Multi-View 3D Video Multicast for Broadband IP Networks

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Abstract—With the recent emergence of 3D-supported TVs, video service providers now face an opportunity to provide high resolution multi-view 3D videos over IP networks. One simple way to support efficient communications between a video server and multiple clients is to deliver each desired view in a multicast stream. Nevertheless, it is expected that significantly increased bandwidth will be required to support the transmission of all views in multi-view 3D videos. However, the recent emergence of a new video synthesis technique called Depth-Image-Based Rendering (DIBR) suggests that multi-view 3D video does not necessarily require the transmission of all views. Therefore, we formulate a new problem, named Multi-view and Multicast Delivery Selection Problem (MMDS), and design an algorithm, called MMDEA, to find the optimal solution. Simulation results manifest that using DIBR can effectively reduce bandwidth consumption by 35% compared to the original multicast delivery scheme.

Index Terms—Multi-view 3D video, IP multicast delivery, depth-image-based rendering.

I. INTRODUCTION

Elezion with 4K and 3D-support were heralded as the future of television at the 2104 Consumer Electronics Show (CES), and many television manufacturers including Samsung, Sony, LG, and Philips have introduced 3D Smart LED TV to markets. Internet video providers, such as YouTube and Netflix, now provide 3D videos and 3D live streaming service to users for Internet-ready 3DTVs. In contrast to traditional 3D videos which offer the users only a single viewpoint, multi-view 3D videos allow the users to choose from a range of viewing angles. Currently the Digital Video Broadcasting (DVB) 3DTV standard supports multi-view 3D videos. In addition to DVB, a more flexible way to distribute 3D media is to stream over the Internet [1], [2]. Several companies and research teams have built demonstration systems for multi-view 3D video service over Internet Protocol (IP) networks [3], [4]. Moreover, research and applications for 3D video broadcast and IP streaming services have been presented [5], [6], allowing IPTV Service companies to provide multi-view 3D video streaming over IP networks [7]. The mist straightforward way to support efficient communications between a video server and multiple terminal users is to deliver every view of a multi-view 3D video in a multicast stream. Nevertheless, while different users enjoy their preferred views, it is expected that the bandwidth requirements in the network will significantly increase to support all views in multi-view 3D videos [8], [9].

Depth-Image-Based Rendering (DIBR) [10] is one promising way to remedy the bandwidth issue in the multi-view 3D video delivery. Because adjacent views usually share many similar contents, the desired view of a client can be synthesized from one nearby left view and one nearby right view, and researchers in image processing and video coding have developed sophisticated DIBR algorithms to ensure good synthesis quality by optimizing the bit allocation between the texture and depth map among views [11], [12]. Therefore, with the capability to render arbitrary views, DIBR has been recognized as an efficient way to provide Free Viewpoint Videos (FVV) applications [13], where each client can arbitrarily specify the desired view. Equipped with DIBR in clients, the bandwidth consumption in a network can be effectively reduced.

However, this approach is subject to several challenges. 1) To avoid the generation of unacceptable disoccluded areas in synthesized virtual views, the left and right views used to synthesize the desired view must be reasonably close to one another [11]. Different users desire different different views, and satisfying these demands require carefully selecting views for transmission so that the desired view of each user can be synthesized with good quality. In other words, the quality constraint in DIBR specifies that the left and right views are allowed to be at most $D$ views away (i.e., $D−1$ views between them), to guarantee good quality of every synthesized view between them. 2) To support more multi-view videos in IP networks, a simple approach is to minimize the bandwidth consumption by transmitting only the minimal number of views required. Nevertheless, since the current IP multicast routing protocols, PIM-SM [4], [5], exploit a shortest-path tree for point-to-multipoint group communications, the network bandwidth to deliver each view varies since each user may prefer a different view. Moreover, to synthesize a view using DIBR, the user must receive two views instead of one, thus a more promising approach is to acquire the close left and right views from nearby users in the corresponding two multicast trees. However, selecting views for delivery to nearby presents a challenge and different view selections for various users results in different tree routing. Therefore, it is desired to have a smart view selection strategy to minimize the total bandwidth consumption in all multicast trees to provide scalable multi-view 3D video services over a network.

Fig. 1 presents an illustrative example for efficient delivery of a multi-view 3D video, which includes one video server, five routers and eight client users. In this example, users 1 to 8 request the preferred views 2, 3, 7, 8, 6, 7, 8, and 4, respectively. One intuitive way, called original multicast delivery scheme, is to multicast each desired view to each client directly, and the views transmitted in each link listed in the parenthesis. The total bandwidth consumption is 45, where the total bandwidth consumption is the sum of the number of views delivered in every edge (see Definition 1). In contrast, a more efficient way is to exploit DIBR to reduce the bandwidth consumption. Take $D = 4$ for an example with the views transmitted in each link listed in the bracket. The total bandwidth consumption can be effectively reduced to 32 by the following selections: $2 \rightarrow (2, 2), 3 \rightarrow (2, 4), 4 \rightarrow (4, 4), 6 \rightarrow (4, 8), 7 \rightarrow (4, 8), 8 \rightarrow (8, 8)$, where $b \rightarrow (a, c)$ represents that view $b$ is synthesized
by views $a$ and $c$ if $a \neq c$; otherwise view $b$ in $b \mapsto (b, b)$ is processed directly. With DIBR, it is only necessary to deliver views 2, 4, and 8 for all clients.

Based on the above observations, we make the first attempt to propose an efficient view selection strategy for multi-view video delivery in IP networks. We formulate a new optimization problem, called Multi-view and Multicast Delivery Selection Problem (MMDS), to minimize the total bandwidth consumption for efficient multi-view 3D video multicast in IP networks. We design an algorithm, called Multi-view and Multicast Delivery Exploration Algorithm (MMDEA), to find an optimal solution of the MMDS problem. Our simulation results manifest that with exploiting DIBR, the bandwidth consumption can be effectively reduced by 35%, comparing to the original multicast delivery scheme. Note that layer encoding multicasting also enables the delivery of multimedia contents to client communities in a cost-efficient manner and can automatically adjust the transmission of the base layer and successive layers according to the available bandwidth. However, the multi-view transmission with DIBR needs to select the transmission views by examining the preferred view of all clients as well as the topology of SPT, resulting a more challenging issue.

