Int. J. Nonlinear Anal. Appl. 14 (2023) 1, 251–262
ISSN: 2008-6822 (electronic)
http://dx.doi.org/10.22075/ijnaa.2022.27598.3658

Comparison between OMA and PD-NOMA in wireless MIMO system with optimized downlink power allocation

Zaid Hashim Jaber[a,b,*], Dheyaa Jasim Kadhim[c], Ahmed Sabah Al-Araji[a]

[a]*Department of Computer Engineering, University of Technology, Baghdad, Iraq*

[b]*Department of Computer Science, College of Science, University of Baghdad, Baghdad, Iraq*

[c]*Department of Electrical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq*

(Communicated by Mohammad Bagher Ghaemi)

Abstract

Different multiple access methods in wireless communications allow multiple contented stations to share the wireless medium. It can be either orthogonal or non-orthogonal. In orthogonal multiple access (OMA), the channel allocation between the contented stations is orthogonal (either by time, frequency, space or code). This is done to avoid interference between the wireless stations. However, it decreases the performance because the number of simultaneous connections is limited by the orthogonal channel resources, which minimizes the degree of freedom per station. On the other hand, non-orthogonal multiple access (NOMA) allows multiple stations to transmit and receive at the same channel resource time and frequency by using another domain. For example, different power levels for different stations or what is known as PD-NOMA. This paper shows that NOMA can improve the performance of wireless communications even with the presence of interference because each station has a full degree of freedom per resource. Besides, PD-NOMA and MIMO have a good combination by taking advantage of MIMO array gain with non-orthogonal access to improve spectral efficiency. By allocating different power to different stations, different optimization objectives are proposed to maximize the fairness, spectral efficiency, and energy efficiency in the downlink channel.

Keywords: DoF, Energy efficiency, Fairness, OMA, PD-NOMA, Spectral efficiency
2020 MSC: 94A10; 94A99

1 Introduction

In the few recent years, the wireless communications have an exponential growth to support different types of applications such as Internet of Things (IoT) [2, 11, 8, 18, 20, 21], Augmented Reality (AR) [18, 21], Machine-to-Machine (M2M) [8, 19, 26] and Wireless Sensor Network (WSN) [9, 12, 20]. That is why the wireless networks have many challenges to offer better performance for these applications including better throughput, latency and a higher number of connections. Multiple station connectivity can be implemented by using different techniques of multiplexing [22]. Most known multiplexing methods such as TDMA, FDMA, CDMA and SDMA are orthogonal which means that the number of active connections is limited to the number of available channel resources in time, frequency, code

*Corresponding author
Email addresses: ce.19.18@grad.uotechnology.edu.iq (Zaid Hashim Jaber), dheyaa@coeng.uobaghdad.edu.iq (Dheyaa Jasim Kadhim), ahmed.s.alaraji@uotechnology.edu.iq (Ahmed Sabah Al-Araji)

Received: March 2022 *Accepted:* May 2022

or space to avoid the interference [8]. For example, Multi-User MIMO (MU-MIMO) [4, 14] is one of the wireless communications multiplexing methods that offer better multiplexing gain by allowing multiple users to share the channel simultaneously using beamforming but the number of active stations is still limited by the number of antenna units at the BS. Besides, the MU-MIMO technique provides array gain because of the existence of multiple antennae. Massive MIMO [5, 13, 17] which is an evolved version of MU-MIMO with a massive number of antenna units and it is one of the most important techniques proposed in 5G. Massive MIMO provides even higher spectral efficiency and energy efficiency but the number of active stations at any time is still limited by the number of the antenna units as with other MIMO techniques.

, On the other hand, NOMA is another multiplexing method [22]. Unlike orthogonal multiplexing, the number of active stations is not limited by channel resources. A single channel resource (frequency, time, space and code) can be shared among several wireless stations which leads to higher throughput, lower latency and massive connectivity. One type of NOMA is implemented in the power domain [1, 10, 15, 22]. In PD-NOMA, successive interference cancellation (SIC) [7, 22, 28] is used in the uplink transmission from the wireless stations to the BS to successively estimate the signal of the strongest station with the highest received power while treating the signals of the weaker stations with lower received power as noise. Then, the strongest signal is subtracted from the overall signal to successively estimate the next strongest signal and so on. While in the downlink transmission from the BS to the wireless stations, SIC with superposition coding (SC-SIC) [22, 28] is used to encode the overall downlink signal. Downlink power is allocated inversely which means that a higher power is allocated to the weakest station. The weakest wireless station receives the overall signal and treats the signal of other stations as noise. But for other stations, the signal of the weaker stations (with higher downlink power allocation) must be subtracted successively and the signals of the stronger stations (with lower downlink power allocation) are treated as noise to estimate the desired downlink signal for each station.

The motivation of this paper is to propose a combination of MIMO and PD-NOMA wireless systems to increase the density of simultaneously active connections by sharing the same channel resources through the non-orthogonal channel access in the power domain as well as improve the system performance by taking the advantage of array gain in MIMO which increases both of the spectral efficiency and energy efficiency. The results of this paper show that PD-NOM has better DoF than OMA. Also, different optimization objectives are proposed for downlink power allocations of different stations to maximize either the fairness, the spectral efficiency or the energy efficiency as shown in the results.

