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QoE-Aware Video Multicast Mechanism in Fiber-Wireless Access Networks

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ABSTRACT In this paper, a video multicast mechanism is studied in fiber-wireless (FiWi) access networks with object to guarantee the quality of experience (QoE) for different users. Firstly, according to the characteristics of scalable video coding, a new QoE evaluation model is built in terms of the video interruption probability, video bitrate and smoothness. Then the optimal transmission path is studied based on the coverage and transmission capabilities of ONU-BS nodes. Specifically, a bipartite graph is constructed based on which the multicast tree is obtained by solving the minimum dominating set problem. Thereafter, a video bitrate adjustment algorithm is proposed to reduce the video interruption probability based on the buffer state on the user side and meet the bitrate requirements for different users during multicast transmissions. Simulation results verify that the proposed scheme performs well in QoE guarantees for different users simultaneously.

INDEX TERMS Fiber-wireless access networks, scalable video coding, quality of experience, multicast adaptation.

I. INTRODUCTION

With the technology enhancements in wireless communications and Internet of Things, there are more and more types of data services emerging and affecting our life [1]–[3]. In particular, video services such as video on demand, live streaming, security monitoring and so on have become more and more indispensable, and will account for higher and higher ratio of total bandwidth resources in future networks [4]. As a result, there will be higher requirements for the next-generation wireless access networks to guarantee low latency, high peak rate and wide network coverage [5]. Fiber-wireless (FiWi) access networks combine the advantage of fiber communications in high capacity and low power, and that of wireless communications in mobility and flexibility. Hence, FiWi access networks is able to provide users better quality of experience (QoE) with lower costs. As a result, FiWi has been considered as one of the most promising technologies in the next generation communication networks.

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The FiWi network architecture is shown in Figure 1, which comprises of the optical network part and wireless mesh network part. The optical network part is a point-to-multipoint tree structure consisting of an optical line terminal (OLT) and multiple optical network units (ONUs). In the downlink direction, the OLT transmits data to the ONUs by means of broadcast communications. Each ONU receives all the data packets and only decodes the one matching its network identification. The wireless mesh network part contains several routers and gateway nodes that combine the functions of ONU and base station together and is consequently usually called as ONU-BS. Due to the flexible structure of wireless mesh networks, when multiple terminals access the network simultaneously, they can access through different nodes without causing link congestion.

Usually, a number of users request the same highly popular video at the same time. While facing such group demand, traditional unicast method repeatedly sends the same content to different users, which results in a great waste of network resources. Differently, FiWi networks have ability in downlink broadcast and transmission diversity.

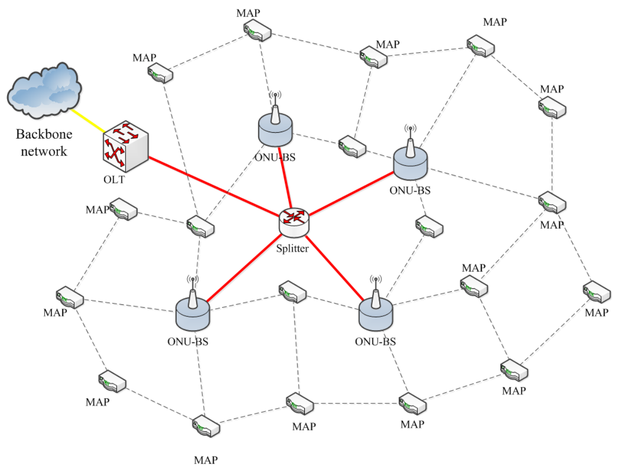

FIGURE 1. Fiber-wireless access network architecture.

Hence, the same content can be transmitted to a group of receivers through multicasting in FiWi networks, which saves network resources and reduces link congestions [7]. Due to the difference of communication conditions among the multicast users, it is difficult to guarantee the requirements of all the users with a fixed video code rate. Therefore, scalable video coding technology (SVC) is widely used in video multicast transmissions to adapt to the heterogeneous requirements of multiple users and time-varying network environments [8]. SVC coding technology encodes video contents into a basic layer (BL) and at least one enhancement layers (ELs) [9]. The basic layer provides minimum video bitrate required to demonstrate the video in lowest quality. The data of the enhancement layer depends on the data of the lower layers. It can only be decoded as long as the data of lower layers are correctly decoded. In addition, users can select different quality layers. The more quality layers are obtained, the higher video quality can be guaranteed. Hence, it is significant to study how to guarantee the video requirements of each user in a FiWi network architecture.

