Optimal Trade-off between Spectral and Energy Efficiency in SM-MIMO Systems

A project thesis submitted in partial fulfilment of the requirements for the award of the degree of

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Students' declaration

We declare that the work presented in this thesis with title **"Optimal Tradeoff between Spectral and Energy Efficiency in SM-MIMO Systems"** towards the partial fulfillment of the requirements for the award of degree of **Bachelor of Technology** in **Electronics and Communication Engineering** submitted to the Department of Electronics and Communication Engineering, Indian Institute of Technology, Roorkee is an authentic record of our own work carried out during the period from August 2017 to May 2018 under the supervision of **Prof. A.K. Chaturvedi**, Dept. of Electronics and Communication Engineering, IIT Roorkee.

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Certificate

This is to certify that the declaration made by the students is correct to the best of my knowledge and belief.

DATE: ....

A.K. Chaturvedi

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Abstract

With the ever increasing demand for high data rate, reduction in bandwidth and lesser power consumption in a wireless communication system, the SM-based MIMO systems have come to become more popular than ever before. However, simply using a SM-MIMO system does not necessarily satisfy all the performance requirements if the system design is not optimal. This optimality is measured in terms of the two most important evaluation metrics for any wireless system design, the Spectral Efficiency (SE) and the Energy Efficiency (EE).

There are a lot of techniques in literature which look to adaptively modify the transmission configuration of a system in order to maximize the SE or EE separately as two different scenarios. However, as is described ahead in Chapter 2, the two metrics are not independent but vary almost as an inverse of the other. Therefore, optimization of either of them results in drastic degradation of the other which defeats the whole purpose of designing an "optimal" communication system. In this work, we propose a method for selecting the optimal transmission configuration on the basis of a new function of SE and EE – we call it Weighted Efficiency Function (WEF). WEF takes into account both SE and EE simultaneously in the optimization, thereby serving the purpose of providing a good trade-off between the two metrics.

Here, we have considered the generalized model of the SM (GSM) to construct a set of operating modes incorporating the different system parameters. The ultimate goal of this work is to select the optimal value of the average transmitted power and number of active RF chains along with the optimal mode selection that maximizes the WEF. This selection is bound by certain constraints such as maximum power consumption, minimum data rate requirement and maximum allowed SER. In the end, we use simulation results to evaluate the performance of the proposed methodology and compare it with the prior work.

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List of Abbreviations

MIMO	Multiple input multiple output
WiMAX	Worldwide interoperability for microwave access
4G	Fourth generation
LTE	Long-term evolution
TA	Transmit antenna
RA	Receive antenna
OFDM	Orthogonal frequency-division multiplexing
FIR	Finite impulse response
SNR	Signal-to-noise ratio
5G	Fifth generation
SE	Spectral efficiency
EE	Energy efficiency
AWGN	Additive white Gaussian Noise
RF	Radio frequency
ICI	Inter-channel interference
SM	Spatial modulation
SMX	Spatial multiplexing
OSTBC	Orthogonal space-time block coding
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
bpcu	Bits per channel use

ML	Maximum likelihood
i.i.d.	Independent and identically distributed
SER	Symbol error rate
APM	Amplitude and phase modulation
PAPR	Peak-to-average power ratio

CHAPTER 1

Introduction to MIMO Systems

Multiple-Input Multiple-Output technology employs multiple transmitters and receivers to enhance the data rate in a wireless communication system. Most of the techniques which improve diversity and beamforming are limited, making MIMO different from them. MIMO technology uses multipath, a radio-wave phenomenon where transmitted information reaches the receiving antenna multiple times via a variety of paths. Many standards in wireless communication including IEEE 802.11n (Wi-Fi), HSPA+ (3G), WiMAX (4G), and LTE make use of MIMO technology [19].

MIMO is particularly utilized for sending and getting more than one data signal at the same time over the same radio channel by taking advantage of multipath propagation. MIMO wireless technology is able to build the capacity of a given channel as a result of employment of multiple antennas. Throughput of channel can be increased with every new antenna added to the framework by increasing the number of TAs and RAs. This makes MIMO one in all the foremost necessary wireless techniques to be utilized. This chapter gives an introduction to basic MIMO systems and its implementation.

1.1 Different MIMO Formats

1.1.1 SISO

The simplest kind of radio link may be defined as SISO – Single Input Single Output. The transmitter as well as receiver operates with one antenna. The advantage of SISO system is its simplicity as it does not need any additional processing. Interference and fading will limit the channel in its performance.

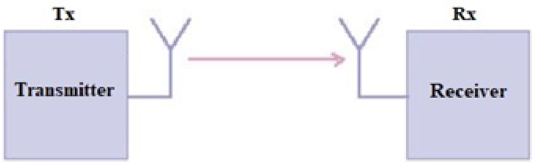

Figure 1.1: SISO - Single Input Single Output.

1.1.2 SIMO

The form in which transmitter has a single antenna and the receiver has multiple antennas can be defined as SIMO – Single Input Multiple Output. Receiver system is modified to receive signals from various independent sources, leading to known as receive diversity. It has been used for several years to combat the effects of interference and fading.

SIMO requires processing in the receiver but it is easy to implement. The level of processing could be limited by size and cost where receiver is located in a mobile device.

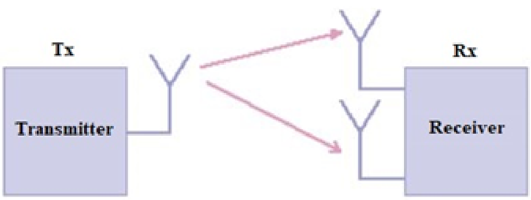

Figure 1.2: SIMO - Single Input Multiple Output.

1.1.3 MISO

Multiple Input Single Output is additionally termed transmit diversity. Two transmitter antennas are used to transmit the same data redundantly, making it easy for receiver to receive the signal. The advantage of using MISO is reduced level of processing needed within the receiver and the space required for the antennas.

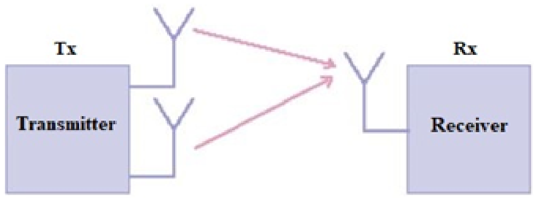

Figure 1.3: MISO - Multiple Input Single Output.

1.2 Diversity Gain

Signal fading is very often due to multipath propagation. Various techniques exist to combat multipath fading which are based on same principle [17]. Same signal is transmitted through several independent paths. Receive diversity and transmit diversity can be increased by increasing the number of RAs and TAs respectively. Fading can affect the channel which impacts the SNR and error rate.

The receiver is supplied with multiple versions of the same signal to increase diversity. By sending the signal through various paths, the probability of getting all the signals affected is significantly reduced. Consequently, diversity balances out a connection and improves performance and error rate. Different diversity modes give various advantages:

- Time diversity: The data can be transmitted using difference time slots in time diversity, e.g. channel coding.

- Frequency diversity: Different frequencies are used to transmit the same signal in frequency diversity. Various technologies such as spread spectrum and OFDM use this mode of diversity.
- Space diversity: Space diversity is used to improve quality and reliability of a wireless link. Antennas are settled in different positions such that various radio paths exist in that environment.

A large number of antennas at each end provide high diversity gains in MIMO systems. Diversity gain can be calculated by finding the number of independent channels in the system, that depends on the position of antennas and the surroundings [18]. For M number of TAs and N number of RAs, the number of sub-channels would be $M \times N$. Hence, the maximum diversity gain equals $M \times N$. The probability of false detection of the received signal can be reduced by increasing the diversity gain.

1.3 System Model

The communication in MIMO systems is performed using a matrix and not just a vector channel, therefore it is doable to transmit multiple signals at the same time and in the same frequency band. This results in higher spectral efficiency. The data stream is encoded and transmitted at the same time by M transmitters. Out of N number of RAs, every antenna receives the signals from all the M TAs. The received signals exhibit ICI due to the distortion introduced by channel.

We mentioned $M \times N$ sub-channels in a system with N receive and M transmit antennas. Each sub-channel between transmitter and receiver exhibits a selective fading and can be modeled as a linear discrete time FIR filter. In the Fig. 1.4, the received signal on the j^{th} receive antenna can be expressed as:

$$y_i = \sum_{i=1}^{M} h_{ij} x_i + n_j \tag{1.1}$$

where y_j is received signal at j^{th} antenna and x_i is the transmitted signal from i^{th} antenna. Variable n_j denotes Gaussian noise with variance σ_n^2 at j^{th} receiver [18]. The complex path between i^{th} TA and j^{th} RA is denoted by h_{ij}. The complex gain coefficient h_{ij} follows Gaussian distribution. System represented in matrix form is:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{1.2}$$

where **H** is the channel matrix, **y** is the column vector of the received signals, **x** is the column vector of the transmitted signals, and **n** is a column vector of the Gaussian noise.

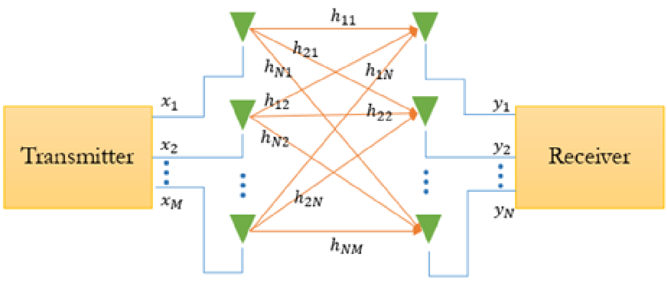

Figure 1.4: MIMO - Multiple Input Multiple Output.