2 Preliminaries

2.1 Uplink Transmission

For PD-NOMA uplink transmission from K stations each equipped with a single antenna to the BS equipped with M antenna units can be represented as:

$$\mathbf{y}_{ul} = \sum_{k=1}^{K} \sqrt{p_{ul}\alpha_k}\mathbf{h}_k x_{ul,k} + \mathbf{n} \tag{2.1}$$

where $\mathbf{y}_{ul} = [y_{ul,1} \dots y_{ul,M}]^T$. p_{ul} is the uplink transmitted power of each station. α_k is the large scale fading value and it must follow that $\alpha_1 > \alpha_2 > \dots > \alpha_K$. $\mathbf{h}_k = [h_{k,1} \dots h_{k,M}]^T$ is the small scale fading vector for M antenna at the BS with zero mean and unit variance and $x_{ul,k}$ is the transmitted signal from station k with zero mean and unit variance and $\mathbf{n} = [n_{ul,1} \dots n_{ul,M}]^T$ is the additive noise vector.

At the BS, to reconstruct the signals of all stations, this must be done successively from the strongest signal to weaker signal as:

$$\hat{x}_{ul,k} = \arg\min_{x \in X} \|\mathbf{y}_{ul,k} - \sqrt{p_{ul}\alpha_k}\mathbf{h}_k x\|^2 \tag{2.2}$$

Then this process is repeated for the next strongest signal as:

$$\mathbf{y}_{ul,k+1} = \mathbf{y}_{ul,k} - \sqrt{p_{ul}\alpha_k}\mathbf{h}_k \hat{x}_{ul,k} \tag{2.3}$$

From equations (2.2) and (2.3), each estimated signal treats the weaker signals as interference. Thus the uplink signal to interference and noise ratio ($SINR$) for each station with normalized noise power becomes:

$$\gamma_{ul,k} = \begin{cases} \frac{p_{ul}\beta_k}{1+p_{ul}\sum_{k'=k+1}^{K}\beta_{k'}}, & k < K \\ p_{ul}\beta_K, & k = K \end{cases} \tag{2.4}$$

where $\beta_k = \alpha_k \left\|\mathbf{h}_k\right\|^2$ is the channel gain.

Using Shannon theory, the uplink rate of station k is:

$$R_{ul,k}^{NOMA} = \log_2(1 + \gamma_{ul,k}) \tag{2.5}$$

From equations (2.4) and (2.5), the uplink spectral efficiency is:

$$SE_{ul}^{NOMA} = \sum_{k=1}^{K} R_{ul,k}^{NOMA}$$

$$= \sum_{k=1}^{K-1} \log_2(1 + \frac{p_{ul}\beta_k}{1 + p_{ul}\sum_{k'=k+1}^{K}\beta_{k'}}) + \log_2(1 + p_{ul}\beta_K) \tag{2.6}$$

Equation (2.6) can be simplified as:

$$SE_{ul}^{NOMA} = \log_2(1 + p_{ul}\sum_{k=1}^{K}\beta_k) \tag{2.7}$$

Equation (2.7) shows that the uplink spectral efficiency using PD-NOMA is proportional to the logarithm of the channel gain sum of all stations. So, increasing the number of the stations increases the uplink spectral efficiency.

On the contrary, the uplink rate of the station k using the OMA uplink transmission from K stations each equipped with a single antenna to the BS equipped with M antenna can be represented as [23, 24, 25]:

$$R_{ul,k}^{OMA} = d_{ul,k}\log_2(1 + \frac{p_{ul}\beta_k}{d_{ul,k}}) \tag{2.8}$$

where $d_{ul,k}$ is the uplink DoF of the kth station which represents the fraction of the resource allocated to the station k such that $0 \le d_{ul,k} \le 1$ and $\sum_{k=1}^{K} d_{ul,k} \le 1$.

The uplink spectral efficiency for K stations using OMA can be represented as [23, 24, 25]:

$$SE_{ul}^{OMA} = \sum_{k=1}^{K} R_{ul,k}^{OMA} = \sum_{k=1}^{K} d_{ul,k}\log_2(1 + \frac{p_{ul}\beta_k}{d_{ul,k}}) \tag{2.9}$$

For equally DoF for all stations ($d_{ul,k} = 1/K$, $\forall k \in K$), the spectral efficiency becomes as [24, 25]:

$$SE_{ul}^{OMA-Eq.} = \frac{1}{K}\sum_{k=1}^{K}\log_2(1 + Kp_{ul}\beta_k) \tag{2.10}$$

The value of $d_{ul,k}$ can be optimized as [23]:

$$d_{ul,k}^{*} = \frac{\beta_k}{\sum_{k'=1}^{K}\beta_{k'}} \tag{2.11}$$

Then the optimized uplink spectral efficiency using OMA becomes as [23]:

$$SE_{ul}^{OMA-Opt.} = \log_2(1 + p_{ul}\sum_{k=1}^{K}\beta_k) \tag{2.12}$$

By comparing equations (2.7) with equations (2.10) and (2.12), the spectral efficiency $SE_{ul}^{NOMA} > SE_{ul}^{OMA-Eq.}$ and $SE_{ul}^{NOMA} = SE_{ul}^{OMA-Opt.}$ but still PD-NOMA has better DoF than OMA methods.

2.2 Downlink Transmission

The overall downlink signal vector from the M antenna BS to the K stations can be given as:

$$\mathbf{x}_{dl} = \sum_{k=1}^{K} \sqrt{\eta_k}\mathbf{x}_{dl,k} \tag{2.13}$$

where η_k is the downlink power constraint coefficient such that $0 \le \eta_k \le 1$ and $\sum_{k=1}^{K} \eta_k \le 1$. $\mathbf{x}_{dl,k} = [x_{dl,k,1} \ldots x_{dl,k,M}]^T$ is the downlink signal vector from the BS to the station k with zero mean and unit variance.

