Quality of Experience Based Beam Scheduling for SVC Video Multicast to Multiple Groups in mmWave Networks

Firat Karababa
TOBB University of Economy and Technology
Ankara, Turkey
Email: fkarababa@etu.edu.tr

Tolga Girici
TOBB University of Economy and Technology
Ankara, Turkey
Email: tgirici@etu.edu.tr

***Abstract*—Scheduling the beams and resources for a SVC video multicast to multi-groups network with beamforming is a challenging issue. In the past, there have been studies on similar issue ignoring multi-group consideration and handling different objectives. In this paper, we study a quality of experience (QoE) based beam scheduling problem for multi-group multicast mmWave networks. A linear programming formulation aiming to maximize the minimum of average user QoE of all groups where each user is guaranteed with a minimum QoE is developed. We also propose a heuristic algorithm with less complexity. Simulation results reveal that our linear programming model increases minimum average QoE compared to benchmark models. Simulations also show that the developed algorithm works close to linear programming model.**

I. INTRODUCTION

As wireless communication networks evolve the demand for bandwidth and data transmission rate gradually increases due to ever growing bandwidth consuming technologies such as live video streaming, social media and IoT. For future wireless networks which is to meet this demand a new spectrum band called millimeter-wave (mmWave) band is considered to be utilised [1]. However, mmWave comes with its own disadvantage of high-path loss due to high-frequency propagation characteristics and this issue must be handled properly [2]. Beamforming which is to focus antenna energy to cover a specific area by utilising active array antennas is a good candidate to overcome this problem [2]. Beamforming also provides with the advantage of serving the users with bad channel conditions with better video qualities in multicast networks. For video transmission applications in 5G mmWave networks, video multicasting which is to transmit a video data to a group of users requesting the same video at one time slot, is a promising technology in order to use spectrum efficiently [3]. H.264/AVC extension of Scalable Video Coding (SVC) standard introduces a layered video encoding concept and has great advantages in terms of video compression and transmission by enabling partial video transmission [4].

Authors in [5] study the reliability and throughput of the wireless channels in SVC multicast communication networks. Using a two phase based layered video multicasting scheme based on superposition coding in order to make the users with bad channel conditions get better video quality by using users with good channel conditions as relays is a good practise for employing high data rates to the system. Layered video multicasting in MIMO networks aiming better video quality received by users by taking the capacity and outage issue into account is discussed in [6]. Given an outage probability and channel capacity, using a dedicated relay node in a system consisting of a base station and users can help to increase the video quality delivered to the users in a considerable measure. Authors in [7] study bandwidth efficiency and throughput in presence-aware LTE multicast networks with active array antennas by adaptively adjusting subcarrier assignment, beam angle and beam direction. Authors in [8] study a resource allocation problem for SVC video multicast in WiMAX networks and aim to enhance quality of service (QoS) for the system. To enable this adaptivity which also provides with some spectrum efficiency, measured SINR (Signal to Interference Noise Ratio) values from users can be utilised by base station. Considering SVC video multicast in WiMAX networks, resource allocation for real time is another problem that must be resolved [9]. It is shown that for real time SVC video transmission, while retaining a minimum data rate for each user, a utility function based on user data rates can be increased for better video quality received by users. Adaptive resource allocation e.g beam, Modulation and Coding Scheme (MCS) rate and time slot for SVC video multicast in wireless networks is studied in [10]. By adaptively scheduling the transmission times and resources, it shown that the total QoE of a one group system can be maximized.

In this paper, a study on QoE based SVC multicasting to multigroups in beamformed mmWave networks is presented with a similar approach as [10]. We introduce SVC multicast to multigroups considering different type of video demands from user groups. The rest of this paper is organized as follows. Section 2 describes the considered system model and gives the problem formulations. Section 3 proposes the developed heuristic algorithm for the problem. Section 4 presents the simulation results of the model and the algorithm and Section 5 adds the concluding remarks.

