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NOMAP: A Pricing Scheme for NOMA Resource Block Selection and Power Allocation in Wireless Communications

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***Abstract*—Non-Orthogonal Multiple Access (NOMA) is one of the promising solutions for next-generation wireless services to mitigate traffic congestion and reduce latency. However, the issues such as regulating network revenue and ameliorating end-user Quality of Experience (QoE) are still open challenges. In this work, we propose the concept of Non-Orthogonal Multiple Access Pricing (NOMAP), to bridge the gap between price and QoE in NOMA resource allocation. The framework was then applied to a NOMA network scenario, and the problems of power allocation and resource block selection were investigated. The main contribution of this paper is to show that higher utilities can be achieved by dynamically pricing the NOMA resource blocks and by allowing the users to have a choice in resource management. In addition, an algorithm to achieve optimality in terms of Nash equilibrium is provided as an implementation example. The simulations carried out using MATLAB showcase the efficacy of the developed NOMAP framework. Furthermore, the results indicate that the proposed pricing significantly outperforms the traditional uniform pricing schemes.**

***Index Terms*—Quality of Experience (QoE), Non-Orthogonal Multiple Access (NOMA), NOMA Pricing, Power Allocation, Resource Block Selection.**

I. Introduction

Non-Orthogonal Multiple Access (NOMA) has been a hot research topic in recent years because it is advocated that this technique is a promising technology for 6G cellular networks and beyond [1]. In comparison to Orthogonal Frequency Division Multiple Access (OFDMA), which is the current de facto standard among the orthogonal multiple access (OMA) techniques, NOMA provides a set of desirable potential benefits, such as improved spectrum efficiency, enhanced connectivity, and reduced latency with high reliability [2]. The fundamental philosophy of NOMA is to cater multiple users simultaneously using the same resources in terms of time, frequency, and space. However, there are several challenges lying ahead in terms of power allocation among users, resource block assignment and strategic pricing. The aforementioned issues are discussed in this paper.

The baseline idea of NOMA is to serve multiple users using the same resource block in terms of time, frequency, and space. NOMA can be designed in either time-frequency domain, code domain or power domain [3]. Power-domain NOMA relies on a classic simultaneous multiple access using a Superposition Coding (SC) strategy to allow more users to access the same resources. At the receiver, Successive Interference Cancellation (SIC) is employed for recovering each communication session [4]. The primary challenge is to strategically allocate power for perfect signal recovery, while improving network revenue. In this work, we come up with NOMA Pricing (NOMAP), a framework which allows the base station to dynamically alter the price for the available power resource. By doing so, the base station can ensure that satisfactory service is provided without negatively affecting the network revenue.

The perceived service satisfaction by the user or Quality of Experience (QoE) has become a key pillar of resource allocation in wireless systems. The QoE observed by end user (EU) has been assessed objectively in terms of throughput and latency, until recently, emphasis has been on subjective metrics such as Peak Signal to Noise Ratio (PSNR) [5]. Although current NOMA designs have demonstrated the potential to largely improve conventional system performance in terms of throughput and latency, their impact on the EUs' QoE is yet to be comprehensively investigated [6]. In this work, we take a step to fortify NOMA QoE by incorporating cost paid as a factor in evaluating user satisfaction.

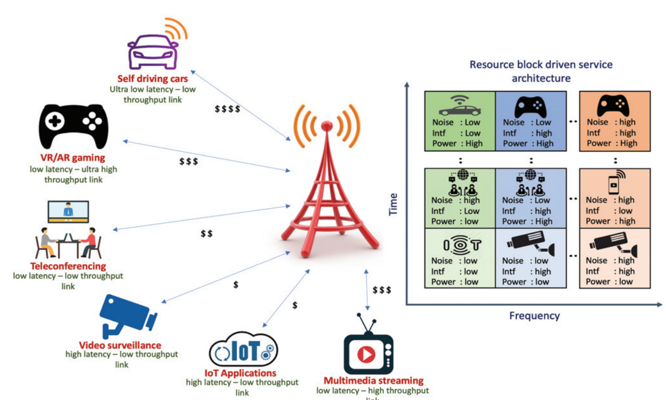

Fig. 1. Next-generation NOMAP architecture: pricing the power allocation and resource block assignment.

