Energy-Efficient Architecture for Receive Spatial Modulation in Large MIMO Systems

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***Abstract*—Cost and power consumption are substantial challenges for multiple-input-multiple-output (MIMO) wireless communication systems when the number of antennas and the operating carrier frequency increase. We present a low cost and low power consumption receive spatial modulation (RSM) architecture based on a simple receiver design. We propose a time-division-duplex (TDD) transmission protocol aimed to reduce the training overhead where the channel knowledge is required only at the base station. Simulation results presented show that the power consumption and the energy efficiency of the proposed RSM architecture outperform the hybrid and conventional MIMO systems.**

***Index Terms*—Massive MIMO, Receive spatial modulation, Hybrid MIMO, Conventional MIMO, Power consumption.**

I. Introduction

The number of antennas at the base station (BS) and the user terminal (UT) are expected to increase extensively for future multiple-input-multiple-output (MIMO) wireless communication systems [1]. The conventional MIMO architecture, developed for centimetre-wave based communications, depends on a fully digital structure where each antenna connected to a radio-frequency (RF) chain and analog-to-digital-converter (ADC), as it is shown in Fig. 1. However, the cost and power consumption of a RF is highly dependent on the spectrum band of interest. Conventional MIMO becomes very challenging with large arrays due to the substantial increase in complexity and energy consumption.

Many techniques have been developed to reduce the cost and the power consumption. In hybrid MIMO systems [2], analog devices (phase shifters) are used to reduce the number of RF chains, but still seize the use of many antennas to maintain high gains. The phase shifter consumes much less power than RF chain and ADC. However, in the fully connected hybrid MIMO in Fig. 2, each RF chain connected to number of phase shifters equals to the number of receive antennas. Thus, the number of phase shifters increases rapidly by increasing the number of RF chains. Consequently, a large number of phase shifters may consume greater power than RF chains and ADCs [3].

In spatial modulation (SM) systems [4], the BS transmits spatial symbol by activating subset of the transmit antennas and as a result the number of RF elements and ADCs are less than the number of transmit antennas. The basic structure of SM is called space shift keying (SSK) [5]. In SSK, only one transmit antenna is active at given time slot. The input bit stream is converted to index of active transmit antenna, and the SSK receiver detects this index. For the sake of increasing the number of transmitted bits per channel use (BPCU), the active antenna transmits data symbol [4]. For further increasing of the transmitted BPCU, more than one antenna is active simultaneously [6].

On the contrary, in receive spatial modulation (RSM) systems, the BS transmits spatial symbol by activating subset of the receive antennas [7]. The SM/RSM systems can simplify the MIMO transceiver and achieve high data rates. Recently, a novel RSM architecture have been reported in [8] for indoor 60 GHz communication. Generalizing the concept of SM/RSM for high frequency communication is an interesting open research problem.

In Fig. 3, we propose a MIMO RSM architecture for a single user system aimed to reduce the power consumption and improve the energy efficiency (EE) at the receiver . The benefits of the proposed architecture result from the following points

- Using small number of RF chains and ADCs which leads to a significant power consumption reduction.
- Exploiting the receive antennas to transfer spatial data which boosts the transmission data rates.
- Operating reliably at high frequencies by performing receive antennas selection to reduce the effect of receive antennas correlation.
- We propose a time-division-duplex (TDD) transmission protocol aimed to reduce the training overhead where the channel knowledge is required only at the BS.

Performance is compared between the proposed system and the hybrid and conventional MIMO systems in terms of power consumption and EE. Simulation results are presented showing that the power consumption and the EE of the proposed RSM architecture outperform the hybrid and conventional MIMO systems.

