The Road to 5G Wireless Systems: Resource Allocation for NOMA

Derrick Wing Kwan Ng

The University of New South Wales
School of Electrical and Telecommunications Engineering

Tsinghua University, Beijing

Jan. 2017

Outline

1. Introduction
   - Overview - 5G Communication Systems
   - Overview - Massive MIMO
   - Overview - Energy Harvesting
   - Overview - 5G NOMA
2. System Model for MC-NOMA
3. Resource Allocation Problem Formulation
   - Performance Measure
   - Problem Formulation
4. Optimization Solution
   - Optimal Solution
   - Suboptimal Solution
5. Simulation Results
6. Conclusions
7. Future Work

Overview - 5G Communication Systems

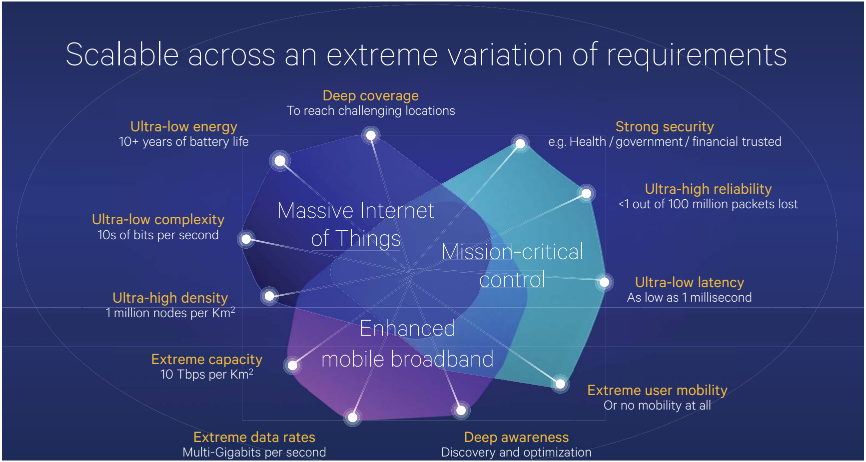


Figure: Qualcomm’s 5G Vision [1].

Key Technologies for 5G

- There is no single technology which can fulfill all the goals....(good and bad)

Table: Key Technologies for 5G.

Massive MIMO [2, 3]	NOMA [4, 5, 6, 7]
mmWave Communications	Full Duplex Communications [8, 9]
Base Station Caching [10]	Mobile Edge Computing
Cloud-based Radio Access Networks	Visible Light Communication
Energy Harvesting [11]–[19]	D2D Communication

Advertisement

Key Technologies for 5G Wireless Systems, Cambridge University Press, Apr. 30 2017

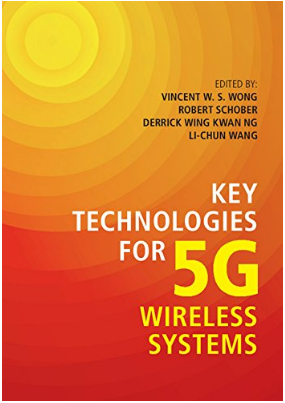


Figure: By Vincent W. S. Wong (Editor), Robert Schober (Editor), **Derrick Wing Kwan Ng** (Editor), Li-Chun Wang (Editor)

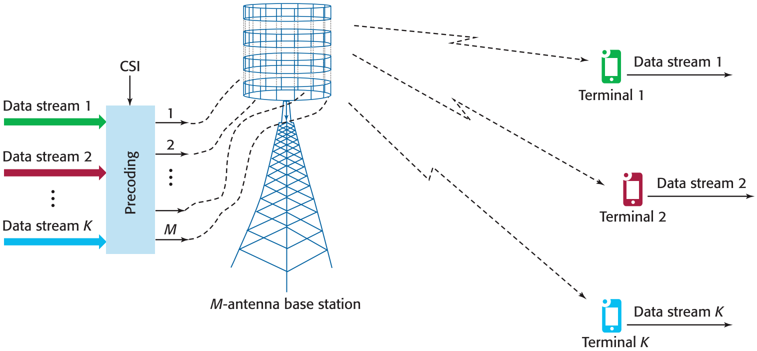
5G Emerging Technologies

Core technologies/methods for fulfilling the strengthen quality of service (QoS) requirements:

- Multiple input multiple output (MIMO) [20, 21]
    - Extra degrees of freedom in resource allocation (diversity and multiplexing ⇒ high data rate)
    - Artificial noise generation for degrading the channel of eavesdroppers (communication security) [22]
    - Information signal beamforming, zero forcing etc. (communication security)

5G Emerging Technologies

- Massive MIMO: 5G technology candidate
  - The use of a very large number of service antennas (e.g., hundreds or thousands) to serve multiple users (each equipped with small number of antennas or even single-antenna) simultaneously