A. RELATED WORKS

In the literature, related studies usually focus on video transmissions in FiWi networks or other networks. In [10], a PON architecture was constructed to enable ONUs to communication with each other directly. Under such architecture, the delay of video-on-demand service was minimized. In [11], a green routing strategy was proposed to reduce energy consumption in FiWi networks with considerations of different quality of service (QoS) requirements and sharing characteristics of FiWi networks. In [12], an energy-efficient multicast scheduling scheme was proposed to maximized the network throughput, including online admission control, basic layer data scheduling and enhancement layer data scheduling. In [13], the authors evaluate the video transmission performance in terms of the worst play delay and proposed a batch processing broadcast mechanism for non-hotspot users while ensuring the demand of hotspot users. In [14], a linear prediction algorithm was proposed to achieve the current network conditions, based on which a QoS-aware video transmission mechanism was further studied. In [15], a QoE-based link adaptation scheme was proposed where retransmissions, modulation and coding strategies were taken into account. In [16], a QoE evaluation model was constructed, based on which a video birate selection scheme was proposed in terms of buffer state. In [17], the authors proposed two multicast schemes to degrade the interruption probability in terms of the characteristics of scalable video: One was based on opportunistic listening and the other was based on resolution modulation. In [18], the scalable video stream was redesign to realize intelligent video transmissions based on effective bandwidth theory in a SDN framework.

Although great efforts have been devoted by the aforementioned works [10]–[18], there are still some potential enhancements in video transmissions in FiWi networks. In specific, works [10]–[14] only focused on the QoS of multicast transmissions while the subjective user experience was not taken into account. Besides, in works [15]–[18], the proposed schemes just focused on the subjective user experience for only one user while heterogeneous requests of different users were omitted.

Motivated by this, we propose a QoE-aware video multicast mechanism to guarantee the heterogeneous requirements in video quality for different users in a FiWi network. Specifically, a QoE evaluation model for SVC video stream services is proposed. A bipartite graph is then constructed in terms of the communication latency from each user to each ONU-BS node. Based on the bipartite graph, the optimal transmission path is obtained by solving the minimum dominating set problem according to the coverage and transmission capabilities of ONU-BS nodes. Thereafter, an algorithm is proposed to select appropriate video bitrate for each user based on the buffer state on user side and the link condition during multicast transmissions. The effectiveness of the proposed mechanism is finally verified by simulation experiments.

The remainder is organized as follows. The QoE evaluation model and the construction of the multicast tree are presented in Section II and Section III respectively. In Section IV the policies for video bitrate selection and multicast adaptation are presented. Simulation results are shown and discussed in Section V. Finally, Section VI concludes this paper.

II. QOE EVALUATION MODEL

QoE characterizes the users' subjective feelings about the quality of the data service, such as the user acceptance of a given multimedia service [19]. Related studies have shown that the frequency and time of re-buffer both have great impacts on the QoE if video content and video length are not taken into account [20]. Additionally, the bitrate switching also brings a QoE deterioration for uses when videos are being played. Therefore, a reasonable QoE evaluation model should be able to interpret how video interruption probability, video bitrate, and video smoothness jointly affect user experience.

A. INTERRUPTION PROBABILITY

The video interruption probability means the ratio of the interruption time to the total playback time, which is used to evaluate the impact of video interruption on the QoE of a video [21]. The SVC video stream can be divided into several groups of pictures (GOP), which is called as video segments in this paper. The number of video segments is fixed as K. Each video segment has a duration of τ and contains a total of F frames. Besides, we use N_k to denote the number of quality layer of the kth video segment and r_n denote the bitrate of the nth layer. Hence the bitrate of each frame holds as

$$R_f^k = \sum_{n=1}^{N_k} r_n \tag{1}$$

The scalability of SVC enables the number of quality layers to be dynamically adjusted for different video segments. Thus, the video segments stored in the buffer can be configured with different bitrates. As a video segment can only be stored in the buffer when it is completely received by a terminal, let B_k denote the amount of data in the buffer when the kth segment is downloaded, there holds

$$B_k = \max\{B_{k-1} - P_k, 0\} + E_k \tag{2}$$

where E_k denotes the data amount of the kth video segment, and P_k denotes the amount of data that has been played before the kth video segment is downloaded. Moreover, E_k and P_k are given as follows:

$$E_k = \frac{\tau}{F} \cdot \sum_{f=1}^{F} R_f^k \tag{3}$$

$$P_k = \frac{\frac{\tau}{F} \cdot \sum_{f=1}^{F} R_f^k}{F' C_k} \times \sum_{f=1}^{F'} R_f \tag{4}$$

where C_k denotes the average throughput when downloading the kth video segment, F' denotes the total number of frames which have been played when the kth video segment is downloaded.

