System Design and Performance Evaluation for Power Domain Non-Orthogonal Multiple Access

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***Abstract*—To meet the 5G requirements on spectral efficiency and connection density, non-orthogonal multiple access (NMA) is becoming an important candidate technology. This paper focuses on power-domain NMA (PNMA) due to the relatively low design complexity and standardization impact. In PNMA, the data of more than one user equipment (UE) are superposed with different transmission power setting at the transmitter, and are separated by utilizing interference cancellation at the receiver. The theoretical performance of PNMA has been shown in some previous research. In this paper, we gives our proposals on PNMA practical system design aspects including base station (BS) scheduling, UE receiver implementation and network signaling, aiming to seek for good trade-off between overall performance and complexity. System-level simulations validate that compared to orthogonal multiple access (OMA), PNMA with our proposed scheduling algorithm can bring 14.16% and 23.88% gain in cell average spectral efficiency (SE) and cell edge SE respectively, as well as improve the number of connected UEs by 55%.**

Keywords - 5G, non-orthogonal multiple access, mutiple user scheduling, interference cancellation

I. INTRODUCTION

In wireless communication, multiple access technology allows several users to share the radio transmission resource. Over the past 20 years, the innovation on multiple access technology is an essential part for each new generation of cellular mobile systems.

LTE and LTE-Advanced networks are now being more and more widely deployed by global mobile operators. Meanwhile, the 5G research towards the year 2020 and beyond has been started in the academia and industry worldwide. Compared with 4G system, two of the key 5G capabilities are to provide higher spectral efficiency and connection density [1]. As seen in Fig. 1, the 1G to 4G cellular systems are mainly based on orthogonal multiple access (OMA) technologies. In recent years, non-orthogonal multiple access (NMA) has attracted more and more interests, and has become an important candidate technology for 5G system [2] [3].

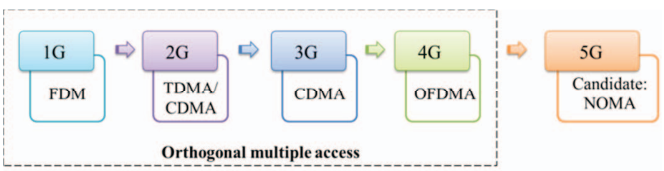

Fig. 1. Multiple Access Technology for Cellular Systems

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NMA allows the simultaneous transmission of more than one layer of data for more than one user equipment (UE) without time, frequency or spatial domain separation. Different layers of data can be separated by utilizing interference cancellation at the receiver. On one hand, the point-to-point link performance of LTE is quite close to the single user channel capacity, thus the improvement in link performance would be limited. On the other hand, NMA can be used to further enhance the spectral efficiency over OMA, in order to achieve the multiple user channel capacity, as shown in some previous research in [4] [5]. In addition, NMA can considerably increase the number of UE connections.

There are various NMA schemes, which can be categorized into three classes: power-domain NMA [5] [6], constellation-domain NMA [7], code-domain NMA [8] [9]. Power-domain NMA (PNMA) has relatively low design complexity and standardization impact among them, which is beneficial for the practical network deployment. Therefore, this paper focuses on the PNMA scheme.

In this paper, we first introduce the PNMA concept and signal model in Section II. Section III analyzes several system design aspects for PNMA. Section IV gives the simulation assumptions. The simulation results are presented and analyzed in Section V. The conclusions are drawn in Section VI.

II. PNMA CONCEPT AND SIGNAL MODEL

In PNMA system, signal transmitter and receiver are jointly optimized, so that multiple layers of data can be simultaneously delivered in the same resource. At the transmitter side, the complex-valued modulated symbols of different UEs are superposed with different transmission power setting, using the same time, frequency and spatial resource. At the receiver side, the symbols of different UEs can be by recovered interference cancellation.

For the sake of presentation simplicity, we will take the downlink two-UE system as example to introduce the PNMA transmitter and receiver operations. Note that PNMA can also be applied to enable downlink simultaneous transmission of more than two UEs and uplink simultaneous transmission of two or more UEs.

A. PNMA Transmitter

As illustrated in Fig. 2, UE 1 and UE 2, belonging to the same cell, are scheduled on same resource and the modulated symbols of the two UEs are superposed directly. Thus the base station (BS) transmission symbol can be expressed by:

$$\mathbf{x}(i) = \sqrt{\alpha}\mathbf{x}_{\text{UE1}}(i) + \sqrt{1-\alpha}\mathbf{x}_{\text{UE2}}(i) \quad (1)$$

where $\mathbf{x}(i)$ represents the complex-valued symbol after linear superposition, i is the symbol index, $\mathbf{x}_{\text{UE1}}(i)$ and $\mathbf{x}_{\text{UE2}}(i)$ denote the complex-valued modulated symbols of UE1 and UE2 respectively, and α is ratio of transmission power allocated to UE 1.

