A Use-It-Or-Lose-It Economic VCG Auction Approach For NOMA Wireless Relay Networks

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***Abstract*—In Non-Orthogonal Multiple Access (NOMA) wireless networks, base station broadcasts the aggregated contents to all users, where short-distance users have stronger signals compared with long-distance users. Stronger signal users can decode and subtract other weaker users' signals without interference and thus they can forward packets to weaker users as relay devices for better network utilization. In traditional NOMA, the decoded information is simply subtracted from the superposition coded signal and the devices do not take advantage of the cached content. In this paper, inspired by the use it or lose it concept, we propose an economic auction-based NOMA relay approach. The proposed strategy utilizes Vickrey-Clarke-Groves (VCG) auction theory to make the optimal relay-user matching decision based on utility models for base station and relay devices. Through VCG auction, relay devices obtain their maximum utility and user equipment get a better service. Simulation results illustrate the potential performance gain of NOMA relay forwarding with VCG auction mechanism.**

***Index Terms*—Non-Orthogonal Multiple Access, Vickrey-Clarke-Groves Auction, Wireless Relay**

I. Introduction

Wireless multimedia communications is one of the most rapidly growing technologies of the decade. Non-Orthogonal Multiple Access (NOMA) network has shown higher network capacity potentials to accommodate tremendous data traffic in future generations of wireless networks [1]. Compared to conventional Orthogonal Multiple Access (OMA) networking schemes, the key distinguishing feature of NOMA is its support of multiple users rather than one single user equipment (UE) utilizing orthogonal resource slots with the aid of non-orthogonal resource allocation. In non-orthogonal multiple access downlink wireless communications, the base station (BS) broadcasts the aggregated contents to all users via superposition coding (SC) [2] . Superposition coding technique is used for aggregating all users' information for broadcasting and successive interference cancellation (SIC) technique is used at the receiver to detect and demodulate the signal [3] .

In the downlink of NOMA network, short-distance users near the base station obtain stronger signals compared with the farther users [4], [5]. While in some cases, the packets are lost through transmission and require a second transmission from the base station. In this scenario, it is better to use short-distance UEs as RNs to forward the information towards UEs rather than the direct transmission from the BS. The essential challenge is: can we leverage these NOMA contents which are already decoded at these short-distance users, and give them incentives to relay to longer distance users? And what would be the appropriate incentive? Benefiting from the SC and SIC technologies, the stronger UEs can decode and subtract weaker users' signals and thus stronger UEs are likely to retransmit or forward signal for weaker UEs if desirable incentive is provided. We propose an economic auction-based NOMA relay matching theory using "use it or lose it" concept. In this theory, closer UEs are considered as relay nodes (RN) to utilize their communication resource forwarding data packets that they already decoded for farther UEs and obtain incentive from the BS. If we do not take this advantage, these contents targeted to longer distance users will simply be used to subtract from the superposition coded signal in the closer UEs, that is a luxury waste for the network.

In order to improve the user's perceived service quality, plenty of research has been carried out in the wireless networks by considering the relay scheme and NOMA technology [6], [7]. Authors in [8] collect a few different forms of cooperative NOMA and relay selection solutions. Additionally, [9] proposes a sequential second auction-based allocation mechanism to optimize system throughput, while [10] proposes a reverse iterative combinational auction allocation mechanism to address throughput maximization in NOMA networks. Relay

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TABLE I
SUMMARY OF NOTATIONS AND PARAMETERS

σ^2	The variance of normalized AWGN.
B	The frequency bandwidth of the NOMA system.
$\|h_i\|^2$	Normalized channel gain of UE_i.
$\|g_{k,i}\|^2$	Normalized channel gain of kth RN to the ith UE.
P_i	Allocated power from base station to UE_i.
$P_{k,i}$	The forwarding power kth RN to the ith UE.
P_r	Relay forwarding power for UE_i.
$SINR_{b(i)}$	SINR of UE_i to decode its own signal from BS.
$SINR_{r(k,i)}$	SINR of UE_m to decode $UE_k's$ signal.
$U_{\mathrm{RN}(k,i)}$	Utility of the kth RN serving the ith UE.
$U_{BS(k,i)}$	Utility of BS with the kth RN serving the ith UE.
y_r	The price for unit power paid to RN by BS.
y_0	The transmission cost for unit power for RN and BS.

