# Orthogonal versus Non-Orthogonal multiplexing in Non-Coherent Massive MIMO Systems based on DPSK

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*Abstract*— **The lack of orthogonal resources to increase the capacity of the communication networks has led to research on new ways to non-orthogonally multiplex the signals of several users. In this paper, we study the viability of multiplexing users' signals by non-orthogonal constellation-based schemes against orthogonal classical multiple access techniques, such as time- or frequency-division multiple access, in non-coherent massive MIMO (NC mMIMO) systems, where the channel state information (CSI) is not required. We use the block error rate (BLER) and the throughput to analyze the behavior of the proposed multiuser NC mMIMO system based on DPSK. We assess the performance of multiplexing the users in the constellation against using other physical resources such as time or frequency. Based on this analysis, we propose a combination of both orthogonal and non-orthogonal schemes to reduce the complexity and increase the system throughput and capacity.**

## I. Introduction

In order to increase the capacity of the communication networks, the signals of multiple users are multiplexed into different orthogonal resources. Typically, the networks use the time or frequency (or code) to carry out this separation among users' signals. The most popular techniques are time division multiple access (TDMA) for time domain and frequency division multiple access (FDMA) for frequency domain [1]. The 3G networks entailed code division multiple access (CDMA) [2] and the 4G technology introduced orthogonal frequency division multiple access (OFDMA) [3]. However, the highly increasing demand for multimedia services has prompted the shortage of orthogonal resources offered by all these techniques, giving rise to new proposals based in non-orthogonal techniques [4].

In addition, the fifth generation (5G) standards look for higher spectral and energy efficiency by including massive multiple input multiple output (mMIMO) techniques [5]. They, however, pose the issue of estimating a large number of channel coefficients for a massive number of antennas. In this context, the non-coherent (NC) techniques are emerging as a key solution to avoid the estimation of the channel. The designs currently proposed for NC massive MIMO (NC mMIMO) are based mainly on energy detection (ED) [6] or phase detection (PD) [7], where the last ones have been shown to require a smaller number of antennas for the same performance (massive but feasible). For NC mMIMO, the constellation scheme with differential encoding and NC detection can be considered as a non-orthogonal multiplexing technique, where the users are multiplexed in the constellation and separated using the advantage of having a large number of antennas at the base station (BS). The drawback is that, as the number of users increases, the number of antennas required for a feasible performance becomes too high. Therefore, the multiplexing of the users in the constellation is more difficult. In addition, for the channels that experience a Rician fading, such as those presented in [8] for the new scenarios in 5G, the line of sight (LOS) component of the channel deteriorates the performance when several users are multiplexed in the constellation domain. This performance loss can be minimized by redesigning the constellation, at the expense of involving additional complexity in the receiver. Conversely, for the single user NC mMIMO based on Differential Phase Shift Keying (DPSK), the performance is very promising, outperforming that achieved by its coherent counterpart [7] and the NC designs based on energy detection, even for Rician fading, as analyzed in [8]. In the case of multiple users, some constellation designs presented in [7] to be applied in the presence of Rayleigh channels are still to able correctly multiplex two users in the constellation domain, and even up to four users employing a suitable channel coding scheme, with a reasonable required number of antennas. However, this is again at the expense of some complexity in the receiver. In addition, [7] showed how NC schemes outperform their coherent counterparts by up to 1 dB using the suitable channel coding scheme with only 20 antennas on the receiver.

In most of the previous works [6], [7], [8] the bit error rate (BER) or symbol error rate (SER) were used as metrics to assess the performance as a function of signal to noise ratio (SNR) or the necessary number of antennas in mMIMO. These metrics allowed to verify the suitability of a correct demodulation of the users' signals in a NC mMIMO system. However, the transmission is usually packet-based and then the block error rate (BLER) and, related to it, the throughput are more meaningful metrics to describe the system behavior.

Against this background and the results obtained so far, both for taking advantage of the opportunity of NC mMIMO and handling the multiplexing of more users' signals, we analyze the appropriateness of performing the novel multiplexing in the constellation domain combined with classical orthogonal techniques such as TDMA. For this purpose, we analyze the required number of antennas based on the BLER and throughput to determine what multiplexing technique is most advisable for a practical implementation. Based on this analysis, we propose a combination of both orthogonal and non-orthogonal schemes as a feasible way to reduce the complexity and increase the number of users and, thus, the system throughput.