5G Emerging Technologies

- Massive MIMO: Transmitter equipped with hundreds antennas serve multiple (e.g. single antenna) receivers [2, 3, 23]
  - Shift the signal processing burden from the receivers to transmitter
  - Allow simple design and cheap receiver
  - Achieve asymptotically optimal performance by using simple precoding design

Table: List of potential research problems for massive MIMO

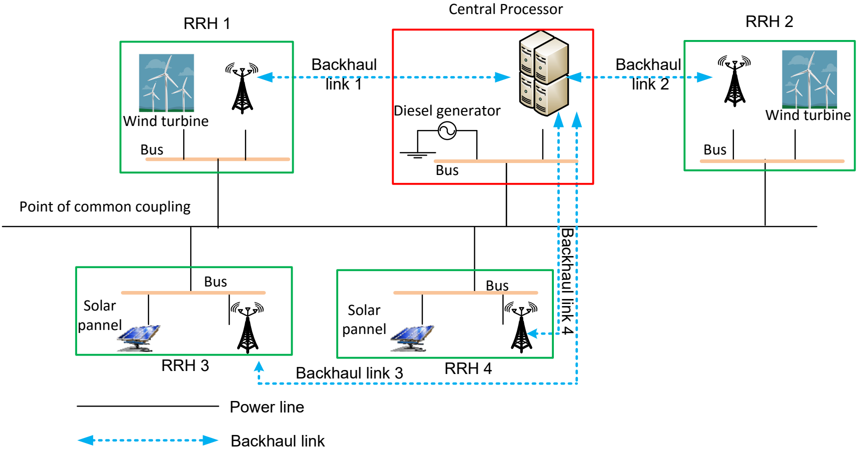
Hardware impairment	Precoding design
Pilot contamination	Energy efficiency
FDD vs TDD	Co-located versus Distributed

5G Energy Harvesting

- Ubiquitous and Self-sustainable Networks
  - Technologies
    - Conventional energy harvesting (scavenging): Collect energy from natural renewable energy sources such as solar, wind, and geothermal heat
    - Advantages: Self- substantiable network
    - Technical challenges (engineering problems): Time varying availability of the energy generated from renewable energy sources $\Longrightarrow$ Perpetual but intermittent energy supply $\Longrightarrow$ Unstable communication service [11, 12]

5G Energy Harvesting

Hybrid powered base station networks



Overview - Energy Harvesting

- “New" energy harvesting technology: RF-based Energy Harvesting/ Wireless powered communications [13]–[19]
    - Collect energy from background radio frequency (RF) electromagnetic (EM) waves from ambient transmitters
        - Major Applications: RFID, body area networks, wireless sensor networks, Machine-to-Machine (M2M) communications, Internet of things (IoT), etc [25, 26].

5G Energy Harvesting

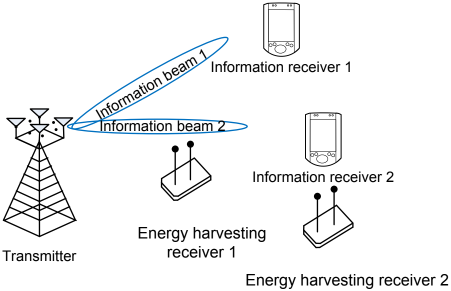


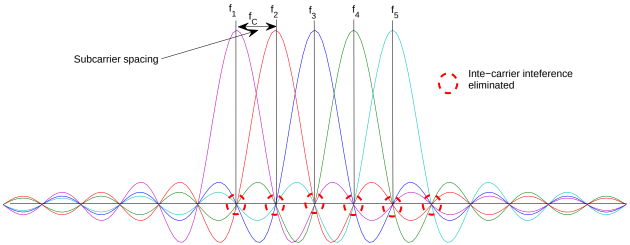
Table: List of potential research problems for massive MIMO

Resource allocation	Protocol design
Model design	Energy efficiency optimization

Overview - NOMA

In 4G communication systems, orthogonal frequency division multiple access (OFDMA):

- A wide band signal is divided into many narrow band subcarriers (e.g. 64→2048) and each subcarrier is assigned to at most one user
- Channel equalization is simplified
- Provide frequency diversity and multiuser diversity

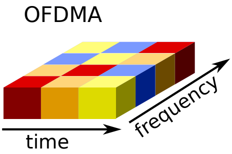


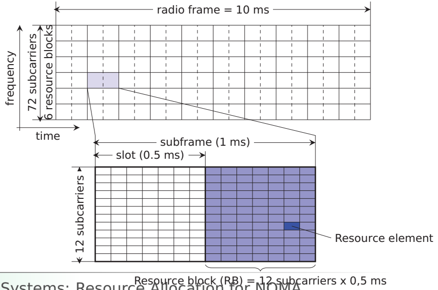
Motivation for NOMA

OFDMA: High flexibility in resource allocation:

The Physical Resource Block (PRB) is the basic unit of allocation.