matching is also a widely studied topic in wireless networks [11], [12], and [13] proposes a relay scheme to decrease termination and blocking probabilities in cognitive radio. Moreover, [14] explores the use of suitable relays to maximize quality of experience (QoE) in multimedia transmission between vehicles in inter-vehicular communications. Vickrey-Clarke-Groves (VCG) theory is a type of sealed-bid auction where bidders submit bids that report their valuations for the items, without knowing the bids of other bidders and the broker assigns the items in a socially optimal manner [15]. Inspired by aforementioned work and theory, a VCG based auction relay matching method is proposed in this paper to address the relay selection and power allocation issue in the NOMA wireless networks.

In the new proposed matching strategy, if there are M users to be retransmitted and N relays in the network, there will be $M \times N$ serving combinations and we aim to select the best matching and pricing strategy to make this deal. Based on the signal to interference plus noise ratio ($SINR$) gain and energy consumption, we build up the utility models for BS and RN respectively. Stackelberg game is a two-player based interaction model, where the leader knows the follower's strategy and makes decisions accordingly. In the first step, we use a two-step Stackelberg game to find the optimal power allocation and pricing solution for each combination that RN and BS get their best response. In the second step, VCG auction mechanism is applied for optimal matching or combinations. More specifically, By treating the maximum utility of RN as the valuation that bidders compete on, the optimal winner RN of the auction and the payment can be obtained through the VCG mechanism by ensuring the efficiency of the auction.

The rest of the paper is organized as follows. In Section II, we firstly state the matching problem and illustrate fundamentals of NOMA network. We propose a solution to this matching problem based on "lose it or use it" theory and build up the mathematical system model for power allocation and pricing strategy in Section III. Furthermore, the best response solution to BS, RN and the strategy for RN matching are proposed in details in Section IV. The algorithm and numerical simulations are performed in Section V. Finally, we conclude our work in Section VI. Key notations and nomenclature of this paper are given in Table I.

II. SYSTEM MODEL

In this section, we firstly state the matching problem and illustrate fundamentals of NOMA wireless network in details. For further analysing the problem, we mathematically define the utility functions for the BS as well as RNs and then formulate the utility maximization problem. Finally, we propose the VCG auction matching model to find out optimal relay for users based on the best response of BS and RNs.

A. Problem Statement

There are multiple NOMA RNs (with better channel conditions and shorter distances to the base station) capable of decoding the information of the users at longer distances. In this situation, UEs have multiple choices among NOMA RNs that are closer to BS, as illustrated in Figure 1. There are some assumptions for this $RN-UE$ matching problem. Firstly, according the power and cache limitation of relay devices in the the real life, we assume each relay can support re-transmission for one end user at most. Secondly, we assume there are less relays than end users asking for second transmission in the network and thus some end users have to request for the second transmission from the BS directly.

