Hardware Emulations

using 5G Toolkit and SDRs: Hands-on

GIGAYASA

For academia only

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1 | Performance Analysis of 2x2 Downlink MIMO in 5G Networks

MIMO systems employ multiple antennas at both the transmitter and the receiver. This allows for the transmission of multiple streams of data simultaneously, effectively increasing the capacity and reliability of the communication link. When combined with good signal processing algorithms, MIMO technology enables the system to meet reliability, throughput, and latency requirements. In this tutorial, we will investigate the reliability and throughput performance of a 1×2, 2×1, and 2×2 MIMO system when configured in transmit diversity, receive diversity, and spatial multiplexing mode.

1.1 | What is MIMO?

MIMO systems consist of multiple antennas at both the transmitter and receiver, resulting in multiple spatial paths between them. These paths experience correlated or independent fading depending on propagation conditions and the spacing between the antennas at each end. The existence of multiple paths between the reduces the probability of deep fade in the link in comparison to SISO, SIMO, and MISO systems. These spatial links in the flat-faded wireless channel, H, are modelled as,

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \dots & h_{1t} \\ h_{21} & h_{22} & h_{23} & \dots & h_{2t} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ h_{r1} & h_{r2} & h_{r3} & \dots & h_{rt} \end{bmatrix} \in \mathbb{C}^{N_r \times N_t},$$

where h_{ij} denotes the wireless channel link between the i-th receive antenna and j-th transmit antennas as illustated in Fig-1.1. The presence of these spatial paths allows the transmitter and receiver to configure the MIMO system in different spatial modes based on the channel conditions. These two modes are known as spatial diversity modes and spatial multiplexing mode.

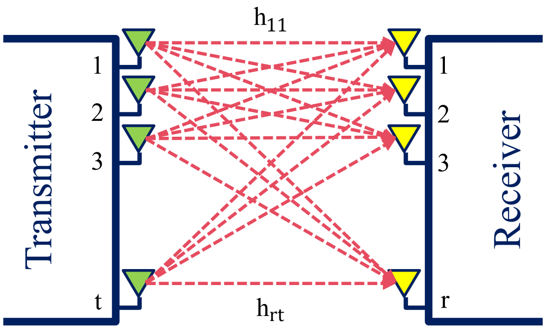


Figure 1.1: MIMO system model

1.1.1 | Basic Reliability analysis of MIMO systems

Lets us assume that the probability of a spatial link failure is p. The reliability of SISO, SIMO, MISO and MIMO are analyzed using probability of reliable communication (p_{rel}) as follows,

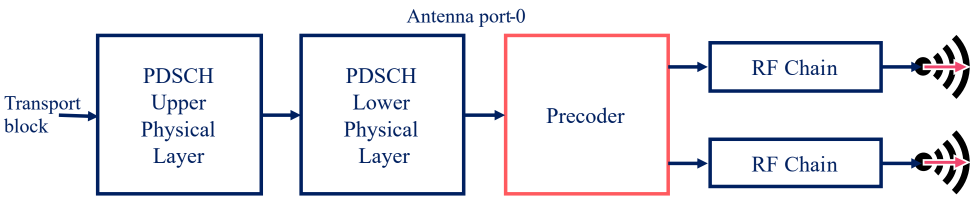
- Reliability of SISO systems, $p_{\text{rel}} = 1 - p$.
- Reliability of SIMO systems, $p_{\text{rel}} = 1 - p^r$.
- Reliability of MISO systems, $p_{\text{rel}} = 1 - p^t$.
- Reliability of MIMO systems, $p_{\text{rel}} = 1 - p^{(r+t)}$.

One can observe that MIMO has the highest reliability for any value of of link failure probability $(0 \leq p \leq 1)$.

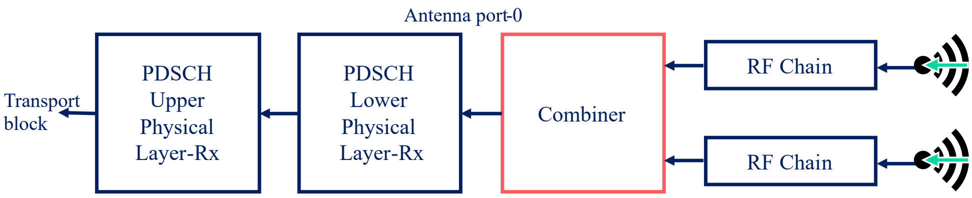
1.1.2 | Spatial Diversity in MIMO Systems

Spatial diversity provides protection against deep fading by combining signals from all transmit antennas which are unlikely to suffer deep fade simultaneously, thus providing reliability. The principle behind spatial diversity is when signal are transmitted from base station through multiple physically separated antennas, they travel through different paths and thus are uncorrelated (in terms of fading) and as a result are unlikely to fade simultaneously. Upon reception at user equipment, these signals can be combined to maximize the signal-to-noise ratio (SNR) . Spatial diversity can achieve:

- Increased reliability (by lowering Block Error Rate (BLER),Bit Error Rate(BER))
- Increased coverage area. In large macro cell, signal transmitted from base station will take highly uncorrelated paths before reaching user equipment.