1.4 Channel Capacity

Channel capacity is defined as the number of bits which can be sent per 1 Hz of bandwidth. It can be used to compare the performance of MIMO framework relative to a single antenna system. The performance of the MIMO system can also be compared with all independent channels system using this criteria. There is a theoretical boundary for the quantity of information that can be passed on a selected channel in the presence of noise. “**Shannon**’s law gives the maximum rate at which error free data can be transmitted over a given bandwidth in the presence of noise" [19]. The expression is in the form:

$$C = B\ \log_2(1 + SNR) \tag{1.3}$$

where C is the channel capacity in bits per second and B is the bandwidth in Hertz. (1.3) shows that there is a limit on the capacity by the signal to noise ratio of the received signal with a given bandwidth. An increase in a channel's SNR brings about minor additions to channel throughput. As a result, signal bandwidth is increased to accomplish higher data rates. But we can not increase the signal bandwidth by increasing the symbol rate of a modulated carrier as it would lead to multipath fading. The maximum channel capacity of a MIMO system which is a function of bandwidth, N spatial streams and SNR is shown in (1.4):

$$C = N \times B \ \log_2(1 + SNR) \tag{1.4}$$

It can be observed that the MIMO technology can be used to significantly increase the capacity of a given channel while still obeying Shannon's law. This makes MIMO systems the main candidate for higher throughput.

1.5 Multi-User MIMO

Multi-User or MU-MIMO, an enhanced form of MIMO technology, enhances the communication capability of every single user. It allows multiple users to access the same channel at the same time. Multi-user MIMO algorithms are developed for systems with the number of users greater than one. The interference between different users is removed by using additional processing. Different scenarios associated with MU-MIMO are Uplink and Downlink.

COMPARISON OF MU-MIMO VS SU-MIMO		
FEATURE	MU-MIMO	SU-MIMO
Main feature	For Mu-MIMO the base station is able to separately communicate with multiple users.	Base station communicates with a single user.
Key aspect	Using MU-MIMO provides capacity gain.	Provides increased data rate for the single user.
Key advantage	Multiplexing gain.	Interference reduction
Data throughput	MU-MIMO provides a higher throughput when the signal to noise ratio is high.	Provides a higher throughput for a low signal to noise ratio.
Channel State Information	Perfect CSI is required.	No CSI needed.

Figure 1.5: Comparison of Multi-User MIMO and Single-User MIMO.

1.5.1 MU-MIMO Advantages

1. MU-MIMO systems provide a direct gain proportional to the number of antennas utilized at the base station using multiple access.
2. MU-MIMO achieves spatial multiplexing gain at the base station without the requirement for multiple antennas.
3. MU-MIMO gives off an impression of being affected less by propagation issues such as antenna correlation and channel rank loss compared to single user MIMO systems.

1.6 From 4G to 5G Enabling Technologies

MIMO system has become a vital component of 4G wireless systems. It is shown that they are able to provide channel capacities that surpass the limits for conventional systems. Systems using tens or hundreds of antennas in the base station are known as Large MIMO systems, often called as massive MIMO systems. On account of their advantages in terms of efficiency in power, very high data rates and increased reliability, large-scale MIMO is expected to be the emerging technology for 5G frameworks [4].

Massive MIMO architecture requires a very large number of TAs such that their distribution is within the area of coverage. Utilizing more antennas makes more degrees of freedom in the spatial domain. There are numerous points of interest of using massive MIMO. The expansion in the quantity of antennas allows to use more number of paths and hence more data can be transferred within a given time. It additionally enhances the SNR of the overall system.

There is a huge increase in data usage as per the reports. The new technologies such as 5G will have to deal with it. Massive MIMO can provide improved broadband services in the future. Cisco appraises that by 2020, there will be 5.5 billion mobile users around the globe [2]. Japan's Softbank network has already deployed the first Massive MIMO network in 2016.

Chapter 2

Spatial Modulation in MIMO

2.1 Paradigm shift from SE to EE

There has been an enormous growth of cellular market all over the world in recent years. With today's coverage, a user can connect almost everywhere. The number of users and the demand for cellular traffic has raised. As indicated by Cisco's estimates predicted, the growth rate of 2010 mobile data traffic was higher than foreseen [2]. The remarkable growth in the market of cellular communication has motivated researchers to develop more advanced technologies and protocols for maximizing both the data rate and achievable throughput. Energy consumption and complexity issues have not been given any specific attention.

The conventional reaction is the proposal of transmission technologies for maximizing the spectral efficiency. Since SE is specifically connected to the thought of Shannon capacity, most by far of transmission technologies have been designed by considering many diverse factors without considering the energy consumption. It is important to develop low complexity and power-efficient solutions that still fulfill the requirements of throughput. Energy Efficiency can be understood as throughput per unit energy.

The EE metric diminishes monotonically with the throughput. The solutions which are energy efficient, are expected to work moderately a long way from the Shannon capacity [5]. There is a SE versus EE tradeoff for the basic AWGN channel which may be formulated as:

$$\eta_{EE} = \eta_{SE} \ [N_0(2^{\eta_{SE}} - 1)]^{-1} \tag{2.1}$$

where η and N_0 denote the efficiency and the receiver noise power spectral density respectively. (2.1) features that the EE decreases monotonically when SE is increased. The conclusion utilizing throughput is that current techniques that are spectral efficient end up being suboptimal in terms of energy efficiency.

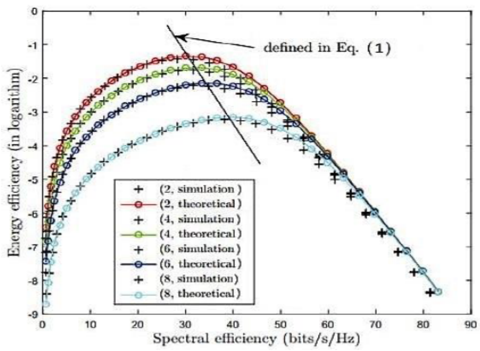

Figure 2.1: EE vs SE for different number of RF chains [5].

2.2 From MIMO to SM-MIMO

By activating all the TAs simultaneously, conventional MIMO systems take advantage of all the antennas by transmitting parallel data from every one of them at the same time. This leads to SE optimization, however this decision does not prompt EE optimization. Contrasted with single-antenna transmissions, MIMO systems get higher data rates and improved error performance after some trade offs [8]:

- As we are sending many data streams at same time, there will be interference between signals. It thus requires additional processing at the receiver.

- requirement of multiple RF chains at the transmitter side in order to have the capacity of transmitting parallel data streams.
- independent power amplifiers for every RF chain. They are power inefficient, consumes most of the power.

These considerations suggest that a major challenge is the design of multiantenna transmission schemes to enhance the EE by keeping various parameters in mind such as a limited number of active RF chains, reduced complexity, ICI and less signal processing at the receiver side. Single-RF MIMO can be acknowledged as a single, activated antenna at the transmitter providing the gains of MIMO communications at any modulation instant [10]. The number of antennas active at same time, i.e., the number of active RF chains decides the complexity and power consumption.

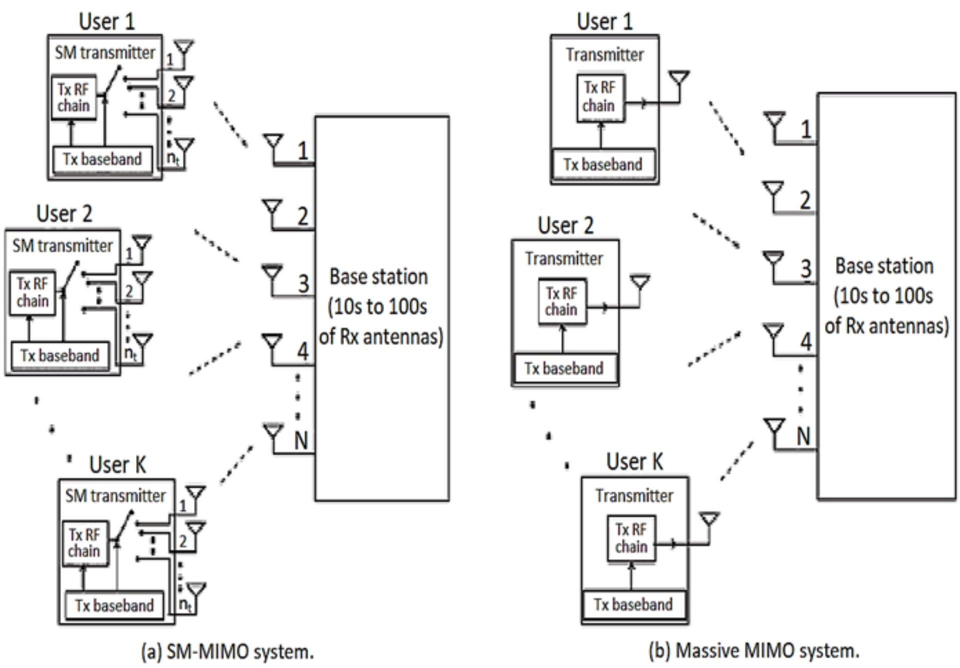

Figure 2.2: Comparison between SM-MIMO and Massive MIMO.

