Orthogonality-Centric Pricing for Wireless Multimedia Multiple Access Networks

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***Abstract*—Non-Orthogonal Multiple Access (NOMA) is one of the promising solutions for next-generation wireless multimedia services to mitigate traffic congestion and reduce latency. Orthogonal Multiple Access (OMA) on the other hand has been used over the years to transmit content wirelessly. The merits offered by OMA would make it co-exist along with NOMA in the upcoming years. The key idea of this paper is to leverage Uber/Lyft ride-share philosophy to design the wireless access pricing model to be "orthogonality-centric"; being aware of the shared NOMA and exclusive OMA access price differences in wireless networks. The efficacy of the developed pricing model is then studied on a hybrid network which supports both NOMA and OMA resource blocks. The utility definitions for both the base station and the mobile user are mathematically modeled and the profit maximization interplay between the two parties is analyzed using game theoretic methods. An algorithm to derive Nash Equilibrium solution is presented. The simulations showcase the efficacy of the developed orthogonality driven pricing framework developed in this paper. Furthermore, the results indicate that the non-uniform orthogonality-centric pricing yields better utilities for both the base station and the end user.**

***Index Terms*—Non-Orthogonal Multiple Access (NOMA), Orthogonal Multiple Access (OMA), Pricing Model, Wireless Communication, Quality of Experience (QoE).**

I. Introduction

The past decade has witnessed a boom in data-intensive multimedia applications such as online gaming [1] and delay-sensitive Internet-of-Things applications such as autonomous driving [2] in wireless systems. Multiple access techniques were formulated to facilitate several mobile users to share the available spectrum efficiently. In contemporary wireless communications, there are two main classifications of coordinated multiple access: Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) [3]. In OMA, the resources are segregated orthogonally in time, frequency, or space to ensure minimum interference of user data. The primary issue with OMA technique is that its spectral efficiency is low when some bandwidth resources, such as subcarrier channels, are allocated to users with poor Channel State Information (CSI).

On the other hand, NOMA caters multiple users simultaneously over time/frequency/space, but with different power levels. This ensures a significant spectral efficiency gain over conventional OMA [4]. Power-domain NOMA employs Superposition Coding (SC) to bundle-up user data for simultaneous transmission over shared resources. Successive Interference Cancellation (SIC) is used at the receiver for segregating the bundled user data [5]. The use of NOMA enables each user to have access to all the subcarrier channels. Therefore, the bandwidth resources allocated to the users with poor CSI can still be accessed by the users with strong CSI, significantly improving the spectral efficiency. Despite of NOMA having several advantages over OMA, it is possible to observe a residual interference due to channel estimation and decoding errors. Furthermore, in a multi-resource block NOMA network, Inter-Block Interference (IBI) becomes a major challenge as it can negatively affect the performance of mobile devices. Indeed, IBI can significantly deteriorate the performance, especially when power allocation is IBI agnostic [6]. Consequently, researchers have proposed a hybrid NOMA–OMA [7-10] switching network to attain the best of both worlds.

The key challenges in implementing such a NOMA-OMA hybrid network are not limited to strategic power allotments and resource rationing for perfect signal recovery. Providing satisfactory Quality of Experience (QoE) has become a key pillar of resource allocation in wireless systems, [11] and a suitable paradigm to improve the QoE of mobile users also need to be addressed. Base stations in the hybrid network should be able to efficaciously distribute the traffic among the available NOMA/OMA resource blocks and concurrently improve the network profits [12]. In this work, we tackle the problems by formulating a ridesharing-inspired QoE-driven pricing scheme called Orthogonality Centric Pricing (OCP). A block diagram for the synonymous OCP pricing architecture is shown in Fig. 1.