For PD-NOMA, the received signal by the station k is:

$$y_{dl,k} = \sqrt{p_{dl}\alpha_k}\mathbf{h}_k^T\mathbf{x}_{dl} + n = \sum_{k'=1}^{K} \sqrt{\eta_{k'} p_{dl}\alpha_k}\mathbf{h}_k^T\mathbf{x}_{dl,k'} + n \tag{2.14}$$

where p_{dl} is the downlink power transmitted by the BS and n is the additive noise.

Each station estimates its signal by estimating the higher power allocated signals (weaker stations) then subtracting them as well as treating the lower power allocated signals (stronger stations) as noise. The downlink $SINR$ for each station with normalized noise power is:

$$\gamma_{dl,k} = \begin{cases} p_{dl}\eta_1\beta_1 \,, & k = 1 \\ \frac{p_{dl}\eta_k\beta_k}{1+p_{dl}\beta_k \sum_{k'=1}^{k-1}\eta_{k'}} \,, & k > 1 \end{cases} \tag{2.15}$$

Using Shannon theory, the downlink rate of the station k is:

$$R_{dl,k}^{NOMA} = \log_2(1 + \gamma_{dl,k}) \tag{2.16}$$

From equations (2.15) and (2.16), the downlink spectral efficiency becomes:

$$SE_{dl}^{NOMA} = \sum_{k=1}^{K} R_{dl,k}^{NOMA}$$

$$= \log_2(1 + p_{dl}\eta_1\beta_1) + \sum_{k=2}^{K} \log_2(1 + \frac{p_{dl}\eta_k\beta_k}{1 + p_{dl}\beta_k \sum_{k'=1}^{k-1}\eta_{k'}}) \tag{2.17}$$

For high downlink power ($p_{dl} \to \infty$) and by applying the downlink power constraint ($\sum_{k=1}^{K} \eta_k \le 1$), the downlink spectral efficiency in equation can be approximated as:

$$SE_{dl}^{NOMA} \approx \log_2(p_{dl}\beta_1) \tag{2.18}$$

Equation (2.18) shows that with high downlink power, the spectral efficiency is mainly affected by the channel gain of the strongest station.

The values of downlink power coefficients (η_1, η_2, ... η_K) can be set to optimize the downlink power allocation for the stations to maximize the fairness, the spectral efficiency or the energy efficiency.

On other side, the uplink rate of the station k using the OMA downlink transmission from the BS equipped with M antenna to K stations each equipped with a single antenna can be represented as [16, 29]:

$$R_{dl,k}^{OMA} = d_{dl,k} \log_2(1 + \frac{p_{dl}\eta_k\beta_k}{d_{dl,k}}) \tag{2.19}$$

As with uplink rate in equation (2.8), $d_{dl,k}$ is the downlink DoF of the station $k$which represents the fraction of the resource allocated by the BS to the station k such that $0 \le d_{dl,k} \le 1$ and $\sum_{k=1}^{K} d_{dl,k} \le 1$.

The downlink spectral efficiency for K stations using OMA can be represented as [16, 29]:

$$SE_{dl}^{OMA} = \sum_{k=1}^{K} R_{dl,k}^{OMA} = \sum_{k=1}^{K} d_{dl,k} \log_2(1 + \frac{p_{dl}\eta_k\beta_k}{d_{dl,k}}) \tag{2.20}$$

For equally DoF and equally power allocation for all stations ($d_{ul,k} = 1/K$ and $\eta_k = 1/K,\ \forall k \in K$), the spectral efficiency becomes as:

$$SE_{dl}^{OMA-Eq.} = \frac{1}{K}\sum_{k=1}^{K} \log_2(1 + p_{dl}\beta_k) \tag{2.21}$$

The value of $d_{dl,k}$ can be optimized as [16, 29]:

$$d_{dl,k}^{*} = \frac{\beta_k}{\sum_{k'=1}^{K} \beta_{k'}} \tag{2.22}$$

Then the downlink spectral efficiency for eqaully downlink power allocation becomes as:

$$SE_{dl}^{OMA-Opt.1} = \log_2(1 + \frac{p_{dl}\sum_{k'=1}^{K} \beta_{k'}}{K}) \tag{2.23}$$

To even improve the downlink spectral efficiency using OMA, let $\eta_k = d_{dl,k}^{*}$. The spectral efficiency is then:

$$SE_{dl}^{OMA-Opt.2} = \sum_{k=1}^{K} d_{dl,k}^{*} \log_2(1 + p_{dl}\beta_k) \tag{2.24}$$

By comparing equations (2.18) with equations (2.21), (2.23) and (2.24) considering high downlink power, PD-NOMA has better DoF and spectral efficiency than OMA methods.

2.3 Proposed Downlink Power Allocation Optimization for PD-NOMA

2.3.1 Fairness Maximization

The fairness of the downlink transmission is maximized by maximizing the minimum rate among all stations [3, 6, 27, 30]. The optimization function is then:

$$\max_{\forall \eta_k} \min(R_{dl,1}^{NOMA},\ \dots,\ R_{dl,K}^{NOMA})\ \ s.t.\ \eta_1 > 0,\ \eta_{k+1} \geq \frac{1}{\mu}\sum_{k'=1}^{k} \eta_{k'},\ \sum_{k=1}^{K} \eta_k \leq 1 \tag{2.25}$$

where $1/\mu$ is the accepted interference level to estimate the desired signal. μ has to be greater than or equal to one to guarantee that the interference power level does not exceed the desired signal power level.