SM is placed with the single-RF Massive MIMO family. All TAs are used to enhance the data rate but by utilizing only a limited number of active RF chains. “The additional feature of

SM–MIMOs is that they outline additional information bits onto a SM constellation diagram. Each constellation element is made by subset of antenna elements" [2]. These unique qualities encourage high-rate MIMO technologies to have enhanced EE and reduced signal processing complexity. SM-MIMO has outperformed numerous MIMO schemes for a large number of TAs, out of which only few are active at the same time.

2.3 Basics of SM-MIMO

2.3.1 How It Works

In this section, we explain the concept of SM-MIMO with the guide of few examples. We denote by M the cardinality of the signal constellation diagram. The number of TAs and RAs is denoted by N_t and N_r, respectively. The receiver uses optimum ML demodulation. For comprehension, we assume $N_t = 2^{n_t}$ and M = 2^m where n_t and m are two positive integers. In Fig. 2.3, SM-MIMO is compared with the conventional SMX scheme and the OSTBC scheme for $N_t = M = 2$.

(a) In SMX–MIMO, a single channel use involves transmission of two PSK/QAM symbols (S1 and S2) from two TAs at the same time. For arbitrary values of N_t and M, the rate of SMX is given by $R_{SMX} = N_t \log_2(M)$ bpcu.

(b) In OSTBC–MIMO, two TAs are used in two channel uses to transmit two PSK/QAM symbols (S1 and S2) at the same time. For values of N_t and M, the rate of OSTBC is $R_{OSTBC} = R_c \log_2(M)$ bpcu, where $R_c = \frac{N_m}{N_{cu}} \leq 1$ is known as rate of space-time block code and N_M is defined as the number of symbols transmitted in N_{cu} channel uses.

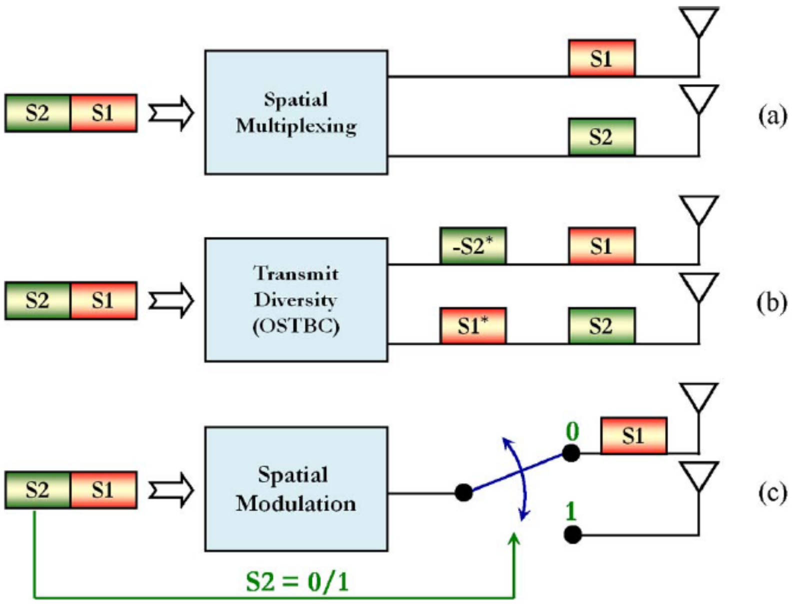

Figure 2.3: Three MIMO concepts: (a) Spatial Multiplexing (b) Transmit diversity (c) SM.

(c) In SM–MIMO, transmission in each channel use involves one direct symbol transmission (S1) and the other symbol (S2) encoded using the index of active TA. Hence, the information symbols are modulated onto two units: a) PSK/QAM symbol; and b) index of active TA. For values of N_t and M, the rate of SM is given by $R_{SM} = log_2(M) + log_2(N_t)$ bpcu.

Now, we will look the encoding mechanism of SM-MIMO in two channel uses for N_t = M = 4. The rate here is $R_{SM} = log_2(M) + log_2(N_t) = 4$ bpcu. The encoder forms blocks of four bits each for transmission. Fig. 2.4 shows the first channel use, '1100' is the block to be encoded. The first $log_2(N_t) = 2$ bits, '11', will determine the TA which is active during transmission (TX_3). And the second $log_2(M) = 2$ bits, '00', will decide the modulated symbol.

Similarly, Fig. 2.5 shows the block to be encoded is '0001' during second channel use. The first $log_2(N_t) = 2$ bits, '00,' will determine the active TA (TX_0), and the second $log_2(M) = 2$ bits, '01,' will determine the modulated symbol.

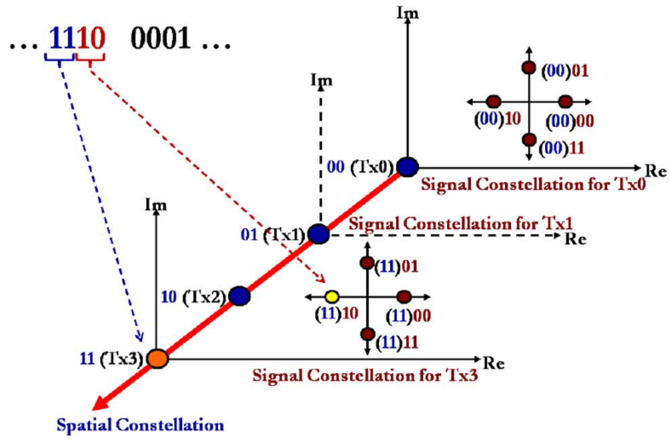

Figure 2.4: 3-D constellation diagram of SM in first channel use [2].

The special characteristics of SM-MIMO highlighted from Figs. 2.4 and 2.5 are [2]:

1. The activated TA depends on input bits, it may change for every channel use. Thus, mapping the information bits to TA indices to increase the transmission rate is a strong method known as TA switching.
2. 2-D signal-constellation diagram formed by modulation scheme is modified to 3-D constellation diagram by adjusting the information bits. The index of active TA provides the third dimension of constellation. The third dimension is named as the **spatial-constellation diagram** in SM-MIMO.

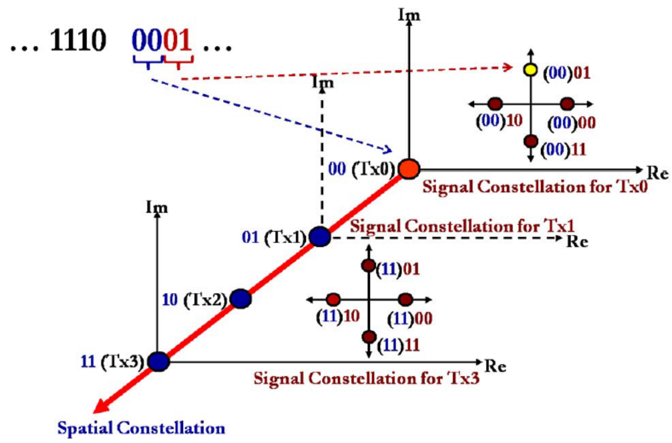

Figure 2.5: 3-D constellation diagram of SM in second channel use [2].

Assuming a frequency-flat channel model, the signal for SM-MIMO can be mathematically modelled as follows:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{2.2}$$

where $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the complex channel matrix, $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is the complex received vector, $\mathbf{x} = \mathbf{e}.s \in \mathbb{C}^{N_t \times 1}$ is the complex modulated vector with $s \in \mathbb{C}^{1 \times 1}$ being the complex PSK/QAM modulated symbol from signal-constellation diagram, $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the complex AWGN at the receiver and $\mathbf{e}$ being the $N_t \times 1$ vector as follows [2]:

$$e_r = \begin{cases} 1, & if\ the\ r^{th}\ TA\ is\ active \\ 0, & if\ the\ r^{th}\ TA\ is\ not\ active \end{cases} \tag{2.3}$$

where $\mathbf{e}_r$ is the r^{th} entry of $\mathbf{e}$ for r = 1, 2. . . .,N_t. N_t = 1 implies only one TA, SM-MIMO is reduced to conventional systems, where only modulation symbol will be encoded. The rate for this particular case is given by $R_0 = \log_2(M)$.

2.3.2 Potential Advantages

Already specified the encoding principle described in 2.3.1, SM-MIMO provides the following favourable circumstances contrasted with MIMO systems:

- Higher throughput: Because of the 3-D constellation diagram, SE of SM-MIMO is higher than that of conventional antenna transmissions.
- Simpler receiver design: As just a single TA is active, there will be no interference for any channel use. The receiver requires no complex processing.
- Simpler transmitter design: Due to a single active RF chain and a number of TAs which are not active, it becomes inexpensive and easy to send.
- Lower transmit power supply: Less the number of RF chains, less would be the power consumed for same output power. The number of TAs has no effect on power dissipation.

2.3.3 Disadvantages

The limitations of SM-MIMO are given below:

- SE suboptimality: Throughput of SM-MIMO is lower than SMX-MIMO on the grounds that some TA elements are not used in every channel use. Subsequently, A large number of TA elements are required in SM-MIMO to achieve the same SE compared to SMX-MIMO system.
- Fast antenna switching: We have seen that the active TA may change in every channel use. Hence, SM-MIMO implementation needs a sufficiently fast RF switch that introduces low insertion losses.
- Time-limited pulse shaping: Unlike the usually utilized shaping filters, SM–MIMO employs time-limited pulse shapes to allow symbol-time switching. Consequently, it is critical to outline a good trade-off between a practical bandwidth occupancy and a constrained time span.

