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Article

Keywords:

Posted Date: April 19th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1497832/v3

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ABSTRACT

This paper presents a reconfigurable intelligent surface (RIS) assisted multi-user (MU) multiple-input multiple-output (MIMO) system. Instead of being applied at the remote RIS, the phase shift vector is applied at the base station (BS) by using an additional precoding stage. The overall system performance is improved by incorporating a double quadrature spatial modulation (DQSM) transmission technique. Results show that the proposed system has gains of up to 17 dB in bit error rate (BER) and a reduction in detection complexity of 51% when compared with the conventional MU-MIMO system based on spatial multiplexing (SMux). Compared with a similar system based on amplify and forward (AF) relay-assisted technique, the proposed system has up to 18 dB gain in BER performance under the same conditions and parameters. Mainly, the proposed system significantly reduces the signal processing required at the RIS.

Introduction

Recently, reconfigurable intelligent surface (RIS) have been proposed as one of the key enabling technologies for beyond 5G/6G wireless communication networks to support a massive number of users at a high data rate, low latency, and secure transmissions with both spectral and energy efficiency¹,²,³. A RIS is a surface of electromagnetic material that can control the phase, amplitude, frequency, and/or polarisation of the impinging signals in a nearly-passive way without the need for radio-frequency (RF) operations⁴,⁵,⁶. For example, the RIS can be designed to coherently combine the signals in the reception. In this way, the RIS changes the destructive effect of the multipath fading channel into a controllable channel that exploits diversity gains to improve the performance of the system. As a result, the overall energy of the transmitted signals can be used more efficiently. Since the RIS does not amplify the signals, RF chains are not required and thermal noise is not added during reflections⁷,⁸.

In particular, some frameworks for the implementation of RIS-assisted multi-user (MU) downlink transmission systems have been recently proposed⁹,¹⁰,¹¹,¹². In these previous works, the design of the system is mainly focused on the optimisation problem for the joint design of the beamforming matrix at the base station (BS) and the phase shift vector at the RIS. As a result, the design of the system leads to a non-convex optimisation problem. Due to the complexity of the system, typically the analysis is proposed for single-antenna users. These type of systems are known as multiple-input single-output (MISO) systems. The main drawback of these approaches is that the system results in highly complex optimisation algorithms which require intensive signals processing and frequent actualisation of the channel state information (CSI) at the RIS. This approach can be a challenge mainly for the future massive multiple input-multiple output (mMIMO) systems¹. Additionally, the practical implementation of RIS-assisted MU-MIMO systems can be complicated considering that the RIS could be located at remote places.

In order to make the implementation of RIS assisted MU-MIMO downlink transmission systems more feasible, a new RIS-MU-DQSM system for MIMO channels is presented in this paper. Two strategies are proposed for the implementation of the system. As shown in Figure 1, some user are free from MU interference (MUI) while other users suffer from MUI. For strategy I, the proposed system uses two precoding stages at the BS. A first precoding stage applies the optimal amplitudes and phases required to pre-cancel the MUI in the second hop (from the RIS to the users). The second precoder is designed to pre-cancel the interference in the first hop (from the BS to the RIS). This strategy guarantees that the signals with the
appropriate amplitude and phase are reflected by the RIS, producing an interference-free signal at the receivers. For strategy II, the system combines the two precoding blocks in just one. This strategy can be used for that users under MUI. The two proposed strategies are evaluated considering a correlated fading channel and two different configurations. Also, the overall system performance is improved by incorporating a double quadrature spatial modulation (DQSM) transmission scheme. Spatial modulation (SM) not only improves the bit error rate (BER) performance but also reduces the detection complexity of the proposed system. Results show that the proposed scheme generates the desired interference-free signals at the mobile station (MS) with diversity gains. Moreover, the proposed system clearly outperforms the conventional MU-MIMO system based on spatial multiplexing (SMux), and the amplify and forward (AF) relay-assisted MU-DQSM system used for reference. To the best of the authors knowledge, the proposed system has not been addressed in previous works.

Results

In this section, we analyse and discuss the BER performance and the detection complexity of the proposed system considering two configurations with different SE and two different scenarios: the uncorrelated and the correlated channels. The results of the proposed system are compared with the conventional MU-MIMO-SMux system and with the recently proposed relay assisted AF-MU-DQSM system under the same conditions and parameters.

BER Performance

For simulations, all systems are using a normalised transmission energy per user, i.e. $\mathbb{E} [\| t_\text{out} x \|] = K$, the same number of Tx/Rx antennas, and the same SE. Also, all systems are using similar precoding strategies and the optimal ML detection criterion alike. In order to carry out fair comparisons, all systems are compared considering MUI. The channel uses a spatial correlation coefficient of $\rho = 0.7$ in the BS and the RIS/relays.