II. SYSTEM MODEL AND PROBLEM FORMULATIONS

The considered network consists of a base station (BS) and a set of users that are randomly distributed on a coverage area. We consider multiple multicast groups of users, where the users in each group demand the same video. Without loss of generality we assume that a user can belong to only one group. The base station has an array of antennas and uses analog beamforming. A fixed beamwidth is chosen from a discrete set of alternatives and used throughout the multicast sessions. The base station can only transmit to a single direction at a given time. Different directions are covered by beam switching in time. We neglect the switching time between beams. An illustration of the considered network is as in Figure 1. For instance, for a beamwidth of 30^o the coverage area is spanned by 12 beams, where the coverage of each beam is fixed. In this setting, the members of a multicast group can be within the coverage region of different beams. We assume idealistic beams, where the radiation pattern is constant within the beamwidth and zero outside. In the optimization framework the base station can optionally use omnidirectional transmission at any given time instead of beamforming. On the other hand, the user equipments only have omni-directional antennas. We assume an additive white gaussian noise (AWGN) channel, distance based pathloss and log-normal shadowing. Transmission power of the base station is considered fixed.

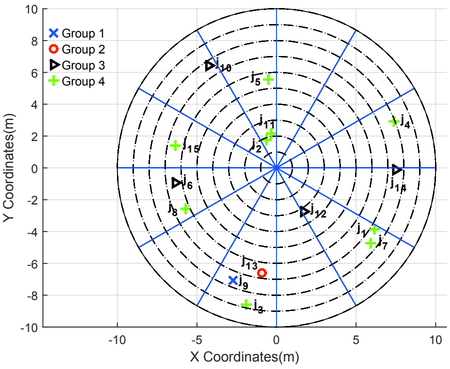

Figure 1: A sample network consisting of 30° beamwidths and 10 users of 4 groups

Time is divided into multiple slots. Video transmissions can be completed in a number of time slots. The video to be multicast is encoded according to SVC standard and consists of a number of layers that can be transmitted to users separately as in [4]. A user can decode a video layer, if it has successfully received that layer and all the lower layes. A group's users can receive a video layer if there exist a MCS rate supported by all the users of that group for the associated beam. The MCS concept and rates are as defined as in IEEE 802.11ad [12]. Each MCS level corresponds to a received signal strength indicator (RSSI) threshold. A MCS can be supported by a user if the RSSI exceeds the corresponding threshold.

We focus on one multicast session for each group which consists of a number of time slots. We assume a fraction of total time is allocated for the video transmissions. We consider the total amount of resource (Ω_{max}) as the time slots per second. This total amount of time resource is limited and shared among the groups dynamically. Each layer of video transmitted to a groups in a beam coverage receives a fraction of this total resource. In this work we are not interested which time slot is allocated to which layer, group and beam. Instead we are interested in the optimal fraction of resources that each transmission will require. Table I presents and explains the notations used throughout this paper.

Table I: Notation Used in the Paper

Notation	**Description**
i	Index of beams
$\mathcal{I}$	Set of beams, $\mid \mathcal{I} \mid= I$
j	Index of users
$\mathcal{J}$	Set of users, $\mid \mathcal{J} \mid= J$
k	Index of MCS rates
I_g	Number of beams that users of multicast group g spans
$\mathcal{K}$	Set of MCS rates, $\mid \mathcal{K} \mid= K$
l	Index of SVC layers
$\mathcal{L}$	Set of SVC layers, $\mid \mathcal{L} \mid= L$
g	Index of multicast groups
$\mathcal{G}$	Set of multicast groups, $\mid \mathcal{G} \mid= G$
q_l	Quality of experience to be gained by a user receiving SVC layer l
$\gamma^l_{j,g}$	Binary variable that shows the SVC layer l is decodable for the user j in multicast group g
τ^l_k	Time slots required per second for receiving the SVC layer l with the MCS rate k
ψ_l	Rate requirement of layer l in bits per second
m_k	Rate provided by transmitting with MCS level k
$\mu^l_{i,k,g}$	Binary variable that shows SVC layer l is transmitted using MCS rate k and beam i for group g
Ω_{max}	Number of time slots per second
$N_{i,k,j,g}$	Binary parameter that shows if user j in multicast group g supports MCS rate k for beam i
M_{min}	Minimum QoE value for each user
$u_{j,g}$	Binary parameter that shows if user j belongs to group g or not
$b_{j,g,i}$	Binary parameter that shows user j in group g is within the beam angle coverage of ith beam