When the amount of remaining data in the buffer cannot satisfy the normal playback requirement in the next moment, i.e., $P_k > B_{k-1}$, the video interruption happens due to the buffer underflow. It is easily proved that the interruption time is related to segment downloading latency and the playable time of the remaining data in the buffer. Let T_B^k denotes the interruption time while downloading the kth video segment, there holds

$$T_B^k = \max\left\{\frac{E_k}{C_k} - \frac{B_{k-1}}{\frac{1}{F'}\sum_{f=1}^{F'} R_f^{k'}}, 0\right\} \tag{5}$$

The cumulative interruption time of the current moment can be expressed as:

$$T_B = \sum_{i=1}^{k} T_B^i \tag{6}$$

Consequently, the video interruption probability holds as

$$Q_{Buff} = \frac{T_B}{T_k + T_B} \tag{7}$$

where $T_k = k \cdot \tau$ denotes the total time length for which the video has been played.

B. VIDEO BITRATE

Video bitrate is closely related to the user viewing experience [22]. Specifically, higher video bitrate usually brings better QoE to the users. In this paper, we resort the average video bitrate to model the QoE, i.e.,

$$Q_{qua} = \frac{1}{k \cdot F}\left(\sum_{i=1}^{k}\sum_{f=1}^{F} R_f^i\right) \tag{8}$$

C. SMOOTHNESS

Video smoothness is another key factor to guarantee the video QoE. When channel condition is poor and video interruption happens, the video has to be switched from high quality layer to low quality layer, and vice versa. Such quality layer switching brings fluctuation to the video bitrate. According to [23], high frequent bitrate switching degrades the video smoothness, which further leads to a low QoE for users. In this paper, the impact of quality layer switching on the QoE is modeled in terms of switching magnitude and switching times, i.e.,

$$Q_{sw} = A_k \cdot e^{|N_k - N_{k-1}|} \tag{9}$$

where A_k denotes the total switching times of video segments that have been played before, and N_k indicates the number of quality layers of the current video segment.

Jointly taking into account the video interruption probability, video bitrate and video smoothness, the comprehensive QoE evaluation model is constructed as follows:

$$\begin{aligned} QoE &= \omega Q_{qua} - 100\lambda Q_{Buff} - \eta Q_{sw} \\ &= \omega \frac{1}{k \cdot F}\left(\sum_{i=1}^{k}\sum_{f=1}^{F} R_f^i\right) - \lambda \frac{T_B}{T_k + T_B} - \eta A_k e^{|N_k - N_{k-1}|} \\ & \quad s.t.\ 1 \le N_k \le N \\ & \qquad \omega + \lambda + \eta = 1 \end{aligned} \tag{10}$$

where ω, λ, η are positive weight parameters corresponding to the effects of video bitrate, interruption probability and smoothness on QoE, respectively.

III. MULTICAST PATH SELECTION

Multicast technology has advantage in saving resources while serving group users, such as transmitting traffic of video live broadcast and that of video meeting [24]. Different from the existing works which constructed multicast tree in terms of shortest path or minimum cost, in this paper, we also consider the coverage and transmission capabilities of ONU-BS nodes.

In traditional FiWi networks, different users with the same video service requirement may be served by different ONU-BSs as long as these BSs meet the QoE requirements. Such mechanism leads to low network resource utilization since multiple ONU-BSs may work for the identical task [25]. Hence, we aim to select as few ONU-BSs as possible to guarantee the QoE requirements of all the users with consideration of user distribution and traffic load of each ONU-BS.

In order to guarantee the delay performance for all the users, each user from the multicast group first broadcasts a registration message to all the ONU-BSs. Such message includes the field "s-time" recording the broadcasting moment. Hence, the ONU-BS can obtain the path delay of registration message through subtracting the value of "s-time" from the reception time. If the delay is within a given threshold D, the ONU-BS can be selected as an alternate node, which denoted by set $S=\{s_1, s_2, s_3 \cdots s_J\}$. Besides, the users of the multicast group is denoted by set $V = \{v_1, v_2, v_3 \cdots v_I\}$. A bipartite graph is then constructed as $G = (S, E, V)$, where V depends S. And E denotes the set of edges connecting ONU-BSs to the users. Specifically, the elements in E holds as

$$e_{ij} = \begin{cases} 1, & if\ Ls_j(t) + Lv_i(t) \le L_j^{\max}(t) \\ 0, & if\ Ls_j(t) + Lv_i(t) > L_j^{\max}(t) \end{cases} \tag{11}$$

where $e_{i,j}$ denotes the link between user v_i and node s_j, $L_j(t)$ denotes the load of s_j at time t, $Lv_i(t)$ denotes the data amount of the video segment requested by v_i, and $L_j^{\max}(t)$ denotes the maximum load of the s_j. Eq. (11) indicates that if the load of s_j is not greater than its maximum load, there is an available path between v_i and s_j, otherwise edge e_{ij} is deleted from the set E.

