NOMA Resource Block As A Commodity Box: Content-Centric QoE-Price Interplay In Wireless Multimedia Communications

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***Abstract*—Wireless multimedia communications is one of the most rapidly growing technologies of the decade. With explosive growth in network traffic, the service providers struggle to provide satisfactory Quality of Experience (QoE) to the users and increase revenue. Non-Orthogonal Multiple Access (NOMA) has been proposed to cater multiple users simultaneously in each resource block by exponentially increasing the network capacity. However, the strategic allocation and trading of NOMA resource blocks are still open issues. In this work, we treat a NOMA resource block as a commodity representing its channel quality and the importance of data it carries. We then chalk-up the innovative and appealing QoE-price interplay to promote NOMA resource block trading as a suitable candidate for future-generation wireless mobile networks. The proposed framework benefits both the utilities of users and service providers. The proposed approach is solved by deriving the Nash Equilibrium of the network interactions using a best-response game. Simulation suggests further exploration of the potentials to the adaptation of proposed framework for NOMA wireless multimedia communications.**

***Index Terms*—Quality of Experience (QoE), Non-Orthogonal Multiple Access (NOMA), NOMA Pricing, Wireless Multimedia Communications**

I. Introduction

Recent advances in wireless mobile communication technologies have changed in adaptation to the way we work remotely. Exchange of information is a basic need of human beings and new technologies are offering novel tools for this very purpose [1]. In the past decade, these technologies have evolved from voice calls and texting to ultra-high-definition (UHD) video and an assortment of virtual reality/ augmented reality (VR/AR) applications. The Cisco Visual Networking Index (VNI) forecasts that the number of devices connected to IP networks will be much more than the global population in the future [2]. On the other hand, multimedia-based services such as video surveillance, remote patient monitoring and virtual classrooms have become part of our lives. This has resulted in increased latency and lower throughput networks.

Non-Orthogonal Multiple Access (NOMA) has been widely studied in the recent years due to its inherent capability to meet wide-ranging demands [3]. In contrast to Orthogonal Frequency Division Multiple Access (OFDMA) where service is provided to one user per orthogonal resource block, NOMA allows the service provider to serve multiple users in the same block simultaneously in terms of space, time, or power. This offers several advantages, including improved spectral efficiency, higher cell-edge throughput, relaxed channel feedback, and low transmission latency [4]. However, a systematic way to allocate the available resources among the users is still an open research topic. The Fig. 1. below shows a three-party interaction between the content provider, service provider and end user. The available resource can be allocated to a single user in OFDMA style or shared between multiple users in NOMA style as shown in the figure.

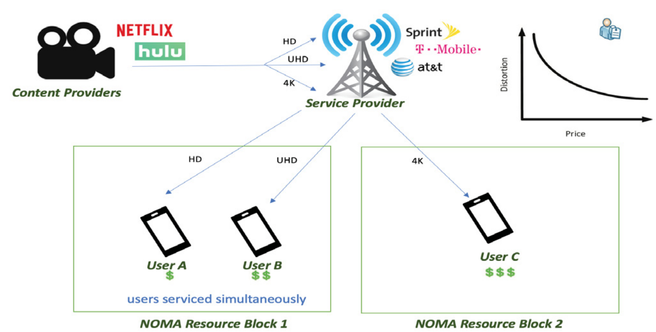

Fig. 1. Typical Interaction in Wireless Multimedia NOMA Communications.

Quality of Experience (QoE) is an indispensable part of wireless multimedia communication performance indicator and is a per-session measure of user satisfaction in terms of utility maximization [5]. With explosive growth in multimedia traffic and devices, wireless service providers around the globe have been struggling to meet the QoE demands of the customers and are moving towards novel pricing schemes such as time dependent pricing, usage-based pricing, application driven pricing, etc. to boost their revenue [6]. These pricing schemes are however uncorrelated with QoE .