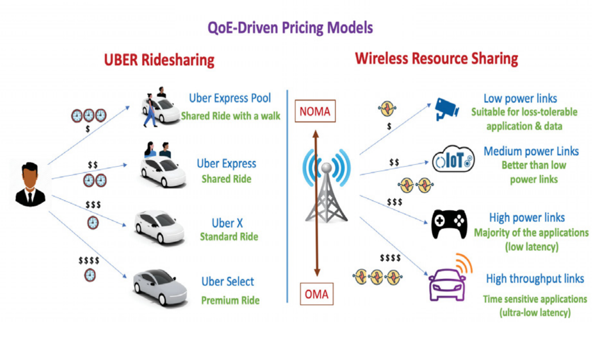

Fig. 1. QoE-Driven Pricing: A comparison of Uber pricing model with proposed orthogonality centric pricing for wireless communication.

QoE driven pricing schemes have found broad recognition in numerous applications such as airline seat selection and uber ridesharing. For example, Uber offers four distinctive choices for end users. The cheapest selection, Uber Express Pool offers a shared ride from a communal pick-up spot which is usually located within a walking distance of all riders. Uber Express, the subsequent cheapest selection, is also a shared ride but the user can choose the pick-up and drop-off locations. The standard Uber X is a the most popular selection where the user, for a higher price, can enjoy a private ride. Uber also offers a high-tier premium experience with Uber Select. The Uber prices these services differently and the customer has a free choice in choosing their ride preference. Uber's pricing algorithm guarantees profits irrespective of ride preferences and delivers satisfactory Quality of Service (QoS) to the customer. In this paper, we propose such a QoE-driven pricing scheme for future wireless multiple access networks.

The applications such as video surveillance and remote sensing have higher error tolerance in comparison to self-driving cars and live streaming of multimedia. The key idea of the developed OCP scheme is to allocate the available resources strategically based on the end-user application and QoE demands. The available links are priced based on their CSI and demand. The user has a free choice to select the link (or links) to purchase at given cost to get the best value for money spent. In this work, we used game theory to show that both the base station and the user equally benefit leveraging the proposed pricing model.

NOMA-OMA hybridization has been widely studied in the literature. The hybrid model was found to be effective for massive Machine Type Communication (mMTC) in ultra-dense networks [7]. Researchers have also carried out performance analysis [8] and latency optimization [9] for hybrid transmission. The relay selection problem in cooperative hybrid networks was also investigated [10]. QoE optimization and novel pricing schemes for such a hybrid network are yet to be investigated and this research aims to provide a novel solution for joint QoE-Profit maximization.

QoE driven pricing schemes have been studied for various engineering applications. QoE has been measured objectively in terms of packet error rate and network throughput, until recently subjective metrices such as distortion reduction have been widely investigated [14]. Smart data pricing [13] and smart media pricing [14] have been proposed to include price as a resource in measuring the QoE subjectively. In our previous work, we developed a prospect theoretic pricing model for capturing the human cognition in distortion reduction for H.265 encoded multimedia communications [15]. We also proposed a novel pricing scheme called NOMA Pricing [16] to price the NOMA resource block based on the QoE delivered. Building upon the success of our pricing models, in this work we propose the OMA pricing scheme to boost the utilities in a hybrid multiple access network.

The remainder of this paper is as follows. In section II, we elaborate on the proposed OCP framework and mathematically formulate the system model. The utility maximizing interplay between the base station and the end user are studied using game theoretic methodologies in Section III. A false-proof Nash Equilibrium solution for both the user and the base station has been discussed for OMA, NOMA, and OMA+NOMA links. MATLAB simulation results are showcased in section IV and conclusions are provided in section V.

II. System Model and Problem Formulation

In this section, we discuss the nuances of OCP framework by implementing it over a minimalistic NOMA-OMA hybrid network. A subjective model to measure the QoE of the user in terms of distortion reduction is presented. The utility definitions for mobile user and the base station are devised and the profit maximization interplay is formulated.