- 12 subcarriers in frequency (= 180 kHz)
- 1 subframe in time (1ms = 14 OFDM symbols)
- Multiple resource blocks can be allocated to a user in a given subframe
- Total number of RBs depends on the operating bandwidth





Motivation for NOMA

However, traditional multicarrier orthogonal multiple access (MC-OMA) systems still underutilize the spectral resources

- Subcarriers are allocated exclusively to one user to avoid multiuser interference
- Subcarriers may be assigned exclusively to a user with poor channel quality to ensure fairness
- Orthogonality cannot be always maintained
    - Hardware imperfection
    - Doppler shift

Motivation for NOMA

To overcome the aforementioned shortcomings, non-orthogonal multiple access (NOMA) has been recently proposed

- Multiplexing multiple users on the same frequency resource
- Pairing users enjoying good channel conditions with users suffering from poor channel conditions
- NOMA is enabled by successive interference cancellation (SIC) at receivers

Channel capacity comparison of OMA and NOMA in an AWGN channel

- NOMA achieves larger multi-user capacity compared to OMA.

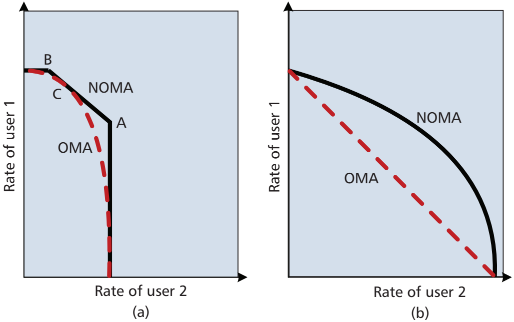
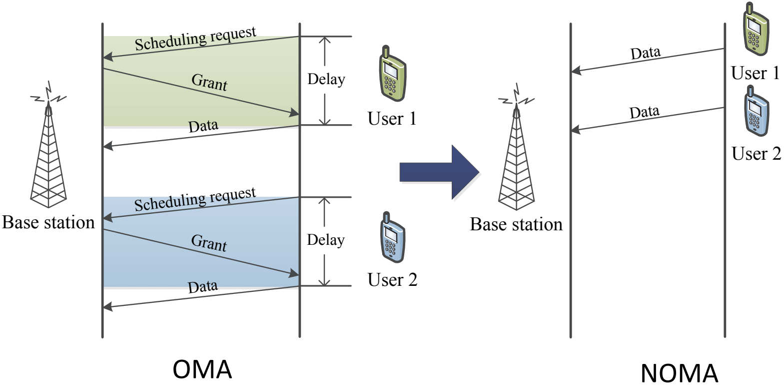


Figure: Channel capacity comparison of OMA and NOMA in an AWGN channel: (a) uplink AWGN channel; (b) downlink AWGN channel.

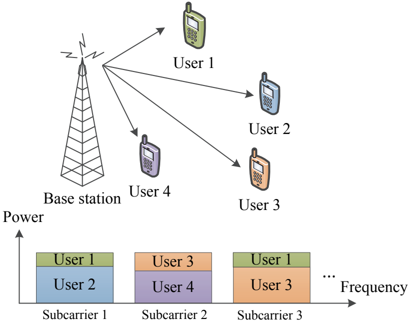
Uplink NOMA

- Transmission latency and signaling cost can be reduced in uplink NOMA
  - Allow multiple uplink users share the same radio resource
  - No scheduling is required
  - The base station performs SIC



System Model

- Resource allocation for a multicarrier NOMA downlink system.



- K downlink users, N_{F} subcarriers
- All transceivers are equipped with a single-antenna.
- All downlink users can perform successive interference cancellation (SIC)
- Each subcarrier can be allocated with at most two users.
- Power and subcarriers are available radio resources to be managed.

System Model

Resource allocation design for MC-NOMA systems is more challenging than for traditional MC-OMA systems

- User pairing on each subcarrier is needed
- SIC ordering on each subcarrier is needed (which user perform SIC and which user do not)
- In next section, we will formulate the power and subcarrier allocation design as a mixed-integer non-convex optimization problem

Performance measure

- Study the weighted throughput of user m and user n on subcarrier i
- Assume $|h_m^i|^2 \leq |h_n^i|^2$

Weighted throughput of user m and user n on subcarrier i:

$$U_{m,n}^i(p_m^i, p_n^i, s_{m,n}^i) = s_{m,n}^i \left[w_m \log_2\left(1+\frac{|h_m^i|^2 p_m^i}{|h_m^i|^2 p_n^i + \sigma_m^2}\right) + w_n \log_2\left(1+\frac{|h_n^i|^2 p_n^i}{\sigma_n^2}\right)\right], \quad (1)$$

where $s_{m,n}^i$ is subcarrier indicator and w_m is the priority of user m.