Due to large difference in transmission capacity between optical network and wireless network, the data is more possibly backlogged on ONU-BS side, which may increase the traffic load for the ONU-BSs. Hence, we apply queue length to measure the traffic load of each ONU-BS. The total queue length of s_j is denoted by Q_j. The time-varying maximum load of s_j can be expressed as

$$L_j^{\max}(t) = \alpha(t)Q_j \tag{12}$$

where $\alpha(t) \in (1/2, 1)$ is modeled to ensure the maximum load is always not greater than the queue length, there holds

$$\alpha(t) = \frac{1}{1 + \exp\left(-\dfrac{BW_j(t)}{PL_j(t)}\right)}, \quad \alpha \in \left(\frac{1}{2}, 1\right). \tag{13}$$

where $PL_j(t)$ represents the average packet loss probability of s_j up to time t, and $BW_j(t)$ denotes the remaining bandwidth of s_j at time t, there holds

$$BW_j(t) = M_j \cdot (1 - \mu_j(t)). \tag{14}$$

where M_j denotes maximum available bandwidth and μ_j represents the average bandwidth utilization.

Therefore, the maximum load of s_j can be expressed as:

$$L_j^{\max}(t) = \frac{Q_j}{1 + \exp\left(\dfrac{BW_j(t)}{PL_j(t)}\right)} \tag{15}$$

Thereafter, all the nodes are checked according to Eq.(11) and Eq.(15), a node is removed from set S if it has no user connections. And then the ONU-BS set and edge set can be updated to $S' = \{s'_1, s'_2, s'_3 \cdots s'_{J'}\}$ and E' respectively. Finally, the new bipartite graph $G = (S', E', V)$ can be obtained, as shown in Figure 2.

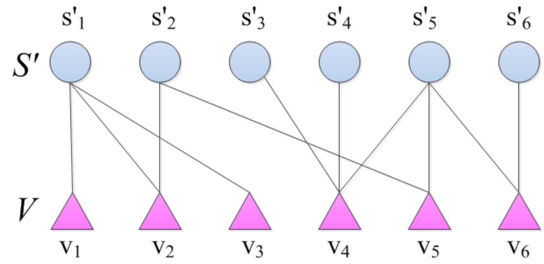

FIGURE 2. Bipartite graph.

For the purpose of selecting as few ONU-BSs as possible to serve all the multicast group users, we use the minimum dominance set to construct a multicast tree based on the obtained bipartite graph, i.e.,

$$\psi = \prod_{j'=1}\left(s'_{j'} + \sum_{v_i \in es'_{j'}} v_i\right). \tag{16}$$

where $es'_{j'}$ represents the set of users that are connected to node $s'_{j'}$. Based on the graph theory, a number of dominating sets can be obtained from (16). In order to minimize the number of branches, the minimum dominating set is selected from the obtained dominating sets, denoted by $\{s'_1, s'_2 \cdots s'_m\}$. Here, m denotes the minimum number of ONU-BSs to sustain the requirements of all the users.

If there exists multiple minimum dominating sets, the ONU-BSs can be selected according to their transmission capability which is related to the processing capability of the device, the current load situation, and the transmission distance. In detail, the transmission capability of node $s_{j'}$ can be modeled as

$$H_{j'}^i(t) = L_{j'}^{\max}(t) / \left(L_{j'}(t) \times d_{j'}^i \times D_{j'}^i\right). \tag{17}$$

where $D_{j'}^i$ represents the transmission delay from user v_i to node $s'_{j'}$, $d_{j'}^i$ represents the corresponding distance. The best ONU-BSs can then be selected by evaluating the transmission capabilities of all ONU-BSs in each minimum dominance set. The corresponding total transmission capability holds as

$$H(t) = \sum_{i=0}^{I} \sum_{j'=0}^{J'} H_{j'}^{i}(t) \quad (18)$$

IV. VIDEO MULTICAST BITRATE ADAPTATION

In this section, a buffer-based video bitrate adaptation mechanism is proposed. For the selection of video bitrates, most researchers implement bitrate adaptation based on accurate estimation of network bandwidth. However, [26] points out that the inaccuracy and unreliability of bandwidth estimation may lead to frequent bitrate changes or low video quality. The user can ascertain buffer state based on the its buffer occupancy radio. Concretely, large buffer occupancy indicates that the user is in a stable playback phase, and vice versa. Hence, the video bitrate should be determined in terms of both buffer status and network status. To meet the heterogeneous requests of different users in multicast, it is necessary to implement video bitrate adaptation in the network. Since the bandwidth of the optical network is large compared to the wireless network, we only need to perform bitrate switch in the ONU-BS side.