In the NOMAP architecture, we introduce price as a resource for resource block assignment and power allocation in

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NOMA. By pricing the QoE, the EU can dynamically decide the amount of power to purchase for a NOMA interaction (downlink). Thus, the NOMAP approach facilitates end-user to achieve satisfactory QoE. The pricing scheme in the next-generation NOMA resource block assignment is shown in Fig.1. The available resources spread across time and frequency are divided into resource blocks and multiple users can be simultaneously catered within a single resource block. Given the dynamic nature of the resource blocks, it becomes challenging to assign them to users. All users may prefer one block (due to lower latency or higher throughput) over the other blocks when the price is uniform. Traffic in one block will result in network congestion and loss in revenue for the base station. In the proposed NOMAP architecture, we price the resource blocks based on noise, interference, and the available power. A new user can join the resource block based on their QoE requirement and application. The main objective of this paper is to show that both the end user and base station can obtain high utilities irrespective of the resource block selected, while meeting all EU QoE requirements.

Under the NOMAP architecture, the base station can dynamically price the available power resources in each resource block. Once the price is declared, the EU can decide the amount of power to purchase to meet their QoE requirement. Also, the EU determines/chooses one of the resource blocks which yields the highest utility and fits its application need. The utility maximization problem between the end user and base station is translated into a two-stage Stackelberg game and we derive the Nash Equilibrium solution using backward induction method. Since such an equilibrium exists for all available resource blocks in a stable fashion, the user's choice of resource block does not affect the network revenue.

Researchers are pushing NOMA as a suitable candidate to improve network capacity in 6G communications [7,8]. The virtual resource allocation and caching strategies are studied in [9]. The problem of effective capacity of NOMA systems subject to delayed quality of service (QoS) are investigated in [10]. NOMA also has a potential to be used for low-latency Vehicle to Vehicle (V2V) communications. The implications on implementing NOMA for V2V broadcast has been studied in [11]. NOMA has also been optimized for V2V communications and its performance analysis has been presented [12].

Furthermore, the QoE enhancement issues in power-domain NOMA have been widely studied. Authors in [13], adopt NOMA for heterogeneous cloud radio access network to investigate the downlink performance. They focused on the energy efficiency issues and proposed a two-stage algorithm for determining the number of cells to maintain the end user QoE requirement. Similarly, a hybrid analog/digital precoding scheme for the base station has been developed for improving the QoE gain of EU [14]. Further in [14], an algorithm for jointly maximizing the energy efficiency in the NOMA power allocation has been presented. Yet another key issue to be tackled before NOMA implementation is to develop a QoE-aware pricing strategy that would benefit both the end user and the base station. Such a framework, called NOMAP, is presented in this paper.

The remainder of this paper is as follows. In section II, we elaborate on the system model and discuss the problem formulations. The translation of the problem in a repeated two-stage Stackelberg game and derivation of Nash equilibrium solution is shown in section III. An algorithm for implementation reference is also provided. MATLAB simulation results are showcased in section IV and conclusions is in section V.

II. System Model

In this section, we present our proposed NOMAP system model, mathematically define the utility equations, and then formulate the utility maximization problem. Applications such as autonomous driving cars, VR/AR gaming, virtual conferencing, video-based surveillance, and multimedia streaming contribute to most of the traffic on the Internet. These applications have varied QoE demands. Therefore, providing them with similar service links and pricing them uniformly does not benefit both the Base Station (BS) and the EU. In the traditional pricing scheme, the EU pays based on the bandwidth or data purchased, and so, the overall quality of service is overlooked. Also, both critical (autonomous vehicle collision detection traffic) and non-critical (diagnostic/ statistical traffic) are treated equally by the network. Under the proposed NOMAP, the resource blocks are treated non-uniformly based on the number of existing users, interference, and average distance from the BS. Henceforth, the cost of using different resource blocks vary. However, high utilities can be achieved, in each of the available resource block, exploiting strategic choices for the price and transmission power.

