# A New MIMO Scheme for Saving Power Consumption

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***Abstract*—In this letter, we introduce a novel transmission scheme to a multi-input multi-output (MIMO) system employing an $M \times M$ antenna structure. The conventional MIMO loads parallel signals onto all transmit antennas to realize essentially $M$ separate channels to achieve high channel capacity. In contrast, the proposed method can dynamically activate a subset of the transmit antennas at each transmission while maintaining the same channel capacity as conventional MIMO. The dynamic activation of the transmit antennas offers a statistically similar advantage to spatial modulation, leading to a reduced number of active RF chains and power saving as well. The theoretical analysis is conducted through the proposed transformation matrix that operates from the signal source to the transmit signal. The effectiveness of this approach is investigated regarding capacity issues and antenna utilization, which are confirmed by simulation results.**

***Index Terms*—Multi-input-multi-output (MIMO), opportunistic nullification, radio frequency (RF) chains.**

## I. Introduction

THE MULTIPLE-INPUT multiple-output (MIMO) technique has been successfully applied in numerous wireless communication systems [1], since it offers high capacity [2], [3] depending on the smallest number of antennas of the transmitter and receiver [4], [5]. In contrast, spatial modulation (SM) was primarily proposed for saving radio frequency (RF) chains, however, at the cost of a capacity reduction in general [6], [7], [8], [9], [10].

To leverage the advantages offered by both aforementioned methods, we introduce a novel approach that uses a transformation matrix to nullify some of the transmit signals at the transmit antennas dynamically, allowing the associated RF chains to be switched off instantly to save power. In comparison with conventional MIMO, although the proposed method does not necessarily require activating all transmit antennas, the channel capacity remains exactly the same. The unique characteristics of this approach are outlined below.

- *Strategy:* Combining the symmetry of the signal constellations, such as BPSK, QPSK, and QAM, with the proposed transformation matrix aims to reduce the number of active RF chains/antennas statistically.
- *Functionality:* Relating the reduced number of RF chains to an on-off mechanism aims to save transmitter power.
- *Complicity:* Using the character of diagonal sub-matrix to reduce the additional complicity in practical operations.

To elaborate on the aforementioned work, this letter is organized as follows: Section II introduces the proposed method and works on capacity issues. Section III figures out the utilization of the RF-chains and Section IV presents the conclusion with the few remarks.

We use the following mathematical notations throughout this letter: boldface uppercase letters denote matrices and boldface lowercase letters denote vectors. The conjugate transpose and the Frobenius norm of a vector or a matrix are denoted by $(\cdot)^\dagger$, and $\|\cdot\|_F$, respectively. Besides, $f_X(x)$ denotes the probability density function (PDF) of a random variable $x$ and $\mathcal{E}\{\cdot\}$ represents the expectation (mean) operator. The combinatorial number $\binom{M}{k}$ denotes the number of $k$ combinations from a set with $M$ elements.

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## II. System Model and Constrained Capacity Issue

In this section, the proposed method is introduced and compared with the MIMO and SM methods theoretically. Additionally, simulation results are presented to substantiate the theoretical studies.

### A. Signal Formulation

The proposed method is designed to reduce the number of active RF chains when using BPSK, QPSK, or QAM modulation in a MIMO transmission system with an $M \times M$ antenna structure as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}, \tag{1}$$

where $\mathbf{y} = [y_1, y_2, \ldots, y_M]^{\mathrm{T}}$ is the received signal in vector form, with $y_m$ denoting the signal received by $m^{\text{th}}$ receive antenna (RA), $\mathbf{H}$ is the channel matrix in dimension of $M \times M$ with its entry $h_{ij}$ representing the $(i,j)^{\text{th}}$ channel coefficient linking the $j^{\text{th}}$ transmit antenna (TA) to the $i^{\text{th}}$ RA, $\mathbf{x} = [x_1, x_2, \ldots, x_M]^{\mathrm{T}}$ denotes the transmit signal, and $\mathbf{z} = [z_1, z_2, \ldots, z_M]^{\mathrm{T}}$ is the noise. It is assumed that both the channel coefficient and the noise obey the normalized independent and identical Gaussian distributions, expressed by $h_{ij} \sim \mathcal{CN}(0,1)$ and $z_i \sim \mathcal{CN}(0, \sigma_z^2)$, respectively.

