Downlink and uplink MIMO-SCMA System

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Abstract. Sparse code multiple access is a promising multiple access technology capable of increasing the spectral efficiency of communication systems. Another technology that can improve the spectral or power efficiency is multiple input multiple output. Combining both technologies offers an advantage over classic approaches. This paper presents downlink and uplink multiple input multiple output sparse code multiple access with spatial diversity to improve performance of classic systems. It considers full rate full diversity of space-time block codes. We propose maximum likelihood multiple input multiple output detection scheme without using message passing algorithm for scenario with 2 and 4 transmitting and one receiving antenna. We also propose maximum ratio combining message passing algorithm detector for uplink model with multiple receiving antenna. Numerical results demonstrate better bit error rate performance compared to classic approaches.

1. Introduction

With the development of technology, the need for higher transmission rate and traffic volume increases every year. Fifth generation (5G) wireless communication system are now being actively developed, intended to provide mass connections and increase throughput. In 5G networks, in addition to mobile communication devices, it is supposed to service a large number of Internet of Things (IoT) devices that perform various functions of monitoring, control and information processing [1]. Providing high-density connections with low latency, low complexity or power consumption with limited time-frequency resources is a challenging issue.

Non-orthogonal multiple access (NOMA) methods are proposed as a technology designed to solve this issue, including sparse code multiple access (SCMA) [2]. In SCMA, user information bits are converted into sparse multidimensional codewords using a 3D codebook. SCMA technology allows to increase the spectral efficiency, number of user connections, and bit error rate (BER) performance compared to other existing access methods.

Another technology capable of increasing the spectral efficiency of communication system is multiple input multiple output (MIMO). MIMO involves the use of multiple antennas at the transmitter and / or receiver. Systems with the combined use of MIMO and SCMA technologies can improve the performance of single-antenna SCMA systems. By using MIMO as spatial multiplexing, it is possible to increase the transmission rate in MIMO-SCMA systems several times. Papers [3-4] describe an increase in the performance of MIMO-SCMA systems when using a joint detector for spatial multiplexing, in comparison with separate MIMO and SCMA detection by using known methods.
MIMO technology can also be used for spatial diversity providing greater BER performance and/or communication range. There are two types of spatial diversity: transmit and receive diversity. Papers [5-6] consider options with space-time block coding on the transmitting side, and [7] consider options with receive diversity.

This paper discusses downlink and uplink MIMO-SCMA systems aimed at improving system BER performance. Since IoT devices are assumed to be compact, energy efficient and inexpensive, the paper considers an option with one antenna per user equipment (UE) and multiple antennas per base station (BS). The architecture of such systems is described, algorithms for decoding by MIMO and SCMA are proposed. In the last section, simulation results are presented, which demonstrate the superiority of the proposed solutions over classical methods.

2. Downlink MIMO-SCMA system model

The downlink MIMO-SCMA model is shown in Figure 1. The BS has $N_{tx}$ antennas and the target user has one antenna.

![Figure 1. Downlink MIMO-SCMA system model.](image)

Information bits $b_{j,t} \in \mathbb{B}^{log_2 M}$ of user $j$ ($1 \leq j \leq J$) in the $t$-th symbol interval ($1 \leq t \leq T$) are converted into $K$-dimensional codeword $c_{j,t} \in \mathbb{C}^{K \times 1}$ using SCMA user codebook $x_{j} \in \mathbb{C}^{K \times M}$ where $\mathbb{B}$ and $\mathbb{C}$ are binary and complex fields, respectively, $M$ is a codebook modulation index. The final codeword at the output of the SCMA Encoder is obtained as follows:

$$s_{t} = \sum_{j=1}^{J} c_{j,t}. \quad (1)$$

These codewords are then encoded into a block of $T$-symbol intervals using the MIMO Encoder as follows:

$$C = \begin{align*}
&\begin{bmatrix}
\text{diag}(s_{1}^1) & \cdots & \text{diag}(s_{1}^{N_{tx}}) \\
\vdots & \ddots & \vdots \\
\text{diag}(s_{T}^1) & \cdots & \text{diag}(s_{T}^{N_{tx}})
\end{bmatrix},
\end{align*}$$

where $\text{diag}(\cdot)$ is a diagonal matrix with vector as a diagonal element, $s_{t}^{N_{tx}}$ is transmitted codeword through $n_{tx}$ antenna during the $t$-th symbol interval. After orthogonal frequency-division multiplexing (OFDM) modulation, the signal is transmitted through the channel.

