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

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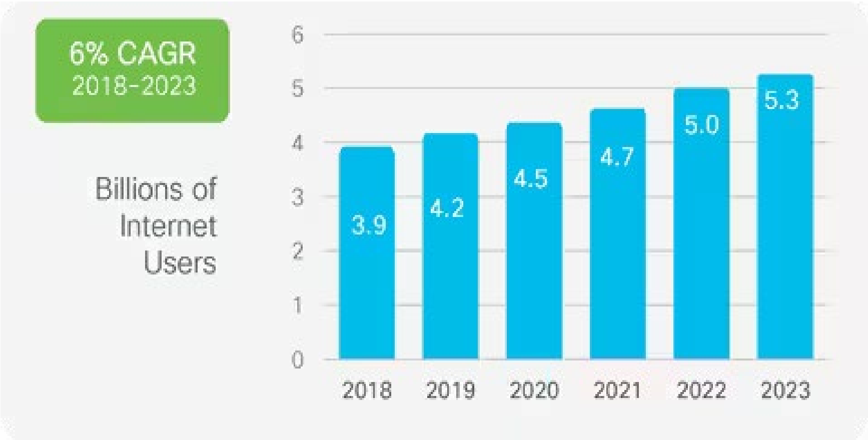
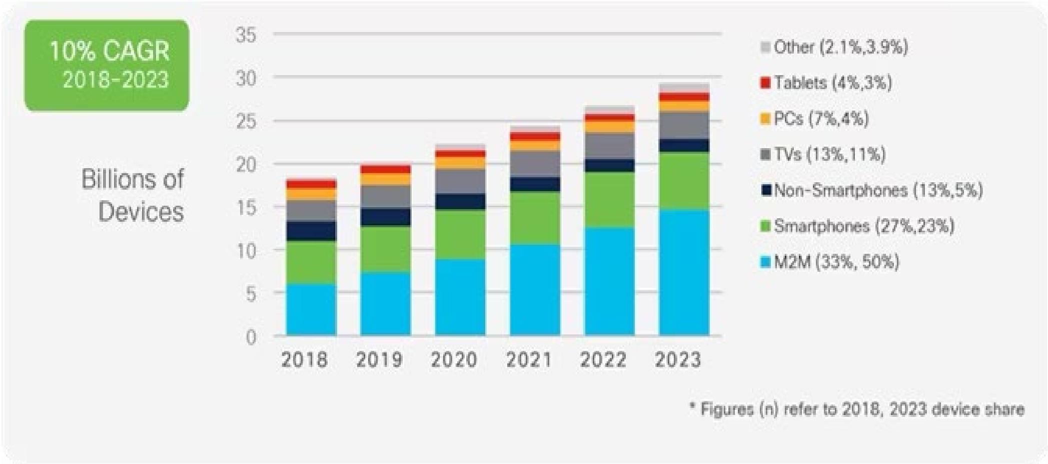
Introduction : Bandwidth at Risk



As of 2022, the estimated number of internet users worldwide was **5.3 billion**, up from 4.9 billion in the previous year. This share represents 66 percent of global population.

Each internet user also has several internet ready-devices.

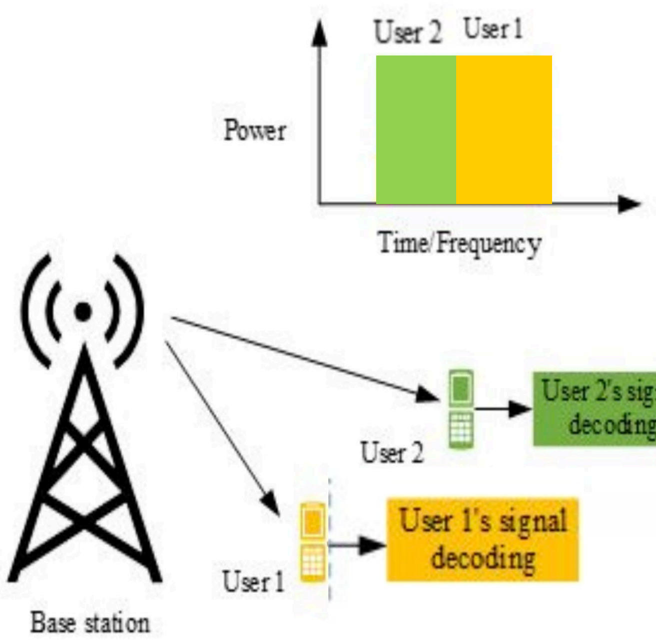
Therefore, the existing wireless communication architecture is struggling to meet the demands of the everyday user.