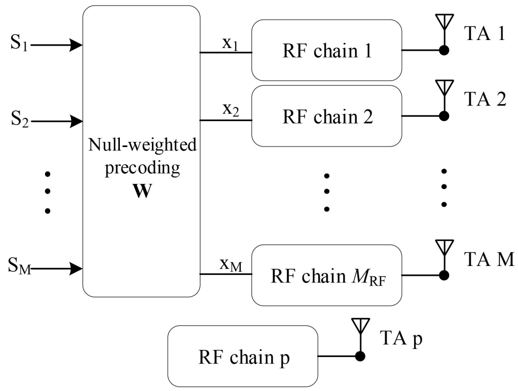



Fig. 1. The transmitter structure from the transform matrix to the antennas.

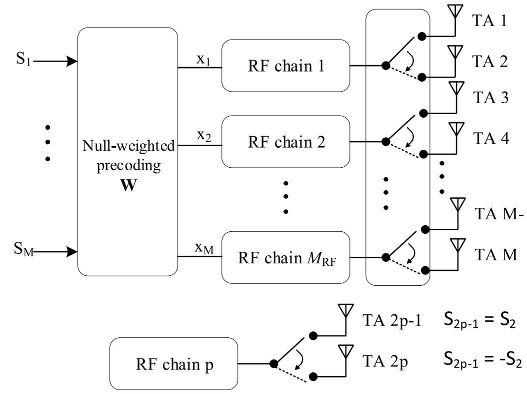



Fig. 2. RF chain reduction of the ON method by using BPSK.

To borrow the MIMO signal-structure in (1), we introduce a transformation matrix

$$\mathbf{W} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 & 0 & \dots & 0 & 0 \\ -1 & 1 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 1 & 1 \\ 0 & 0 & 0 & \dots & -1 & 1 \end{bmatrix}_{M\times M}, \tag{2}$$

to change the channel-input by

$$\mathbf{x} = \mathbf{W}\mathbf{s}, \tag{3}$$

where $\mathbf{s} = [s_1, s_2, \dots, s_M]^{\mathrm{T}}$ is the information symbols of the transmission in the vector form and $\mathbf{W}$ is the proposed transformation matrix in the dimension of $M \times M$.

Actually, the transformation matrix $\mathbf{W}$ consists of M/2 sub-matrix

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \tag{4}$$

in the diagonal positions.

For simplifying the calculations latter, we note a feature of $\mathbf{W}$ by

$$\mathbf{W}^{-1} = \mathbf{W}^{\dagger} \tag{5}$$

where $\mathbf{W}^{-1}$ and $\mathbf{W}^{\dagger}$ are the inverse- and transpose conjugate matrix of $\mathbf{W}$ respectively.

By organizing two adjacent information symbols, sequentially, into symbol-pairs, e.g., $\{s_1, s_2\}$, $\{s_3, s_4\}, \dots, \{s_{M-1}, s_M\}$, we defining a symmetric signal-pair when $s_i = s_{i+1}$, and asymmetric one when $s_i = -s_{i+1}$.

The sub-matrix (4) can nullify one of its outputs when the input is either a symmetric- or asymmetric symbol pair. For example, inputting a symmetric symbol pair leads to $x_{i+1} = 0$, while an asymmetric symbol pair results in $x_i = 0$. However, when the symbol pair is neither symmetric nor asymmetric, no outputs can be nullified, i.e., $x_i, x_{i+1} \neq 0$.

In the operation, each transmission activates the RF chains, where the input $x_i \neq 0$. However, for those RF chains with $x_i = 0$, inactivation occurs as illustrated in Fig. 1. In fact, by switching off and on the power of the RF chains when their inputs are zero and non-zero respectively, each RF chain operates in an on-off mode. Here, we term this technical strategy as the opportunistic nullification (ON) method to emphasize its power-saving ability.