The best way to achieve a higher fairness is by having equal SINR for all stations as:

$$s = \gamma_{dl,1} = \gamma_{dl,2} = \dots = \gamma_{dl,K} \tag{2.26}$$

The downlink power coefficient value is then:

$$\eta_k^{*} = \begin{cases} \frac{s}{p_{dl}\beta_1}\ , & k = 1 \\ (\frac{1}{p_{dl}\beta_k} + \sum_{k'=1}^{k-1} \eta_{k'}^{*})s\ , & k > 1 \end{cases} \tag{2.27}$$

By using the power constraint $\sum_{k=1}^{K} \eta_k^{*} = 1$ and substituting the values of η_k^{*} in term of s, we get a K-orders polynomial equation of s. Then, the optimal value of s is the largest real value root of this polynomial equation.

For simple scenario consisting of two stations only, equation (2.26) can be given by:

$$s = \gamma_{dl,1} = \gamma_{dl,2} \tag{2.28}$$

Then from equation (2.28), power constraints coefficients are:

$$\eta_1^{*} = \frac{s}{p_{dl}\beta_1} \tag{2.29}$$

$$\eta_2^* = \frac{s^2}{p_{dl}\beta_1} + \frac{s}{p_{dl}\beta_2} \tag{2.30}$$

Since $\eta_1^* + \eta_2^* = 1$, we get:

$$s^2 + (1 + \frac{\beta_1}{\beta_2})s - p_{dl}\beta_1 = 0 \tag{2.31}$$

Then the optimal value of s is for two stations is the largest real value root of equation (2.31) as:

$$s = -\frac{1}{2}(1 + \frac{\beta_1}{\beta_2}) + \frac{1}{2}\sqrt{(1 + \frac{\beta_1}{\beta_2})^2 + 4p_{dl}\beta_1} \tag{2.32}$$

The optimal power constraint coefficients in equation (2.27) must follow the constraint functions in optimization equation (2.25). Otherwise, the optimal power constraint coefficients can be obtained using other objective functions as in the upcoming subsections.

After computing the downlink power coefficients, the fairness for K stations can be measured by using Jain's equation as:

$$fairness = \frac{(\sum_{k=1}^{K} \gamma_k)^2}{K \sum_{k=1}^{K} \gamma_k^2} \tag{2.33}$$

From equation (2.33), the maximum value of $fairness$ is equal to one when all stations are allowed to access the channel with the same downlink $SINR$. On the contrary, the lower value of $fairness$ is $1/K$ with only one active station is allowed to access the channel while other stations remain idle which is the case of the orthogonal access. In summary, the fairness maximization is achieved when $fairness$ approaches to one.

2.3.2 Spectral Efficiency Maximization

The maximum downlink spectral efficiency is achieved by allocating all of the downlink power to the station that has the strongest channel gain. But other stations become idle which is against the main principle of NOMA with multiple stations can share the downlink channel resources. Besides, this leads to the worst possible fairness. To avoid this situation, the interference level $(1/\mu)$ constraint must be included in the optimization objective function as:

$$\max_{\forall \eta_k} SE_{dl}^{NOMA} \;\; s.t. \;\; \eta_1 > 0, \; \eta_{k+1} \geq \frac{1}{\mu}\sum_{k'=1}^{k} \eta_{k'}, \; \sum_{k=1}^{K} \eta_k \leq 1 \tag{2.34}$$

The Lagrange multiplier function is then:

$$\begin{aligned}\mathcal{L}(\eta_1, ..., \eta_K, \lambda_0, ..., \lambda_K) = \log_2(1 + p_{dl}\eta_1\beta_1) + \sum_{k=2}^{K} \log_2(1 + \frac{p_{dl}\eta_k\beta_k}{1 + p_{dl}\beta_k \sum_{k'=1}^{k-1} \eta_k'}) \\ + \lambda_0\eta_1 + \sum_{k=1}^{K} \lambda_k(\eta_{k+1} - \frac{1}{\mu}\sum_{k'=1}^{k-1} \eta_{k'}) + \lambda_K(1 - \sum_{k=1}^{K} \eta_k)\end{aligned} \tag{2.35}$$

where $\lambda_0, ..., \lambda_K$ are the Lagrange multipliers.

To simplify the Lagrange function, let $q_k = \sum_{k'=1}^{k} \eta_{k'}$. Then, the objective function can be written as:

$$\max_{\forall q_k} SE_{dl}^{NOMA} \;\; s.t. \;\; q_1 > 0, \; q_{k+1} \geq (1 + \frac{1}{\mu})q_k, \; q_K \leq 1 \tag{2.36}$$

The Lagrange multiplier function is then:

$$\begin{aligned}\mathcal{L}(q_1, ..., q_K, \lambda_0, ..., \lambda_K) = \sum_{k=1}^{K-1} (\log_2(1 + p_{dl}q_k\beta_k) - \log_2(1 + p_{dl}q_k\beta_{k+1})) + \log_2(1 + p_{dl}q_K\beta_K) \\ + \lambda_0 q_1 + \sum_{k=1}^{K} \lambda_k(q_{k+1} - (1 + \frac{1}{\mu})q_k) + \lambda_K(1 - q_K)\end{aligned} \tag{2.37}$$

From equation (2.37), the optimal value of q_k is:

$$q_k^* = (\frac{\mu}{1+\mu})^{K-k} \tag{2.38}$$

Finally, the optimal value of η_k is:

$$\eta_k^* = \begin{cases} q_1^* = (\frac{\mu}{1+\mu})^{K-1}, & k=1 \\ q_k^* - q_{k-1}^* = \frac{1}{\mu}(\frac{\mu}{1+\mu})^{K-k+1}, & k>1 \end{cases} \tag{2.39}$$

2.3.3 Energy Efficiency Maximization

The optimization function to maximize the energy efficiency for PD-NOMA system is:

$$\max_{\forall q_k} \frac{B \cdot SE_{dl}^{NOMA}}{p_c + p_{dl} q_K} \;\; s.t. \;\; q_1 > 0, \; q_{k+1} \geq (1+\frac{1}{\mu})q_k, \; q_K \leq 1 \tag{2.40}$$

where B is the channel bandwidth, p_c is a fixed circuit power of the BS and $q_k = \sum_{k'=1}^{k} \eta_{k'}$.

