Evolution of NOMA Toward Next Generation Multiple Access

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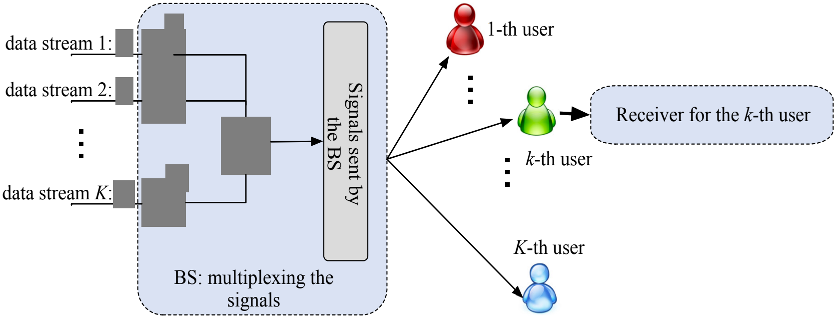
Outline

Non-orthogonal Multiple Access (NOMA)

- What is multiple access (MA)?
  - Techniques to serve multiple users with limited bandwidth.
  - An example for downlink multiple access



Non-orthogonal Multiple Access (NOMA)

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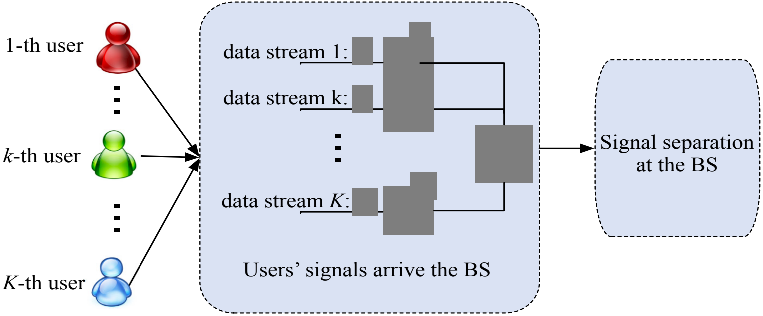
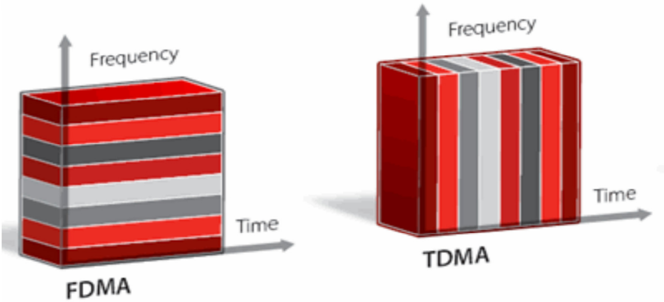


Non-orthogonal Multiple Access (NOMA)

- What kind of multiple access techniques have been used?
  - We have been using orthogonal multiple access (OMA).
  - TDMA: Orthogonal (non-overlapping) time slots are allocated to users.
  - FDMA: Orthogonal (non-overlapping) frequency channels are allocated to users.



Non-orthogonal Multiple Access (NOMA) - (1/2)

Disadvantages of OMA

- Dilemma to realize a better trade-off between throughput and user fairness, illustrated in the following example:
  - A user with a poor connection to the base station (BS) is served by using OMA.
  - Spectral efficiency is low since this user cannot utilize the allocated bandwidth efficiently.
  - Since OMA is used, the bandwidth resources occupied by this user cannot be shared by the others.
- Difficult to support massive connectivity
  - Recall that the three key requirements for 5G are to support high throughput, low latency and massive connectivity

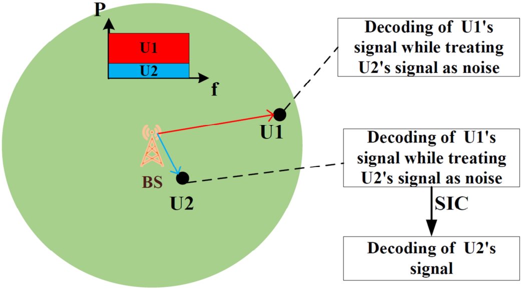
Non-orthogonal Multiple Access (NOMA) - (2/2)