The rest of the paper is organized as follows. Section II describes the system model and formulates the MMDS problem. Section III demonstrates the idea of MMDEA by first considering two fundamental special cases and then extend it to the general case. Section IV presents the simulation results and we conclude this paper in Section V.

The network consists of a shortest path directed tree $T = (V, A, s)$ spanning a video server and all clients, where $V$ and $A$ denote the set of nodes and directed edges, respectively, and $s$ is the root of $T$, which is considered to be the multi-view video server in the network. The set of terminal nodes of $T$ is denoted by $\Omega_T$, which represents the set of clients in the network. The directed path from $s$ to $t \in \Omega_T$ is denoted by $P_{s,t}$. Let $\mathcal{V} \subseteq \mathbb{N}$ denote the universal set of views in a multi-view 3D video, and $\rho_T : \Omega_T \to V$ denotes a preferred-view function, i.e., each terminal node $t$ selects a desired view $\rho_T(t)$ from $V$. Let $\mathcal{V}_p \subseteq V$ denote the set of all desired views by all clients.

Let $D$ denote the DIBR quality constraint. The MMDS problem aims to find an optimal view-selection function (i.e., assigns a view or two nearby views to each client) to minimize the total bandwidth consumption in the network. More specifically, given the set of preferred views $\mathcal{V}_p$, let $\theta : \mathcal{V}_p \to V \times V$ be a view-selection function that assigns each preferred view $v \in \mathcal{V}_p$ an ordered pair of views $(\theta(v)_l, \theta(v)_r)$ from $V$, where $\theta(v)_l = \theta(v)_r$ or $\theta(v)_l < \theta(v)_r$. For a view-selection function $\theta$, we say that $\theta$ satisfies $\mathcal{V}_p$ with respect to $D$ if $\theta$ satisfies the following three conditions: 1) $\theta$ fits the DIBR quality constraint, i.e., $0 \leq \theta(v)_l - \theta(v)_r \leq D$ for all $v \in \mathcal{V}_p$; 2) the left and right views $\theta(v)_l$ and $\theta(v)_r$ (i.e., $\theta(v)_l \neq \theta(v)_r$) cannot be further synthesized by other views. Specifically, if $\theta(v)_l > \theta(v)_r$, $\theta(v')_l = \theta(v')_r$ must hold for $v' = \theta(v)_l$ or $v' = \theta(v)_r$. 3) $\theta$ has no crossing view selections, i.e., if $\theta(v)_l \neq \theta(v)_r$ for some view $v$, no view $v'$ can be assigned $(\theta(v')_l, \theta(v')_r)$ with $\theta(v)_l < \theta(v')_l \leq \theta(v)_r$ or $\theta(v)_l < \theta(v')_r \leq \theta(v)_r$. We formulate the MMDS problem as follows.

**Definition 1**: Given a rooted tree $T = (V, A, s)$, a universal view set $V$, a preferred-view function $\rho_T$ and thus $\mathcal{V}_p$, and the DIBR quality constraint $D$, the MMDS problem is to find a view-selection function $\theta$ such that $\theta$ satisfies $\mathcal{V}_p$ with respect to $D$, and the total bandwidth consumption defined in (1) is minimized.

$$\text{cost}(\theta) = \sum_{e \in A} \left| \bigcup_{t \in \Omega_T} \{ \theta(\rho_T(t)_l), \ell, \theta(\rho_T(t)_r), r \} \right|. \quad (1)$$

The cost in (1) indicates that every view selected for the clients will be counted once on every edge of the paths from the root to the clients. Therefore, the objective function encourages two or more clients that share many common edges in their paths from the root to exploit the same views, while each view can be directly processed by a client or be regarded a the left or right view for synthesis with DIBR. Let $\theta^*$ denote an optimal view-selection function to the MMDS problem. After $\theta^*$ is decided, the set of views required to be transmitted at the video server $s$ will be

$$\mathcal{V}^* = \bigcup_{v \in \mathcal{V}_p} \{ \theta^*(v)_l, \theta^*(v)_r \}. \quad (2)$$

In this paper, we explore the fundamental problem of providing efficient multi-view 3D multicasts over broadband IP networks, where each client has sufficient bandwidth to receive two views. The problem with some clients only able to receive one view is a special case of the problem, by enforcing that the desired view cannot be synthesized.

1 For convenience, we assume that the views provided by the video server are finite, distinct, and are presented by consecutive positive integers.

2 The DIBR quality constraint $D$ is a positive integer with $D \geq 2$. 

Fig. 1: Multi-view 3D video multicast routing.
An intuitive approach to address the MMDS problem is to iteratively select the view that can serve the most number of clients in order to reduce the total bandwidth consumptions. Nevertheless, the strategy does not carefully examine the network structure and identify the closely clients that share a long common path from the root. In addition, it does not consider the desired views of multiple clients jointly to find out the views that can be shared by those client as the left and right views for synthesis with DIBR. As $D$ and the number of views increase, the problem become more challenging since it will impose much more choices during the selection of views for each client. As a result, instead of trying all possible choices of views to minimize the total bandwidth consumption, we present an algorithm called Multi-view and Multicast Delivery Exploration Algorithm (MMDEA) to systematically derive an optimal solution for the MMDS problem with dynamic programming. In the following, we will first present the algorithm with $D = 2$ and $3$ and then extend it to the general case. The algorithm can be implemented by the SDN controller or the video server, where the routing information of the shortest-path tree is able to be acquired by ICM traceroute.

### A. Dynamic Programming Formulation

To effectively minimize the total bandwidth consumption, we propose MMDEA based on dynamic programming. MMDEA first divides the desired views set $\mathcal{V}_\rho$ into multiple non-overlapping maximal segments $\mathcal{V}_\rho^1, \mathcal{V}_\rho^2, \ldots, \mathcal{V}_\rho^n$ such that the gap (the largest value of $|v_i - v_j|$ with no view from $v_i$ to $v_j$ in $\mathcal{V}_\rho$) in each segment is no larger than $D$. For example, if $D = 3$ and $\mathcal{V}_\rho = \{1, 2, 3, 5, 9, 10, 15, 17, 18\}$, then we can divide $\mathcal{V}_\rho$ into three segments: $\mathcal{V}_\rho^1 = \{1, 2, 3, 5\}$, $\mathcal{V}_\rho^2 = \{9, 10\}$ and $\mathcal{V}_\rho^3 = \{15, 17, 18\}$.

