Comparison Study between NOMA and SCMA

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Abstract—In this paper, the performance and system complexity of the candidate multiple access (MA) techniques for the next generation of cellular systems, namely, non-orthogonal multiple access (NOMA) (in this paper, we consider power domain MA as NOMA) and sparse code multiple access (SCMA), are investigated. To this end, for each MA technique, a resource allocation problem considering heterogeneous cellular networks (HetNet) is formulated. We apply successive convex approximation (SCA) method to each problem and obtain their solutions. The simulation results show that SCMA-based system achieves better performance than NOMA-based one at the cost of more complexity.

Index Terms— NOMA, SCMA, resource allocation, optimization problem, successive convex approximation (SCA).

I. INTRODUCTION

Wireless data traffic is dramatically growing and is expected to grow thousand fold in the next decade [1, 2]. The fifth generation of wireless networks (5G) is being designed to cope with the excessive data rate demands of future multimedia applications. There are many challenges which should be addressed in such a network. Multiple access (MA) techniques have an essential role in improving the performance of mobile communication systems. Non-orthogonal multiple access (NOMA) or power domain MA and sparse code multiple access (SCMA) techniques are promising MA techniques for 5G which have been investigated recently. The main principle of NOMA approach is applying superposition coding (SC) in the transmitter side for assigning each sub-carrier to multiple users and successive interference cancellation (SIC) in the receiver side to cancel the other users signals (interference from other users sharing the same subcarrier). On the other hand, SCMA is a code book based multiple access technique where each subcarrier can be assigned to multiple users with applying an appropriate code book assignment. In [3], the authors studied NOMA performance from the information theory aspect. System-level performance for NOMA in downlink has been investigated in [4]. In [5] and [6], the authors evaluated the throughput and outage of NOMA approach. SCMA as a MA technique has been introduced in [7]. In [8], a resource allocation method to maximize the energy efficiency in SCMA-based system has been studied. In [9], the authors introduced SCMA as a multiple access technique which improves the spectrum efficiency. In [9], different NOMA techniques such as pattern division multiple access (PDMA), SCMA, and multi-user shared access (MUSA) are studied, and their link-level performances are compared with each other, in this paper, power domain NOMA is not studied, also, the considered MA methods are not investigated from resource allocation and receiver complexity perspective. Features, challenges, and future research trend of the MA techniques of 5G have been investigated in [10].

The main contributions of this paper are summarized as follows:

• We consider two MA techniques, namely, NOMA and SCMA, which are candidates of MA techniques in 5G. The performance of these techniques, measured based on the system sum-rate and complexity, is studied and compared to each other.

• For each technique, we consider a downlink resource allocation problem in the context of heterogeneous cellular networks (HCN) based on which we evaluate and compare the performance of these techniques.

• To solve the resource allocation problems, an iterative algorithm is devised. In NOMA-based system, in each iteration, power and sub-carriers are allocated separately. To solve the subcarrier allocation problem arithmetic geometric mean approximation (AGMA) is applied. The power allocation problem is solved by using SCA approach and applying dual method. In SCMA-based system, in each iteration, power and code books are allocated separately in which code book allocation is solved by AGMA and power allocation is solved by using SCA approach and applying dual method.

This paper is organized as follows. In Section II, system model and problem formulation for the two MA techniques are presented. In Section III the iterative algorithms to obtain the solution of the optimization problems are developed. In Section IV the implementation complexity is investigated. Simulation results are presented in Section V and the paper is concluded in Section VI.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider the downlink of a HCN system with one macro base station and $F - 1$ small base stations (BSs). Total number of users is $M$ and the total number of available subcarriers is $N$. With these definitions, the system model and problem formulation of each MA technique is defined as follows:

A. NOMA-based system

In this system model, $h_{m,f}^n$ indicates the channel coefficient between user $m$ and BS $f$ on subcarrier $n$. $p_{m,f}^n$ shows the transmit power of BS $f$ to user $m$ on subcarrier $n$ and $\rho_{m,f}^n \in \{0, 1\}$ is a binary variable that indicates the subcarrier allocation of user $m$ in BS $f$, e.g., $\rho_{m,f}^n = 1$ if the subcarrier $n$ is allocated to user $m$ in BS $f$, otherwise $\rho_{m,f}^n = 0$. Moreover, the set of BSs is shown by...
$\mathcal{F} = \{1, 2, \ldots, F\}$ where MBS is shown by $f = 1$, the set of all users in BS $f$ is shown by $M_f = \{1, 2, \ldots, M_f\}$ which $\sum_{f \in \mathcal{F}} M_f = M$. Also, for the sake of simplicity the notations $P_m = [p_{m,1}, \ldots, p_{m,N}], \ P_f = [p_{1,1}, \ldots, p_{M_f}]^T$, $P = [P_1, \ldots, P_f]^T$, $P_m = [p_{m,1}, \ldots, p_{m,N}]^T$, $P_f = [p_{1,1}, \ldots, p_{M_f}]^T$ and $\rho = [\rho_1, \ldots, \rho_f]^T$ are used.

In NOMA-based systems, users are sorted based on their channel gain, i.e., $|h_{f,n_{c}}|^2 \geq |h_{f,n_2}|^2 \geq \cdots \geq |h_{f,M_f}|^2$, and for sorted users, we have $p_{1,n_{c}} \leq p_{2,n_{c}} \leq \cdots \leq p_{M_f,n_{c}}$. Based on the NOMA approach, in the transmitter side, users signals are multiplexed in power domain by applying SC, and in the receiver side, each user removes the other user’s signals by using SIC approach. Each user can remove the signals of the users with lower order, and considers the signals of users with higher order as noise. Therefore, the SINR of user $m$ on sub-carrier $n$ in BS $f$ is obtained by

$$\gamma_{m,n}^f = \frac{p_{m,n}^f |h_{f,n}|^2}{\sum_{p \neq m} p_{p,n}^f |h_{f,n}|^2 + \sigma^2_m},$$

where $I_{m,n}^f$ is obtained as $I_{m,n}^f = |h_{f,n}^m|^2 \sum_{i=1}^{m-1} \rho_i n_{c}^f n_{i} + \sum_{f \neq \mathcal{F} / f} (\sum_{m \in M_f} \rho_m n_{c}^f |h_{f,n}^m|^2)$ and $\sigma^2_m$ indicates the noise power of user $m$ on sub-carrier $n$ in BS $f$. Therefore, the rate of user $m$ on sub-carrier $n$ in BS $f$ is obtained by $r_{m,n}^f = \log(1 + \gamma_{m,n}^f)$. Accordingly, the system sum-rate is equal to $R(P, \rho) = \sum_{f \in \mathcal{F}} \sum_{m \in M_f} \sum_{n \in \mathcal{N}} r_{m,n}^f(P, \rho)$. Furthermore, we impose a total transmit power constraint for each BS in the system as $\sum_{m \in M_f} \sum_{n \in \mathcal{N}} p_{m,n}^f \rho_m n_{c} \leq p_{\text{max}} \forall f$. The proposed resource allocation problem based on NOMA approach is formulated as:

$$\max \sum_{f \in \mathcal{F}} \sum_{m \in M_f} \sum_{n \in \mathcal{N}} r_{m,n}^f(P, \rho)$$

s.t.:

$$\sum_{m \in M_f} p_{m,n}^f \rho_m n_{c} \leq p_{\text{max}} \forall f,$$

$$p_{m,n}^f \geq 0, \forall m, n, f,$$

$$\sum_{m \in M_f} p_{m,n}^f \leq L_T, \forall n, f,$$

$$p_{m,n}^f \in \{0, 1\}, \forall m, n, f,$$

where (2d) demonstrates that each subcarrier can be assigned to at most $L_T$ users simultaneously.