In our previous work, we introduced NOMA Pricing (NOMAP); a novel pricing framework which allows the service provider to dynamically alter the price for utilizing a resource block. Under the proposed NOMAP, the user can choose the resource block to join and dynamically decide the amount of power to purchase for wireless transmission. The protocol also allowed the service provider to distribute users

2022 IEEE Wireless Communications and Networking Conference (WCNC) | 978-1-6654-4266-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/WCNC51071.2022.9771582

across all resource blocks and simultaneously improve profits. Simulation studies carried out indicated a significant boost in end-user QoE. In this paper, we extend the NOMAP research by chalking up a QoE-price interplay for multimedia driven NOMAP framework. We also address the limitations of our previous model such as the generic numerical presentation of QoE, non-availability of packet-level distortion information to model multimedia data, and the non-concavity of the utility functions.

This paper presents a case study of the proposed model on a NOMA downlink network consisting of a service provider, five resource blocks and ‘n’ users requesting multimedia content. The interactions between the users and service provider have been translated into a best response game. Due to dynamic nature of the network, the users can sometime achieve best utility, called Pure Strategy Nash Equilibrium (PSNE), by obtaining service in one of the available resource blocks. Most often, such a solution does not exist, and users must mix between the available resources to achieve best utility, also called as Mixed Strategy Nash Equilibrium (MSNE). Both cases are considered in this study and the solutions are discussed in entirety.

Apart from NOMA, researchers have been investigating other technologies such as pattern-division multiple access (PDMA) [7] and special division multiple access (SDMA) [8]. PDMA maximizes the diversity and minimizes the overlaps among multiple users to design non-orthogonal patterns. SDMA on the other hand, is like code division multiple access (CDMA) but instead of using user-specific spreading sequences, SDMA distinguishes different users by using user-specific channel impulse response. Compared to these techniques, researchers believe NOMA has the potential and scope to replace OFDMA [9-10]. Researchers are also investigating QoE enhancement techniques [9] and energy efficient algorithms for NOMA implementation [10]. However, most of the work overlook the profit maximization issues faced by the service providers. In our work, we jointly address QoE amplification for NOMA user and profit maximization of service provider.

Multimedia QoE intensification is another popular area of research. Smart Media Pricing [11] and Smart Data Pricing [12] have been proposed to include price as a resource in measuring the QoE. Service level models such as video packet offloading [13] and incentivized caching [14] to reduce network congestion have also been investigated. Our work differs from these works as we formulate the QoE-price interplay over a network access protocol. By formulating our model over existing NOMA protocol, the framework becomes independent of end-user applications.

The rest of the paper is organized as follows: In section II, we describe the system model and mathematically formulate the utility equations for both user and service provider. The stability of the framework is demonstrated using a best-response game and the game theoretic solution is presented in Section III. Simulation results from MATLAB are discussed in Section IV and we conclude the paper in Section V.

II. System Model

In this section, we provide a brief review of the NOMAP framework and then derive the proposed QoE-price interplay for NOMA wireless multimedia. Under the NOMAP architecture, the base station or service provider can dynamically price the available resources (resource blocks) by monitoring the channel conditions and network traffic. The user then can join one of the available resource blocks based on their QoE requirement and obtain service. In this work, we leverage the NOMAP framework to model the multimedia transactions between the end-user and service provider in a NOMA network. The service provider has several copies of multimedia data available encoded using different parameters. These packets have different distortion-values and sizes. The service provider also assigns the prices for utilizing the resource blocks dynamically. The user then decides the resource block to join and decide amount of data to purchase. The price of data and amount of data purchased jointly determine the QoE of the user.

In this work, we consider the multimedia data available with service provider to be encoded with High Efficiency Video Coding (HEVC), also known as H.265 encoding. Under this encoding, the videos are broken down into smaller fragments called Group of Picture (GOP) with unequal importance. These fragments can either be a I (Inter frame), P (forward predicted frames) or B (bi-directional predicted frames). The I frames are independent and the most important, while the P frame can be predicted from the I frame. The B frames are least important, and they can be both forward and backward predicted using I and P frames [15]. An encoded sequence with just I frames would be large but has very high quality whereas a sequence with I, P and B frames is smaller and has lesser quality. We assume that several qualities of the same video (different combinations of I, P and B) are pre-available with the service provider and can be readily transmitted upon request.