The rest of the paper is organized as follows. The system model for both ways of multiplexing multiple users' signals is introduced in Section II. The analysis of the NC mMIMO behavior using BLER is presented in Section III. The orthogonal and non-orthogonal multiplexing schemes and their combination is analyzed in terms of throughput in Section IV. Finally, we conclude in Section V with some remarks.

## II. System Model and Multiplexing

We evaluate two modes of multiplexing the signals of $J$ single-antenna users in an uplink NC mMIMO system with $R$ antennas at the BS, namely non-orthogonally using the constellation as proposed in [7], denoted in this work as *Constellation Multiplexing Scheme* (CMS) against orthogonally multiplexing the users's signals in the time domain, denoted here as TDMA Multiplexing Scheme (TMS). It should be noted that the orthogonal multiplexing may be performed in the same way in the frequency domain or code domain instead of the time domain. We have chosen the time domain as an illustrative example for the analysis.

The two multiplexing schemes are shown comparatively in Fig. 1 for $J = 2$ users.

1) For CMS, $J$ users transmit simultaneously their signals multiplexed in the new constellation domain, sharing the same time slot.
2) For TMS, $J$ users transmit consecutively in different time slots as corresponding to TDMA.

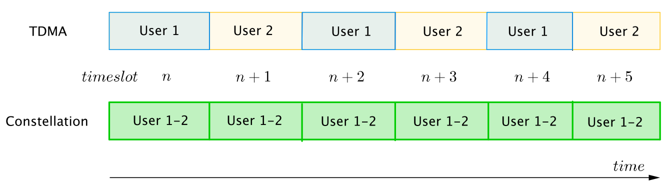


Fig. 1. Schematic for multiplexing $J = 2$ users in CMS or TMS.

As shown in Fig. 2, symbols for user $j$, $s_j$, are based on different $M-PSK$ schemes of order $M$ for each user, then in a time instant $n$ a differential encoding is employed as follows

$$x_j[n] = s_j[n]x_j[n-1]. \quad (1)$$

The propagation channel from user $j$ to the $r$-th antenna of the BS is represented by Rayleigh fading $CN(0,1)$ and additive, white, Gaussian noise (AWGN) components as $CN(0,\sigma^2)$. Hence, we define the reference signal noise ratio as $SNR = \frac{J}{\sigma^2}$.

In the CMS case, the multiplexing is performed by the superposition of each user's individual constellations (IC) which are meticulously designed.

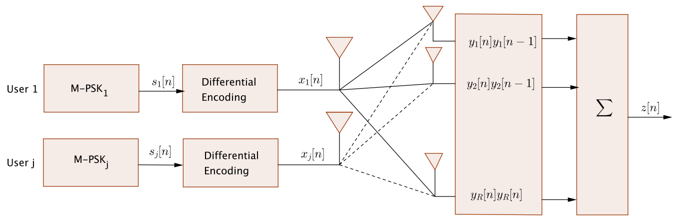


Fig. 2. System model for NC mMIMO based on DPSK (CMS and TMS).

In the receiver, the symbols from all users are combined at the BS in the decision variable $z$, representing the joint constellation of size $M^J$ symbols. In each joint symbol all the individual symbols are multiplexed. In Fig. 3, CSM for $J = 2$ users is shown as an example. The relation between individual symbols $s_j$ (left: blue circles for user 1 and red crossing for user 2) and joint symbols (right) is unique by design. For example: the joint symbol $AF$ in the joint constellation arises from symbol $A$ (user 1) plus symbol $F$ (user 2). Thanks to the large $R$, the channel effects are averaged out and the users' signals can be well separated at the BS.

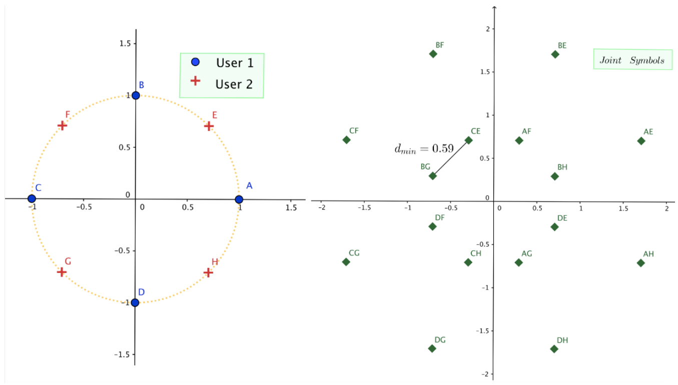


Fig. 3. CMS for $J = 2$ users. Individual (left) and Joint constellation (right)