Let’s assume that the channel is flat fading channel and quasistatic, i.e. the channel coefficients are constant during one block. Thus, the received signal $y = [(y_1)^T, \ldots, (y_T)^T]^T$ is as follows:

$$y = C \cdot h + n, \quad (2)$$

where $(\cdot)^T$ denote the transpose operation, $h = [(h_1)^T, \ldots, (h_{N_{tx}})^T]^T$ is a channel gain vector between transmit and receive antennas, $n = [(n_1)^T, \ldots, (n_T)^T]^T$ is an independent and identically distributed complex Gaussian noise vector $\mathcal{CN}(0, \sigma^2)$. $y_T, n_t$ and $h_{ntx}$ are $K$-dimensional vectors.

Equation (2) can also be written in another form:

$$y' = H \cdot x + n',$$
where \( \mathbf{y}' = f(\mathbf{y}) \) is a prefiltered received signal, \( \mathbf{x} = \left[ (\mathbf{s}_1)^T, ..., (\mathbf{s}_{N_{tx}})^T \right]^T \) is a vector of transmitted codewords, \( \mathbf{H} \) is a MIMO channel matrix, which is given by
\[
\mathbf{H} = \begin{bmatrix}
\text{diag} \left( \mathbf{h}_1^1 \right) & \cdots & \text{diag} \left( \mathbf{h}_1^{N_{tx}} \right) \\
\vdots & \ddots & \vdots \\
\text{diag} \left( \mathbf{h}_T^1 \right) & \cdots & \text{diag} \left( \mathbf{h}_T^{N_{tx}} \right)
\end{bmatrix}.
\]

The classic detecting method is the optimum maximum likelihood (ML) detector, which performs the metric
\[
\hat{\mathbf{x}} = \arg \min_{\mathbf{x} \in \zeta} \| \mathbf{y}' - \mathbf{H} \cdot \mathbf{x} \|^2,
\] (4)
where \( \zeta \) is the set of all possible values of \( \mathbf{x} \).

ML detector in (4) requires searching over all possible elements of the set \( \zeta \), which leads to great computational complexity. The BER performance close to the ML detector can be achieved by using the joint message passing algorithm (JMPA) detector with less computational complexity [3-4]. However, the complexity of JMPA depends exponentially on the number of transmit antennas and is still high.

Another way to reduce computational complexity is to separately detect MIMO and SCMA. For this, single-symbol ML decodable linear space-time block codes (STBCs) with code rate \( R = 1 \) were chosen.

MIMO detection is as follows:
\[
\hat{s}_i = \arg \min_{\mathbf{s} \in \zeta} \| f_i(\mathbf{s}) \|,
\] (5)
where \( f_i(\mathbf{s}) \) is ML detecting metric, \( \zeta \) is a set of \( \mathbf{s}_i \).

Detection of SCMA symbols usually involves message passing algorithm (MPA) which requires information about the noise characteristics. The noise only affects the selection of \( \hat{s}_i \), so there is no need for MPA. Since we know the set of transmitted codewords \( \zeta \), we can unambiguously determine which set of codewords users \( \mathbf{c}_j \) formed (1). This correspondence can be described by a searching matrix:
\[
\mathbf{P} = \begin{bmatrix}
p_{1,m_1} & \cdots & p_{1,m_j} \\
\vdots & \ddots & \vdots \\
p_{L,m_1} & \cdots & p_{L,m_j}
\end{bmatrix},
\]
where \( L = M^J \) is the number of elements of the set \( \zeta \), \( 1 \leq m_j \leq M \) is the index of the codeword of the \( j \)-th user, \( p_{l,m_j} \) shows which \( m_j \) formed \( l \)-th element of the set \( \zeta \). The set \( \zeta \) and the searching matrix \( \mathbf{P} \) can be calculated offline and stored in memory.