**B. SCMA-based system**

An SCMA encoder is a mapping from $\log_2(J)$ bits to a $N$-dimensional codebook of size $J$ [11]. The N-dimensional codewords of a codebook are sparse vectors with $U$ ($U < N$) non-zero entries, which refers to $U$ specific subcarriers. Based on the SCMA approach, codebooks which are composed of subcarriers are the basic resource unit in networks [8, 11], and if each codebook consists of $U$ subcarriers, there are $C(N, U) = \frac{N!}{(N-U)!U!}$ codebooks in the considered system. The set of codebooks is shown by $C = \{1, 2, \ldots, C\}$. Notation $q_{m,c}$ indicates codebook assignment between user $m$ and codebook $c$ in BS $f$ with $q_{m,c}^f = 1$ if codebook $c$ is allocated to user $m$ in BS $f$ and otherwise $q_{m,c}^f = 0$. In addition, notation $\rho_{m,c}^f$ shows the mapping between subcarriers and codebooks with $\rho_{m,c}^f = 1$ if codebook $c$ consists of subcarrier $n$ in BS $f$ and otherwise $\rho_{m,c}^f = 0$. We assume that the mapping between codebooks and subcarriers are fixed, i.e., $\rho$ is a known parameter. In addition, notation $\eta_{m,c}^f$ shows the transmit power of BS $f$ to user $m$ on codebook $c$. Note that $\rho_{m,c}^f$ is assigned to subcarrier $n$ in codebook $c$ based on a given proportion $\eta_{m,c}^f$, with $0 \leq \eta_{m,c}^f \leq 1$ determined based on codebook design and satisfies $\sum_{c \in C} \eta_{m,c}^f = 1 \forall c$. Therefore, the SINR of user $m$ on codebook $c$ in BS $f$ is given by

$$\gamma_{m,c}^f = \frac{q_{m,c}^f \sum_{n \in \mathcal{N}} \eta_{m,c}^f |h_{f,n}^c|^2}{I_{m,c}^f + (\sigma^2_m)^2},$$

where $I_{m,c}^f$ is obtained by $I_{m,c}^f = \sum_{f \in \mathcal{F}} \sum_{m \in M_f} \sum_{n \in \mathcal{N}} \eta_{m,c}^f p_{m,n}^f |h_{f,n}^c|^2$. From (3), the achievable rate for user $m$ on codebook $c$ is given by $r_{m,c}^f = \log(1 + \gamma_{m,c}^f)$. Accordingly, the system sum-rate is given by $R_{\text{total}} = \sum_{f \in \mathcal{F}} \sum_{m \in M_f} \sum_{c \in C} r_{m,c}^f(P, Q)$. Also, the power constraint for each BS is given by $\sum_{m \in M_f} \sum_{c \in C} \eta_{m,c}^f p_{m,c}^f \leq p_{\text{max}} \forall f$. Consequently, the problem formulation of joint power and code book assignment in SCMA system is formulated as follows:

$$\max_{Q, P} \sum_{f \in \mathcal{F}} \sum_{m \in M_f} \sum_{c \in C} r_{m,c}^f(P, Q)$$

s.t.:

$$\sum_{m \in M_f} \sum_{c \in C} \eta_{m,c}^f p_{m,c}^f \leq p_{\text{max}}, \forall f,$$

$$p_{m,c}^f \geq 0, \forall m, c, f,$$

$$\sum_{c \in C} \eta_{m,c}^f p_{m,c}^f \leq K, \forall n, f,$$

where (2d) indicates that each sub-carrier can be reused at most $K$ times.

**III. SOLUTION OF THE PROPOSED PROBLEMS**

**A. NOMA-based system**

The resource allocation problem of NOMA-based system is non-convex and includes both integer and continuous variables. Therefore, the available methods to solve convex optimization problem can not be applied directly. To solve this problem, an iterative algorithm is exploited where in each iteration, the main problem is decoupled into two sub-problems: subcarrier allocation and power allocation. In each iteration, the subcarrier allocation is solved by applying AGMA method. Moreover, the power allocation is computed by applying SCA for low complexity (SCALE) approach. An overview of the algorithm to solve the main problem is presented in Algorithm II

1) **Sub-carrier allocation**: The problem of sub-carrier allocation is formulated as

$$\max_{\rho} \sum_{f \in \mathcal{F}} \sum_{m \in M_f} \sum_{n \in \mathcal{N}} r_{m,n}^f(\rho)$$

s.t. (2b, 2d, 2e).
Algorithm 1 Overview of the solution algorithm

I: Initialize \(\rho(0), P(0)\) and set \(k = 0\) (iteration number).