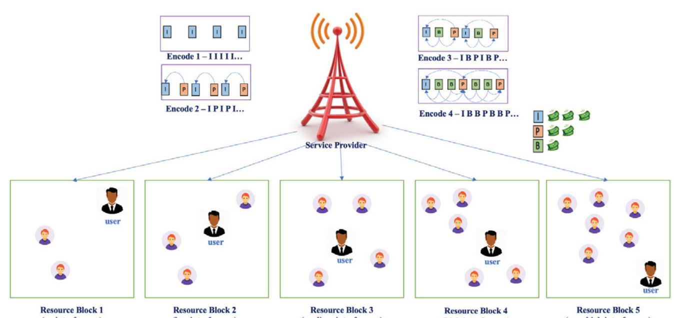

Fig. 2. System model: A multimedia NOMA network with single service provider and five differently priced resource blocks to choose from.

The proposed system model is showcased in Fig. 2. above. The system consists of a single service provider. The service provider has the multimedia content available in four different $H.265$ encoded schemes ($IIIII\ldots, IPIPIP\ldots, IBPIBP\ldots$, and $IBBPBBP\ldots$). The minimalistic network also consists of five different

NOMA blocks each consisting of n users. Under NOMA, all users in NOMA blocks are catered simultaneously. The users closer to the base station cause interference to the user. Therefore, based on number of users closer to the base station than the user is used to categorize the resource blocks as no, low, medium, high, or very high interference blocks respectively. Under the proposed framework, the base station will provide the cost of utilizing a resource block based on the interference and other channel conditions.

For example, in a no interference block, the user can save money by purchasing more B frames as the channel would require very few retransmissions. On a high interference block, the user will be tempted to purchase all I frame since the retransmission rate is high and cost of using the block is cheap. Therefore, the user is in a dilemma to decide the amount of data to purchase and block to join that would maximize their QoE. This dilemma leads to our problem formulation: *What is an optimal pricing strategy of the service provider to promote users to buy more data? Which resource block (or blocks) should the user join and how much data should the user request at a price declared by the service provider to maximize their utility?* In this section, we formulate the utility equations of user and provider mathematically and an equilibrium solution is discussed in the next section.

A. Quality of Experience (QoE) model

The QoE is the direct measure of end-user satisfaction in multimedia communications. QoE has been traditionally measured in terms of throughput and latency. In this work, we propose a complex three-dimensional QoE model for user i in terms of multimedia distortion-reduction q_j, packet signal to noise ratio P_k and multimedia content preference γ as shown in equation (1) below.

$$\mathrm{QoE}_i = \frac{\mathrm{a}_1}{1+\mathrm{e}^{-\mathrm{a}_2\left(\sum_{\mathrm{j}=1}^{\mathrm{m}} \mathrm{q}_\mathrm{j} \prod_{\mathrm{k}\in\pi_\mathrm{j}} 1-\mathrm{P}_\mathrm{k}\right)+\mathrm{a}_3*\gamma+\mathrm{a}_4}} \tag{1}$$

The content preference γ is a measure of user's personal preference for a multimedia data. For example, some users could have a higher interest towards live-action sports video, while some users may not be interested in sports at all. These users would have different values for γ. The values $a1, a2, a3$ and $a4$ are positive parameters used to fine-tune the QoE model. These values can be altered based on the end-user application during implementation. The choice of these parameters does not influence the equilibrium of the solution. The total number of frames that are to be transmitted to the user is given by m.

