Video Streaming in Content-Centric Mobile Networks: Challenges and Solutions

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***Abstract*—The massive amounts of mobile traffic generated by unprecedented demands for high-quality video content fast approach the communication capacity of current network infrastructure. Novel solutions are required, including using Content-Centric Mobile Networks (CCMN), which make use of storage, computation and bandwidth resources of the whole network to support traffic offloading and large-scale content sharing in wireless mobile networks. The unicast-based interest routing in CCMNs is known for fast content delivery with low resource consumption, but video information management and mobility of mobile nodes significantly influence the performance of video delivery. This article reviews first recent studies and discusses the research challenges for content distribution and delivery in CCMNs. The article then presents an innovative Video Streaming solution in CCMNs (VSCC), which proactively leverages a content-centric multi-region video content management method and a mobility-adaptive content-centric video delivery mechanism to improve the performance of video delivery. Simulation results demonstrate that VSCC achieves high video sharing efficiency and increased Quality of Service (QoS) levels in comparison with two state of the art approaches.**

***Index Terms*—content-centric, video streaming, caching, mobility, routing**

I. Introduction

CONTENT-Centric Mobile Networks (CCMN) [1], a state-of-the-art wireless mobile network framework spawn from Content-Centric Networking (CCN) [2], aggregates resources (i.e., computing, storage and bandwidth) from the whole wireless heterogeneous network environment to provide geographical closest content access and support large-scale and high-efficiency content sharing. As Fig. 1 illustrates, mobile users access video content in CCMNs via various smart terminals equipped with multiple network interfaces such as WiFi, WAVE and 4G/5G.

Provision of delay-sensitive video services at high QoS levels in CCMNs is one of the most important issues. The exponential growth in the demand for videos, including high-definition video, and increase in Quality of Experience (QoE) expectations trigger massive traffic demand, which results in backbone network overload. CCMNs employ *all-to-cache* and *broadcasting-based content delivery* approaches (including content lookup and data transmission) to achieve near-end content fetching, which results in huge consumption of resources, unsustainable for the mobile nodes with limited capacity and short battery life.

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In order to achieve economic content delivery, CCMNs also employ *unicast-based interest routing* (UIR) based on *region-oriented content management* (RCM). The nodes collect and maintain video information (VIM) in limited regions (e.g. lookup paths) by message exchange to quickly forward interest packets. The balance between the maintenance cost of VIM and lookup performance determines the efficiency of UIR. Increasing cache hit rate in regions by extending the scale of maintained VIM consumes massive resources, which results in mobile nodes' overload. Balancing supply and demand to improve cache hit rate in regions by demand awareness and cache scheduling reduces the scale of maintained VIM, but interest variation also results in increasing message overhead. On the other hand, the involvement of mobility severely influences both video distribution and performance of lookup and transmission. Because the nodes act as content carriers, content moves between regions with the movement of carriers. The nodes increase the frequency of message exchange to ensure validity of collected VIM. Moreover, the node mobility may lengthen the geographical distance between relay nodes in lookup and return paths, increasing both the delay of lookup and transmission and risk of packet loss. Therefore, a key issue in this paper is mitigating the negative effect of influencing factors on video sharing performance in CCMNs by using 1) a video content management region (VCMR) construction with economic content management and 2) a video delivery method accommodating node mobility.

This article discusses the challenges of deployment of video streaming services in CCMNs and introduces an innovative Video Streaming solution in CCMNs (VSCC) to reduce the effect of the negatively influencing factors. VSCC designs a novel content-centric multi-region video content management method, which achieves low-cost content management and local balance of supply and demand with low redundancy in built VCMRs. Based on optimized content distribution, VSCC proactively leverages a mobility-adaptive content-centric video delivery method to speed up the process of content routing and data transmission, ensuring low delivery delay and high user QoE.

II. Challenges of Video Streaming in CCMNs

By making use of resource scheduling based on content caching to achieve near-end content fetching, CCMNs can

