet the data transmission. Packet loss is mainly caused by consumers not being able to receive packets during handover. The reason why the packet loss rate of CDMM is lower than other methods is that CDMM can quickly obtain the latest network address of the consumer through NRS to quickly redirect data packets to the consumer's new location. This process can be completed within a certain period of time, thereby reducing the packet loss rate. MAP-ME and OPMSS need to transmit special data packets to realize data redirection. The time to complete this process depends on the actual network topology and link delays. When the mobile data rate is higher than 4 Mbit/s, we found that the packet loss rate of OPMSS increases significantly, because the bandwidth of its switching path cannot meet the data transmission requirements, resulting in link congestion and packet loss. Similarly, when the mobile data rate is higher than 6 Mbit/s, the switching path formed by MAP-ME cannot meet the requirements of data transmission, and MAP-ME also causes a large number of data packets to be lost. The results in Figure 5(b) also prove that CDMM performs better than MAP-ME and OPMSS in terms of packet loss rate in congestion scenarios. CDMM can predict the congestion of the switching path in advance by detecting, and switch the mobile data to the non-congested path, which can effectively prevent a single switching path from failing to meet the transmission requirements of mobile data, resulting in massive packet loss.

5.3.3. *Handover delay.* Under different mobility support approaches, we measured the handover delay experienced by the consumer, and the results are shown in Figure 6. We note that handover delay of CDMM is related to the value of T_{RA}. The larger the value set by T_{RA}, the larger handover delay of CDMM. In other words, the handover delay of CDMM is related to the delay of the access router obtaining the new address of the mobile device from the NRS. When T_{RA} is set to 1 ms and 5 ms, the handover delay of CDMM is lower than other methods. When T_{RA} is set to 10 ms, CDMM's handover delay is close to the handover delay of MAP-ME and OPMSS. OPMSS and MAP-ME have similar handover delay, because in this experiment, they both achieve data redirection by propagating special packets at the same distance. Therefore, in order to ensure the handover delay, it is necessary to deploy the NRS as close as possible to the access router,

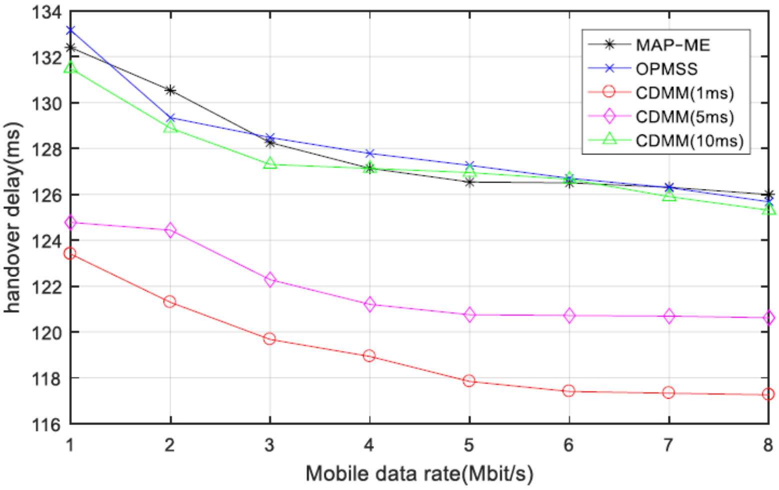
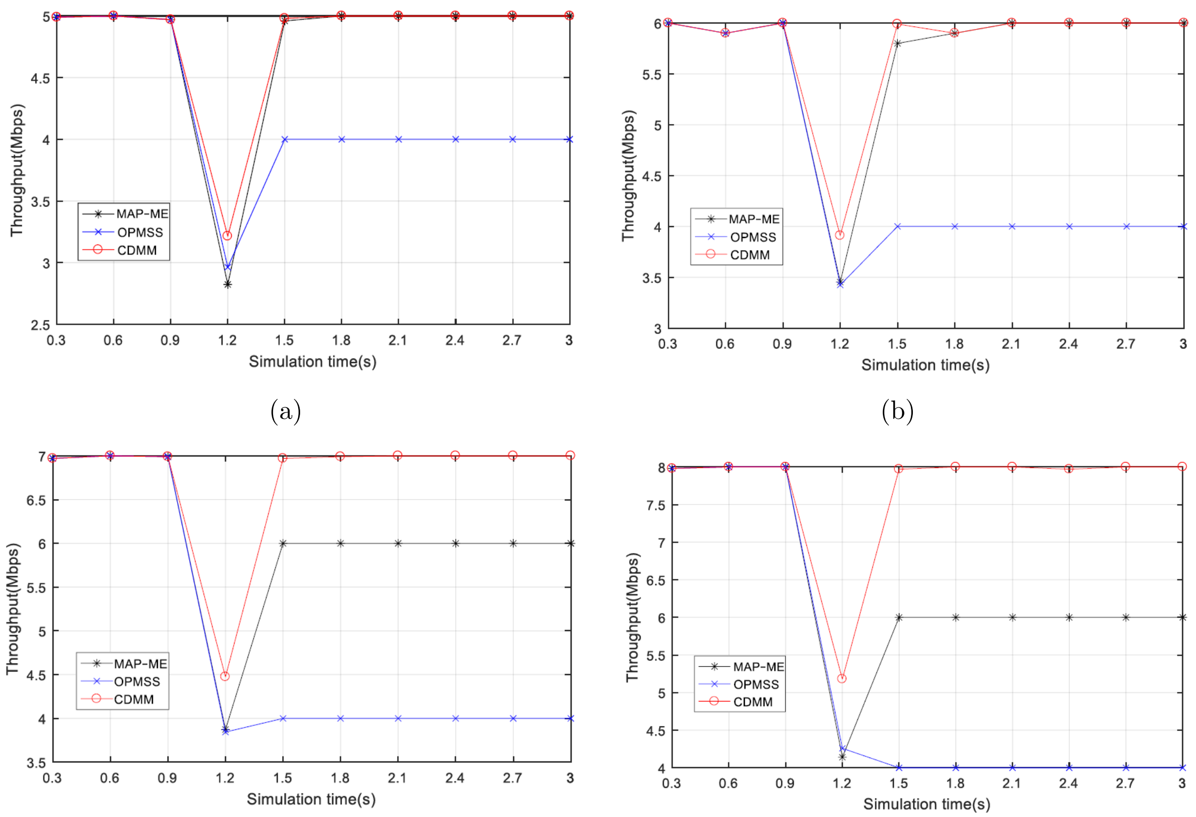