It is interesting to observe that when applying BPSK to signal modulation, the two input symbols of each sub-matrix (4), e.g., $s_i$ and $s_{i+1}$, are either symmetric or asymmetric. Consequently, one of the two outputs must be zero, allowing for the effective replacement of the two corresponding RF chains by switching one RF chain between two antennas, as illustrated in Fig. 2. As a result, the number of RF chains can be halved. More comprehensive discussions regarding the utilization of higher-order signal modulations will be conducted later.

As to the additional complexity of the ON method, we start the analysis from the signal reception by

$$\hat{\mathbf{x}} = \mathbf{W}^{-1}\mathbf{H}^{-1}\mathbf{y} = \mathbf{W}^{-1}\mathbf{H}^{-1}\mathbf{H}\mathbf{W}\mathbf{s} + \mathbf{z}, \tag{6}$$

where $\hat{\mathbf{x}}$ is the recovered symbol vector. The complexity of the conventional MIMO can be found at the calculations of $\mathbf{H}^{-1}\mathbf{H}$, while $\mathbf{W}^{-1}\mathbf{W}$ adds more and consumes much less calculating resources because either $\mathbf{W}^{-1}$ or $\mathbf{W}$ consists of 2x2 sub-matrices in the diagonal form.

### B. Capacities of the ON Method

Though the ON method does not necessarily require activating all transmit antennas at each transmission, it can still maintain the same capacity as that of the conventional MIMO, as demonstrated below.

Prove: taking (3) into (1) yields

$$\mathbf{y} = \mathbf{H}\mathbf{W}\mathbf{s} + \mathbf{z}, \tag{7}$$

where $\mathbf{y}$ is the received signals.

Assuming that each element of $\mathbf{s}$, e.g., $s_i$, obeys independent identical Gaussian distribution of the same variance, the channel capacity can be calculated by

$$\begin{aligned} C_{ON} &= \log_2\left|\mathbf{I}_M + \frac{1}{\sigma_z^2}\mathbf{H}\mathbf{W}\mathbf{R}_S\mathbf{W}^{\dagger}\mathbf{H}^{\dagger}\right| \\ &= \log_2\left|\mathbf{I}_M + \frac{E_s}{\sigma_z^2}\mathbf{H}\mathbf{W}\mathbf{W}^{\dagger}\mathbf{H}^{\dagger}\right| \\ &= \log_2\left|\mathbf{I}_M + \frac{E_s}{\sigma_z^2}\mathbf{H}\mathbf{H}^{\dagger}\right|, \end{aligned} \tag{8}$$

where $C_{\text{ON}}$ represents the constrained capacity of the ON method. It is noted that $|\mathbf{HWW}^{\dagger}\mathbf{H}^{\dagger}| = |\mathbf{HH}^{\dagger}|$ in (8), because of $\mathbf{WW}^{\dagger} = \mathbf{I}$ resulted by (5), where $\mathbf{I}$ is a identity matrix.

Further, we calculate the constrained capacity for the use of finite alphabets by

$$\begin{aligned}\gamma_{\text{ON}} &= M\log_2 L \\ &\quad - \frac{1}{L^M}\mathcal{E}_{\mathbf{H}}\left\{\sum_{k'=1}^{L^M}\mathcal{E}_{\mathbf{z}}\left\{\log_2\sum_{k=1}^{L^M} e^{-\left(\frac{\|\mathbf{HW}(\mathbf{s}_k-\mathbf{s}_{k'})+\mathbf{z}\|_F^2-\|\mathbf{z}\|_F^2}{\sigma_z^2}\right)}\right\}\right\} \\ &= M\log_2 L \\ &\quad - \frac{1}{L^M}\mathcal{E}_{\mathbf{H}}\left\{\sum_{k'=1}^{L^M}\mathcal{E}_{\mathbf{z}}\left\{\log_2\sum_{k=1}^{L^M} e^{-\left(\frac{\|\mathbf{H}(\mathbf{s}_k-\mathbf{s}_{k'})+\mathbf{z}\|_F^2-\|\mathbf{z}\|_F^2}{\sigma_z^2}\right)}\right\}\right\} \\ &= M\log_2 L \\ &\quad - \frac{1}{L^M}\mathcal{E}_{\mathbf{H}}\left\{\sum_{k'=1}^{L^M}\mathcal{E}_{\mathbf{z}}\left\{\log_2\sum_{k=1}^{L^M} e^{-d_{kk'}/\sigma_z^2}\right\}\right\}, \qquad (9)\end{aligned}$$