In a hybrid multiple access network, the resources available with the base station, spread across time and frequency, are presented in the form of resource blocks. The base station then divides the available resource blocks into traditional OMA and shared NOMA blocks as shown in Fig. 2. The base station sets the OMA resource block price as fixed, in a way similar to traditional taxi. The OCP framework allows the various NOMA resource blocks to be priced differently, typically cheaper in a way similar to ridesharing applications such as Uber/Lyft. Furthermore, the OCP framework permits the end-user to have a choice in link selection once the price for all available blocks is declared.

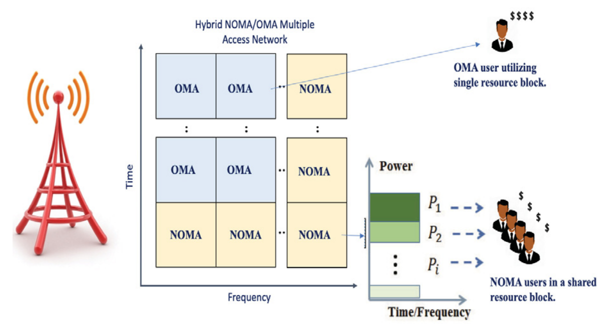

Fig. 2. System Model: OCP on a hybrid NOMA-OMA Network

A. Utility Function Definition of the Mobile User

The OCP aims to improve the QoE of the mobile user by allowing the user to purchase a set of resource blocks through which the data is transmitted. Typically, the end user would pick the OMA blocks to purchase important and time-sensitive data. The lower price offered on NOMA blocks encourages the users to purchase the unimportant data through NOMA blocks.

The contemporary video encoding such as H.265, H.266, AV1, etc. encode the multimedia data into inter-dependent frames with unequal importance (QoE contribution). Thus, successful transmission of few frames is significantly important than few other frames. The mobile user requests a group of multimedia frames $j = 1, 2, \ldots, n$ with unequal importance from the base station over the hybrid NOMA-OMA channel. Without loss of generality, we assume that the frames are sorted based on their frame-level quality contribution. The frames with higher quality contribution $j = 1, 2, \ldots, m$ are typically transmitted over OMA while the frames with lower quality contribution $j = m+1, m+2, \ldots, n$ are purchased over the shared NOMA links.

The QoE of the mobile user is modelled as a function of Peak Signal to Noise Ratio (PSNR) and the Packet Error Rate (PER). Since the frames are inter-dependent in nature, successful transmission and decoding of k ancestor frames contribute to the PSNR of j^{th} frame. The set of k ancestor frames which the j^{th} frame refers to is denoted by π_j. The QoE equation can be written as the sum of quality contribution of each frame purchased.

$$QoE = \sum_{j=1}^{m} PSNR_j \prod_{k \in \pi_j} (1 - PER_{k_{\text{oma}}}) + \sum_{j=m+1}^{n} PSNR_j \prod_{k \in \pi_j} (1 - PER_{k_{\text{noma}}}) \quad (1)$$

The PER can be expressed as a function of Bit Error Rate (BER) and the bit length of the corresponding packet l_k. The x denotes either OMA or NOMA based on the resource block.

$$PER_k = 1 - (1 - BER_x)^{l_k} \quad (2)$$

Quadrature Amplitude Modulation with square constellation (M-QAM) is considered for transmission of data over both the NOMA and OMA links, as the transmission rate can be dynamically adjusted based on the channel quality. The BER of a single-input single-output Gaussian noise OMA channel for the QAM can be estimated as shown below [17-19].

$$BER_{oma} = \frac{2}{b}\left(1 - \frac{1}{2^{\frac{b}{2}}}\right) \operatorname{erfc}\left(\sqrt{\frac{3}{2\left(2^b - 1\right)} \frac{P_{OMA}|h|}{R_s N_0}}\right) \quad (3)$$

where P_{oma} represents the transmission power of the link and the noise power density is denoted as N_o. The channel gain/loss is presented as h and R_s is the symbol rate of the modulation scheme.