A. BITRATE ADAPTION ON USER SIDE

1) VIDEO BITRATE ADAPTATION

The transmission of video streams can be divided into the initial phase and the stable phase [27]. As the initial delay has little impact on the QoE of users, we mainly focus on the stable phase. Though buffer occupancy ratio does not directly affect the bitrate of the video, but it is easy to cause playback interruption when the buffer occupancy ratio is low and buffer overflow when buffer occupancy ratio is high. Hence, to adapt the video bitrate, we resort to a lower threshold $B_{\min}^{k-1}$ and upper threshold $B_{\max}^{k-1}$ to characterize the data amount in the buffer when downloading the $(k-1)$th video segment, there holds

$$B_{\min}^{k-1} = \max\left\{B_2^{k-1}, P_{k-1}\right\} \quad (19)$$

$$B_{\max}^{k-1} = B - B_{\min}^{k-1} \quad (20)$$

where B_2^{k-1} is the length of the first two video segments in the buffer when the $(k-1)$th video segment is downloaded, B represents the total buffer capacity.

The probability of video interruption can be reduced by adapting video bitrate based on the buffer occupancy ratio. Besides, in order to avoid large fluctuation of video bitrate, the quality layer should only be risen or reduced one level during any time slot. It can be divided into the following three cases according to the relationship between the data amount B_{k-1} of the buffer and the buffer thresholds:

Case 1: $B_{k-1} \leq B_{\min}^{k-1}$. In this case, the amount of data in the buffer may temporarily satisfy the demand in the next moment before the next video segment arrives. But it is easy to cause an interruption as the playback time increases. Therefore, in order to reduce interruption time and frequency of subsequent playback interruptions, the number of quality layers is reduced to ensure that video segment can be quickly downloaded to the buffer. The quality layer can be adjusted according to the following expression

$$N_k = \max\left(N_{k-1} - 1, 1\right) \quad (21)$$

where N_{k-1} denotes the number of layers of the $(k-1)$ th video segment.

Case 2: $B_{\min}^{k-1} < B_{k-1} < B_{\max}^{k-1}$. In this case, the playback will not be interrupted for a short period of time because the data amount in the buffer can meet the playback needs in the next moment. Since the network state is time-varying, in order to avoid buffer overflow or underflow, we use probability ρ to determine whether the video bitrate switch is needed or not. Considering the total number of bitrate switching before the kth video segment, the buffer occupancy ratio ρ can be expressed as

$$\rho = \frac{2}{\pi} \arctan\left(\frac{\log\left(1 + \frac{1}{A_k + 1}\right) * e^{-\frac{N_{k-1}}{N}}}{1 - \frac{B_{k-1}}{B}}\right) \quad (22)$$

Eq.(22) indicates that the number of quality layers of the kth video segment should be reduced when the number of switching times A_k is large and the buffer occupancy is relatively small, and vice versa.

Case 3: $B_{k-1} \geq B_{\max}^{k-1}$. In this case, the amount of data in the buffer is greater than the upper threshold and thereby buffer overflow occurs easily. Although the overflow does not directly affect the video playback, it causes a waste of certain resources. In order to avoid buffer overflow and provide users with a better viewing experience, bitrate should be adjusted in the next video segment. If the current video segment is with the highest video bitrate, the number of quality layers of the next video segment remain unchanged. If $N_{k-1} < N$, the number of layers of the next video segment should be increased. We have

$$N_k = \min\left(N_{k-1}+1, N\right) \quad (23)$$

In all, the bitrate adaptive scheme is summarized in Algorithm 1.