3. Design cases with \( N_{tx} = 2 \) and \( N_{tx} = 4 \)
This section presents two full rate full diversity STBCs for \( N_{tx} = 2 \) and \( N_{tx} = 4 \) with corresponding decoding methods. STBC with \( N_{tx} = 2 \) corresponds to Alamouti code [8] and STBC with \( N_{tx} = 4 \) is QOSTBC with minimum Decoding Complexity (MDC-QOSTBC) [9].

3.1. STBC for \( N_{tx} = 2 \)
For an option with \( N_{tx} = 2 \), the known Alamouti scheme is given as
\[
\mathbf{C}_2 = \begin{bmatrix}
\text{diag} \left( \mathbf{s}_1 \right) & \text{diag} \left( \mathbf{s}_2 \right) \\
-\text{diag} \left( \mathbf{s}_2^* \right) & \text{diag} \left( \mathbf{s}_1^* \right)
\end{bmatrix}.
\]

In accordance with (3), the received signal has the form of
\[
\begin{bmatrix}
\mathbf{y}_1 \\
\mathbf{y}_2
\end{bmatrix} = \begin{bmatrix}
\text{diag} \left( \mathbf{h}_1 \right) & \text{diag} \left( \mathbf{h}_2 \right) \\
\text{diag} \left( \mathbf{h}_2 \right) & -\text{diag} \left( \mathbf{h}_1^* \right)
\end{bmatrix} \cdot \begin{bmatrix}
\mathbf{h}_1 \\
\mathbf{h}_2
\end{bmatrix} + \begin{bmatrix}
\mathbf{n}_1 \\
\mathbf{n}_2
\end{bmatrix}.
\]
The ML detector estimates according to (5) can be found by minimizing the metrics

\[ f_1(s_1) = |s_1|^2 \sum_{i=1}^{2} |h_i|^2 - (y_1 h_1 s_1^* + y_1 h_1 s_1 + y_2 h_2 s_1 + y_2 h_2 s_1^*), \]

\[ f_2(s_2) = |s_2|^2 \sum_{i=1}^{2} |h_i|^2 - (y_1 h_2 s_2^* + y_2 h_2 s_2 - y_2 h_1 s_2 - y_2 h_1 s_2^*), \]

where all operations in (6) are performed element by element.

3.2. STBC for \( N_{tx} = 4 \)

To achieve full diversity, the original constellation must be rotated by an angle of \( \phi = \tan(1/2)/2 \). The MDC-QOSTBC matrix is as follows:

\[
C_4 = \begin{bmatrix}
\text{diag} \left( s_1^R + js_1^I \right) & \text{diag} \left( s_2^R + js_2^I \right) & \text{diag} \left( -s_1^R + js_1^I \right) & \text{diag} \left( -s_2^R + js_2^I \right) \\
\text{diag} \left( -s_1^R - js_1^I \right) & \text{diag} \left( s_2^R - js_2^I \right) & \text{diag} \left( s_1^R + js_1^I \right) & \text{diag} \left( -s_2^R - js_2^I \right) \\
\text{diag} \left( -s_1^R + js_2^I \right) & \text{diag} \left( -s_2^R - js_2^I \right) & \text{diag} \left( s_1^R - js_1^I \right) & \text{diag} \left( s_2^R + js_2^I \right) \\
\text{diag} \left( s_1^R + js_2^I \right) & \text{diag} \left( s_2^R + js_2^I \right) & \text{diag} \left( -s_1^R - js_1^I \right) & \text{diag} \left( s_2^R - js_2^I \right) \\
\end{bmatrix}
\]