For $m \leq k$, let $c_{m, k}$ denote the minimum cost of a view-selection function $\theta_{m, k}$ with the set of desired views as $\{v_m, v_{m+1}, \ldots, v_k\} \cap \mathcal{V}_\rho$, where the two boundary views $v_m$ and $v_m$ must be selected in $\theta_{m, k}$. In other words, $c_{m, k}$ is the minimum total bandwidth consumption to serve the clients with the desired views from $v_m$ to $v_k$, and $v_m$ and $v_k$ are the boundary views and thus need to be transmitted directly or be generated by views using DIBR synthesis. The cost induced from any views not in $\{v_m, v_{m+1}, \ldots, v_k\} \cap \mathcal{V}_\rho$ is not included in $c_{m, k}$. Consequently, the minimum total bandwidth consumption to the MMDS problem is

$$c_{m, M} = \min_{\forall \mathcal{V}_\rho^i} \sum_{i=1}^{n} c_{m, M_i}$$

for $\mathcal{V}_\rho = \{v_m, v_{m+1}, \ldots, v_M\}$, where $v_m$ and $v_M$ denote the minimum and the maximum view in $\mathcal{V}_\rho$, respectively.

It is worth noting that, although only the views in $\mathcal{V}_\rho$ are desired, some views in $\mathcal{V}\setminus\mathcal{V}_\rho$ may still be selected in the solution for synthesis with DIBR in order to minimize the total bandwidth consumption. For simplicity, we will focus on deriving $c_{m, M}$ for each segment $\mathcal{V}_\rho^i = \{v_m, \ldots, v_M\}$ in the rest of this paper. In the following, we explore the fundamental cases with $D = 2$ and $3$ to derive $c_{m, k}$ systematically for each $k \in \{m, m+1, \ldots, M\}$.

### B. Special Case

In this section, we aim at establishing the recursive relation of $c_{m, k}$ for DIBR with $D = 2$ and $3$. We first consider the case of $D = 2$. Two fundamental costs are involved to find $c_{m, k}$. The first one is $c_{k, k}$, which represents the total bandwidth consumption to multicast view $v_k$ to every client that subscribes the view. In other words, $c_{k, k}$ is the cost of the multicast tree to span all clients that subscribe $v_k$. In addition, for any subset $\mathcal{V}'$ of $\mathcal{V}_\rho$ and two boundary views $v_t$ and $v_r$ such that $v_t - v_r \leq D$ and $v_t < v < v_r$ for every view $v \in \mathcal{V}'$, let $\phi_{v_t, v_r}(v)$ denote the expansion-cost function, which is additional bandwidth consumption to multicast view $v_t$ and $v_r$ to every client that subscribes $v \in \mathcal{V}'$ between $v_t$ and $v_r$, in order to synthesize view $v$ with DIBR, if the multicast tree for the views in $\{v_t, v_r\}$ has been constructed. In other words, $\phi_{v_t, v_r}(v)$ is the additional cost required to expand the multicast tree that has spaned other clients subscribing views in $\{v_t, v_r\}$ to reach the clients subscribing the views in $\mathcal{V}'$. For simplicity, let $\phi_{v_t, v_r}(v) = 0$ if $\mathcal{V}' \cap \mathcal{V}_\rho = \emptyset$. In the following, we first define $c_{k, k}$ as follows.

$$c_{k, k} = \begin{cases} c_{k, k} & \text{if } v_k \in \mathcal{V}_\rho \\ \infty & \text{if } v_k \not\in \mathcal{V}_\rho \text{ and } v_k \text{ is not generated by any view} \\ 0 & \text{if } v_k \not\in \mathcal{V}_\rho \text{ and } v_k \text{ is generated by some views.} \end{cases}$$

If $D = 2$. Let $c_{m, k}$ denote the bandwidth consumption to serve the clients with the desired views from $v_m$ to $v_k$, where $v_k$ is employed to serve the clients subscribing $v_k$ only. By contrast, let $c_{m, k}$ denote the bandwidth consumption for the same clients, but $v_k$ here is also exploited to serve the clients for synthesizing $v_{k-1}$ with DIBR. The following lemma shows that $c_{m, k}$ can be obtained by comparing $c_{m, k}$ and $c_{m, k}$, where the proof explains the detailed multicast operations for all possible cases.

**Lemma 1**: For $D = 2$ and $k \in \{m, m+1, \ldots, M\}$, let $J = \{0, 1\}$, and we have

$$c_{m, k} = \min\left\{c_{m, k}^0 = \min\{c_{m-1, k-1} + c_k \in J \} = \min\{c_{m-1, k-2} + c_k + \phi_{v_{k-1}, v_k}\} \right\}$$

**Proof**: We prove the lemma by induction on $k$. The result holds clearly for $k = m$. Suppose it holds $c_{m', k'}$ for every $k' < k$. Assume that $v_{k-1} \in \mathcal{V}_\rho$. There are two possible cases as follows.

**Case 1**: view $v_k$ is not involved in the view synthesis. This implies that no view from $v_m$ to $v_{k-1}$ is synthesized by $v_k$. If $v_{k-1} \not\in \mathcal{V}_\rho$, then we have $v_{k-1} \rightarrow (v_{k-1}, v_{k-1})$, implying that $c_{m, k} = c_{m-1, k-1} + c_k$. Alternatively, for $v_{k-1} \not\in \mathcal{V}_\rho$, since the gap of $\mathcal{V}_\rho$ is no larger than $D$, $v_{k-2} \not\in \mathcal{V}_\rho$ and $v_{k-1} \not\in \mathcal{V}_\rho$, and thus we have $v_{k-1} \rightarrow (v_{k-1}, v_{k-1})$. On the other hand, there are two possible cases for $v_{k-2}$, i.e., $v_{k-2} \rightarrow (v_{k-2}, v_{k-2})$ or $v_{k-2} \rightarrow (v_{k-3}, v_{k-1})$. In the former case, $c_{m, k} = c_{m-2, k} + c_k$ holds; in the latter case, $c_{m, k} = c_{m-1, k-1} + c_k$ holds.