The PER P_k is defined as the number of packets in error after forward error correction divided by the total number of received packets. P_k is related to the Bit Error Rate (BER) and bit length of the corresponding packet l_k [5]. The set of ancestor frames which the frame j refers to is denoted by π_j.

$$P_k = 1-(1-BER)^{l_k} \tag{2}$$

The BER at user's device can be estimated from desirable multimedia packet Single to Noise Ratio (SNR), once the modulation scheme to be used for transmission is determined. We assume that M-ary quadrature amplitude modulation (M-QAM) is used in our NOMA network and the BER for M-QAM schemes can be expressed as follows

$$BER = \frac{2}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)\operatorname{erfc}\left(\sqrt{\frac{3b}{2\left(2^b-1\right)}\frac{E_b}{N}}\right) \tag{3}$$

The equation (3) above gives the theoretical relationship between BER and energy per bit to noise power density ratio $\frac{E_b}{N0}$. SNR can be calculated by $SNR_{rx} = \frac{E_b}{N0}b$ and $\frac{E_b}{N}$ for NOMA communication can be obtained from transmission power P_t, wireless channel loss information h, and symbol rate R_s as shown in the equation (4)

$$\left(\frac{E_b}{N}\right)_i = \frac{P_i\left|h_i\right|}{\sum_{k=i+1}^{N} P_k\left|h_k\right|^2 + R_S N_0} \tag{4}$$

where Pi and hi denote the power transmitted and Rayleigh fading channel gain between user and provider, respectively. The noise power in the communication channel is given by $R_s N_o$. The users closer to the provider than the end-user cause interference and these users are represented by k. Combining equation (3) and (4), the BER for NOMA driven multimedia communications derived as shown in equation (5).

$$\begin{aligned} BER = {} & \tfrac{2}{b}\left(1-\tfrac{1}{2^{\frac{b}{2}}}\right) \\ & \operatorname{erfc}\left(\sqrt{\tfrac{3}{2(2^b-1)}\tfrac{P_t|h|}{\sum_{k=i+1}^{N} P_k|h_k|^2+R_S N_0}}\right) \end{aligned} \tag{5}$$

B. Utility of the User

The overall utility of the user is defined as the QoE gain subtracted by the cost paid to the service provider. The cost paid to the provider is modeled as a function cost per bit of data transmitted y_j and the amount of multimedia transaction bits l_j.

The utility maximization problem for the user is to determine the amount of data l_j to purchase at given price y_j subjected to data length constraints where l_{min} and l_{max} represent minimum number of bits required for meaningful encoding of the multimedia data and the maximum number of bits that can be supported within a frame.

$$\begin{aligned} max \quad & U_{user} = QoE_i - y_i l_j \\ & \text{s.t. } U_{\text{user}} \geq 0 \\ & l_{\min} < l_j < l_{\max} \end{aligned} \tag{6}$$

C. Utility of the Service Provider

The objectives of the service provider are to meet the guaranteed QoS goals and improve the revenue. The utility of the service provider can be modeled as the income from the user subtracted by the service provider costs. The cost on the service provider is three-fold. The first overhead on the service provider is the transmission cost proportional to the amount of energy expelled to transmit data from the provider to the user.

$$\psi_{\text{energy}} = \alpha \frac{l_j T_p}{b R_S} \tag{7}$$

Where α is defined as the currency value per unit energy consumption. The transmission power is given by T_p and the amount of data transmitted is denoted by l_j. b and R_s denote the modulation co-efficient and symbol rate respectively. The second overhead for the provider is the money involved in source coding of the data. It can be effectively modeled as

$$\psi_{\text{coding}} = \beta \sum_{j=1}^{m} q_j / l_j \tag{8}$$

where β is the cost per bit of source coding. Since the users in the resource block are transmitted simultaneously, interference occurs, and some frames must be retransmitted. The retransmission cost on the service provider is modeled as a logarithmic function of successful transmission probabilities of the ancestor frames. Here ancestor frames refer to the set of previously transmitted frames on whose successful decoding the current frame depends upon.

$$\psi_{\text{retransmission}} = \varepsilon \sum_{j=1}^{m} \log \prod_{k \in \pi_j} (1 - P_k) \tag{9}$$

where ε denotes the currency value for per bit of retransmission. The overall utility of the service provider is shown in the equation below. The goal of the service provider is to determine and declare the right price for utilizing each of the resource blocks. Thereby improving the profits.