where $\gamma_{\text{ON}}$ is the constrained capacity of the ON method and $d_{kk'} = \|\mathbf{H}(\mathbf{s}_k - \mathbf{s}_{k'}) + \mathbf{z}\|_F^2 - \|\mathbf{z}\|_F^2$ with $k = 1, 2, \ldots, L^M$, and $L$ is the modulation order. It is noted that the second equality holds though $\mathbf{HW}$ is replaced by $\mathbf{H}$ because the role of $\mathbf{W}$ is to change the element $(hw)_{i,j}$, by $(h_{i,j} + h_{i,(j+1)}\frac{(-1)^j+1}{2} - h_{(i+1),j}\frac{(-1)^{(j+1)}+1}{2})/\sqrt{2}$, that does not change the statistic propriety of $h_{i,j}$, which is an independent identical Gaussian variable.

It is clearly found that the results of (8) and (9) are exactly the same as the channel capacity [11] and constrained capacity [12] of the conventional $M \times M$ MIMO.

–Proved.

### C. Constrained Capacities of Grouped Spatial Modulation

To facilitate comparisons between the ON- and SM methods on the capacity issue, we calculate the constrained capacities of grouped spatial modulation (GSM) under the assumption that both methods use the same number of antennas.

Here, the GSM method divides its $M$ antennas into $M/2$ groups, each of which selects one between two antennas, according to the bit's value mapped onto the antennas, to be activated at each transmission. The decision to employ the aforementioned GSM for comparison stems from the compatibility of both methods, which operate in a parallel manner when BPSK modulations are used.

The constrained capacity of the GSM can be calculated by [13] and [14],

$$\begin{aligned}C_{\text{GSM}} &= \log_2\frac{2^{M/2}/|\mathbf{\Sigma}_{\mathbf{ch}}|\cdot e^{-\mathbf{y}^H(\mathbf{\Sigma}_{\mathbf{ch}})^{-1}\mathbf{y}}}{\sum_{\mathbf{x}'_{\mathbf{ch}}} 1/|\mathbf{\Sigma}_{\mathbf{ch}'}|\cdot e^{-\mathbf{y}^H(\mathbf{\Sigma}'_{\mathbf{ch}})^{-1}\mathbf{y}}} \\ &\quad + \log_2\left|\mathbf{I}_M + \frac{E_s}{\sigma_z^2}\mathbf{H}_{\mathbf{ch}}\mathbf{H}_{\mathbf{ch}}^{\dagger}\right|, \qquad (10)\end{aligned}$$

where $C_{\text{GSM}}$ is the channel constrained capacity, $\mathbf{x}_{\mathbf{ch}}$ denotes the selected transmit antenna pattern, $\mathbf{H}_{\mathbf{ch}}$ is the corresponding selected columns of channel matrix $\mathbf{H}$, and the covariance matrix $\mathbf{\Sigma}_{\mathbf{ch}}$ is calculated by

$$\mathbf{\Sigma}_{\mathbf{ch}} = \mathbf{H}_{\mathbf{ch}}\mathbf{H}_{\mathbf{ch}}^{\dagger}E_s + \sigma_z^2\mathbf{I}_M. \qquad (11)$$

where $E_s$ is assumed to obey the Gaussian distribution.