Without loss of generality, we assume the channel condition of UE 1 is better than that of UE 2, i.e., UE 1 is located at cell center and UE 2 is located at cell edge. To facilitate the UEs' signal separation at receiver, the power allocated to cell center UE should be lower than that to cell edge UE, i.e., α < 0.5 in equation (1). In addition, the sum of the two UEs' power is subject to the constraint of BS maximum transmission power.

B. PNMA Receiver

As discussed in section II-A, the signal power of UE 1 is lower than that of UE 2. Thus at UE 1 receiver side, in order to decode the desired signal for UE 1, UE 2's signal should be reconstructed and cancelled at first, as shown in Fig. 3 (a). Considering that UE 2's MCS (modulation and code scheme) is selected based on its own channel condition and the channel condition of UE 1 is better than UE 2, there is a quite high possibility that UE 1 can correctly obtain UE 2's signal. Therefore, it is assumed that UE 2' signal can be completely cancelled, and the relationship between UE 1's received SINRs in PNMA mode and OMA mode can be expressed as:

$$SINR_{\text{PNMA, UE1}} = \alpha \times SINR_{\text{OMA, UE1}} \quad (2)$$

At UE 2 receiver side, although the signal intended for UE 1 is contained in the received signal, with lower signal power for the UE 1 compared to the desired signal, it is still possible for UE 2 to correctly decode the desired signal. So UE 2 can treat UE 1 signal as noise and decode its desired signal directly, as shown in Fig. 3 (b). In such case, the relationship between UE 2's received SINRs in PNMA mode and OMA mode can be denoted as:

$$SINR_{\text{PNMA, UE2}} = (1-\alpha) \Big/ \left(\alpha + \frac{1}{SINR_{\text{OMA, UE2}}} \right) \quad (3)$$

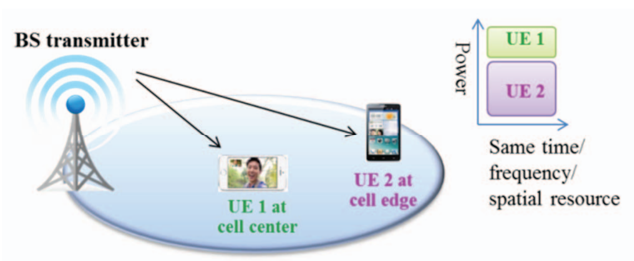
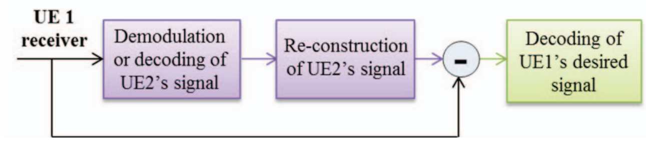
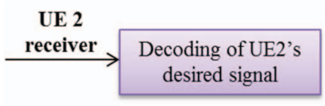


Fig. 2. Illustration of PNMA Transmitter



(a) UE1 Receiver



(b) UE2 Receiver

Fig. 3. Illustration of PNMA Receiver

III. PNMA PRACTICAL SYSTEM DESIGN

The main idea and signal model for PNMA have been introduced in section II. To ensure that PNMA feature can work effectively in real networks, it is critical to consider the practical system design aspects including: BS scheduling, UE receiver implementation and network signaling.

A. BS Scheduling

1) Categorization of cell center UEs and cell edge UEs

As introduced in section II, for PNMA, two UEs with different channel conditions are co-scheduled on the same radio transmission resource. Let CL_k be the coupling loss between UE k and its serving cell, where the coupling loss includes path-loss, penetration loss, shadow fading and sector antenna gain, i.e., fast fading is excluded. To facilitate the PNMA UE pairing, we propose to set one coupling loss threshold CL_{thre} to divide all the UEs into two sets:

- If $CL_k \le CL_{thre}$, UE k is a cell center UE and $k \in U_{center}$, where U_{center} denotes the cell center UE set;
- If $CL_k > CL_{thre}$, UE k is a cell edge UE and $k \in U_{edge}$, where U_{edge} denotes the cell edge UE set.