CHAPTER 3

Problem Formulation and Solution Proposed

To improve the performance of SM-based MIMO systems in terms of their SE and EE, approaches involving adaptive designs have been proposed in the past [2], [10]. The aim of this work is to design a system that adaptively operates in a transmission configuration that is optimal in some sense. In order to achieve this objective, we have considered the link adaptive design as in [11]–[13]. There has been a lot of effort and study to improve the error rate or maximize SE with a given SER or maximize EE by switching between modulation designs and MIMO & SM-MIMO [11]–[13]. Unlike most of the aforementioned works, here we have looked to use the generalized SM (GSM) model of the spatial modulation by varying the number of active RF chains as was proposed in [1].

This work, though being highly inspired from the results in [1], focuses on solving a problem which is more practical and intuitive than the one proposed there which uses a framework of SM-based techniques with various space-signal constellations, transmission rates and number of activated antennas. Thus, instead of maximizing the performance metrics SE and EE independently [1], we look to strike a good trade-off between the two by taking both of them into account in a single transmission. We have used a pre-decided set of various transmission modes, each with a different modulation order, average transmission power per antenna and minimum allowed overall transmitted power. The channel characteristic is assumed to be Rayleigh fading with non-zero large-scale fading loss and spatial correlations. We then propose a Weighted Efficiency Function (WEF) as defined in Section 3.2.1, which considers a weighted sum of SE and EE in different proportions. The maximization of this function over the available transmission power for each mode and then across the different modes in the candidate set yields the optimal transmission configuration which achieves the best transmission rate for a given bandwidth while keeping the power consumption also in check. The optimization problem considers a constraint on the maximum limit of power and allowed SER while a minimum limit on the bit rate required. To derive the lower boundary of the transmitted power, the upper limit of the error specification is used in the closed form approximation of the SER as described in Section 3.1.3. Although the solution involves a simple, naïve exhaustive search among all points, the complexity of the SER calculation is quite high. However, this can also be reduced by pre-computing all the parameters of the different modes and storing them in a look-up table [1].

3.1 Framework for Problem Definition

3.1.1 System and Signal Models

The system model we have considered assumes point-to-point MIMO system with number of transmit antennas as N_t, number of receive antennas as N_r and number of simultaneously active RF chains as $N_{a,m}$ in a particular mode m of the predefined candidate set $\mathbf{\Phi}$ of size M. Moreover, the number of RF chains is chosen such that $N_{a,m} \leq min(N_t, N_r)$ where $min(N_t, N_r)$ is the minimum of N_t and N_r. As is evident from the definition of $N_{a,m}$, we have adopted the GSM-based model of MIMO for transmission. Also, we have assumed that the transmitter has a-priori knowledge of channel spatial correlations and large-scale fading loss. Now, the goal is to choose the optimal number of RF chains for each mode using the given system parameters and then the best mode of operation amongst them. The selected mode is then used to map the information bits to the transmitted SM-based signal which is detected by the receiver. This complete model is shown in Fig 3.1.

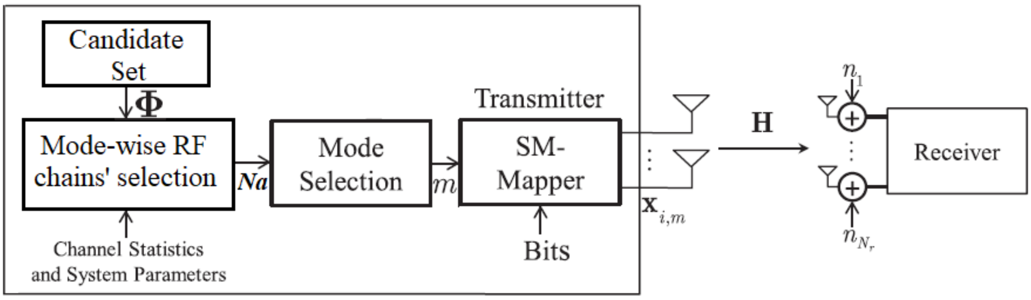

Figure 3.1: System model for the SM-based MIMO.

The signal model for the baseband MIMO system with flat fading is given by

$$\mathbf{y} = \sqrt{\frac{G_a P_{tr,m}}{d_{loss}}}\,\mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2}\mathbf{x}_{i,m} + \mathbf{n} \tag{3.1}$$

where $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is the received signal; $\mathbf{R}_t \in \mathbb{C}^{N_t \times N_t}$ and $\mathbf{R}_r \in \mathbb{C}^{N_r \times N_r}$ are the transmit correlation and receive correlation matrices; $\mathbf{H}_w \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix of the uncorrelated Rayleigh fading channel. The elements of $\mathbf{H}_w$ are assumed to be zero mean, i.i.d. complex white Gaussian random variables with unit variance. $P_{tr,m}$ is the average transmit power of mode m in any current configuration, d_{loss} is the large-scale fading loss, G_a is the power gain of the transmit and receive directive antennas, $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the zero mean, complex white Gaussian noise with variance σ_n^2 and $\mathbf{x}_{i,m} \in \mathbb{C}^{N_t \times 1}$ is the i^{th} complex SM-based signal transmitted via mode m.

Since we have considered the GSM model, the APM symbol involves all of the activated antennas only. The SM-based signal [2] can therefore be written as:

$$\mathbf{x}_{i,m} = \frac{1}{\sqrt{N_{a,m}}}\left(\sum_{k=1}^{N_{a,m}} \mathbf{e}_{l_{i,m}^{(k)}}\, s_{k,i,m}\right) \tag{3.2}$$

where $l_{i,m}^{(k)}$ represents the index of the k^{th} antenna used in $\mathbf{x}_{i,m}$, $\mathbf{e}_i$ is the $N_t \times 1$ vector with only i^{th} entry 1 and others 0, and $s_{k,i,m}$ is the k^{th} string of bits multiplexed using APM having constellation size N_m. The number of spatial constellation points active at a given $N_{a,m}$ in mode m is

$$N_{l,m} = 2^{\left\lfloor \log_2 \binom{N_t}{N_{a,m}} \right\rfloor}. \tag{3.3}$$

The total number of points in the spatial constellation diagram is

$$N_{c,m} = (N_m)^{N_{a,m}} N_{l,m} \tag{3.4}$$

and the rate of transmission is

$$b_m = \log_2(N_{l,m}) + N_{a,m} \log_2(N_m) \tag{3.5}$$

where b_m is also the spectral efficiency of the system in bpcu or bits/s/Hz.

3.1.2 Power Consumption Model

Taking into consideration both the transmission power and the circuit power consumption, the model for the power consumed on the transmitter side when operating in mode m is given by $P_{tot,m} = P_{cc,m} + \eta^{-1}\kappa_m P_{tr,m}$, where $P_{cc,m}$ is the total circuit power consumption of mode m, κ_m is the PAPR of the adopted modulation technique in mode m and η is the power amplifier efficiency. Considering the variable number of active RF chains in the GSM model and including its effect on the overall power consumed in the circuit, the total power consumption [14], [15] for mode m is formulated as:

$$P_{tot,m} = R_{c,m}P_c + N_{a,m}BP_b + P_f + N_{a,m}P_{c1} + N_{a,m}BP_{c2} + N_{a,m}\eta^{-1}\kappa_m P_{T,m} \tag{3.6}$$

where P_c is the power consumed in the process of channel coding, P_b is the factor responsible for the power consumption in baseband processing, P_{c1} and P_{c2} are the factors for circuit power consumption which depend on the system parameters, P_f is the fixed power consumption in the circuit, $P_{T,m} = P_{tr,m}/N_{a,m}$ is the average transmit power per antenna, $R_{c,m} = Bb_m$ is the rate of transmission in bits/s for mode m and B is the bandwidth. It is important to note that this model only considers the power consumption at transmitter side for simplicity, and can be further extended as per the need.

3.1.3 SER Approximation for SM-Based MIMO Systems

Here, we discuss a closed-form approximation of SER in SM-based MIMO systems for transmission via Rayleigh fading channel. Considering that ML detector is employed at the receiver, the upper bound for the SER $p_{ser}^{(m)}$ in mode m for a given channel realization can be expressed as [16]

$$p_{ser}^{(m)} \leq \sum_{i=1}^{N_{c,m}} \sum_{j=1, i \neq j}^{N_{c,m}} \frac{Q(\sqrt{D})}{N_{c,m}} \tag{3.7}$$

where $D = (\rho_m/2) \left\| \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t^{1/2} (x_{i,m} - x_{j,m}) \right\|^2$ and Q($\cdot$) is the standard Q-function. Since the expectation of this function, i.e. $\mathbf{E}\left\{Q(\sqrt{D})\right\}$ is equal to the pairwise symbol error probability $P(x_{i,m} \to x_{j,m})$, we use the following approximation. Considering that $\mathbf{R}_r$ has distinct nonzero eigenvalues, the pairwise error probability can be expressed as [1]

$$P(x_{i,m} \to x_{j,m}) = \frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P} \xi_k} \left(\frac{1}{\rho_m \psi_{ij,m}} \right)^P \tag{3.8}$$

where $\psi_{ij,m} = (\mathbf{x}_{i,m} - \mathbf{x}_{j,m})^H \mathbf{R}_t (\mathbf{x}_{i,m} - \mathbf{x}_{j,m})$, $\xi_1, \ldots, \xi_P$ are the distinct nonzero eigenvalues of $\mathbf{R}_r$, $P \leq N_r$ denotes the rank of $\mathbf{R}_r$ and ρ_m is the average SNR given by

$$\rho_m = \frac{(G_a \; P_{tr,m})}{(\sigma_n^2 \; d_{loss})} \tag{3.9}$$

Using the approximation (3.8) in the expression for $p_{ser}^{(m)}$ bound in (3.7), the final bound for SER in mode m is obtained as:

$$p_{e,m} = \mathbf{E}\left\{p_{ser}^{(m)}\right\} \lessapprox \frac{\frac{(2P-1)!}{P!(P-1)!}}{N_{c,m}} \frac{\rho_m^{-P} \psi_{c,m}}{\prod_{k=1}^{P} \xi_k} \tag{3.10}$$

where $\psi_{c,m} = \sum_{i=1}^{N_{c,m}} \sum_{j=1, i \neq j}^{N_{c,m}} (\psi_{ij,m})^{-P}$. The performance of the above approximation is also evaluated in [1] with the conclusion that it gives accurate result for SER less than 10^{-5}.