All NOMA resource blocks in the hybrid model can support a set of g users $y = 1, 2, \ldots, g$. The BER of the user i in NOMA channel is modelled considering the wireless channel gain/loss information h, and power transmitted $P_{i_{NOMA}}$. The set users closer to the base station than the mobile user i can potentially cause interference and the index of these users are represented by $y = 1, 2, \ldots, i-1$. [22]

$$BER_{noma} = \frac{2}{b}\left(1 - \frac{1}{2^{\frac{b}{2}}}\right) \operatorname{erfc} \left(\sqrt{\frac{3}{2\left(2^b - 1\right)} \frac{P_{i_{\text{NOMA}}}|h|}{\sum_{y=1}^{i-1} P_{y_{\text{NOMA}}} \left|h_y\right|^2 + R_s N_0}}\right) \quad (4)$$

The utility definition of the mobile user is presented as the QoE expectation subtracted by the financial costs spent on NOMA and OMA resource blocks. The user may choose to purchase one of the NOMA-OMA resource blocks or a combination of both.

$$U_{\text{user}} = QoE - y_{\text{noma}} \sum_{j=1}^{m} l_j - y_{\text{oma}} \sum_{j=m+1}^{n} l_j \quad (5)$$

The optimization problem of the mobile user is to determine the amount of power to purchase at the given cost and how to segregate the content into different NOMA links and OMA links to achieve best possible QoE.

$$\begin{aligned} &\underset{P_{\text{oma}}, P_{\text{noma}}}{\text{maximize}} && U_{\text{user}} \\ &\text{subject to:} && P_{j_{\min}} < P_j < P_{j_{\max}} \end{aligned} \quad (6)$$

B. Utility Function Definition of the Base Station

In traditional hybrid multiple access network, conjunction of uniform pricing and resource blocks dynamics makes the resource allocation a challenging issue. All users may prefer one block (due to lower noise, for example) over another block. The proposed OCP allows the base station to dynamically analyze the CSI and traffic to come up with optimal pricing for both OMA and NOMA block. Let y_{oma} and y_{noma} denote the OMA and NOMA resource block prices (i.e., the per-bit price to transfer user data), respectively. The utilization cost of OMA resource block is higher than the NOMA block.

$$y_{oma} \geq y_{noma} \quad (7)$$

The expenditure on the base station side C_x is defined as the cost per unit energy required to transmit a frame over the wireless channel. It is determined by the total sum of packet lengths L, transmission power per bit P_x, symbol rate R_s and the b is the modulation co-efficient.

$$C_x = \frac{P_x L}{b R_s} \quad (8)$$

The utility function of the base station will be presented as the total revenue from all users subtracted by the communication costs incurred in all the OMA and NOMA blocks. The set of packets transferred in NOMA blocks and OMA blocks are represented as $j = 1, 2, \ldots, m$ and $j = m+1, m+2, \ldots, n$ respectively.

$$U_{BS} = y_{noma} \sum_{j=1}^{m} l_j + y_{oma} \sum_{j=m+1}^{n} l_j - \alpha \frac{P_{OMA}}{b.R_s} \sum_{j=1}^{m} l_j - \beta \frac{P_{i_{NOMA}}}{b \cdot R_s} \sum_{j=m+1}^{n} l_j \quad (9)$$

where α and β are defined as the currency value for unit energy consumption for OMA and NOMA links respectively. The utility optimization problem for the base station is to determine the optimal value for y_{oma} and y_{noma} that would maximize their utility.

$$\begin{aligned} &\underset{y_{\text{oma}}, y_{\text{noma}}}{\text{maximize}} && U_{BS} \\ &\text{subject to:} && U_{BS} > 0 \\ &&& y_{oma} \geq y_{noma} \end{aligned} \quad (10)$$

III. Nash Equilibrium Analysis

The hybrid NOMA-OMA wireless network presents the user with multiple choices of links to purchase for data transmission. The user could choose to utilize the low interference OMA links (like UberX) and pay a premium price. Alternatively, the user could bear some interference and utilize a shared NOMA link (like UberPool), potentially paying less. Thus, two essential questions need to be addressed: *1) What is the optimal price for OMA-NOMA blocks set by base station; to balance the traffic and improve profits? 2) What is the optimal amount of OMA-NOMA power the user should purchase and by doing so, choose the right resource block?.* The key idea of the OCP framework is to find a win-win equilibrium solution that would yield the base station and user with high utilities, such that no party has an incentive to deviate from that solution. Such a strategic solution is called as Nash Equilibrium.