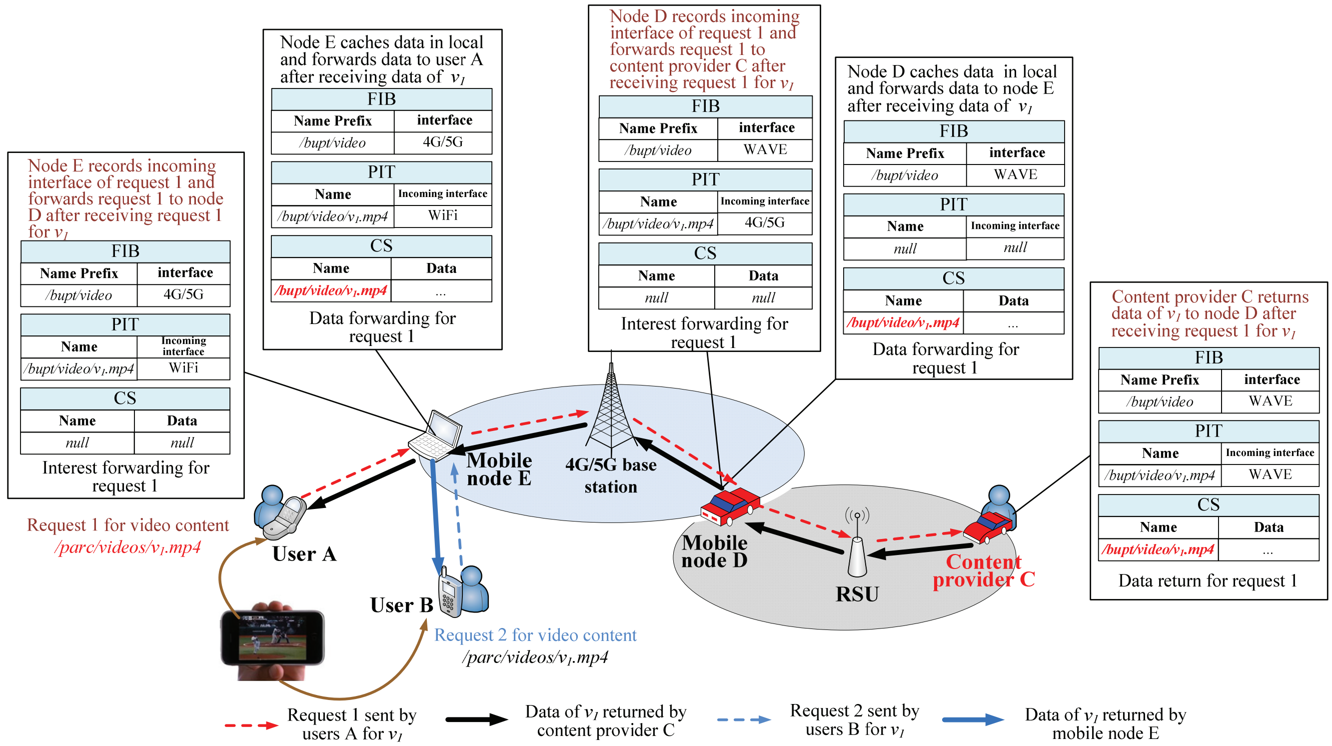

Fig. 1. Video streaming services in content-centric mobile networks

reduce lookup and transmission delay and decrease packet loss probability, which is highly beneficial for video streaming services [3]. The UIR based on RCM can achieve more efficient content delivery than all-to-cache methods and broadcasting-based content delivery, but needs to address the issue of video distribution optimization with low maintenance costs, while also keeping relatively stable node mobility in VCMR.

A. Video Distribution in CCMNs

There are many recent studies for UIR based on RCM. For instance, the random caching strategy [4][5] allows CCN nodes (CNs) to independently determine whether to cache or not the received content based on a probability function. The suggestion-based caching strategy [6] relies on suggestions from upstream nodes in the caching path to take caching decisions. In [7], by calculation of centrality of CNs along the content delivery path, the CNs with high centrality values are selected as relay nodes to get high cache hits. However, content management in small regions such as caching paths cannot ensure high cache hit rates in VCMR due to limited cached resources. In order to achieve high cache hit rates in VCMRs, some methods attempt to extend these VCMRs. For instance, the cooperative caching strategy [8] builds autonomous node groups to reduce redundancy copies and lookup delay by supervision of node states. The increase in the cost associated to collecting and updating the content information leads to node overload when extending the VCMRs. In particular, departure of intra-VCMR nodes and joining of extra-VCMR nodes caused by node mobility result in variation of video distribution in VCMRs. The frequent maintenance updates for VIM further aggravates resource consumption, which results in mobile node overload.

By making use of demand awareness and cache scheduling to optimize video distribution in VCMRs, balance between supply and demand of videos can achieve high performance of content lookup (e.g. fast discovery of providers in VCMRs) and economy (e.g. smaller scale of maintained VIM in limited area than that of extended VCMRs). However, demand awareness and cache scheduling also trigger frequent message exchanges between mobile nodes. The intra-VCMR nodes need to deal with video distribution variation caused by interest change and mobility of nodes. The continuous interest collection required by accurate estimation of interest variation results in high message overhead in order to implement on-demand caching with low redundancy.

The traditional methods of VCMR construction rely on simple partition according to geographic area (i.e. lookup path and one-hop range), which do not consider interest-related factors for definition of relationship between intra-VCMR nodes. The watched videos reflect interests of users, namely user demand for videos. Even if the interests evolve, the new interests may be similar to the original interests. For instance, if the nodes are interested in comedy series, they also like to watch comedy movies instead of drama movies. If VCMRs are composed of nodes which have high-level interest similarity for videos, similar cache and demand between nodes enable content requests to be responded fast by intra-VCMR nodes (i.e. video demand self-sufficiency in VCMR). Moreover, the similar interests not only strengthen the logical links between nodes and lengthen the update period of node state, but also ease the discovery and capture of interest variation. For instance, if two nodes are interested in NBA, they do not need to frequently exchange messages including state and VIM due to active video sharing between each other. Once a user/node wants to watch soccer World Cup, the other node quickly becomes aware of the interest variation due to the change of interaction frequency and shared content. The investigation of interest similarity in the relationship between intra-VCMR nodes can reduce content management cost and increase cache hit rate in VCMRs. A key issue is how to accurately estimate similarity of interest in videos between nodes. Additionally, node mobility is also an important influencing factor for UIR-based video delivery performance. The investigation of similarity for node mobility in the process of VCMR construction enables VCMRs have relatively stable boundaries, which reduces the frequency of update VIM due to video distribution variation caused by node mobility. Another key issue is how to accurately estimate similarity of movement behaviors between nodes.