$$U_{SP} = U_{\text{user}} - \psi_{\text{energy}} - \psi_{\text{coding}} - \psi_{\text{retranmission}} \tag{10}$$

$$\text{s.t. } U_{SP} \geq 0$$

III. Best Response Game

In this section, we translate the QoE-price interplay into a two-stage game and determine the Nash Equilibrium solution of the game. Nash equilibrium of the game is defined as the set of strategies, one for user and one for the service provider such that both players have no incentive deviating from that strategy [16]. The way to derive the equilibrium depends upon where or not the utility equation is concave. For a concave function, the solution is unique and can be obtained by using a two-stage Stackelberg game as shown in our previous work [17,18]. In our current work, we consider a generic QoE model and since it is difficult to prove concavity of the utility definitions, we use a generalized best response game to obtain the solution.

Best response game is defined as a process to obtain a single strategy or a set of strategies that produces the greatest payoff for a player given all the other players' strategies [16]. In a generalized best response game, three scenarios are plausible. A) Existence of a unique strategy that yields best utility to all the players, B) Existence of multiple strategies that all yield best utilities to all players, C) Non-existence of unique strategies. The solutions of the games where a unique or multiple strategy exist are called as pure strategy Nash equilibrium (PSNE). While no such straight-forward solution exists, the users must mix among the available strategies to achieve equilibrium. Such a solution is called as mixed strategy Nash equilibrium (MSNE). In this section, steps to derive both the solutions are discussed and a general-purpose algorithm is presented for implementation reference.

A. Pure Strategy Nash Equilibrium Analysis

For the sake of illustration, the PSNE solution is derived for the minimalistic NOMA network formulated in section II. The multimedia content is available with the service provider with four different encoding scheme each having different lengths. The total number of NOMA resource blocks considered is five and the five different prices are considered between y_{min} and y_{max} as the prices to be set by the service provider. The five prices and four video encodings result in 20 different combinations. The utilities corresponding to these combinations are calculated using the utility definition and are tabulated as shown in the figure below. The same procedure is repeated for all five resource blocks, resulting in 100 combinations which are captured as a three-dimensional utility matrix.

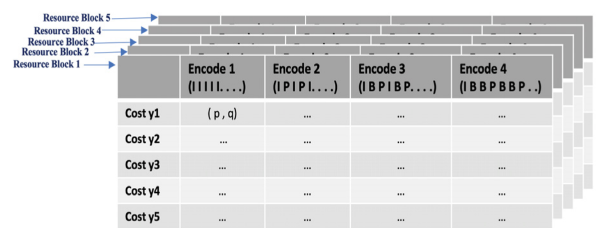

Fig. 3. An illustration of three-dimensional utility matrix.

The PSNE solution is derived from the three-dimensional table using Iterated Elimination of Strictly Dominating Strategies (IESDS) [16]. IESDS is a three-step process which simplifies the game based on the strategies the players will never play and yields one or more PSNE for the players.

Step 1: Analysis from user standpoint

In the first step, we will assume that provider has made a choice and choose the optimal value corresponding to the selection. For example, we assume that the user has declared the cost $y = y1$, we identify the video sequence that yields the best utility and mark it. This process is repeated for all values of cost.

Step 2: Analysis from service provider standpoint

The previous step is repeated from the service provider's perspective. The user's choice of video is assumed, and the best price that yield highest utility are determined and marked.

Step 3: Determination of mutual best response

The matrix is examined to determine if both utility values corresponding to user and service provider are marked in any of the cell. If so, that cost and length corresponding to that cell is the PSNE solution. If more than one such cells are available, any of the solution can be chosen. This solution is stable and has a no-regrets property.

B. Mixed Strategy Nash Equilibrium Analysis

MSNE solution is derived when IESDS fails to yield at least one mutual best response in the constructed matrix. MSNE solution is a set of probabilities with which the user should mix two or more strategies to yield an equilibrium.