(a) MIMO transmitter architecture for spatial diversity

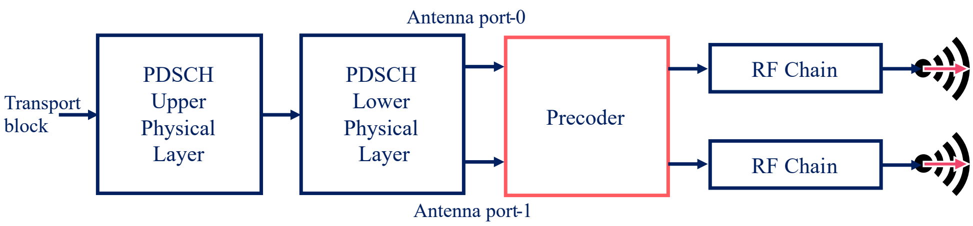


(b) MIMO receiver architecture for spatial diversity

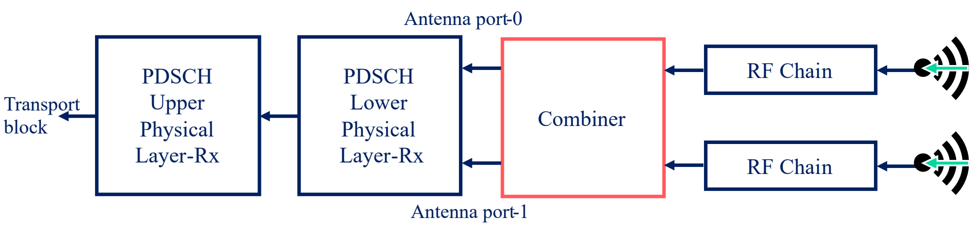
Figure 1.2: MIMO architecture for spatial diversity

1.1.3 | Spatial Multiplexing in MIMO Systems

The primary objective of 5G data communication is to achieve higher throughput (in bits/sec). This can be achieved by spatial multiplexing, wherein multiple parallel distinct streams of data is transmitted from the base station. In contrast to spatial diversity, which achieves higher reliability, spatial multiplexing achieves higher throughput.



(a) MIMO transmitter architecture for spatial multiplexing



(b) MIMO receiver architecture for spatial multiplexing

Figure 1.3: MIMO architecture for spatial multiplexing

1.2 | MIMO Aspects in 5G

5G has concept of 'antenna port', which is different from physical 'antenna elements'. At the transmitter, the payload data and demodulation reference signal(DMRS)/pilot are loaded onto antenna ports. The transmissions using the same antenna port experience the same propagation channel, since transmission of a port is done via a single RF chain. Consequently, the payload data and DMRS in PDSCH are loaded on the same port, which ensure that both payload data and DMRS experience the same propagation channel. This allows user equipment to estimate the channel using DMRS, and thereby decode payload using the same channel estimate.

For instance, for SSB, the PSS,SSS and PBCH use the antenna port 400,i.e. all three transmission share the same antenna port and so are transmitted such that they experience the same propagation channel. Antenna port 400 is mapped onto specific antenna elements which radiate across the air-interface using a single RF chain.

1.2.1 | MIMO: Transmitter

The mapping between port to physical antenna can either be one-to-one or one-to-many. One-to-one mapping is done at lower band, since it does not require beamforming (beamforming requires multiple physical antenna elements). Considering an example for this experiment, transmission of 2×2 MIMO in the downlink.

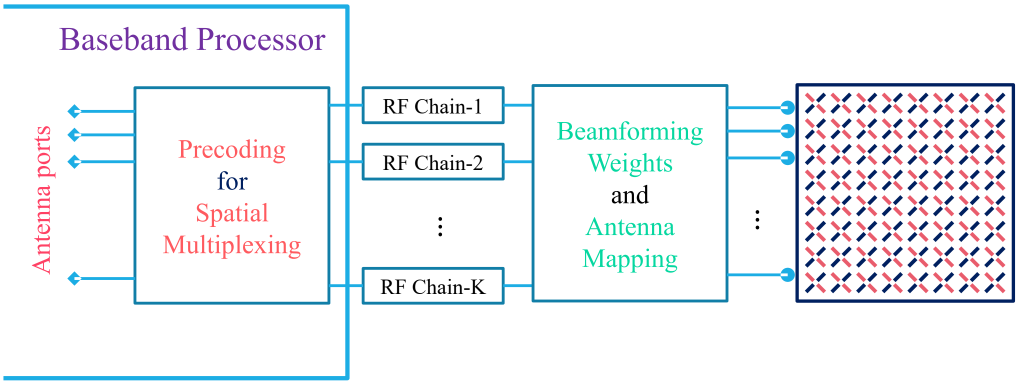


Figure 1.4: One to one mapping between antenna port and physical antenna element for 2×2 MIMO.

