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Optimized Joint Unicast-Multicast Panoramic Video Streaming in Cellular Networks

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***Abstract*—In this paper we present Joint Unicast-Multicat Panoramic Streaming (JUMPS) over the cellular network. JUMPS optimizes the resource allocation for a group of eMBMS (evolved Multicast Broadcast Multimedia Systems) users to enhance their experience while leveraging the inherent diversity in both users' network conditions and field of view (FoV). The key intuition is combining unicast and multicast, for tiled panoramic content, would enable facilitate using the right amount of resources for every tile considering the tile popularity and receiving user link quality. We compare JUMPS performance to state-of-the-art solutions and show that it significantly improves users' received FoV bitrate and reduces their battery by reducing the number of resource blocks that users have to listen to. These results are consistent across various scenarios that vary across user group link conditions, FoV diversity, and available network resources.**

***Index Terms*—360-degree Video, Panoramic Video Streaming, Video Tilling, FoV Optimization, Spherical Video**

I. Introduction

The advance in Virtual reality (VR) and Augmented reality (AR) technologies fuels the popularity of panoramic media. The global VR market is anticipated to reach 44.7 billion USD by 2024 [1]. The users' appetite to immersive video is spreading to various applications. In a recent survey [2], approximately 45% of users expect to use VR-based tours and entertainment videos. Additionally, 30% of users expect to use VR for live events and education. Realizing these expectations implies developing novel solutions to optimally stream immersive content while efficiently using scarce wireless resources.

Streaming high-quality panoramic content requires using Ultra-HD resolutions, e.g., 4K and above, which impose high data-rate requirements than traditional videos. Hence, several solutions, e.g., [3], [4] optimize panoramic content delivery by considering various techniques. By exploiting the limited field of view (FoV) of end-users, the streaming quality of different portions of the panorama is tuned to ensure the best viewable quality. This approach is known as FoV optimization and is commonly combined with rate adaptation techniques to accommodate operating conditions, e.g., variable link quality. It is also common that such optimizations leverage tiled encoding by which the video is split into multiple non-overlapping tiles. However, these techniques would not suffice to enable streaming popular content to a large number of users. In this scenario, multicasting the content evolves as a key solution to optimally utilize network resources and delivering high-quality content.

Multimedia Broadcast Multicast Services (eMBMS) [5] standardize the architecture and delivery mechanisms of content to a large number of users in cellular systems. The content is delivered over one or more base stations (BS) within an eMBMS *service area*. A Multicast Coordination Entity (MCE) is a special eMBMS node responsible for the administration of the radio resources of service area BSs. The MCE manages the allocated eMBMS radio resources and determines the modulation and coding schemes utilized to deliver the content. Hence, the design of MCE resource management algorithms plays an essential role in the performance of eMBMS. The design of MCE resource management solutions is addressed in various papers, e.g., [3]–[8]. However, some solutions are limited to traditional videos [6]–[8]; i.e., they are agnostic to FoV optimization. Recent work, e.g., [3], [4], optimize eMBMS resource management by splitting users into multiple groups of distinct link conditions and identify the quality of multicasted tiles in each group. These solutions overlook the independence of encoded tiles that can be leveraged to improve resource utilization and user experience.

The independence of tile encoding and user FoV enables using different transport modes for streaming tiles in multi-user scenarios. Hence, tiles can be sent using both unicast and multicast to ensure the best user experience and improve system resource utilization. Additionally, hybrid transport is orthogonal to other network-level and user-level eMBMS resource management designs and hence can be combined with them to further improve resource utilization and user experience. In this paper, we formulate the joint unicast-multicast delivery of panoramic video (JUMPS) as an optimization problem for a group of users. We extensively investigate the performance of the JUMPS and compare it to state-of-the-art solutions while considering scenarios varying in user link conditions, FoV diversity, and available network resources. Our results show that JUMPS improves the FoV bitrate of users and reduces their battery consumption.

The rest of the paper is organized as follows: Section II presents relevant background and related work. The proposed technique formulation and implementation are covered in Section III followed by our performance evaluation in Section IV. We then conclude and present future work in Section V.

