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A Power Auction Approach For Non-Orthogonal Multiple Access Wireless Relay Communications

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***Abstract*—Drastic growth in multimedia driven applications is pushing the boundaries of current wireless networks, commending for better power efficient communications. Non-Orthogonal Multiple Access (NOMA) has been adopted to improve the coverage area, spectrum, and energy efficiency in the next generation wireless access networks. Meanwhile, the potentials of Device-to-Device (D2D) relay communications also sparks an interest among the researchers to improve power efficiency due to the shorter distance between relay and receiver. In this paper, we are considering a NOMA power allocation approach in wireless network with support of D2D relay communications. We explore auctioning techniques for power purchasing to incentivize the relaying devices. The main contribution of this work is to show that the users can significantly improve their Quality of Experience (QoE) and relaying devices can maximize rewards using the proposed power auction approach in the NOMA relay framework. Solutions for two auctioning techniques - sealed first price auction and sealed second price auction - have been discussed in this manuscript for power allocation. Simulations studies and the results indicate Vickery-Clarke-Groves (VCG) second price auction as a suitable paradigm to boost user QoE and reward the participating relays power transmission in the NOMA wireless networks. The results also showcase that NOMA Relay networks are sustainable and reduce the net power transmitted to meet user demands.**

***Index Terms*—Non-Orthogonal Multiple Access (NOMA), VCG Auction, Wireless Relay Communications, Power Efficiency.**

I. Introduction

Non-Orthogonal Multiple Access (NOMA) has been extensively considered as one of the most promising technologies in the next generation green wireless networks [1]. In NOMA downlink wireless communications, the base station broadcasts the aggregated contents to all users in the network via superposition coding, and users decode the broadcast contents via successive interference cancellation. Therefore, numerous end users (EU) can be catered simultaneously using the same resources in terms of time, frequency, and space. NOMA saves energy and increases network capacity significantly. However, since all the users' signals are superposition coded, the data of the users with stronger signal (strong EU) cause severe interference to users with weaker signal (weak EU).

Device-to-Device (D2D) communication has a potential to improve throughput, power efficiency, delay, and fairness of all EUs in the network [2]. Therefore, a D2D network can be employed in conjunction with NOMA to negate the interference caused by stronger EU and increase the communication Quality of Experience (QoE) provided to the weaker EU. However, there are several challenges lying ahead in terms of incentivizing the relay users (RU) to scavenge content and promoting EUs to purchase data from the relay. These challenges are jointly addressed in this research.

In NOMA Communications, the EU with stronger signals (channel gain) can decode and subtract weaker users' signals without interference, but in the process introduces certain latency overheads. Therefore, users at shorter distances with stronger signals would decode the contents of EU signals at longer distances with weaker signals. During the next time slot, these shorter distance users can potentially serve as a relay. If EUs are willing to cache the offloaded content, the relaying user can prepare a new aggregated signal using superposition coding and transmit using NOMA as shown in Figure 1. This relay process can be repeated many times to maximize the communication quality of the receiving user [3].

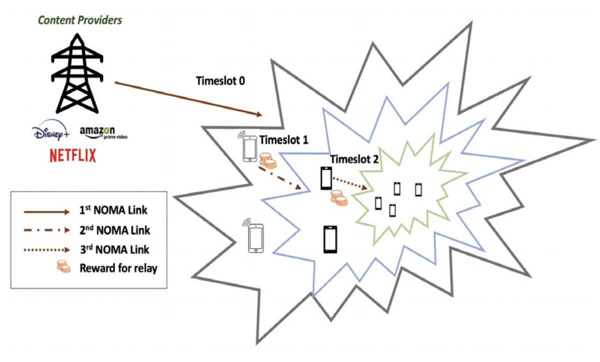

Fig. 1. Illustration of NOMA Relay Scheduling to Improve End User QoE

The RU spends time and money to forward the offloaded content to the farther EUs and so, must be properly incentivized. In this paper, we propose a framework where the incentive comes as an additional payment from the EUs. The EUs may choose to use the relaying service and have a choice in picking up a suitable relaying node. Since the network is competitive and all EUs search for the best relaying node, we propose an auction mechanism to determine the proper relay and the corresponding payment. By choosing an optimal relaying node, significant power saving can be achieved in a network. Two different sealed auction schemes namely the first price auction and second price auction are analyzed in this manuscript. The strong EUs have an incentive to participate in the proposed auction driven D2D NOMA communications as it would be a luxury waste to just subtract and discard the contents (targeted towards longer distance users).