In accordance with (3), the received signal has the form of

\[
\begin{bmatrix}
y_1^R \\
y_1^I \\
y_2^R \\
y_2^I \\
\end{bmatrix} = H_4 \cdot \begin{bmatrix}
s_1^R \\
s_1^I \\
s_2^R \\
s_2^I \\
\end{bmatrix} + \begin{bmatrix}
n_1^R \\
n_1^I \\
n_2^R \\
n_2^I \\
\end{bmatrix},
\]

where \((\cdot)^R\) and \((\cdot)^I\) denote real and imaginary part, respectively, \(H_4\) is given by

\[
H_4 = [A_1 \cdot h' \ B_1 \cdot h' \ \ldots \ A_4 \cdot h' \ B_4 \cdot h']
\]

All input elements in (7) are given in (8):

\[
A_q = \begin{bmatrix}
A_q^R & -A_q^I \\
A_q^I & A_q^R \\
\end{bmatrix}, \quad B_q = \begin{bmatrix}
-B_q^R & -B_q^I \\
-B_q^I & -B_q^R \\
\end{bmatrix}, \quad 1 \leq q \leq 4,
\]

\[
A_1 = \begin{bmatrix}
1_K & 0 & 0 & 0 \\
0 & 1_K & 0 & 0 \\
0 & 0 & 1_K & 0 \\
0 & 0 & 0 & 1_K \\
\end{bmatrix}, \quad A_2 = \begin{bmatrix}
0 & 1_K & 0 & 0 \\
-1_K & 0 & 0 & 0 \\
0 & 0 & 0 & 1_K \\
0 & 0 & -1_K & 0 \\
\end{bmatrix}, \quad A_3 = \begin{bmatrix}
1_K & 0 & 0 & 0 \\
0 & -1_K & 0 & 0 \\
0 & 0 & 1_K & 0 \\
0 & 0 & 0 & -1_K \\
\end{bmatrix},
\]

\[
B_1 = \begin{bmatrix}
0 & 0 & j1_K & 0 \\
0 & 0 & 0 & j1_K \\
0 & j1_K & 0 & 0 \\
0 & 0 & j1_K & 0 \\
\end{bmatrix}, \quad B_2 = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & -j1_K \\
0 & 0 & 0 & j1_K \\
0 & 0 & 0 & 0 \\
\end{bmatrix}, \quad B_3 = \begin{bmatrix}
0 & 0 & 0 & -1_K \\
0 & 0 & 1_K & 0 \\
1_K & 0 & 0 & 0 \\
0 & -1_K & 0 & 0 \\
\end{bmatrix}, \quad B_4 = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1_K \\
0 & 0 & 1_K & 0 \\
1_K & 0 & 0 & 0 \\
\end{bmatrix}, \quad h' = \begin{bmatrix}
h_1^R \\
h_1^I \\
h_2^R \\
h_2^I \\
\end{bmatrix},
\]

where \(1_K\) is identity matrix of size \(K \times K\). ML detecting metrics are given in (9)
\begin{align*}
f_1(s_1) &= \left(\sum_{i=1}^{4} |h_i|^2\right) \left(|s_1^R|^2 + |s_1^I|^2\right) + 2 \cdot \text{Re}\{s_1^R \alpha - s_1^I \beta - s_1^R s_1^I y\} \\
f_2(s_2) &= \left(\sum_{i=1}^{4} |h_i|^2\right) \left(|s_2^R|^2 + |s_2^I|^2\right) + 2 \cdot \text{Re}\{s_2^R \chi - s_2^I \delta - s_2^R s_2^I y\} \\
f_3(s_3) &= \left(\sum_{i=1}^{4} |h_i|^2\right) \left(|s_3^R|^2 + |s_3^I|^2\right) + 2 \cdot \text{Re}\{s_3^R \alpha + js_3^I \beta + s_3^R s_3^I y\} \\
f_4(s_4) &= \left(\sum_{i=1}^{4} |h_i|^2\right) \left(|s_4^R|^2 + |s_4^I|^2\right) + 2 \cdot \text{Re}\{s_4^R \chi + js_4^I \delta + s_4^R s_4^I y\}
\end{align*}

\begin{align*}
\alpha &= -h_1 y_1^i - h_2 y_2 - h_3 y_3 - h_4 y_4, \\
\beta &= -h_3 y_1^i - h_4 y_2 - h_1 y_3 - h_2 y_4, \\
\chi &= -h_2 y_1^i + h_1 y_2 - h_4 y_3 + h_3 y_4, \\
\delta &= -h_4 y_1^i + h_3 y_2 - h_2 y_3 + h_1 y_4.
\end{align*}

where all operations in (9) are performed element by element. After obtaining the estimates, we should rotate \( s_i \) by the angle of \( \psi = -\phi \) to restore the constellation and decode the SCMA.

