VCG Auction Based Optimal Allocation for Scalable Video Communication in 4G WiMAX

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***Abstract*—In this paper, we propose a novel application of the Vickrey-Clarke-Groves (VCG) auction based time-frequency resource allocation for H.264 SVC based scalable video transmission in 4G wireless systems. The net transmitted video quality corresponding to the given bitrate constrained wireless system can be maximized by optimally allocating the OFDMA time-frequency resources amongst the video streams requested by the different unicast/ multicast groups. However, such a centralized allocation is susceptible to subversion resulting from misrepresentation of the characteristic video parameters by malicious users. This, in addition to resulting in a degradation of the net video quality, might also benefit the users reporting incorrect parameter values through disproportionate resource allocation. Our simulation results demonstrate that application of the proposed VCG procedure maximizes the net utility in broadcast/ multicast video streaming when true characteristic parameters are reported, while punishing malicious users when one or more parameters are misreported.**

I. Introduction

Wireless multimedia streaming services have witnessed a tremendous surge in demand with the deployment of 4G broadband wireless cellular networks. Technologies such as WiMAX, LTE provide high data rates and reliable wireless services to the users. Some applications based on video transmission are mobile TV, high speed interactive gaming, video conferencing and multimedia streaming. Modern 4G systems like WiMAX, which incorporate Orthogonal Frequency Division for Multiple Access (OFDMA), necessitate the development of optimal schemes for time-frequency resource allocation and management.

In this context of wireless video transmission, H.264 scalable video coding (SVC) [1] has been proven to be ideally suited for video coding due to its ease of rate adaptability as suited to the wireless link quality. SVC based video transmission ensures fairness in QoS by transmitting the coarse base layer of the scalable video stream to all the end-users subscribing to the video service under consideration. Compared to the spatial and temporal modes of scalability, the quantization parameter of a video stream can be adapted on a much finer scale and allows for greater flexibility towards optimal time-frequency resource allocation. Our previous work in [2] for optimizing the bitrate of a video has addressed the issue of optimal quantization parameter selection for video quality maximization in the context of 4G resource allocation. However, the allocated bitrate and quality of video depends critically on the intrinsic video motion parameters. The optimal solution and the highest video quality is hence obtained only when the parameters are reported accurately by the unicast/ multicast subscribers or service providers. Malicious users can distort the resource allocation scheme at the QoS enforcement points (such as base stations and service gateways in WiMAX) by misreporting the parameter values thereby resulting in suboptimal resource allocation and disproportionate benefits to the malicious users.

Game theory [3]-[4] based resource allocation provides an ideal framework to optimally allocate resources in the presence of such distorting malicious users. Its applications have been recently extended to the field of wireless communication, especially in the context of resource optimization [5]. In the context of 4G wireless video communication, game theory based Vickrey−Clarke−Groves auction procedure can be adapted for time-frequency (TF) resource allocation. The auctioned item in this context is the bitrate corresponding to the allotted TF resources, and the bidders/ decision makers are the service providers or users themselves. The auctioneer is the QoS policy enforcer in the 4G wireless network. This interaction between various decision makers is akin to a strategic game and the decision makers are also termed as players in the nomenclature of game theory. We assume that all the players are rational and are driven towards utility maximization. Each user reports the characteristic video parameter values to the policy enforcer to calculate the sum utility function. Unlike conventional utility based exclusively on video quality, the VCG procedure employs the pricing based net utility function, which prices the TF resources in accordance with the allotment. Hence, users misreporting the parameters are punished by the QoS enforcer through higher resource pricing, in turn resulting in a reduced net utility for the malicious user. Hence, the VCG procedure naturally discourages users' malicious tendency towards misreporting and forces them to report accurate parameter values for maximizing net utility.

Some research regarding the use of game theory with malicious users has been considered in [6] in the context of peer-to-peer live streaming. The research in [7] proposes a Vickerey scheme for computing the shortest path in a decentralized network. The authors in [8] present the application of VCG procedure in mechanism design. In this paper we are primarily concerned about the misreporting of the quantizer based rate and quality parameter values. The framework can readily be extended to VCG based optimization for malicious users misreporting other parameter values. The bitrate and quality of video can be modeled as function of the quantization parameter and frame rate. Hence, the VCG based TF bitrate optimization can be performed through the robust framework of convex optimization [9]. Simulation results presented in the end demonstrate the effectiveness of the proposed VCG framework for video pricing based optimal OFDMA resource allocation and malicious user retribution.