Each PNMA candidate UE set is composed of one cell center UE and one cell edge UE. Assuming that N_{center} and N_{edge} respectively denote the number of cell center and cell edge UEs in the considered cell, there are $N_{center} \times N_{edge}$ PNMA candidate UE sets with the proposed scheme. In contrast, if UE categorization is not considered, the number of candidate UE sets is $(N_{center} + N_{edge}) \times (N_{center} + N_{edge} - 1)$, which results in obvious computation complexity increase for practical scheduler.

2) Power allocation for co-scheduled PNMA UEs

As seen in equation (1), the power allocation ratio α is an important factor to be decided. For the two UEs co-scheduled on the same resource, one potential power allocation algorithm is to search all the possibilities of α and find the one that maximizes the scheduling metric. However, this algorithm does not only bring high computation complexity, but also increase network signaling overhead[1]. Thus an alternative algorithm is proposed: pre-define a power allocation ratio set containing a limited candidate values of α, and select one α for each resource unit. In this way, both computation complexity and signaling overhead can be reduced.

3) UE scheduling

For each resource scheduling unit, BS scheduler decides to schedule one UE or two UEs, based on the proportional fairness (PF) criterion [10]. The set of UE(s) and the associated power allocation ratio that maximizes the PF factor are selected:

$$\{k1, k2, \alpha\} = \arg \max_{\substack{k1 \in U_{center} \\ k2 \in U_{edge}}} \left(\frac{R_{k1}(s,n,\alpha)}{T_{k1}(n)} + \frac{R_{k2}(s,n,\alpha)}{T_{k2}(n)} \right) \quad (4)$$

where *k1* is the cell center UE index and *k2* is the cell edge UE index, $R_k(s,n,\alpha)$ denotes the pre-estimated instantaneous UE throughput with power ratio α at frequency instance *s* and time instance *n*, $T_k(n)$ is the already successfully delivered throughput for UE *k* at time instance *n*.

To determine the MCS and $R_k(s,n,\alpha)$ for PNMA UE, CQI (channel quality indicator) are re-calculated based on the existing CQI assuming OMA operation. More specifically, for cell center UE, the OMA CQI reported from UE is firstly mapped to the corresponding OMA SINR, then the PNMA SINR is obtained according to equation (2), and finally this PNMA SINR is used to determine the MCS level and calculate $R_k(s,n,\alpha)$. The similar operations are conducted to determine the MCS and $R_k(s,n,\alpha)$ for cell edge UE except that PNMA SINR is obtained according to equation (3).

When calculating the PF factor for each UE pair in each resource unit, the α values in the set {0, 0.1, 0.2, 0.3, 0.4, 1} are considered. If $\alpha = 0$ is selected, it means that only one cell edge UE is scheduled; if $\alpha = 1$ is selected, only one cell center UE is scheduled; if α = 0.1, 0.2, 0.3 or 0.4 is selected, one cell center UE and one cell edge UE are co-scheduled and they share the same transmission resource.

B. UE Receiver Implementation

In PNMA mode, the cell center UE receiver needs to first cancel the cell edge UE's signal, in order to correctly decode its desired signal. This indicates that UE should have the capability of interference cancellation (IC) to enable PNMA.

[1] Network signaling should be provided to inform the power allocation ratio to the PNMA UEs, for data demodulation purpose.

With increasing baseband processing capability in terminal chipset, IC capable receivers have been introduced in LTE-Advanced Release 12, which are used for dealing with inter-cell and intra-user inter-stream interference [11]. So IC is feasible from UE implementation perspective, and the existing IC receivers can be re-used with some modifications to mitigate the intra-cell inter-user interference in PNMA.

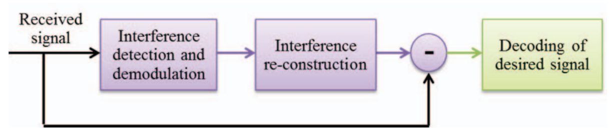
Various candidate IC receiver types can be applicable for PNMA, and they can be divided into two classes: symbol level IC and code word level IC, as shown in Fig. 4. The two classes of receivers have different trade-offs between performance, complexity and network signaling overhead.