QoE-driven pricing schemes have found wide acceptance in other applications such as airline seat selection and Uber ride-sharing. For example, Uber offers four different choices for end users. The cheapest option, Uber Express Pool offers a shared ride from a common pick-up spot which is usually located within a walking distance of all riders. Uber Express, the second cheapest option, 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 option where the user, for a higher price, is not required to share the ride. Uber also offers a high-tier premium experience with Uber Select. The Uber prices these services differently. However, the EU has the final decision in choosing the type of service they want to utilize. All four services allow the users to commute to their destinations and Uber produces revenue irrespective of the rider service choice. In this work, we are proposing such a QoE-driven pricing, NOMAP, for wireless NOMA communications.

For simplicity, we consider a minimalistic network with a single BS and three NOMA resource blocks as shown in Fig. 2. All resource blocks have (n) active users. However, the distance between these users and the BS is different in different blocks, affecting the overall interference. In the first resource block, the existing (n) users are closer to the BS in comparison to the new EU. Therefore, the signals corresponding to the previous (n) users introduce interference to the EU. Therefore, this resource block is categorized as "High Interference" and so the EU has to purchase a large amount of power to meet their QoE requirements. However, in such a high interference setting, the base station would charge a low cost for the power, to promote the EU to join the resource block. The third resource block has (n) existing users located farther than the EU from the BS. In this setting, the signals corresponding to the farther (n) users can be decoded and subtracted using SIC by the EU. Therefore, this resource block is categorized as "low interference" and the QoE requirements of the EU can be met by purchasing lower power. NOMAP allows the BS to capitalize on the low interference, and so the power resources would be priced higher. The second resource block is categorized as "mild interference" as it has (n) existing users located at the either side of EU. In all three resource blocks, by incorporating price as a resource, NOMAP allows EU to get best value for money spent.

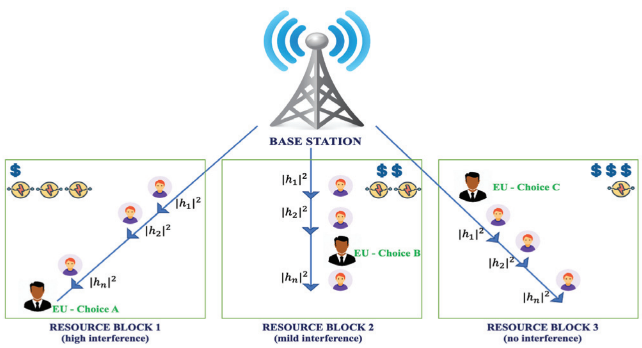

Fig. 2. System model: a NOMAP minimal network with a single BS and three priced resource blocks to choose from.

Although we consider a simple model with three resource blocks and (n) users each, the solution derived can be easily expanded to higher number of resource blocks and unequal user distribution. The proposed solution in the paper is focused on boosting the QoE of the new EU. Every time a new user joins or leaves the NOMA resource block, the NOMAP solution is derived again to achieve optimality. Like the new EU, all users in the network can adopt to the NOMAP model to boost their individual utility. Thus, all users and the BS are benefitted from the framework.