The rest of the paper is organized as follows. Section II describes the scalable video model used in the paper. Section III describes the VCG procedure based resource allocation. In section IV we present the behavior of the net utility function based on the reported video characteristic parameter values. Finally, we conclude the paper in section V.

II. Scalable Video Model

In this section we present the quantization parameter based quality and bitrate models for H.264 scalable video encoding. The bitrate of the partial video streams can be obtained by encoding the video at various quality levels using the Joint Scalable Video Model (JSVM) reference video codec [10]. It has been demonstrated in literature [11] that the bitrate $R(q,t)$ of a video can be expressed as independent normalized functions of the frame rate t and quantization parameter q. The rate model [2] as described therein can be represented as,

$$\begin{aligned} R(q,t) &= R_{\max} R_t(t) R_q(q) \\ &= R_{\max}\left(\frac{1-e^{-ct/t_{\max}}}{1-e^{-c}}\right) e^{d(1-q/q_{\min})}, \end{aligned} \tag{1}$$

where $R_{\max}$ is the maximum bitrate of a video when coded at the finest quantization parameter $q_{\min}$ and the highest frame rate $t_{\max}$. The quantities $R_t(t), R_q(q)$ are the normalized rate functions of the frame rate t and quantization parameter q respectively, defined as,

$$R_t(t) \triangleq \left(\frac{1-e^{-ct/t_{\max}}}{1-e^{-c}}\right),\ R_q(q) \triangleq e^{d(1-q/q_{\min})}.$$

The parameter c characterizes the variation of the normalized rate function $R_t(t)$ as a function of the frame rate t, and is obtained through a least-squares fit between model and actual rates of the JSVM coded scalable bit-streams. The function $R_q(q)$ characterized by the parameter d gives the variation of the rate with the quantization parameter q, also obtained by minimizing the mean-squared error between the modeled and actual rate. Similarly, the quality of a video can be expressed as independent normalized functions of t and q. This quality model described in [2] is given as,

$$\begin{aligned} Q(q,t) &= Q_{\max} Q_t(t) Q_q(q) \\ &= Q_{\max}\left(\frac{1-e^{-at/t_{\max}}}{1-e^{-a}}\right)(\beta q+\gamma), \end{aligned} \tag{2}$$

where $Q_{\max}$ is maximum quality of a video when coded with the minimum quantization parameter $q_{\min}$ and the highest frame rate $t_{\max}$, $Q_t(t), Q_q(q)$ are the normalized quality functions of the frame rate t and quantization parameter q respectively, defined as,

$$Q_t(t) \triangleq \frac{1-e^{-at/t_{\max}}}{1-e^{-a}},\ Q_q(q) \triangleq \beta q+\gamma.$$

The quality function $Q_t(t)$ describes the variation in quality as a function of the frame rate t and is characterized by the parameter value a. The function $Q_q(q)$ is a decreasing affine function of the quantization parameter, which describes the decrease in quality with increasing quantization parameter q. For a fixed frame rate t_f, the bitrate and quality of video depend exclusively on the quantization parameter. We denote by n_i, m_i and r_i, the number of users in a multicast group, the number of bits in a symbol and the coding rate respectively. The optimal TF resource allocation for sum video quality maximization corresponding to a fixed symbol rate R_S can be computed as the solution of the convex optimization problem,

$$\begin{aligned} \max.\ & \sum_{i=1}^{N} n_i Q^i(q_i,t_f) \\ \text{s.t.}\ & \sum_{i=1}^{N} \frac{R^i(q_i,t_f)}{m_i r_i} \leq R_S \\ & q_{\min} \leq q_i \leq q_{\max},\ 1 \leq i \leq N, \end{aligned} \tag{3}$$

where N is the number of unicast users or multicast groups. The functions $R^i(q_i,t_f)$ and $Q^i(q_i,t_f)$ are the bitrate and quality corresponding to the i^{th} video sequence, for the choice of quantization parameter q_i at a fixed frame rate t_f. The optimal solution of the problem stated above has been derived in our previous work [2] using the Lagrange dual variable λ as,

$$\lambda^* = \frac{q_{\min}}{R_S}\left(\sum_{j=1}^{N} n_j Q_{\max} Q_t^j(t_f)\frac{\beta_j}{d_j}\right). \tag{4}$$