2) BUFFER ADJUSTMENT

Due to the heterogeneous requests of multicast users and different link states, the buffer occupancy ratios of multicast users differ from each other. Users with buffer occupancy ratios greater than the upper threshold are prone to overflow events that results in packet loss. The user's request cannot be suspended because the next video segment is sent by the ONU-BS at the same time in the multicast scenario. In order to effectively avoid the buffer overflow, the high quality layer parts of the video can be discarded appropriately while switching to the high video bitrate. Note that the video segments within $B_{\min}^{k-2}$ cannot be allowed to be discarded in order to ensure stable playback of the video. The buffer adjustment

Algorithm 1 Bitrate Adaptive Algorithm

Input: Buffer thresholds B_{max}, $B_{\min}$; initial video bitrate R_1 meaning the quality of the user request; the number of video segments K;
Output: The number of quality layers of the next video segment N_k;
Initial phase:
Update buffer B_k according to Eq.(2) based on the initial request video segment bitrate.
Stable phase:
Updating B_{k-1}, $B_{\min}^{k-1}$ and $B_{\max}^{k-1}$ according to Eq.(19) and Eq.(20) **do**
if $B_{k-1} \leq B_{\min}^{k-1}$ **then**
  $N_k = \max(N_{k-1} - 1, 1)$
else
  if $B_{k-1} \geq B_{\max}^{k-1}$ **then**
    $N_k = \min(N_{k-1}+1, N)$ and adjust the buffer.
  else
    if $B_{\min}^{k-1} < B_{k-1} < B_{\max}^{k-1}$ **then**
      Judging the probability ρ according to Eq.(22) and adjust the quality layer of the video segment.
    end if
  end if
end if

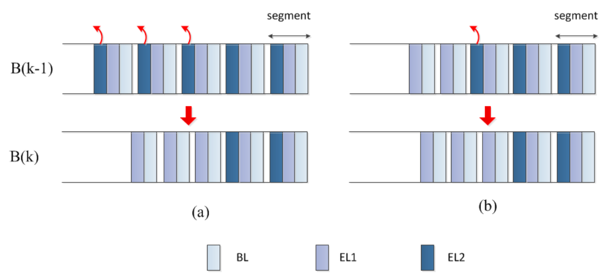

FIGURE 3. Dynamic adjustment of the buffer.

process is depicted in Figure 3. In particular, there are two cases while carrying out buffer adjustment.

Case 1: If the video segment bitrates are all the same, select the highest quality layer to discard, as shown in Figure 3(a).

Case 2: If there exists bitrate difference among video segments, determine the lowest bitrate as benchmark and discard all the quality layer higher than such benchmark, as shown in Figure 3(b).

We highlight that reducing the bitrate of the cached video segment degrades the video quality, however, it can effectively avoid video interruption caused by buffer overflow. In other words, the QoE of users can be guaranteed through sacrificing the bitrate and smoothness of the video.

B. BITRATE ADAPTION DURING MULTICAST TRANSMISSION

Focusing on the heterogeneous video bitrate requirements from different users, conventional method is to select the video bitrate requested by the users with the worst link quality in the group or the lowest video bitrate requested by the users [28]. This method can ensure that each user successfully receives the video segment, but the user with better link quality does not fully utilize the link resources. If the bitrate requested by the user with the best link quality or the highest video bitrate requested is used as the transmission standard of the group of users, the user with good link quality can enjoy a high QoE. However, users with poor link quality suffers a large delay and a high video interruption probability.

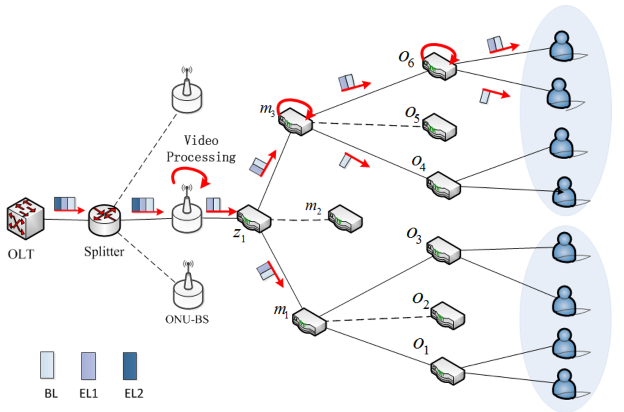

FIGURE 4. Example of a multicast tree.

With existing transmission scheme, the bitrate can only be determined in terms of the end-to-end available throughput while it can not be adjusted flexibly in intra-network nodes. In this paper, we focus on how to process the video stream in ONU-BSs located across the transmission path. The video bitrate can be appropriately reduced when a video segment is being forwarded by ONU-BSs.