Ref: Cisco Visual Networking Index: Forecast and Trends White Paper

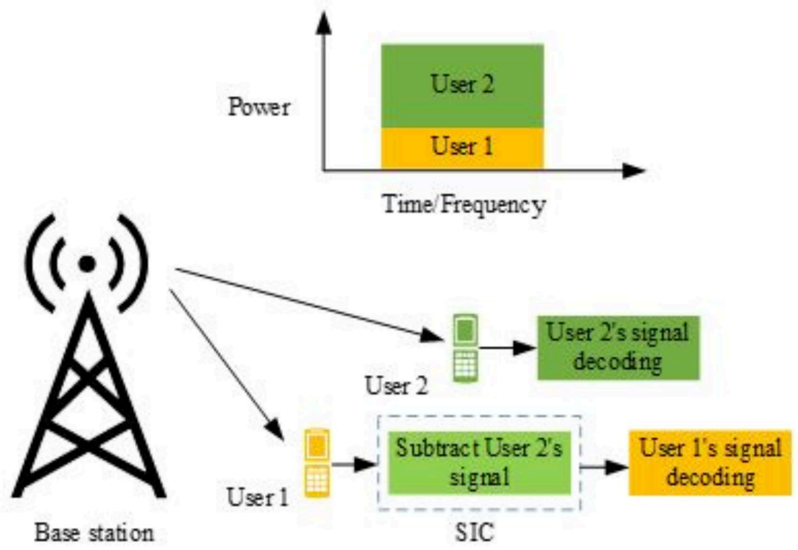
Orthogonal Multiple Access

- This modern-day network access scheme is called **Orthogonal on Multiple access (OMA).**
- In OMA, the base station is able to support exactly one user during a time/frequency slot.
- This ensures that the user's signals do not interfere with one another.
- However, this limits the total number of users a base station can support and introduces latency as the number of users in a network increase.



Ref: Islam, S.M., Zeng, M. and Dobre, O.A., 2017. NOMA in 5G systems: Exciting possibilities for enhancing spectral

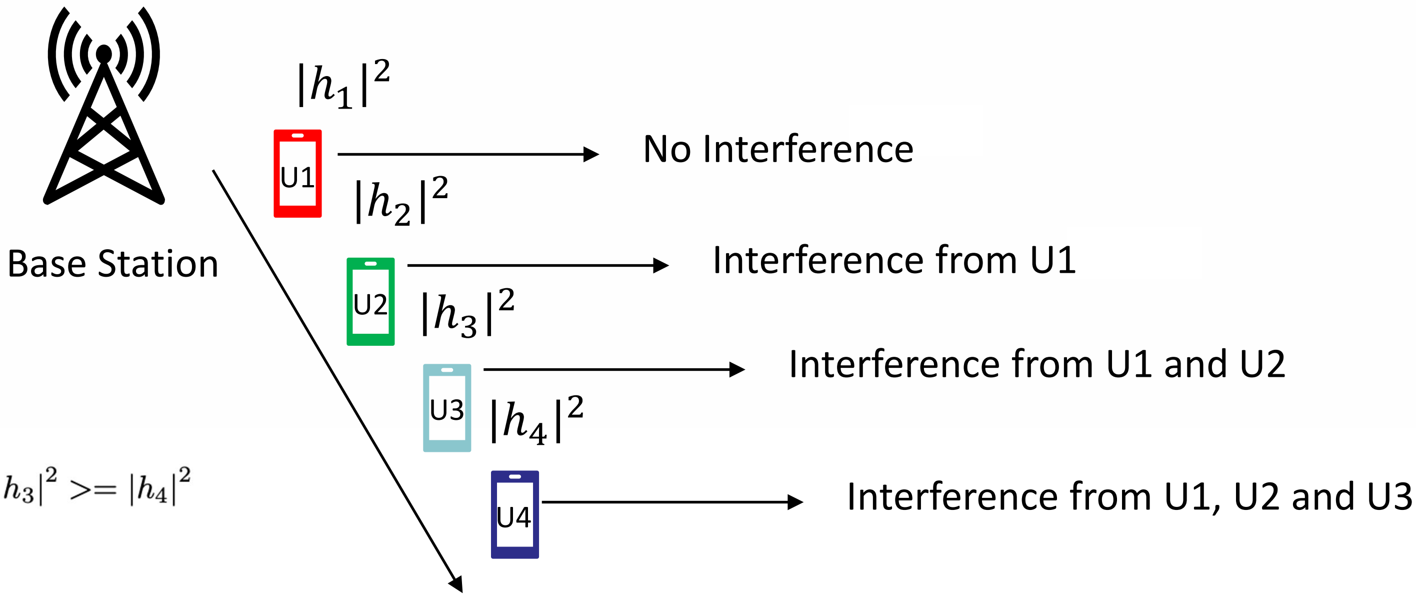
Non-Orthogonal Multiple Access



- **Non-orthogonal Multiple Access (NOMA)** has a potential to decrease latency & improve spectral efficiency in future wireless networks.
- The base stations uses **Superposition Coding (SC)** to generate a superimposed signal of all users to be transmitted simultaneously.
- The user would employ **Successive Interference Cancellation (SIC)** to decode their data from the overlaying signal.