For the uncorrelated fading channel, and the $(4 \cdot 2) \times 32 \times 8$ configuration, the proposed RIS-MU-DQSM-II system has $17$ dB and $15$ dB BER performance gains when compared with the conventional MU-MIMO-SMux and the AF-MU-DQSM systems respectively as shown in Figure 2(a). For the $(8 \cdot 4) \times 64 \times 32$ configuration, the proposed RIS-MU-DQSM-II system has $14$ dB and $18$ dB BER performance gains when compared with the conventional MU-MIMO-SMux and the AF-MU-DQSM systems, respectively, as shown in Figure 2(b).

As shown in Figure 3, when the correlated fading channel is considered, the RIS-MU-DQSM-II and the AF-MU-DQSM schemes are affected by 7dB to 15dB approximately. Under this scenario, the conventional MU-MIMO-Smux system is affected only by 5dB. This result can be explained by the reflecting mirrors or the relaying antennas affected by the spatial correlation. On the other hand, the proposed RIS-MU-DQSM-I was only affected by 2-3 dB. It means that the ZF technique is robust under the correlated fading scenario. Note that users who are free of MUI (marked as RIS-MU-DQSM-I*) have a similar BER performance that the other users under MUI. This fact shows the robustness of the BD technique used to avoid interference in the second hop. It is worth noting that when the proposed schemes are using a reduced number of mirrors in the RIS they have similar BER performance than the conventional MU-MIMO-SMux scheme. However, when an increased number of mirrors are used, the proposed RIS-MU-MIMO-DQSM-II, clearly outperforms both schemes used as reference.
Figure 2. BER Performance comparison for the the uncorrelated fading channel. (a) SE of 8 bpcu/user, L=2, (b) SE of 12 bpcu/user, L=4

Detection complexity results
In order to get fair comparisons, all systems are using optimal ML detection criterion. Table 1 shows a comparison of the detection complexity for all systems considering the two configurations used as study cases. The results show that considering the $(4\cdot2) \times 8 \times 8$ configuration with an SE of 8 bpcu, the RIS-MU-DQSM-I and the RIS-MU-DQSM-II systems have 25% and 16% lower detection complexity respectively when compared with the conventional MU-MIMO-SMux scheme. Considering the $(8\cdot4) \times 32 \times 32$ configuration with an SE of 12 bpcu, the proposed RIS-MU-DQSM-I and the RIS-MU-DQSM-II systems have 56% and 51% lower detection complexity respectively when compared with the conventional MU-MIMO-SMux system used as reference. The AF-MU-DQSM system used as a second reference has the same detection complexity as the RIS-MU-DQSM-II system since they are using the same modulation, precoding and detection strategies.

Table 1. Detection complexity of the evaluated systems.

<table>
<thead>
<tr>
<th>System configuration</th>
<th>RIS-MU-DQSM-I</th>
<th>RIS-MU-DQSM-II</th>
<th>AF-MU-DQSM</th>
<th>MU-MIMO-SMux</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(4\cdot2) \times 8 \times 8$</td>
<td>9,088</td>
<td>10,112</td>
<td>10,112</td>
<td>12,032</td>
</tr>
<tr>
<td>$(4\cdot2) \times 8$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(8\cdot4) \times 32 \times 32$</td>
<td>283,648</td>
<td>316,416</td>
<td>316,416</td>
<td>643,072</td>
</tr>
<tr>
<td>$(8\cdot4) \times 32$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion
RIS-based systems have strongly attracted attention since they improve the performance of the systems by optimising the use of radiated energy. However, one drawback of the RIS-based system is the control of phases and amplitudes of the impinging signals in the RIS. Typically, an additional control unit in the RIS is required. However, this approach can be a challenge mainly when the RIS is located far from the transmitter or BS. The results obtained in this work show that the proposed system can effectively be used to pre-modify the amplitude and phases of the signals reflected by the RIS. This fact is important since in this case the processing required in the RIS is transferred to the BS where the hardware and software capabilities of the system make signal processing more adequate. Additionally, the utilised DQSM transmission scheme improves the overall performance and reduces the detection complexity of the system\(^1\)\(^8\). Comparing the two proposed schemes, it is showed that the RIS-MU-DQSM-I scheme has the lowest detection complexity. However, this scheme requires that $N_r = N_f$ for perfect interference cancellation. This limitation is overcome by the proposed RIS-MU-DQSM-II scheme which also outperforms by 2 dB and 6 dB in BER the RIS-MU-DQSM-I scheme for the same SE. It is worth noting that in comparison with the conventional MU-MIMO-SMux system, the RIS degrades the BER performance of the system when a limited number of mirrors is used. However, when $N_r$ is greater than $N_f$, the RIS-based system takes advantage of diversity and significantly improves in BER.

As expected, the proposed system clearly outperforms the previous AF-MU-DQSM scheme. This fact is mainly due to the total quantity of noise in the RIS-based systems compared with the relay-assisted scheme used as a reference. However, it is fair
However, the design of CSI dissemination strategies is beyond the scope of this work. As has been proposed in previous works, this paper.