The optimal i^{th} quantization parameter is obtained as,

$$q_i{}^* = q_{\min}\left(1-\frac{1}{d_i}\ln\left(\frac{Q_{\max}Q_t^i(t_f)q_{\min}\beta_i m_i r_i}{R_{\max}^i R_t^i(t_f)\lambda^* d_i}\right)\right) \tag{5}$$

The bitrate and quality of the video sequence can be obtained by substituting q_i in (1) and (2) respectively. Higher quality video requires video to be coded with a lower value of quantization parameter, resulting in higher bitrate. Further, the quantization parameter q can be employed as a convenient handle to adapt the video bitrate as per the constraints imposed by the video streaming scenario. Therefore, knowledge of the characteristic video parameters a, c, d, β, γ is critical for optimizing the bitrate and quality of the streamed videos. Naturally, such a TF allocation procedure at the QoS enforcement point is subject to manipulation by malicious users who intend to subvert the allocation process, thereby achieving a disproportionate fraction of the resources. The VCG procedure presented below can be employed effectively to mitigate the effect of parameter misreporting through pricing based retribution targeting the dishonest users.

III. VCG based Video Resource Allocation

In this section we present the VCG pricing [4] based TF resource allocation procedure for video quality maximization. We consider the variation of the net VCG allocated utility as a function of the reported parameters d and β and demonstrate that its application in video rate and quality optimization leads to maximization of the net utility function. The utility function in this context of unicast/ multicast video transmission, is the quality of video, which is given as the quality relation as a function of the quantization parameter in (2). The player/ user might misreport the parameter values and subvert the allocation towards achieving disproportionate bitrate and therefore high quality video at the cost of reduced quality to the other users. The overall utility and efficient allocation of bitrate to different videos is thus compromised. Such malicious users are penalized through the VCG auction based TF resource pricing, which automatically leads to higher pricing and net utility reduction for the users misreporting the characteristic video parameter values. Let the actual and the reported utility function of the i^{th} user be denoted by $Q^i\left(q_i, t_f\right)$ and $M^i\left(q_i, t_f\right)$ respectively. The QoS enforcer determines the optimal allocation as per the reported utility functions $M^i\left(q_i, t_f\right)$. Let $\mathbf{q}^*$ denote the optimal quantization parameter allocation determined from the above convex optimization frame work. Also, let the quantity $Y_i\left(M_{-i}\left(\right)\right)$ for the i^{th} user be defined as a function of the $N-1$ utility functions $M^j\left(q_j, t_f\right) \forall j \neq i$ as,

$$Y_i\left(M_{-i}\left(\right)\right) = \max_{\underline{q}} \sum_{\substack{j=1 \\ j \neq i}}^{N} M^j(q_j, t_f).$$

The price p_i of the allocated TF resources for the i^{th} user is given by the relation,

$$p_i = Y_i\left(M_{-i}\left(\right)\right) - L_i(q^*), \tag{6}$$

where the quantity $L_i(q^*) \triangleq \sum_{\substack{j=1 \\ j \neq i}}^{N} M^j(q_j^*, t_f)$. It can be readily demonstrated that such a VCG auction based pricing scheme results in serving appropriate retribution to the dishonest subscribers and service providers. Consider the net utility Z_i of the i^{th} player given as,

$$Z_i \triangleq Q^i({q_i}^*, t_f) - p_i, \tag{7}$$

which is essentially the raw video quality adjusted for the price paid towards experiencing it. The above net utility Z_i can be expressed in terms of the true utility function $Q^i\left(q_i, t_f\right)$ and the reported utility function $M^i\left(q_i, t_f\right)$ as,

$$Z_i = \underbrace{Q^i({q_i}^*, t_f) + \sum_{\substack{j=1 \\ j \neq i}}^{N} M^j(q_j^*, t_f)}_{U_i(\mathbf{q}^*)} - \max_{\underline{q}} \sum_{\substack{j=1 \\ j \neq i}}^{N} M^j(q_j, t_f) \tag{8}$$