Step 1: Apply IESDS to reduce the utility matrix

Contrary to the PSNE algorithm where we determine the strategy a user or service provider will play. Here we determine the options that both players would never play. For example, if a value of $y = yc$ yields higher utilities for all the encoded videos than $y = yd$, then the provider would never announce price $y = yd$. Therefore $y = yd$ can be eliminated from the table. This procedure is carried over and over for both user and provider until all redundant entries are removed.

Step 2: Determination of Mixing Probabilities

Once the redundant entries are removed, we end up with a simplified matrix. The options in the matrix are mixed with a probability to attain equilibrium. We define $\mu_1, \mu_2, \ldots \mu_i$ as the probabilities in which the user will choose the available encoding schemes and $\eta_1, \eta_2, \ldots \eta_j$ as the probabilities in which the provider will choose the price. For the solution to exist stably, the provider's utility gain between any of the pure strategies played by user with the probability μ_i. Similarly, user's utility should be indifferent for any price declared by provider with probability η_j. The probabilities are subjected to constrains $\mu_i \geq 0$, $\eta \geq 0$, $\mu_i = \eta_j = 1$. The mixing probabilities can be then be determined by solving a set of linear equations. Simplified numerical examples to understand the PSNE and MSNE methodologies are illustrated in [19].

C. Algorithm Design

Algorithm 1 PSNE and MSNE Strategies

1) **Initialization:**
   1.1. Initialize all the variables in the utility equations.
   1.2. The total number of price options between y_{min} and y_{max} is given by u. v denotes the total number of GOP options and w denote the entire number of resource blocks available.
2) **Iterations:**
   For: number of resource blocks
      Pick current resource block as current resource block
      For: number of encoded videos
         pick v = current encoding scheme
         iterate over all prices and mark best response
      eliminate entries using IESDS.
      For: number of price intervals between y_{min} and y_{max}
         pick v = current encoding scheme
         iterate over all prices and mark best response
            if: best response u is also a best response v
               Declare corresponding $\{y, l\}$ as PSNE and break.
      eliminate entries using IESDS.
   2.1. initialize a probability vector corresponding to the size of matrix
   2.2. Formulate and solve two quadratic equations for MSNE solution.
3) **Output:** The optimal $\{l^*, y^*\}$ for PSNE solution and the sets of l, y along with their mixing probabilities$\mu_1, \mu_2, \ldots \mu_i$ and $\eta_1, \eta_2, \ldots \eta_j$ for MSNE solution.

A realistic NOMA network can have a service provider who can announce u different prices subjected to pricing constraints. Similarly, the provider can have v different encoded versions of a same video and the user can have w different resource blocks to choose and join to obtain service. Therefore, a generalized utility matrix will have a dimension of $uxvxw$. A pseudocode to determine the solutions is presented as Algorithm. 1.

IV. Simulation Study

In this section, the performance of the developed model has been evaluated. The simulations were carried out on MATLAB and the multimedia data used in this simulation is obtained using $MPEG - 4$ $H.265$ codec. Three different test video sequences namely $Netflix\,square\,and\,timelapse$, $Netflix\,pier\,seaside$ and $control\,burn$ were encoded using four different schemes $(IIIII\ldots, IPIPIP\ldots, IBPIBP\ldots, andIBBPBBP\ldots)$. The $q_(j)$ and $l_(j)$ values were determined from the encoded data sets. The system parameters used to fine tune the QoE model $a1 - a4$ were chosen as $3.8, 4.9, 3.6$ and 3.5 respectively based on video quality tests conducted by K. Yamagishi, et.al [20]. The bit error rate (BER) was set at $1e - 6$. The user personal preference γ was set at 0.5 and the variable cost parameters are $0.1, 1, 0.5$ and 4 respectively.