C. Network Signaling

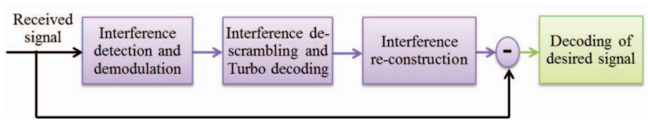
For cell center UE in PNMA, to successfully demodulate or decode cell edge UE's signal, it needs to know the transmission parameters of the interference (i.e., cell edge UE) in each time instance. For symbol level IC, interference parameters that can enable are interferer channel estimation and interferer detection at symbol level are needed. For code word level IC, interference parameters used for interference de-scrambling and Turbo decoding are also needed, in addition to the required interference parameters for symbol level IC. Therefore:

- Interference parameters required for symbol level IC at cell center UE: reference signal configuration, number of data layers and modulation scheme.
- Interference parameters required for code word level IC at cell center UE: reference signal configuration, number of data layers, modulation scheme and code rate, HARQ (hybrid automatic repeat request) redundancy version, UE RNTI (radio network temporary identity).
- In addition, power allocation ratio, i.e., α, is needed for both cell center and cell edge UEs.

It should be noted that the accuracy of the interference parameters has direct impact on the PNMA performance. In real systems, these parameters can be obtained by network signaling if UE blind detection is not possible.



(a) Symbol Level IC



(b) Code Word Level IC

Fig. 4. IC Receiver Structure

IV. SIMULATION ASSUMPTIONS

System-level simulations are carried out to investigate PNMA performance in practical environments. LTE based OMA system is also evaluated for comparison. There are 19 macro sites in the network, each site contains 3 sectors and each sector corresponds to one cell. The wrap-around multi-cell layout is applied to approximate the outer layers' interference. Adaptive modulation and coding (AMC) has been assumed to select the most suitable MCS for each resource unit depending on channel condition. Other simulation assumptions are listed in TABLE I.

For PNMA, the BS scheduling algorithm proposed in section III-A is used. Regarding the power allocation for each PNMA UE pair, six candidate α values in the set {0, 0.1, 0.2, 0.3, 0.4, 1} are considered, and the α that maximizes the PF factor is selected. To study the impact of coupling loss threshold, PNMA performance with five different thresholds in the set {90.0, 92.5, 95.0, 97.5, 100.0}dB are simulated. In addition, code word level IC is assumed at the cell center UE receiver.

TABLE I. SYSTEM-LEVEL SIMULATION PARAMETERS

Parameters		Configurations
Cellular Layout		Hexagonal grid, 19 macro sites, 3 cells per site
BS inter-site distance		500 m
Average number of UEs per cell		10
UE distribution		Uniform in entire network
Carrier frequency		2 GHz
System bandwidth		10 MHz
Transmission power		46 dBm
Distance-dependent path-loss and shadowing fading		ITU Urban Macro [12]
Thermal noise		-174dBm/Hz
Noise figure at UE		9 dB
Number of antennas (BS,UE)		(1, 2)
BS antenna pattern	**Horizontal**	$A_H(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right]$ $\theta_{3dB} = 70$ degrees, $A_m = 25$ dB
	Vertical	$A_V(\theta) = -\min\left[12\left(\frac{\theta-\theta_{etilt}}{\theta_{3dB}}\right)^2, SLA_v\right]$ θ_{3dB}=10, SLA_v=20 dB, θ_{etilt} = 12 degrees
	Combining method in 3D antenna pattern	$A(\varphi,\theta) = -\min\{-[A_H(\varphi)+A_V(\theta)], A_m\}$
Antenna gain		17dBi for sector antenna
Channel model		ITU Urban Macro [12]
UE speed		3 km/h
Available α values		0, 0.1, 0.2, 0.3, 0.4, 1
Traffic model		Full buffer
Link-to-system level mapping		Exponential Effective SIR Mapping (EESM)
Available modulation schemes		QPSK, 16QAM, 64QAM
Available MCSs		29 MCSs based on LTE specification [13]
Channel coding		Turbo

V. SIMULATION RESULTS

This section presents the simulation results for OMA system and PNMA system with different coupling loss thresholds.

A. Impact of Coupling Loss Threshold CL_{thre}

For PNMA, each of the UEs in the network is categorized as a cell center UE or a cell edge UE by comparing its coupling loss with the configured threshold. The impact of coupling loss threshold on PNMA performance is analyzed in this sub-section. The ratios of cell center UE and cell edge UE are shown in TABLE II, and TABLE III depicts the cell average spectral efficiency (SE) and 5% cell edge SE[2].

It can be observed from TABLE II that the ratio of cell center UE increases with the coupling loss threshold. When the threshold equals to 95.0 dB, the gap between the ratios of cell center and cell edge UE is minimized, the numbers of cell center UEs and cell edge UEs are very close. Moreover, a good trade-off between cell average and cell edge SE is achieved when the threshold is set as 95.0 dB, as shown in TABLE III.