II. System Model

A. System Model

We consider a downlink (DL) of single user MIMO system with N_t antennas at the BS and N_r antennas at the UT. We propose a RSM MIMO system where the BS is fully digital and the UT structure is illustrated at Fig. 3. The proposed receiver relies on energy-efficient devices that can be represented as follows

- RF chain and high precision ADC: these devices are the most power consuming so we use two RF chains and two high precision ADCs for any number of receiver antennas.
- Amplitude detector (AD): it is a cheap analog device that detects the amplitude of the RF signal in absolute value and operates at high frequencies with high sensitivity and negligible power consumption [9]. TABLE I in [10] shows that the AD can operate at frequency range from (1GHz to 85GHz) with sensitivity from (-5dBm to -50dBm).
- 1-bit ADC: it consumes low power as the power consumption of the ADC grows exponentially with number of quantization bits.
- Phase shifters: we use number of phase shifters equals to N_r for the uplink transmission only while the hybrid system in Fig. 2 uses phase shifters much more than N_r.

B. Power Consumption

According to [3], the power consumption of the different receivers components can be expressed in the following table

TABLE I
RECEIVERS COMPONENTS POWER CONSUMPTION

$P_{\text{LNA}} = P_{\text{ref}}$	$P_{\text{PS}} = 1.5P_{\text{ref}}$	$P_{\text{RF chain}} = 2P_{\text{ref}}$
$P_{\text{ADC}} = 10P_{\text{ref}}$	$P_{\text{SW}} = 0.25P_{\text{ref}}$	$P_{\text{BB}} = 10P_{\text{ref}}$

where $P_{\text{PS}}, P_{\text{SW}}$ and P_{BB} are the phase shifter, switch and baseband power consumption respectively.

The DL receiver power consumption of the proposed system P_p (Fig. 3), conventional MIMO P_C (Fig. 1) and hybrid MIMO P_H (Fig. 2) can be expressed as

$$P_P = N_r\left(P_{\text{LNA}} + P_{\text{SW}}\right) + \left(P_{\text{RF chain}} + P_{\text{ADC}}\right) + P_{\text{BB}} \quad (1)$$

$$P_C = N_r\left(P_{\text{LNA}} + P_{\text{RF chain}} + P_{\text{ADC}}\right) + P_{\text{BB}} \quad (2)$$

$$P_H = N_r\left(N_{rf}+1\right)P_{\text{LNA}} + N_r N_{rf} P_{\text{PS}} + 2N_{rf}\left(P_{\text{RF chain}} + P_{\text{ADC}}\right) + P_{\text{BB}} \quad (3)$$

where N_{rf} is the number of RF chains.

We define the EE as the transmission bit rate for a given bit error rate (BER) per the receiver power consumption that can be expressed as

$$\text{EE} = \text{BPCU}\frac{\text{BW}}{P_r} \quad (4)$$

where BW is the bandwidth and P_r is the receiver power consumption.

III. Transmission Protocol

We consider TDD system with uplink (UL)/DL channel reciprocity and the channel state information (CSI) is known at the BS. In general, the UL/DL RF chains are different and the equivalent channel is not reciprocal. The RF chains requires calibration [11] to achieve the channel reciprocity. In Fig. 4, we present a DL TDD transmission protocol for the proposed

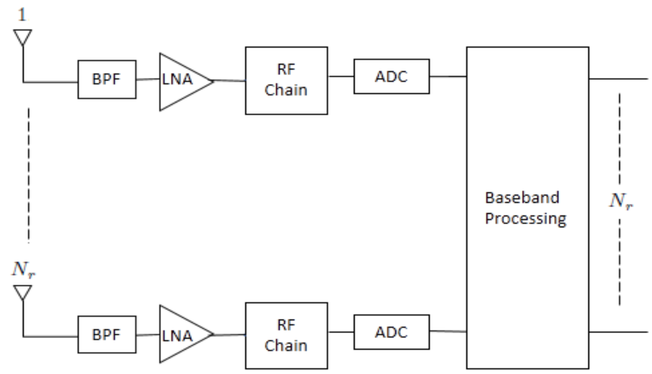

Fig. 1. Conventional MIMO receiver.