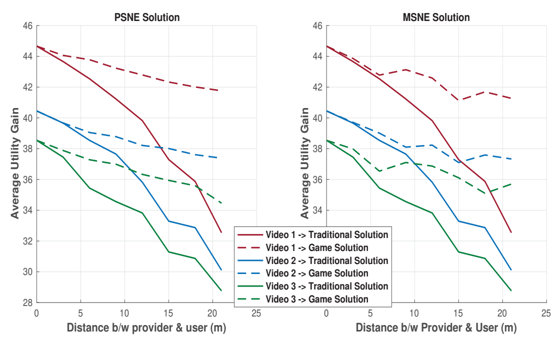

Fig. 4. An illustration of three-dimensional utility matrix.

The PSNR and utility drops as the distance between the user and service provider increases due to noise and interference. The PSNE and MSNE solution for all three videos where derived using the algorithm proposed for varying distances as shown in the Fig. 4. In the traditional pricing approach, utility drops rapidly with distance due to distortion. However, since price is incorporate as a resource in our model, the user's utility does not reduce significantly with distance. Therefore, the users will be willing to join a resource block with higher interference since desirable QoE can be achieved by paying less. The service provider also benefits by being able to manage traffic congestions. The bumps in the MSNE solution are due to the random flipping between the solutions.

The PSNR gains of the users are compared against the channel noise for four different resource blocks in Fig. 5. In a no interference setting (Block 1), the price charged would be high and retransmission rates are low. Therefore, the user tends

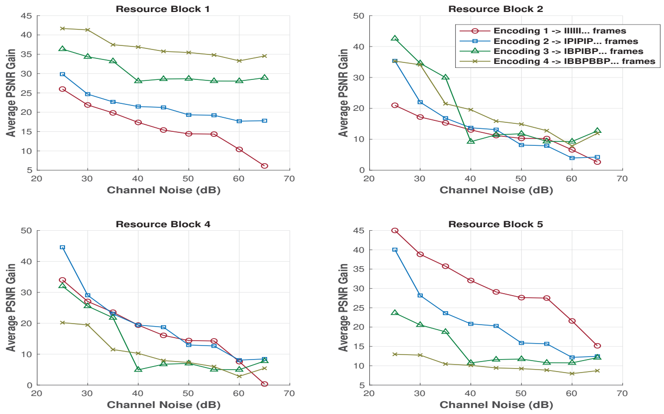

Fig. 5. An illustration of three-dimensional utility matrix.

to purchase more P and B frames. Since price is incorporated as a resource the IBBPBBP encoding yields highest utility. In a high interference setting (Block 4), the cost of utilizing the resource block is low, therefore the user would want to purchase all I frame. Since retransmission rate is high, the user would be better off purchasing the independent I frame rather than the B and P frames which depend on successful transmission of ancestor frames. The transmission of user preference for various encoding schemes among the different resource blocks are captured in Fig. 5. The result testaments the implementation of NOMA pricing scheme for next-gen wireless multimedia.

V. Conclusions

Explosive growth in wireless mobile video devices has resulted in a demand for efficient network access schemes to improve spectral efficiency and system capacity. Although NOMA is a promising technology, key issues such as dynamic pricing and strategic resource allocation are challenges. On the other hand, service provider QoE and revenue are dropping, and they are in look out for new pricing solutions. The issues are jointly studied in this work by considering QoE-price interplay between user and service provider for resource allotment and utility maximization, by treating NOMA resource blocks as commodity boxes. More specifically, the wireless channel quality of the resource blocks and the quality contribution of the data carried in those resource blocks are considered. The framework has been studied over a minimalistic NOMA network, and game theoretic solutions were leveraged to determine equilibrium solutions. Simulation study were also carried out using H.265 encoded HEVC data, and the results advocate in favor of the proposed framework, as a suitable paradigm to improve the efficacy of next-gen NOMA wireless multimedia communications.

VI. Acknowledgement

This research was supported in part by National Science Foundation Grants No. 2010284 and No. 2010012 on Non-Orthogonal Multiple Access Pricing for Wireless Multimedia Communications.

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