The Lagrange multiplier function is then:

$$\begin{aligned} \mathcal{L}(q_1, ..., q_K, \lambda_0, ..., \lambda_K) = \frac{B \cdot SE_{dl}^{NOMA}}{p_c + p_{dl} q_K} (\sum_{k=1}^{K-1} (\log_2(1+p_{dl} q_k \beta_k) - \log_2(1+p_{dl} q_k \beta_{k+1})) \\ + \log_2(1+p_{dl} q_K \beta_K) + \lambda_0 q_1 + \sum_{k=1}^{K} \lambda_k (q_{k+1} - (1+\frac{1}{\mu})q_k) + \lambda_K(1-q_K)) \end{aligned} \tag{2.41}$$

By setting $\bigtriangledown_{q_K} \mathcal{L}(q_1, ..., q_K, \lambda_0, ..., \lambda_K)$ to zero, we get (if $K > 1$):

$$p_c \beta_K + p_{dl} q_K \beta_K - (1 + p_{dl} q_K \beta_K) \ln(\frac{\prod_{k=1}^{K} (1+p_{dl} q_k \beta_k)}{\prod_{k=2}^{K} (1+p_{dl} q_k \beta_k)}) = 0 \tag{2.42}$$

The equation (2.42) is valid only if $K > 1$. For $K = 1$, we get:

$$p_c \beta_1 + p_{dl} q_1 \beta_1 - (1 + p_{dl} q_1 \beta_1) \ln(1 + p_{dl} q_1 \beta_1) = 0 \tag{2.43}$$

The solution of equation (2.43) is:

$$\hat{q}_K = \hat{q}_1 = \frac{e^{(W(\frac{p_c \beta_1 - 1}{e})+1)} - 1}{p_{dl} \beta_1} \tag{2.44}$$

where $W(\cdot)$ is the Lambert W function such that $z = W(ze^z)$.

For K stations in general, this value $\hat{q}_K$ gives an optimal energy efficiency for $K = 1$ and sub-optimal energy efficiency for $K > 1$. To even improve the energy efficiency, we propose a modified version of $\hat{q}_K$ as:

$$\hat{q}_K = \frac{e^{(W(\frac{p_c \beta_K - 1}{e})+1)} - 1}{p_{dl} \beta_K} \tag{2.45}$$

The value of $\hat{q}_K$ is suboptimal for maximizing the energy efficiency but it must follow the downlink power constraint which is $q_K \leq 1$, then the optimal value is:

$$q_K^* = \min(\hat{q}_K, 1) \tag{2.46}$$

Finally, the optimal value of η_k is:

$$\eta_k^* = \begin{cases} q_K^* (\frac{\mu}{1+\mu})^{K-1}, & k=1 \\ \frac{q_K^*}{\mu} (\frac{\mu}{1+\mu})^{K-k+1}, & k>1 \end{cases} \tag{2.47}$$

3 Results

As mentioned previously, PD-NOMA has better DoF compared with OMA. With PD-NOMA, all of the channel resource (time or frequency) is allocated to all the stations simultaneously. On the other hand, a fraction of the channel resource is allocated to each station depending on its DoF. Because of that, the main advantage of NOMA over OMA is to allow multiple stations access within the same channel resource which improves the overall throughput and reduces the access delay. Figure 1 shows the DoF of PD-NOMA (uplink and downlink) versus OMA with equally DoF for all stations and OMA with optimized DoF from equations (2.11) and (2.22) with respect to the number of the stations and each station has a large scale fading value $\alpha_k = 1/2^{k-1}$.

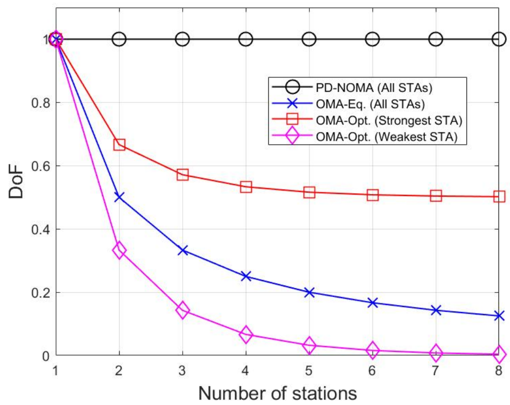


Figure 1: PD-NOMA vs. OMA DoF

Figure 1 shows that all stations have a full DoF with PD-NOMA. While OMA with equally DoF stations, the DoF decreases when increasing the number of contented stations. In the Final case which is OMA with optimized DoF, the DoF of the weakest approaches to zero especially when $\beta_{strongest} \gg \beta_{weakest}$ which means that the weakest station has mostly no channel allocation.

The uplink spectral efficiency of PD-NOMA versus OMA (equally DoF and optimized DoF) is shown in Figure 2 when each station has $p_{ul} = 22\, dB$ and $\alpha_k = 1/2^{k-1}$ using a different number of antenna units (M) at the BS.