3.2 From SE- and EE-based Selection to WEF-based Selection

Here, we first look to motivate our problem definition by discussing the mode selection techniques prevalent in literature. Section 3.2.1 contains the SE- and EE-based selection as part of the prior work. The next section then describes their shortcomings in terms of limited application and how they can be tackled. We also go on to elaborate on the significance of WEF and the superiority of the WEF-based proposed method over the prior methods. Finally, we state the mechanism for selecting the optimal transmission configuration on the basis of this function.

3.2.1 Prior Work

The two methods discussed ahead involve maximization of SE and EE respectively over a predefined set of modes. Each mode defines a fixed value of the spectral efficiency and the number of active RF chains which can then be realized using different modulation techniques.

3.2.1.1 SE-based mode selection

Given a constraint on the maximum allowed average transmit power for each mode $P_{tr,max}$ and a maximum allowed value of the SER $p_{e,max}$, the problem for SE-based mode selection is:

$$\max_{m\in\mathbf{\Phi},\ P_{tr,m}} \quad b_m \quad s.t. \quad P_{tr,m} \leq P_{tr,max},\ p_{e,m} \leq p_{e,max} \tag{3.11}$$

where $p_{e,m}$ is the expectation of SER for mode m. Since each mode already contains a fixed value of the SE, the maximization is only over the different modes and not within a mode. The next thing is to choose the value of $P_{tr,m}$ at which to operate. This is as simple as the fact that the higher the average transmitted power, the more the number of active RF chains for a fixed $P_{T,m}$ and hence, the greater the SE. Thus, $P_{tr,m}$ is kept equal to $P_{tr,max}$. Since, we need to decide the best transmission mode for highest SE, we first need to form a set of the modes qualifying the constraints. For this purpose, we use the SER approximation in (3.10) and the fact that $P_{tr,m} = P_{tr,max}$ to label a mode as qualifying if

$$\frac{\psi_{c,m}}{N_{c,m}} \frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P} \xi_k} \left(\frac{G_a \; P_{tr,max}}{\sigma_n^2 \; d_{loss}} \right)^{-P} \leq p_{e,max} \tag{3.12}$$

The last step is a simple exhaustive search amongst all the qualifying modes to select the one with the largest specification of SE.

3.2.1.2 EE-based mode selection

Apart from the constraint on $P_{tr,m}$ and $p_{e,m}$, maximization of EE involves an extra constraint on the spectral efficiency b_m. The optimization problem is formulated as:

$$\max_{m \in \mathbf{\Phi},\, P_{tr,m}} \quad \mu_m = \frac{R_{c,m}}{P_{tot,m}} \quad s.t. \quad b_m \geq b_{min},\; P_{tr,m} \leq P_{tr,max},\; p_{e,m} \leq p_{e,max} \tag{3.13}$$

where μ_m is the energy efficiency of mode m and b_{min} is the minimum requirement for SE. Since $N_{a,m}$ is fixed for each mode, maximization over $P_{tr,m}$ can be replaced by maximization over $P_{T,m}$. Substituting for $P_{tot,m}$ from (3.6) and using the relation (3.10), the above problem is simplified as:

$$\begin{aligned}
\max_{m \in \mathbf{\Phi},\, P_{T,m}} \quad & \mu_m = \frac{1}{P_c + \frac{P_f}{B b_m} + \frac{N_{a,m}}{b_m}\left(P_b + \frac{P_{c1}}{B} + P_{c2} + \frac{\eta^{-1} \kappa_m P_{T,m}}{B} \right)} \\
s.t. \quad & b_m \geq b_{min},\; P_{T,m} N_{a,m} \leq P_{tr,max}, \\
& \frac{\psi_{c,m}}{N_{c,m}} \frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P} \xi_k} \left(\frac{G_a \; P_{T,m} N_{a,m}}{\sigma_n^2 \; d_{loss}} \right)^{-P} \leq p_{e,max}
\end{aligned} \tag{3.14}$$

Considering the noise power as $\sigma_n^2 = B N_0$ where N_0 is the power spectral density of the noise, and with the knowledge that maximum EE is obtained at $p_{e,m} = p_{e,max}$ in order to minimize $P_{tot,m}$, we substitute the value of $P_{T,m} N_{a,m}$ from the error constraint in (3.14) to the power constraint. Doing so, we obtain:

$$\max_{m \in \mathbf{\Phi}} \;\; \mu_{m,e} \quad s.t. \quad b_m \geq b_{min},\; \frac{B N_0 d_{loss}}{G_a} \left[\frac{\psi_{c,m}}{N_{c,m} \; p_{e,max}} \frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P} \xi_k} \right]^{1/P} \leq P_{tr,max} \tag{3.15}$$

where

$$\frac{1}{\mu_{m,e}} = P_c + \frac{P_f}{Bb_m} + \frac{N_{a,m}}{b_m}\left(P_b + \frac{P_{c1}}{B} + P_{c2}\right) + d_{loss}\frac{N_o\eta^{-1}\kappa_m}{G_a b_m}\left(\frac{(2P-1)!}{P!(P-1)!}\frac{\psi_{c,m}}{p_{e,max}.N_{c,m}.\prod_{k=1}^{P}\xi_k}\right)^{1/P} \tag{3.16}$$

is the inverse of the reformulated EE at the equality of the error constraint. Now, similar to the SE-based mode selection, a set of qualifying modes is constructed satisfying the two constraints in (3.15), and then the one yielding the maximum value of $\mu_{m,e}$ is selected for transmission.

3.2.2 Proposed Methodology

As stated in the above sections, the aforementioned techniques treat SE and EE maximization as two independent problems and try to find the best mode of operation separately in the two cases. The optimal value of SE is obtained when the power constraint is met with equality, thus maximizing power and minimizing SER, as can be inferred from (3.10). Similarly, EE is maximized at the equality of error constraint, thus maximizing SER within the specified limits and minimizing the transmitted power. However, in each scenario the other metric suffers drastically. Considering this fact from the practical point of view, it is highly inefficient to select the mode of operation simply on the basis of one out of SE and EE. Hence, we propose a new method for defining and selecting the modes along with optimum number of active RF chains that provides a good trade-off between the two metrics.

3.2.2.1 WEF : A Trade-off between SE and EE

As the name suggests, we use a weighted sum of the two efficiency functions SE and EE to define the Weighted Efficiency Function $F^{SE,EE}$ as:

$$F^{SE,EE} = k(SE) + (1-k)(EE) \tag{3.17}$$

where $0 \leq k \leq 1$ is the relative weight of SE with respect to EE in the WEF. This function forms the basis of our optimization problem and the selection of optimal transmission configuration.

The significance of this function is that it eliminates the shortcomings of the prior methods by considering both SE and EE together in a single instance of operation rather than maximizing them independently as separate problems. The necessity for doing so is very intuitive from the fact that the two metrics are related to each other (refer Section 2.1) and thus varying one quantity affects the other.

This makes it clear that the two problems are actually not independent but related to one another and what better way to combine them than using a weighted sum of the two efficiencies normalized by their respective maximum values. This ensures that the two quantities are unitless and within the same scale of 0 to 1. Thus, (3.17) can be written as:

$$F^{SE,EE} = k\ b_{m,norm} + (1-k)\ \mu_{m,norm} \tag{3.18}$$

where $b_{m,norm}$ and $\mu_{m,norm}$ are the normalized values of b_m and μ_m respectively obtained by dividing them by their respective maximum values. This normalization also ensures that the final value of $F^{SE,EE}$ also lies on the same efficiency scale, i.e. $[0,1]$. Moreover, the value of k is also an important factor in $F^{SE,EE}$ and can be varied between 0 and 1 depending upon the application. High data rate requirement implies that we select k in the second half of 1 whereas selecting k less than 0.5, on the other hand, is suitable for low power consumption models.

3.2.2.2 WEF-based Selection of Optimal Transmission Configuration

Here, we first describe the formulation of our problem statement on the basis of the function defined above. Next, we propose a solution for the same to obtain the optimal transmission configuration in terms of the transmitted power, number of active RF chains and the mode of operation from the candidate set, given some constraints.