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II. Background and Related Work

A. Optimized panoramic video streaming

Optimizing the delivery of panoramic video in resource-constrained systems leverage multiple dimensions to compromise the tradeoff between streaming quality, robustness, and network load. FoV-based optimized delivery represents a common technique in delivery solutions [9], [10]. These solutions use various FoV prediction strategies like simple extrapolation to advanced deep-learning techniques. The predicted FoV is leveraged in various ways from only sending the predicted FoV portion of the panorama [9], [10] or sending this FoV with a higher quality in comparison to the rest of the panorama. These solutions are made possible by leveraging various coding techniques including tiled coding [11] and layered encoding [12]. In tiled coding, the panorama is projected to a two dimensional and is then split into a matrix of smaller tiles that are independently encoded. While tiled encoding increases the flexibility of FoV streaming, it introduces encoding overhead. It is reported that FoV optimizations may reduce the bandwidth requirements to 25% of the full panorama [13].

B. eMBMS resource allocation

eMBMS introduces a few nodes to the Evolved Packet Core (EPC) architecture to enable point-to-multipoint communication over shared bearers. These nodes include MCE (Multi-cell/multicast Coordination Entity), MBMS-GW (MBMS Gateway) and BM-SC (Broadcast Multicast Service Centre). The MCE is responsible for radio resource management that involves BS's PHY/MAC configurations and session-level decisions, such as user grouping and video quality selection. The BM-SC interfaces with content providers and control service level functions, such as session management. The MBMS-GW is responsible for forwarding MBMS packets to each BS involved in the service. eMBMS defines a single frequency network (SFN) [7] mode in which multiple BSs synchronizes the content transmission over the same physical resources. More recently, Single Cell Point to Multipoint (SC-PTM) is introduced in 3GPP Release 13 to ensure a flexible deployment of multiple services and improve the resource utilization efficiency. Additionally, MBMS operation on Demand (MooD) enables dynamic switching between Unicast and Broadcast over LTE, based on configured triggers.

Optimizing the utilization of eMBMS resources necessitates handling the diversity in underlying operating conditions to combat physical constraints, such as user link quality diversity and base station (BS) load diversity. When users have distinct link quality, the MCE has to set the modulation and coding scheme (MCS) to the weakest link to ensure that the stream is decodable by all users. Hence, users with better channel conditions have to watch low-quality content leading to reducing the overall user experience. Additionally, they have to receive content for a longer time leading to excessive battery consumption. Such negative impacts can be reduced by *grouping* users [6] into multiple non-overlapping sets of users with similar network conditions and split eMBMS resources among these groups to ensure the best experience for different user groups. SFN clustering [7] represents another technique by which the service area is split into multiple non-overlapping SFNs that can be configured separately. This technique allows changing the quality of served content in the BSs of the service area to accommodate diversity in both BS load and user link quality in various BSs. User grouping and SFN clustering can be combined to achieve optimal resource utilization and user experience [8].

C. Optimized Panoramic Streaming in eMBMS

In [14], authors propose DMAF as a dynamic SFN cluster formation algorithm that maximizes the system aggregate data rate (ADR) assuming scalable video coding for the distributed content. DMAF achieves this by creating several SFN Areas based on the heterogeneity of the channel quality indicators (CQIs) and users' geographical distribution and deliver various video qualities in these areas. DMAF also employs user grouping depending on users' CQI. Thus, all users receive the base quality while users in good channel conditions receive higher quality.

In [4], Ahmadi et al. propose a multicast DASH-based tiled streaming solution using a rigorous analysis of 1300 panoramic videos, including tile weights and rate adaptation. The proposed algorithm divides users into subgroups based on their channel conditions and tile weights and determines the bitrate for each tile in each subgroup. Moreover, tiles in the FoV are served using the highest bitrate, while other tiles are assigned bitrates proportional to the probability of changing the FoV. Eltobgy et al. [3] propose VRCast to ensure smooth FoV quality and conserve the mobile battery while trying to achieve fair resource distribution. Specifically, VRCast proposes two dynamic programming algorithms. The first split users to a number of groups and assign each group a number of resources. The second one defines the quality of every streamed tile in each group. VRCast is evaluated using trace-driven simulations that showed its superior performance to the state-of-the-art. These solutions only consider multicasting transport and overlooked the potential of hybrid transport modes that we explore in JUMPS.