We assume that in resource allocation, quality of experience (QoE) of users and groups is taken into account. QoE is a measure of degree of satisfaction achieved by a video consumer. There are other measures such as throughput, packet loss rate, delay and jitter (i.e Quality of Service) or Peak Signal to Noise Ratio (PSNR), which are objective quality measures. Unlike those, QoE is a subjective quality measure, which is typically measured by obtaining opinion scores from a panel of viewers. We assume that each SVC layer corresponds to a QoE, where q_l is the QoE corresponding to layer l. q_l values are based on the experience of end-user and gathered through a Mean Opinion Score (MOS) based study [11]. The QoE of a user is the sum of QoE's from the SVC layers that it receives.

A. Optimisation Problem Formulation

We formulate an optimisation problem to schedule the transmission of SVC layers for multiple groups of users covered by different beams, using the available MCS's. We assume that the overall QoE of a multicast group is the sum of QoE's of the users in the group. Average QoE of a group is the total QoE divided by the number of users in the group. The objective of the optimisation problem is to maximize the minimum of average QoE of each multicast group while ensuring a minimum QoE score to all users. We solve this problem by allocating the available time slot resources to the multiple groups and beams using the optimal MCS levels. The proposed Mixed Integer Linear Programming (MIP) model in this study is named Maximize the Minimum of the Group Averages (MMGA) and formulated as follows.

$$U_{MMGA}: \quad \max_{\overline{\mu},\overline{\gamma}} \left\{ \min_{g \in G} \left\{ \frac{\sum_{j=1}^{J} \sum_{l=1}^{L} q_l \gamma_{j,g}^l}{\sum_{j=1}^{J} u_{j,g}} \right\} \right\} \tag{1}$$

subject to:

$$\Omega_{max} \geq \sum_{g=1}^{G} \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{l=1}^{L} \tau_k^l \mu_{i,k,g}^l \tag{2}$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} \mu_{i,k,g}^l N_{i,k,j,g} \geq \gamma_{j,g}^l, \forall j \in \mathcal{J}, g \in \mathcal{G}, l \in \mathcal{L} \tag{3}$$

$$\gamma_{j,g}^l \geq \gamma_{j,g}^{l+1}, \forall j \in \mathcal{J}, g \in \mathcal{G}, l \in \mathcal{L}/1 \tag{4}$$

$$\sum_{l=1}^{L} q_l \gamma_{j,g}^l \geq M_{min}, \forall j \in \mathcal{J}, g \in \mathcal{G} \tag{5}$$

Equation (1) is the objective function of our proposed model and aims to maximize the minimum of the QoE averages of all groups. Binary decision variable $\gamma_{j,g}^l$ becomes 1 if user j in group g receives SVC layer l and 0, otherwise. Constraint (2) defines the total resource constraint in time slots per second for all of the layer transmissions in the system. Here,

$$\tau_k^l = \left(\frac{\psi_l}{m_k} \right), \forall k \in \mathcal{K}, l \in \mathcal{L} \tag{6}$$

and

$$\psi_l = 44 \left(\frac{2^{(QP_l - 4)/6}}{16} \right)^{-\alpha} \cdot \left(\frac{fps_l}{30} \right)^{\beta} Mbit/s, \forall l \in \mathcal{L} \tag{7}$$

where ψ_l is the bits/sec rate requirement of layer l and m_k is the bits/sec rate provided by transmitting with MCS level k [10]. Video layer parameters QP_l and fps_l are described in Section IV.