**Case 2**: view $v_k$ is involved in the synthesis for $v_{k-1}$. In this case, we have $v_{k-1} \not\in \mathcal{V}_\rho$ and $v_{k-1} \rightarrow (v_{k-2}, v_{k-2})$. Note that views $v_{k-2}$ and $v_{k-1}$ cannot be further synthesized by other views and thus need be transmitted directly if they are in $\mathcal{V}_\rho$. If $v_{k-2} \not\in \mathcal{V}_\rho$, then we do not exploit the view synthesis, we have $c_{m, k} = c_{m-2, k} + c_k + \phi_{v_{k-1}, v_k}$; otherwise, $c_{m, k} = c_{m-1, k} + c_k + \phi_{v_{k-2}, v_k}$, implying that (4) holds. Since $c_{m, k}$ is a minimization, the smaller one of the above two cases is the minimum cost of $c_{m, k}$. The lemma follows.
After finding the minimum cost \( c_{m,k} \) with the above recursive relation, the optimal view-selection function \( \theta_{m,k} \) can be obtained from \( c_{m,k} \) by backtracking with \( (3) \) and \( (4) \) as follows.

**Case 1:** \( c_{m,k} \) is derived from \( c_{m,k}^0 \) in \( (3) \). If \( c_{m,k}^0 = c_{m,k} \), we set \( v_k \mapsto (v_k, v_k) \), i.e., \( v_k \) is transmitted directly. If \( v_k \in V\rho \), we set \( v_k \mapsto (v_k-1, v_k-1) \), i.e., \( v_k \) is also transmitted directly. Afterwards, \( c_{m,k-1} \) is processed similarly to find \( \theta_{m,k-1} \). On the other hand, if \( v_k \notin V\rho \), we set \( v_k \mapsto (v_k-3, v_k-1) \) because it is more bandwidth efficient to multicast view \( v_k \) for \( v_k \), instead of directly transmitting \( v_k \). Afterwards, \( c_{m,k-2} \) is processed similarly to find \( \theta_{m,k-2} \). By contrast, if \( \theta_{m,k}^0 = c_{m,k-2} + c_k \), \( v_k \in V\rho \) and \( v_k \notin V\rho \) must hold, and we have \( v_k \mapsto (v_k-2, v_k-2) \) and \( v_k \mapsto (v_k, v_k) \), respectively, i.e., views \( v_k \) and \( v_k \) are transmitted directly. Afterwards, \( c_{m,k-2} \) is processed similarly to find \( \theta_{m,k-2} \).

**Case 2:** \( c_{m,k} \) is derived from \( c_{m,k}^1 \) in \( (4) \). Suppose \( c_{m,k}^1 = c_{m,k-2} + c_k + \Phi(v_k-1, v_k, v_k) \) for some \( j \in \{0, 1\} \). We set \( v_k \mapsto (v_k \rightarrow v_k, v_k) \) and \( v_k \mapsto (v_k, v_k) \) for \( v_k-1 \), \( v_k-1 \in V\rho \). In other words, \( v_k \) is synthesized from the two neighbor views. Afterwards, \( c_{m,k-2} \) is processed similarly to find \( \theta_{m,k-2} \).

**D = 3.** For \( v_k \), only \( v_k \rightarrow v_k \) and \( v_k \rightarrow v_k \) can exploit \( v_k \) for synthesis with DIBR. The possible cases for \( v_k \rightarrow v_k \) include \( v_k \rightarrow (v_k \rightarrow v_k, v_k) \) (non-synthesis), \( (v_k \rightarrow v_k, v_k) \), or \( (v_k, v_k) \), while \( v_k \rightarrow v_k \rightarrow (v_k, v_k) \) (non-synthesis), \( (v_k \rightarrow v_k, v_k) \), or \( (v_k, v_k) \) are also possible. Although there are nine combinations to jointly examine \( v_k \rightarrow v_k \) and \( v_k \rightarrow v_k \), it is necessary to examine only three of them. The first reason is that a selected view cannot be further synthesized. For example, for \( v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \), view \( v_k \rightarrow v_k \) cannot be further synthesized. Secondly, no cross synthesis is allowed. For example, \( v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \) is not allowed to o-exist simultaneously since the view synthesis of view \( v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \) is transmitted directly. Thirdly, the combinations that do not exploit \( v_k \) for synthesis with DIBR has been considered when we derive \( c_{m,k-1} \), such as \( v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \rightarrow v_k \).

Specifically, Table I summarizes the new notations for \( D = 3 \). Let \( c_{m,k}^0 \) denote the bandwidth consumption to serve the clients with the desired views from \( v_m \) to \( v_k \), where \( v_k \) is employed to synthesize \( v_k \). Let \( c_{m,k}^0 \) denote the bandwidth consumption for the same clients, but \( v_k \) here is exploited to synthesize both \( v_k-1 \) and \( v_k-2 \). Thus, \( c_{m,k} \) for \( D = 3 \) can be obtained by following the recursive relation.

**Lemma 2:** For \( D = 3 \), \( k \in \{m, m + 1, \ldots, M\} \), let \( J = \{0, 1, 2\} \), and we have

\[
\begin{align*}
    c_{m,k} & = \min \left\{ c_{m,k-1}^0 + c_k + \Phi(v_k-1, v_k, v_k) \right\} \quad (5) \\
    c_{m,k} & = \min \left\{ c_{m,k-2}^0 + c_k + \Phi(v_k-2, v_k, v_k) \right\} \quad (6) \\
    c_{m,k} & = \min \left\{ c_{m,k-3}^0 + c_k + \Phi(v_k-3, v_k, v_k) \right\} \quad (7)
\end{align*}
\]

**Algorithm 1.** Multi-view and Multicast Delivery Exploration Algorithm (MMDEA)

**Input:** A rooted tree \( T = (V, A, s) \), a universal view set \( V \), a preferred-view function \( \rho_T \), and the DIBR quality constraint \( D \).

**Output:** The minimum total bandwidth consumption \( \text{cost}(\theta^*) \) of a view-selection function \( \theta^* \) which satisfies \( V\rho \) with respect to \( D \).