The IC design for CMS shown in Fig. 3 is based on placing all symbols of a given user at equal distances and also keeping the same distance between any two symbols of all the users. In order to arrange for these distance properties, the users are intercalated in the unit circle and hence, all users will experience the same error performance, namely *equal error protection* (EEP). In this work, for exemplifying the performance of the NC mMIMO we employ EEP schemes, while any other constellation design may be chosen from [7].

In the TMS case, a single user transmits at each time slot using an $M-PSK$ scheme followed by differential encoding according to (1). Thus, the IC used in Fig. 2 per user coincides with the joint constellation since there is no multiplexing in the constellation.

## III. Analysis of the NC mMIMO BLER

We consider a classical transmission frame where packets (or blocks) are transmitted in each time slot, and we define the following parameters:

- $L$ is the length of a packet measured in number of symbols per packet.
- $F$ is the total number of packets transmitted in the considered time for a simulation.
- The number of bits per symbol for each user is $p = \log_2 M$, then the total number of bits per packet is $pL$.

Then, the packet error rate is given by the block error rate (BLER) that can be expressed as a function of SER or BER as follows

$$BLER = 1-(1-BER)^{pL} = 1-(\sqrt[p]{1-SER})^{pL} = 1-(1-SER)^{L}. \quad (2)$$

The SER can be found by using the bound defined in [9] as follows

$$Pe \approx \frac{1}{\mathfrak{K}} \sum_{m=0}^{\mathfrak{K}-1} Q\left(\frac{d_{min}^{m}}{\sqrt{2\mathfrak{I}}}\right), \quad (3)$$

where $d_{min}^{m}$ is the distance of the constellation point $m$ to its nearest neighbor and $\mathfrak{I}$ is the power of noise plus interference due to the multi-user transmission defined for our EEP scheme as follows (more details in [7])

$$\mathfrak{I} = \frac{J^2 + 2\sigma^2 J + \sigma^4}{R}. \quad (4)$$

## IV. Analysis of the performance of the proposed multiplexing schemes

In CMS we are introducing inter-user interference (IUI) due to the non orthogonality among users, but $J$ users can individually make use of the fully available bandwidth. Conversely, in TMS the interference is suppressed at the expense of reducing the bandwidth or time for each user, which is shared among them. Which one is better depends on how many users are multiplexed and how many antennas $R$ can be used to average the interference. Hence, the objective of this analysis is to find $R$ and $J$ for which CMS is better than TMS.

For this purpose, we analyse the throughput ($\gamma$), which measures the rate of successful packet delivery in bits per channel use (bpcu). In order to consider that a transmission is successful, a certain BLER has to be satisfied. Therefore, we calculate the throughput on the basis of the BLER for each multiplexing proposal as follows

$$\gamma_{CMS}[bpcu] = \begin{cases} 0 & BLER_{MU} > BLER_0 \\ (1-BLER_{MU})\log_2 M & BLER_{MU} < BLER_0 \end{cases} \quad (5)$$

$$\gamma_{TMS}[bpcu] = \begin{cases} 0 & BLER_{SU} > BLER_0 \\ \dfrac{(1-BLER_{SU})\log_2 M}{J} & BLER_{SU} < BLER_0 \end{cases} \quad (6)$$

We can see in (5) and (6) that using a simplification the throughput will be zero if the BLER does not go below a certain threshold, $BLER_0$. This value is typically defined by the standards or depending on the application. For example, in LTE [3] a threshold of $BLER_0 = 10\%$ must be guaranteed to consider the transmission successful. Meanwhile, for URLL communications this value can be more restrictive. In addition, note that for the same BLER, the throughput achieved by TMS is lower than that achieved by CMS due to the time or frequency sharing. However, the high interference in CMS increases BLER faster than in TMS, thus there is a crossing point in the performance of both schemes. We are interested in finding this crossing point.

### A. CMS versus TMS multiplexing

First, we analyze the BLER and the throughput which each user achieves individually inside a multiuser environment when we use CMS or TMS. We consider a NC mMIMO-DPSK system with $J = 2$ users and varying SNR and number of antennas. In general we focus in low or moderate SNR values to exemplify the energy efficiency that can be achieved with mMIMO. We use $L = 10$, unless otherwise stated. This value is a small value that can be typical of M2M scenarios, an interesting application of the NC schemes in the 5G context.