A. Quality of Experience (QoE) model

The EU joins one of the NOMA resource blocks and requests service from the BS. In a general case, there are M resource blocks to choose from, and the BS serves (n) users in each block. We assume that all wireless links experience independent and identically distributed (i.i.d.) block Rayleigh fading and Additive White Gaussian Noise (AWGN). All (n) users in each block share the same physical channel resources such as frequency spectrum bandwidth, time slots, and spreading codes. Benefiting from SC and SIC technologies at transmitter and receiver, respectively, the transmission rate achievable for (i^{th} user) user in a resource block R_i can be modeled using the Shannon–Hartley theorem:

$$R_i = B \log_2 \left(1 + \frac{P_i \left|h_i\right|^2}{\sum_{k=i+1}^{N} P_k \left|h_k\right|^2 + \sigma^2}\right) \tag{1}$$

where B is the amount of bandwidth purchased to transmit data. P_i and h_i denote the power transmitted and Rayleigh fading channel gain between BS and EU, respectively. The noise power in the communication channel is given by σ^2. The users closer to the BS than the EU cause interference and these users are represented by k.

The QoE is a per-session measure of EU satisfaction in terms of utility maximization. The two-level logarithmic function has been widely adopted in modeling the QoE equations in wireless communications as it has been proved to be able to introduce concavity to the utility function by subtracting a linear cost function [15, 16]. Therefore, NOMAP QoE can be quantified as the logarithmic function of the allocated resource, and it is given by equation:

$$QoE_i = \alpha \log_2 \left(1 + B \log_2 \left(1 + \frac{P_i \left|h_i\right|^2}{\sum_{k=i+1}^{N} P_k \left|h_k\right|^2 + \sigma^2}\right)\right) \tag{2}$$

where α represents the payoff parameter or currency gain for the logarithmic QoE.

B. Utility of the End User

The EU buys service from the BS to boost its utility. The linear cost function is formulated as a function of cost y_i paid by the user (i) proportional to the amount of power P_i purchased to utilize the NOMA resource block.

$$\psi_{EU} = y_i P_i \tag{3}$$

The overall utility of the EU by choosing any of the resource block is modeled as the QoE subtracted by the cost paid, as shown in equation (4). $P_{i_{\min}}$ and $P_{i_{\max}}$ represent the minimum power required for successful transmission and the maximum power available per user with the BS respectively.

$$\begin{aligned} U_{EU} &= QoE_i - y_i P_i \\ s.t.U_{EU} &\geq 0 \\ P_{i\,\min} &< P_i < P_{i\,\max} \end{aligned} \tag{4}$$

The optimization problem for EU rests on determining the amount of power needed to purchase in each of the NOMA resource block that would yield the best utility. The EU then has a free choice to choose one of the resource blocks based on the budget and QoE requirement.

C. Utility of the Base Station

The objectives of the BS are to achieve high revenue and ensure guaranteed Quality of Service (QoS). The transmission cost ψ_{TX} is defined as the cost per unit energy required to transmit a frame over the wireless channel. It is determined by the packet length l, transmission power P_i, constellation size of modulation scheme b and the bandwidth B. λ is defined as the currency value per unit energy consumption.

$$\psi_{TX} = \lambda \frac{l.P_i}{b.B} \quad (5)$$

The overall utility of the BS for catering EU in one of the NOMA resource blocks is defined as the income from the EU subtracted by the data transmission cost.

$$U_{BS} = y_i P_i - \lambda \frac{l.P_i}{b.B} \quad (6)$$
$$s.t. U_{BS} \geq 0$$

The optimization problem for the BS is straight forward. The BS has no control over the resource block the EU would occupy. The objective of the BS is to determine the cost y_i for each of the resource blocks such that the BS has no disincentive if the EU prefers one block over the other.

III. Nash Equilibrium Analysis

It is assumed that the BS and EU are both rational, selfish, and constantly strive to maximize their profits. The optimization problem in the previous section is first translated into a two-stage Stackelberg game. Stackelberg game is a leader-follower based interaction model, where the leader knows the follower's strategy and makes decisions accordingly. Here, we consider BS as the leader (decides on cost first) and EU as the follower (determines power resource to purchase). The game is then pursued using backward induction to determine the Nash Equilibrium solution $\{P_i^*, y_i^*\}$. Nash equilibrium of the developed game is defined as the set of strategies, one for EU and one for the BS such that both parties have no incentive deviating from that strategy [17].