Ref: Islam, S.M., Zeng, M. and Dobre, O.A., 2017. NOMA in 5G systems: Exciting possibilities for enhancing spectral

NOMA Drawback

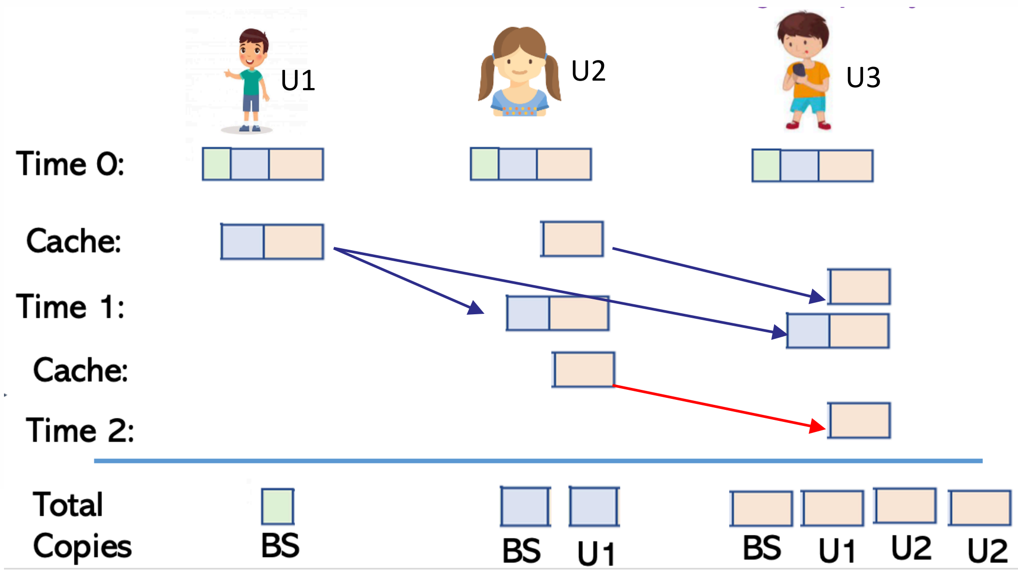


Channel gain:

$|h_1|^2 >= |h_2|^2 >= |h_3|^2 >= |h_4|^2$

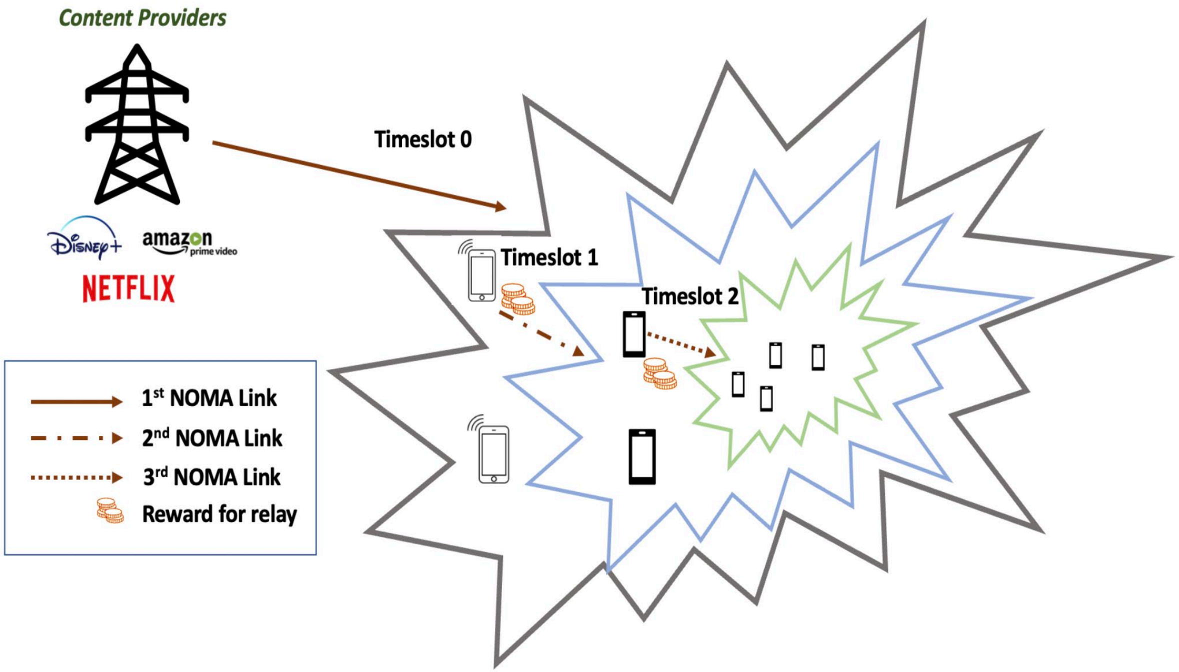
- As the number of users in a NOMA block increase, the users with worser channel gain experience higher levels of interference.