The QSM vectors are denoted by \( \tilde{x} \). The DQSM constellation is defined as \( A = \{1, -1, j, -j\} \).

The channel matrix gain between the BS and the RIS is defined as \( G \in \mathbb{C}^{N_r \times N_t} \). The channel matrix gain between the RIS and the \( k \)-th MS is defined as \( H_k \in \mathbb{C}^{N_t \times N_r} \). The channel model is defined for two scenarios. First, a quasi-static Rayleigh fading channel is considered where its elements are assumed to be independent and identically distributed (i.i.d.) complex Gaussian random variables with mean zero and variance one, \( \mathcal{CN}_t(0, 1) \). Additionally, a more realistic channel model where the spatial correlation between the RIS mirrors is considered. We assume that perfect CSI is available at the BS and all MS or users. It is worth noting that obtaining CSI can be a challenging task. As has been proposed in previous works, this task can be carried out using control links between the BS and the users when the line-of-sight (LoS) path is absent in this channel. However, the design of CSI dissemination strategies is beyond the scope of this work.

### Transmission

In the transmitter, the input of the \( k \)-th DQSM block intended for the \( k \)-th MS is composed by a sequence of bits \( a_k = \{a_n\}_{n=1}^m \), with \( a_n \in \{0, 1\} \). The DQSM constellation is defined as \( \mathcal{A} = \{\tilde{x}_k/\tilde{x}_k \in \mathbb{C}^{L \times 1}\} \). The output vector of the \( k \)-th DQSM block \( \tilde{x}_k \in \mathcal{A} \) is defined as

\[
\tilde{x}_k = (\tilde{x}_1, \tilde{x}_2, \ldots, \tilde{x}_L)^T,
\]

where the index in \( \tilde{x}_k \) denotes the transmitted signal in the \( k \)-th position. In order to generate the DQSM signals, two QSM signals should be generated first. In the following subsections, we describe how QSM and DQSM signals are generated, the general precoding strategy utilised and the general expression of the received signals in the MS.

### QSM Signals

The QSM vectors are denoted by \( \tilde{x}_1 \in \mathbb{C}^{L \times 1} \) and \( \tilde{x}_2 \in \mathbb{C}^{L \times 1} \) with components \( x'_{k} \in \{0, s_R, s_I\} \) where \( s_R \) and \( s_I \) represent the real and the imaginary parts of the quadrature amplitude modulation of \( M \)-th order \((M\text{-QAM})\) symbol \( s \) respectively.

![Figure 3. BER Performance comparison for the the correlated fading channel with a correlation factor of \( \rho = 0.7 \). (a) SE of 8 bpcu/user, L=2, (b) SE of 12 bpcu/user, L=4](image)
output vector of the $k$-th QSM block $\tilde{x}_k$ is defined as
\[
\tilde{x}_k = (\tilde{x}_1^k, \tilde{x}_2^k, \ldots, \tilde{x}_L^k)^T, \quad k \in \{1, 2\},
\]
where the index in $\tilde{x}_k^i$ denotes the transmitted signal in the $k$-th position. In order to generate the QSM vector $x$, the input bit sequence is divided into three streams. One stream is used to modulate a $M$-QAM signal and the other two streams (spatial bits) are used to modulate the position in the QSM output vector. For an input bit sequence of length $m_{QSM} = m_{DQSM}/2$, the first $\log_2(M)$ bits modulate a $M$-QAM symbol, the remaining $2\log_2(L) = m_{QSM} - \log_2(M)$ bits are divided into two streams with $\log_2(L)$ spatial bits each. These spatial bits modulate the position of the $M$-QAM symbol in the output vector $x_i \in \mathbb{C}^{L \times 1}$ using an SM block as follows: the real part of the $M$-QAM symbol is assigned to a specific position in the output vector, while the remaining $L - 1$ positions are set to zero. The imaginary part of the $M$-QAM symbol is assigned to another or even the same position in the output vector. Finally, these two signals are combined to obtain the QSM output vector $x$.

The DQSM signals are generated using two branches of the QSM basic transmission scheme. This technique is used mainly because it has good BER performance, improved spectral efficiency (SE), and low detection complexity. In order to generate the DQSM signal, the sequence of input bits $a_k = \{a_i\}_{i=1}^{m_k}$ is divided into two flows. Each one of these flows, composed by the sequence $b_k = \{a_i/2\}_{i=1}^{m_k}$, is fed into a QSM block. The QSM block generates the outputs $x_1 \in \mathbb{C}^{L \times 1}$ and $x_2 \in \mathbb{C}^{L \times 1}$. These signals are weighted by the factors $B_1$ and $B_2$. These values for $B_1$ and $B_2$ guarantee the maximal Euclidean distance between symbols, resulting in the optimal possible values. These two signals are combined to generate the DQSM output vector $\tilde{x}_k$ as $\tilde{x}_k = B_1\tilde{x}_1 + B_2\tilde{x}_2$. The number of bits that can be transmitted using QSM is
\[
m_{QSM} = \log_2(M) + 2\log_2(L),
\]
where $M$ is the size of the $M$-QAM constellation and $L$ is the length of the transmission vector $\tilde{x}_k$ intended for the $k$-th user.