Several studies have considered the conjunction of D2D communication and NOMA technology [4-6]. For example, D2D assisted NOMA relay has been proposed to improve the Signal to Interference plus Noise Ratio (SINR) of far EUs [4]. In another case, power-domain multiplexing for the D2D enabled cellular networks has been studied. Researchers have proposed a novel joint-mode selection framework and research allocation scheme with interlay mode to improve the system sum rate and the D2D access rate [5]. The best user selection problem in a D2D NOMA network has been studied to improve the signal-to-interference-plus-noise ratio (SINK) [6]. In this paper, we propose an alternative incentive-driven resource allocation and relay selection framework for NOMA relay communications leveraging Auction Theory.

The EUs of the heterogeneous wireless network are selfish and non-cooperative in the sense that they are only interested in maximizing their own utilities. Therefore, competition triumphs cooperation during resource procuring. Auction has been widely studied and applied in network selection and resource allocation [7, 8]. Auction has also been applied to address several challenges in wireless networks including competitive spectrum sharing [9], power optimization in D2D networks [10] and video traffic offloading [11]. In this work, we study auction mechanisms in NOMA driven D2D network for relay node selection and analyze its performance. In our previous works [12-13], we explored game theory based pricing solutions for QoE-centric NOMA networks.

The remainder of this paper is organized as follows. In section II, we present the utility functions for the EU and relay. The overall system model and problem formulations are discussed. The utility maximization problem between relay and EU is analyzed using auction theory, and the optimall solutions are presented in section III. A numerical example is also discussed for an in-depth study. Simulation studies are carried out and the results are showcased in section IV. Conclusions and insights into future work are provided in Section V. The key notations and nomenclature used in this paper are summarized in Table I.

II. System Model and Utility Definitions

In a NOMA network, users in a resource block request for data from the base station/ content provider. During the downlink transmission, the base station aggregates all the content together and sends a single superimposed signal. The EUs can then decode their own data and offload the data belonging to farther users. In our framework, the EUs can then prepare a new superimposed signal of all farthest users and relay the content during the next time slot. The relay is compensated by the farther users for the retransmission.

To demonstrate the proposed framework, we consider a minimalistic network with four EUs comprising a NOMA wireless network as shown in Figure 2. Let $|h_i|^2$ denote the channel gain of EU_i. Without loss of generality, we assume that the EUs are ordered based on their channel gain.

TABLE I
The summary of key notations in this paper.

Symbol	Comments
i	Set of EUs in the network. i=1,2,3,4.
j	Subset of EUs in the network. j=1,2,...i-1
$\|h_i\|^2$	Channel gain for EU_i - original transmission.
$\|h_{j,i}\|^2$	Channel gain for EU_i - retransmission from EU_j.
$\|P_i\|^2$	Power allocated by BS for EU_i.
$\|P_{j,i}\|^2$	Power allocated by EU_j for EU_i.
σ^2	Variance of the normalized AWGN.
α, β	System parameters to fine tune QoE model
χ_i	cost parameter for EU_i - original transmission
δ_i	cost parameter for EU_i - retransmission from EU_j
L	Length of the $i-th$ frame (bits).
B	Symbol rate in the transmission.
b	Modulation size in the transmission.