D2D Relay Enabled In NOMA



- D2D or Device-to-Device communication has a potential to improve throughput, power efficiency, delay, and fairness of all EUs in the network.
- The shortcoming of NOMA can easily be negated by enabling D2D communication in a NOMA Network.
- In a D2D enabled NOMA, the users with higher channel gain can cache and forward the packets to users with weaker channel gain to improve their overall SINR.

Envisioned D2D Enabled NOMA Network

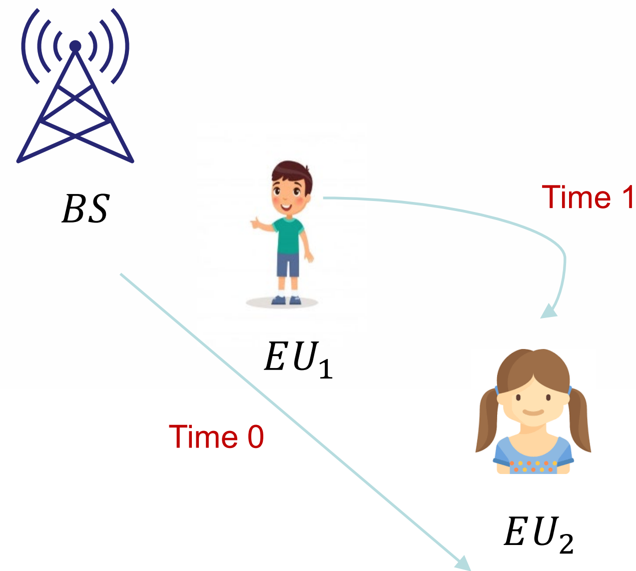


- For the stronger channel gain users to cache and forward the information – a suitable incentive needs to be provided.
- In this work, we propose solutions from Auction theory to find the optimal price for the retransmitted data.

QoE Modelling

Let $|h_i|^2$ denote the channel gain of UE_i. Without loss of generality, we assume that the UEs are ordered based on their channel gain:

$$|h_1|^2 >= |h_2|^2 >= |h_3|^2 >= |h_4|^2$$



The SINR for EU1 can be represented as

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

The SINR for EU2 can be represented as

$$SINR_{EU_2} = \frac{P_2|h_2|^2}{P_1|h_2|^2 + \sigma^2}$$

→ Interference from EU1

The user EU2 also receives another copy of the information from EU1 during the next timeslot

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

→ Power allocated by EU1 for EU2

→ Channel b/w EU1 and EU2

→ SINR Gain D2D communication

QoE Modelling

Assuming that all the EUs cache and retransmit the data to weaker users. The Generalized SINR gain for a user EU_i can be expressed as

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

→ SINR Gain from BS transmission (time 0)

$$+ \sum_{k=1}^{N-i-1} \frac{P_{i,i+k+1} \left|h_{i,i+k+1}\right|^2}{\sum_{l=1}^{i-k} P_{l,i+k+1} \left|h_{i,i+k+1}\right|^2 + \sigma^2}$$