Since DQSM is used, the system has doubled the SE compared to the QSM scheme. As an example of DQSM mapping rule, let us consider the DQSM output vector in (1) with size $L = 2$. Table 2 shows the first 16 values of an 8-bit input sequence using optimal weights of $B_1 = 1$ and $B_2 = B_1/2$. The 8-bit input sequence $a_k = \{a_i\}_{i=1}^{m_k}$ is divided into two streams $b_1$ and $b_2$ of 4 bits each, as shown in column 1. Stream $b_1$ is intended to modulate the QSM 1 signals (column 2), while stream $b_2$ is intended to modulate the QSM 2 signals (column 3). It can be seen that the stream $b_1 = 0000$ generates the output $x_1 = (1 + j, 0)$ in QSM 1. Stream $b_2$ modulates the QSM 2 as follows: the first two input bits (less significant bits) in column 1 modulate a 4-QAM symbol and the remaining two bits modulate the position in which they appear in the output vector $x_2$. More specifically, the real part of the $M$-QAM symbol is assigned to a specific position in the QSM 2 output vector, while the imaginary part can be assigned to another or even the same position. It can be seen in the third column of Table 2, that a total of $2\log_2(L) = 2$ bits can be modulated in the spatial constellation for this example.

**General precoding**

As shown in Figure 1(a), the precoder is composed of two stages. Users under MUI, $\{U_1, U_2, \ldots, U_j\}$ are first taken to Precoder 1. The Precoder 1 is intended to pre-cancel the MUI in the second hop (from the RIS to the MS). The output of the Precoder 1 is the vector $x_1$ defined as
\[
x_1 = \sum_{k=1}^{K} W_k \tilde{x}_k = (x_1, x_2, \ldots, x_{N_c})^T.
\]
In Precoder 1, the vectors $\tilde{x}_k$ are precoded by the matrices $W_k \in \mathbb{C}^{N_r \times N_r}$, where $N_r \leq N_s$ is the number of reflecting mirrors intended for users under MUI and $N_r' \leq N_s'$ is the number of receive antennas in the subset under MUI. The vector $x_1 \in \mathbb{C}^{N_r \times 1}$ contains the signals required at the RIS in order to pre-cancel the MUI in the second hop.

Users which are not under MUI, $\{U_{j+1}, U_{j+2}, \ldots, U_K\}$ are concatenated in the vector $x_2$ and then are taken to Precoder 2. The input vector to the Precoder 2 is the concatenated vector
\[
x = (x_1^T, x_2^T)^T.
\]

The Precoder 2 is designed to pre-cancel the interference in the first hop (from the BS to the RIS). It guarantees that the signals with appropriate phases and amplitudes are reflected by the RIS. Let us consider a linear precoding in this stage. Then, the output signal $t_k \in \mathbb{C}^{N_r \times 1}$ of the Precoder 2 can be defined as
\[
t_k = Fx,
\]
where $F \in \mathbb{C}^{N_r \times N_r}$ is a precoding matrix.
where the elements of the matrix $\mathbf{R}_T$ are assumed to be independent and i.i.d. complex Gaussian random variables with mean zero and variance one, $\mathcal{CN}(0,1)$.

The matrices $\mathbf{R}_r$ and $\mathbf{R}_t$ are the Rx and Tx correlation matrices respectively. The correlation matrix is defined using the

$$
\mathbf{R}_r = \frac{1}{2} \mathbf{H} \mathbf{R}_t \mathbf{H}^H
$$

Table 2. DQSM Signal generation example
for $M = 4, L = 2$.

<table>
<thead>
<tr>
<th>Input bits, $a_k$</th>
<th>QSM 1 $x'_1$</th>
<th>QSM 2 $x'_2$</th>
<th>Output signal DQSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_1$ $b_2$</td>
<td>$1+j,0$</td>
<td>$1+j,0$</td>
<td>$1.5+1.5j,0$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0000$</td>
<td>$1+j,0$</td>
<td>$0.5+1.5j,0$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0010$</td>
<td>$1+j,0$</td>
<td>$1.5+0.5j,0$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0011$</td>
<td>$1+j,0$</td>
<td>$0.5+0.5j,0$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0100$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0101$</td>
<td>$1+j,0$</td>
<td>$0.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0110$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$0111$</td>
<td>$1+j,0$</td>
<td>$0.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1000$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1001$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1010$</td>
<td>$1+j,0$</td>
<td>$0.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1011$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1100$</td>
<td>$1+j,0$</td>
<td>$0.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1101$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1110$</td>
<td>$1+j,0$</td>
<td>$0.5+j,0.5j$</td>
</tr>
<tr>
<td>$0000$</td>
<td>$1111$</td>
<td>$1+j,0$</td>
<td>$1.5+j,0.5j$</td>
</tr>
</tbody>
</table>