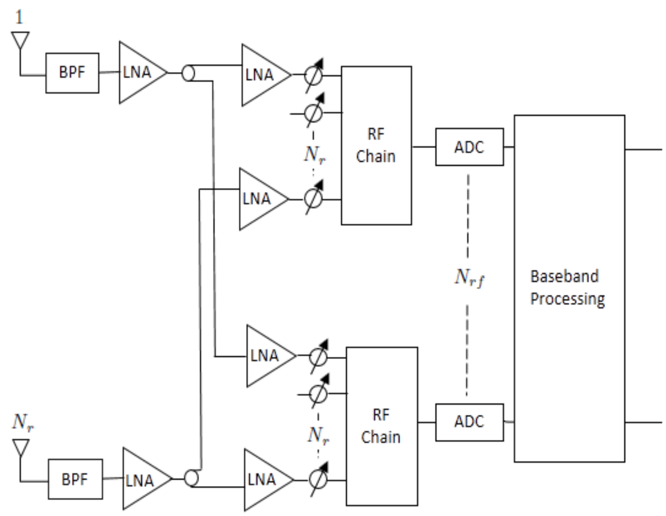

Fig. 2. Fully connected hybrid MIMO receiver.

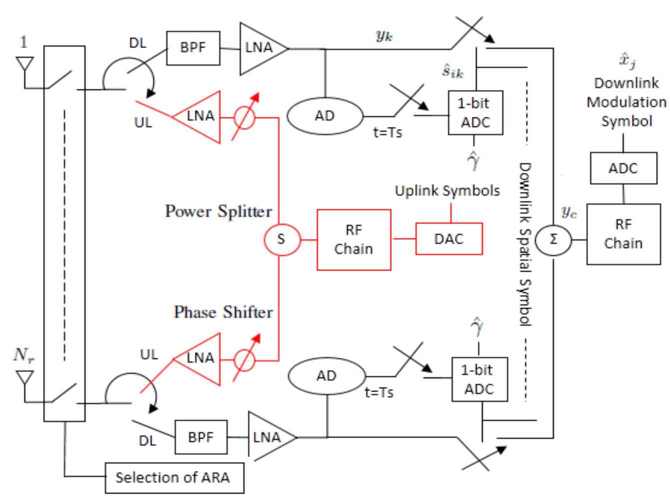

Fig. 3. UL circuitry (red) and DL circuitry (black) at the receiver in the proposed downlink RSM scheme.

UL training	DL training	DL data

Fig. 4. DL TDD transmission protocol

system. The proposed protocol can work efficiently for low and average mobility systems where the channel coherence time can be larger than the TDD frame length [12].

A. UL Training

The UT transmits pilot symbols to allow the BS acquire the CSI. We propose a simple UL circuit based phase shifters that can achieve the optimal training pilot symbols matrix (PSM). In channel estimation, the optimal scaled least squares PSM can be implemented by phase shifters as it can be designed based discrete-Fourier-transform basis as described in eq. (13) of section IV in [13]. In this method, N_r pilot symbols are needed to estimate the channel [13]. The channel estimation error (ϵ) was given by eq. (20) in [13] and can be expressed as

$$\epsilon = \frac{\sigma^2 N_r^2 N_t \mathrm{tr}\{\mathrm{E}\big[\mathbf{H}\mathbf{H}^H\big]\}}{\sigma^2 N_r^2 N_t + P_t \mathrm{tr}\{\mathrm{E}[\mathbf{H}\mathbf{H}^H]\}} \tag{5}$$

where $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix, σ^2 is the noise variance and P_t is the transmit power. When N_t or N_r increases as in the massive MIMO case, the estimation error in (5) can be asymptotically approximated as eq. (21) in [13]

$$\epsilon_\infty = \mathrm{tr}\{\mathrm{E}\big[\mathbf{H}\mathbf{H}^H\big]\} \tag{6}$$

where the error depends on the strength of the channel. By considering the clustered millimeter wave channel model in [2] with path-loss P_l, the asymptotic channel estimation error in (6) becomes $\frac{N_t N_r}{P_l}$.

B. DL Training

The BS sends pilot symbols to allow the UT estimates the 1-bit ADC threshold. In [14], the maximum likelihood threshold estimator is proved showing that the system performance with the estimated threshold approaches the exact threshold by transmitting one pilot symbols.