→ SINR Gain from retransmission EU_1 to EU_{i-2}

$$+ \frac{P_{i,i+1} \left|h_{i,i+1}\right|^2}{\sigma^2}$$

→ SINR Gain from retransmission EU_{i-1}

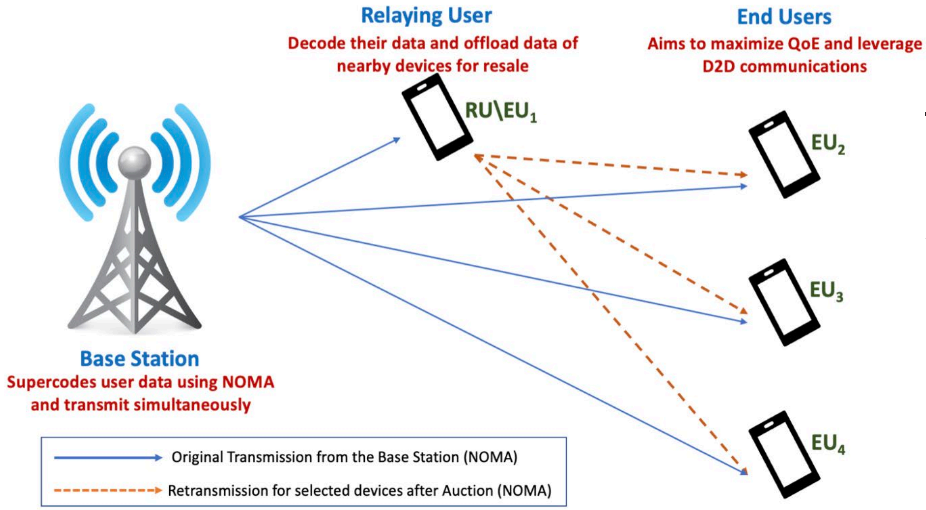
The two-level logarithmic function has been widely adopted in modelling the QoE equations in wireless communications.

$$QoE_i = \alpha \, log_2 \left(1 + \; B \, log_2\left(1 + SINR_{EU_i}\right)\right)$$

→ Data Rate using Shannon Capacity Theorem

Ref: Z. Su, Q. Xu, M. Fei and M. Dong, “Game Theoretic Resource Allocation in Media Cloud with Mobile Social Users”, IEEE Transactions on Multimedia, Vol.18, No. 8, August 2016.

Utility Definitions



To demonstrate the solution, we consider a single round of retransmission. (time-slot 1 and EU1)

Solution is independent of the number of rounds and can be easily extended.

Utility of the user (EU)

$$U_{EU_i} = QoE_i - y_i P_i - \delta_i P_{1,i}$$

- δ_i → Cost for unit power (retransmission)
- $P_{1,i}$ → Power purchased for retransmission

$y_i P_i$: Interplay b/w BS and EU. Solution derived using Game theory. (Previous work)

$\delta_i P_{1,i}$: Interplay b/w Relay and EU. Solution derived using Auction theory.

Utility Definitions

Cost of the relay

The transmission cost is determined by the packet length l, transmission power $P_{i,m}$, constellation size of modulation scheme b and the bandwidth B. λ_m is defined as the currency value per unit energy consumption

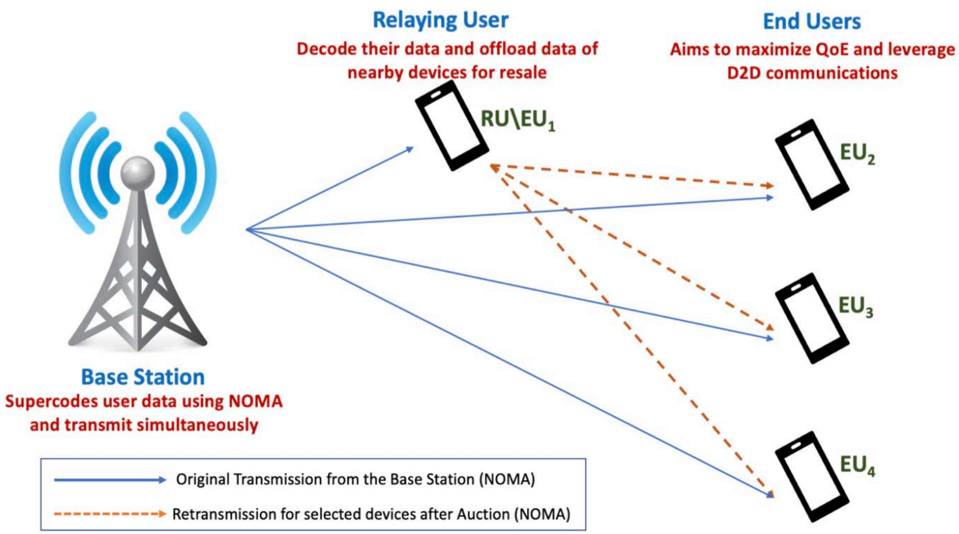
$$Cost_{relay} = \lambda_m \frac{lP_{i,m}}{b.B}$$

Utility of the Relay

Utility of the relay would be the money paid by the user for retransmission subtracted by the cost spent in caching the content.