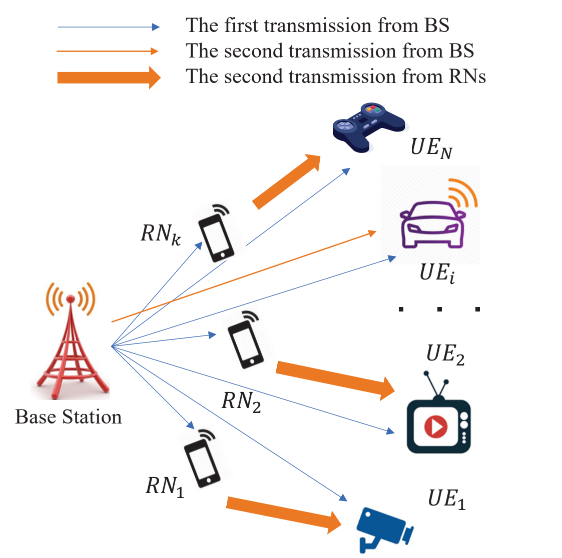

Fig. 1. Downlink model with the first and second transmission

B. NOMA Relay Fundamentals

We first introduce the fundamentals for NOMA donwlink and relay forwarding. We consider there are N UEs (denoted as UE_1 UE_N) receiving from information from the base station in the downlinnk phase as illustrated in Fig. 1. Assume all UEs experience independent and identically distributed block Rayleigh fading and additive white Gaussian noise and equipped with a normalized channel gain denoted as h_i. Here we order UEs with the increasing channel gain h_i to BS as $h_1 \leq h_2 \leq \ldots \leq h_N$. In the NOMA downlink wireless transmission, each UE can decode its own signal from the received signal with signal to interference plus noise ratio ($SINR$).

$$SINR_{b(i)} = \frac{P_i \left|h_i\right|^2}{\sum_{j=i+1}^{N} P_j \left|h_i\right|^2 + \sigma^2}, 1 \leq i \leq N \quad (1)$$

Where the σ^2 denotes the normalized $AWGN$ noise.

Each UE makes use of SIC technique to decode weaker UEs' signals and subtract them to obtain its own signal, while weaker users treat stronger UEs' signals as noise. And thus the SINR of UE_i to decode UE_k's signal ($k > i$) is represented as follows.

$$SINR_{\mathrm{i}}^{k} = \frac{p_{k,i} \left|g_{k,i}\right|^2}{\sum_{j=i+1}^{k} p_{j,i} \left|g_{k,i}\right|^2 + \sigma^2}, 1 \leq i, k \leq N \quad (2)$$

In this model, the retransmission $SINR$ from the kth RN to the ith UE can be represented Equation (3).

$$SINR_{\mathrm{r(k,i)}} = \frac{p_{r(k,i)} \left|g_{k,i}\right|^2}{\sum_{j=i+1}^{k} p_{r(j,i)} \left|g_{k,i}\right|^2 + \sigma^2}, i < k \quad (3)$$

C. Use It Or Lose It Concept For NOMA Relay

Quality of experience is a per-session measure of UE satisfaction. The goal of power control strategy in NOMA network is to improve the overall QoE performance of UE. In the second transmission, the model of the QoE of ith UE supported by k^{th} RN is given in Equation (4).

$$QoE_{r(k,i)} = \log_2\left(1 + B\log_2\left(1 + SINR_{\mathrm{r(k,i)}}\right)\right) \quad (4)$$

Since we do not know the specific power $p_{k,i}$ for users we use the allocation in the first transmission to approximate.The range of φ is $(0, 1)$ in the simulation part. Therefore, the retransmission $SINR$ from the kth RN to the ith UE can be simplified as Equation (5).

$$SINR_{\mathrm{r(k,i)}} = \frac{p_{k,i} \left|g_{k,i}\right|^2}{\sum_{j=i+1}^{k} p_{k,i} \left|g_{k,i}\right|^2 + \sigma^2} \approx \frac{P_{k,i} \left|g_{k,i}\right|^2}{\varphi + \sigma^2} \quad (5)$$

where φ is a approximation value of $\sum_{j=i+1}^{k} p_{k,i} \left|g_{k,i}\right|$ in the second transmission and $p_{k,i}$ is based on the channel gain between different UEs and RNs.