Since the problem of maximizing WEF is not as trivial as selecting the edge of the power or error constraint, we need to scan the complete range of the allowed transmitted power for each mode. As the value of $P_{tr,m}$ is varied for a particular mode m, the number of active RF chains and hence the SE should both be open to change. Unlike the earlier cases, this requires these two quantities to be variables within each mode instead of being predefined for a mode. Keeping this in mind, we redefine the modes in our candidate set as shown in Table 3.1.

Table 3.1: Definition of the Transmission Modes in our Candidate Set

Mode	Modulation Technique	$P_{T,m}$ (dBm)	$P_{tr,m_{min}}$ (dBm)
1	BPSK	10.00	5.12
2	QPSK	13.01	6.96
3	8-QAM	14.77	8.76
4	16-QAM	16.02	10.29
5	32-QAM	16.99	11.49
6	64-QAM	17.78	13.09
7	128-QAM	18.45	14.80
8	256-QAM	19.03	17.00

As is clear from the table, both $N_{a,m}$ and b_m have been eliminated from the definition of the modes. The mode specifies the modulation technique each with a unique modulation order. The value of $P_{T,m}$ is obtained by calculating the average transmitted power per symbol for that constellation, keeping the bit energy and symbol duration constant. The procedure for computing $P_{tr,m_{min}}$ is described later in this section.

Given the constraints of $p_{e,max}$, $P_{tr,max}$ and b_{min} and the mode definitions as above, we now need to find the best fit value of $P_{tr,m}$ and mode index that maximizes the WEF. Therefore, the problem can be formulated as:

$$\max_{\mathbf{\Phi},\, P_{tr,m}} \quad F^{SE,EE} \;\; s.t. \;\; b_m \geq b_{min},\; p_{e,m} \leq p_{e,max},\; P_{tr,m} \leq P_{tr,max} \tag{3.19}$$

The maximization over the different modes in the candidate set $\mathbf{\Phi}$ is as simple as constructing a set of qualifying modes followed by an exhaustive search as described in Section 3.2.1. However, the maximization over $P_{tr,m}$ is not that trivial. The first step is determining the complete range of permitted values of $P_{tr,m}$ for each mode. The upper limit of this range is a constant irrespective of the mode and is given by $P_{tr,max}$ as specified. For computing the lower bound, $P_{tr,m_{min}}$, we examine the relations in (3.9) and (3.10). Since, $P_{tr,m}$ is a decreasing function of $p_{e,m}$, the value of $P_{tr,m_{min}}$ is obtained by substituting the specification for maximum allowed SER, $p_{e,max}$ in

(3.10). Doing so, the expression for minimum allowed $P_{tr,m}$ is given by

$$P_{tr,m_{min}} = \frac{\sigma_n^2 d_{loss}}{G_a} \left[\frac{\psi_{c,m}}{N_{c,m}\ p_{e,max}} \frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P} \xi_k} \right]^{1/P} \tag{3.20}$$

The value of $p_{e,max}$ and other constants used in calculating the entries in Table 3.1 is given in Appendix. Using (3.20) in (3.19), the problem reduces to

$$\max_{\mathbf{\Phi},\ P_{tr,m}} \quad F^{SE,EE} \quad s.t. \;\; b_m \geq b_{min},\ P_{tr,m_{min}} \leq P_{tr,m} \leq P_{tr,max} \tag{3.21}$$

The second step of the method involves an iterative search for the optimal value of $P_{tr,m}$ within the range computed above for each mode. If this value satisfies the constraint on the rate b_m, it is selected; otherwise the next best value that satisfies it is searched for, and so on. Although the complexity of this search is high, it can be easily reduced by pre-computing and storing the partial results in a lookup table for later use [1]. Once the optimal value of $P_{tr,m}$ is known for a mode m, the optimal number of active RF chains and the maximum value of $F^{SE,EE}$ for that mode can also be computed at that $P_{tr,m}$. Repeating this procedure for each mode, the global optimal value for P_{tr}, N_a and mode index m is obtained by finding the best among the various solutions for the different modes, i.e. the one which provides the maximum $F^{SE,EE}$. Since, this final step just involves a naïve search across the modal solutions, it does not add anything significant to the overall complexity.

CHAPTER 4

Results and Discussion

In this chapter, we look to evaluate the performance of our proposed WEF-based method for selection of optimal transmission configuration with the help of simulation results. We also provide a comparison between the results obtained using our methods and those using the prior methods in literature. The values used for different parameters and constants involved in the computation are given in Appendix.

In the first section, we study the variation of SE and EE with the average transmitted power $P_{tr,m}$ for each mode separately. A comparison amongst the modes in terms of SE and EE at the same transmitted power is also done in table 4.1. Next, the variation of WEF with the transmitted power is observed at $k = 0.5$ in Section 4.2 and the results are compared with those obtained for SE and EE. Section 4.3 contains the results for mode selection v/s power on the basis of SE and EE separately. The last section then shows the variation of optimal value of $F^{SE,EE}$ and the corresponding mode selected with power at four different values of k. In the end, the optimal transmission configuration in terms of m, P_{tr} and N_a at six different values of k is shown in Table 4.2.

4.1 Variation of SE and EE with Power

Fig. 4.1 shows the variation of SE in bits/s/Hz with the average transmitted power in mWatts for each mode. As is clear from the plots, the value of SE increases with increase in power, irrespective of the mode. This can be easily understood from the fact that since the average transmitted power per antenna is a constant for each mode, an increase in transmitted power increases the number of active RF chains which in turn leads to an increase in the SE for that mode as per (3.5).

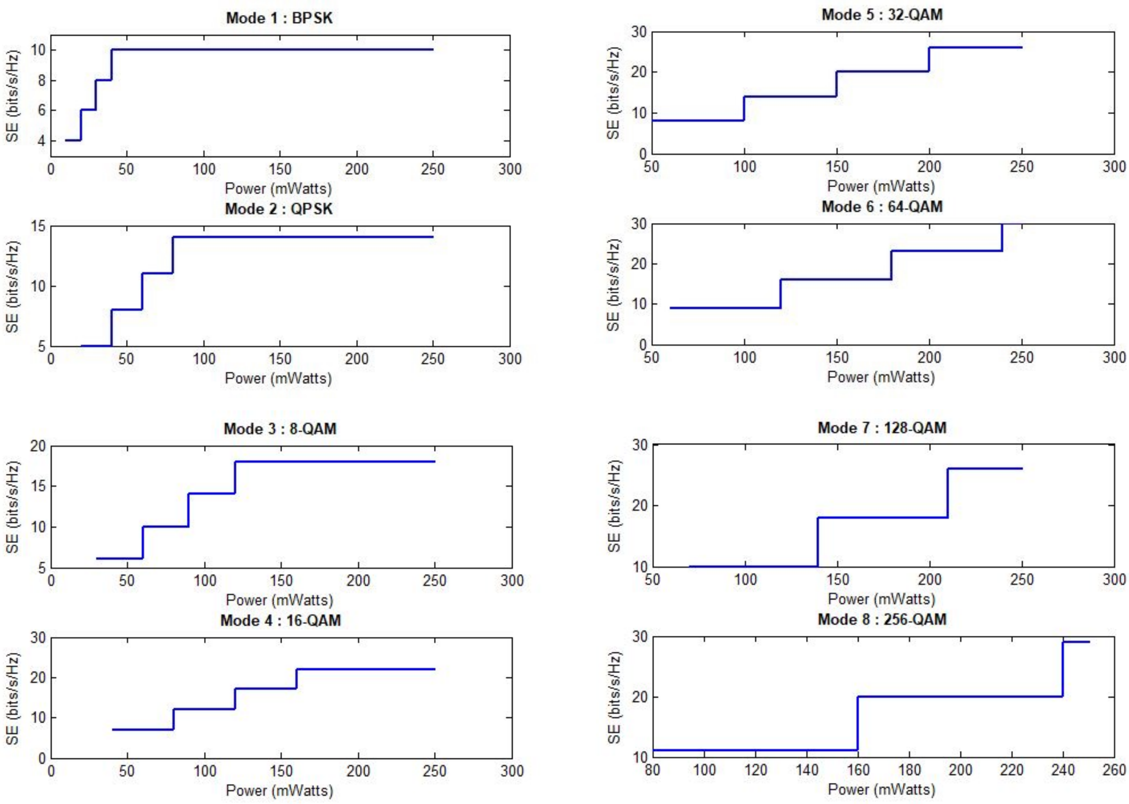

Figure 4.1: Variation of SE with transmitted power for each mode.

The nature of these curves is similar to step functions because only discrete values of RF chains is allowed which increases only when the power increases by an amount equal to the power used by one antenna. It is worth noting that all the plots have 4 or less steps because a maximum of only 4 values are allowed for RF chains since $1 \leq N_{a,m} \leq N_r = 4$. As can be inferred from the scale on the SE-axis, the maximum value of SE increases with the modulation order of the mode from a maximum of 10 bits/s/Hz for BPSK to 30 bits/s/Hz for 256-QAM. This is because the data rate is bound to increase with the modulation order, for a fixed bit energy and symbol duration.

Fig. 4.2 below shows the variation of the EE with the average transmitted power for each mode separately. The value of EE is plotted in bits/μJ and that of power in mWatts. These curves are also similar to step functions with a maximum of 4 steps for the same reason as curves for SE. However, these curves have a decreasing trend because as the RF chains increase, the transmitted power increases which increases the total power consumption thus reducing the EE. Also, exactly opposite to SE, EE decreases with the modulation order on an average. This is because of the increase in the transmission power per antenna with the modulation order which eventually increases the total power again.