B. Video Delivery in CCMNs

The video delivery based on UIR allows relay nodes forward interest packets to the next node based on the apriori knowledge of collected VIM [9]. Because the video providers (VPs) return the requested data along the reversed lookup paths, the length of the lookup paths is an important influencing factor. The more/less the number of relay nodes in the lookup paths, the higher/lower the delay of lookup and transmission is. If the interest packets are forwarded to the VPs having enough bandwidth and low hop count with video requesters (VRs), the delay of routing and transmission and the negative influence of node mobility for performance of video delivery are kept at low levels. A key issue is how to find the appropriate VPs in the process of interest routing.

It is difficult to search for the VPs with enough bandwidth and low hop count in CCMNs. The cross-VCMR content lookup is inevitable due to interest variation and limitation of cached content in VCMRs. The node mobility negatively influences the performance of video delivery with long lookup paths. The increase in the geographical distance between relay nodes in the lookup paths lengthens the delay of data transmission and results in high risk of data loss. This also consumes larger amounts of resources and decreases the mobile nodes' energy levels. Therefore other important aspects are energy efficiency [10] and ensuring the stability of data return paths.

III. Proposed Innovative Video Streaming Solution in CCMNs (VSCC)

Fig. 2 illustrates the proposed VSCC architectural design. It includes a novel **Content-centric Multi-region Video Content Management** method, which focuses on optimizing video content distribution and relies on two components:

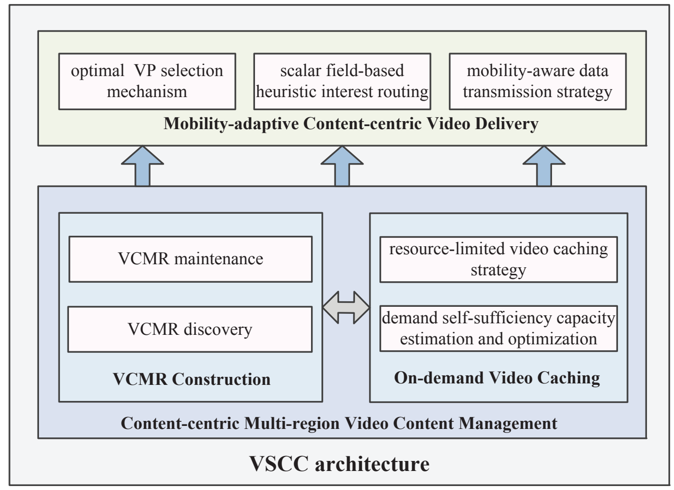

Fig. 2. VSCC architecture

• *VCMR Construction* by VCMR discovery and maintenance to achieve collection and maintenance of VIM, including video ID, VP ID and available bandwidth of VP and hop count with VP, in local and adjacent regions;

• *On-demand Video Caching* by demand self-sufficiency capacity estimation and optimization model and strategy of resource-limited video caching to adjust video distribution in terms of collected information of video caching and demand.

VSCC architecture also includes an innovative **Mobility-adaptive Content-centric Video Delivery** method, which focuses on efficiency and quality of interest routing and data transmission and relies on three components:

• *Optimal VP selection mechanism* which makes use of modeling delivery capacity and defining optimization objective in terms of collected VIM.

• *Scalar field-based heuristic interest routing strategy* which uses iteration of searching optimal relay nodes to find the optimal VP and delivery path.

• *Mobility-aware data transmission strategy* which employs the awareness of movement behaviors of relay nodes, VRs and VPs to maintain stability of reverse path.

IV. Content-centric Multi-region Video Content Management

A. VCMR Construction

In order to achieve low-cost maintenance of VIM in regions with appropriate scale, we construct the VCMRs composed of nodes with similar interests and mobility by common interest capture and similarity estimation of movement behaviors.

1) Common Interest Capture between Nodes: The common interests enable nodes store similar videos to meet the demand with each other. We estimate interest similarity between nodes by investigating similarity of historical traces of video playback.