Reception

The impinging signals at the RIS are defined as

$$
r \triangleq \sqrt{1/\alpha} \mathbf{G}_x,
$$

where $\mathbf{G}_x \in \mathbb{C}^{N \times 1}$ is the signal vector transmitted by the BS and $\sqrt{1/\alpha}$ is an attenuation factor. These signals are reflected by the RIS without adding noise. Then, the received signal by the $k$-th user in the destination is given by

$$
\mathbf{y}_k = \sqrt{\gamma_k} \mathbf{H}_k \mathbf{G}_x + \mathbf{n}_k,
$$

where $\mathbf{n}_k \in \mathbb{C}^{N \times 1}$ stands for the noise. The noise samples are assumed to be independent and identically distributed (i.i.d) with $\mathcal{CN}(0, \sigma^2)$. $\sqrt{\gamma_k}$ is the signal-to-noise ratio (SNR) at the destination. Differently from previous works, instead of applying the phase shifts vector at the RIS, in this work, the signals with optimal phases and amplitudes required at the RIS are evaluated and implemented in the BS.

Channel model

For the channel model, we consider a flat fading Rayleigh channel where both the BS and the RIS are affected by spatial correlation. Note that mirrors can be optimally selected for a particular user in order to minimise the spatial correlation in the RIS. However, this approach is beyond the scope of this work. The proper operation of the system requires that each user could be illuminated by a subgroup of mirrors of at least $N'_t = N_r$. If $N'_t > N_r$, the receptor can take advantage of diversity gains.

In this work, we assume that the RIS is able to control the reflection angles of the mirrors in order to follow the position of each user in the system. This task can be done by using a low-speed reverse channel which can be also used for CSI actualisation. Under these considerations, spatial correlation is mainly caused in the first hop. In order to evaluate the effects of the spatially correlated fading channel, the following Kronecker model is considered

$$
\mathbf{G} = \mathbf{R}_r^{1/2} \mathbf{H} \mathbf{R}_t^{1/2},
$$

where the elements of the matrix $\mathbf{H}$ are assumed to be independent and i.i.d. complex Gaussian random variables with mean zero and variance one, $\mathcal{CN}(0,1)$.

The matrices $\mathbf{R}_r$ and $\mathbf{R}_t$ are the Rx and Tx correlation matrices respectively. The correlation matrix is defined using the

$$
\mathbf{R}_r = \frac{1}{2} \mathbf{R}_t \mathbf{R}_r^H
$$
following exponential model

\[ R = \begin{bmatrix} 1 & \rho^* & \rho^{2*} & \ldots & \rho^{N_t-1*} \\ \rho & 1 & \rho^* & \ldots & \rho^{N_t-2*} \\ \rho^2 & \rho & 1 & \ldots & \rho^{N_t-3*} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \rho^{N_t-1} & \rho^{N_t-2} & \ldots & 1 \end{bmatrix}, \]  

(11)

where \( \rho < 1 \) is the correlation coefficient. The correlation matrix \( R \) can be used to model both matrices \( R_r \) and \( R_t \). In this work, we consider a correlated channel in the transmission and the reception side of the first hop for all evaluated systems.

### Interference cancellation

As shown in Figure 1(b), MUI can be present in the system whenever two or more users are under the same beams. However, other users which are far away, are free from interference. In general, the complete transmission block is precoded by using a zero-forcing (ZF) technique. Since the RIS does not have the capacity to cancel the interference produced in the first hop, the ZF technique is adequate for this precoding stage. Additionally, for that user under MUI, a block diagonalization (BD) precoding technique is first used. The BD technique is implemented to design the phase and the amplitude of the reflected signals in the RIS. Note that the ZF technique cancels the channel. However, CSI in the second hop is used to transmit the spatial modulated signals assuring that the complete information can be retrieved by the users in the destination. For the implementation of the system two strategies are used. Strategy I is used when some users are under MUI, as shown in Figure 1(b). Strategy II can be used when all users are under MUI or all users can see the entire RIS.

#### Strategy I. Users free from MUI

In this strategy, firstly a BD technique is used in Precoder 1 at the BS to generate the signals with appropriate phases required by the RIS in order to cancel the interference in the second hop. Then, a ZF technique is used in the Precoder 2 to pre-cancel the interference in the first hop.