The service from RN to UE in the second transmission should provide the same or better QoE compared with the signal from BS in the first time transmission.

$$P_{r(k,i)} \geq \frac{P_{b(i)} g_i^2 \sigma^2}{\left(\sum_{i=i+1}^{k} p_{r(j,i)} g_{j,i} + \sigma^2\right) \left|g_{k,i}\right|^2} = P_{rm(k,i)} \quad (6)$$

Based on Equation (5), we can get the power range for RNs in this model as $\left[\mathrm{P_{rm(k,i)}}, \mathrm{P_{min}}\right]$, in which $P\,\mathrm{rm}(k,i)$ is minimum relay power to support the relay service with better SINR.

1) Utility function of base station: In our work, we assume the incentive of RN directly comes from the payment of BS. Since the information is lost in the transmission from BS to UEs, in the second transmission BS prefer QoE that RNs can supply. BS will transmit signal to UEs with the same or higher lost if do not hire RNs to forward and thus RNs save the service and cost for BS. The saving as well as revenue parts can be measured by QoE of UEs and the outcome part is the payment to RNs. Therefore, we define the utility of BS as the QoE of UEs subtract the payment for RNs. Utility of base station based on received QoE of each UE in the second relay forwarding multimedia service is illustrated in Equation (7).

$$U_{BS(k,i)} = \alpha \cdot QoE_{r(k,i)} - y_r \cdot P_{r(k,i)} \quad (7)$$

where α represents the payoff parameter for $QoE_{r(k,i)}$ and $P_{r(k,i)}$.

2) Utility function of relay Nodes: In our work, we assume the incentive of RN directly comes from BS rather that UEs. Therefore the utility of RN is defined as the incentive obtained from BS minus the forwarding cost. The payment of weak UE is determined by its obtained utility from the relaying service. The cost of RN is correlated with its energy consumption for the data relaying, proportional to the forwarding power $P_{r(k,i)}$.

$$U_{\mathrm{RN}(k,i)} = y_r P_{r(k,i)} - \mathbb{C}_{R2U} = \left(y_r - y_0\right) P_{r(k,i)} \quad (8)$$

where y_0 is the cost for relay to forward. The auction theory is used for choosing the optimal relay for each user in order to achieve the maximum utility.

Generally speaking, the base station would like to purchase the relaying service in order to improve the perceived utility. On the other hand, RNs are willing to provide the data relaying service as well, as long as they can obtain positive utilities from selling the service. There are several potential relay nodes for selection since all of them are capable to decode end user's signal and provide the relaying service. Thus, our objective is to solve the relay selection problem by jointly considering relay's utility gain and base station's utility gain.

III. VCG Auction For NOMA Relay Selection

Based on the system model, the relay matching strategy can be formulated into two steps: optimization of utility functions and the optimal relay selection. To address the NOMA relay selection issue, we develop a VCG auction solution between multiple RNs and the long distance UEs. In this VCG NOMA relay auction, RNs will act as the bidders with objectives to win the RN opportunity to serve the UEs.

The fist step is to find out the best response of BS and RN for power and pricing strategy in each $BS-RN-UE$ combination. The optimization problem can be translated into a two-stage Stackelberg game. Both base station and relay devices obtain their maximum utility when the game get Nash

Equilibrium. EUs get the lost information from the second transmission with a better QoE.

The second step is to select the optimal relay for each user using VCG auction. As a typical sealed-bid auction, the NOMA relay nodes submit their bids that report their service valuation they can reach in the relay forwarding, without knowing the bids of others. In this step, the utility function of relay is considered as the service valuation and thus the maximum utility value from the first step is used for bidding in the game. Then, the base station serving as the broker will assign the relay service in a socially optimal manner. In this step, the utility function of relay is considered as the valuation and thus the maximum utility value from the first step is used for bidding in the game. Winners of the game are the optimal relays for UEs.