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

Auction of NOMA Relay

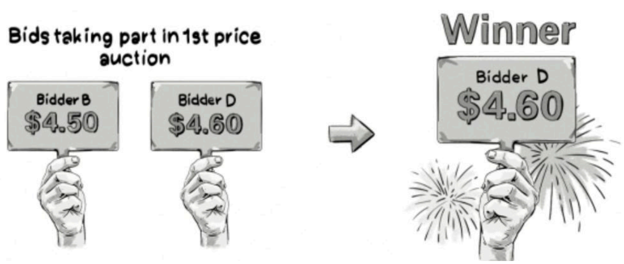


Examples of bids placed for timeslot 1

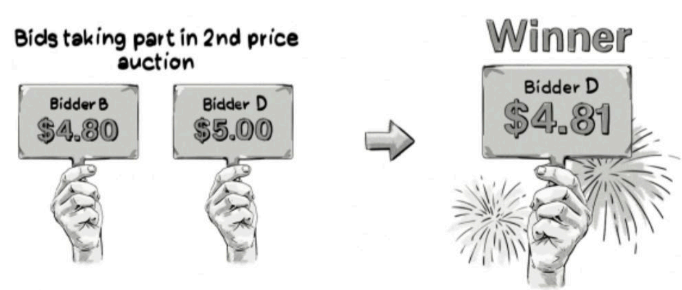
	EU_2	EU_3	EU_4
$Power1$	2	3	5
$Power2$	-	2.5	4
$Power3$	-	-	3

We consider one round of retransmission – the solution can however be extended multi-level relaying.

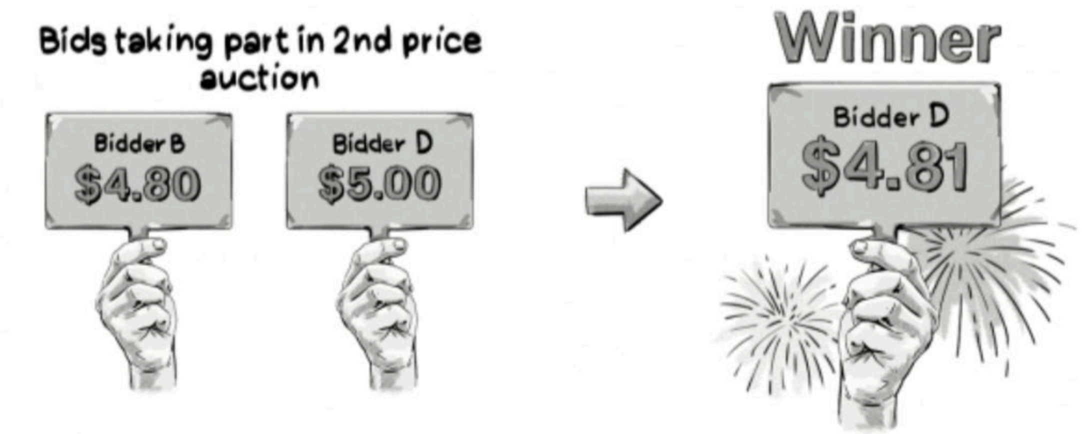
First Price Sealed Bid Auction



Second Price Sealed Bid Auction



Second Price Auction is stable (No regrets)



Truth telling is the dominant strategy. Therefore, the user bid their actual valuation.

Imagine you are the winner:

- You pay less than your valuation of service
  - Increase bid?
    - Still win and pay second price
  - Decrease bid?
    - Still win and pay second price
    - Lose and pay nothing.

Imagine you are the loser:

- You pay less than your valuation of service
  - Increase bid?
    - Still lose and pay nothing
    - win.. But pay more than you value the service
  - Decrease bid?
    - Still lose and receive nothing.

Computation of Bid – First Price Auction

Theorem 1: In FPSBA with two risk-neutral bidders whose valuations, v_1 and v_2, are Independent and identically distributed random variables drawn from uniform distribution $U(0,1)$, (1/2 v_1, 1/2 v_2) is the bases Nash equilibrium strategy

Proof: Assume that the $bidder_2$ bids $1/2v_1$ based on the theorem above and $bidder_1$ bids arbitrary $s1$. Then, $bidder_2$ wins every time when $s_1 < 1/2v_1$ and loses otherwise. The expected utility for the $bidder_1$ can be computed as:

$$\begin{aligned} E\left[bidder_1\right] &= \int_0^{2s_1} (v_1 - s_1)\, dv_2 + \int_{2s_1}^{1} (0) dv_2 \\ &= (v_1 - s_1)\, v_2\big|_0^{2s_1} \\ &= 2v_1 s_1 - 2s_1^2 \end{aligned} \quad (15)$$

We can determine the best response for $bidder_1$ to $bidder_2$'s strategy by taking the first order derivative of equation (15) and setting it equal to zero.

$$\begin{aligned} \frac{\partial}{\partial s_1}\left(2v_1 s_1 - 2s_1^2\right) &= 0 \\ 2v_1 - 4s_1 &= 0 \\ s_1 &= \frac{1}{2} v_1 \end{aligned} \quad (16)$$

Lemma 1: 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 $(n-1/n\ v_1,\ n-1/n\ v_2\ \ldots\ n-1/n\ v_n)$.

Therefore, the Nash Equilibrium 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.