The last term $\max_{\underline{q}} \sum_{\substack{j=1 \\ j \neq i}}^{N} M^j\left(q_j, t_f\right)$ in the above expression is independent of the reported utility function of the i^{th} user. Hence, it can be observed that $U_i\left(\mathbf{q}^*\right)$ for player i is maximum for the allocated resource $\mathbf{q}^*$, calculated as per the optimization framework, only when the reported utility function $M^i({q_i}^*, t_f)$ coincides with the true utility function $Q^i({q_i}^*, t_f)$. Thus, the VCG procedure effectively punishes malicious users who deliberately misrepresent their video parameters. This TF resource allocation based on the VCG procedure is applied to all the N players/ service providers participating in the given scenario. We now present the algorithm for computing Z_i below.

Suppose k is the indice of video sequence applying VCG procedure.
for d_l/β_l **do**
    {
    for $i = 1 \rightarrow N$ **do**
        - Compute λ^* using R_S in (4) with j initialized to i.
        - Compute quantization parameter ${q_i}^*$ using (5).

        if ${q_i}^* < q_{\min}$ **then**
            - set ${q_i}^* = q_{\min}$
            else if ${q_i}^* > q_{\max}$
            - set ${q_i}^* = q_{\max}$

        end
        - Compute $R^i({q_i}^*, t_f)$ using ${q_i}^*$ and (1).
        - $R_S : R_S - R^i({q_i}^*, t_f)$.

    end
    if ${q_i}^* = q_{\min}$ **then**
        - $R_S : R_S - \sum\left(R^i({q_{\min}}^*, t_f)\right)$.
        - Repeat **for** loop for remaining sequences for optimal solution.

    end
    } OPTIMAL;
    - Compute $\hat{q}_k$ from R_k/ Q_k using d_t/β_t to avoid violation of constraints.
    - Excluding the k^{th} sequence, repeat OPTIMAL to obtain $Y_k(M_k())$.
    - Compute Z_k for every d_l/β_l.

end
Select maximum Z_k.

IV. Simulation Results

As in our previous work [2], we consider the WiMAX profile with OFDMA symbol duration of 5 ms each for UL and DL, with 2048 subcarriers, corresponding to 1440 data subcarriers and an effective downlink symbol rate of $R_S = 6.336$ Msps. For analyzing the behavior with respect to the parameters, we consider a scenario, where N=9 video sequences of different resolutions (QCIF, CIF, 4CIF) are being streamed with $n_i = 1$, coding rate of the i^{th} group $r_i = \frac{5}{6}$ and modulation order $m_i = 2$ corresponding to QPSK modulation and frame rate $t_f = 30$ fps. The values of the video characteristic parameters a, c, d, β, γ corresponding to these video sequences are specified in [2]. We consider the optimal allocation of TF resources in this scenario to the different groups and the net utility corresponding to accurate and misreporting of d, β parameters. We begin by specifically considering two separate cases in which a single subscriber of the standard test video sequence football CIF [12] misreports the parameter values d (rate parameter) and β (quality parameter). The scenario with multiple users misreporting multiple parameters is considered in the later simulations.

A. Behavior Corresponding to Misreporting d

In this section we illustrate the effect of false reporting of parameter d for the standard football video sequence on

Case	I	II	III
d_3	1.49	0.4	3.4
q_3	27.82	24.48	23.36
R^3	1621.9	4076.6	789

TABLE I
Quantization parameter and Bitrate for sequence football Case I:$d = d_t$, Case II:$d < d_t$, Case III:$d > d_t$

Case	I	II	III
β_3	-0.0258	-0.03	-0.02
q_3	27.82	25.6	28.98
R^3	1621.9	1832.2	1308.5