- A promising solution is to break orthogonality → NOMA
  - The key idea of NOMA is to encourage spectrum sharing
  - Details for the advantages of NOMA are to be given in the remaining of this tutorial.
- NOMA is gaining ground on the competition of multiple access techniques for the next generation wireless networks
  - 3GPP Release 14: a study item for applying NOMA to downlink (MUST) - 15 different proposals
  - 3GPP Release 15 (E-UTRA) : MUST was formally included
  - 3GPP Release 16: a study item for applying NOMA to uplink (NoMA) - close to 30 different proposals
  - Divergency is the most valuable lesson from the 5G standardization activities for NOMA
  - Efforts towards convergency are key for NOMA in 6G

Outline

Using Users' Different Channel Conditions (1/2)

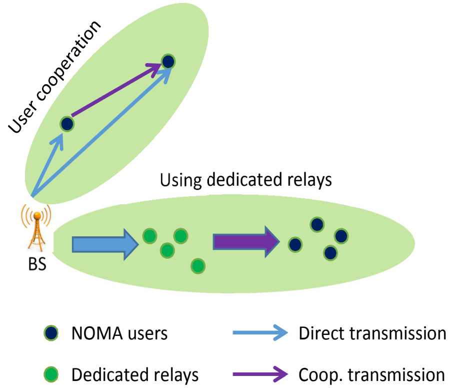
A simple example - Power-domain NOMA



- All the users are served at the same time, frequency and code, but with different power levels.
- Users with better channel conditions get less power.
- Successive interference cancellation (SIC) is used.

Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System level performance evaluation of downlink non-orthogonal multiple access (NOMA)", in PIMRC 2013.
Z. Ding, Z. Yang, P. Fan and H. V. Poor, "On the Performance of Non-Orthogonal Multiple Access in 5G Systems with Randomly Deployed Users", IEEE SPL, 2014.

Using Users' Different Channel Conditions (2/2)

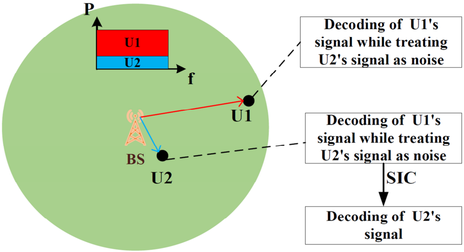


- Cooperative NOMA
  - One NOMA strong user helps another NOMA weak user
  - Using dedicated relays

Using Users' Heterogeneous QoS Requirements (1/2)

A simple example - Cognitive-radio inspired NOMA (CR-NOMA)

- Users might have similar channel conditions, but different QoS requirement
- For example, consider the following two-user scenario:
- User 1 might be a sensor and needs to be served at a small data rate only.
- User 1 can be viewed as a primary user in conventional CR networks.



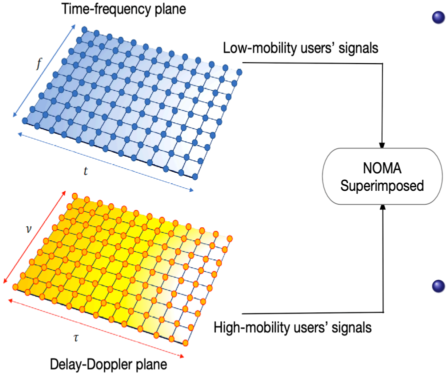
Using Users' Heterogeneous QoS Requirements (2/2)

- User 1 can be viewed as a primary user in a CR network:
  - If OMA is used, the orthogonal bandwidth allocated to user 1 cannot be accessed by other users.
  - Spectral efficiency is low since user 1 has a small data rate
- The use of NOMA is equivalent to the application of CR:
  - User 2 is served without consuming extra bandwidth.
  - Avoid relying on power control and channel difference.
  - An extreme uplink example - users have the same channel gains and User 1 has less TX power

$$R_1 = \log\left(1 + \frac{P_1|h_1|^2}{P_2|h_2|^2+1}\right) \underset{2P_1=P_2\to\infty}{\approx} \log\left(1+\frac{1}{2}\right) \approx 0.59 bits/s/Hz$$

Z. Ding, P. Fan and H. V. Poor, "Impact of User Pairing on 5G Non-Orthogonal Multiple Access Downlink Transmissions", IEEE TVT, 2016

Using Users' Heterogenous Mobility Profiles



- High-mobility users' signals are placed in the delay-Doppler domain
  - Their channels in the delay-Doppler domain become time-invariant
  - Simplify channel estimation and detection
- Low-mobility users' signals are placed in the time-frequency domain
  - Introduce spectrum sharing and improve spectral efficiency
  - Improve the OTFS resolution