**Method:**

// Initialization stage
Identify the service range \( V\rho \leftarrow V\rho \cup \cdots \cup V\rho \); \( \text{cost}(\theta^*) \leftarrow 0 \);

// Exploration stage
foreach segment \( V\rho = \{v_m, \ldots, v_M\} \) do

for \( k = m \) to \( M \) do

\[
\begin{align*}
    c_{m,k} & = \min \left\{ c_{m,k-1}^0 \right\} \quad (5) \\
    c_{m,k} & = \min \left\{ c_{m,k-2}^0 + c_k \right\} \quad (6) \\
    c_{m,k} & = \min \left\{ c_{m,k-3}^0 + c_k \right\} \quad (7)
\end{align*}
\]

return \( \text{cost}(\theta^*) \);}

**C. General Case**

In last section, we have established the recursive formulas to derive \( c_{m,k} \) for \( k \in \{m, m + 1, \ldots, M\} \) with \( D = 2 \) and 3. However, when \( D \) grows, the number of combinations required to be examined grows rapidly. The reason is that during the derivation of \( c_{m,k} \), all views \( v_k, v_k+1, v_k+2, \ldots, v_k \) are able to select \( v_k \) for synthesis with DIBR. Therefore, it becomes much more difficult to derive \( c_{m,k} \). Algorithm 1 presents the pseudocode of MMDEA. The input parameters include a computed single-source shortest path rooted tree \( T = (V, A, s) \), a universal view set \( V \) provided by the video server, a preferred-view function \( \rho_T \) which assigns each terminal node of \( T \) a desired view from \( V \), and the DIBR quality constraint \( D \). MMDEA determines the minimum total bandwidth consumption \( \text{cost}(\theta^*) \) of a view-selection function \( \theta^* \) such that \( \theta^* \) satisfies \( V\rho \) with respect to \( D \). In the following, we present Multi-view and Multicast Delivery Exploration Algorithm (MMDEA), which includes two stages: Initialization and Exploration. The first stage initializes and identifies the service range for all desired views by the clients. The second stage explores each segment of the service range separately and consider each possible view selection combinations to determine the minimum total bandwidth consumption in the network.

1) Initialization Stage: In the initialization stage, it is necessary to identify the service range based on the preferred-view function to ensure the each subscribed view is able to be directly transmitted or synthesized by other views. Therefore,
the same as the approach described for $D = 2$, it can be achieved by first selecting the views in non-decreasing order, and then by dividing the desired views set $V^d_o$ into multiple non-overlapping maximal segments $V^d_1, \ldots, V^d_{o'}$ such that the gap in each segment $V^d_i$ is no larger than $D$.

2) Exploration Stage: Initialization stage defines the service range to satisfy the clients. In this stage, each segment $V^d_o$ is horizontally explored separately in order to pursue the minimum total bandwidth consumption in the network. More specifically, the goal of this stage is to derive $c_{m,M}$ for each segment $V^d_i = \{v_m, \ldots, v_M\}$, which represents the minimum total bandwidth consumption to serve all clients that subscribe views from $v_m$ to $v_M$. MMDEA explores $V^d_i$ systematically and derive $c_{m,k}$ for all $k \in \{m, m+1, \ldots, M\}$ according to the derived values of $c_{m,k-D}, c_{m,k-D+1}, \ldots, c_{k-1}$ and $c_k$. This is because when $v_k$ is involved in the computation of $c_{m,k}$, only the views $v_m, v_{m-D+1}, v_{m-D+2}, \ldots, v_{k-1}$ can select $v_k$ for synthesis with DIBR. In addition, the difficulty lies in that the choices for the views from $v_{k-D+1}$ to $v_k$ may affect the choices for the views from $v_m$ to $v_{k-D}$. To derive $c_{m,k}$ correctly, it is necessary to record all costs obtained in the computation of $c_{m,k}$ for further examining in the wider service ranges in order to minimize the total bandwidth consumption.

The notion of exploration stage goes as follows. If $v_k$ is not exploited to synthesize any other view, clearly $c_{m,k} = c_{m,k}^0 = \min_{\theta_{m,k} \in \Theta_{m,k}} \{c_{m,k-1}^\theta, c_{m,k-2}^\theta, \ldots, c_{k-1}^\theta\} + c_k$, such as Eq. (5) for $D = 3$. Otherwise, it is necessary to examine different view selection combinations that exploit $v_k$ for synthesis with DIBR. To find $c_{m,k}$ in this case, MMDEA sequentially examines the case that a view $v_{k-d}$ is transmitted, where $D \geq d \geq 2$. In addition, every other view between $v_{k-d}$ and $v_k$ is synthesized from the two views accordingly. For example, when $D = 3$, $v_{k-2}$ and $v_{k-3}$ are examined sequentially and assumed to be transmitted, as explained in Eq. (6) and Eq. (7), respectively. Note that the case with $d = 1$ is not considered because $v_k$ here exploited to synthesize a view (i.e., at least view $v_{k-1}$).

Specifically, for view $v_{k-d}$, denote $E_d = \{c_{m,k-D+1}, \ldots, c_{k-1}\}$, where all views in $E_d$ are forced to select $(v_{k-d}, v_k)$ for synthesis with DIBR. This is because when $k - d$ is the maximum index (other than $k$) such that $v_{k-d}$ is transmitted directly in $\theta_{m,k}$, no views between $v_{k-d}$ and $v_k$ can transmitted directly and thus must select $(v_{k-d}, v_k)$ for synthesis with DIBR, for otherwise it will create crossing view selections, which is forbidden in the definition of the MMDPS problem. Fig. 2 presents an illustrative example. Therefore, it is necessary to multicast view $v_{k-d}$ to not only the clients subscribing view $v_{k-d}$ but also all the other clients subscribing the views in $E_d$.

For $d \in \{1, 2, \ldots, \min\{m, k - D\}\}$, let $c_{m,k}^d$ denote the bandwidth consumption to serve the clients with the desired views from $v_m$ to $v_k$, where $v_k$ is employed to synthesize for all the views from $v_{k-1}$ to $v_{k-d}$. MMDEA computes and store $c_{m,k}^d$ sequentially for $d = 0, 1, 2, \ldots, \min\{m, k - D\} - 1$ according to $c_{m,k-D}^j, c_k$ and $\sum_{v \in E_d} \Phi_{\{v_{k-d}, v_k\}}$ where $j \in J = \{0, 1, 2, \ldots, \min\{m, k - D\} - 1\}$. In other words, $c_{m,k}^d$ is obtained by looking up the previous derived values $c_{m,k-D}$ and $c_k$, together with the expansion cost, where each view $v$ in $E_d$ selects $v_{k-d}$ and $v_k$ for synthesis. The corresponding view-selection function for $c_{m,k}^d$ is denoted by $\theta_{m,k}^d$, and will be stored in the set $\theta_{m,k}$ for further reference. After finding $c_{m,k}^d$ for all $k = m, m+1, \ldots, M$, the minimum cost $c_{m,k}$ is derived by the minimum of $c_{m,k}^0$ and $c_{m,k}^d$ for all possible $d \in \{1, 2, \ldots, \min\{D, k - m\} - 1\}$.