4. Uplink MIMO-SCMA system model

Figure 2 shows the uplink MIMO-SCMA system model. The BS has \( N_{rx} \) antennas.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Uplink MIMO-SCMA system model.}
\end{figure}

In this model, the data bits \( b_j \) are converted to codewords \( c_j \) by the SCMA Encoder. After passing through the channel, the received signal is described as

\[ y^{(r)} = \sum_{j=1}^{J} \text{diag} \left( h_j^{(r)} \right) \cdot c_j + n^{(r)} \]

where \( h_j^{(r)} \) is a channel gain vector of the \( j \)-th user from transmitting antenna to \( r \) receiving antenna.

We propose maximum ratio combining MPA, named MRC-MPA, for multiuser detection (MUD) of multiplexed codewords. MRC-MPA was proposed based on the MPA algorithm in [10] and presented in Algorithm 1. This algorithm can be used for single input single output SCMA (SISO-SCMA) with parameter \( N_{rx} = 1 \).

Algorithm 1: Maximum Ratio Combining Message Passing Algorithm:

- Input arguments: \( y^{(r)}, h_j^{(r)}, \chi_j \) and \( \sigma^2, \forall r, j \),
• Initialization: \[ P(\mathbf{c}_j, m_j) = \frac{1}{M}, \quad \forall \ j, m_j \]

\[ V_{j \rightarrow k}^{(0)}(\mathbf{c}_j, m_j) = \frac{1}{M}, \quad U_{k \rightarrow j}^{(0, r)}(\mathbf{c}_j, m_j) = 1, \quad \forall \ j, k, m_j, r \text{ if edge } (j, k) \text{ exist} \]

• Iterative: for \( t = 1, \ldots, T \)

\[ \forall \ j, k, m_j, r \text{ if edge } (j, k) \text{ exist} : \]

\[ U_{k \rightarrow j}^{(c, r)}(\mathbf{c}_j, m_j) = \sum_{j}^{\text{com}} \left( \exp \left[ -\frac{1}{\sigma^2} \left( y_k^r - h_{k,i}^r c_{k,m,i}^{(\text{com})} - \sum_{i \in \partial k \setminus j} h_{k,i}^r c_{k,m,i}^{(\text{com})} \right) \right] \prod_{i \in \partial k \setminus j} V_{i \rightarrow k}^{(t)}(\mathbf{c}_{i,m_i}^{(\text{com})}) \right) \]

\[ V_{j \rightarrow k}^{(t)}(\mathbf{c}_{j,m_j}) = P(\mathbf{c}_{j,m_j}) \prod_{r=1}^{N_{rx}} \left( \prod_{(i \in \partial k \setminus j)} U_{i \rightarrow j}^{(t-1, r)}(\mathbf{c}_{j,m_j}) \right) \]

Normalization:

\[ V_{j \rightarrow k}^{(t)}(\mathbf{c}_{j,m_j}) = \frac{V_{j \rightarrow k}^{(t)}(\mathbf{c}_{j,m_j})}{\sum_{m_j = 1}^{M} V_{j \rightarrow k}^{(t)}(\mathbf{c}_{j,m_j})} \]

• Final probability: \( \forall \ j, m_j \)

Calculate \[ U_{k \rightarrow j}^{(T+1, r)}(\mathbf{c}_{j,m_j}) \]

\[ V_j(\mathbf{c}_{j,m_j}) = P(\mathbf{c}_{j,m_j}) \prod_{r=1}^{N_{rx}} \left( \prod_{k \in \partial j} U_{k \rightarrow j}^{(T+1, r)}(\mathbf{c}_{j,m_j}) \right) \]