A. Best Response of Base Station

As we can see from equation (9), the utility of BS in each RN-UE matching combination, $P_{BS(k,i)}$ is combination of two-level logarithmic function minus a linear function on power $P_{r(k,i)}$, that is not a monotonic decreasing or a increasing function. We can find out the first derivative of $P_{BS(k,i)}$ respect to $P_{r(k,i)}$ is a monotonic decreasing function, because the second derivative of $P_{BS(k,i)}$ respect to $P_{r(k,i)}$ is always negative, which is shown in Equation (9) and (10).

$$\frac{\partial U_{BS(k,i)}}{\partial P_{r(k,i)}} = \frac{\alpha |g_{k,i}|^4}{\ln^2(2)\left(1+B\log_2\left(1+\frac{|g_{k,i}|^2 p}{\varphi+\sigma^2}\right)\right)\left(|g_{k,i}|^2 p+\varphi+\sigma^2\right)} - y_r \quad (9)$$

$$\frac{\partial^2 U_{BS(k,i)}}{\partial^2 P_{r(k,i)}} < 0 \quad (10)$$

The first order derivative of $U_{BS(k,i)}$ is a monotonically decreasing function and the function $U_{BS(k,i)}$ have a maximum value in a fixed value range. Thus $U_{BS(k,i)}$ would obtain its peak value when the first derivative $\frac{\partial U_{BS}}{\partial P_{r(k,i)}} = 0$. The optimal price is denoted as $y_{r'(k,i)}$.

We choose the optimal power under certain system constraints in Equation (6).

Deriving the first derivative of $U_{BS(k,i)}$ respect to $y_{r(k,i)}$ to zero can get the relationship between the optimal power amount ($y_{r'(k,i)}$) for RN and the optimal price (denoted as y_{ropt}) paid by BS.

B. Best Response of Relay Device

The utility of RN is the payment from the BS subtract the cost of RN denoted as C_{R2U}. Since the first order derivative of $U_{RN(k,i)}$ to $y_{r(k,i)}$ is a not a monotonically decreasing function so we use global searching method to find out he maximum function value of $U_{RN(k,i)}$ in a fixed power value range shown in Equation (11).

$$U_{RN(k,i)} = \left(y_{r'(k,i)} - y_0\right) P_{r(k,i)} \quad (11)$$

The maximum value of utility U_{RNk} is the best utility that the kth RN can obtain by serving the ith UEs.

C. VCG Auction Valuation Analysis

In the previous two steps, we get the best price and power allocation for every $RN-UE$ combination. From the view of RN, the peak value of utility function can be considered as the valuation function in VCG auction theory and used for matching. The basic auction environment consists following principle [16]:

• Bidders i= $1, 2 \ldots, n$.

• Bidder observers the objective and gives its value of the object, denoted as U_i.

• Bidder $i's$ information and v_i are independent of bidder $i's$ so bidder's information and valuation are private in the sense that it does not affect the bid or valuation of any other users. valuation.

One outstanding feature of VCG auction is that the truthful object valuation of individual bidder is ensured due to the weakly dominant strategy property. As a typical sealed-bid auction, the NOMA RN submit their bids that report their service valuation they can reach in the relay forwarding, without knowing the bids of others. In this step, the utility function of relay is considered as the service valuation. Thus the maximum utility value of RN is used for bidding in the game, that is give in Equation (13).

$$X\left(\hat{U_{RN}}\right) \in \operatorname{argmax} \sum_i \widehat{U_{RN}}(x) \quad (12)$$

in which $\widehat{U_{RNi}}(x)$ is the relay valuation (utility) function set.

$$P_i(\hat{v}) = \max \sum_{j\neq i} \widehat{v}_j(x) - \sum_{j\neq i} \widehat{v}_j(X(\hat{v})) \quad (13)$$

The payment $P_i(\hat{v})$ is calculated using Equation (14). The total social utility that the ith bidder is ignored. The strong relay will be the bidder in the auction game and the outcome of the VCG auction will determine which bidder wins the relay service opportunity.