For the CMS case, we multiplex two users in the constellation with EEP as shown Fig. 3. In this constellation, all users experience the same performance, thus the same BLER and throughput. We calculate the throughput for each user from BLER using (5). On the other hand, in TMS case we can analyze the performance for one user in its corresponding time instant, which is the single user performance reduced by a factor due to the time sharing. Then, from the BLER for TMS, we calculate the throughput using (6). In Fig. 4 the throughput for CMS and TMS with $J = 2$ is shown. The simulation is carried out over $F = 20,000$ packets and a size of the constellation $M = 2$. We can see that we need to use in TMS $R$ =5 antennas at the BS with SNR=3 dB, $R$ =15 with SNR=0 dB and $R$=40 with SNR=-3 dB in order to receive correctly the packets. By contrast, in CMS we need 10, 50 and 100 antennas for SNR $\in \{3, 0, -3\}$ dB. In this case, for $M = 2$, in TMS each user achieves a maximum $\gamma = 0.5$ bpcu with 10, 20 and 50 antennas. For the same throughput, CMS needs more antennas than TMS, however CMS achieves a higher maximum throughput, reaching 1 bpcu. For low $R$, using TMS is better than CMS, because we do not have mMIMO conditions. From Fig. 4 we conclude that for moderately high $M$, multiplexing in constellation is recommended against time because we achieve higher throughput with an affordable number of antennas when we employ mMIMO.

Now, we analyze what happens when we increase the number of users $J$. In Fig. 5 CMS and TMS for 2, 4, 6, 8 and 10 users are shown. We can see that all users in CMS always achieve the maximum $\gamma$ for a given $M$. Instead, TMS reduces the throughput for each user as $J$ increases. However, TMS is able to demodulate all users with a smaller $R$, whilst CMS needs 30 antennas for 2 users, 550 antennas for $J = 4$ users and, for more users, over 1,000 antennas are needed, which implies that increasing the size of constellation to multiplex

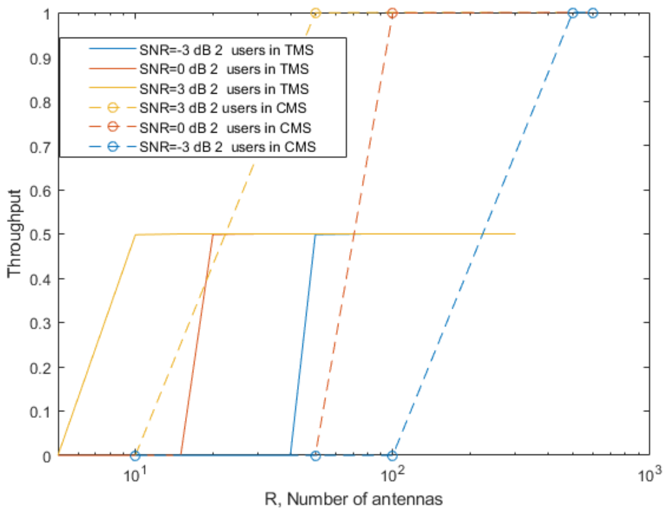


Fig. 4. Comparison Throughput of 2 users in TMS and CMS for $M = 2$, $L$=10 and $F$ =20,000.

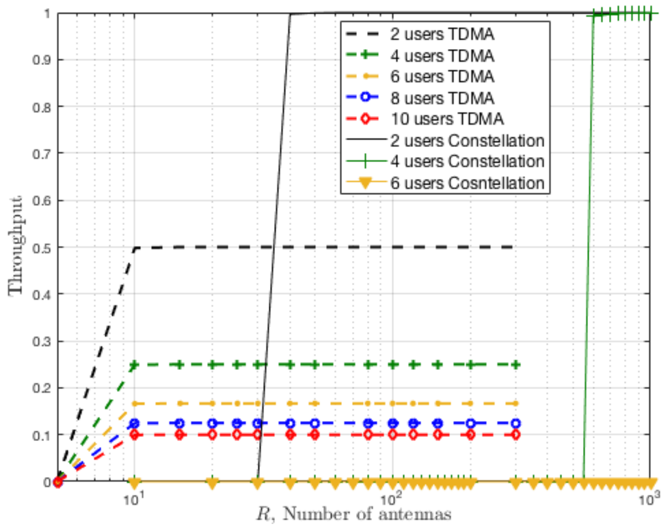


Fig. 5. Comparison Throughput of multiuser system in TMS and CMS for $M = 2$, $L$=10 and $F$ =20,000.

many users leads to unfeasible $R$ for CMS. Since depending on $R$ one or the other may be preferable, we propose to combine both schemes in the next section.