Let the two historical playback traces $tr_i = (v_a, v_b, ..., v_m)$ and $tr_j = (v_c, v_d, ..., v_n)$ be video vectors of two nodes n_i and n_j, where number of items in tr_i and tr_j is NT_i

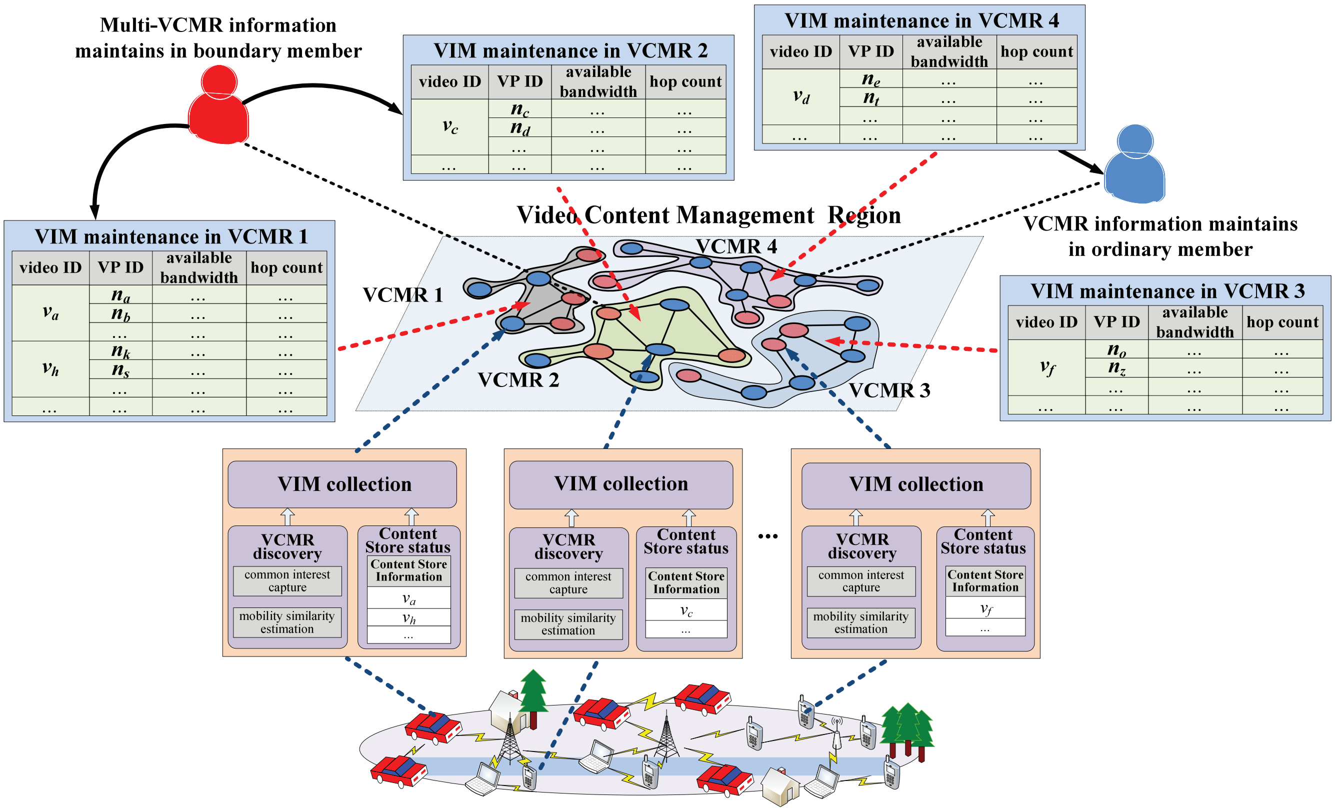

Fig. 3. An illustration of video content management region construction

and NT_j, respectively. Because the video is described by multiple attributes such as name, authors, actors, abstract, etc., the content similarity is calculated by employing the Euclidean distance. The matching results among items in vectors corresponding to any two nodes form a $NT_i \times NT_j$ similarity matrix which is defined as: $\begin{bmatrix} S_{ac} & \cdots & S_{mc} \\ \vdots & \ddots & \vdots \\ S_{an} & \cdots & S_{mn} \end{bmatrix}$. We can obtain a NT_i-dimensional similarity vector $\left(\sum_{e=c}^{n} S_{ae}/NT_j, \sum_{e=c}^{n} S_{be}/NT_j, \ldots, \sum_{e=c}^{n} S_{me}/NT_j \right)$ where $\sum_{e=c}^{n} S_{ae}$ denotes the sum of the Euclidean distance for the items in first column. The Euclidean norm of similarity vector can be obtained according eq. (1).

$$S\left(n_i, n_j\right) = \left(\sum_{k=a}^{m} \left(\sum_{l=c}^{n} S_{kl}/NT_j \right)^2 \right)^{1/2} \tag{1}$$

We use $S\left(n_i, n_j\right)$ to represent the interest similarity level between n_i and n_j. In fact, VCMR is also considered as a set of VPs and nodes interested in videos.

2) Similarity Estimation of Movement Behaviors between Nodes: As VCMRs have distinct geographical boundary, the high similarity of movement traces between nodes ensure VCMR stability. We employ the method for calculation of the similarity of movement behaviors for VPs and nodes interested in videos in wireless heterogeneous networks proposed in our previous work [3]. The common interests and similar mobility between nodes can support the local offloading of video traffic.