The interaction between the base station and the end user can be formulated as a sequential game, as the base station first declares the price for utilizing every block and then the user chooses the best block at given price subjected to the the power constrains. A generalized best response approach is presented in this paper to determine the most favorable outcome for a user and the pricing strategy for the base station. A player's best response is a strategy or a set of strategies that produces the greatest payoff given all the players' strategies [20]. There are three common scenarios because of the interaction: *1) There is a unique strategy (single resource block) that yields the best profit to both user and base station; 2) Multiple strategies (two or more resource blocks) that maximize the utility; 3) No unique strategy available*. 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, we solutions are briefly discussed and a general-purpose algorithm is presented as an implementation reference.

A. Pure Strategy Nash Equilibrium Analysis

The profit driven interactions between the both base station and end user is translated into a game theoretic interaction and is analyzed in this subsection. The PSNE Nash equilibrium solution of the game is given by the following definition.

Definition I: *PSNE of the best response game is the strategy set $\{p^*, y^*\}$ that produces the greatest payoff given all other game strategies, such that $U_{user}(p^*, y^*) > U_{user}(p_j, y^*)$ for all strategies p_j of the end user and $U_{BS}(p^*, y^*) > U_{BS}(p^*, y_j)$ for all strategies y_j of the base station respectively. The optimality for the user is to choose the NOMA/OMA resource block which has offers the transmission power closest to the Nash Equilibrium solution.*

The necessary and sufficient condition under which the PSNE solution exists for the base station are governed using the following Lemmas.

Lemma 1: If there is only one resource block subjected to the power constrain $P_{j_{min}} < P_j < P_{j_{max}}$ of the user to purchase frame j, then the base station can charge the user with the maximum price $y^* = y_{max}$.

Lemma 2: If $P_{j_{min}} \neq P_{j_{max}}$, then there is at least one resource block which can transmit the frame j with a price $y^* < y_{max}$.

Lemma 3: If M is the only resource block in the resource block that yields the highest utility U_{user}, then the base station increases the price of that resource block until the resource block M is the only choice of user to achieve highest possible utility.

The interactions in the hybrid network are modeled as a sequential game. Therefore, once the base station decides the price based on the above-mentioned lemmas, the user would be able to compute the transmission power that yields the best utility and purchase data through the resource block offers the Nash Equilibrium power. During implementation, all the strategies for both the user and base station are tabulated as a three-dimensional utility matrix and the PSNE solution can then be derived using Iterated Elimination of Strictly Dominating Strategies (IESDS). The methodology has been discussed in entirety in our previous work [21].

B. Mixed Strategy Nash Equilibrium Analysis

When there is no PSNE solution (unique OMA or NOMA resource block) that yields the best utility to user, they can leverage the hybridization in the multiple access to purchase the critical frames via OMA and the remaining frames via NOMA. The challenge for the user is to determine how the multimedia data should be split so that some of the content can be purchased via OMA and the rest by NOMA.

The optimal strategy can be determined by first building the payoff matrix for each of the available resource blocks. The user now must choose multiple research blocks to obtain the data. A set of probabilities with which the user should mix two or more resource blocks can be determined using game theoretic technique – IESDS and likelihood estimation [20].