D. Example

In this section, we demonstrate the computation of the minimum total bandwidth consumption in Fig. 1 using MMDEA under $D = 4$. The set of desired views is $V^d_o = \{v_m = v_2, v_3, v_4, v_6, v_7, v_8 = v_M\}$. Since the gap in $V^d_o$ is no larger than $D$, only one segment needs to consider. Initially, $c_{2,2} = 7$. Afterwards, $c_{2,3}$ must be obtained by the view-combination that do not involve $v_3$, i.e., $c_{2,3} = c_{2,4} = c_{2,2} + c_3 = 14$. Now consider $c_{2,4}$. We have $J = \{0, 2\}$. Firstly, $c_{2,4} = c_{2,3} + c_4 = 21$. In the exploration stage, $d = 2$ and we get $E_d = \{v_3\}$. So we obtain $c_{2,4}^2 = \min_{\theta_{2,4}}(c_{2,2} + c_4 + \Phi_{\{v_3\}}) = 17$. Thus $c_{2,4} = \min\{c_{2,4}^2, c_{2,4}^4\} = 17$.

The corresponding assignments of $c_{2,4}^0$ and $c_{2,4}^2$ will be stored in the set $\theta_{2,4} = \{\theta_{2,4}^0, \theta_{2,4}^2\}$ for further reference, where $\theta_{2,4}^0: v_{2d} \mapsto (v_2, v_2)$, $v_3 \mapsto (v_3, v_3)$, $v_4 \mapsto (v_4, v_4)$, and $\theta_{2,4}^2: v_{2d} \mapsto (v_2, v_2)$, $v_3 \mapsto (v_2, v_3)$, $v_4 \mapsto (v_4, v_4)$, respectively. Next, consider $c_{2,5}$. We have $J = \{0, 2, 3\}$. Firstly, $c_{2,5} = c_{2,4} + c_5 = \infty$ as $v_5 \notin V^d_o$ and $v_5$ is not generatebly obtained from $v_2$ to $v_4$ in $c_{2,5}$. In the exploration stage, $d = 2$ and $3$. For $d = 2$, we have $E_d = \{v_4\}$ and $c_{2,5}^2 = \min_{\theta_{2,5}}(c_{2,3} + c_4 + \Phi_{\{v_4\}}) = 23$. For $d = 3$, we have $E_d = \{v_4, v_4\}$ and $c_{2,5}^3 = \min_{\theta_{2,5}}(c_{2,2} + c_4 + \Phi_{\{v_4, v_4\}}) = 19$. So $c_{2,5}$ is the minimum among $c_{2,5}^0$, $c_{2,5}^2$, and $c_{2,5}^3$, which results in $c_{2,5} = 19$. Similarly, $c_{2,6} = 19$. The value of $c_{2,7}$ can be obtained similarly as $c_{2,7} = \min_{\theta_{2,7}}(c_{2,3} + c_4 + \Phi_{\{v_4, v_4\}}) = 28$, where $J = \{0, 2, 3, 4\}$. The value of $c_{2,8}$ can be obtained similarly as $c_{2,8} = \min_{\theta_{2,8}}(c_{2,2} + c_4 + \Phi_{\{v_4, v_4\}}) = 17 + 15 = 32$, where $J = \{0, 2, 3, 4\}$, and the corresponding view-selection function $\theta_{2,8}$ is $v_{2d} \mapsto (v_2, v_2)$, $v_3 \mapsto (v_2, v_3)$, $v_4 \mapsto (v_4, v_4)$, $v_6 \mapsto (v_4, v_4)$, $v_7 \mapsto (v_4, v_4)$, and $v_8 \mapsto (v_8, v_8)$. Consequently, the minimum total bandwidth consumption with respect to $D = 4$ in this example is $c_{m,M} = c_{2,8} = 32$.

E. Optimality

The solution optimality of MMDEA relies on the correctness of $c_{m,k}$ for all $k \in \{m, m+1, \ldots, M\}$, which can be proved similarly as in Lemma 4 by induction on $k$. If $v_k$ is not exploited to synthesize any other view in $\theta_{m,k}$, clearly $c_{m,k} = c_{m,k}^0$; otherwise, the value $c_{m,k}$ must be obtained by examining all subproblems that must exploit $v_k$ for synthesis with DIBR. The algorithm checks all possible view selection combinations for the views from $v_{k-D+1}$ to $v_{k-1}$ as only these views have the abilities to exploit $v_k$ for synthesis with DIBR. Thus the optimization problem for $v_m, \ldots, v_k$ (i.e., $c_{m,k}$) can be obtained by looking up the subproblem $v_m, \ldots, v_{k-d}$ (i.e., $c_{m,k-d}$). Since $c_{m,k}$ is a minimization, by comparing the optimal solution among $c_{m,k}^0$ and $c_{m,k}^d$ for all possible $d$, the optimal solution $c_{m,k}^d$ is derived.
F. Time Complexity

Now we analyze the time complexity of MMDEA. For any \( v_k \in \mathcal{V}_r \), the multicast tree for the computation of \( c_{m,k} \) can be obtained by running a tree transversal to identify the edges in \( T \) in which the edge has shortest \( s, t \)-paths through it for some client user \( t \in \Omega_r \) with that \( t \) prefers view \( v_k \) (i.e., \( \rho_r(t) = v_k \)). Similarly, the multicast tree for the computation of \( \Phi^v(v_k,v_r) \) for any \( v^r \subseteq \mathcal{V} \) can be similarly determined as \( c_{k,r} \). Thus, \( c_{k,r} \) and \( \Phi^v(v_k,v_r) \) can be computed in time \( O(|\mathcal{V}|) \).

The initialization stage and the union stage clearly takes \( O(|\mathcal{V}|) \) time to complete. The time complexity of MMEDA is \( O(|\mathcal{V}| \cdot |\mathcal{D}|) \), where \( |\mathcal{V}| \) is the number of nodes in the network and \( |\mathcal{V}| \) is the total number of views provided by the server.