B. Comparison of OMA and PNMA

Based on the observation in section V-A, we set the coupling loss threshold as 95.0 dB for PNMA, and compare the OMA and PNMA performance in this sub-section. Fig. 5 and Fig. 6 give received SINR cumulative distribution function (CDF) curves

TABLE II. RATIOS OF CELL CENTER UE AND CELL EDGE UE

CL_{thre}	Ratio of cell center UE	Ratio of cell edge UE
90.0 dB	40.9%	59.1%
92.5 dB	47.0%	53.0%
95.0 dB	52.5%	47.5%
97.5 dB	60.7%	39.3%
100.0 dB	71.4%	28.6%

TABLE III. DOWNLINK SE WITH DIFFERENT CL_{thre}

CL_{thre}	Cell average SE (bps/Hz)	5% cell edge SE (bps/Hz)
90.0 dB	2.175	0.0604
92.5 dB	2.181	0.0615
95.0 dB	2.177	0.0638
97.5 dB	2.150	0.0577
100.0 dB	2.121	0.0572

[2] The cell edge SE is defined as the UE SE at 5% level of the CDF.

and UE throughput CDF curves respectively, as the cell average SE and 5% cell edge SE are presented in TABLE IV.

As shown in Fig. 5, the downlink received SINR of PNMA is poorer than that of OMA. When two UEs are co-scheduled on the same resource in PNMA system, the two UEs share the BS transmission power and thus the desired signal power is lower than that in OMA system, as seen in equation (2) and (3). In addition, for the cell edge UE receiver in PNMA mode, the signal intended for cell center UE is treated as noise, which degrades the received SINR further.

In PNMA system, although the received SINR is decreased, UE throughput performance is obviously improved, as shown in Fig. 6. This is because one resource unit can be assigned to two UEs in PNMA mode, resulting in more resources allocated to each UE. TABLE IV indicates that PNMA can achieve 14.16% and 23.88% gain in cell average SE and cell edge SE respectively.

As proposed in section III-A, the BS can decide to schedule one or two UEs for each resource unit, according to the PF criterion. The ratios of resource units scheduling one and two UEs are collected and given in TABLE V. We can observe that in 55% of the system resource, two UEs' data are simultaneously transmitted. As a result, compared with OMA system, PNMA system can improve the number of connected UEs by 55%.

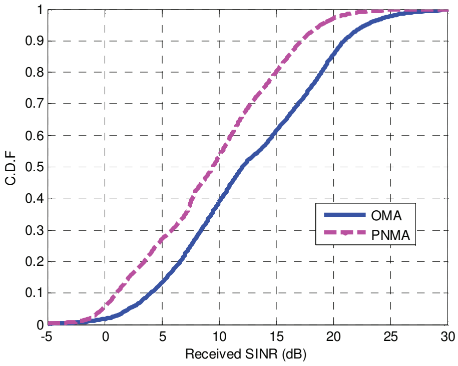


Fig. 5. Received SINR CDF of OMA and PNMA

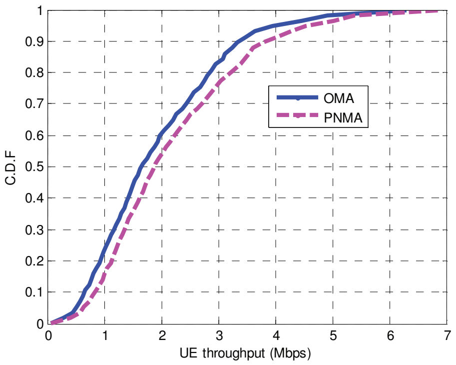


Fig. 6. UE Throughput CDF of OMA and PNMA

TABLE IV. DOWNLINK SE OF OMA AND PNMA

	Cell average SE (bps/Hz)	5% cell edge SE (bps/Hz)
OMA	1.907	0.0515
PNMA	2.177	0.0638
Gain of PNMA over OMA	14.16%	23.88%

TABLE V. RATIOS OF RESOURCE UNITS SCHEDULING ONE AND TWO UES

	Ratio of resource units scheduling one UE	Ratio of resource units scheduling two UEs
OMA	100%	0%
PNMA	45%	55%

VI. CONCLUSIONS

PNMA is identified as a candidate 5G technology to provide higher spectral efficiency and support more UE connection. In this paper, BS scheduling, UE receiver implementation and network signaling issues for PNMA were analyzed and our proposals on how to handle these issues were given. Moreover, system-level simulations were performed to show the PNMA performance gain over OMA in practical environments.

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