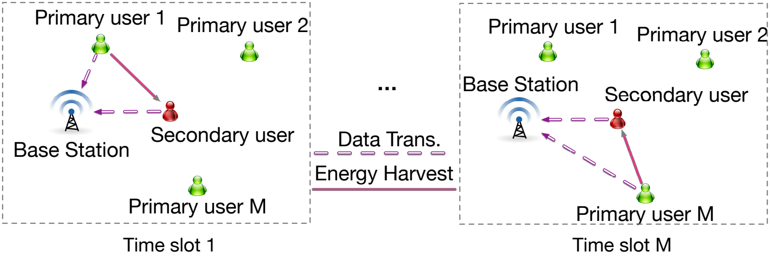
Z. Ding, R. Schober, P. Fan and H. V. Poor, OTFS-NOMA: An Efficient Approach for Exploiting Heterogenous User Mobility Profiles, IEEE Trans. Communications, 2019

Using Users' Heterogenous Energy Profiles

Consider a simple uplink scenario with two users, a primary user (with power supplies) and a secondary user (energy constrained).

- Using wireless power transfer (WPT)
  - With the use of NOMA, the secondary user is admitted to the primary user's channel
  - The energy-constrained user's transmission is powered by the energy harvested from the non-energy-constrained user's signal
  - Hybrid SIC is also applicable here
- Using backscatter communication (BackCom)
  - The energy-constrained device reflects and modulates the signals sent by the non-energy-constrained device
  - The non-energy-constrained user's signal becomes a fast fading channel - leading to some effects not observed for WPT-NOMA

An Example for Energy and Spectrum Cooperation



- Both SWIPT and BacCom can be used for energy cooperation.

Z. Ding, Harvesting Devices' Heterogeneous Energy Profiles and QoS Requirements in IoT: WPT-NOMA vs BAC-NOMA , IEEE Trans. Communications, 2021.

Any Other Forms of NOMA?

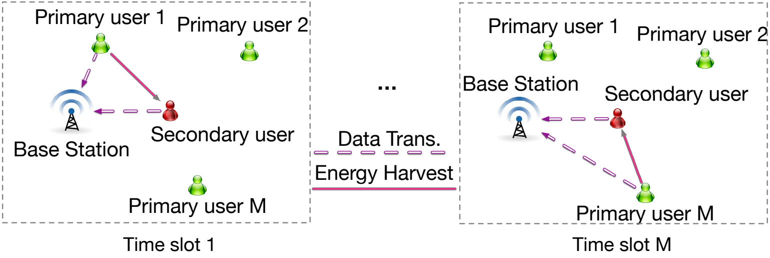
- There are many important other forms of NOMA, each of which might be optimal to a particular application scenario
- For example, the latest 3GPP framework, NoMA, contains more than 30 variants
- Essentially they are based on the same principle: avoid using orthogonal resources to serve users
- This principle can be the key to the evolution of the next-generation mobile network
- In the following, we will show how this principle can be applied to different communication networks

Outline

Motivations

- Backscatter communication (Back-Com) is the key enabler of ambient IoT
  - Back-Com can also provide additional spatial degrees of freedom
  - Back-Com is a truly green communication technique
  - Back-Com circuit design is quite mature, and hence realistic/practical
- BAC-NOMA ensures energy and spectrum cooperation simultaneously
- What are the challenges to design BAC-NOMA?
  - Double attenuation
  - All frequency/space 'jamming'

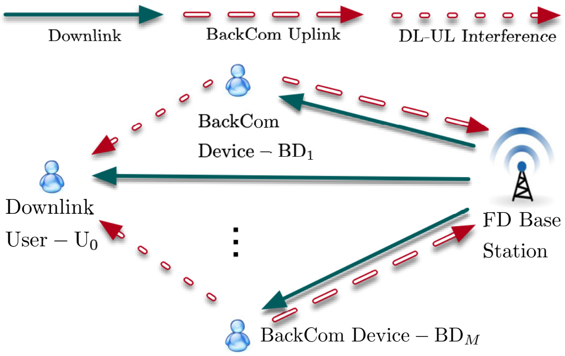
Example 1 for Energy and Spectrum Cooperation



- Focus on the use of BacCom for energy cooperation.