Computation of Bid – Second Bid Auction

Proposition 1: The VCG mechanism is 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.

Proof:

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

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

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

$$x^* = \arg\max_x \left\{ \sum_i v_i(x) \right\} \tag{17}$$

where x^* denotes the socially efficient action.

Step 2: The total welfare of the society, not counting the $bidder_i$ is computed as

$$\sum_{j \neq i} v_j \left(x^*\right) \tag{18}$$

Step 3: The change to this welfare if the $bidder_i$ is not part of the society is then calculated as

$$x^*_{-i} = \arg\max_x \left\{ \sum_{j \neq i} v_j(x) \right\} \tag{19}$$

Step 4: The measure of much the bidder i contributes to the rest of the society is computed (may be negative)

$$\mathcal{C}_i(v)) = \sum_{j \neq i} v_j \left(x^*\right) - \sum_{j \neq i} v_j \left(x^*_{-i}\right) \tag{20}$$

VCG Auction

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 and 2.

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

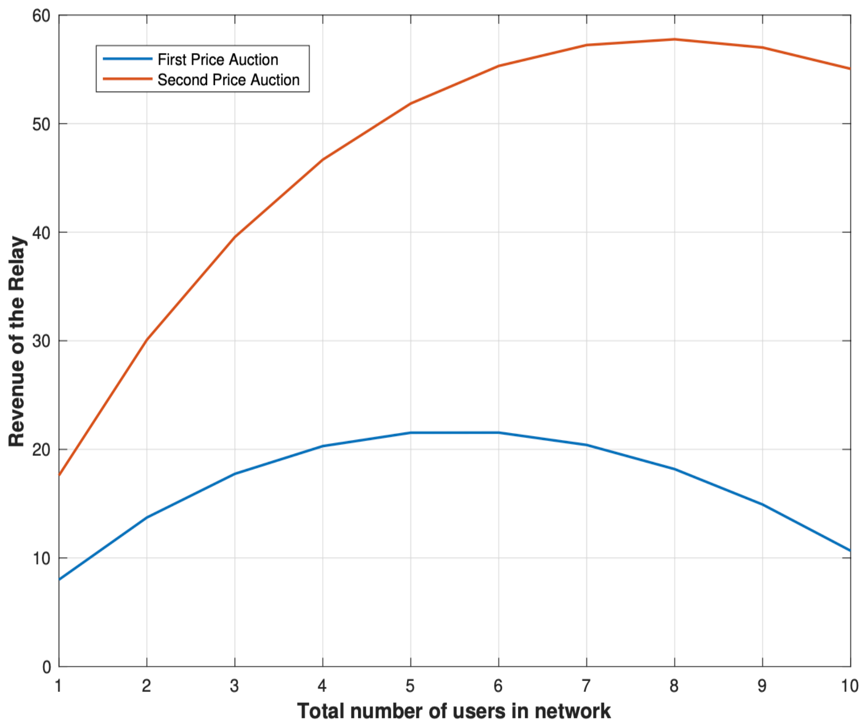
For First Price Auction, the Nash Equilibrium solution is 2/3 v_i. The winning bids would be 2/3 x 2 for EU2. 2/3 x 2.5 for EU3 and 2/3 x 3 for EU4. The total price paid by the users to obtain the same service using the first price auction would be $4.9999.

Simulations- Utility gain of user

The revenue of the relay is a concave function as expected with respect to the number of users supported in relay re-transmission as shown.

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.