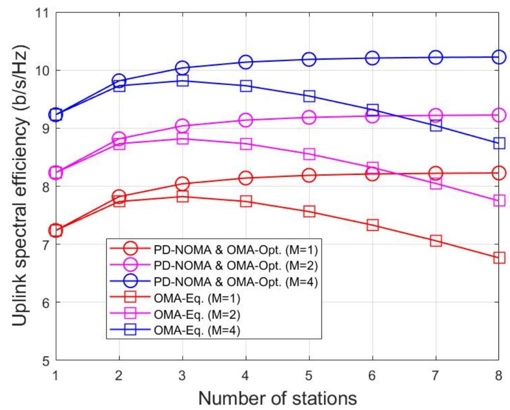


Figure 2: Uplink spectral efficiency

Figure 2 shows that the uplink spectral efficiency is improved using PD-NOMA over OMA with equal DoF for all stations given by equation (2.10). The only case that the maximum uplink spectral efficiency approaches the uplink spectral efficiency of PD-NOMA is when DoF is optimized as in equation (2.12) which has very low DoF for the weakest station. Also, the spectral efficiency is increased in MIMO systems while increasing the number of antenna units (M) at the BS because of the array gain. Moreover, the number of the active stations using PD-NOMA can exceed the number of antenna units at the BS which means that PD-NOMA has better connectivity over the MIMO linear processing like maximum rate combining (MRC) and zero-forcing (ZF) because the number of the active stations using these techniques are limited by the number of antenna units at the BS.

The percentage of the uplink spectral efficiency of PD-NOMA over OMA with equally DoF is illustrated in Table 1.

Table 1: Uplink spectral efficiency improvement of PD-NOMA over OMA with equally DoF stations

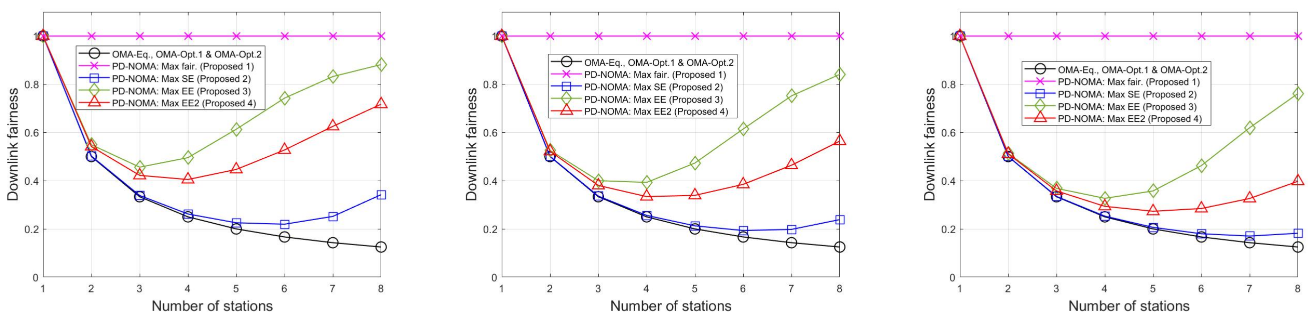
No. of stations	PD-NOMA vs. OMA-Eq. M=1	M=2	M=4
2	1.088%	0.969%	0.871%
3	2.819%	2.511%	2.261%
4	5.208%	4.637%	4.171%
5	8.270%	7.349%	6.601%
6	12.013%	10.651%	9.544%
7	16.453%	14.554%	13.009%
8	21.610%	19.077%	17.007%

For the downlink transmission using PD-NOMA, the downlink power must be allocated to each station based on their channel gain. While in OMA, a fraction of channel resource (DoF) is allocated to each station as well as the downlink power is allocated to each of them. In this work, we purposed three optimization objectives for downlink power allocation: fairness maximization, spectral efficiency maximization and energy efficiency maximization. Using parameters in Table 2, the results in Figures 4, 5 and 6 show the performance of PD-NOMA with different optimized objectives compared with OMA in different cases (OMA-Eq., OMA-Opt. 1 and OMA Opt.2 from equations (2.21), (2.23) and (2.24) respectively) in MIMO system when the BS equipped with M antennas (M=1, 2 and 4).

Table 2: Downlink transmission parameters

Parameter	Value
p_{dl}	30 dB
α_k	$1/2^{k-1}$
μ	1
B	20 MHz
p_c	20 dB

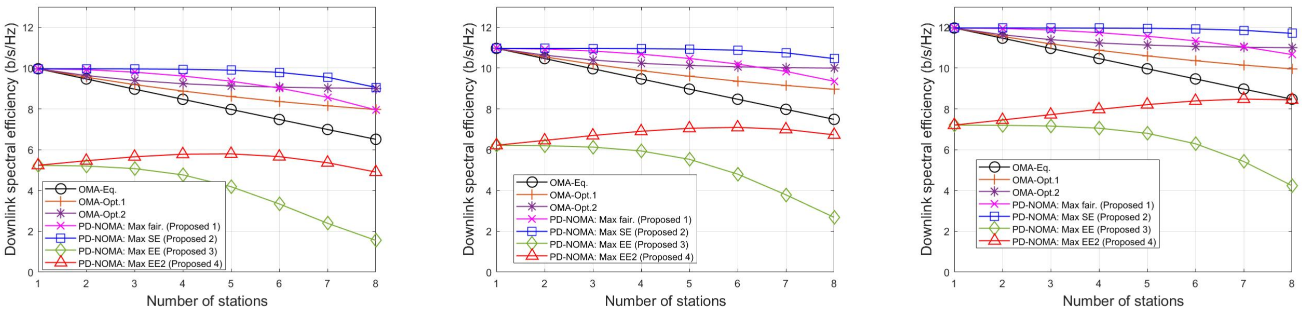
Figure 3 shows the fairness of the downlink transmission. PD-NOMA has better fairness over OMA because of the absence of multiple active stations per channel resource. The downlink power allocation coefficients with fairness maximization guarantee a 100% $fairness$ for all stations over the channel in spite of the number of active stations (all stations access the channel simultaneously and all of them have the same $SINR$).