Figure 6. Comparison of handover delay between different mobility support methods

so that the access router can obtain the latest network address of the mobile device as soon as possible after sensing the mobile device's movement.

5.3.4. *Throughput.* Under different mobile methods and different mobile data rates, we calculated the average number of packets received by the consumer per unit simulation time to determine the level of successful delivery of data packets. Observing Figure 7(a) to Figure 7(d), we find that before 0.9 s, different mobile approaches have the same throughput. Because the consumer moves after one second, the throughput level of the consumer is equivalent before the mobile handover. From 0.9 s to 1.2 s, the throughput dropped significantly, mainly due to packet loss during consumer switching. From 0.9 s to 1.5 s, during the period of mobile handover, the throughput of CDMM is higher than that of MAP-ME and OPMSS. The handover delay of CDMM is lower than other methods, so the throughput of CDMM changes the least. After 1.5 seconds, when the mobile data rate is 5 Mbit/s, 6 Mbit/s, 7 Mbit/s and 8 Mbit/s, the throughput of OPMSS is maintained at 4 Mbit/s. The reason for this phenomenon is that the bandwidth of the bottleneck link of the switching path of OPMSS is 4 Mbit/s. Similarly, we can find that when the mobile data rate is 7 Mbit/s and 8 Mbit/s, the throughput of MAP-ME can only reach the bandwidth 6 Mbit/s of the bottleneck link of its switching path. Overall, we can conclude that the proposed CDMM can enable mobile data to be transmitted on handover paths that can meet their transmission needs, thereby guaranteeing the throughput of mobile users.



(a)

(b)

(c)

(d)

FIGURE 7. Comparison of throughput between different mobility support methods at different mobile data rates: (a) Mobile data rate: 5 Mbit/s, (b) mobile data rate: 6 Mbit/s, (c) mobile data rate: 7 Mbit/s, (d) mobile data rate: 8 Mbit/s

6. **Conclusions.** This paper discusses how to dynamically change the switching path according to the change of the actual network environment in ICN mobility support. First, we propose a mobility support method for dynamically changing mobile switching paths based on congestion detection. In order to sense network congestion in time and change the mobile switching path as soon as possible, we propose a late-binding node switching mechanism. Finally, we conducted a simulation experiment to evaluate the performance of our proposed method. Experimental results show that our method can enhance mobility support and has good performance in terms of average packet delay, packet loss rate, handover delay and throughput.

In future work, we should further consider how to choose the switching path. In the current solution, mobile data can only be processed by one late-binding node, so only one switching path can be used for transmission. We can think about using multiple late-binding nodes to process packets to achieve multi-path transmission and further improve mobile users' QoE.

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