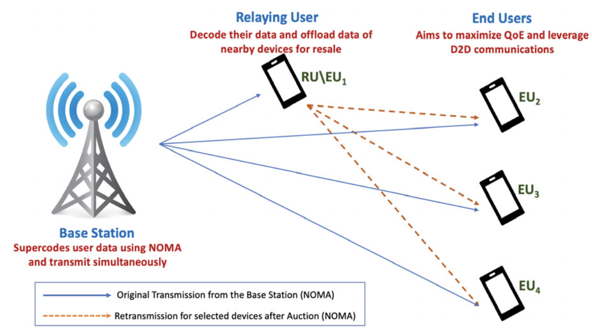

Fig. 2. System Model: D2D Communication enabled NOMA Network

$$|h_1|^2 >= |h_2|^2 >= |h_3|^2 >= |h_4|^2 \tag{1}$$

The base station sends the data of all the EUs during the time slot 0. Each EU would then apply Successive Interference Cancellation (SIC) to decode their own signal with the SINR as shown below [14]:

$$\mathrm{SINR}_{EU_i} = \frac{P_i\,|h_i|^2}{\sum_{k=1}^{i-1} P_k\,|h_i|^2 + \sigma^2} \tag{2}$$

where P_i and h_i^2 denote the power transmitted and channel gain between base station and EU_i, respectively. The noise power in the communication channel is given by σ^2. The users closer to the BS (stronger EU) than the EU_i cause interference and this subset of users are represented by k. Since EU_1 is the strongest EU in the proposed network, there is no interference and the SINR can be represented as

$$SINR_{EU_1} = \frac{P_1\,|h_1|^2}{\sigma^2} \tag{3}$$

As soon as EU_1 decodes its data, it can choose to offload the content belonging to the farthest users. The SINR gain for

EU_1 to decode the signals of other users EU_i where $i = 2, 3, 4$ is given by

$$SINR_{EU_1,EU_i} = \frac{P_i |h_1|^2}{\sum_{k=1}^{i-1} P_k |h_1|^2 + \sigma^2} \tag{4}$$

The EU_1, as the RU can now repackage the signals of farther users and retransmit during the next time slot. The utility of the EU_2 without opting for relay retransmission would be just the SINR gain from the base station and is given by

$$\text{SINR}_{EU_2} = \frac{P_2 |h_2|^2}{P_1 |h_2|^2 + \sigma^2} \tag{5}$$

However, if EU_2 decide to purchase the retransmitted data by EU_1, then the SINR gain can be represented as shown in equation 6 below. It is worth noting that EU_2 is the closest user (strongest EU) for retransmission and so there is no effect of interference in the received signal from the RU.

$$SINR_{EU_2} = \frac{P_2 |h_2|^2}{P_1 |h_2|^2 + \sigma^2} + \frac{P_{1,2} |h_{1,2}|^2}{\sigma^2} \tag{6}$$

where $P_{1,2}$ and $|h_{1,2}|^2$ denote the power allocated by EU_1 for retransmission and the channel gain for the link between EU_1 and EU_2. The general equation of the SINR for user i when EU_1 acts as the relaying user RU is given as follows according to [3]:

$$\text{SINR}_{EU_i} = \frac{P_i |h_i|^2}{\sum_{k=1}^{i-1} P_k |h_i|^2 + \sigma^2} + \frac{P_{1,i} |h_{1,i}|^2}{\sum_{l=2}^{i-1} P_{1,l} |h_{1,i}|^2 + \sigma^2} \tag{7}$$

where l represents the set of users that cause interference (stronger EU) during the retransmission. In a general case, where the remaining $(N-1)$ users are decoding the weaker user signals and relaying them in the concurrent $(N-1)$ time slot, the SINR gain of the user i can be significantly increased. As an example, the SINR gain for the user EU_4 is shown below

$$\begin{aligned}\text{SINR}_{EU_4} = &\frac{P_4 |h_4|^2}{\sum_{k=1}^{3} P_k |h_4|^2 + \sigma^2} + \frac{P_{1,4} |h_{1,4}|^2}{\sum_{l=2}^{3} P_{1,l} |h_{1,4}|^2 + \sigma^2} \\ &+ \frac{P_{2,4} |h_{2,4}|^2}{P_{2,3} |h_{2,4}|^2 + \sigma^2} + \frac{P_{3,4} |h_{3,4}|^2}{+\sigma^2}\end{aligned} \tag{8}$$

where $P_{1,4}$ and $|h_{1,4}|^2$ denote the power allocated by EU_1 for retransmission and the channel gain for the link between EU_1 and EU_4. Similarly, $P_{2,4}$ and $P_{3,4}$ denote power allocated by users EU_2 and EU_3 for the retransmission service; $|h_{2,4}|^2$ and $|h_{3,4}|^2$ denotes the corresponding channel gains.