The figure 1.4 use an single cross-polar antennas. Antenna port 1000 (has both PDSCH payload and DMRS)is mapped on one physical antenna element while antenna port 1001 is mapped onto another physical antenna element. Both these antenna elements are connected to RF chain respectively, resulting in transmission of 2 streams. Figure 1.5 shows port 1000 which include both the payload and the DMRS with configuration II, the pink shade depicts payload data while the blue shade shows the pilot. Port 1000 and port 1001 has payload and DMRS at same location(s), therefore only port 1000 is depicted.

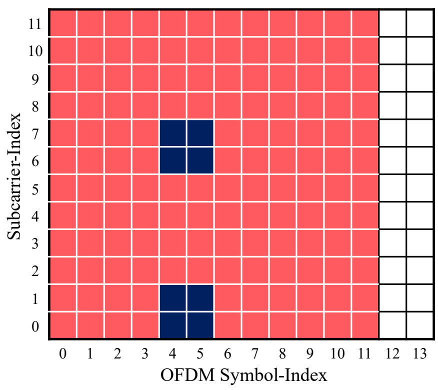


Figure 1.5: An example of port 1000 from 5G toolkit

1.2.2 | MIMO: Receiver

At UE the two parallel streams (for antenna port 1000 and antenna port 1001) are super imposed as shown in equation below:

$$Y = HX + N, \tag{1.1}$$

where H is 2×2 channel matrix, $X = [x_1, x_2]$, $Y = [y_1, y_2]$, where x_1 and x_2 are the payload/DMRS from antenna port 1000 and antenna port 1001 respectively. y_1 and y_2 are the superimposed reception of payload/DMRS from antenna port 1000 and antenna port 1001. Equation 12.1 is pictorially represented in figure 1.6 below.

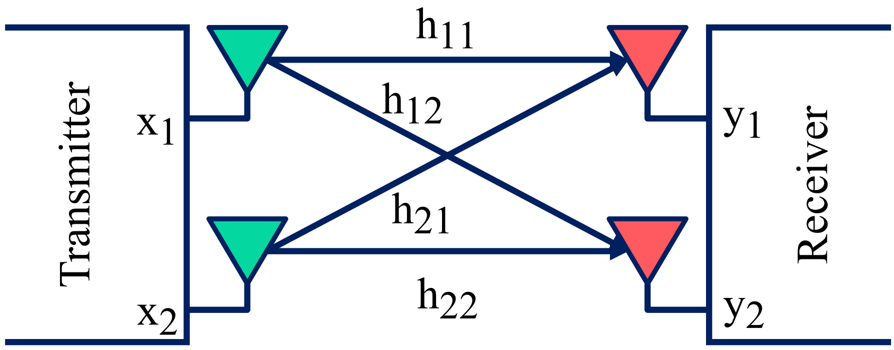


Figure 1.6: Representation of 2×2 MIMO system.

From figure 1.6, the received vectors y_1 and y_2 are given as:

$$y_1 = h_{11} \times x_1 + h_{12} \times x_2 \tag{1.2}$$

$$y_2 = h_{21} \times x_1 + h_{22} \times x_2 \tag{1.3}$$

Here the antenna(s) depicts two RF chain, which transmits two layers/ports of data.

1.3 | Results

The general simulation parameters are given in table 1.1 below:

Table 1.1: Simulation parameters and evaluation methodology

Parameters	Value
Carrier frequency (f_c)	1000 MHz
Bandwidth (B)	30 MHz
FFT size (N_{FFT})	1024
Subcarrier spacing (Δf)	30 KHz
Numbers of Resource Blocks (RBs) (N_{RB})	10
Numbers of Slots (N_s)	7 (PDSCH) + 1 (SSB)
Numbers of base station	1
PDSCH mapping type	"mapping type B"
maxLength (single or double DMRS)	"len1"
startSymbol (OFDM start symbol)	0
configurationType	"Configuration-type-1"
dmrsTypeAPosition	"pos2"
dmrsAdditionalPosition	"pos2"
rank	1/2
mcsIndex	0 to 28
mcsTable	"pdschTable1"
Transmitter-receiver separation	1m

The above parameters hold for every result unless otherwise specified. In this experiment, we will investigate the performance of two modes of MIMO: spatial diversity and spatial multiplexing. The simulation methodology is exactly same as the one used in last tutorial-?? which transmits the SSB first for time-frequency synchronization and CFO estimation. Followed by transmission of 7 slots of PDSCH for performance evaluation. The experiments though has been carried out for 1 or 2 layers.