The product between similarity levels of interest and movement behaviors denotes *relationship levels* between nodes. We propose a **VCMR discovery** method by making use of the relationship levels. Initially, each node n_i forms a VCMR $R_i = (n_i)$ and estimates relationship levels with one-hop neighbor nodes by exchange of historical traces of playback and movement. If the relationship level between n_i and a neighbor node n_j is highest among all one-hop neighbors of n_i and n_j, n_i and n_j form a new VCMR $R_i = (n_i, n_j)$. n_i and n_j continue to search new VCMR members from their one-hop neighbor nodes. If the relationship level between a node n_k and any member (n_i or n_j) in R_i is higher than the relationship level between n_k and one-hop neighbor nodes, then n_k joins into R_i. Similarly, if a node n_h is a member in R_h and the relationship level between n_h and any member in R_i is higher than the relationship level between n_h and other members in R_h, then n_h leaves R_h and joins R_i. By repeating this process, the nodes in CCMNs are grouped into numerous VCMRs with different sizes. When the number of members in VCMRs is 1, the number of one-hop neighbor nodes of members in VCMRs determines calculation load of VCMR discovery, otherwise the number of intra-VCMR members determines calculation load of VCMR discovery. Therefore, the complexity of VCMR discovery algorithm is $O(n)$.

Obviously, any VCMR is a dynamic node group, namely the members in a VCMR can leave and join another VCMR at any time according to relationship levels. We further propose a **VCMR maintenance** mechanism. The nodes in VCMRs are divided into two categories: *ordinary* and *boundary* members. If a node n_i and the one-hop neighbor nodes of n_i belong to the same VCMR, n_i is considered as an *ordinary* member. The *ordinary* members are responsible for maintaining VIM in current VCMR by performing periodical message exchange with their one-hop neighbor nodes. If the one-hop neighbor nodes of a node n_j include the members belonging to other VCMRs, n_j is considered as a *boundary* member. Because *boundary* members can obtain extra-VCMR VIM by performing periodical message exchange with the one-hop neighbor nodes, they not only maintain intra-VCMR VIM, but also collect and disseminate extra-VCMR VIM. If the video demand is not met by intra-VCMR members, the interest packets are forwarded to other VCMRs with the help of the *boundary* members. If the relationship levels between members in a VCMR keep decreasing trend, these members continually leave current VCMR and join other VCMRs, namely the VCMR is removed in CCMNs.

As Fig. 3 shows, the nodes are grouped into four VCMRs and maintain their own VCMRs, respectively. The boundary members (red nodes) can be aware of VIM in adjacent VCMRs and spread the adjacent VCMR IDs to enable ordinary members (blue nodes) to know the interfaces with other VCMRs. The interaction between boundary members promotes dissemination of VIM between adjacent VCMRs. In order to reduce the redundancy copies, the node mobility can be considered as the intermediary of VIM exchange among VCMRs. The mobile nodes act as the carriers to exchange VIM between remote VCMRs, which enables video diversity and reduce redundancy copies in VCMRs.

B. On-demand Video Caching

The variation of video user demand is one of the main reasons for the imbalance between supply and demand and the replacement of cached content. The content caching based on demand awareness can promote cache hit rate in VCMRs and avoid frequent cache replacement. The playback traces of nodes describe demand range. The union set of demand range of all members in VCMRs is considered as demand range of VCMRs. The event - the request of members falling into the demand range of current VCMR - is considered as a hit. We use the ratio between hit number and total request number to **estimate demand self-sufficiency level** in VCMR. If a VCMR has high hit ratio, it has strong self-sufficiency capacity and the members only need to cache the requested video outside the demand range. Overwise, a low hit ratio denotes that there is severe variation of video demand. Therefore the members need to implement extensive video caching: the on-path videos with high similarity levels with the videos requested by the VCMR members should be cached.

In order to ensure provision of enough bandwidth for the requested videos, we construct a **Resource-limited Video Caching Optimization Model**. Each cached video v_i in a VCMR has a waiting queue q_i. When the providers of v_i receive an interest packet and cannot provide video data due to the limited bandwidth, the new request nodes enter into q_i. We assume that the enqueue process of interest packets follows the Poisson distribution at the side of the providers of v_i. Due to fluctuations in the serving capacity and in network environment, there are random and dynamic variations of serving time of the providers, and therefore we also assume that the dequeue process has a random distribution. Consequently the waiting queue q_i for each item of content meets the M/G/1 queuing model. We formulate the following programming problem: how to distribute the limited storage capacity of the mobile nodes to minimize the length of queue corresponding to all cached videos in VCMRs. The uniform decrease of the length of all queues is defined as the optimization objective. We further propose a **video caching strategy**, which enables the difference in the length of the queues to be minimum. If the queue q_i has the largest length among all queues, the on-path nodes on the v_i delivery path preferentially cache v_i. The number of cached v_i is defined as the lower bound of $L_i - \overline{L}$ where L_i denotes the length of q_i and $\overline{L}$ is the average value of length of all queues. We reselect a new queue which has maximum length among all queues and distribute the available caching space according to the above definition. By iteratively repeating the above process, the number of redundant copies in VCMRs is kept low. The low-redundancy copies greatly save the storage space of mobile nodes to cache sought-after videos in terms of the demand. The number of requested videos in VCMRs determines the calculation load of the resource-limited video caching optimization, so the complexity of caching optimization algorithm is $O(n)$.