The game is repeated for all the M resource blocks to derive solutions. In this section, we show that a Nash Equilibrium solution exists stably for every single resource block by leveraging the NOMAP architecture. The EU can then choose solution that yields the highest utility and meets the QoE requirement.

A. Nash Equilibrium Power Selection for End User

The analysis is first carried out for the EU as we use backward induction. Since the EU does not know the strategy of BS, we derive a best response equation which establishes a relationship between the two game variables P_i and y_i.

Property 1: *The utility function of the EU is concave with respect to its transmission power P_i purchased.*

Validation: The two-level logarithmic QoE model when subtracted by a linear cost function introduces concavity to the utility equation.

Property 2: *A unique Nash equilibrium solution for the EU's power selection problem exists in the NOMAP architecture.*

Validation: Since the utility equation is concave, the first order derivative can be equated to zero to determine a unique fixed relationship between the cost y_i set by the BS and amount of power P_i purchased by the EU.

The Nash Equilibrium equation derived will hold true for all M resource blocks. Therefore, the solution may be derived just once and be reused by plugging values corresponding to different resource blocks.

B. Nash Equilibrium Cost Selection for Base Station

The BS being the leader of the game, knows the strategy (fixed relationship) derived by the EU. By plugging in the relationship in the utility equation of BS, the number of unknown parameters can be reduced from two to one. The Nash Equilibrium y_i^* can then be derived using Newton method in a way similar to [18] leveraging the lemmas below.

Lemma 1: *A real function which is differentiable must be a continuous function.*

Validation: By reducing the number of unknowns from two to one, the utility equation of BS becomes a function of price y_i. This function is both real and differentiable.

Lemma 2: *A continuous real function on a closed interval must contain a maximum value and a minimum value.*

Validation: Since the Nash equilibrium transmission power is bounded within a close interval $P_{i\min} < P_i < P_{i\max}$, the cost set by BS will also be bounded between $y_{i\min} < y_i < y_{i\max}$. The optimal cost y_i^* can be determined by performing a search between the intervals.

After computation, the BS announces the cost y_i^*. The EU can then determine the power P_i using the relationship derived.

C. Algorithm for NOMAP Implementation

Algorithm 1 NOMAP Implementation - Stackelberg Game

1) **Initialization:**
   - 1.1. Initialize the cost parameters α and λ.
   - 1.2. Define the channel parameters: channel bandwidth B, interference H and channel noise σ.
   - 1.3. Set the transmission parameters: length of packet l and modulation constellation size b.
   - 1.4. Choose the simulation step size X.
2) **Iterations:**
   - 2.1. The algorithms solve for the best responses P_i^*, y_i^* for all the M resource blocks setting and obtain M unique Nash Equilibrium solution.
   - 2.2. **For** i=1: M (iterate through resource blocks)
   - 2.3. Initialize $U_{BS}^m = U_{EU}^m = P_i = y_i = 0$
   - 2.4. Let $\chi = y_{i\min} : X : y_{i\max}$
   - 2.5. **For** j=1: Y (iterate through price range)
   - 2.6. Set $\gamma = \chi$(i)
   - 2.7. Compute $u_{BS}(\chi(j))$
     - 2.7.1 if $u_{BS}(\chi(j)) \geq U_{BS}^m$
       - 2.7.1.1 Update U_{BS}^m = $u_{BS}(\chi(j))$
       - 2.7.1.2 Set y_i= γ
       - 2.7.1.3 Calculate P_i using EU's derived strategy
     - 2.7.2 End **if**
   - 2.8. Determine the values of U_{BS}^m and U_{EU}^m using the utility definitions.
   - 2.9. End **for**
   - 2.10. Choose the max U_{EU}^m as $U_{EU}^{m^*}$. Alternatively, a different constraint can be leveraged to choose the resource block.
   - 2.11. Recompute the corresponding values of $\{P_i^*, y_i^*\}$ and also obtain the $U_{BS}^{m^*}$.
3) **Output:** The algorithm determines the Stackelberg game equilibrium $\{P_i^*, y_i^*\}$ for all the resource blocks. A resource block is then picked based on overall utility and QoE requirement. The corresponding utilities of BS and EU are computed.