IV. Simulations and Results Analysis

In this section, we carry out numerical simulation to evaluate the system performance in the NOMA wireless links with the proposed VCG mechanism. As shown in Fig. 1, we consider the BS serves three relays and four UEs at the same time and in the same frequency block using NOMA communication.

TABLE II
Parameters and Their Values Used in the Simulation

Symbol	Range
$\lvert h_i \rvert^2$	$(1 \sim 40)dB$
P_i	$(0 \sim 1)w$
P_r	$(0 \sim 1)w$
σ^2	$0dBm$
B	$0.5MHz$
y_0	5
α	10

Simulations are taken with the BS power budget in a range from 0 to 1 watt. We have power ratio $P_{BS(A)} : P_{BS(B)} = P_{BS(B)} : P_{BS(C)} = P_{BS(C)} : P_{BS(D)} = 0.2$. The maximum power that RN can support for ENs is the same as BS power budget. In the first transmission from BS to UEs, sum of power of UEs is the power budget. The simulation parameters are shown in Table II.

In the second transmission, channel gain based on the distance between different RNs and UEs are shown in Table III.

TABLE III
CHANNEL GAIN BETWEEN RNS AND UES

Channel gain(dB)	User A	User B	User C	User D
Relay 1	30	20	15	10
Relay 2	10	10	20	20
Relay 3	5	15	30	40

Using VCG auction relay matching algorithm with the power budget of $0.2W$, the maximum as well as optimal utility for three RNs and four UEs combinations are shown in Table IV.

TABLE IV
THE RELAY UTILITY FOR RN-UE COMBINATION AND MATCHING RESULTS

Relay utility	User A	User B	User C	User D
Relay 1	**3.6718**	3.5562	3.3102	3.2802
Relay 2	3.3113	3.2862	**3.5709**	3.5526
Relay 3	2.7913	3.4744	3.6713	**3.7146**

Based on Equation (14) we choose the best RN for users using VCG auction and the results are highlighted in the Table 3. The best strategy is three combinations: Relay 1 - User A, Relay 2 - User C, Relay 3 - User D and the last User B should be serviced by BS directly.

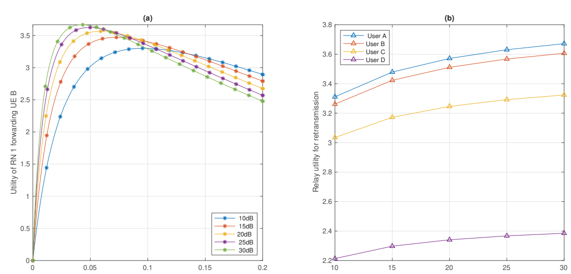

Fig. 2. (a) RN utility in different channel quality to support $UserB$, (b) The maximum utility of RNs with $0.2w$ budget supporting UEs

In the Fig. 2(a), the utility of RN with different channel gain to support $UserB$ with $0.2w$ power budget is illustrated. We can find out that as the channel gain increases and channel quality gets better, the optimal power for RN decreases because RNs can lower power can support the same service as BS for UEs. In the Fig. 2(b), the maximum utility of different RNs with $0.2w$ budget supporting $UserA$, $UserB$, $UserC$ and $UserD$ are shown. We can see as the RN channel gain increases, the maximum of RN to support users increases. Due to interference estimated by the initiate power allocation, supporting $UserA$ can gain more utility than other UEs for RNs with the same channel gain.

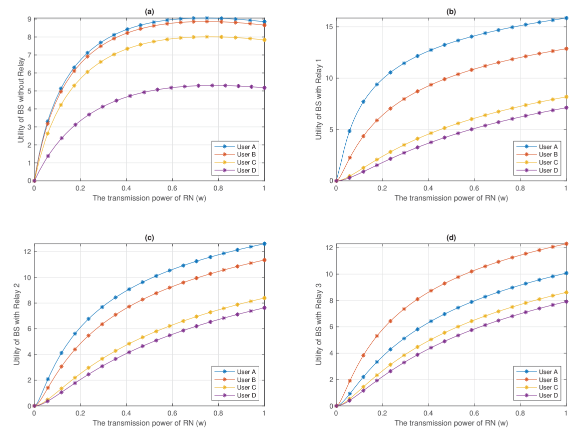

Fig. 3. (a) BS utility supporting users without RNs $UserB$, (b) BS utility supporting users with Relay 1, (c) BS utility supporting users with Relay 2, (d) BS utility supporting users with Relay 3.