(a) $M = 1$ (b) $M = 2$ (c) $M = 4$

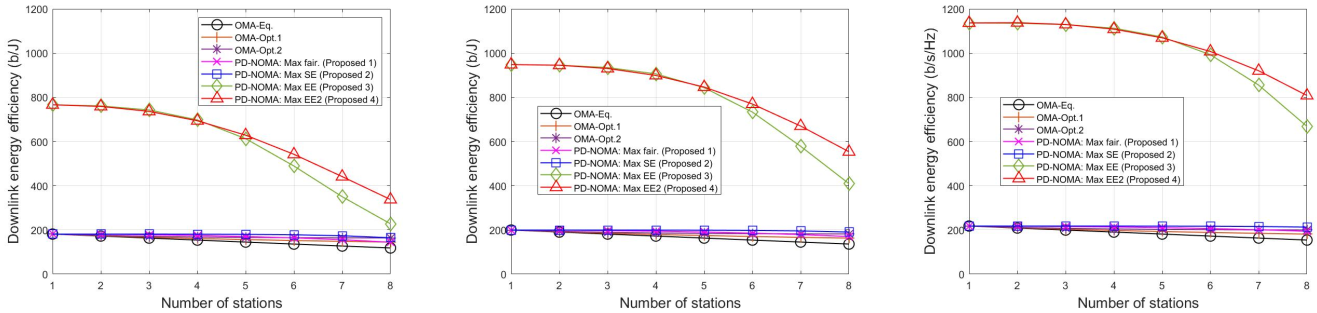
Figure 3: Downlink fairness

Figure 4 shows the spectral efficiency of the downlink transmission of PD-NOMA versus OMA. PD-NOMA with spectral efficiency maximization objective has better downlink spectral efficiency than other cases. While PD-NOMA with energy efficiency maximization objectives have lower spectral efficiency because the downlink power is not fully allocated ($q_k^* = \sum_{k=1}^{K} \eta_k < 1$) as given by equations (2.44) and (2.45) to achieve higher energy efficiency and as shown in Figure 5. Also, both the spectral efficiency and the energy efficiency are increased when increasing the number of antenna units at the BS because of the array gain.



(a) $M = 1$ (b) $M = 2$ (c) $M = 4$

Figure 4: Downlink spectral efficiency



(a) $M = 1$ (b) $M = 2$ (c) $M = 4$

Figure 5: Downlink energy efficiency

Moreover, the percentage of the downlink spectral efficiency improvement of PD-NOMA with spectral efficiency maximization over OMA methods is illustrated in Table 3.

Table 3: Downlink spectral efficiency improvement of PD-NOMA over OMA methods

No. of stations	PD-NOMA vs. OMA methods								
	OMA-Eq.			OMA-Opt.1			OMA-Opt.2		
	$M=1$	$M=2$	$M=4$	$M=1$	$M=2$	$M=4$	$M=1$	$M=2$	$M=4$
2	5.259%	4.766%	4.356%	4.324%	3.924%	3.589%	3.440%	3.126%	2.862%
3	11.049%	9.986%	9.098%	8.373%	7.591%	6.931%	5.995%	5.457%	4.996%
4	17.375%	15.692%	14.263%	12.026%	10.939%	9.993%	7.662%	7.038%	6.470%
5	24.124%	21.867%	19.870%	15.075%	13.873%	12.733%	8.408%	7.926%	7.374%
6	30.882%	28.356%	25.880%	17.082%	16.193%	15.070%	8.004%	8.077%	7.758%
7	36.592%	34.695%	32.111%	17.143%	17.456%	16.801%	5.803%	7.218%	7.541%
8	39.082%	39.757%	38.050%	13.661%	16.762%	17.479%	0.569%	4.654%	6.403%

4 Conclusion

This paper discusses the importance of PD-NOMA as a promising technology for wireless communications that increases the number of active connections even with a limited number of channel resources. This leads to enhanced performance of the wireless communications compared with the conventional OMA methods by increasing the DoF of the stations. Moreover, the spectral efficiency and spectral efficiency are improved when using PD-NOMA with MIMO, especially when the channel gain difference between stations becomes higher. The PD-NOMA in MIMO has a big advantage due to the higher connectivity and the array gain. In this paper, the uplink and downlink transmission of PD-NOMA versus OMA in MIMO systems are discussed and analyzed. Besides, different optimization objectives are proposed for downlink power allocation in the downlink transmission. The results of this paper show that PD-NOMA has better performance than OMA methods in many aspects, like fairness, spectral efficiency, and energy efficiency, especially when it is combined with MIMO.

References

[1] A. Akbar, S. Jangsher and F.A. Bhatti, *NOMA and 5G emerging technologies: A survey on issues and solution techniques*, Comput. Networks **190** (2021), 107950.

[2] N. Alkhazaali, R. Aljiznawi, S. Jabbar and D. Kadhim, *Mobile communication through 5G technology (Challenges and Requirements)*, Int. J. Commun. Network Syst. Sci. **10** (2017), no. 5, 202–207.

[3] M. S. Ali, H. Tabassum and E. Hossain, *Dynamic user clustering and power allocation for uplink and downlink non-orthogonal multiple access (NOMA) systems*, IEEE Access **4** (2016), 6325–6343.

[4] B. Bellalta, J. Barcelo, D. Staehle, A. Vinel and M. Oliver, *On the performance of packet aggregation in IEEE 802.11ac MU-MIMO WLANs*, IEEE Commun. Lett. **16** (2012), no. 10, 1588–1591.

[5] E. Björnson, J. Hoydis and L. Sanguinetti, *Massive MIMO has unlimited capacity*, IEEE Trans. Wireless Commun. **17** (2018), no. 1, 574–590.