IV. EXTENSION

In this section, we consider a generalization of the MMDS problem which allows crossing-view selections, i.e., the views in \( \mathcal{V}_r \) of a client can select \( \Phi^v(v_k,v_r) \) for synthesis with DIBR. Therefore, it is necessary to examine the case that a view \( v_k \in \mathcal{V}_r \) can select views for synthesis with DIBR that may create \( \Phi^v(v_k,v_r) \) for any \( v^r \subseteq \mathcal{V} \). The initialization stage and the union stage clearly takes \( O(|\mathcal{V}|) \) time to complete. The time complexity of MMEDA is \( O(|\mathcal{V}| \cdot |\mathcal{D}|) \), where \( |\mathcal{V}| \) is the number of nodes in the network and \( |\mathcal{V}| \) is the total number of views provided by the server.

### Algorithm 2. Multi-view and Multicast Delivery Exploration Algorithm (E-MMDEA)

**Input:** A rooted tree \( T = (V, A, s) \), a universal view set \( \mathcal{V} \), a preferred-view function \( \rho_r \), and the DIBR quality constraint \( D \).

**Output:** The minimum total bandwidth consumption \( \text{cost}(\theta^*) \) of a view-selection function \( \theta^* \) to the E-MMDS problem.

**Method:**

// Initialization stage

Identify the service range \( \mathcal{V}_p \subseteq \mathcal{V}_r \), a preferred-view function \( \rho_r \), and DIBR quality constraint \( D \).

\[ \text{cost}(\theta^*) \leftarrow 0; \]

// Exploration stage

**foreach** segment \( \mathcal{V}_p \) \( \leftarrow \{ v_m, \ldots, v_M \} \) do

for \( k = m \) to \( M \) do

\[ c_{m,k} \leftarrow \min \{ c_{m,k-1}, c_{m,k-2}, \ldots, c_{m,k-D} \} + c_k; \]

\[ J \leftarrow \{ 0 \}; \]

for \( d = 2 \) to \( D \) do

\( J \leftarrow J \cup \{ d \}; \)

\[ \Theta(d) \leftarrow \{ \theta(v) = (v_m, v_r) \mid r - d \leq D, \]

\( \leq k, v_m \leq v_r \leq v \leq v_r \notin E_d \}; \]

\( \Gamma_d \leftarrow \text{all possible view selection combinations by the views in } I_d \text{ or } E_d \) such that each selection combination satisfies \( V_p \) w.r.t. \( D \).

\( \text{return cost}(\theta^*) \);
to $c_{m,k-d}^t, c_k$ and $\sum_{v \in E_d} \Theta^v \{v\} \in E_d$, where $j \in J = \{0, 1, 2, \ldots \}$.
\[ \sum_{v \in E_d} \Theta^v \{v\} \in E_d \]
where $\Gamma$ is the computation of $c_{m,k}$. In other words, $c_{m,k}^t$ is obtained by looking up the previous derived values $c_{m,k-d}^t$ and $c_k$, together with the expansion cost, where each view $v$ selects $\theta(v), \ell$ and $\theta(v), r$ for synthesis with DIBR with $\theta(v) \in \Gamma$, and each view $v$ in $E_d$ selects $vk_{k-d}$ and $vk_{k}$ for synthesis. If $F(d, \Gamma) \cap \{vk_{k-d}, \ldots, vk_{k-d}\} \neq \emptyset$, i.e., $\Gamma$ contains at least one additional fixed view, the value of $c_{m,k}^t$ can be derived according to $c_{m,k-d}^t, c_k$ and $\sum_{v \in E_d} \Theta^v \{v\} \in E_d$.

All possible $F'$ in the computation of $c_{m,k}^t, F'$, where $c_{m,k-d}^t$ is defined similarly to $c_{m,k}, F'$ with $c_{m,k-d}^t$ as the minimum total bandwidth consumption for the fixed views in $F'$ must be transmitted directly. In other words, $c_{m,k-d}^t$ is the minimum total bandwidth consumption to serve all clients subscribing views from $\text{vk}_{m-d} \text{vk}_{k-d}$ such that two boundary views $\text{vk}_{m}, \text{vk}_{k-d}$ and all views in $F'$ must be transmitted directly. The corresponding view-selection function for $c_{m,k}^t$ is denoted by $\Gamma_{m,k}$, and will be stored in the set $\bar{\Gamma}_{m,k}$ for further reference. After finding $c_{m,k-d}^t$ for all $k = m, m+1, \ldots, M$, the minimum cost $c_{m,k}^t$ is derived by the minimum of $c_{m,k}^t$ and $c_{m,k-d}^t$ for all possible $\Gamma \in \Gamma_d$, where $d \in \{1, 2, \ldots \}$.

\[ \min \{D, k-m \}-1 \}

\section{V. Heuristic Algorithm Design}

\subsection{A. Design of H-MMDEA}

Even though MMDEA is able to optimally select optimal views and deliver optimal multi-view videos over IP networks, the algorithm results in a high computational cost for the network with large $D$. To address this issue, we propose a heuristic algorithm called H-MMDEA to acquire the solution in a linear time. Recall that the complexity of MMDEA comes from two parts. First, it examines a great number of view transmissions as performing each exploration. To reduce the complexity, we design H-MMDEA to improve multicast delivery by iteratively examining alternative transmissions, instead of examining large number of possible view transmissions for the optimal solution.

H-MMDEA includes three steps: 1) Desired View Setting, 2) Alternative View Examination, and 3) Multicast Delivery Adjustment. In the first step, the multi-view video server delivers the views directly based on the desired views clients request. In the second step, the routers in the network examine alternative view transmission for desired views. In the third step, the server selects the most efficient alternative view transmission and adjusts the multicast delivery. H-MMDEA iteratively processes steps 2 and 3 if alternative view transmissions have a better performance. Algorithm 3 details H-MMDEA.

\section{VI. Simulations}

In this section, we compare MMDEA with the existing multicast scheme in a real network [16] and in the networks generated by Inet [17].

We first conduct the simulation in a small real network called the Kentucky Datalink Network (K) with 754 nodes and 895 links, and a large network (L) with 10000 nodes and 20576 links. We compare MMDEA with the original multicast delivery scheme (OMDS), in which all desired views are multicast separately to the clients without exploiting DIBR.