- Successful SIC can be performed, since

$$\log_2\left(1 + \frac{|h_n^i|^2 p_m^i}{|h_n^i|^2 p_n^i + \sigma_n^2}\right) \geq \log_2\left(1 + \frac{|h_m^i|^2 p_m^i}{|h_m^i|^2 p_n^i + \sigma_m^2}\right). \quad (2)$$

Problem Formulation

Problem: Maximization of the weighted system throughput

$$\underset{\mathbf{p},\mathbf{s}}{\text{maximize}} \quad \sum_{i=1}^{N_{\mathrm{F}}}\sum_{m=1}^{K}\sum_{n=1}^{K} s_{m,n}^{i}\left[w_m \log_2\left(1+\frac{|h_m^i|^2 p_m^i}{|h_m^i|^2 p_n^i+\sigma_m^2}\right)+w_n \log_2\left(1+\frac{|h_n^i|^2 p_n^i}{\sigma_n^2}\right)\right]$$

s.t.

$$\text{C1: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{m=1}^{K}\sum_{n=1}^{K} s_{m,n}^{i}(p_m^i + p_n^i) \le P_{\max},$$

$$\text{C2: } s_{m,n}^i \in \{0,1\}, \quad \forall i,m,n,$$

$$\text{C3: } \sum_{m=1}^{K}\sum_{n=1}^{K} s_{m,n}^i \le 1, \ \forall i,$$

$$\text{C4: } p_m^i \ge 0, \ \forall i,m, \qquad (3)$$

Blue color = non-convex objective function

Red color = non-convex constraint

Even if the subcarrier allocation is given, NP-hard

Optimal Solution

- In this section, we apply monotonic optimization to obtain the global optimal solution
- Monotonic optimization can converge to the global optimal solution of non-convex optimization problems by exploiting the monotonicity of the considered problem
  - The objective function is needed to be a increasing function
  - The feasible set is needed to be a normal set (the convex set belongs to normal sets)
  - The global optimal point is attained on the upper boundary
  - Approach the global optimal solution by constructing a sequence of polyblocks

Optimal Solution

- Rewrite the weighted throughput in an equivalent form

$$\begin{aligned} & U_{m,n}^{i}(p_m^i, p_n^i, s_{m,n}^i) \\ = & w_m \log_2\left(1+\frac{s_{m,n}^i H_m^i p_m^i}{s_{m,n}^i H_m^i p_n^i+1}\right)+w_n \log_2(1+s_{m,n}^i H_n^i p_n^i) \\ = & w_m \log_2\left(1+\frac{H_m^i \tilde{p}_{m,n,m}^i}{H_m^i \tilde{p}_{m,n,n}^i+1}\right)+w_n \log_2(1+H_n^i \tilde{p}_{m,n,n}^i) \\ = & \log_2(u_{m,n}^i)^{w_m} + \log_2(v_{m,n}^i)^{w_n}, \end{aligned} \qquad (4)$$

where $H_m^i = \frac{|h_m^i|^2}{\sigma_m^2}$, $u_{m,n}^i = 1 + \frac{H_m^i \tilde{p}_{m,n,m}^i}{H_m^i \tilde{p}_{m,n,n}^i+1}$, $v_{m,n}^i = 1 + H_n^i \tilde{p}_{m,n,n}^i$, and $\tilde{p}_{m,n,m}^i = s_{m,n}^i p_m^i$.

Optimal Solution

- Then, we define

$$f_d(\tilde{\mathbf{p}}) = \begin{cases} 1 + H_m^i(\tilde{p}_{m,n,m}^i + \tilde{p}_{m,n,n}^i), & d = \Delta, \\ 1 + H_n^i \tilde{p}_{m,n,n}^i, & d = D/2 + \Delta, \end{cases} \qquad (5)$$

$$g_d(\tilde{\mathbf{p}}) = \begin{cases} 1 + H_m^i \tilde{p}_{m,n,n}^i, & d = \Delta, \\ 1, & d = D/2 + \Delta, \end{cases} \qquad (6)$$

where $\Delta = (i-1)K^2 + (m-1)K + n$ and $D = 2N_{\mathrm{F}}K^2$.