V. Mobility-adaptive Content-centric Video Delivery

The video delivery determines the QoE level of users such as startup delay and playback continuity. RUFS in [9] relies on dissemination of recent success routing information between mobile nodes to fast locate suppliers by periodical sharing info with one-hop neighbors. However, the mobile nodes maintain with difficultly large-scale routing information due to their limited capacity, so that the success rate of interest routing is relatively low. Moreover, neglecting the mobility of relay nodes in the reverse path increases the transmission delay and consumes large number of energy of mobile nodes.

In order to reduce the delay of video lookup and transmission, the interest packets should be forwarded to VPs which have enough bandwidth and near geographic distance with VRs. As all members in a VCMR are aware of the intra-VCMR VIM, VRs and relay nodes **select optimal VP according to the following optimization problem:**

$$\begin{aligned} &\underset{n_p \in VCMR}{\text{minimum}} \;\; f_{n_x}(n_p) = (1-\alpha)\frac{C_R}{C_{n_p}} + \alpha\frac{D_{xp}}{D_{TTL}-1} \\ &\text{subject to} \;\; C_{n_p} \geq \max\{\sum_{k=1}^{h} s_k/t, C_R\} \\ &\qquad\qquad 0 \leq D_{xp} \leq D_{TTL}\text{-}1 \end{aligned} \tag{2}$$

where n_p and n_x are a VP and a relay node, respectively; C_{n_p} is available bandwidth of n_p and C_R is the bandwidth required by the video playback rate of n_x; D_{xp} is the hop count between n_x and n_p; s_k and D_{TTL} denote the size of data packet and the time-to-live (TTL) of interest packet, respectively. If the mobile users need h data packets to complete the startup, $C_{n_p} \geq \max\{\sum_{k=1}^{h} s_k/t, C_R\}$ represents that the available bandwidth of n_p is greater than the bandwidth needed by smooth playback. $\sum_{k=1}^{h} s_k/t$ denotes the bandwidth required by the delivery time of h data packets in order for the acceptable startup delay of n_x; C_R is the bandwidth required by the video playback rate. This is because the users leave video system with high probability once they are subjected to the longer startup delay. $0 \leq D_{xp} \leq D_{TTL}$-1 denotes the range of hop count between n_x and n_p. $\alpha \in (0, 1)$ is a weight value in order to regulate the influence levels of bandwidth and hop count.

The interest routing in CCMNs is considered as a dynamic multi-objective-oriented optimal VP search process. Therefore, we propose a **scalar field-based heuristic interest routing method** in order to fast find optimal VP in VCMR by the selection of appropriate next-hop relay node. As Fig. 4(a) shows, if a request node n_i wants to fetch video data d_j from VPs $n_a, n_b, ..., n_q$ in current VCMR, n_i sends the requested video ID to all one-hop neighbor nodes $n_c, n_d, ..., n_y$. At the same time, n_i calculates the own values of objective function $f_{n_i}(n_a), f_{n_i}(n_b), ..., f_{n_i}(n_q)$ according to collected VPs' available bandwidth and hop count between VPs and n_i. n_i continues to select an optimal solution $f(n_i, p^*) = \min[f_{n_i}(n_a), f_{n_i}(n_b), ..., f_{n_i}(n_q)]$ and can be considered as a point in scalar field. After the neighbor nodes receive the video ID, they also are mapped to the point in scalar field by the selection of optimal solutions among the objective function values. Based on the field theory, n_i selects an optimal node n_j as the next-hop relay node according to the following equation.

$$\begin{aligned} \text{argmax}\, \{&[f(n_i, p^*) - f(n_c, p^*)], [f(n_i, p^*) - f(n_d, p^*)], \\ &\ldots, [f(n_i, p^*) - f(n_y, p^*)]\} \end{aligned} \tag{3}$$

As Fig. 4(b) shows, n_j adds n_i's ID and the own ID into the received interest packet and still continues to select the optimal next-hop relay node n_e from the own neighbor nodes in terms of the above method. n_e stores the ID of n_i, adds the own ID to the interest packet and continues to search for the optimal VP. When n_e finds that there is the optimal VP n_q in the one-hop neighbor nodes in terms of the node ID corresponding to calculated optimal solution, n_e directly forwards the interest packet to n_q. In fact, the decrement for the optimal values to the routing path from n_i to n_q is largest among all available routing paths. The discoverable VP has the smallest hop count to n_i and sufficient available bandwidth to support fast data transmission. Even if the geographical location of the optimal VP changes, the interest packets are continually forwarded along the decreasing direction of the optimal values of the objective function. The number of one-hop neighbor nodes of VRs and relay nodes in the lookup paths determines the calculation load of the scalar field-based heuristic interest routing method, so the complexity of the interest routing algorithm is $O(n)$.