Definition II: *MSNE of the best response game is the set of probabilities $\vec{\mu} = (\mu_1, \mu_2...)$ and $\vec{\eta} = (\eta_1, \eta_2...)$ one for end user and one for base station such that the players get the same payoff (utility gain) when they play a strategy with probability μ_i and η_i respectively.*

A MSNE solution would allow the user to segregate the multimedia data among the available NOMA and OMA resource block. Derivation of such a solution is discussed in entirety in our previous work [21].

C. Algorithm Design

In this subsection, we present an algorithm to be implemented on a hybrid NOMA-OMA network, that can determine the set of resource blocks for the user and sets of prices for the base station to yield best utilities. The algorithm outputs the Nash Equilibrium solution. It is worth noting that the Nash Equilibrium solution does not aim to get the best possible utility for one player but gets a stable solution that provided no incentive for the any of the player to deviate from the solution. An algorithm for implementation reference is provided in this manuscript as Algorithm 1 below.

Algorithm 1 Implementation of OCP framework

1) **Initialization:**
   - 1.1. Pre-set the known parameters in the utility definitions.
   - 1.2. The total number of price options between y_{min} and y_{max} is given by u. The total amount of NOMA and OMA resource blocks available in the hybrid multiple access network is give by v.
2) **Iterations:**
   - **For:** number of resource blocks
     - Pick v: current resource block as optimal resource block
     - **For:** number of price intervals between y_{min} and y_{max}. Step size: 500.
       - pick u = current price as the optimal price
       - iterate over all prices and mark best response
     - Compute the utility of user for all the resource blocks and mark the optimal power against the optimal price.
     - Eliminate entries using IESDS.
     - **if:** if best response of user is also a best response of base station
       - Declare corresponding y, l as PSNE solution
       - Output the OMA/NOMA resource block v as the solution.
     - **Else:** PSNE solution does not exist
       - initialize a probability vector corresponding to the size of matrix
       - Formulate and solve the set of quadratic equations for obtain the mixing probabilities for the MSNE solution.
3) **Output:** The optimal $\{p^*, y^*\}$ for PSNE solution along with the resource block v and the sets of p, y, corresponding resource blocks along with their mixing probabilities$\mu_1, \mu_2, \ldots \mu_i$ and $\eta_1, \eta_2, \ldots \eta_j$ for MSNE solution.

IV. Simulation Study

The performance of the developed model has been evaluated and the simulations were carried out on MATLAB. The cost parameters were initialized as $\alpha = 1$ and $\beta = 1$. The channel SNR was set to 25 dB. The choice of modulation size and length of packet were 2 and 10000 respectively. The simulation step size was set to 500 to get finer curves. Three different test video sequences namely "Netflix Square and Time lapse", "Netflix Pier Seaside" and "control burn" were encoded using four different $MPEG-4\ H.265$ codec schemes ($IIIII\ldots, IPIPIP\ldots, IBPIBP\ldots,$ and $IBBPBBP\ldots$) to obtain the multimedia test data.

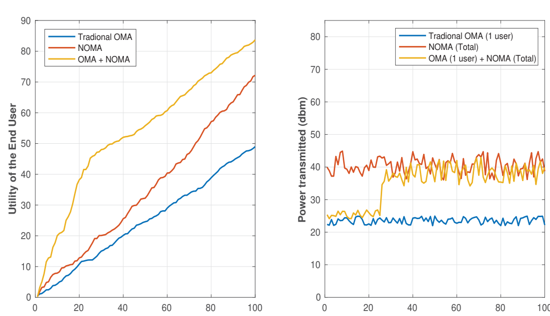

Fig. 3. Analysis of end user utilities in the hybrid NOMA-OMA network

The utility of the end user for a fixed budget was analyzed using the proposed OCP framework. Without loss of generality, it was assumed that frames were ordered based on their importance. The total number of users considered for the simultaneous transmission of data in a NOMA link is four. From the Fig. 3., it can be observed that utility of the user increases with amount of data transmitted. Simulation demonstrates that a combination of OMA and NOMA channels yield the highest utility to the user. The figure on the right captures the amount of power transmitted for a single user in an OMA link and all set of n users in a NOMA link. It can be observed that the mobile end user will be able to achieve higher utilities, for similar power levels, by splitting up the data strategically (MSNE solution) between the NOMA and OMA links.