- We further define

$$\mathbf{z} = [z_1, \ldots, z_D]^T = [u_{1,1}^1, \ldots, u_{K,K}^{N_{\mathrm{F}}}, v_{1,1}^1, \ldots, v_{K,K}^{N_{\mathrm{F}}}]^T. \qquad (7)$$

Optimal Solution

- Now, the original problem can be written as a standard monotonic optimization problem as:

Problem: Maximization of the weighted system throughput

$$\begin{aligned} \underset{\mathbf{z}}{\text{maximize}} \quad & \sum_{d=1}^{D} \log_2(z_d)^{\mu_d} \\ \text{s.t.} \quad & \mathbf{z} \in \mathcal{Z}, \end{aligned} \tag{8}$$

where the feasible set $\mathcal{Z}$ is given by

$$\mathcal{Z} = \left\{ \mathbf{z} \mid 1 \leq z_d \leq \frac{f_d(\tilde{\mathbf{p}})}{g_d(\tilde{\mathbf{p}})}, \tilde{\mathbf{p}} \in \mathcal{P}, \mathbf{s} \in \mathcal{S}, \forall d \right\},$$

where $\mathcal{P}$ and $\mathcal{S}$ are the feasible sets spanned by constraints C1, C3, and C4.

Optimal Solution

- The equivalent monotonic optimization problem in (8) can be solved optimally via outer polyblock approximation algorithm.

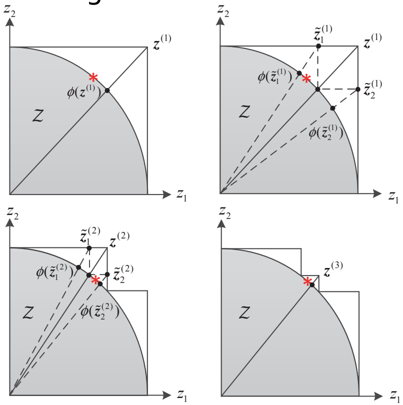


Figure: Illustration of the outer polyblock approximation algorithm for $D = 2$. The red star is the optimal point on the boundary of the feasible set $\mathcal{Z}$.

Optimal Solution

- The proposed monotonic optimization based resource allocation algorithm achieves the globally optimal solution. However, the computational complexity grows exponentially with $D = 2N_{\mathrm{F}}K^2$.
- In next section, we propose a suboptimal algorithm to reduce complexity while achieving a close-to-optimal performance.

Suboptimal Solution

- The product term $\tilde{p}^{i}_{m,n,m} = s^{i}_{m,n} p^{i}_{m}$ is an obstacle for efficient algorithm design.
- We adopt the big-M formulation to decompose the product terms. In particular, we impose the following additional constraints:

C5: $\tilde{p}^{i}_{m,n,m} \leq P_{\max} s^{i}_{m,n}, \ \forall m, n, i,$

C6: $\tilde{p}^{i}_{m,n,m} \leq p^{i}_{m}, \ \forall m, n, i,$

C7: $\tilde{p}^{i}_{m,n,m} \geq p^{i}_{m} - (1 - s^{i}_{m,n}) P_{\max}, \ \forall m, n, i,$ and

C8: $\tilde{p}^{i}_{m,n,m} \geq 0, \ \forall m, n, i.$

Suboptimal Solution

- Then, we rewrite the non-convex integer constraint C2: $s_{m,n}^{i} \in \{0,1\}$ in its equivalent form:

  C2a: $\sum_{i=1}^{N_\mathrm{F}}\sum_{m=1}^{K}\sum_{n=1}^{K} s_{m,n}^{i} - \sum_{i=1}^{N_\mathrm{F}}\sum_{m=1}^{K}\sum_{n=1}^{K} (s_{m,n}^{i})^2 \leq 0$ and

  C2b: $0 \leq s_{m,n}^{i} \leq 1, \ \forall m,n,i.$

- However, the constraint C2a is still a non-convex constraint.

Suboptimal Solution

- In order to handle the non-convex constraint C2a, we incorporate it as an additive penalty function term into the objective function :

Suboptimal resource allocation problem:

$$\begin{aligned} \underset{\tilde{\mathbf{p}},\mathbf{s}}{\text{minimize}} \quad & \sum_{i=1}^{N_{\mathrm{F}}}\sum_{m=1}^{K}\sum_{n=1}^{K} -\log_2\Big(1+\frac{H_m^i \tilde{p}_{m,n,m}^i}{H_m^i \tilde{p}_{m,n,n}^i+1}\Big)^{w_m} - \log_2\big(1+H_n^i \tilde{p}_{m,n,n}^i\big)^{w_n} \\ & +\eta\Bigg(\sum_{i=1}^{N_{\mathrm{F}}}\sum_{m=1}^{K}\sum_{n=1}^{K} s_{m,n}^i - \sum_{i=1}^{N_{\mathrm{F}}}\sum_{m=1}^{K}\sum_{n=1}^{K} (s_{m,n}^i)^2\Bigg) \\ \text{s.t.} \quad & \text{C1, C2b, C3–C8}, \end{aligned} \quad (9)$$

where $\eta \gg 1$ is a large constant which acts as a penalty factor to penalize the objective function for any $s_{m,n}^i$ that is not equal to 0 or 1.