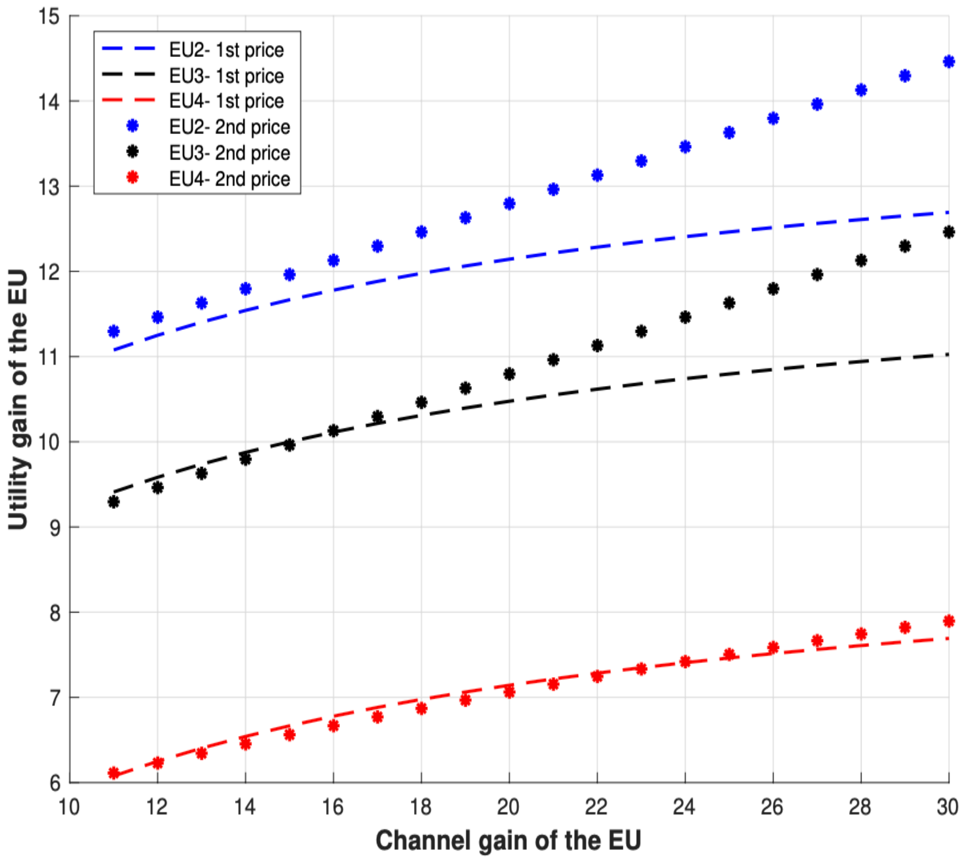
It can be noted that the second price VCG auction yields significantly better utility for the relay for any number of users supported.



Simulations- Utility gain of end user

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 |h1|2, while the environment among three E U s was kept stable (i.e., |h1,2 |, |h1,3 |, |h1,4 | remain unchanged).

From the figure, it can be observed that the second price approach (VCG) performs better as the channel gain increases across EUs .



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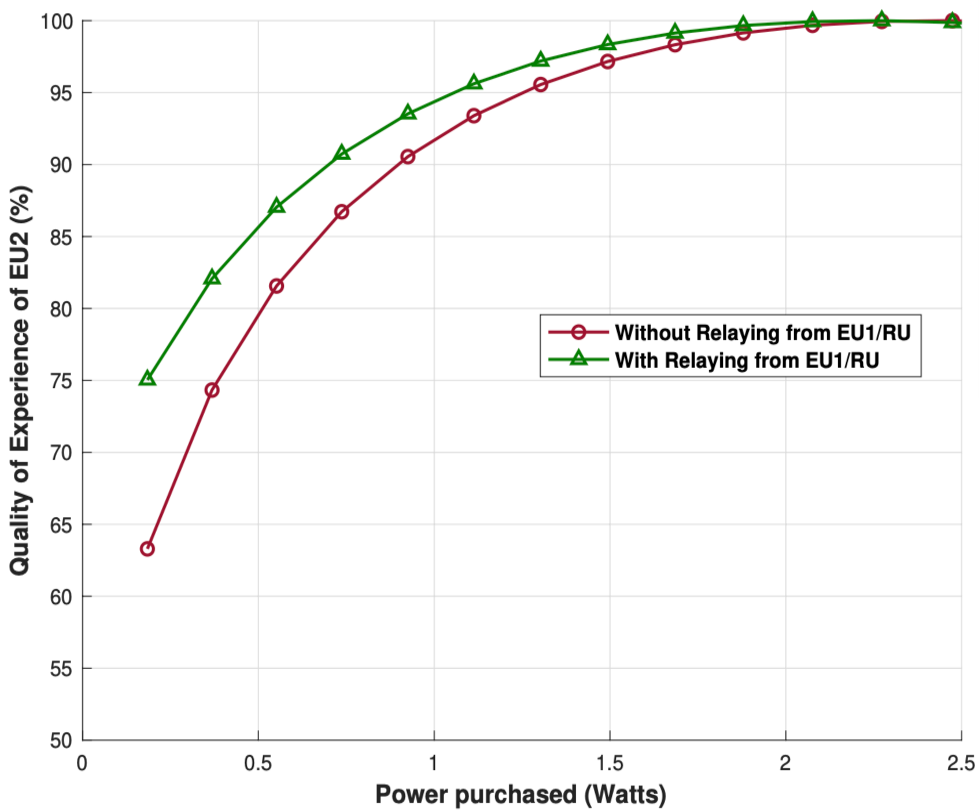
Simulations- Quality of Experience



Quality of Experience for EU_2 with and without the extra retransmission from RU. QoE is a concave function, and it can be visualized.

The $\frac{P_{1,2}|h_{1,2}|^2}{\sigma^2}$ retransmission adds term to the $SINR_{EU2}$, 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.

Conclusion

- 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.

Thank you!

Q&A