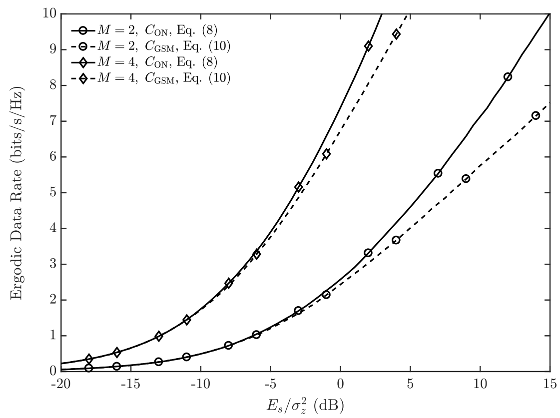



Fig. 3. Comparisons of Ergodic constrained capacities between the ON and GSM methods over Rayleigh channel.

For the use of the finite alphabets to the signal modulations, the constrained capacity is calculated by

$$\begin{aligned}\gamma_{\text{GSM}} &= \frac{M}{2}\log_2(2L) - (2L)^{-M/2} \\ &\quad \times \sum_{k'=1}^{(2L)^{M/2}}\mathcal{E}_{\mathbf{z}}\left\{\log_2\sum_{k=1}^{(2L)^{M/2}} e^{-d_{kk'}/\sigma_z^2}\right\}, \qquad (12)\end{aligned}$$

with $d_{kk'} = \|\mathbf{H}(\mathbf{x}_k - \mathbf{x}_{k'}) + \mathbf{z}\|_F^2 - \|\mathbf{z}\|_F^2$ by $M \times 1$ vector $\mathbf{x}_k$ denoting the $k^{\text{th}}$ variation of transmitted signals in the GSM, $k = 1, 2, \ldots, (2L)^{M/2}$, where $\gamma_{\text{GSM}}$ is the achievable data rate of the GSM.

### D. Simulated Comparison

In this subsection, simulations are conducted to compare the constrained capacities between the ON- and GSM methods in fading channels.

At first, the capacities' comparisons between the ON- and GSM methods are made based on computing the ergodic values (8) and (10). The outcomes are plotted in Fig. 3, where $\bar{E}_s$ represents the averaged symbol energy of the signals obeying the Gaussian distribution. Secondly, the Ergodic achievable data rates of both methods are also compared by computing ergodic values of (9) and (12). The results are shown in Fig. 4, where the signal modulations of BPSK and QPSK are used as the input signals. It is found that in the case of either a Gaussian distributed signal or finite alphabet signal, the ON method can obtain gains over the GSM method.

For the use of finite alphabets, saturations are observed in the performance of both methods at high SNR. However, in the lower SNR region, it is noted that the gain increases with higher signal energy-to-noise ratios.

The BER performances of both methods are simulated using the hard decision method. Once again, the advantage of the ON method is evident in Fig. 5, where the ON method slightly but consistently outperforms the grouped SM in terms of BER compared to its counterpart.

Apart from the capacity advantage analyzed above, it is worth mentioning that the GSM system requires sending pilots to its receiver for identifying every antenna, i.e., the bits

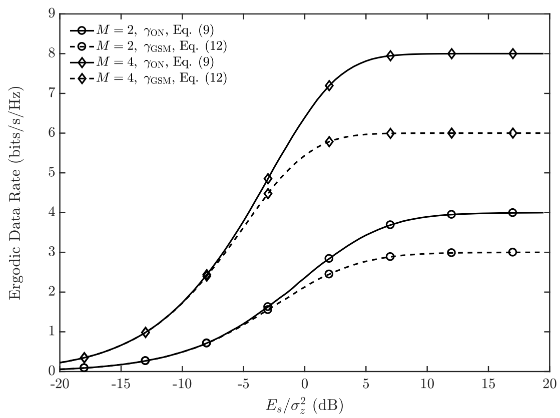



Fig. 4. Comparisons of Ergodic achievable data rates between the ON and GSM methods over Rayleigh channels.