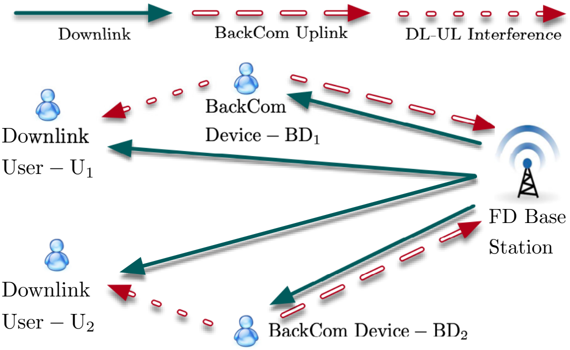
Z. Ding, Harvesting Devices' Heterogeneous Energy Profiles and QoS Requirements in IoT: WPT-NOMA vs BAC-NOMA , IEEE Trans. Communications, 2021.

Example 2 for Energy and Spectrum Cooperation



Z. Ding and H. V. Poor, On the Application of BAC-NOMA to 6G umMTC , IEEE Communications Letters, 2021.

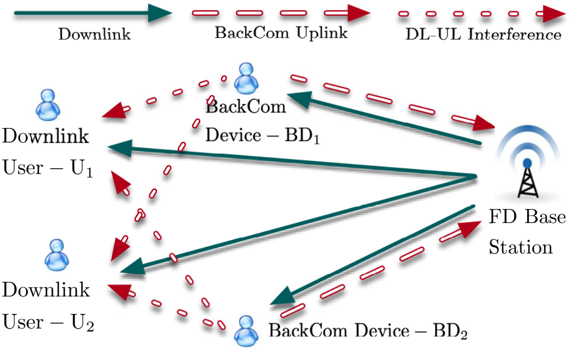
Example 2 for Energy and Spectrum Cooperation



A quick question: if there are 2 OFDMA downlink users, is it possible for some BackCom devices to transmit on one subcarrier and other devices on the other subcarrier?

Z. Ding and H. V. Poor, Advantages of NOMA for Multi-User BackCom Networks, IEEE Communications Letters, 2021.

Example 2 for Energy and Spectrum Cooperation



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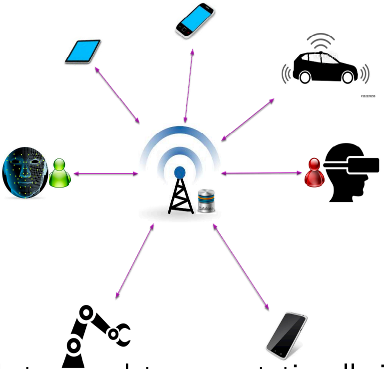
Outline

Introduction (1/2)



What is MEC?

- Each user needs to complete computationally intensive latency-critical tasks.
- Users offload their tasks to the MEC server.
- Then, the users download the outcomes from the server.

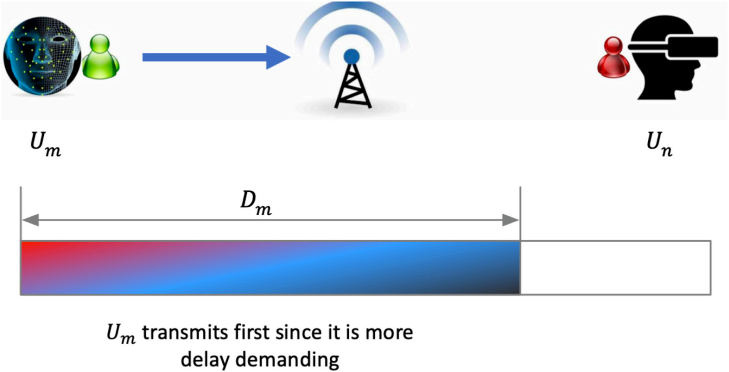
Introduction (2/2)

Why if OMA is used for MEC offloading

- Users take turn offloading
- Take a two-user case as an example

Z. Ding, P. Fan, and H. V. Poor, "Impact of Non-orthogonal Multiple Access on the Offloading of Mobile Edge Computing", IEEE Trans. Commun., 2019.

Introduction (2/2)