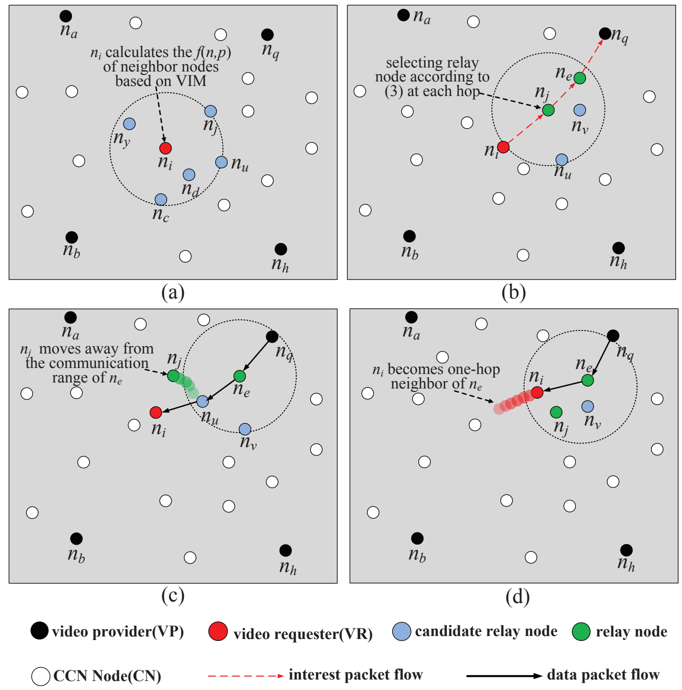

Fig. 4. Mobility-adaptive content-centric video delivery process in VSCC

After n_q receives the interest packets, it returns the requested video data to n_i. In view of the influence of the mobility on the performance of data transmission using the original routing path, the stability of routing (reverse) path determines the transmission delay of video data. In order to address this, we design a **mobility-aware data transmission strategy based on the reverse path maintenance**. Because the ID of relay nodes is added to the interest packets, all relay nodes know the information of routing path from VRs to their next-hop nodes. For instance, n_j and n_e store the information of sub-path $n_i \rightarrow n_j \rightarrow n_e$ and $n_j \rightarrow n_e \rightarrow n_q$, respectively. The relay nodes focus on the maintenance of the routing path by message exchange to fetch the movement behaviors of all one-hop neighbor nodes.

n_j requires one-hop neighbor nodes detect the hop count to n_i and n_e and extracts the candidate nodes which has the one-hop distance to both n_i and n_e. As Fig. 4(c) shows, once the distance(hop count) between n_j and n_i is greater than 1, n_j randomly selects a replacement node n_u from the candidate nodes and informs n_u the routing information including the ID of n_i and n_e. At the moment, n_j also sends the ID of n_u to n_i and n_e, which keeps the connectivity of reverse path. Similarly, once n_e finds the distance between n_e and n_j is greater than 1, it disseminates the routing information to the selected replacement node n_v and enables n_j and n_q know the ID of n_v by sending the messages. On the other hand, if the relay nodes find the distance to the previous-hop nodes in the routing path decrease, they update the path information

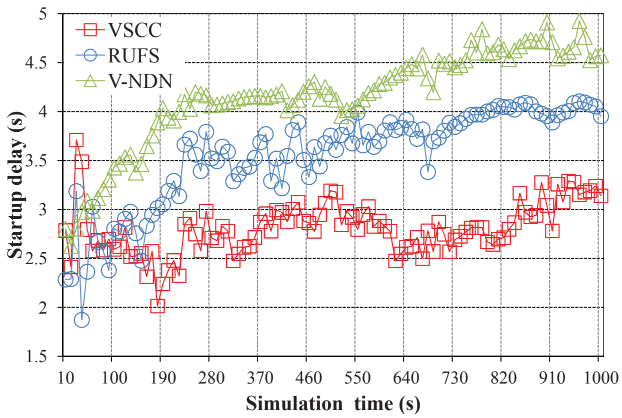

Fig. 5. Startup delay variation with the simulation time

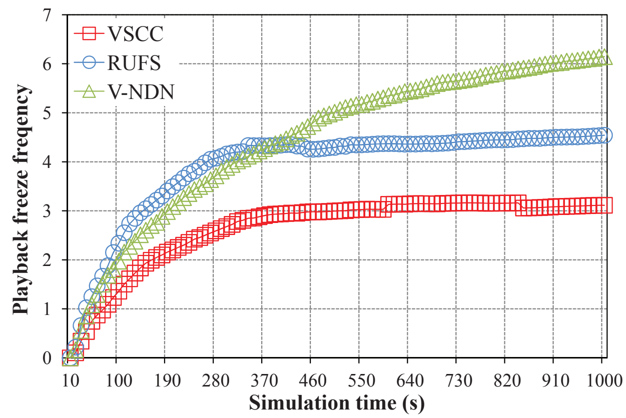

Fig. 6. Playback freeze frequency variation with the simulation time

and disseminate to the related relay nodes. For instance, as Fig. 4(d) shows, n_e finds n_i as its one-hop neighbor node, namely the distance to n_i changes from 2 to 1, n_e re-extracts the candidate nodes in terms of the distance to n_i and n_q and informs n_j quit the path. This reduces consumption of network bandwidth and improves performance of data transmission.