[6] J. Choi, *Power allocation for Max-Sum rate and Max-Min rate proportional fairness in NOMA*, IEEE Commun. Lett. **20** (2016), no. 10, 2055–2058.

[7] Z. Ding, R. Schober and H. V. Poor, *Unveiling the importance of SIC in NOMA systems—part 1: State of the art and recent findings*, IEEE Commun. Lett. **24** (2020), no. 11, 2373–2377.

[8] W. Ejaz, A. Anpalagan, M. A. Imran, M. Jo, M. Naeem, S. B. Qaisar, and W. Wang, *Internet of Things (IoT) in 5G Wireless Communications*, IEEE Access **4** (2016), 10310-10314.

[9] S. Q. Jabbar and D. J. Kadhim, *IA proposed adaptive bitrate scheme based on bandwidth prediction algorithm for smoothly video streaming*, J. Engin. **27** (2021), no. 1, 112-–129.

[10] Z.H. Jaber, D.J. Kadhim and A.S. Al-Araji, *Medium access control protocol design for wireless communications and networks review*, Int. J. Electric. Comput. Engin. **12** (2022), no. 2, 1711–1723.

[11] D.J. Kadhim and O.A. Hamad, *Improving IoT applications using a proposed routing protocol*, J. Engin. **20** (2014), no. 11, 50—62.

[12] H.I. Kobo, A.M. Abu-Mahfouz and G.P. Hancke, *A survey on software-defined wireless sensor networks: Challenges and design requirements*, IEEE Access **5** (2017), 1872–1899.

[13] E.G. Larsson, O. Edfors, F. Tufvesson and T.L. Marzetta, *Massive MIMO for next generation wireless systems*, IEEE Commun. Mag. **52** (2014), no. 2, 186–195.

[14] R. Liao, B. Bellalta, M. Oliver and Z. Niu, *MU-MIMO MAC Protocols for Wireless Local Area Networks: A Survey*, IEEE Commun. Surveys Tutor. **18** (2016), no. 1, 162–183.

[15] M. Liaqat, K.A. Noordin, T. Abdul Latef and K. Dimyati, *Power-domain non orthogonal multiple access (PD-NOMA) in cooperative networks: an overview*, Wireless Networks **26** (2020), no. 1, 181–203.

[16] Y. Liu, G. Pan, H. Zhang and M. Song, *On the capacity comparison between MIMO-NOMA and MIMO-OMA*, IEEE Access **4** (2016), 2123–2129.

[17] T.L. Marzetta and H.Q. Ngo, *Fundamentals of massive MIMO*, Cambridge University Press, Cambridge, UK, 2016.

[18] Q. V. Pham, F. Fang, V.N. Ha, M.J. Piran, M. Le, L.B. Le, W.J. Hwang and Z. Ding, *A survey of multi-access edge computing in 5G and beyond: Fundamentals, technology integration, and state-of-the-art*, IEEE Access **8** (2020), 116974–117017.

[19] J. W. Raymond, T.O. Olwal and A.M. Kurien, *Cooperative communications in machine to machine (M2M): Solutions, challenges and future work*, IEEE Access **6** (2018), 9750–9766.

[20] K. Shafique, B.A. Khawaja, F. Sabir, S. Qazi and M. Mustaqim, *Internet of things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios*, IEEE Access **8** (2020), 23022–23040.

[21] S.K. Sharma, I. Woungang, A. Anpalagan and S. Chatzinotas, *Toward tactile iInternet in beyond 5G era: Recent advances, current issues, and future directions*, IEEE Access **8** (2020), 56948–56991.

[22] M. Vaezi, Z. Ding and H.V. Poor, *Multiple access techniques for 5G wireless networks and beyond*, Springer, Cham, Switzerland, 2019.

[23] Z. Wei, J. Guo, D.W.K. Ng and J. Yuan, *Fairness comparison of uplink NOMA and OMA*, IEEE 85th Vehicular Technol. Conf.(VTC Spring), 2017, p. 1–6.

[24] Z. Wei, L. Yang, D. W.K. Ng and J. Yuan, *On the performance gain of NOMA over OMA in uplink single-cell systems*, IEEE Glob. Commun. Conf. (GLOBECOM), 2018, pp. 1–7.

[25] Z. Wei, L. Yang, D.W.K. Ng, J. Yuan and L. Hanzo, *On the performance gain of NOMA over OMA in uplink communication systems*, IEEE Trans. Commun. **68** (2020), no. 1, 536–568.

[26] Y. Wu, N. Zhang and K. Rong, *Non-orthogonal random access and data transmission scheme for machine-to-machine communications in cellular networks*, IEEE Access **8** (2020), 27687–27704.

[27] Z. Yang, W. Xu, C. Pan, Y. Pan and M. Chen, *On the optimality of power allocation for NOMA downlinks with individual QoS constraints*, IEEE Commun. Lett. **21** (2017), no. 7, 1649–1652.

[28] J. Zeng, T. Lv, R.P. Liu, X. Su, M. Peng, C. Wang and J. Mei, *Investigation on evolving single-carrier NOMA into multi-carrier NOMA in 5G*, IEEE Access **6** (2018), 48268–48288.

[29] M. Zeng, A. Yadav, O.A. Dobre, G.I. Tsiropoulos and H.V. Poor, *On the sum rate of MIMO-NOMA and MIMO-OMA systems*, IEEE Wireless Commun. Lett. **6** (2017), no. 4, 534–537.

[30] J. Zhu, J. Wang, Y. Huang, S. He, X. You, and L. Yang, *On optimal power allocation for downlink non-orthogonal multiple access systems*, IEEE J. Selected Areas Commun. **35** (2017), no. 12, 2744–2757.