The other decision variable $\mu_{i,k,g}^l$ is a binary variable that takes value 1 if layer l is transmitted to users of group g in beam direction i using MCS level k, and 0 otherwise. Binary parameter $N_{i,k,j,g}$ takes value 1 if user j group g has RSSI enough to receive transmissions directed to beam i using MCS level k. Then, constraint (3) describes the requirement that user j in group g can receive layer l if and only if any transmission to its direction is made with an MCS level that it supports. Constraint (4) states that layer $l+1$ can be received by a user if and only if layer l is also received by this user. Finally, constraint (5) guarantees a minimum QoE value for every user in the system.

As benchmarks to the developed MILP model objective we introduce three other objective fucntions in this study. The constraints being the same as Inequality (2)-(5) the three benchmark MILP models have three different objective functions. The benchmarks are Maximize the Minimum of Group QoE Sums(MMGS) model, Maximize the Minimum QoE of all Users (MMU) model, Maximize the Total (MT) model and their objective functions are defined in Equation (8), Equation (9) and Equation (10).

$$U_{MMGS}: \quad \max_{\overline{\mu},\overline{\gamma}} \left\{ \min_{g \in G} \left\{ \sum_{j=1}^{J} \sum_{l=1}^{L} q_l \gamma_{j,g}^l \right\} \right\} \tag{8}$$

$$U_{MMU}: \quad \max_{\overline{\mu},\overline{\gamma}} \left\{ \min_{g \in G, j \in J} \left\{ \sum_{l=1}^{L} q_l \gamma_{j,g}^l \right\} \right\} \tag{9}$$

$$U_{MT}: \quad \max_{\overline{\mu},\overline{\gamma}} \left\{ \sum_{g=1}^{G} \sum_{j=1}^{J} \sum_{l=1}^{L} q_l \gamma_{j,g}^l \right\} \tag{10}$$

III. PROPOSED GREEDY ALGORITHM

Although an MILP formulation is developed in this study, it's solution is NP-hard and therefore a polynomial-coplexity beam scheduling algorithm is required to reduce the complexity and the cost. Our proposed algorithm is presented in Algorithm 1.

Let I_g denote the number of beams that users of group g spans and $n_{i,g}$ denote the number of layers transmitted by BS to the users in group g and within angle coverage of beam i using the beam i. Let f_g be a binary variable vector showing group g has further resources to continue with the algorithm i.e if $f_g = 0$ group g has resources for more multicast sessions, if $f_g = 1$ group g is out of resources for further multicast sessions.

The algorithm starts with the resource allocation to groups. Each group gets time slot resources proportional to the number of beams its users are in (Line 1). Please note that we do not divide the resources in proportions of number of users in the groups. Next step of the algorithm is an iteration in which beam and rate allocation problem is solved for each group and beam pair. This iteration is done until there are no resources left or all the layers are received by all the groups from all the beams (Lines 3-20). For the proposed algorithm omni-beam is not used as opposed to the MILP model, only the directional beams are used. At each iteration, each beam i and group g is checked. If there exists some users belonging to group g within the coverage of beam i, the transmitted layer count to this groups associated users is increased by one (Lines 8-9). The highest MCS rate supported by all the users in this group and beam for this layer is chosen (Line 10). The system variables are updated accordingly and the condition of meeting the resources are checked. If the resource constraint is violated then the variables are updated back to its iteration start states and a flag showing resources are finished for this group's users in this beam is raised (Line 16). If there is no violation, the algorithm goes with the next iteration.