If the requested videos are outside the local VCMR, the interest packets are directly forwarded to the boundary nodes which know the VPs caching the requested videos in other external VCMRs. The boundary nodes help VRs to forward the interest packets in terms of the above routing method.

VI. Performance Evaluation

In order to evaluate the proposed VSCC solution, we compare the performance of VSCC with two state-of-the-art solutions RUFS [9] and V-NDN [11] in terms of startup delay and playback freeze frequency during 1000 s simulation time by using the NS-3 network simulator. The three solutions were deployed in a wireless mobile network environment which includes 200 CNs deployed in a 2000×2000 m^2 square area, which exchange messages with each other via an IEEE 802.11p WAVE interface. The movement behaviors of mobile nodes follow the Manhattan mobility model [12]. The mobile nodes join the video system in terms of a Poisson distribution. The video server stores 60 video files where the length of each file is 100 s. The playback behaviors of mobile nodes follow the created synthetic user viewing log entries based on the statistics from [13].

Fig. 5 compares the startup delay, which is defined as the time span between the time when the VR sends first interest packet and the time when the VR receives enough data packets to complete startup process. VSCC results keep lower levels than those of RUFS and V-NDN during the whole simulation time. Fig. 6 compares the playback freeze frequency, where playback freeze frequency is defined as the occurrence times of playback freeze per second during the whole simulation time. The lower the playback freeze frequency is, the smoother the playback process experienced by users is. The red curve corresponding to VSCC results is lower than those of RUFS and V-NDN, demonstrating improved behaviour of VSCC in this regard.

As mentioned, VSCC makes use of an on-demand caching method to balance supply and demand for video content in terms of collected VIM and similar node mobility in VCMR, which increases the probability of near-end access to the desired videos. Additionally, VSCC fast searches for the optimal VP with low hop count to VRs and enough bandwidth by using the scalar field-based heuristic interest routing method, and makes use of the stable reverse paths to immediately return video data by employing the mobility-aware data transmission strategy. The low hop count between VRs and VPs and the stable reverse paths not only reduces the delay of lookup and transmission, but also decreases the probability of data loss, avoiding high startup delays and reducing the playback freeze frequency caused by re-seeking lost data. Therefore, VSCC has low startup delay and low playback freeze frequency. RUFS employs the on-path content caching method to achieve the local resource balance between supply and demand, and makes use of UIR to search VP by exchange of recent successful routing information with one-hop neighbors. However, the on-path content caching method only achieves video distribution optimization in small range, which cannot ensure near-end resource access with high probability. Moreover, the mobility of mobile nodes results in the change of collected routing information by opportunistic exchange with encountered nodes, which greatly reduces video lookup hit rate and increases startup delay and playback freeze frequency. V-NDN employs the traditional all-to-cache method to regulate the video content distribution in order to reduce the geographic distance between VRs and VPs. The mobile nodes difficultly bear the cost of consuming huge resources of storage and bandwidth for the near-end video fetching. Moreover, V-NDN makes use of the broadcasting-based interest routing method to search videos, which wastes network bandwidth. The triggered network congestion also greatly increases startup delay and playback freeze frequency.

VII. Conclusion

This article discusses research challenges for content caching and routing and analyzes the main influence factors for the performance of video sharing in CCMNs. Then the article proposes an innovative Video Streaming solution in CCMNs (VSCC). Testing results show how, by implementing a content-centric multi-region video content management method and a mobility-adaptive content-centric video delivery strategy, VSCC obtains better performance than two alternative state-of-the-art proposals for future high QoE-oriented video streaming solutions in CCMNs. Future work will consider other factors (e.g. energy-efficiency [10] and video frame priority [14]) to further enhance the performance of VSCC.

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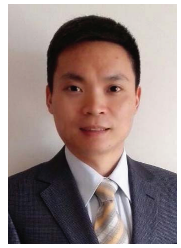

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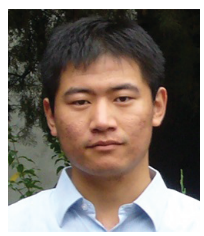

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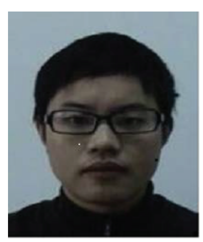

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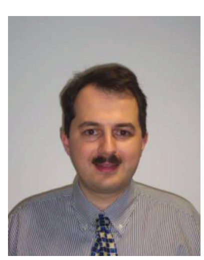

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