Normalization:

\[ V_j(\mathbf{c}_{j,m_j}) = \frac{V_j(\mathbf{c}_{j,m_j})}{\sum_{m_j = 1}^{M} V_j(\mathbf{c}_{j,m_j})} \]

• Getting bits: \( \forall \ j \)

\[ \hat{b}_j = \arg \max_{m_j} \left( V_j(\mathbf{c}_{j,m_j}) \right) \]

5. Simulation results

This section provides simulation results for the models described in Sections 2 and 4. SCMA system has \( M = 4, J = 6 \) users and \( K = 4 \) OFDM subcarriers, so the overload factor is 150%. The SCMA codebook is taken from [11]. The number of iterations MPA is \( N_{iter} = 8 \). The receiver knows the ideal channel state information and \( \sigma^2 \). Figures 3 and 4 show the BER performance for downlink and uplink MIMO-SCMA compared to OFDMA-QAM-8 with spectral efficiency 3 bit/s/Hz, respectively.
As shown in Figure 3, SISO-SCMA has a 13.7 dB gain over OFDMA-QAM-8 for BER = 10^{-4}. The use of MIMO allowed an additional gain of 5.6 dB and 6.9 dB relative to SISO-SCMA for the case with 2 and 4 antennas, respectively, while for OFDMA-QAM-8 these gains were 13.1 dB and 18.3 dB. Reducing the computational complexity for Alamouti code can be obtained by using the zero forcing and MPA detectors separately. An additional research is also needed to find the optimal constellation rotation angle $\phi_{\text{opt}}$, which can increase the BER performance of MIMO-SCMA with MDC-QOSTBC.

As shown in Figure 4, SISO-SCMA has a 15.9 dB gain over OFDMA-QAM-8 for BER = 10^{-4}. Such reception allowed us to achieve 8.5 dB and 14.65 dB gain for uplink SCMA and 17.5 dB and 26.5 dB for uplink OFDMA-QAM-8 for the case with 2 and 4 reception antennas. The resulting gains show that
the proposed MRC-MPA algorithm can be used for MUD. Figure 5 compares the downlink and uplink MIMO-SCMA models.

![BER Performance of Downlink and Uplink MIMO-SCMA](image)

**Figure 5.** BER performance of downlink and uplink MIMO-SCMA.

As shown in Figure 5, the BER performance of uplink SISO-SCMA is the same as that of downlink SISO-SCMA. The use of spatial diversity significantly increases the BER performance of SCMA communication systems. Moreover, this effect is more pronounced for uplink systems. For BER = 10^-4 the gain for uplink compared to downlink is about 3.5 dB for diversity order 2 and 8.5 dB for diversity order 4. The gain obtained in uplink allows to reduce energy costs for signal transmission which is especially important in IoT systems.

6. **Conclusion**
The architecture for the generation and processing of signals of energy efficient MIMO-SCMA systems is offered. It considers communication channels with two and four antennas at the BS and one at the UE. For such configurations, it is proposed to use STBCs, namely Alamouti code for two antennas and MDC-QOSTBC for four antennas. The paper also considers a method for MIMO decoding and SCMA decoding based on ML and a searching matrix. The proposed MRC-MPA algorithm allows to detect SCMA symbols for the case of multiple receiving antennas. To assess the performance of the proposed methods, a simulation model of the MIMO-SCMA communication system was built which compares BER performance with SISO-SCMA, as well as classical solutions SISO-OFDMA-QAM and MIMO-OFDMA-QAM. A quasistatic flat fading channel was considered as a transmission medium. The simulation result showed a significant (more than 15 dB) gain when using the proposed solutions compared to SISO-OFDMA-QAM. It was also noted that the BER performance for uplink is higher than for downlink (more than 5 dB for 4 antennas) which allows optimizing the UE energy efficiency. The use of SCMA can increase the number of serviced UEs for a single BS. Both results show that the proposed methods can be used in energy efficient IoT systems.

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