Figure 4 depicts an example of the transmission process in a partial multicast tree. In order to maximize QoE for all users, user requests and link transmission capabilities are both taken into account. The number of quality layers needed by each node in the considered network can be determined by

$$N_k^{z_1} = \max\left\{\max\left(N_k^{o_1}, N_k^{o_3}\right), \max\left(N_k^{o_4}, N_k^{o_6}\right)\right\} \quad (24)$$

where $N_k^{z_1}$ represents the number of quality layers required for node z_1 to receive the kth video segment, and $N_k^{o_1}$ represents the number of layers required by the node o_1. The video bitrate that the node should receive is updated by sequentially performing quality assessment on all the child nodes in the multicast tree. The node then converts the high bitrate video to the desired low bitrate video according to the routing table. As shown in Figure 4, node o_4 only needs to receive one quality layer. After being processed by node m_3, the highest quality layer is discarded and then sent to o_4. This multicast method can meet the needs of each user, effectively avoiding network congestion and improving the viewing experience of all users. The multicast routing scheme is summarized in Algorithm 2.

V. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed QoE-aware video multicast mechanism (QAVMM) with the help of simulation experiments. To highlight the advantage of the proposed mechanism, we also employ the AMBA

Algorithm 2 Multicast Routing Algorithm

Input: User requests video segment bitrate, number of quality layers N_k;
Output: Routing forwarding table;
for each node **do**
  Update the number of quality layers that the node needs to receive step by step according to Eq.(24).
end for

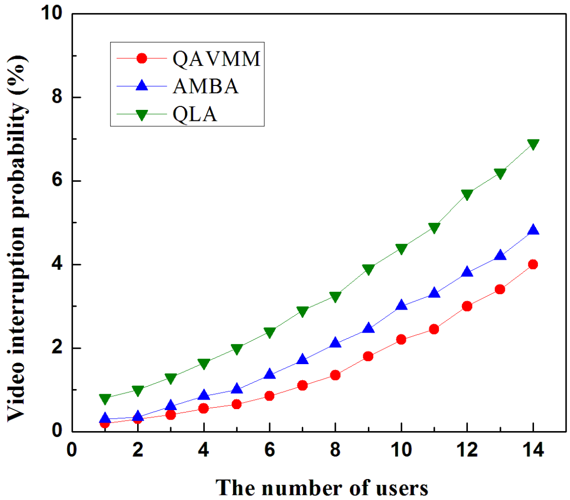

FIGURE 5. Video interruption probability under different user numbers.

algorithm [21] and the QLA algorithm [15] as comparisons here. The AMBA algorithm determines the video bitrate based on buffer underflow probability which is assessed according to the time-varying channel throughput. The QLA algorithm assigns appropriate number of retransmissions and transmission rate to each quality layer, and adjust the video bitrate based on an utility function. We consider a small-scale network scenario with 1 OLT and 8 ONU-BSs. The network coverage is set to 500 $m \times 500$ m. The number of multicast users varies from 1 to 14 and the buffer capacity is set to 300MB. The available bandwidth range for each user is set to [0,10]Mbps. The video is encoded into three quality layers, including the basic layer 1.2 Mbps and two enhancement layers of 2.83 Mbps and 5.5 Mbps respectively. The GOP is set to 30, the resolution of a video frame is set to 1280*720, and the frame rate is set to 30 fps.

Figure 5 shows the video interruption probability varying with the number of users. It is observed that the interruption probability increases with the number of users. The proposed QAVMM performs better than the other two schemes. The reason is that QAVMM takes buffer state into account on user side and set two thresholds to avoid buffer underflow while adjusting video bitrate. Hence, the video interruption probability can be effectively reduced. The performance of AMBA is close to QAVMM since it also determines the video bitrate based on the buffer state. Differently, QLA adjusts the video bitrate in terms of an utility function aiming to reduce retransmission times, which is irrelative to buffer state and thereby suffers the worst interruption performance.

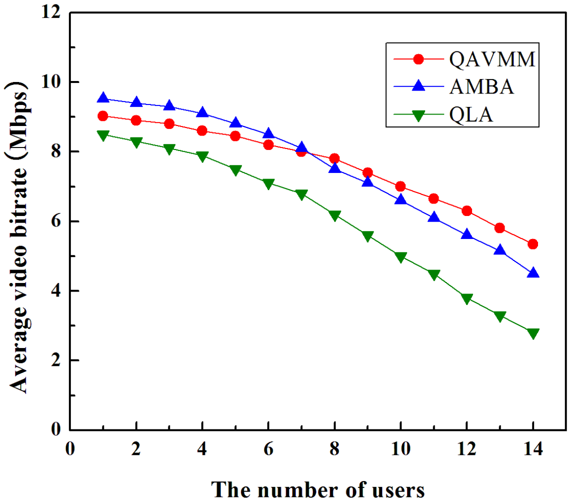

FIGURE 6. Average video bitrate under different user numbers.