Let us consider a ZF precoding in Precoder 2. The precoding matrix is defined as \( F = G^+ \). Then, the output can be written as

\[ t_k = G^+ x, \]

(12)

where \( G^+ \), represent the inverse of the channel matrix \( G \). Substituting equation (12) in equation (9) we obtain

\[ y_k = \sqrt{\gamma_k} H_k x + n_k. \]

(13)

Equation (13) represents the signals received for all users. For that users which are free from MUI, the received signal is

\[ y'_k = \sqrt{\gamma_k} H_k x_2 + n_k. \]

(14)

Since \( y'_k \) is free from MUI, only the Precoder 2 is used to precancel the interference. For that user under MUI, substituting equation (5) in equation (13), the received signal \( y_k \) by the \( k \)-th user is

\[ y_k = \sqrt{\gamma_k} H_k \sum_{k=1}^{K} W_i \tilde{x}^k_i + n_k, \]

(15)

which can be rewritten as

\[ y_k = \sqrt{\gamma_k} H_k W_i \tilde{x}^k_i + \sqrt{\gamma_k} H_k \sum_{i=1, i \neq k}^{K} W_i \tilde{x}^k_i + n_k. \]

(16)

The first term in equation (16) is the signal intended for the \( k \)-th user, the second term is the interference produced by the other users in the system, whereas the third term is noise. The mathematical model of the complete system can be represented as

\[
\begin{bmatrix}
y_1 \\
y_2 \\
\vdots \\
y_K
\end{bmatrix} =
\begin{bmatrix}
H_1 & H_1 & \ldots & H_1 \\
H_2 & H_2 & \ldots & H_2 \\
\vdots & \ddots & \ddots & \vdots \\
H_K & H_K & \ldots & H_K
\end{bmatrix}
\begin{bmatrix}
W_1 \tilde{x}^1 \\
W_2 \tilde{x}^1 \\
\vdots \\
W_K \tilde{x}^1
\end{bmatrix}
+ 
\begin{bmatrix}
n_1 \\
n_2 \\
\vdots \\
n_K
\end{bmatrix},
\]  

(17)
where we set $\sqrt{\gamma_k} = 1$ without loss of generality. In order to eliminate the interference term, we require that $H_k W_i = 0, \forall i \neq k$, where 0 denotes an all-zero matrix. This equation can be written as

$$H_k W_k = 0, \quad k = 1, 2, \ldots, K, \quad (18)$$

where the matrix $H_k$ contains all user's matrices in the system except that of the $k$-th user. i.e.

$$H_k = [(H_1)^H, \ldots, (H_{k-1})^H, (H_{k+1})^H, \ldots, (H_K)^H]^H. \quad (19)$$

The matrix $W_k$ can be obtained by decomposing $H_k$ into its singular values as

$$H_k = U_k [S_k, 0] \left[V_k^{(1)} V_k^{(0)}\right] H, \quad (20)$$

where $U_k$ is a unitary matrix, $S_k$ is a diagonal matrix containing the non-negative singular values of $H_k$ with dimension equals to the rank of $H_k$, 0 is an all-zero matrix, $V_k^{(1)}$ contains vectors corresponding to the nonzero singular values and $V_k^{(0)}$ contains vectors corresponding to the zero singular values. The matrix $V_k^{(0)}$ contains the last $N_r$ columns of $V_k$, which form an orthogonal basis that is in the null space of $H_k$. Then, $H_k$ can be used as the precoding matrix $W_k$ in Precoder 1. Note that the BD technique is applied for $N_t = KN_r$. Considering equation (18), the received signal is reduced to

$$y_k = H_k W_k \tilde{x}_k + n_k, \quad (21)$$

which is an interference-free signal. Finally, the complete system is reduced to

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_K \end{bmatrix} = \begin{bmatrix} H_1 W_1 & \cdots & 0 \\ 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & H_K W_K \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \vdots \\ \tilde{x}_K \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_K \end{bmatrix}, \quad (22)$$

which shows the cancellation of the undesired components in the destination.

**Strategy II. Users under MUI**

Strategy II combines the channel matrix $G$ and all channel matrices $H_k$ in order to generate an equivalent channel matrix for each user. Then, the BD technique can be used to precancel the interference in both hops at the same time. Strategy II can be used when all user are under MUI or when all users see the complete RIS. Let us consider an equivalent matrix defined as $H_k^{eq} \triangleq (H_k G) \in C^{N_t \times N_r}$. Then, the received signal for the $k$-th user can be rewritten as

$$y_k = \sqrt{\gamma_k} H_k^{eq} t_k + n_k, \quad (23)$$

Considering $P = I$ in the Precoder 2, it follows that $t_k = x$. Now, considering a precoding matrix $Z_k^{eq} \in C^{N_t \times N_r}$ for the $k$-th user, the transmission vector in Precoder 1 can be written as

$$t_k = \sum_{k=1}^{K} Z_k^{eq} \tilde{x}_k, \quad (24)$$

The received signal by the $k$-th user can be written as

$$y_k = \sqrt{\gamma_k} H_k^{eq} \sum_{k=1}^{K} Z_k^{eq} \tilde{x}_k + n_k, \quad (25)$$

which can be also expressed as

$$y_k = \sqrt{\gamma_k} H_k^{eq} Z_k^{eq} \tilde{x}_k + \sqrt{\gamma_k} H_k^{eq} \sum_{i=1, i \neq k}^{K} Z_i^{eq} \tilde{x}_i + n_k, \quad (26)$$

where the first term in equation (26) is the signal sent to the $k$-th user, the second term is the interference produced by the other users in the system, whereas the third term is the noise. In order to remove the interference term we require that $H_k^{eq} Z_i^{eq} = 0, \forall i \neq k$. 