III. Joint Unicast and Multicast Panoramic Streaming

A. JUMPS Overview

JUMPS leverages the independence of tile encoding and the diversity in user FoV and channel conditions to improve both network resource utilization and user experience. In eMBMS systems, it is common that users are split into groups with similar link condition, which is typically captured by their reported channel quality indicator (CQI). Within every group users still feature a noticeable diversity in their link condition and FoV tiles. The reported CQI is directly mapped to the spectral efficiency of individual users. In a group including users with CQI between 1 and 7, the highest spectral efficiency is ten times the lowest spectral efficiency. Typically, the spectral efficiency of an eMBMS group is set to the lowest one of all users to ensure proper reception of multicasted data. In tiled panoramic videos, users could be exploring different areas of the panorama. These areas map to different sets of tiles. Hence, the popularity of different tiles dynamically varies over time. Hence, multicasting all tiles could lead to inefficient use of resources. JUMPS is designed to optimize the user experience while allocating eMBMS resources for a group of users by deciding the optimal transport for every tile. JUMPS achieves this by formulating the optimization program presented in the following section.

B. JUMPS Optimization

We consider a set of users, denoted as U, watching a panoramic tiled video in SC-PTM eMBMS mode. The video is split into multiple tiles that are encoded to a number of quality representations forming a set denoted as Q. Users are generally watching different portions of the panorama with the aggregate of these portions mapping to a set of tiles denoted as T. We assume that users' FoV information is provided to JUMPS through the system [3]. We use U_t to denote a subset of users watching tile t. We also use b_{tq} to denote the bitrate of tile $t \in T$ when streamed at quality $q \in Q$. Additionally, we use σ_u to denote the spectral efficiency of user $u \in U$. The users for the multicast group that is served content at the minimum spectral efficiency in the group, denoted as σ. The group is assigned R RBs for its traffic.

We formulate an optimization problem that maximizes the total user experience subject to resource constraints while leveraging both unicast and multicast for video transmission.

Program 1:

$$\max \sum_{t \in T} \sum_{q \in Q} \sum_{u \in U_t} \omega_{tu} \log(b_{tq}) \{m_{tq} + \mu_{utq}\} \tag{1}$$

such that

$$\sum_{t \in T} \sum_{q \in Q} \left(m_{tq} \left\lceil \frac{b_{tq}}{\sigma} \right\rceil + \sum_{u \in U_t} \mu_{utq} \left\lceil \frac{b_{tq}}{\sigma_u} \right\rceil \right) \leq R \tag{2}$$

$$\sum_{q} m_{tq} \leq 1, \qquad \forall t \in T \tag{3}$$

$$\sum_{q} m_{tq} + \mu_{utq} = 1 \forall t \in T, u \in U_t \tag{4}$$

$$Variables \quad m_{tq}, \mu_{utq} \in \{0, 1\} \forall t \in T, q \in Q, u \in U \tag{5}$$

where m_{tq} is a binary variable set to 1 when tile t is multicasted at quality q and μ_{utq} is a binary variable set to 1 when tile t is unicasted at quality q to user u. ω_{tu} represents the importance of tile t for user u. This importance can be set in a binary fashion by setting it to 1 if the user FoV includes tile t. Alternatively, the importance may be set to represent tile t importance to the user experience. It is known for example that center tiles are more important to user experience than edge tiles. Hence, position-dependent weights can be used.

The logarithmic function in the objective reflects the marginal utility decreases as the quality rate increases. Additionally, it will help to reduce the variation in quality across different tiles. Eq. (2) ensures that the total resources for both unicasted and multicasted tiles are limited to the available resources. Additionally, constraints (3) and (4) ensure that every user receives every tile in his FoV only once. The objective and constraints of Program 1 are linear in the problem binary variables. Hence, Program 1 can be solved using any integer programming solvers.

C. JUMPS Operation

With JUMPS, users would receive their tiles over both unicast and multicast bearers. To ensure that unicasted tiles are not delayed, e.g., by other unicast traffic, we propose that every eMBMS device maintains a dedicated high priority bearer for unicasted tiles. This can be attained in long term evolution (LTE) networks by assigning this bearer a suitable QoS class identifier (QCI). We propose setting QCI 80 for unicasted tiles bearer. This QCI is suitable for low latency evolved mobile broadband applications with a tight packet budget delay (~10 ms) and loss error rate (~10^{-6}).