Figure 6 shows the average video bitrate varying with the number of users. It is observed that the average video bitrate decreases as the number of users increases. Interestingly, AMBA performs better than QAVMM when the number of users is small (e.g., less than 7 users in the simulation). However, QAVMM is less sensitive to the number of users compared to AMBA, and hence it turns to perform better while there are more users adding in the considered network. This is because QAVMM just allows one quality layer changes between two adjacent two video segments. Also, QAVMM will discard some quality layers to avoid buffer overflow. Differently, AMBA adjusts the video bitrate based on the bandwidth and link quality. As the number of users increases, the resources for each user decreases, which degrades the average bitrate. Besides, QLA suffers the worst average bitrate performance since it only adjusts the video quality based on throughput.

Figure 7 depicts the smoothness performance under these three schemes. The video switching times is recorded from a video with 2-hour length. It is observed that switching frequency of the video bitrate increases with the number of users. The performance of the QAVMM algorithm is not much different from the performance of the AWBA algorithm. The reason is that QAVMM needs to switch the video quality in order to avoid buffer overflow. Differently, QLA adjusts the video bitrate in terms of network throughput which is dominated by the time-varying wireless channel.

Figure 8 shows the impact of the number of users on average QoE performance. Since video interruption has a greater impact on the user experience on video watching, we set the impact factor of video interruption probability $\lambda = 0.5$, the video bitrate impact factor $\omega = 0.3$ and the smoothness factor $\eta = 0.2$. It is observed that the average quality of experience decreases as the number of users increases due to the finite network resources. Also, the proposed QAVMM perform best among the three scheme since the video interruption probability is controlled in a low level.

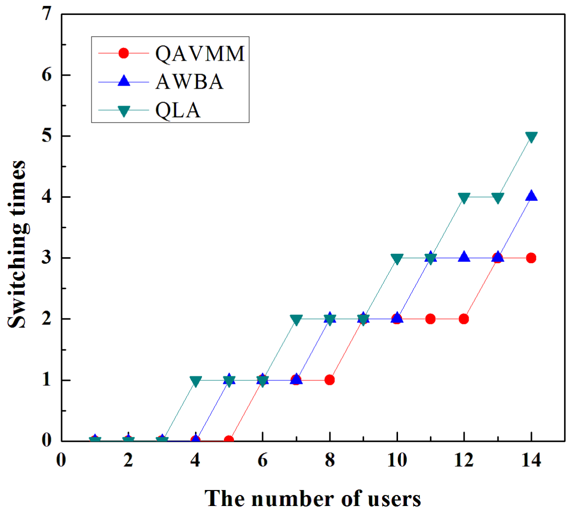

FIGURE 7. Switching frequency under different user numbers.

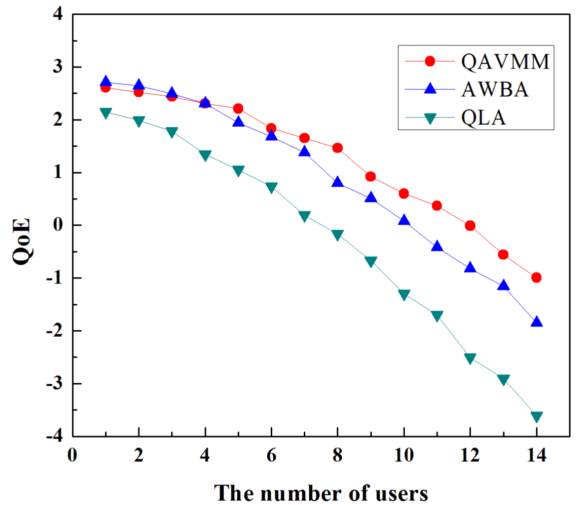

FIGURE 8. Quality of experience under different user numbers.

VI. CONCLUSION

In order to make full use of network resources and improve the QoE performance of multicast users in FiWi networks, a QoE-aware video multicast mechanism was proposed in this paper. The user experience quality assessment model was established based on the video interruption probability, video bitrate and video smoothness. Besides, the multicast tree was built based on the transmission capabilities of ONU-BSs which are selected through solving the minimum dominating set from the bipartite graph. Moreover, we shown how to select the video bitrate for a video segment based on the dynamic buffer state and how to control the video quality layer during multicast transmission in terms of link state and user request. Simulation results verified that the proposed scheme effectively guaranteed the QoE performance of different users. Future works will mainly focus on a more realistic FIWI network scenario and analyze how various practical network parameters affect the QoE of users.

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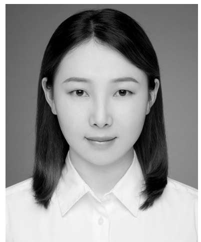

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