### *B. Hybrid CMS and TMS multiplexing*

In order to achieve the maximum possible throughput and, at the same time, the minimum $R$, we propose to schedule users by combining TDS with CMS. In Fig. 6 the throughput for $J = 4$ and $M = 2$ is shown. We simulate three options of distributing users between TMS and CMS. First, the four users are multiplexed in the time (pure TMS); second, four users are multiplexed in constellation (pure CMS); the last one, we schedule 2 users in constellation and the other two in the time as shown in Fig. 7. We can see in Fig. 6 that in the hybrid option (circled line) we achieve an intermediate throughput between both pure modes, in addition, the number of antennas required to start the reception of correct packets is reduced from 550 to 30 antennas, equivalent to a 94.5% reduction, with the corresponding throughput reduction of 50 %. However, this reduction is lower compared to the $R$ reduction between pure CMS and TMS, since the reduction in throughput corresponds to 50% for a 90% reduction in $R$. In other words, with the hybrid mode we have gained 25% in throughput with only a 3% increase in the number of antennas.

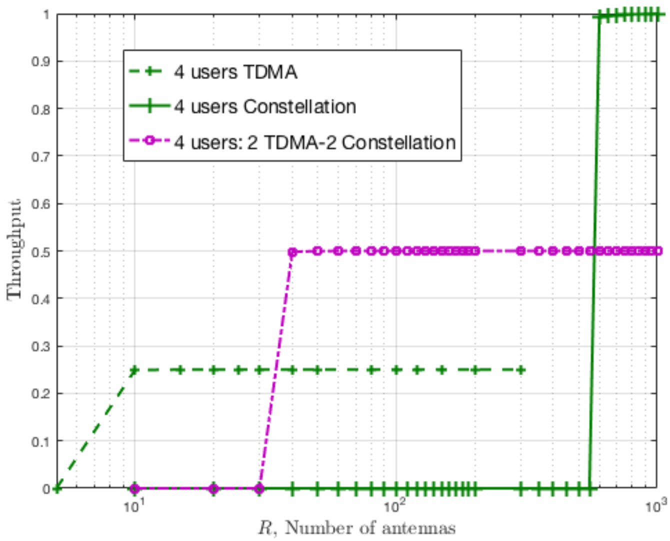


Fig. 6. TMS combined with CMS for $J = 4$ users, $M = 2$ and SNR=3 dB.

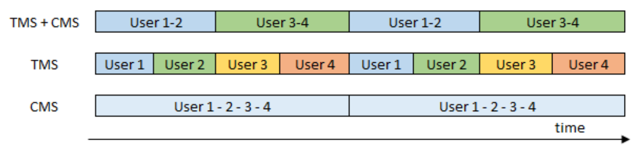


Fig. 7. Schematic for multiplexing $J = 4$ users combined in TMS-CMS.

In Fig. 8 we show the throughput for $J = 8$ users for the three combinations shown in Fig. 9. The first option is scheduling four users grouped in CMS (4-CMS) and, in turn two groups in TMS (2-TMS). The second option for 8 users is 2 users multiplexed in constellation (2-CMS) resulting in 4 groups in time (4-TMS). The third option is the 8 users multiplexed in time (8-TMS). We can see that for a $R =$ 30 antennas which is suitable for mMIMO we achieve twice the throughput. However, if we include more users in the constellation than in TDMA, this number of antennas is too high for a feasible mMIMO. Then, it is preferable when combining both schemes introducing more users in TDMA than in the constellation.

In Fig. 10 we show the throughput for $L = 1,000$. We can see that the $R$ required for demodulation is higher than for $L = 10$ shown in Fig. 5 due to the fact that the probability of having errors in the packet is higher.