This design also implies the ability of the base station scheduler to support class-based scheduling. Note that as program 1 is solved, the MCE would instruct the base station how the group RB budget is split for both multicasted and unicasted tiles. The number of RBs that JUMPS' user would listen to would be smaller than the total number of allocated RBs, which would be split between the RBs used by the multicast traffic channel (MTTC) and RBs used for unicasted tiles. Note that JUMPS would use fewer RBs for both MTTC as some of the tiles would be used for unicast traffic. Additionally, unicasted tiles will generally need fewer RBs as they are transmitted at the user spectral efficiency, i.e., not the group spectral efficiency. Hence, JUMPS is expected to reduce user battery consumption as its users listen to fewer RBs.

Hybrid transport for JUMPS can also be implemented in a multi-tier scenario. For example, multicasted tiles are sent over 4G eMBMS, and unicasted tiles are sent over 5G networks. However, the resource constraint should be split into two constraints in this case. These constraints are expressed as follows:

$$\sum_{t \in T} \sum_{q \in Q} m_{tq} \left\lceil \frac{b_{tq}}{\sigma} \right\rceil \leq R_{4G}$$

$$\sum_{t \in T} \sum_{q \in Q} \sum_{u \in U_t} \mu_{utq} \left\lceil \frac{b_{tq}}{\sigma_{u5G}} \right\rceil \leq R_{5G}$$

where R_{4G} and R_{5G} represent the allocated resources for the service in 4G and 5G networks, respectively; σ_{u5G} represents the spectral efficiency of user u in 5G networks.

IV. Performance Evaluation

In this section, we first illustrate our simulation setup first followed by the performance evaluation results.

A. Simulation setup

Our performance evaluation is based on a custom-built simulator using Python. We consider a panoramic video projected to a rectangular 4k frame (3840×2160) encoded to 8×8 tiles

TABLE I: Simulation Paramaters

Num. of users	5,10,20,40,80
Panorama bitrates	6, 8, 10, 14 (Mbps)
Panorama resolution	3840×2160
Tiling configuration	8×8
Group CQI	B:[2-7] | G:[8-15]
Spectral efficiency (bits/RB)	[20, 31, 50, 79, 116, 155, 195, 253, 318, 360, 439, 515, 597, 675, 733]
PoV CoV	D:(0.5, 0.2) | F:(0.25, 0.1)
η	L:1.1 | A:1.5

and four quality bitrates (6, 8, 10, 14 Mbps). These rates are selected according to 3GPP recommendations for VR services [15]. For simplicity, we assume that all tiles have the same data rate that equals the quality rate divided by the number of tiles per frame. We assume that video users are split into groups of users with similar link conditions. The CQI of each user is uniformly selected from a range of CQIs. In our simulations, we consider two CQI ranges including [2,7] and [8-15] to represent weak (W) and good (G) group link condition, respectively. We consider various group sizes ranging from 5 to 80 users. The user FoV is set to 1280×720 with the PoV randomly selected using normal distribution whose mean is set to the frame center and a tunable coefficient of variation. Such tuning enables simulating the possible diversity in users' region of interest (RoI). Specifically, we use PoV CoV (0.5, 0.2) to represent scenarios with diversified RoI (D) and (0.25, 0.1) for scenarios with focused RoI. For the diversified FoV case, the number of requested tiles observed in our simulations is 20-38 tiles for the smallest group (5 users). These numbers grow to 32-46 tile for 80-user group. In the focused FoV case, these numbers drop to 20-32 and 32-36 respectively for 5-user and 80-user groups.

We assume that each user group is allocated a number of resource blocks that can be expressed as

$$RBs = \eta\,|T|\,ceil(b_{t1}/\sigma),$$

where η represents a scaling factor ≥ 1 to reflect the abundance of system resource, $|T|$ represents the number of tiles to be streamed to users. Note that $\eta = 1$ represents the minimum number of resources needed to ensure the possibility of multicasting all tiles at the lowest quality to the user group. We use η to represent different scenarios with distinct resource availability. Specifically, we use $\eta = 1.1$ to represent scenarios with limited resources (L) and $\eta = 1.5$ to represent scenarios with abundant resources (A). Table I summarizes our key simulation parameters.