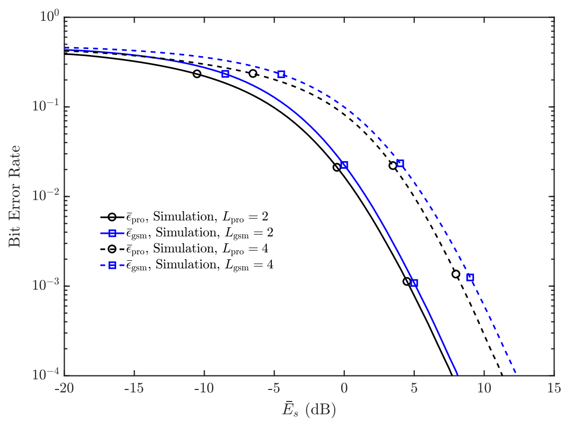


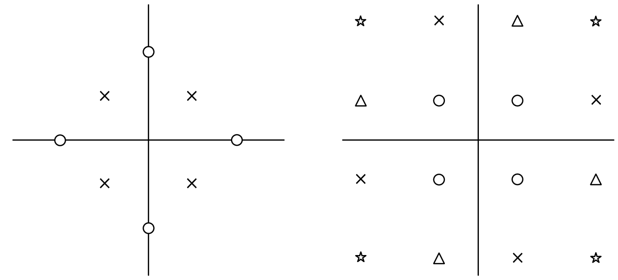

Fig. 5. BER performance comparisons between ON method and GSM transmissions.

defined onto the antennas, while the ON method does not. Thus, in comparison, saving bandwidth of the pilots can be another benefit of the ON method for gaining spectral efficiency practically.

## III. Analysis of Average Active RF Chains

The distinctive feature of the ON method lies in its ability to reduce active RF chains without any loss of channel capacity compared with conventional MIMO. Each RF chain can actually have two types of inputs: signals of non-zero amplitude or zero amplitude. Hence, the RF chains can operate in an on-off mode for power-saving purposes, as mentioned in the section above.

In the $p^{\rm th}$ sub-matrix of (4), for using $L$-ary phase-shift keying (PSK) or the $L$-ary quadrature amplitude modulation (QAM) $p \in \{1, 2, \ldots, M/2\}$, both cases of $s_{2p-1} = s_{2p}$ and $s_{2p-1} = -s_{2p}$ occur at the same probability $1/L$, where $L$ is the modulation order. For example, as shown in Fig. 6, the probabilities that $s_{2p-1} = s_{2p}$ and $s_{2p-1} = -s_{2p}$ are both 1/8 for the 8QAM constellation in (a) and both 1/16 for the 16QAM in (b).



(a) 8QAM (b) 16QAM

Fig. 6. APM constellations.

With the transformation matrix $\mathbf{W}$, we have

$$\begin{cases} x_{2p-1} = \sqrt{2} s_{2p-1} \\ x_{2p} = 0 \end{cases} \tag{13}$$

in the case of $s_{2p-1} = s_{2p}$, and

$$\begin{cases} x_{2p-1} = 0 \\ x_{2p} = \sqrt{2} s_{2p-1} \end{cases} \tag{14}$$

in the case of $s_{2p-1} = -s_{2p}$. Therefore, in either of these cases, the number of RF chains can be reduced by half by the sub-matrix.

However, in the cases other than $s_{2p-1} = s_{2p}$ and $s_{2p-1} = -s_{2p}$, expressed as $s_{2p-1} = ae^{j\theta} s_{2p}$ by excluding the conditions where $a = 1$ and $\theta = 0$ or $\pi$, both transmitted signals $x_{2p-1}$ and $x_{2p}$ are non-zero for the $p^{\rm th}$ sub-matrix.

As a result, half of the inputs to the RF chains with the $p^{\rm th}$ sub-matrix can be opportunistically nullified at the probability $2/L$, i.e., in both cases $s_{2p-1} = s_{2p}$ and $s_{2p-1} = -s_{2p}$. For example, the transmitted signals $x_{2p-1}$ and $x_{2p}$ are listed in Table I for the cases of $s_{2p-1} = s_{2p}$ and $s_{2p-1} = -s_{2p}$ with the quadrature phase shift keying (QPSK) modulation, i.e., $s_m \in \{1, j, -1, -j\}$, $m = 1, 2, \ldots, M$, $p = 1, 2, \ldots, M/2$, where $j = \sqrt{-1}$ is the imaginary unit. There are four cases in total for the two QPSK symbols $s_{2p-1}$ and $s_{2p}$, i.e., $s_{2p-1} = s_{2p}$, $s_{2p-1} = -s_{2p}$, $s_{2p-1} = js_{2p}$, and $s_{2p-1} = -js_{2p}$. In the latter two cases, both the transmitted signals $x_{2p-1}$ and $x_{2p}$ are non-zero values. That is, the probability that one of the two TAs in every group has a null input value within a QPSK-modulated transmission is 1/2.