This condition can be written as
\[ \mathbf{H}_k^{Eq} \mathbf{Z}_k^{Eq} = 0, \quad k = 1, 2, \ldots, K, \]  
(27)
where the matrix \( \mathbf{H}_k^{Eq} \) contains all users matrices in the system except that of the \( k \)-th user, i.e.
\[ \mathbf{H}_k^{Eq} = \left[ (\mathbf{H}_1^{Eq})^H, \ldots, (\mathbf{H}_{k-1}^{Eq})^H, (\mathbf{H}_{k+1}^{Eq})^H, \ldots, (\mathbf{H}_K^{Eq})^H \right]^H. \]  
(28)

The matrix \( \mathbf{Z}_k^{Eq} \) is obtained decomposing \( \mathbf{H}_k^{Eq} \) into its singular values as
\[ \mathbf{H}_k^{Eq} = \mathbf{U}_k [\mathbf{S}_k, 0] \begin{bmatrix} \mathbf{V}^{(1)}_k \mathbf{V}^{(0)}_k \end{bmatrix}^H. \]  
(29)

Similar to equation (20), \( \mathbf{S}_k \) is a diagonal matrix containing the non-negative singular values of \( \mathbf{H}_k^{Eq} \) and the matrix \( \mathbf{V}^{(0)}_k \) contains the last \( N_r \) columns of \( \mathbf{V}_k \), which form an orthogonal basis that is in the null space of \( \mathbf{H}_k^{Eq} \). Eliminating the interference term in equation (26), the received signal can be rewritten as
\[ \mathbf{y}_k = \sqrt{\gamma_k} \mathbf{H}_k^{Eq} \mathbf{Z}_k^{Eq} \hat{\mathbf{s}}_k + \mathbf{n}_k, \]  
(30)
which is an interference-free signal. Finally, the complete system can be represented as
\[
\begin{bmatrix}
\mathbf{y}_1 \\
\mathbf{y}_2 \\
\vdots \\
\mathbf{y}_K
\end{bmatrix} =
\begin{bmatrix}
\mathbf{H}_1^{Eq} \mathbf{Z}_1^{Eq} & \cdots & 0 \\
0 & \cdots & 0 \\
\vdots & \cdots & \vdots \\
0 & \cdots & \mathbf{H}_K^{Eq} \mathbf{Z}_K^{Eq}
\end{bmatrix}
\begin{bmatrix}
\hat{\mathbf{x}}_1 \\
\hat{\mathbf{x}}_2 \\
\vdots \\
\hat{\mathbf{x}}_K
\end{bmatrix}
+ \begin{bmatrix}
\mathbf{n}_1 \\
\mathbf{n}_2 \\
\vdots \\
\mathbf{n}_K
\end{bmatrix},
\]  
(31)

where \( \sqrt{\gamma_k} = 1 \) without loss of generality. Note that, differently from Strategy I, the precoding matrix \( \mathbf{Z}_k^{Eq} \) can be used for arbitrary values of \( N_s \). From here on, the systems based on the Strategy I and Strategy II shall be refereed as RIS-MU-DQSM-I and RIS-MU-DQSM-II respectively.

**Detection**

Assuming that the receiver has perfect knowledge of the channel gains, the maximum likelihood (ML) criterion compares the Euclidean distance between the received signal and all possible noiseless received signals in the system. The optimal ML detection criterion for the RIS-MU-DQSM-I system is defined as
\[ \hat{\mathbf{x}}_k = \arg \min_{\mathbf{x} \in \mathbb{C}^{m \times p}} \| \mathbf{y}_k - \mathbf{H}_k \mathbf{W}_k \mathbf{D} \|_F^2. \]  
(32)

where the matrix \( \mathbf{D} \in \mathbb{C}^{N_r \times 2^m} \) accounts for the complete group of possible noiseless DQSM signals in the reception. For those users who are free from MUI, \( \mathbf{W}_k = \mathbf{I} \) in equation (32). For the RIS-MU-DQSM-II system, the ML detection criterion is defined as
\[ \hat{\mathbf{x}}_k = \arg \min_{\mathbf{x} \in \mathbb{C}^{m \times p}} \| \mathbf{y}_k - \mathbf{H}_k \mathbf{G} \mathbf{Z}_k^{Eq} \mathbf{D} \|_F^2. \]  
(33)