We compare JUMPS with the resource assignment algorithm of VRCast [3]. Note that VRCast scheme multicast tiles outside T at the lowest quality to ensure streaming robustness. For a fair comparison, we only consider optimization over T as the robustness element can be integrated into both approaches. We solve Program 1 using Gurobi 9.0 Solver[1]. Our reported results represent the outcome of 50 runs over which users' PoV and CQI are randomly identified for the given simulation configuration. We found that JUMPS' average solution time is less than 250 millisecond for groups up to 80 users in an Intel® Core™ i7-6700HQ CPU (2.60GHz) with 8GB RAM. Hence, JUMPS solution time is sufficiently small to be used in real systems.

Our key performance metrics include the quality distribution of the streamed tiles, the average user FoV bitrate, which is estimated as the average of the bitrate of user FoV tiles, and the percentage of received RB per user which is estimated as the sum of RBs for the multicast traffic channel and the received RBs for unicasted tiles. In VRCast, users must have to listen to all RBs used for multicast, while in our approach, users receive multicast RBs and some of unicast RBs that carry their unicasted tiles. Note also that JUMPS multicast RBs are typically fewer than VRCast multicast RBs.

B. *Performance Evaluation Results*

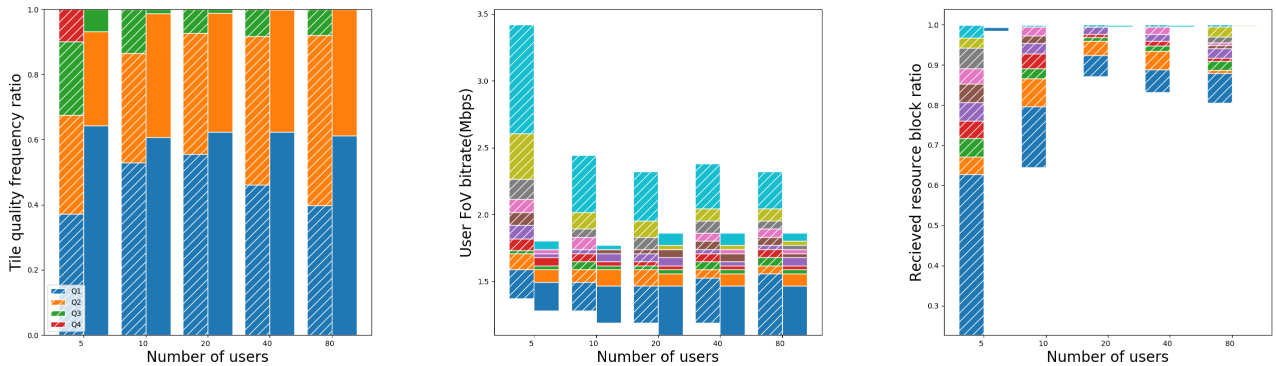
We present the results for the following scenarios

- Users with Diversified FoV, Weak Link Condition, and Limited resource network (DWL)
- Users with Diversified FoV, Good Link Condition, and Limited resource network (DGL)
- Users with Diversified FoV, Weak Link Condition, and Abundant resource network (DWA)
- Users with Focused FoV, Good Link Condition, and Limited resource network (FGL)

1) DWL Scenario: Figure 1a plots the stacked cumulative distribution function (CDF) of tile quality and illustrates that JUMPS (hashed bars) delivers higher quality tiles than VRCast. For example, in 5-user case, JUMPS deliver 38% with Q1, 30% with Q2, 22% with Q3, and 10% with Q4 while VRCast streams around 62% of tiles at Q1, 30% at Q2, and the remaining 8% at Q3 and no tiles are streamed at the highest quality Q4. The improved tile quality is consistently observed for different sizes of user groups. The tile quality improvements naturally led to consistent improvement in the user FoV bitrate. Figure 1b plots the FoV bitrate CDF as a stacked bar plot for ten percentiles. Across all simulated group sizes, JUMPS facilitates higher FoV bitrates than VRCast. In every user configuration, the FoV bitrate of 20-60% users is higher than the highest bitrate supported by VRCast. Additionally, JUMPS also boosts the minimum FoV bitrate for all scenarios except the 80-user case. Figure 1c plots 10-percentile stacked plot CDF for the received RBs for both JUMPS and VRCast. This figure shows that JUMPS users receive much fewer RBs in comparison to VRCast users, and hence, would save in their battery consumption. The highest savings are attained with smaller user groups (5-10 users). In the five-user case, 50% of users receive less than 80% of the RBs. Our data analysis shows that 35% of tiles are unicasted in the 5-user DWL case.