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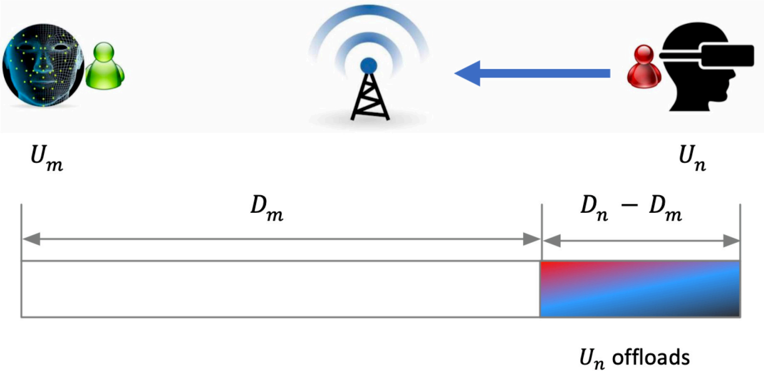
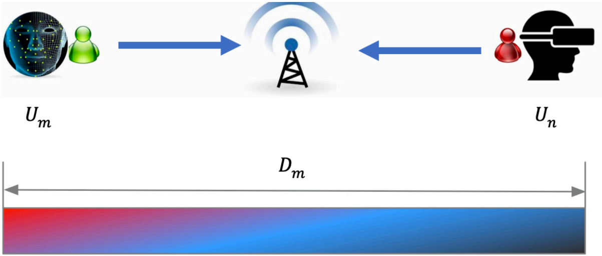
Introduction (2/2)



A drawback of OMA-MEC

- U_n has to wait until U_m finishes its offloading
- Limited time available to U_n (an extreme case is $D_n \approx D_m$)

Delay-Efficient NOMA-MEC

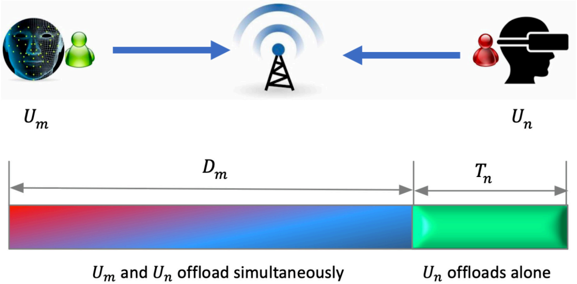


U_m and U_n offload simultaneously

A potential issue

- U_n's offloading time and power are fixed, to avoid performance degradation at U_m
- Can U_n still finish its offloading with D_m?

Energy-Efficient NOMA-MEC



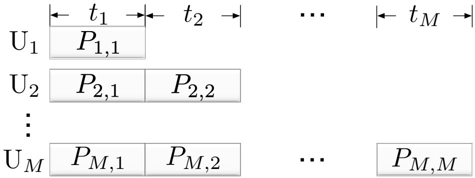
Forcing U_n within D_m can be energy-inefficient.

- The period of D_m is 'noisy'
- A more energy efficient way is hybrid implementation, i.e., allocating a dedicated time slot to U_n
- A few interesting conclusions were made to the two-user case

Z. Ding, J. Xu, O. A. Dobre and H. V. Poor, Joint Power and Time Allocation for NOMA-MEC, IEEE TVT, 2019

General NOMA-MEC in Multi-User Networks (1/4)

The two-user NOMA-MEC scheme can be generalized to a multi-user scenario as follows:



Z. Ding, D. Xu, R. Schober and H. V. Poor, "Hybrid NOMA Offloading in Multi-User MEC Networks", IEEE TWC, 2022.

General NOMA-MEC in Multi-User Networks (2/4)

Need to solve the following multi-objective optimization problem:

$$\min_{\mathbf{x}} \quad \mathbf{E}_M \triangleq \begin{bmatrix} E_2 & \cdots & E_M \end{bmatrix}^T \tag{P1a}$$

$$\text{s.t.} \quad \sum_{n=1}^{m} t_n R_{m,n} \geq N, \quad 2 \leq m \leq M \tag{P1b}$$

$$\sum_{n=1}^{m} t_n \leq D_m, \quad t_m \geq 0, \quad 2 \leq m \leq M \tag{P1c}$$

$$0 \leq P_{m,n} \leq P_m^{\mathrm{OMA}}, \quad 2 \leq m \leq M, 1 \leq n \leq m, \tag{P1d}$$

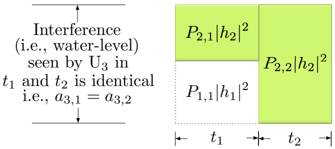
General NOMA-MEC in Multi-User Networks (3/4)

A heuristic algorithm can be developed

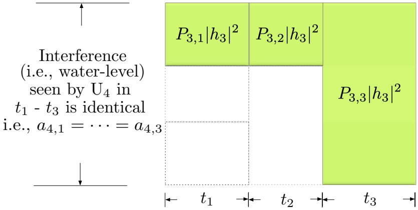
- Resource allocation in a successive manner
- Closed-form solutions are available
- Important insight can be obtained by analysing the closed form solutions
    - Hybrid NOMA outperforms pure NOMA
    - Hybrid NOMA outperforms OMA, if the delay deadlines are not urgent
    - Hybrid NOMA is Pareto optimal