For the rest of the manuscript, we will consider a single level relaying, with EU_1 acting as the only RU in the NOMA network as shown in Figure 2. The equations and solution derived can easily be extended to multiple levels of relaying.

A. Utility of the Users (EU)

The utility of the user can be subjectively defined as the per-session measure of the user satisfaction (QoE) with respect to the money spent to obtain the desired service. The QoE obtained through the wireless channel can be formulated using a two-level logarithmic function of allocated resource [15], and it is given by:

$$QoE_{EU_i} = \alpha \log_2 (1 + \beta \log_2 (1 + SINR_{EU_i})) \tag{9}$$

The user EU_i experiences two types of costs: the cost paid to the base station, represented by χ_i to obtain the service, and the cost paid to the relaying device, represented by δ_i to obtain retransmission. The strongest user EU_1/RU does not have the relaying cost. The overall utility of the user can be defined as the total QoE gain subtracted by the costs incurred by the user.

$$Utility_{user} = U_{EU_i} = QoE - \chi_i P_i - \delta_i P_{1,i} \tag{10}$$

where P_i and $P_{1,i}$ represent the power allocated by the base station and relaying user RU for user EU_i respectively. In this paper, we assume that users EU_i do not have any control over the cost χ_i and power P_i set by the base station. The user can compete with other users to obtain the best possible relaying service at the right price to improve their utility. The optimization problem for the user is to determine the right bid δ that would maximize their overall utility U_{EU_i}.

B. Utility of the Relay (RU)

The stronger EUs can offload the data of the users who are farther away and serve as a relay (RU) during the next time slot. The utility of the relay comes from the EUs that are farther away and require additional D2D transmission service to improve their QoE. In our 4-EU minimalistic demonstration system, we consider only the strongest user EU_1 to act as relay RU and we also consider one round of retransmission.

$$\psi_{RU_i} = \lambda_i \frac{LP_{1,i}}{bB} \tag{11}$$

The transmission cost of the relay ψ_{RU} to provide retransmission to user i 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 per bit $P(1,i)$ for user i, constellation size of modulation scheme b and the allocated spectrum B. λ is defined as the currency value per unit energy consumption for user i.

$$Utility_{RU/EU_1} = \sum_{m=2}^{N} \delta_m P_{1,m} - \sum_{m=2}^{N} \lambda_m \frac{LP_{1,m}}{bB} \tag{12}$$

where m denotes the set of users from EU_2, EU_3, and EU_4 that decided to obtain the retransmission service through relay. The objective of the relay is to choose and cater the set of farther users (via auction - winners) to maximize their utility.

III. Auction Based Power Selection

In this section, we discuss two different auction schemes to obtain the optimal solution for the NOMA Relay Problem. Optimal solution is defined as the price which the user is willing to pay and power relay is willing to allocate for the service respectively. A rudimentary auction setting consists of bidders $i = 1, \ldots, n$ and one object to be sold. In this case weaker EUs act as bidders and the object to be sold is the retransmitted data.

The bidder (i) with utility function $U_(EU_i)$ observers the network conditions and gives valuation (bid) for the object, denoted as v_i. Bidder EU_i's information and v_i are independent of bidder EU_j's bid and perspective of the service. In other words, bidder's information and valuation are private (sealed auction) in the sense that it does not affect anyone else's valuation.

The sequence of auction events are as follows:

Step 1: The EUs scan the channel to determine the channel gain and interference.

Step 2: In the beginning of the auction, the relay announces their capacity C in terms of power available for allocation and list of data available for retransmission.

Step 3: Each user EU interested in obtaining service during the next time slot places bid to the relay.

Step 4: The auction ends and the RU announces the winner / set of winners.