Building on the analysis above, an algorithm to implement the NOMAP framework and derive the Nash Equilibrium is presented. In this algorithm, the resource block is chosen based on the highest utility achieved. However, the algorithm can be fine-tuned based on the end application to choose the resource block differently. The choice of resource block does not alter the Nash Equilibrium. Under NOMAP, the EU and BS always achieve best utility irrespective of the resource block picked.

The cost of computing of the proposed algorithm is $O(M, X)$ where M and X are number of resource blocks and iteration step size. Alternatively, a table look-up approach can be adopted and updated with the equilibrium power and equilibrium cost during the sparse time periods between the NOMA transmissions. The best responses can directly be searched from the table whenever the algorithm needs to be performed. This would reduce the computing complexity and latency between the transmissions.

IV. Simulation Study

To validate the efficiency of the developed QoE-aware NOMAP framework and to test its competence against the traditional pricing schemes predominantly used in OMA, simulation studies were conducted using MATLAB. The cost parameters were initialized as $\alpha = 5$ and $\lambda = 2$. The channel SNR was set to $25dB$. The choice of modulation size and length of packet were 2 and 10000 respectively. The simulation step size was set at $X = 500$ to get finer curves.

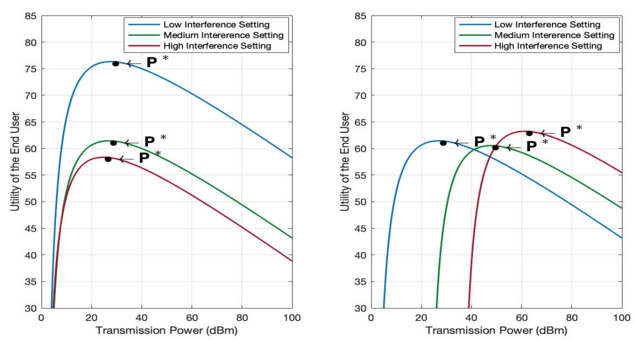

Fig. 3. Utility of EU: traditional pricing (left) vs proposed NOMAP (right)

In the previous section, we showed mathematically that the utility of the EU is always concave due to the two-level logarithmic QoE model. In the traditional pricing scheme, all the resource blocks (interference levels) are priced uniformly. Therefore, the Nash Equilibrium price yields different utilities for EU based on resource block choice as shown in Fig. 3(left). However, NOMAP introduces non-uniform pricing which ensures that the EU can achieve similar utilities, irrespective of the interference levels shown in Fig. 3(right).

The quality of wireless channel is inherently time varying. As the noise increases, the BER increases as well. In the Fig. 4, we compare the impact of BER on the EU's utility. The BER impacts the overall utility of the EU. However, in traditional pricing schemes, the impact of the deteriorating channel is proportional to the interference levels. In contrast, since price is used as a resource in NOMAP scheme, the deterioration is indifferent among the different resource blocks.