- Problem (9) is still non-convex due to its objective function

Suboptimal Solution

- Now, we rewrite problem (9) as

$$\begin{aligned} \underset{\tilde{\mathbf{p}},\mathbf{s}}{\text{minimize}} \quad & F(\tilde{\mathbf{p}}) - G(\tilde{\mathbf{p}}) + \eta(H(\mathbf{s}) - M(\mathbf{s})) \\ \text{s.t.} \quad & \text{C1, C2b, C3–C8}, \end{aligned} \tag{10}$$

where

$$F(\tilde{\mathbf{p}}) = \sum_{i=1}^{N_{\mathrm{F}}} \sum_{m=1}^{K} \sum_{n=1}^{K} -w_m \log_2(1+H_m^i(\tilde{p}_{m,n,m}^i + \tilde{p}_{m,n,n}^i)) \\ - w_n \log_2(1+H_n^i \tilde{p}_{m,n,n}^i),$$

$$G(\tilde{\mathbf{p}}) = \sum_{i=1}^{N_{\mathrm{F}}} \sum_{m=1}^{K} \sum_{n=1}^{K} -w_m \log_2(1 + H_m^i \tilde{p}_{m,n,n}^i),$$

$$H(\mathbf{s}) = \sum_{i=1}^{N_{\mathrm{F}}} \sum_{m=1}^{K} \sum_{n=1}^{K} s_{m,n}^i, \text{ and } M(\mathbf{s}) = \sum_{i=1}^{N_{\mathrm{F}}} \sum_{m=1}^{K} \sum_{n=1}^{K} (s_{m,n}^i)^2.$$

Suboptimal Solution

- The $F(\tilde{\mathbf{p}})$, $G(\tilde{\mathbf{p}})$, $H(\mathbf{s})$, and $M(\mathbf{s})$ are convex functions and the problem in (10) belongs to the class of difference of convex (d.c.) function programming.
- As a result, we can apply successive convex approximation to obtain a local optimal solution.
- For any feasible point $\tilde{\mathbf{p}}^{(k)}$ and $\mathbf{s}^{(k)}$, we have the following inequalities

$$G(\tilde{\mathbf{p}}) \geq G(\tilde{\mathbf{p}}^{(k)}) + \nabla_{\tilde{\mathbf{p}}} G(\tilde{\mathbf{p}}^{(k)})^T (\tilde{\mathbf{p}} - \tilde{\mathbf{p}}^{(k)}) \text{ and} \tag{11}$$

$$M(\mathbf{s}) \geq M(\mathbf{s}^{(k)}) + \nabla_{\mathbf{s}} M(\mathbf{s}^{(k)})^T (\mathbf{s} - \mathbf{s}^{(k)}). \tag{12}$$

Suboptimal Solution

- Therefore, for any given $\tilde{\mathbf{p}}^{(k)}$ and $\mathbf{s}^{(k)}$, we can obtain an upper bound for (10) by solving the following convex optimization problem:

Suboptimal resource allocation problem:

$$\begin{aligned} \underset{\tilde{\mathbf{p}},\mathbf{s}}{\text{minimize}} \quad & F(\tilde{\mathbf{p}}) - G(\tilde{\mathbf{p}}^{(k)}) - \nabla_{\tilde{\mathbf{p}}} G(\tilde{\mathbf{p}}^{(k)})^T(\tilde{\mathbf{p}} - \tilde{\mathbf{p}}^{(k)}) \\ & +\eta\Big(H(\mathbf{s}) - M(\mathbf{s}^{(k)}) - \nabla_{\mathbf{s}} M(\mathbf{s}^{(k)})^T(\mathbf{s} - \mathbf{s}^{(k)})\Big) \\ \text{s.t.} \quad & \text{C1}, \text{C2b}, \text{C3–C8}, \end{aligned} \tag{13}$$

- The optimization problem in (13) is convex and can be solved efficiently by standard convex program solver such as CVX.
- Then, we employ an iterative algorithm to tighten the upper bound.