Since the $M/2$ groups of data streams are independent, the average number of RF chains required in the ON method an opportunistic input-nulled transmission, denoted by $M_{\rm ON}^{\rm RF}$, is calculated using

$$\begin{aligned} M_{\rm ON}^{\rm RF} &= \sum_{k=0}^{M/2} \binom{M/2}{k} (M/2 + k)(1 - 2/L)^k (2/L)^{M/2-k} \\ &= \frac{L-1}{L} M = M - \frac{M}{L}, \end{aligned} \tag{15}$$

while that of conventional MIMO is $M_{\rm Con}^{\rm RF} = M$.

Fig. 7 compares the ON method and conventional MIMO for the antenna utilizations, where the average number of the active RF chains are plotted against the number of bits per symbol, i.e., $\log_2 L$, at $M = 2$, where $M$ is the number of the RF chains: The reduction of the active RF chains of the ON

TABLE I
AN ILLUSTRATION OF THE QPSK MODULATION WITH ON METHOD

| QPSK Symbols | | Transmitted Signals | | Note |
|---|---|---|---|---|
| $s_{2p-1}$ | $s_{2p}$ | $x_{2p-1}$ | $x_{2p}$ | |
| 1 | 1 | $\sqrt{2}$ | 0 | The input of TA $2p$ is nullified. |
| $j$ | $j$ | $\sqrt{2}j$ | 0 | |
| $-1$ | $-1$ | $-\sqrt{2}$ | 0 | |
| $-j$ | $-j$ | $-\sqrt{2}j$ | 0 | |
| 1 | $-1$ | 0 | $\sqrt{2}$ | The input of TA $2p-1$ is nullified. |
| $j$ | $-j$ | 0 | $\sqrt{2}j$ | |
| $-1$ | 1 | 0 | $-\sqrt{2}$ | |
| $-j$ | $j$ | 0 | $-\sqrt{2}j$ | |

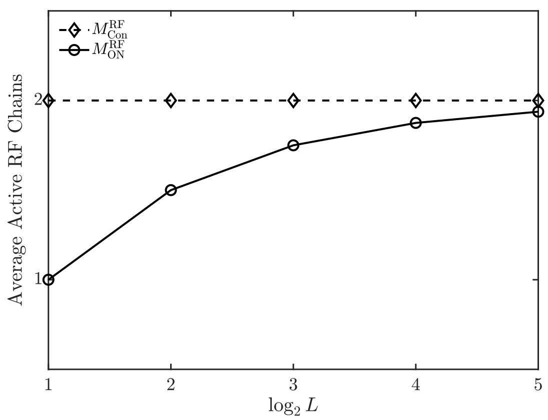



Fig. 7. Average active RF chains versus the number of bits per symbol, $\log_2 L$.

is found to increase with decrease of the order of the symbol modulation. This trend highlights the statistical feature of the power saving of the transmitter.

Actually, the practical merit of the ON method lies in the reduction of active RF chains, as a large portion of power is consumed by these chains. By switching off the power of inactive RF chains, power consumption can be reduced accordingly. By examining the results in Fig. 7, we find that using lower-order signal modulations is better than using higher-order signal modulations in terms of power savings. It can be inferred that the ON method shows its highest efficiency when using BPSK and limitations with higher-order modulations.

## IV. CONCLUSION

The letter introduces a transformation matrix designed for application in the antenna structure of conventional MIMO systems, thereby establishing a novel MIMO scheme in a broader context. The theoretical significance of this letter lies in achieving the exact same channel capacity as conventional MIMO while statistically employing a fewer number of active transmit antennas. The practical advantage is evident in the power-saving achieved at the transmitter. The validity of this approach is confirmed through simulation results.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