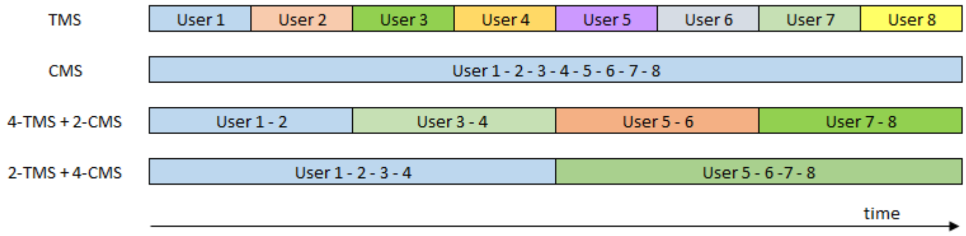


Fig. 9. Schematic for multiplexing $J = 8$ users combined in TMS-CMS.

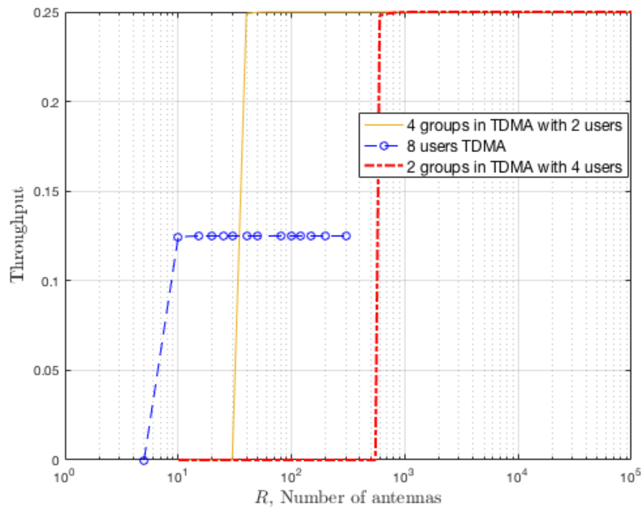


Fig. 8. TMS combined with CMS for $J = 8$ users, $M = 2$ and SNR=3 dB.

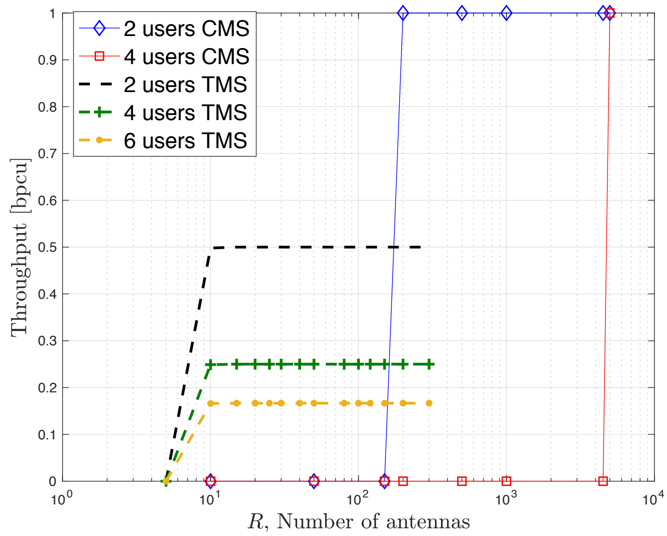


Fig. 10. Comparison Throughput of a MU system in TMS and CMS for M=2 and L=1,000.

## V. Conclusions

The analysis of the BLER and the throughput have allowed us to validate the behavior of the proposed multiuser NC mMIMO system based on DPSK in a packet-based communication network. We have analyzed the performance obtained when multiplexing users in the constellation against other classical techniques such as TDMA. The CMS requires a higher number of antennas at the BS than TMS, although CMS provides a higher maximum throughput than TMS. However, in some cases, the demodulation of multiple users multiplexed in the constellation could require an excessively large and non-practical number of antennas. Therefore, it is necessary to properly manage the tradeoff between throughout and the number of antennas, to reach an optimal operational point.

In order to take advantage of increasing the throughput with CMS, while we may reduce the number of antennas with TDS, we have proposed combining both schemes. Then, it is possible to multiplex 8 users using only 30 antennas and multiplying by two the throughput with respect to orthogonal multiplexing. In addition, we conclude that it is preferable to have a hybrid scheme with more groups multiplexed in time and a few users in constellation rather than having all users in pure CMS or TMS, finding a good tradeoff between the number of antennas and the achievable throughput.

## Acknowledgment

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