Results – Simulation Parameters

Table: System parameters

Carrier center frequency and system bandwidth	2.5 GHz and 5 MHz
The number of subcarriers, N_{F}	64
The bandwidth of each subcarrier	78 kHz
User noise power, σ_m^2	-125 dBm
BS antenna gain	10 dBi

- Baseline scheme 1: suboptimal power and subcarrier allocation scheme in [1]
- Baseline scheme 2: random subcarrier allocation scheme
- Baseline scheme 3: traditional MC-OMA scheme

Results – Average system throughput versus maximum transmit power at the BS

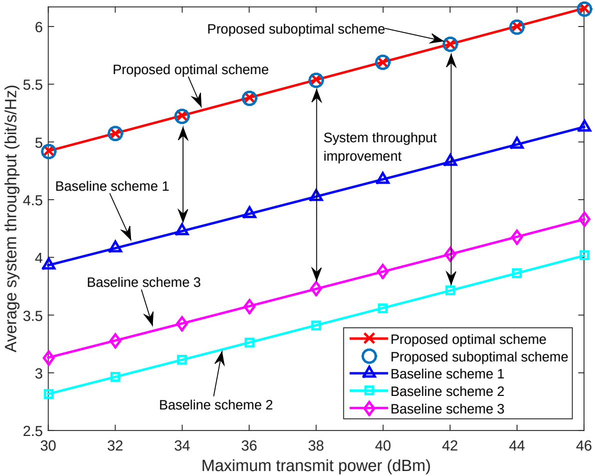


Figure: Average system throughput versus the maximum transmit power at base station.

Results – Average system throughput versus number of users

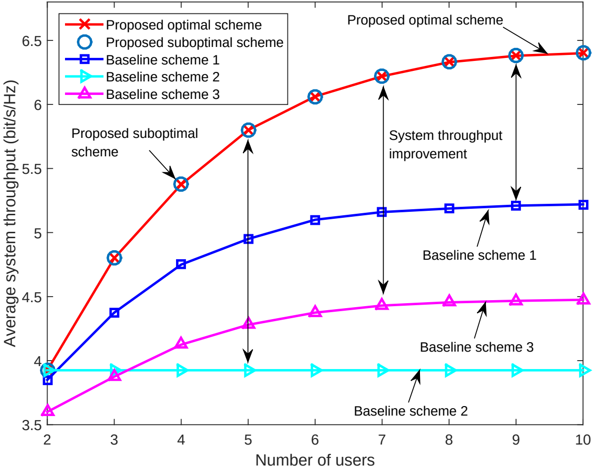


Figure: Average system throughput versus the number of users.

Conclusions

- The resource allocation algorithm for MC-NOMA systems was formulated with the objective to maximize the weighted system throughput
- The proposed problem is solved optimally by using monotonic optimization method
- The low-complexity suboptimal scheme is proposed to achieve close-to-optimal performance
- Simulation results unveiled a significant improvement in system performance compared to conventional MC-OMA system.

Future Work

- Employ NOMA transmission scheme in full-duplex (FD) systems to further improve system throughput.
- Investigate MISO-NOMA system where the BS is equipped with multiple antennas.
- Study resource allocation design for MC-NOMA system where multiplex arbitrary number of users on each subcarrier.
- Study robust resource allocation design for NOMA systems where the channel gains are imperfectly known.
- Study resource allocation design for uplink NOMA systems.

References

[1] (2015) Qualcomm’s 5G Vision. [Online]. Available: https://www.qualcomm.com/invention/technologies/5g

[2] T. Marzetta, “Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas,” *IEEE Trans. Wireless Commun.*, vol. 9, pp. 3590–3600, Nov. 2010.

[3] D. W. K. Ng, E. Lo, and R. Schober, “Energy-Efficient Resource Allocation in OFDMA Systems with Large Numbers of Base Station Antennas,” *IEEE Trans. Wireless Commun.*, vol. 11, pp. 3292 –3304, Sep. 2012.

[4] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, “Optimal Joint Power and Subcarrier Allocation for MC-NOMA Systems,” *accepted for presentation at IEEE Global Commun. Conf. 2016*. [Online]. Available: http://arxiv.org/abs/1503.06021

[5] ——, “Optimal Joint Power and Subcarrier Allocation for Full-Duplex Multicarrier Non-Orthogonal Multiple Access Systems,” *accepted for presentation, TCOM*. [Online]. Available: http://arxiv.org/abs/1503.06021

[6] Z. Wei, D. W. K. Ng, and J. Yuan, "Power-efficient resource allocation for MC-NOMA with statistical channel state information," *CoRR*, vol. abs/1607.01116, 2016. [Online]. Available: http://arxiv.org/abs/1607.01116

[7] Z. Wei, J. Yuan, D. W. K. Ng, M. Elkashlan, and Z. Ding, "A survey of downlink non-orthogonal multiple access for 5g wireless communication networks," *CoRR*, vol. abs/1609.01856, 2016. [Online]. Available: http://arxiv.org/abs/1609.01856

[8] Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, "Multi-Objective Optimization for Robust Power Efficient and Secure Full-Duplex Wireless Communication Systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5511–5526, Aug. 2016.