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**Algorithm 3. Heuristic View and Multicast Delivery Exploration Algorithm (H-MMDEA)**

**Input:** The multicast SPT routing $G = (V, E)$; request view $y_{tk}$ for each $t \in T$ and $k \in K$.

**Output:** The set of selected views $M_s$ and multiview video multicast delivery $x_{ijk}$ for each $(i, j) \in E$ and $k \in K$.

**Method:**

1. Obtain a postorder set $\tilde{V}$ which orders nodes in $G$.
2. Initial setting: $M_i = \{\}, M_k^{\text{best}} = \{\}, u(M_k^{\text{best}}) = 0$, for $i \in V, k = 0, C = \{\}, M_s$ and $u(M_s)$ can be obtained by directly delivering desired views.
   
   while $u(M_s) < u(M_k^{\text{best}})$ do
     
     foreach $v_k \in M_s \setminus \{v_1, v_K\}$ do
       
       $S(v_k) \leftarrow \{\{l, r\} | r-l \leq D, \leq k < l, r, l \in M_s\}$;
       
       foreach $\{l, r\} \in S(k)$ do
         
         foreach $i \in T$ do
           
           if $M_i = \{v_k\}$ then
             
             $M_i = \{l, r\}$,
           
           foreach $i \in \tilde{V} \setminus T$ do
             
             $M_i = \bigcup_{i \in \tilde{V}} M_i$;
             
             $u(M_i) = \sum_{i \in V} u(M_i) + |M_i|$;
             
             if $u(M_i^{\text{best}}) > u(M_i^{\text{best}})$ then
               
               $M_i^{\text{best}} = M_i^{\text{best}}$;
           
           if $u(M_s) > u(M_i^{\text{best}})$ then
             
             $M_i = M_i^{\text{best}}$,
         
       return

We change the number of views, quality constraint $D$, and the size of networks, i.e., number of clients in the simulation. The performance metrics include the total bandwidth consumption in the network and the percentage of clients exploiting DIBR to synthesize the desired views. All algorithms are implemented in an IBM server with four Intel Xeon E7-4820 2.0 GHz CPUs and 48 GB RAM. Each simulation result is averaged over 100 samples.

**A. Scenario 1: Size of Networks**

Fig. 3 compares MMDEA with OMDS under the Kentucky Datalink Network (K) and the large network (L) with different numbers of views, where $D$ is 5. The total bandwidth consumption increases in both schemes with the number of views. Nevertheless, bandwidth consumption for MMDEA is about 35% lower thanks to the efficient aggregation of views with DIBR. More importantly, the improvement becomes more significant when clients are provided with an expanded selection of view. In MMDEA, not all desired views need to be transmitted. As the number of views exceeds 20, the total bandwidth consumption saturates in both schemes. For OMDS, almost all views are transmitted, while any nearby two transmitted views in MMDEA can be separated with at most $D-1$ views.

Fig. 4 shows the percentage of clients receiving two views in the Kentucky Datalink Network (K) and large network (L). The number of views $|V|$ is set to 12. When $D$ increases, the percentages of clients synthesizing the desired view in the two networks also grows, which implies that it is not
necessary to directly transmit the desired views to all clients since many clients can synthesise their desired views from views subscribed by other clients, thus effectively reducing total bandwidth consumption.

**B. Scenario 2: Synthesized range**

Fig. 5 evaluates MMDEA with different value of $D$ for the Kentucky Datalink Network (K) and the large network (L) with the number of views set at 12. The total bandwidth consumption is efficiently reduced as $D$ increases, indicating that it is unnecessary to set a large $D$ because marginal improvement becomes small as $D$ increases, thus indicating that a small $D$ (i.e., limited quality degradation) is sufficient to effectively reduce bandwidth consumption in the networks.

**C. Scenario 3: Number of views**

Fig. 7 shows the impact of DIBR on different numbers of views in a video. The bandwidth consumption in both schemes increases as the video contains more views. The reason is that more views need to be transmitted since desired view of each client follows the uniform distribution. Nevertheless, the result manifests that MMDEA consistently outperforms the OMDS for varied numbers of views.

**D. Scenario 4: Number of clients**

Fig. 6 shows that the total bandwidth consumption increases in both schemes with more clients. Performance is evaluated under the Kentucky Datalink Network. $|V|$ and $D$ are respectively set to 12 and 5. Nevertheless, MMDEA achieves an improvement of about 50% thanks to the efficient aggregation of views with DIBR. More importantly, it is worth noting that the improvement becomes more significant with more clients in the network because it is easier to find a nearby client that subscribes to a close left view or right view, thus increasing the chance to leverage DIBR.

**E. Scenario 5: Distribution of client preferences**

Figs. 8 and 9 examine the impact of the distributions of the preferred views. Performance is evaluated using the Kentucky Datalink Network, and the desired views follow the Uniform distribution (U), Gaussian distribution (G) and Zipf distribution (Z) in this scenario. The Zipf distribution is written as $f(l; s, |V|) = (1/l^s)/(\sum_{n=1}^{|V|} 1/n^s)$, where $l$ is the preference rank of a view, $s$ is the value of the exponent characterizing the distribution, and $|V|$ is the number of views. We set $s = 2$ and $|V| = 12$ in the Zipf distribution, which means that clients prefer subscribing only a few important views. In the Gaussian distribution, the smaller variance represents that the desired views of clients are more concentrated. The mean is set at 0.5$|V|$, and the variance is set at 4 and 16 in this paper. The result indicates that the transmitted views can be more efficiently aggregated as the client requirements are more concentrated in only a few views. This conforms that many applications in which a few major views (i.e., the front sides of objects) are more preferred by users.

In Figs. 9 and 10 it is observed that the bandwidth consumption in both the Gaussian and Zipf distributions is also smaller than that in the uniform distribution.

**VII. Conclusions**

With the recent emergence of 3D-supported TVs, this paper proposes a method for bandwidth-efficient multi-view 3D video multicast over IP networks. By exploiting the DIBR, simulation results show the proposed MMDEA algorithm effectively minimizes total bandwidth consumption by 35% in large networks, and the improvement increases with the number of views and clients, especially in practical scenarios where the clients are more interested in a few select front views in multi-view 3D videos.

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