C. DL Data

In order to overcome the correlation between the receive antennas, the BS selects the best N_a receive antennas to be active based on the channel conditions. The problem of receive antennas selection is studied in [15] to combat the receive antennas correlation where the active antennas are selected to maximize the channel capacity. The proposed antennas selection criterion is presented later in this section. The BS can inform the UT about the active receive antennas (ARA) through control channel. The BS transmits spatial and modulation data symbols. The entries of the spatial symbol $\mathbf{s}_i$ are ones and zeros such that $\mathbf{s}_i$ includes N_a bits from the input bit stream where $i \in \{1, \cdot\cdot\cdot, 2^{N_a} - 1\}$ and $\mathbf{s}_i \neq [00 \cdots 0]^T$. The modulation symbol $x_j \in M$ size constellation where $j \in \{1, \cdots, M\}$. The number of transmitted $\mathrm{BPCU} = (N_a + \log_2 M)$.

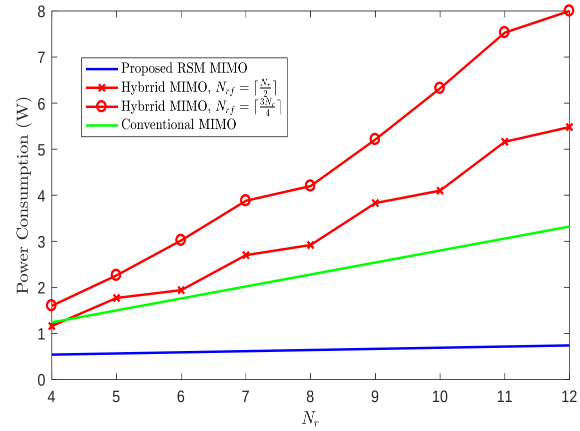

Fig. 5. Power consumption of various MIMO transceivers architectures.

The transmitted ($\mathbf{x}_i^j$) and the received ($\mathbf{y}$) vectors can be expressed

$$\begin{aligned} \mathbf{x}_i^j &= \sqrt{\beta P}\mathbf{B}\mathbf{s}_i x_j \\ \mathbf{y} &= \sqrt{\beta P}\mathbf{H}\mathbf{B}\mathbf{s}_i x_j + \mathbf{n} \end{aligned} \tag{7}$$

where $\mathbf{B} = \mathbf{H}_a^H \left(\mathbf{H}_a\mathbf{H}_a^H\right)^{-1}$ is a zero forcing precoding matrix, $\mathbf{H}_a$ is the channel between the BS and the ARAs, $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is independent identically distributed complex gaussian noise vector, β is used to fix the transmit power and $\beta^{-1} = \mathrm{Tr}\left\{\mathbf{B}^H\mathbf{B}\right\} = \mathrm{Tr}\left\{(\mathbf{H}_a\mathbf{H}_a^H)^{-1}\right\}$. The received signal per the k^{th} ARA can be given as

$$y_k = \sqrt{\beta P} s_{ik} x_j + n_k \tag{8}$$

where s_{ik} is the k^{th} entry of $\mathbf{s}_i$.

For a given N_a, the BS chooses the superior N_a rows from $\mathbf{H}$ to get $\mathbf{H_a}$ such that β is maximized which implies maximizing the received signal power.

The optimal maximum likelihood spatial symbol detector is proved in [14] where

- At first, the AD connected to each ARA measures the amplitude of the received signal in (8). The output of the k^{th} AD is compared with a threshold to estimate $\hat{s}_{ik}$. The UT estimates the threshold during the DL training.
- After estimating the spatial symbol, the combined signal $y_c = \sum_{k=1}^{N_a} \sqrt{\beta P} \hat{s}_{ik} s_{ik} x_j + \hat{s}_{ik} n_k$ passes through the RF chain to decode x_j as illustrated in Fig. 3.