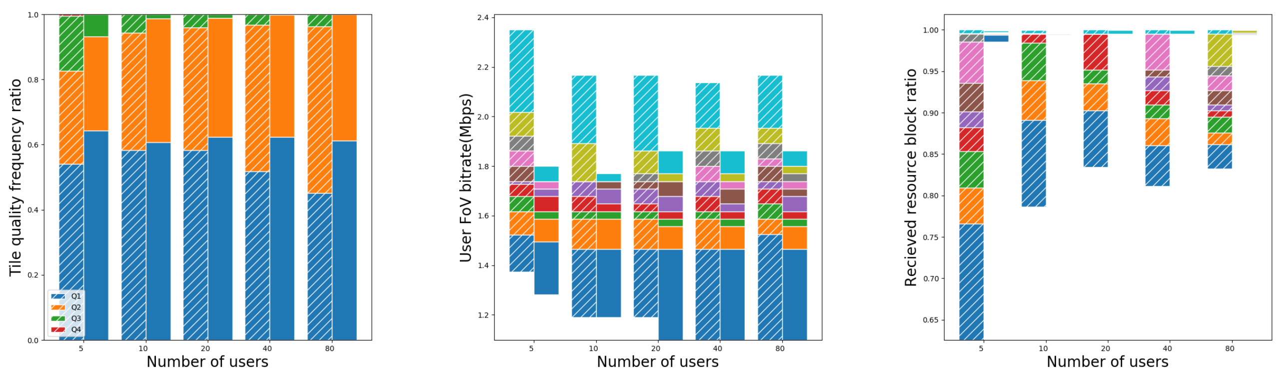
2) DGL Scenario: Figure 2 plots our key performance

[1]https://www.gurobi.com/



(a) Tile quality frequency. (b) User FoV bitrate (c) Receieved Resource Blocks

Fig. 1: Performance results for DWL scenario. JUMPS uses hashed bars while solid bars represent VRCast.



(a) Tile quality frequency. (b) User FoV bitrate (c) Receieved Resource Blocks

Fig. 2: Performance Results DGL scenario JUMPS uses hashed bars while solid bars represent VRCast.

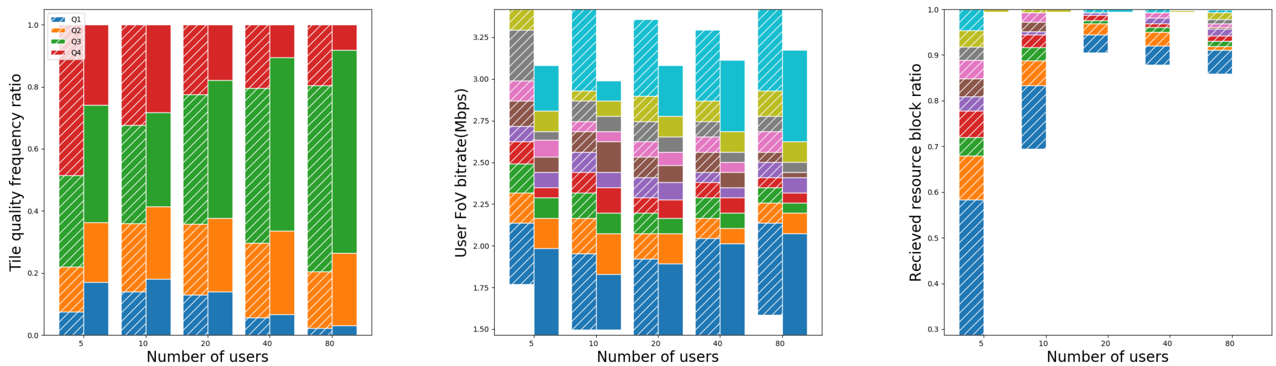
metrics for the DGL scenario and illustrates that similar performance gains would be attained for user groups with good channel conditions. Figure 2a illustrates that JUMPS transmits more tiles at higher qualities (Q2 and Q3) in comparison to VRCast for all user group sizes. For the case of 5-user group, JUMPS sends around 18% tiles at Q3 while VRCast only sends 5% of tiles at Q3. Figure 2b shows that the FoV bitrate of 10 of JUMPS users is higher than the highest datarate supported by VRCast. This improvement is attributed to the ability to unicast tiles to users with good channel conditions leading to not only improving the video quality but also reducing the power consumption as these users receive fewer RBs. Figure 2c shows that JUMPS allows $10\% - 50\%$ users across all scenarios receive at most 90% of the RBs received by VRCast users. More notable for the 5-user group case, 10% of users receive only 30% to 58% of the RBs received by VRCast users leading to substantial power savings.