Algorithm 1 QoE Based Adaptive Beam Allocation (QBABA)

```
1: Inputs: $\tau_k^l, N_{i,k,j,g}, forallj \in \mathcal{J}, \forall g \in \mathcal{G}, \forall l \in \mathcal{L}$
2: Initialize: $\gamma_{j,g}^l = 0, \quad \mu_{i,k,g}^l = 0, \forall j \in \mathcal{J}, \forall g \in \mathcal{G}, \forall l \in \mathcal{L}, n_{i,g} = 0, \forall i \in \mathcal{I}, \forall g \in \mathcal{G}, \quad f_g = 0, \forall g \in \mathcal{G}, \quad \Omega_{res}^g = \frac{\Omega_{max}}{I_g}, \forall g \in \mathcal{G},$
3: while $\exists g$ s.t. $f_g = 0$ do
4:   for $i \in \mathcal{I}, g \in \mathcal{G}$ do
5:     if $\exists j$ s.t. $b_{j,g,i} = 1 \wedge n_{i,g} < L$ then
6:       $\gamma_{j,g}^{\prime l} \leftarrow \gamma_{j,g}^l \forall j, g, l$
7:       $\mu_{i,k,g}^{\prime l} \leftarrow \mu_{i,k,g}^l, \forall i, k, g, l$
8:       $n_{i,g} \leftarrow n_{i,g} + 1, \; l^* = n_{i,g}$
9:       $\gamma_{j,g}^{\prime l^*} \leftarrow 1$
10:      $\mu_{i,k^*,g}^{\prime l^*} \leftarrow 1$, for $k^* \leftarrow max\{k \mid N_{i,k,j,g} = 1\}$
11:      if $(\Omega_{res}^g - \tau_{k^*}^{l^*} \geq 0)$ then
12:        $\Omega_{res}^g \leftarrow \Omega_{res}^g - \tau_{k^*}^{l^*}$
13:        $\gamma_{j,g}^l \leftarrow \gamma_{j,g}^{\prime l}, \forall j, g, l$
14:        $\mu_{i,k,g}^l \leftarrow \mu_{i,k,g}^{\prime l}, \forall i, , k, g, l$
15:      else
16:        $f_g = 1$
17:      end if
18:    end if
19:  end for
20: end while
```

IV. SIMULATION RESULTS

To evaluate the simulation results of MMGA model with MMGS, MMU and MT models together with QBABA algorithm, extensive simulations are performed. We solved the model using GAMS optimisation tool and simulated the GAMS results and the heuristic algorithm using Matlab R2014b. We have considered a network that consists of 100 users and a BS. The users are divided among 4 groups and a user can belong to one and only one group. Users are randomly distributed to the groups with some weights i.e group 1 has 1x probability to have a user whereas group 2-3-4 has 2x-4x-8x probability to have the same user. The users are randomly distributed to the network. There are 9 MCS rates and 8 SVC layers each QoE of which may differ. QP_l, fps_l and associated q_l values are taken from [11]. α and β values are 1.1 and 0.55. The MCS rates indexed from 13 to 21 in IEEE 802.11ad are used. The transmission power of BS antenna is 200 mW and fixed. The path loss model and the formulation for received power is as in [3] and expressed as Equation 11 where G_T and G_R are transmitter and receiver antenna gains, P_T is transmit power, $\mathcal{C}$ is a constant, PL_0 is the path loss at 1 meter, a is path loss exponent which will be taken 2 throughout this study, d is the distance between transmitter and receiver antennas. PL_0 can be calculated by using Equation 12 where λ is the wavelength of the 60GHz signal which is commonly used in mmWave networks [3]. There are 100 slots per second and each user is guaranteed to be given a QoE score of 2.7. We have simulated the system for four different beamwidth; 30°, 60°, 90°, 180°. The simulation parameters are summarised in Table II.

$$P_R = G_T + G_R + P_T - \mathcal{C} - PL_0 - 10a\log_{10}(d) \tag{11}$$

$$PL(dB) = 10log_{10}\{(4\pi/\lambda)^2 d^a\} \tag{12}$$

Table II: Simulation Parameters

Parameters	**Values**
Total amount of beams, I	12,6,4,2
Total amount of users, J	100
Total amount of MCS rates, K	9
Total amount of SVC layers, L	8
Total amount of multicast groups, G	4
Quality of experience to be gained by a user receiving SVC layer l, q_l	{1.2, 0.8, 0.7, 0.6, 0.6, 0.4, 0.4, 0.4}
Number of time slots per second, Ω_{max}	100
Minimum QoE value for each user, M_{min}	2.7
MCS rates, m_k	{693, 866.25, 1386, 1732.5, 2079, 2772, 3465, 4158, 4504} Mbps
QP_l	{46, 42, 38, 34, 30, 26, 22, 18}
fps_l	{7.5, 7.5, 7.5, 15, 15, 15, 30, 30}