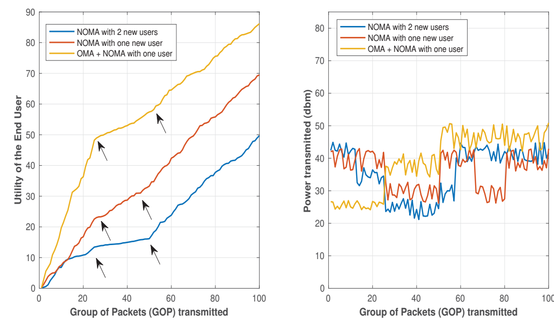

Fig. 4. Impact of network dynamics on end user utilities

In wireless communication, the network is highly dynamic and time varying. The impact of users joining and leaving the NOMA resource block occupied by the mobile user was studied in Fig.4. Every time a new user enters the resource block, the utility of the mobile user is affected. If the new user is closer to the base station than the existing mobile user, the new user's signal will introduce interference to the existing users, and if the new user happens to be further away, the signal will not introduce interference. The figure captures the effect of interference on the system. The arrows in the figures indicate the point at which users enter and leave the NOMA block respectively. The initial number of users in the NOMA link was set to 4. The power allocated by the base station varies based on the CSI. Once again for fixed budget, it was observed that the combination of NOMA and OMA links yield the best utility for the user.

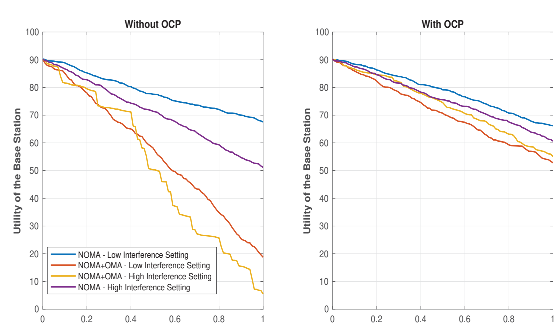

Fig. 5. Analysis of base station utilities against operating costs

The utility of the base station is compared against the operating costs α and β. The values of the operating costs were altered from 0 to 1 and the utilities of the base station were observed with and without the proposed OCP framework. The Fig.5 illustrates that the proposed scheme improves the utility of the base station significantly. One OMA link and two NOMA links (low/high interference) were chosen for the simulation. Under traditional uniform pricing, the utility of the base station drops with the channel quality and user preference to occupy a channel with less interference. By dynamically allocating the price for occupying the available resources, the base station is able to distribute the traffic among all the available links and earn similar income irrespective of the type of resource blocks the mobile user utilize for their communications.

V. Conclusions

The future wireless network is envisioned to support superior data rates and provide connectivity to a massive number of devices to satisfy the increasing demand for data services. Uberization of shared wireless network resources based on the multiple access schemes appears to be fitting to the data demand. In this work, we propose a novel wireless resource pricing framework, called OCP, for such a hybrid multiple access network with NOMA and OMA resource blocks. The intricacies of the proposed OCP framework were analyzed on a hybrid access network, and several game theoretic techniques to achieve the win-win solution between the base station and the mobile user have been presented. Simulations were also carried out to observe base station and end user behavior in the hybrid access network. The preference of users to choose a combination of NOMA-OMA over standard NOMA and OMA resource blocks testaments the hybrid multiple access schemes. Furthermore, the rise of both base station and end user utilities warrants the potentials of the proposed OCP framework for hybrid NOMA-OMA networks. It is worth noting that the OCP framework yielded desirable utility for users when both OMA and NOMA resource blocks are leveraged. On the contrary, utilization of just NOMA resource blocks yielded the highest utility for the base station, due to the increased capacity introduced by NOMA.

VI. Acknowledgement

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