[9] D. W. K. Ng, Y. Wu, and R. Schober, "Power efficient resource allocation for full-duplex radio distributed antenna networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2896–2911, 2016.

[10] L. Xiang, D. W. K. Ng, R. Schober, and V. W. Wong, "Cache-enabled physical-layer security for video streaming in wireless networks with limited backhaul," *CoRR*, vol. abs/1612.01189, 2016. [Online]. Available: https://arxiv.org/abs/1612.01189

[11] D. Ng, E. Lo, and R. Schober, “Energy-Efficient Resource Allocation in OFDMA Systems with Hybrid Energy Harvesting Base Station,” *IEEE Trans. Wireless Commun.*, vol. 12, pp. 3412–3427, Jul. 2013.

[12] I. Ahmed, A. Ikhlef, D. Ng, and R. Schober, “Power Allocation for an Energy Harvesting Transmitter with Hybrid Energy Sources,” *IEEE Trans. Wireless Commun.*, vol. 12, pp. 6255–6267, Dec. 2013.

[13] L. Varshney, “Transporting Information and Energy Simultaneously,” in *Proc. IEEE Intern. Sympos. on Inf. Theory*, Jul. 2008, pp. 1612 –1616.

[14] D. W. K. Ng, E. S. Lo, and R. Schober, “Robust Beamforming for Secure Communication in Systems With Wireless Information and Power Transfer,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4599–4615, Aug 2014.

[15] P. Grover and A. Sahai, “Shannon Meets Tesla: Wireless Information and Power Transfer,” in *Proc. IEEE Intern. Sympos. on Inf. Theory*, Jun. 2010, pp. 2363 –2367.

[16] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, “Simultaneous Wireless Information and Power Transfer in Modern Communication Systems,” *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 104–110, Nov. 2014.

[17] Z. Ding, C. Zhong, D. W. K. Ng, M. Peng, H. A. Suraweera, R. Schober, and H. V. Poor, “Application of Smart Antenna Technologies in Simultaneous Wireless Information and Power Transfer,” *IEEE Commun. Magazine*, vol. 53, no. 4, pp. 86–93, Apr. 2015.

[18] R. Zhang and C. K. Ho, “MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer,” *IEEE Trans. Wireless Commun.*, vol. 12, pp. 1989–2001, May 2013.

[19] X. Chen, Z. Zhang, H.-H. Chen, and H. Zhang, “Enhancing Wireless Information and Power Transfer by Exploiting Multi-Antenna Techniques,” *IEEE Commun. Magazine*, no. 4, pp. 133–141, Apr. 2015.

[20] D. W. K. Ng, E. S. Lo, and R. Schober, “Dynamic resource allocation in mimo-ofdma systems with full-duplex and hybrid relaying,” *IEEE Trans. Wireless Commun.*, vol. 60, no. 5, pp. 1291–1304, May 2012.

[21] J. Chen, X. Chen, W. H. Gerstacker, and D. W. K. Ng, “Resource allocation for a massive mimo relay aided secure communication,” *IEEE Transactions on Information Forensics and Security*, vol. 11, no. 8, pp. 1700–1711, Aug. 2016.

[22] D. W. K. Ng, E. S. Lo, and R. Schober, “Secure Resource Allocation and Scheduling for OFDMA Decode-and-Forward Relay Networks,” *IEEE Trans. Wireless Commun.*, vol. 10, pp. 3528–3540, Oct. 2011.

[23] Y. Wu, R. Schober, D. W. K. Ng, C. Xiao, and G. Caire, “Secure massive mimo transmission with an active eavesdropper,” *IEEE Trans. Inf. Theory*, vol. 62, no. 7, pp. 3880–3900, Jul. 2016.

[24] E. Boshkovska, D. W. K. Ng, N. Zlatanov, and R. Schober, “Practical Non-Linear Energy Harvesting Model and Resource Allocation for SWIPT Systems,” *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2082–2085, Dec. 2015.

[25] F. Zhang, S. Hackworth, X. Liu, H. Chen, R. Sclabassi, and M. Sun, “Wireless Energy Transfer Platform for Medical Sensors and Implantable Devices,” in *Annual Intern. Conf. of the IEEE Eng. in Med. and Biol. Soc.*, Sep. 2009, pp. 1045–1048.

[26] V. Chawla and D. S. Ha, “An Overview of Passive RFID,” *IEEE Commun. Magazine*, vol. 45, pp. 11–17, Sep. 2007.

Q&A