The proposed MILP model with 3 other benchmark MILP models and the proposed MILP model with the proposed heuristic algorithm is simulated as shown in Figures 2-3.

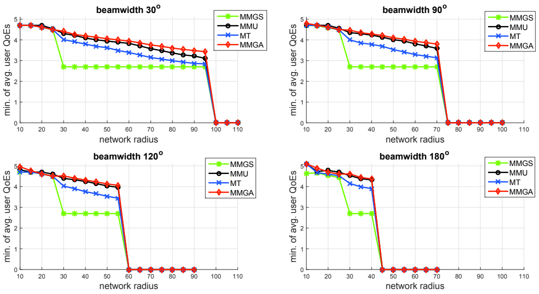

Figure 2: Average QoE comparisons for 4 different models

Figure 2 shows that smaller beamwidth provides with better system coverage. This is of course due to the physical advantage of beamforming antennas. It is clear that the proposed model which is MMGA has the best performance over the other models. MMGS model is the worst model since it has nothing to do with user average QoEs rather the group sum QoEs are more concerned. Therefore MMGS model can be considered as worst model in our case. The groups with many users will naturally have high sum QoE values whereas the groups with less users will have less sum QoE. MMGS model will try to increase the sum QoE of the group with less users and to be able to this the user QoEs of the group with many users will be forced to the minimum value which is M_{min}. Therefore, the minimum of average user QoEs of groups will

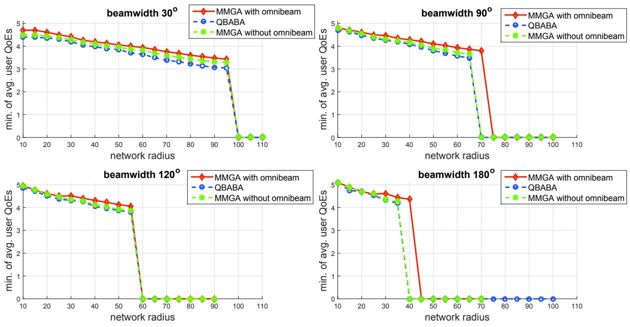

Figure 3: Average QoE comparisons for MILP model and heuristic algorithm

be $Mmin$ which is 2.7 for our simulations. This result can be clearly observed in Figure 2. From the simulation results, it can be seen that the MT model also works worse than MMGS model. This is due to the reason that MT model tries to increase the total sum QoE of the system and this is not concerned with user average QoEs. However MT model still works better than MMGS model since MT model does not force a set of users' QoE values to minimum. The performance of MMU model is close to MMGA. This result can be justified since always trying to increase the worst user QoE of the system serves as increasing the minimum group average QoE. The developed algorithm is actually works with a similar logic to MMU model where it aims to perform close to MMGA model. Since the performances of MMGA and MMU models are pretty close it is proper to compare the MMU inspired algorithm with MMGA model.

Figure 3 shows the simulation results of the proposed MILP model MMGA and proposed algorithm QBABA. The MMGA model is simulated for both omni-beam is used case and omni-beam is not used case. Since omni-beam is not used in QBABA algorithm, the performance of the algorithm can be better compared with MMGA in this way. From the results it can be seen that the performance of omni-beam used MMGA case is always the best whereas the performance of QBABA is close to the performance of MMGA with no omni-beam used case. It can be stated that as beamwidth increases and gets close to the width of omni-beam which is 360^o, the performances of MMGA with omni-beam, MMGA without omni-beam and QBABA get closer. This is understandable since as the beamwidth gets higher it gets close to omni-beamwidth and the performances of models and the algorithm get more close.