TABLE II
AVERAGE N_a OF THE PROPOSED SYSTEM

N_r	4	5	6	7
Average N_a	1.374	1.936	1.996	2.37
N_r	8	9	10	11
Average N_a	2.396	2.644	2.698	2.824

IV. SIMULATION RESULTS

Simulation results are presented comparing the power consumption and the EE of the proposed RSM system with con-

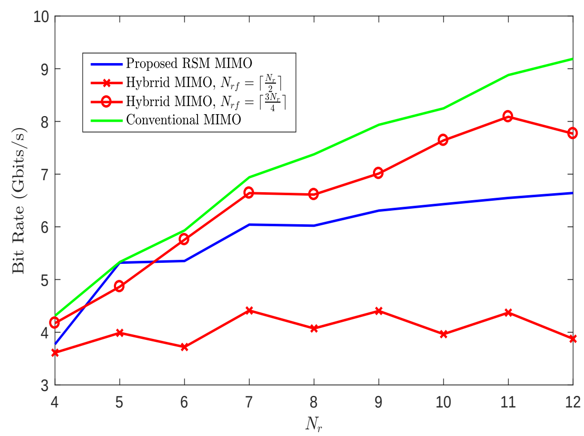

Fig. 6. Bit rate of different MIMO transceivers architectures.

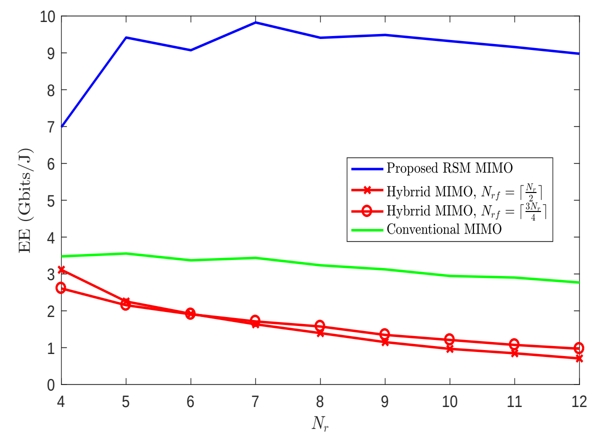

Fig. 7. Energy efficiency of different MIMO transceivers architectures.

ventional MIMO and hybrid MIMO. In the simulation environment, we use the clustered millimeter wave channel model in [2], $P_{\text{ref}} = 20\text{mW}$ [3], we consider 28GHz carrier frequency with 1GHz bandwidth (BW), noise power $= -84\text{dBm}$, the distance between BS and UT is 50 meter, path-loss $= 120\text{dB}$ [16] , $P = 40\text{dBm}$, $\text{BER} = 10^{-5}$. We consider fully digital BS for all architectures where $N_t = 32$, We determine the number of BPCU by applying the following algorithms

- In conventional MIMO, we use singular value decomposition (SVD) precoding and decoding and fix the same constellation for all active modes. We allocate the power such that each active mode achieves symbol error probability 10^{-5}. We repeat this procedure for different constellations and take the maximum number of transmitted bits.
- In hybrid MIMO, the SVD decoder is designed using hybrid precoding [2] and the same procedure as in conventional MIMO is performed.
- In the proposed system, we fix the constellation symbol and select the spatial symbol to get $\text{BER} = 10^{-5}$, repeat for different constellations and take the maximum number of transmitted bits. The BER of the proposed system is proved in [14].

In Fig. 5, the proposed RSM receiver consumes the lowest power because it uses only one RF chain and one ADC. In hybrid MIMO, the number of phase shifters increase rapidly with N_{rf} so it consumes higher power than conventional MIMO when N_{rf} increases.

In Fig. 6, the bit rate is the number of transmitted BPCU multiplied by the BW at $\text{BER} = 10^{-5}$. The bit rate increases with N_{rf} so the conventional MIMO system is superior to the other architectures. The gap between the proposed RSM system and the conventional MIMO arose as a result of using only one RF chain.

In Fig. 7, the bit rate of the proposed RSM increases with N_r with small additional receiver power consumption so its EE is the best while the hybrid system is the worst.

Table II shows that the average N_a of the proposed system increases with N_r with small additional receiver power consumption which contributes to the bit rate and improves the energy efficiency.

V. Conclusion

In this paper, we have proposed a simple MIMO RSM structure and we presented a transmission protocol aimed to reduce the training overhead where the channel is required only at the BS. We studied the power consumption and the EE of different MIMO transceivers showing that the proposed system outperforms hybrid and conventional MIMO systems.

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