Step 5: The amount to be paid is computed based on the auction dynamics and the demand is revealed (that is, information needed for EUs to determine whether to offload data during next relay's retransmission).

A. First Price Auction

A first price sealed-bid auction (FPSBA), also known as blind auction, is a common type of auction. In this auction, all bidders simultaneously submit sealed bids so that no bidder knows the bid of any other participant. The highest bidder pays the price that was submitted [16].

Computation of the valuation:

The actual valuation of the retransmission service is computed using backward induction technique. It is easy to prove that the utility of the user U_{EU_i} is concave with respect to the amount of power transmitted by taking the second order derivate of equation (10) as shown below

$$\frac{\partial^2 U_{EU_i}}{\partial P_{1,i}^2} = -\frac{\alpha\beta \cdot (\beta \ln(SINR_{EU_i}+1) + \beta + 1)}{(SINR_{EU_i}+1)^2 (\beta \ln(SINR_{EU_i}+1)+1)^2} \tag{13}$$

The above equation is always negative because the numerator terms: α, β & $SINR$ are all positive and, all terms in the denominator are squared. The valuation v_i for the retransmission service that would maximize the utility of the client can be computed by equating the first derivative to zero. The result is shown in equation (14)

$$v_i = \delta_i = \frac{\alpha\beta}{(SINR_{EU_i}+1)(\beta \ln(SINR_{EU_i}+1)+1)} \tag{14}$$

Computation of the Bid:

Once the valuation of the retransmission service is determined, the EU must decide on the amount they are willing to pay, conditional on it being the highest bid. It is worth noting that there is a tradeoff between the probability of winning and amount paid upon winning. Also, the bidders do not have a dominant strategy.

In FPSBA, the valuations (v_1 and v_2) of the two risk-neutral bidders, are Independent and Identically Distributed random variables drawn from uniform distribution $U(0,1)$. And so, $(1/2 * v_1,\ 1/2 * v_2)$ is the bases equilibrium strategy profile.

The optimal solution derived can easily be extended to a multiplayer auction. In FPSBA with n risk-neutral agents whose valuations are Independent and Identically Distributed random variables drawn from a uniform distribution on [0,1], the (unique) symmetric equilibrium is given by the strategy profile $((n-1)/n * v_1,\ (n-1)/n * v_2\ ,\ (n-1)/n * v_n)$ according to [17].

Therefore, the optimal bid for the users EU_2, EU_3 and EU_4 in our proposed system model for relaying service by RU will be $2/3$* $v2$, $2/3$ *v_3 and $2/3$ *$v4$, respectively.

B. Second Price Auction

A second price sealed-bid auction (SPSBA) is a type of auction where bidders submit bids that report their valuations, without knowing the bids of the other bidders. The bidder with the highest bid wins the auction, however, pays the second highest bidders bid. Inspired by the Vickery-score auction in [18], the Vickery-Clarke-Groves (VCG) mechanism is adopted as the second price auction game. An outstanding feature of VCG auction is that the truthful object valuation of individual bidder is ensured due to the weakly dominant strategy property [19].

Computation of the valuation:

The valuation for the SPSBA is determined like the FPSBA. The valuation is shown in equation (14).

Computation of the Bid:

The bidding in the SPSBA VCG auction is governed by the following. The VCG mechanism is considered efficient. All bidders have a dominant strategy to announce their true valuation (i.e., announcing truthfully $v_i = \delta_i$ is the best strategy irrespective of the other bidders' announcements). When they do so, the efficient outcome is enacted by the VCG mechanism. We examine this through two cases.

case 1: $bidder_i$ wins with the auction by announcing v_i and pays $\mathcal{C} < v_i$

The bidder pays a price - lower than their bid. Therefore, no incentive to go higher or lower. If the bidder's bid goes below the second highest bidder, they lose.

case 2: $bidder_i$ loses with the auction by announcing v_i and pays nothing

The bidder has no incentive to go lower as they still lose. If the bidder goes above the highest bid, the bidder ends up paying more than the actual valuation. Therefore, the truth-telling is the most dominant solution.