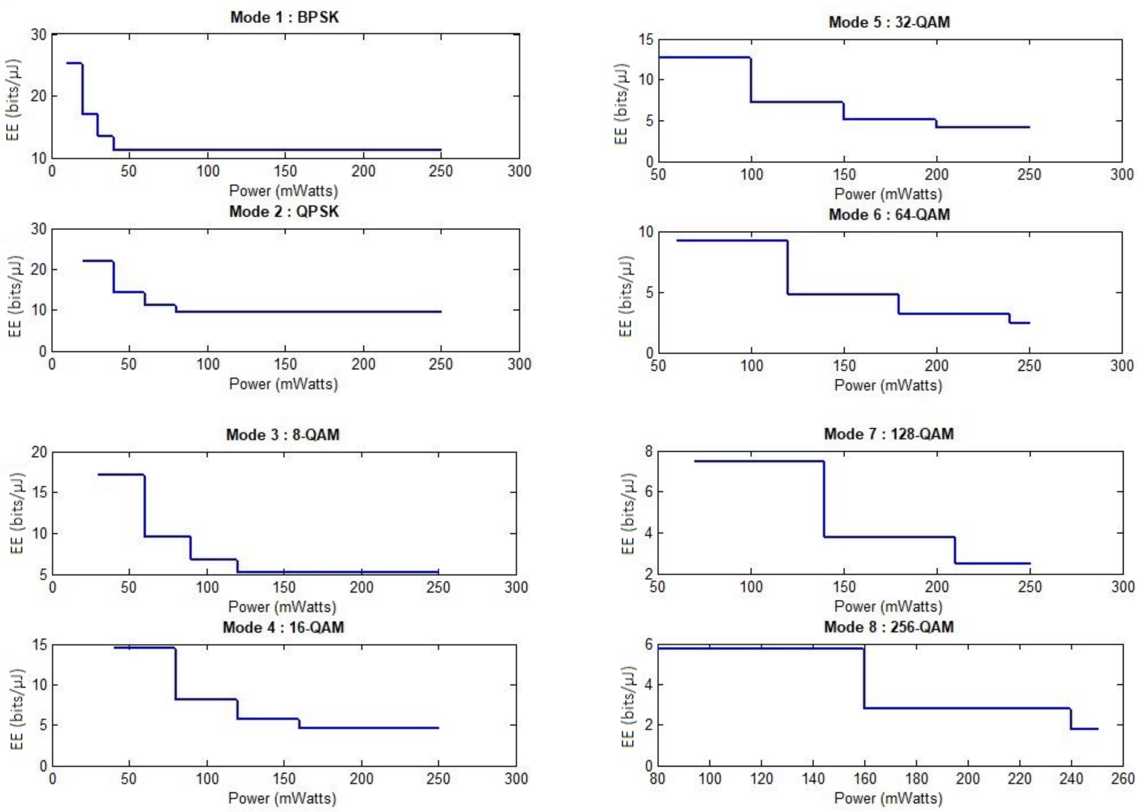

Figure 4.2: Variation of EE with transmitted power for each mode.

The table below shows how SE and EE vary across different modes when all the modes operate at the same transmitted power. This has been shown for 3 different values of the transmitted power. The general trend, as can be expected, is that SE increases and EE decreases with the order of modulation. Similarly, as discussed above, SE increases and EE decreases with the average transmission power for the same mode.

Table 4.1: Variation of SE (bits/s/Hz) and EE (bits/μJ) with modulation order at 3 different values of transmission power : 80mW, 160mW, 240mW.

	P_{tr} = 80 mW		P_{tr} = 160 mW		P_{tr} = 240 mW	
N_m	SE	EE	SE	EE	SE	EE
2	10	11.256	10	11.256	10	11.256
4	14	9.555	14	9.555	14	9.555
8	10	9.595	18	5.237	18	5.237
16	12	8.128	22	4.564	22	4.564
32	8	12.691	20	5.185	26	4.156
64	9	9.153	16	4.753	30	2.415
128	10	7.452	18	3.775	26	2.497
256	11	5.722	20	2.775	29	1.761

4.2 Variation of WEF with Power

Fig. 4.3 illustrates the variation of WEF with the average transmitted power for each mode separately at equal weightage point $k = 0.5$. These values of WEF are obtained using (3.18), i.e. after normalization of EE and SE for each mode independently. Therefore, the value of WEF also lies between 0 and 1 here. Since SE and EE had opposite trends with both transmitted power and the mode index, we can expect their effects to be nullified in WEF. The plots clearly show no bias to either smaller or larger values of power as they are neither monotonically decreasing nor monotonically increasing. The values mostly vary between 0.55 and 0.7 for all the modes, again showing no bias towards any specific modulation order. This proves that WEF is actually a very good trade-off between SE and EE that provides a truly optimal solution considering both equally. The results agree with the statement made during problem formulation that maximization of WEF over $P_{tr,m}$ is not as trivial as optimization of SE or EE. The curves are again similar to step functions for the same reason stated earlier.

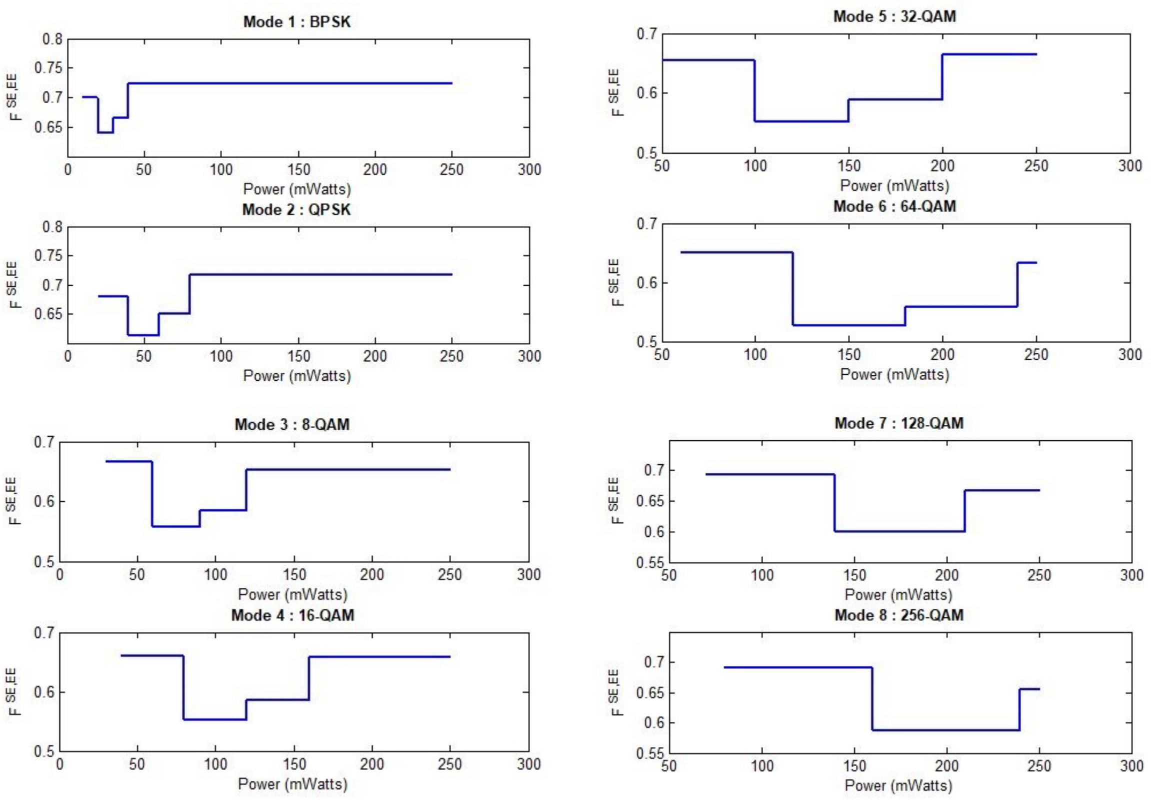

Figure 4.3: Variation of WEF with transmitted power for each mode at $k = 0.5$.

4.3 SE- and EE-based Optimal Mode Selection

The two plots in Fig. 4.4 show how the selection of optimal mode on the basis of SE and EE respectively, vary with the average transmitted power. Although the curves do not obey any well-defined pattern, there does exist an overall trend. The mode with greater modulation order tends to get selected at higher transmission power while at lower power, the mode with lesser modulation order is selected in both optimization problems. This suggests that in order to reap benefits of both SE and EE, a smaller constellation should be employed at low power and a larger constellation at high power.