TABLE II
Quantization parameter and Bitrate for football Case I:$\beta = \beta_t$, Case II:$\beta_m < \beta_t$, Case III:$\beta_m > \beta_t$

the overall bitrate allocation. Case I, II and III in table I demonstrate the allotted quantization parameter and corresponding bitrate when $d_m = d_t$, $d_m < d_t$ and $d_m > d_t$ respectively at $R_S = 6.336$ Msps for the standard football CIF sequence. Consider the adverse scenarios, where the user/ service provider reports $d_m = 0.4 < d_t$ shown in case II. This results in suboptimal allocation of TF resources, with a disporportionate alloation of $R^3 (q_3, t_f) = 4076.6$ Kbps. This is at the cost of decrease in video quality of the rest of the users. In the later simulations it is shown that the application of the VCG procedure ensures that such malicious users are punished through a reduction in the net utility resulting from the VCG allocation. When $d_m = 3.4 > d_t$ as considered in case III, the alloted bitrate $R^3 (q_3, t_f) = 789$ Kbps is much less than the rate 1621.9 Kbps (corresponding to case I). Hence, there is no incentive for the malicious user to misreport a lower value of the parameter d. However, the actual video encoded with this lower value of the allocated quantization paramter $q = 23.36$ will have bitrate $R^3 (q_3, t_f) > 1621.9$ Kbps (corresponding to case I) and thus results in violating the overall bitrate constraint. Hence, the malicious user in this scenario is forced to compute the quantization parameter $\hat{q}_3$ corresponding to the allocated bitrate of 789 Kbps to ensure that the rate constraints are not violated. This results in lower quality $Q^3 (\hat{q}_3, t_f)$.

B. Behavior Corresponding to Misreporting β

We now consider the effect of misreporting of the parameter β of a video sequence on the overall TF resource allocation. Case I, II and III in table II shows the computed quantization parameter and allotted bitrate of video sequences when $\beta = \beta_t$, $\beta_m = -0.03 < \beta_t$ and $\beta_m = -0.02 > \beta_t$ respectively at $R_S = 6.336$ Msps for sequence football CIF. When the misreported $\beta_m = -0.030 < -0.0258$ as in case II, the optimal bitrate allocation results in $R^3 (q_3, t_f) = 1832.2 > 1621.9$ Kbps and the difference $1832.2 - 1621.9 = 210.3$ Kbps is obtained from taking the share of bits from other videos. Hence, similar to reporting a lower value of d as seen above, the malicious user has an incentive to report a lower value of the parameter β. For case III, corresponding to $\beta > -0.0258$, the bitrate obtained $R^3 (q_3, t_f) = 1308.5 < 1621.9$ Kbps, as shown in table II. The quality $Q^3 (q_3, t_f)$ is less compared to the case when β_t is reported. Hence, there is no incentive for the malicious user to report higher values of the quality parameter β.

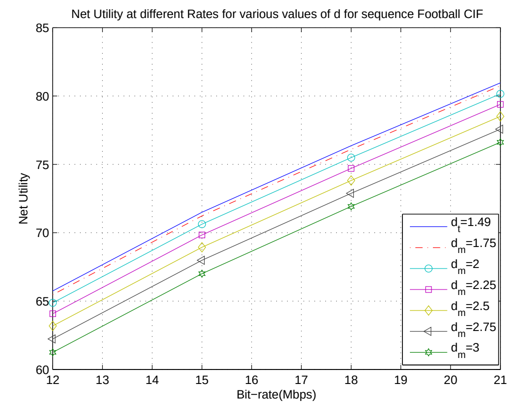

Fig. 1. Net utility function vs. Rate at various values of parameter d for sequence football CIF :d_t=true value, d_m=misreprted value

C. VCG Procedure based TF Resource Allocation

In this section we illustrate the efficacy of the VCG procedure based resource allocation described in section III towards punishing such malicious users and reducing their net utility, thereby discouraging false reporting of the video parameters. Similar to the scenarios considered above, we consider the video streaming of $N = 9$ video sequences with $m_i \in \{1, 2, 4, 6\}$ and $r_i \in \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{5}{6}\}$. The TF resources are allocated as per the optimal solution corresponding to the reported utility function maximization in (3) at the VCG price p_i computed in (6). Fig.1 and Fig.2 show the net utility function as a function of the symbol-rate R corresponding to the VCG procedure based TF resource allocation for the video sequence football. It can be seen therein that the net utility function is maximum when the true parameters $d = d_t = 1.49$ and $\beta = \beta_t = -0.0258$. Hence, the VCG procedure penalizes the users misreporting the video characteristic parameters by decreasing their net utility. In these scenarios we only consider false reporting of a single parameter (either d or β, but not both) by a single user. Below, we consider the scenario where multiple users simultaneously misreport one or more characteristic video parameters.