**Detection complexity**

The detection complexity (\( \eta \)) of the analysed systems is evaluated by counting the total number of floating-point operations (flops) required for the detection. All systems are compared considering the optimal ML detection criterion. For real additions, multiplications, and comparisons 1 flop is carried out. For complex additions and multiplications, 2 and 6 flops are carried out, respectively, while subtractions and divisions take the same number as additions and multiplications respectively. Multiplication of \( m \times n \) and \( n \times p \) complex matrices uses \( 8mp \) flops. Obtaining \( \mathbf{Q}_k = \mathbf{H}_k \mathbf{W}_k \) in equation (32) requires \( 8N_r^2 N_s \) flops. In order to obtain the noiseless version of the received signal in equation (32) we multiply \( \mathbf{Q}_k \in \mathbb{C}^{N_r \times N_f} \) by the matrix \( \mathbf{D} \in \mathbb{C}^{N_r \times 2^m} \) which represent all Rx antennas for the user \( k \). This multiplication requires \( 8N_r^2 2^m \xi \) flops. Note that when some spatial symbols are set to zero, the real size of the spatial constellation is reduced in the same proportion. The factor \( \xi \) is introduced to take into account the reduction of the size of the spatial constellation in comparison to the conventional QAM constellations. This factor is obtained by counting the number of zeros-value inputs in the real or imaginary parts of matrix \( \mathbf{Q}_k \).
\[ \xi = \frac{\text{Number of zero entries}}{\text{Constellation length}} \]  

(34)

Subtraction in the ML criterion requires \(2N_r 2^m\) flops, obtaining the absolute values require \(3N_r 2^m\) flops, combining the received signals of each Rx antenna requires \(2N_r 2^m\) flops and comparing all results to find the minimum requires \(2(2^m)\) flops. Adding these partial results, we obtain \(7N_r 2^m \xi\) flops approximately. Finally, adding all these partial results, the detection complexity for the RIS-MU-DQSM-I system is

\[ \eta_I \approx 8N_r^2 N_t + 8N_r^2 2^m \xi + 7N_r 2^m \xi. \]  

(35)

The detection complexity for the RIS-MU-DQSM-II system is obtained as follows: The product of \(H_k \in \mathbb{C}^{N_r \times N_s}\) by \(G \in \mathbb{C}^{N_r \times N_t}\) requires \(8N_r N_s N_t\) flops. Multiplying by the matrix \(Z_k^{2^m} \in \mathbb{C}^{N_t \times N_t}\) requires \(8N_r^2 N_t\) flops. Multiplying by matrix \(D \in \mathbb{C}^{N_r \times 2^m}\) requires \(8N_r^2 2^m\). Similar to equation (35), the ML criterion requires \(7N_r^2 2^m \xi\) flops approximately. Adding all these partial results we obtain the detection complexity for Strategy II as

\[ \eta_{II} \approx 8N_r N_s N_t + 8N_r^2 N_t + 8N_r^2 2^m \xi + 7N_r 2^m \xi. \]  

(36)

In equation (35) and equation (36) \(\xi\) takes into account that the lattice of the DQSM constellation is reduced by the inserted zeros\(^{13}\). Then, for the conventional MU-MIMO-SMux system \(\xi = 1\). For the RIS-MU-DQSM schemes, the factor \(\xi\) is evaluated by directly counting the entries with zero value in the real or imaginary parts of the spatial constellation. Considering a SE of 8 bits per channel use (bpcu)/user we get \(\xi = 0.75\), meanwhile for SE of 12 bpcu/user \(\xi = 0.4375\) is obtained.

**Conclusion**

In this paper, a novel RIS-MU-DQSM downlink transmission system has been presented. Instead of being applied at the remote RIS, the phase shift vector is designed and applied at the BS, which simplifies the design and implementation of the system. Two different strategies were proposed and evaluated for the implementation of the proposed system. In the reception, the BER performance and the detection complexity of the system were improved by incorporating spatial modulation (DQSM). Results show that the proposed RIS-MU-DQSM-I strategy, has the lowest detection complexity. However, in this case, the ZF precoding imposes the condition \(N_t = N_r\). This limitation was overcome by the RIS-MU-DQSM-II strategy which exploits the diversity gain in the RIS and clearly outperforms in BER the conventional MU-MIMO-SMux system and a similar system based on AF relay under the same condition and parameters. Mainly, the proposed RIS-MU-DQSM system reduces the signals processing in the RIS which makes it suitable for practical implementations in 5G and beyond systems.

**References**


Acknowledgements
The author gratefully acknowledge funding from Universidad Panamericana and the project FONDECYT Regular 1211132.

Author contributions statement
F.R.C.S. and C.G. conceived the main idea and experiments; J.A.P.F and J.S. wrote the manuscript; C.A.M., J.A.P.F, and J.S. conducted the experiments; F.R.C.S and V.B.K. interpreted the results. All authors analysed the results and reviewed the manuscript.
Competing interests
The authors declare no competing interests.

Data availability
Data sharing is not applicable to this article as no new data were created or analysed in this study.