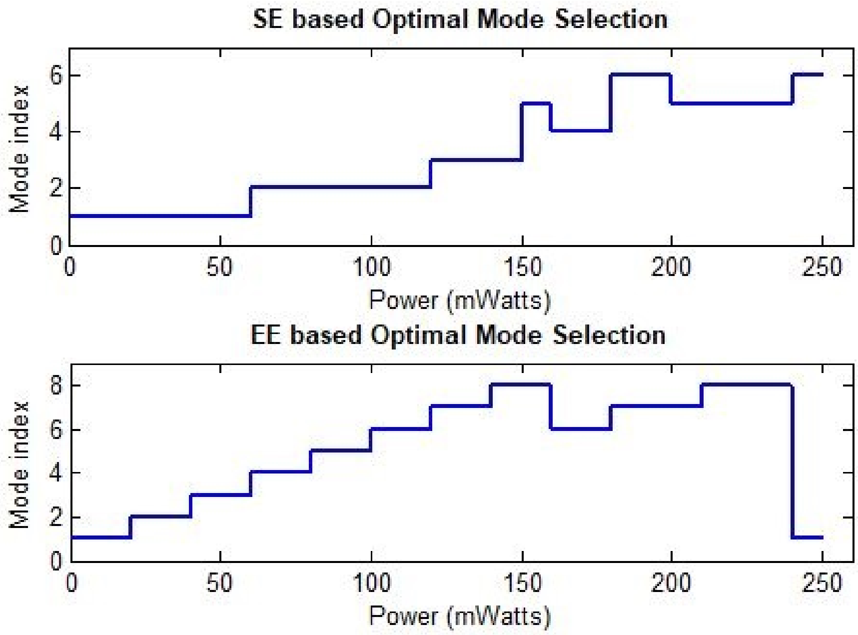

Figure 4.4: Optimal Mode Selection based on SE and EE respectively.

4.4 WEF-based Selection of Optimal Mode and Power

Fig. 4.5 shows the optimal mode selected on the basis of WEF as the power is varied over the complete permissible range. Along with the mode index, it also shows the value of WEF of the selected mode at that power. This WEF is the maximum across all the modes at that power, because that is how the optimal mode is selected. Thus, it is referred to as $F_{max}^{SE,EE}$. This is repeated for 4 different values of $k : 0.35, 0.45, 0.55, 0.65$. As was the case with SE- and EE-based mode selection, a higher mode is selected at high power and a lower mode at low power although not always. This trend becomes increasingly dominant as the weightage of SE is increased from 0.35 to 0.65. Moreover, the global maximum of WEF has a decreasing trend at $k = 0.35$ which changes to an increasing trend at $k = 0.65$. This is due to the fact that at lower values of k, EE is more dominant in WEF which is a decreasing function of power while at higher values of k, SE is more dominant which makes the overall WEF an increasing function.

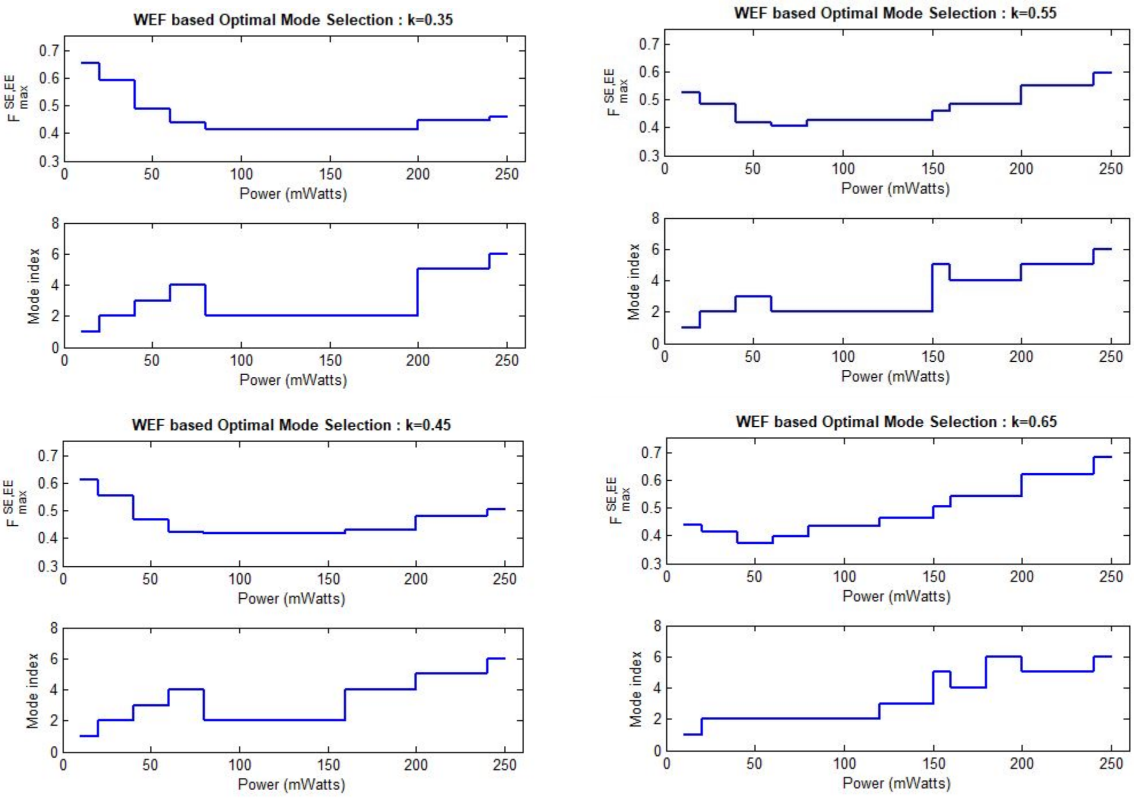

Figure 4.5: Variation of maximum value of WEF and selected mode index with transmitted power for 4 different values of k : 0.35, 0.45, 0.55, 0.65.

Table 4.2 illustrates the optimal transmission configuration selected at different values of the weight factor k. This is obtained for each value of k by finding the maximum of the corresponding $F^{SE,EE}_{max}$ curve. This is the global maximum of WEF : $F^{SE,EE}_{MAX}$. The value of transmitted power at which this is obtained and the mode selected at that power are their respective global optimal values, P_{tr} and m. Subsequently, the optimal value of active RF chains is obtained by dividing this P_{tr} by the per antenna transmitted power of the selected mode, i.e. $P_{T,m}$.

The two trends in the curves of Fig. 4.5 discussed above suggest that at low value of k, a smaller value of the transmitted power and the mode with lesser modulation order are more likely to be selected. However, at high value of k, higher power and greater modulation order are more likely. This is confirmed by the final WEF-based optimization results derived here.

Table 4.2: Selection of Optimal Transmission Configuration : $m,\ P_{tr}\ and\ N_a$ at 6 different values of k.

k	$F_{MAX}^{SE,EE}$	Mode index	P_{tr} (mW)	N_a
0.3	0.740	2	20.01	1
0.4	0.653	1	10.06	1
0.5	0.566	1	10.06	1
0.6	0.638	6	121.33	2
0.7	0.728	7	210.19	3
0.8	0.819	8	239.71	3

4.5 Comparison of WEF-based Selection with SE- and EE-based Selection

This section provides a comparison of the SE and EE achieved after optimization when we go for WEF-based selection as supposed to that in SE- and EE-based selection. In SE-based selection, optimal transmission is achieved at 251 mWatts transmit power and values of the efficiencies turn out to be SE = 30 bits/s/Hz and EE = 2.4153 bits/μJ which after normalization become 1 and 0.096 respectively. In EE-based selection, on the other hand, SE and EE are 4 bits/s/Hz and 25.175 bits/μJ respectively obtained at 10.1 mWatts power. These values become 0.133 and 1 after normalization. This clearly shows that in either optimization, the other metric suffers drastically. However, in WEF-based selection, say at k = 0.6, the SE and EE achieved after optimization are 0.533 and 0.189 respectively. Although, none of the two quantities reach their maximum, but the proposed method atleast ensures that both of them are within acceptable limits.

Chapter 5

Conclusion

Through the course of this work, we discovered the different techniques and issues involved in the design of SM-MIMO systems and studied its differences with the conventional MIMO systems. We learnt about the different performance evaluation metrics in SM-MIMO such as SE & EE and studied about the recent advances in literature with respect to these metrics. We came across a lot of work in this field that looked to optimize the system settings on the transmitter side on the basis of SE and EE independently but none of them attempted to combine the two in the optimization problem. This resulted in designs that are optimal with respect to SE and EE separately but suboptimal when both of them are evaluated together. Thus, the goal of this proposal is to eliminate these shortcomings in the prior methods. This can be achieved through the WEF which integrates the two metrics in a single problem definition.

We proposed a new definition for the modes in the candidate set over which the maximization of WEF takes place. Using this definition of modes and certain constraints on the transmit power, data rate and allowed SER, we found the optimal number of RF chains and mode index at each value of the transmitted power in range allowed by the constraints. This formed our intermediate result in the search for the global optimal value of the transmitted power and the mode index on the basis of WEF. We compared this with the SE- and EE-based mode selection to verify that our result actually provided a good trade-off between SE and EE. The globally optimal transmission configuration was then obtained from the intermediate result. This was followed by a further analysis of the global optimum at different weightage of SE in the WEF to assert that the results of the proposed method agrees with all the intuitive relations.

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Appendix

The values of the different system parameters used in generating the simulation results are as follows [14], [15] : $p_{e,max} = 10^{-6}$, $P_{tr,max} = 24$ dBm, $b_{min} = 3$ bits/s/Hz, $N_0 = -174$ (dBm/Hz), $G_a = 1$, $\eta = 0.35$, $d_{loss} = 102$ dB, $B = 1$(MHz), $P_c = 10^{-8}$, , $P_f = 0.1$, $P_b = 4.09 \times 10^{-9}$ $P_{c1} = 0.04$, and $P_{c2} = 1.3 \times 10^{-8}$. We evaluate the results with $N_t = 8$, $N_r = 4$, $\mathbf{R}_t = \mathbf{I}_{N_t}$ and $\mathbf{R}_r = \mathbf{I}_{N_r}$ where $\mathbf{I}_N = N \times N$ identity matrix.