We assume the following misreported parameter values $\beta_1 = -0.025, \beta_3 = -0.020, \beta_5 = -0.030, d_3 = 2.2, d_4 = 1.8, d_6 = 2.4$, with user 3 misreporting both d and β considered for simulations in Fig.3 and Fig.4. In Fig. 3 we plot the net utility of user 3 corresponding to misreporting $d_m = 2.2 > d_t = 1.49$ and several possible misreports of $\beta \neq \beta_t$ and $d \neq d_t$. It can be seen that, amongst all the net

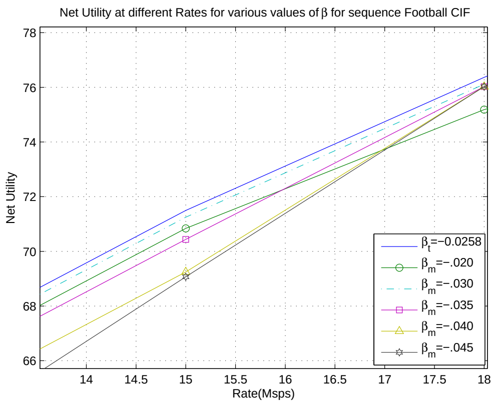

Fig. 2. Net utility function vs. Rate at various values of parameter β for sequence football CIF :β_t=true value, β_m=misreprted value

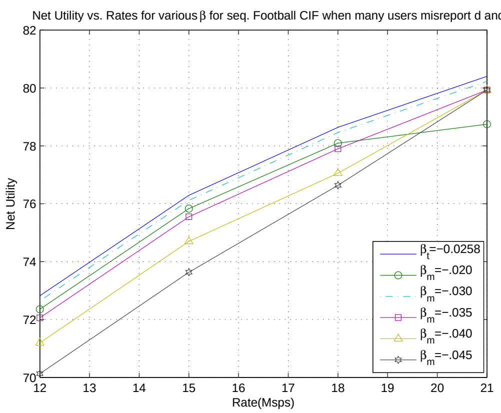

Fig. 3. Net utility function vs. Rate at various values of parameter β for sequence football CIF and other misreports :β_t=true value, β_m=misreprted value

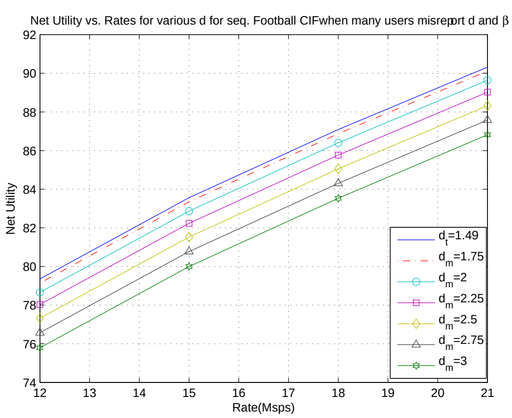

Fig. 4. Net utility function vs. Rate at various values of parameter d for sequence football CIF and other misreports :d_t=true value, d_m=misreprted value

utility curves, the one corresponding to $\beta = \beta_t = -0.0258$ results in the maximum net utility. Similarly, in fig. 4 we plot the net utility for the false reporting of $\beta_m = -0.020 > \beta_t$ and several possible misreports of the rate parameter d and quality parameter β. Once again, it can be seen that reporting the true value of $d = d_t = 1.49$ results in net utility maximization for user 3. Thus, application of the VCG procedure results in penalizing the parameter misreporting malicious users, thereby encouraging users to report the true characteristic video parameters, thus resulting in optimal TF resource allocation.

V. Conclusion

In this work we have presented a novel VCG procedure based approach for optimal TF resource allocation towards scalable video transmission. In conventional 4G resource allocation based on sum quality maximization, there is an incentive for malicious users to misreport the video quality parameters towards disproportionately higher resource allocation, thus leading to suboptimality and subversion of the scheduler operation at the base station. The proposed VCG procedure is effective for resource allocation in such scenarios, since it punishes malicious users through pricing based optimal resource allocation, thereby discouraging false reports. Further, the incidental outcomes of the above VCG based allocation are the price points for the allocated TF resources. Hence, the proposed scheme can also be used as an effective TF resource pricing algorithm for use in the OSS module of the core network, which in turn leads to overall optimal resource allocation.

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