II: Repeat:

III: Set \(\rho = \rho(k)\) and find a solution for problem \(\mathcal{P}\) by applying SCA approach and assign it to \(P(k+1)\),

IV: Find \(\rho(k+1)\) by solving \(\mathcal{P}\) with \(P = P(k+1)\),

V: When \(|P(k) - P(k-1)|\leq \gamma\) stop.

Otherwise, set \(k = k + 1\) and go back to III.

Output: \(\rho(k)\) and \(P(k)\) are adopted for the considered system.

To solve problem \(\mathcal{P}\), we relax \(\rho_{m,n}\) to be a real value between zero and one \((0 \leq \rho_{m,n} \leq 1)\). Then, \(\rho_{m,n}\) can be interpreted as a portion of time that sub-carrier \(m\) is assigned to user \(n\) in BS \(f\) [14], [17]. It can be shown that the objective of problem \(\mathcal{P}\) can be written as follows:

\[
\min \rho \prod_{f \in F, m \in M_f, n \in N} \frac{\left|h_{m,n}^f\right|^2 \sum_{i=1}^{m-1} \rho_{i,n} p_{f,i,n} + I_{m,n}^f + (\sigma_{m,n}^f)^2}{\left|h_{m,n}^f\right|^2 \sum_{i=1}^{m} \rho_{i,n} p_{f,i,n} + I_{m,n}^f + (\sigma_{m,n}^f)^2}
\]

s.t.: \(2a, 2d, 2c\).

The AGMA inequality is expressed as \(\sum_{i=1}^{K} v_i u_i \geq \prod_{i=1}^{K} v_i u_i\), where \(v = [v_1, \ldots, v_K]\), \(u = [u_1, \ldots, u_K]\) and \(\sum_{i=1}^{K} u_i = 1\) [18]. In order to apply AGMA we define \(X = \left|h_{m,n}^f\right|^2 \sum_{i=1}^{m} \rho_{i,n} p_{f,i,n} + I_{m,n}^f + (\sigma_{m,n}^f)^2\). By applying AGMA inequality we have

\[
X \geq \prod_{f \in F, m \in M_f, n \in N} \frac{\rho_{m,n} \rho_{f,m,n} \left|h_{m,n}^f\right|^2}{W_{m,n}^f} \prod_{f \in F, m \in M_f, n \in N} \frac{\rho_{m,n} \rho_{f,m,n} \left|h_{m,n}^f\right|^2}{R_{f,m,n}^f}
\]

where \(W_{m,n}^f = p_{f,m,n} \left|h_{m,n}^f\right|^2\) and \(R_{f,m,n}^f = \frac{\left|h_{m,n}^f\right|^2 \rho_{f,m,n}}{X}\).

Consequently, the subcarrier allocation problem is written as follows:

\[
\min \rho \prod_{f \in F, m \in M_f, n \in N} \frac{\left|h_{m,n}^f\right|^2 \sum_{i=1}^{m-1} \rho_{i,n} p_{f,i,n} + I_{m,n}^f + (\sigma_{m,n}^f)^2}{\left|h_{m,n}^f\right|^2 \sum_{i=1}^{m} \rho_{i,n} p_{f,i,n} + I_{m,n}^f + (\sigma_{m,n}^f)^2}
\]

s.t.: \(2b, 2c\).

To apply SCALE method, an inequality is used to approximate the objective function with a tight lower bond as follows [15]:

\[
\alpha \log(z) + \beta \leq \log(1 + z),
\]

where \(\alpha = \frac{Z_0}{Z_0 + 1}, \beta = \log(1 + Z_0) - \frac{Z_0}{Z_0 + 1} \log(Z_0)\). By applying inequality \(9\), the objective function of problem \(\mathcal{P}\) is replaced by \(\sum_{f \in F} \sum_{m \in M_f} \sum_{n \in N} \alpha_{m,n} \log(\gamma_{m,n}^f) + \beta_{m,n}^f\).