Fig. 3 shows the benefits of relay forwarding to BS. BS utility without RN to forward is shown in Fig. 3(a) and three situations the help of different relays are respectively shown in fig. 3(b), (c) and (d). We can find out When the power is very low under 0.1, it is more efficient to transmit directly by BS while the BS mostly earns more utility especially when the transmission power is high. Therefore BS saves power and resource in the second transmission to four users with RN.

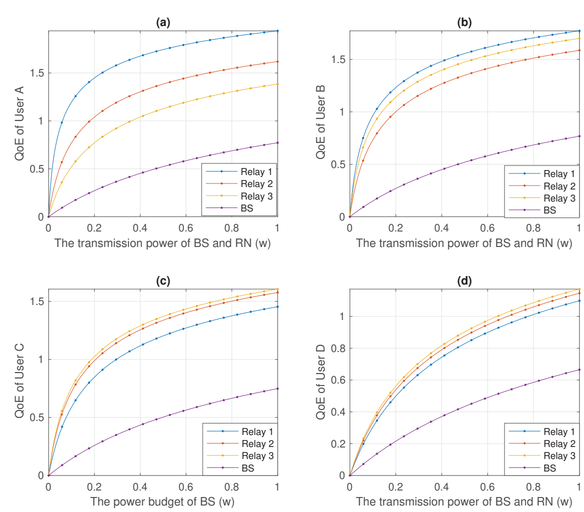

Fig. 4. (a) QoE of $UserA$ when different RNs support it,(b) QoE of $UserB$ when different RNs support it,(c) QoE of $UserC$ when different RNs support it,(d) QoE of $UserD$ when different RNs support it.

In the Fig. 4, we compare QoE of the four users if they are supported by different RNs and BS. we can find out that users can obtain better service with relay than BS directly. In the four sub-figures, QoE of UEs are respectively compared in four situations: with the help of relay 1, 2, 3 and without relay. Although different relays shows different performance for the network, QoE of all users significantly with relay forwarding. Therefore UE receive more power and resource in the second transmission from RN rather than BS.

In the Fig. 5, we compare the utility of relay in the optimal $BS - UE$ combination and the utility of relay in a random combination as Relay A - User 1, Relay B - User 2, Relay C - User 3. The power budget is $1w$ and tranmission power increases from $0.2w$ to $1w$, we can see that VCG auction relay trategy shows better performance than non-auction theory from the perspective of relay and thus better allocated power and matching.

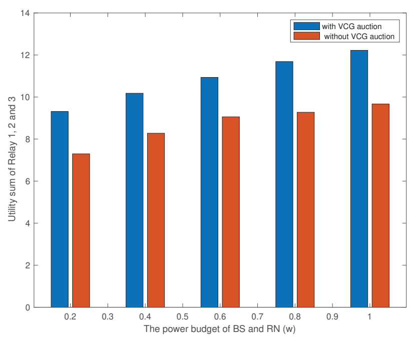

Fig. 5. RN utility sum mechanism

From the results shown in the table and figures, we can find out the relay transmission shows higher $SINR$ than BS service in the first and second transmission. Benefiting from VCG auction theory, relays can obtain higher utility than matching theory without auction process. Based on the advantages of relay services and NOMA network, BS costs less in the second transmission with relay involved. From the perspective of UEs, they get better quality of service using the proposed matching method.