3) DWA Scenario: Figure 3 shows the results for the DWA scenario. The performance results show that JUMPS maintains high performance gains for small user groups but this improvement diminishes for larger user groups with only less than 10% users showing higher FoV bitrate. Additionally, 90% or more of users have to receive 90% of the resource blocks. Hence, the performance gains for large user groups diminish in the case of abundant system resources.

4) FGL Scenario: Figure 4 shows the results of the FGL scenario. As users become more interested in a specific area of the panorama, the overlap in their FoV tiles increases, and more users are watching every tile. Hence, multicasting the tiles become more sensible and the difference between JUMPS and VRCast diminishes. This conclusion becomes evident for large user groups. However, JUMPS still outperforms VRCast in case of small user groups (5-10 users) as shown in Figures 4a-4c.

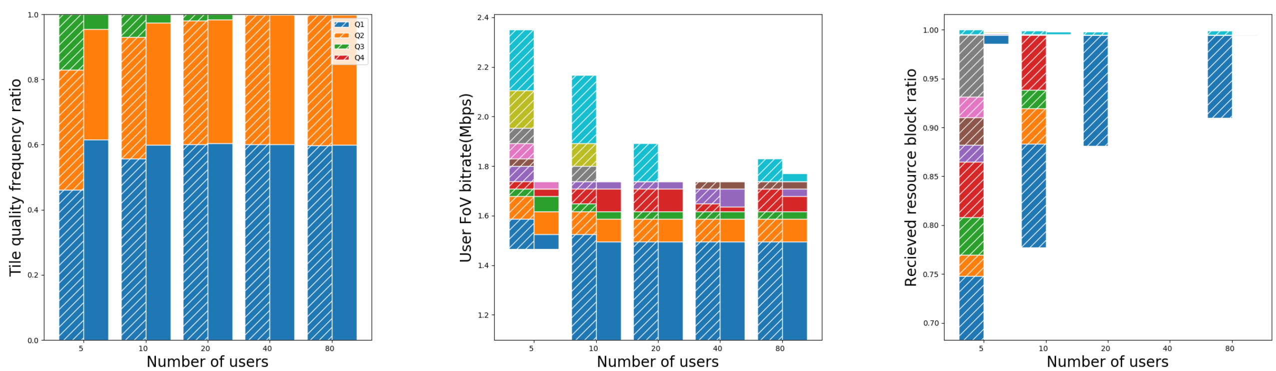
V. Conclusions

This paper proposes JUMPS as a new resource management scheme for delivering popular panoramic content to user groups in cellular systems. JUMPS exploits both unicast and multicast to improve system resource utilization and allows panoramic video users to enhance their received video quality and reduce battery consumption. Our evaluation shows that JUMPS always significantly improves the performance for small user groups independent of their link condition or



(a) Tile quality frequency. (b) User FoV bitrate (c) Receieved Resource Blocks

Fig. 3: Performance Results for DWA scenario. JUMPS uses hashed bars while solid bars represent VRCast.



(a) Tile quality frequency. (b) User FoV bitrate (c) Receieved Resource Blocks

Fig. 4: Performance Results for FGL scenario. JUMPS uses hashed bars while solid bars represent VRCast.

their FoV diversity. For larger groups, JUMPS maintains high-performance margins for scenarios with limited network resources but this margin diminishes in systems with abundant resources or when users focus on a specific region of the panorama. As future work, we consider generalizing JUMPS to manage cellular resources for multiple user groups and multiple base stations (SFN case).

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