From Figure 2 and Figure 3 two results can be deduced. The first one as the beamwidth used in the system is increasing, the system coverage is decreased. The second result is that as the beamwidth used in the system is increasing, the minimum of average QoEs of multicast groups is increasing. To decide which beamwidth to use within the system, system designer should evaluate these two aspects and decide according to the need of the system.

As shown in simulation results our developed MILP model outperforms all the other benchmark models. Also simulation results reveal that our proposed heuristic algorithm is within the 10 percent performance interval of proposed MILP model which means the proposed algorithm can solve the problem with less complexity and time with confidence.

V. CONCLUSION

A QoE based adaptive beam scheduling problem for multi-group multicast mmWave networks is studied. A linear programming formulation aiming to maximize the minimum of average user QoE of all groups where each user is guaranteed with a minimum QoE is developed. We also propose a heuristic algorithm with less complexity. Simulation results reveal that our linear programming model increases minimum average QoE compared to benchmark models. Simulations also show that the developed algorithm works close to linear programming model. We propose an MILP model and showing it to be NP-hard we also developed an heuristic algorithm. Our simulation results show that proposed algorithm stays in a 10 percent performance interval to the MILP model.

As future work, instead of fixed beamwidth for each beam, varying beamwidth for each beam can be studied. Also a power optimization perspective can be added to the study instead of using fixed transmit power for the antenna.

REFERENCES

[1] Rappaport T.S., et al.: 'Millimeter wave mobile communications for 5G cellular: It will work!', *IEEE Access*, 2013, **1**, pp. 335–349

[2] Rappaport T.S., et al.: ' Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results', *IEEE Comm. Magazine,*, 2014, **52-2**, pp. 106–113

[3] Park H., Park S., Song T., Pack S.: 'An incremental multicast grouping scheme for mmWave networks with directional antennas', *IEEE Commun. Lett.*, 2013, **17**,(3), pp. 616–619

[4] Schwarz H., Marpe D., Wiegand T.: 'Overview of the scalable video coding extension of the H.264/AVC standard', *IEEE Trans. on Circuits and Systems for Video Tech.*, 2007, **17**,(9), pp. 1103–1120

[5] Elgendi M., Nasr O.A., Khairy M.M.: 'Cooperative multicasting based on superposition and layered coding', *IET Communications*, 2014, **8-3**, pp. 267–277

[6] Hwang D., Chau P., Shin J, Lee T.J.: 'Two cooperative multicast schemes of scalable video in relay-based cellular networks', *IET Communications*, 2015, **9-7**, pp. 982–989

[7] Chu M., Yang Q., He Q., Kwak K.S.: 'Resource allocation for preference-aware multicasting in active array aided LTE networks', *Wireless Communications and Signal Processing (WCSP), 2015 International Conference on*, 2015

[8] Huang C.W., Wu P.H., Lin S.J., Hwang J.N.: 'Layered video resource allocation in mobile WiMAX using opportunistic multicasting', *WCNC 2009*, 2009

[9] Deb S., Jaiswal S., Nagaraj K.: 'Real-time video multicast in WiMAX networks', *IEEE Infocom 2008*, 2008

[10] Park H., Singh K.D., Piamrat K., Bonnin J.-M., Viho C.: 'Adaptive beam scheduling for scalable video multicast in wireless networks', *Electronics Letters*, 2014, **50**, pp. 1165–1167

[11] Singh K.D., Piamrat K., Park H., Viho C., Bonnin, J.M.: 'Optimising QoE for scalable video multicast over WLAN', *Proc. Int. Symp. on Personal, Indoor and Mobile Radio Communications*, 2013, pp. 2131–2136

[12] 'IEEE Std 802.11ad-2012, IEEE 802 part11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications - Amendment 3: Enhancements for very high throughput in the 60GHz band',2012