Then by transforming \(p_{m,n}^f = \exp(\tilde{p}_{m,n}^f)\), the standard form of convex maximization problem in the new variables \(p_{m,n}^f\) is achieved as follows:

\[
\max \sum_{f \in F} \sum_{m \in M_f} \sum_{n \in N} \alpha_{m,n} \log(\gamma_{m,n}^f) + \beta_{m,n}^f
\]

s.t. \(\sum_{m \in M_f} \sum_{n \in N} \exp(p_{m,n}^f) \leq p_{\text{max}}, \forall f,\)

\[
\exp(\tilde{p}_{m,n}^f) \geq 0, \forall m, n, f.
\]

To show the concavity of objective function, we rewrite it as follows:

\[
\sum_{f \in F} \sum_{m \in M_f} \sum_{n \in N} \alpha_{m,n} \log(\rho_{m,n}^0 \left|h_{m,n}^f\right|^2) + \tilde{p}_{m,n}^f
\]

\[-\log \left(\left|h_{m,n}^f\right|^2 \sum_{i=1}^{m-1} \rho_{i,n} p_{f,i,n} \exp(\tilde{p}_{i,n}^f)\right) + \sum_{f \in F} \sum_{m \in M_f} \sum_{n \in N} \rho_{m,n}^f \left|h_{m,n}^f\right|^2 + N_0)\right)\] + \beta_{m,n}^f. \quad (11)

Each term in \(11\) is concave, and therefore, the new objective function is concave. We note that log-sum-exp function is convex [16].

To find a power allocation better than \(P(k)\) \((k\) is the outer loop iteration number), when \(\rho = \rho(k)\) an iterative power allocation algorithm that has been shown in Algorithm 2 is used. The algorithm can be started by simple high-SINR approximation \(\beta^0 = 0\) and \(\alpha^0 = 1\). The output of this algorithm is \(P(k+1)\), and \(P(k)^s\) \((s\) is the inner loop iteration number) is considered as power allocation calculated after \(k\)th iteration. Finally, we have \(P(k+1) = P(k)^S\) where \(S\) is the maximum predefined inner loop iteration number. To solve the

Algorithm 2 POWER ALLOCATION ALGORITHM

I: Initialization: Set \(s = 0, P(k)^0 = P(k), \beta = 0\) and \(\alpha = 1, S\).

II: Repeat:

III: Find \(P(k)^s\), by solving problem \(10\),

IV: Update \(\beta\) and \(\alpha\) at \(Z_0 = \gamma_{m,f}^S\left(P(k)^S\right)\),

V: When \(s = S\) or convergence, stop, otherwise, set \(s = s + 1\) and go back to III.

Output: \(P(k+1) = P(k)^S\)
Lagrangian function of the problem (10) is formulated as:
\[
L(\tilde{p}, \lambda) = \sum_{f \in \mathcal{F}} \sum_{m \in \mathcal{M}_f} \sum_{n \in \mathcal{N}} \alpha_{m,n}^f \log(\gamma_{m,n}^f (\exp(\tilde{p}_{m,n}^f))) + \beta_{m,n}^f \\
+ \sum_{f \in \mathcal{F}} \lambda_f (p_{\max}^f - \sum_{m \in \mathcal{M}_f} \sum_{n \in \mathcal{N}} p_{m,f}^n \exp(\tilde{p}_{m,f}^n)),
\]
where \( \lambda \) is the vector of Lagrange multipliers. The dual objective function is given by
\[
g(\lambda, \delta) = \max_{\tilde{p}} L(\tilde{p}, \lambda, \delta).
\]
The dual problem is solved by finding stationary point of (12) with respect to \( \tilde{p} \) with \( \{\lambda\} \) fixed. To find the stationary point of (13), we write
\[
\frac{d(L(\tilde{p}, \lambda, \delta))}{dp_{m,n}^f} = 0.
\]
Then, after simplifying (14) and applying transformation \( p_{m,c}^f = \exp(\tilde{p}_{m,c}^f) \), the power allocation problem in standard form of convex problem is achieved by
\[
\begin{align*}
\max_{\mathcal{F}} & \sum_{m \in \mathcal{M}_f} \sum_{n \in \mathcal{N}} q_{m,n}^f \exp(\tilde{p}_{m,n}^f) \\
\text{s.t.:} & \sum_{m \in \mathcal{M}_f} q_{m,n}^f \exp(\tilde{p}_{m,c}^f) \leq p_{\max}^f, \forall f, \\
& \exp(\tilde{p}_{m,c}^f) \geq 0, \forall m, n, f.
\end{align*}
\]
After applying dual method, taking derivatives (to find stationary point), and some manipulations, \( p_{m,c}^f \) is given by
\[
p_{m,c}^f = \left[ \frac{\alpha_{m,c}^f}{\lambda_f + \sum_{j \in \mathcal{F}(f)} \sum_{m \in \mathcal{M}_j} \theta_{m,c}^j \sum_{n \in \mathcal{N}} h_{m,n}^j |Y_{m,n}^j|^2 / \gamma_{m,c}^j} \right]^{1/2} \\
\sum_{n \in \mathcal{N}} h_{m,n}^j |Y_{m,n}^j|^2 / \gamma_{m,c}^j.
\]