V. Conclusion

Inspired by use it or lose it concept, an economic VCG auction approach is proposed for downlink NOMA relay wireless networks in this paper. Firstly, a two-step Stackelberg game is applied on the utility models for BS and RN to find the maximum network utility. Then VCG auction is adopted to let BS make the optimal $RN - UE$ matching strategy. Through VCG auction, BS and RN obtain their maximum utilities and UEs get good service directly from the relay rather than the BS. Finally, simulation demonstrates the potentials of utility improvement of NOMA relaying service with VCG auction mechanism.

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References

[1] Saito, Yuya, et al. ”Non-orthogonal multiple access (NOMA) for cellular future radio access.” 2013 IEEE 77th vehicular technology conference (VTC Spring). IEEE, 2013.

[2] Islam, SM Riazul, et al. ”Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges.” IEEE Communications Surveys & Tutorials 19.2 (2016): 721-742.

[3] Ding, Zhiguo, et al. ”A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends.” IEEE Journal on Selected Areas in Communications 35.10 (2017): 2181-2195.

[4] Zhao, Jingjing, et al. ”NOMA-based D2D communications: Towards 5G.” 2016 IEEE global communications conference (GLOBECOM). IEEE, 2016.

[5] K. M. K. Ramamoorthy, W. Wang, and K. Sohraby, “NOMAP: A pricing scheme for noma resource block selection and power allocation in wireless communications,” in 2021 IEEE International Symposium on Local and Metropolitan Area Networks (LANMAN), pp. 1–6.

[6] Jiang, Xu, et al. ”Power consumption minimization of UAV relay in NOMA networks.” IEEE Wireless Communications Letters 9.5 (2020): 666-670.

[7] K. M. K. Ramamoorthy, W. Wang, K. Sohraby “A Power Auction Approach For Non-Orthogonal Multiple Access Wireless Relay Communications,” in Proc. IEEE International Conference on Communications (ICC) Workshop on Green and Sustainable Networking (GreenNet), Jun. 2023.

[8] Ding, Zhiguo, Huaiyu Dai, and H. Vincent Poor. ”Relay selection for cooperative NOMA.” IEEE Wireless Communications Letters 5.4 (2016): 416-419.

[9] Xu, Chen, et al. ”Interference-aware resource allocation for device-to-device communications as an underlay using sequential second price auction.” 2012 IEEE international conference on communications (ICC). IEEE, 2012.

[10] Xu, Chen, et al. ”Efficiency resource allocation for device-to-device underlay communication systems: A reverse iterative combinatorial auction based approach.” IEEE Journal on Selected Areas in Communications 31.9 (2013): 348-358.

[11] Yi Zhang and Li Yu, ”A novel matching model of win-win situation for optimal relay selection in cognitive radio networks,” Proceedings 2013 International Conference on Mechatronic Sciences, Electric Engineering and Computer (MEC), 2013, pp. 2110-2113.

[12] K. M. K. Ramamoorthy and W. Wang, ”A QoE-Driven Pricing Scheme for Inter-Vehicular Communications With Four-Stage Stackelberg Game,” in IEEE Transactions on Vehicular Technology, vol. 71, no. 3, pp. 3121-3130, March 2022.

[13] Q. Wang, W. Che, G. Monti, F. Mastri and M. Mongiardo, ”On the Use of Matching Networks and Relays for Maximizing the Gains of IR WPT Links,” 2019 IEEE MTT-S International Wireless Symposium (IWS), 2019, pp. 1-3

[14] Yi, Changyan, and Jun Cai. ”Two-stage spectrum sharing with combinatorial auction and stackelberg game in recall-based cognitive radio networks.” IEEE Transactions on Communications 62.11 (2014): 3740-3752.

[15] Varian, Hal R., and Christopher Harris. ”The VCG auction in theory and practice.” American Economic Review 104.5 (2014): 442-45.

[16] Menezes, Flavio M., and Paulo K. Monteiro. An introduction to auction theory. OUP Oxford, 2004.