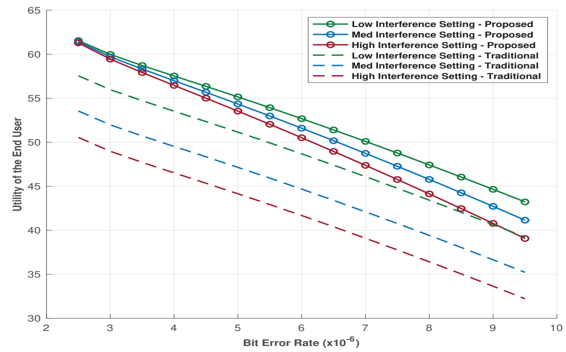

Fig. 4. Utility of EU on a deteriorating channel

The resource block based wireless communication framework introduces two new challenges to the BS. Firstly, the BS could find that all users prefer one resource block over the other and so, the network becomes imbalanced. Secondly, the revenue stream from the resource blocks is non-uniform. Fig. 5 (left) shows the traditional pricing approach where maximum attainable utility is different in different resource blocks. NOMAP framework benefits the BS as much as it benefits the EU. Since we introduce price as a resource, the EU pays higher price for a low interference channel and lower price for a high interference channel. The non-uniformity in price ensures that the BS can achieve high utility in all its resource blocks as shown in Fig. 5 (right).

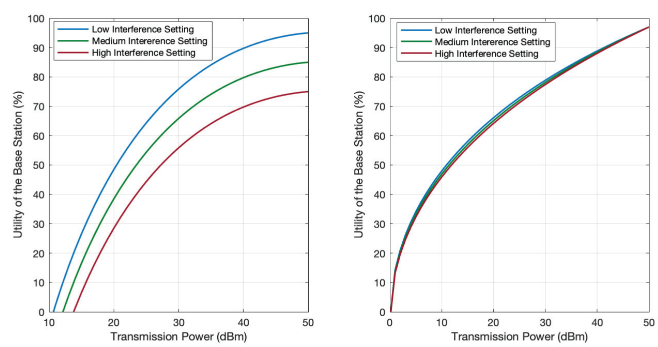

Fig. 5. Utility of BS: traditional pricing (left) vs proposed NOMAP (right)

In wireless communication, the network is dynamic and time varying. Users tend to enter and leave a NOMA resource blocks at arbitrary times. Every time a new user enters the resource block in which another EU already exists, the utility of the EU is distorted. If the new user is closer to the BS than the EU, the user's signal will introduce interference (scenario A) to the network and if the user happens to be further away, the signal will introduce noise (scenario B) to the EU. In Fig 6, the aforementioned situation is examined by comparing the traditional pricing with NOMAP. Under NOMAP, the utility of the EU reduces very slightly under scenario A and the reduction in utility under scenario B is negligible. However, we were able to observe a significant reduction in utility for the traditional pricing approach when new user introduces interference. This result further advocates for the use of NOMAP architecture for NOMA communications.

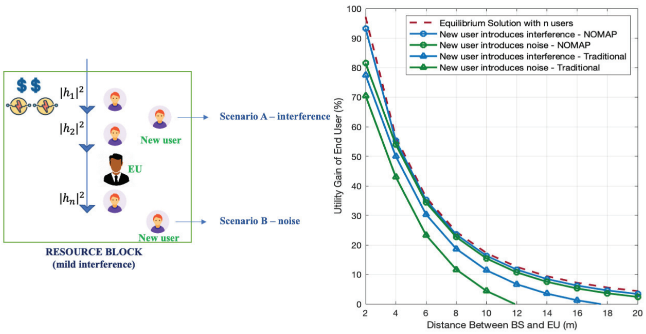

Fig. 6. Utility gain with addition of a new user in the resource block

V. Conclusions

In this research, the NOMAP concept is introduced to price the NOMA resource block selection with power allocation. The developed framework has been applied and analyzed on a minimalistic NOMA network scenario consisting of a single BS and three NOMA resource blocks. The Nash Equilibrium solution that would yield high utilities to both BS and EU under NOMAP have been derived and an algorithm for further implementation has been provided. The simulation results indicate that the proposed NOMAP concept with the resource block pricing model has potential to simultaneously improve the network capacity, boost the BS revenue and enhance the EU QoE.

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