1.3.1 | Spatial Multiplexing

Observation 1: *Spatial multiplexing enhances the throughput of wireless communication system. The same can be verified through hardware emulations.*
From table 1.2, it can be observed that for MCS indices 0 and 4 (QPSK modulation), the throughput and spectral efficiency are 8.75 Mbps, 22.414 Mbps, and 0.291 bits/sec/Hz, 0.747 bits/sec/Hz, respectively. The highest MCS index for which BLER is 0 is 15; beyond this index, the BLER starts to deteriorate. Additionally, the maximum MCS index for which throughput is non-zero is 24. Beyond this MCS index, the BLER is one resulting in zero throughput. Furthermore, it's important to understand that the channel is not very well conditioned due to the collocation of transmit and receive antennas, resulting in highly correlated channels.

Table 1.2: Performance of MIMO in spatial multiplexing mode for different MCS indices

MCS Index	Q_m	Code rate (r)	Throughput	Spectral Efficiency	BLER
0 (QPSK)	2	0.117	8.75 Mbps	0.291 bits/sec/Hz	0
4 (QPSK)	2	0.300	22.414 Mbps	0.747 bits/sec/Hz	0
10 (16 QAM)	4	0.332	50.19 Mbps	1.673 bits/sec/Hz	0
15 (16 QAM)	4	0.601	89.628 Mbps	2.9876 bits/sec/Hz	0
18 (64 QAM)	6	0.455	100.086 Mbps	3.336 bits/sec/Hz	0.02
20 (64 QAM)	6	0.553	117.488 Mbps	3.916 bits/sec/Hz	0.063
22 (64 QAM)	6	0.650	4.198 Mbps	0.139 bits/sec/Hz	0.971
23 (64 QAM)	6	0.702	4.098 Mbps	0.136 bits/sec/Hz	0.974
24 (64 QAM)	6	0.753	0 Mbps	0 bits/sec/Hz	1

1.3.2 | Spatial Diversity

Observation 2: *Spatial diversity enhances the reliability of wireless communication system. The same can be verified through hardware emulations.*
In spatial diversity mode, a single layer is communicated using multiple transmit antennas and/or multiple receive antennas. The experiment compares the spatial diversity performance of three systems. The first is a 2×2 MIMO system where one single layer is transmitted using two antennas and received using two antennas. The second is a MISO system where the single PDSCH layer is transmitted using two antennas but received using only one antenna. The third is a SIMO system with a single transmit antenna and two receive antennas. All antennas are co-located on a single 2×2 MIMO SDR without transmitting with precoding and no careful combining has been applied at the receiver. All systems outperform 1×1 SISO systems in terms of throughput and reliability 1.3. However, it is counter-intuitive that the MISO system outperforms the MIMO system. This could be due to the lack of transmit-precoding and receive combining or near-field effects. Further analysis is required to understand these aspects, and updates will be made in the future to achieve the expected results.
As observed from table 1.3, 2×2 MIMO with spatial diversity improves the reliability of the system as BLER is 0 till MCS index of 22. 22 is highest MCS index for which BLER is 0. For spatial diversity, even for MCS index of 28 the BLER is not equal to 1, thereby providing higher reliability.

1.4 | Useful Links

The following texts provides some useful links for further reading

- Fundamentals of Massive MIMO networks
- MIMO in 5G Networks

Table 1.3: Performance evaluation (Throughput (η, in Mbps), BER and BLER) for spatial diversity for SIMO (1×2), MISO (2×1) and MIMO (2×2) transmitting single layer for different MCS indices (I_{MCS}).

MCS Parameters			MIMO			MISO			SIMO		
I_{MCS}	Q_m	r	η	BER	BLER	η	BER	BLER	η	BER	BLER
0	2	0.117	4.44	0	0	4.44	0	0	4.44	0	0
4	2	0.300	11.20	0	0	11.20	0	0	11.20	0	0
10	4	0.332	24.65	0	0	24.65	0	0	24.65	0	0
15	4	0.601	44.81	0	0	44.81	0	0	44.81	0	0
22	6	0.650	73.53	0	0	73.53	0	0	73.53	0	0
27	6	0.888	36.88	0.002	0.63	94.26	7.4×10^{-6}	0.061	49.17	0.005	0.51
28	6	0.925	18.57	0.009	0.82	24.14	0.016	0.767	13.00	0.008	0.875

Note: η is system throughput in Mbps. I_{MCS} is MCS index used to compute the modulation order (Q_m) and code-rate (r).

- Link level simulations for MIMO systems with SVD based precoding and combining in 5G networks
- Downlink beam-management in 5G Networks
- AI-ML for CSI compression and reconstruction in 5G networks.

2 | References