### IV. IMPLEMENTATION COMPLEXITY ON THE RECEIVER SIDE

In the NOMA-based system, to achieve appropriate signals in each receiver, SIC method is applied. The complexity of the SIC method is calculated as follows.

We suppose \( G \) sub-carriers is assigned to each user, and in each subcarrier, there are \( L_T \) superimposed signals. We also assume that in each subcarrier, \( L_T - 1 \) signals (as the interference) should be canceled. By considering NOMA approach, the received signal at each receiver is given by \( y = Hx + n \), where \( H \) is the channel matrix of size \( G \times L_T \) and \( x = (x_1, \ldots, x_{L_T}) \) is the vector of transmit signals of size \( L_T \). To estimate the signals, the minimum mean square error (MMSE) detector is applied. By MMSE, the first estimated signal is given by \( \hat{x} = Dy \) where \( D \) is the transformation matrix calculated as \( D = \min_{\Omega} E[\|x - \Omega y\|^2] \), whose solution is given by \( D = (H^T H + \sigma^2 I)^{-1} H^T \). Consequently, the complexity order of SIC receiver is approximately given by \( O((L_T^2 + 2L_T^2)(G)(L_T - 1)) \). We note that the complexity order of calculating \( A^{-1} \) and \( A^H A \) (with size \( n \times n \)) is \( n^3 \).

In SCMA-based system on the receiver side, message passing approach (MPA) method is applied. The complexity order of this method is given by \( O(I_T (\pi^d)) \), where \( \pi \) indicates the codebook set size, \( I_T \) denotes the total number of iterations, and \( d \) denotes the non-zero elements in each row of the matrix \( X \) where \( X = (x_1, \ldots, x_n) \) is the factor graph matrix. In other word, \( d \) is the maximum number of signals superimposed on each subcarrier. In Table 1 with some numerical examples, we show that the complexity of SCMA receiver is higher than NOMA receiver.

As we can see, the complexity of MPA method is higher than SIC, and therefore, the trend of researches is to achieve methods which decrease the complexity of SCMA receiver system.
\[ p_{m,n}^f = \left[ \frac{\sum_{i=m+1}^{M_f} \alpha_{i,n}^f (p_{i,n}^f)^\gamma_f}{\lambda_f + \sum_{i=m+1}^{M_f} \alpha_{i,n}^f} + \sum_{j \in F(f)} \sum_{m \in M_f} \alpha_{m,n}^j \frac{|h_{m,n}^j|^2 p_{m,n}^j}{|h_{m,n}^j|^2 P_m^j} \right]^{-1}. \]  

(15)

In this section, system sum-rate for both system model and compared with each other. The numerical results show, SCMA technique achieves better system sum rate than NOMA technique, and the system complexity of SCMA is higher than NOMA. Therefore, we can say one of the important challenges of SCMA is designing low complexity receiver.

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