General NOMA-MEC in Multi-User Networks (4/4)

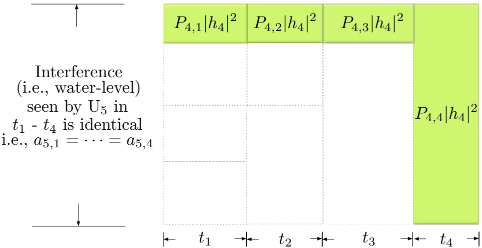
- Hybrid NOMA power allocation is similar to water filling



(a) After U_2 finishes offloading



(b) After U_3 finishes offloading



Outline

Introduction

Why to use the terahertz (THz) band?

- The sub-6 GHz bands become extremely crowded
- A huge amount of bandwidth in the THz band can be available to communications

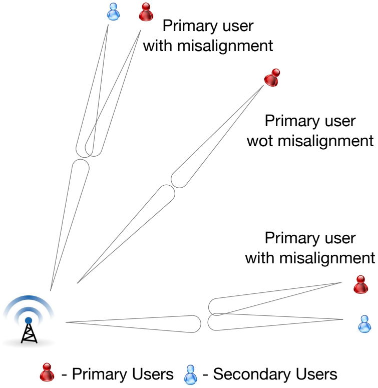
Why to apply NOMA in THz networks?

- Emerging applications of 6G can soon make the THz spectrum as crowded as those sub-6G Hz bands
    - e.g., immersive AR and VR, wireless transmission of UHD video, holographic-type services, etc.
- The use of NOMA can improve the efficiency to use THz bandwidth.

The feature of THz transmission also facilitates the implementation of NOMA

NOMA Assisted THz Networks - Example 1

Beam alignment errors can be utilized as opportunities for implementing NOMA

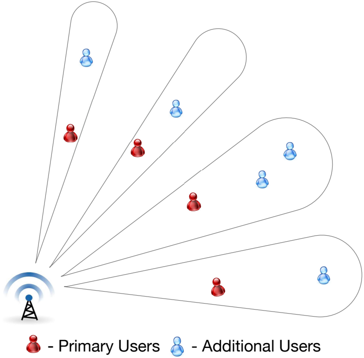


Z. Ding and H. V. Poor, Design of THz-NOMA in the Presence of Beam Misalignment, IEEE Communications Letters, 2022.

NOMA Assisted THz Networks - Example 2

Consider a legacy system with primary users served by preconfigured beams

NOMA is used as an add-on to serve more additional users



Z. Ding and H. V. Poor, Joint Beam Management and Power Allocation in THz-NOMA Networks, IEEE Trans. Communications, submitted in 2022.

Using Preconfigured Beams as Bandwidth Resources (1/2)

- Potentials:
  - Similar to OFDM subcarriers, these beams can be used to serve additional users as bandwidth resources
  - No extra spectrum is needed
  - No change to the legacy network (transparent to legacy users)
- Limits:
  - Unlike OFDM subcarrier, they are not orthogonal resources.
  - Inter-beam interference is a kill factor
  - Performance is degraded with more beams available

Z. Ding and H. V. Poor, Joint Beam Management and Power Allocation in THz-NOMA Networks, IEEE Trans. Communications, submitted in 2022.

Using Preconfigured Beams as Bandwidth Resources (2/2)

Beam allocation can be an existing new direction, not only for THz-NOMA, but also for MIMO-NOMA

- As subcarrier allocation for OFDMA, so much to explore

How is beam allocation different from subcarrier allocation?

- Consider a case with one and multiple beams (subcarriers)
- In OFDM, water filling is used, i.e., the user uses all subcarriers with different power
- In THz-NOMA, optimal beam allocation strategy is to use a single beam due to inter-beam interference
- Various techniques, such as beam aggregation, can be used to combat inter-beam interference

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Z. Ding, Potentials and Limits of Using Preconfigured Spatial Beams as Bandwidth Resources: Beam Selection vs Beam Aggregation, IEEE Communications Letters, submitted.

Thank you for your attention!

We are still a long way to the design of next-generation multiple access (NGMA) techniques

IEEE ComSoc built an Emerging Technologies Initiative (ETI) on NGMA

- Its mission is to provide a research and networking platform for researchers to collaborate, exchange ideas, and promote initiatives on NGMA
- Become a member of the ETI and find more information at https://ngma.committees.comsoc.org/

Articles and their codes are available at GitHub

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