VCG Auction Mechanism:

Step 1: The efficient outcome of VCG mechanism for the NOMA relaying service auction is a Groves mechanism $(x^*, \mathcal{C}_i(v))$ such that

$$x^* = \arg\max_x \left\{ \sum_i v_i(x) \right\} \tag{15}$$

where x^* denotes the socially efficient action.

Step 2: The total welfare of the society, not counting the bidder EU_i is computed as

$$\sum_{j \neq i} v_j\left(x^*\right) \tag{16}$$

Step 3: The change to this welfare if the bidder EU_i is not part of the society (community of bidders) is then calculated as

$$x^*_{-i} = \arg\max_x \left\{ \sum_{j \neq i} v_j(x) \right\} \tag{17}$$

Step 4: The measure of how much the bidder EU_i contribute to the rest of the society is then computed (may be negative).

$$\mathcal{C}_i(v)) = \sum_{j \neq i} v_j\left(x^*\right) - \sum_{j \neq i} v_j\left(x^*_{-i}\right) \tag{18}$$

where $\mathcal{C}_i(v)$ denotes the amount of money paid by the auction winners and it is also the cost of individual bidders.

C. Numerical Example

The valuation of EU_2, EU_3 and EU_4 to obtain the relaying service from RU are tabulated in Table II. The EU_2 being the closest user can only opt for the highest power (no interference). The EU_3 can pay higher for best power (no interference) or pay a little bit less for power option 2. EU_4 can choose to be the closest (only) user with high power, second user with lesser power (power 2) and third user with much lesser power (power 3 - more interference).

TABLE II
ILLUSTRATION : AN EXAMPLE OF VCG AUCTION

	EU_2	EU_3	EU_4
$Power1$	2	3	5
$Power2$	-	2.5	4
$Power3$	-	-	3

Step 1: The relay will choose to service all the three users as the combined bid is the highest $(2+2.5+3) > (3+4) > 5$.

Step 2: Cost for EU_2: The cost is computed ignoring EU_2 = 3+4 = 7. With EU_2 in the society, the money from other users is 2.5+3=5.5. The EU_2 pays 7-5.5=1.5. Similarly cost of EU_3 and EU_4 can be computed as 1 (5-4) and 2 (4.5-2.5).

Step 3: The RU provides retransmission for all the three users for prices \$1.5, \$1 and \$2 respectively; earning a total of \$4.5

Alternatively, if FPSBA is used, the solution is $2/3\ v_i$. The winning bids would be 2/3 x 2 for EU_2. 2/3 x 2.5 for EU_3 and 2/3 x 3 for EU_4. The total price paid by the users to obtain the same service using the first price auction would be \$4.9999. The example above illustrates that the user is able to achieve higher utility using the SPSBA.

IV. NUMERICAL STUDY

In this section, we carry out simulations to evaluate the performance of the NOMA Relay network with both the FPSBA and SPSBA. The channel gain $|h_i|^2$ for the simulation was set between 0∼40 dB. The transmission power P and the noise power σ^2 were in the range 10∼30 dBm and 1∼5 dBm respectively. The data rate B was set at 20 Mbps and the data length L was set at 300 Mbits. The system parameters α and β were set at 1 and 10 respectively.

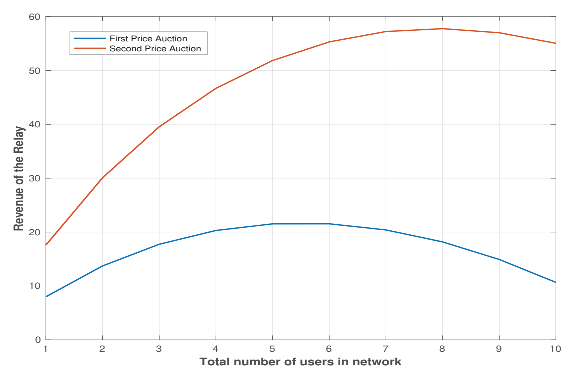

Fig. 3. Comparison: Revenue of Relay - FPSBA and SPSBA

The revenue of the relay is a concave function with respect to the number of users supported in relay retransmission as shown in Figure. 3. As the number of users increase, the interference increases, and the users do not make high bids. Therefore, the relay would be able to achieve optimal utility by choosing the right combination (subset) of users. It can be noted that the second price VCG auction yields significantly better utility for the relay for any number of users supported.

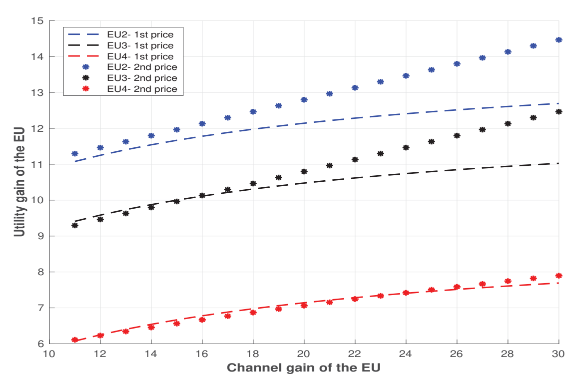

Fig. 4. Utility gain of the EU versus the channel gain

In Figure. 4, we evaluate the impacts of different channel gains on UEs' SINR gain. In this simulation, we assume only the downlink channel RU is changing (i.e., RU moves towards the BS will cause the increase of $|h_1|^2$, while the environment among three EUs was kept stable (i.e., $|h_{1,2}|$, $|h_{1,3}|$, $|h_{1,4}|$ remain unchanged). From the figure, it can be observed that the SPSBA (VCG) performs better as the channel gain increases across EUs'. From the figures 3 and 4, it can be concluded that VCG auction provides better performance for both the EU and RU.

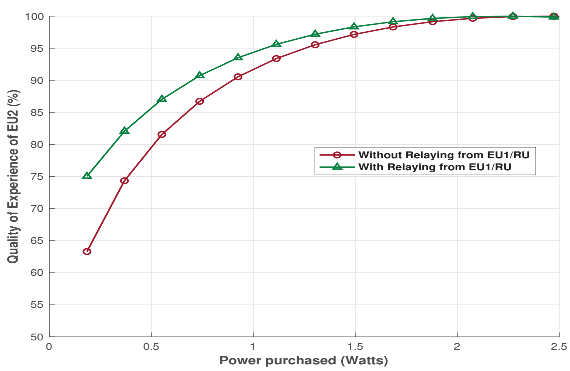

Fig. 5. Quality of Experience of EU2 with and without NOMA relay retransmission

Finally, we compare the Quality of Experience (equation (9)) for EU_2 with and without the extra retransmission from RU. In section III, we proved that the QoE is a concave function, and it can be visualized in the Figure. 4. The retransmission adds $\frac{P_{1,2}|h_{1,2}|^2}{\sigma^2}$ term to the $SINR_{EU_2}$, further boosting the QoE. It can also be absorbed that the EUs' participating in relay retransmission can achieve higher QoE at lower transmission power levels. This result indicates that the base station can also potentially benefit from the proposed framework by achieving higher spectral efficiency.

V. Conclusions and Future Work

In this paper, we propose a framework which takes advantage of the fact that a NOMA user with shorter distance naturally decodes the data packets of all users with longer distances. Thus NOMA relay has significant power saving potentials in comparison with direct retransmission from the base station. Therefore, with proper incentive for transmission power, the short distance users (stronger EU) can act as relay in the NOMA network. Two different auction techniques FPSBA and SPSBA (VCG) are leveraged to obtain the optimal solution for the proposed relay power auctioning approach. The results indicate that all three parties: the base station, relay RU and end user EU benefit from the proposed scheme. It was also observed that the VCG auction outperforms FPSBA in optimal network with good channel gain and minimal interference.

As for the future work, we are analyzing the performance of the proposed scheme in a hybrid NOMA-OMA network. We are also looking into other auction techniques such as open price auction and bid sharing auction as a suitable paradigm for modeling sustainable NOMA relay communications.

VI. Acknowledgement

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