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Research Article

Impact of Mutual Coupling and Polarization of Antennas on BER Performances of Spatial Multiplexing MIMO Systems

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This paper is aimed at studying the impacts of mutual coupling, matching networks, and polarization of antennas on performances of Multiple-Input Multiple-Output (MIMO) systems employing Spatial Multiplexing (SM). In particular, the uncoded average Bit Error Rate (BER) of MIMO systems is investigated. An accurate signal analysis framework based on circuit network parameters is presented to describe the transmit/receive characteristics of the matched/unmatched antenna array. The studied arrays consist of matched/unmatched compact copolarization and polarization diversity antenna array. Monte-Carlo numerical simulations are used to study the BER performances of the SM MIMO systems using maximum-likelihood and/or zero-forcing detection schemes. The simulation results demonstrate that the use of matching networks can improve the BER performance of SM MIMO systems significantly, and the BER performance deterioration due to antenna orientation randomness can be compensated by use of polarization diversity antenna arrays.

1. Introduction

The emerging Multiple-Input Multiple-Output (MIMO) wireless communication techniques are attentively studied in the last decades because these can prominently improve the transmission rates and qualities of wireless communication systems [1–4]. The MIMO wireless communication techniques are the key technologies for future wideband wireless communications. An important challenge of implementation of MIMO wireless communication techniques on mobile terminals and access points is to place multiple antennas in a physical size constrained volume. The serious mutual coupling between compact antennas will cause impedance mismatch and the element active pattern distortions, thus make the performance of MIMO communication systems to degrade [5–8].

Prior works show the uses of multiport matching networks and polarization antennas to construct compact antenna arrays in limited volumes while maintain the channel capacity of MIMO systems. In [8–11] multiport decoupling and matching, networks are utilized to reduce the mutual coupling between antenna elements of compact receive arrays. The results show that when lossless matching networks are used, the MIMO systems with compact receive arrays of which the spacings between antennas elements are only 0.1λ can approach the similar channel capacity to MIMO systems with largely spaced antenna arrays, where λ is the wavelength. Polarization diversity antenna are also considered to improve the capacity further while maintaining the array size as studied in [12–15].

To realize the transmission rate and quality advantages of MIMO wireless communication systems, specified space-time coding schemes must be used, such as Spatial Multiplexing (SM) scheme [16, 17], and Space-Time Block Coding (STBC) scheme [18]. The obvious measurable criterion for space-time coding systems is the Bit Error Rate (BER) over approached transmission rates. Thus, the BER performance of space-time coding systems would be considered to evaluate the impacts of mutual coupling, matching networks and polarization diversity on MIMO wireless communications.

Prior works usually use analytical channel model to study the performance of space-time coding systems, such as complex Gaussian distributed channel models or correlation separated channel models [17–19]. Though the performance

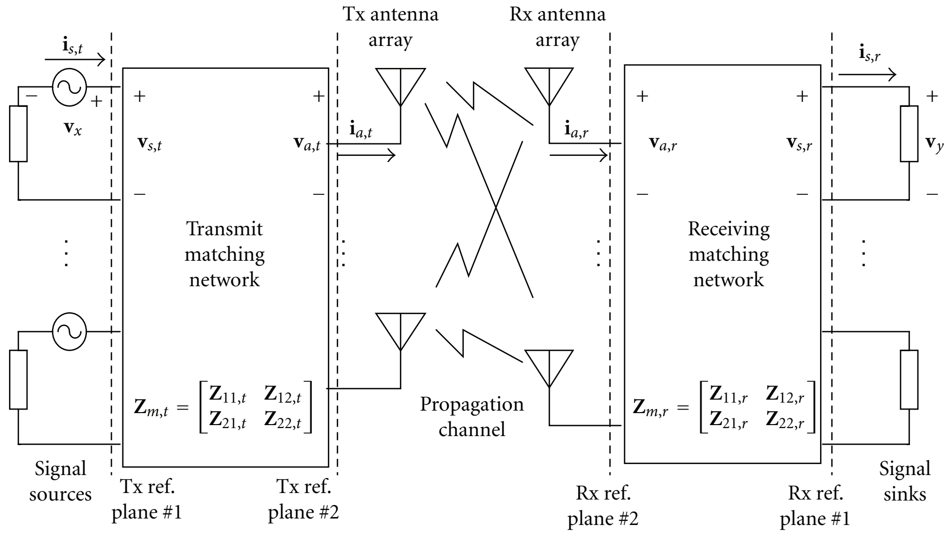

Figure 1: Anaysis framework of the MIMO systems considering mutual coupling and matching networks.

analyses of space-time coding schemes based on analytical channel models are important and effective for MIMO systems with nearly ideal antennas, those analyses are not appropriate for studying the impacts of mutual coupling and polarization diversity of compact antennas on BER performances of MIMO systems. This is because the analytical models usually ignore the influence of specified antennas and radio frequency branches and do not reflect the physical characteristics of the channels; thus the analytical models can not be used to evaluate the design of antenna arrays and/or RF branches for MIMO systems using specific space-time coding schemes [20].

The paper studies the impacts of mutual coupling, matching networks, and polarization diversity on BER performances of SM MIMO systems using the accurate circuit network signal model. The rest of the paper is divided into 4 sections: in Section 2, the complete system model based on circuit network parameters is presented; in Section 3, the BER performances of SM MIMO systems are studied, and the effects of the mutual coupling and matching networks are investigated; the impacts of polarization diversity antenna are studied in Section 4; in Section 5, the conclusions are drawn.

2. Analysis Framework

The RF chains of MIMO systems are shown in Figure 1, consisting of transmitters, matched transmit antenna array, propagation channel, matched receive antenna array, and receivers. The matching networks are assumed to be passive and lossless but are not needed to be reciprocal.

The n_t independent signal sources with real output impedance R_0, which is the characteristic impedance of the RF system and the transmission line, are used to create the transmitted signals, respectively. The currents on the RF system ports can be represented as

$$\mathbf{i}_{s,t} = \left(R_0\mathbf{I} + \mathbf{Z}_{s,t}\right)^{-1}\mathbf{v}_x, \tag{1}$$

where $\mathbf{Z}_{s,t}$ is the input impedance matrix of the (matched) transmit antenna array as in Figure 1, and $\mathbf{v}_x$ is the voltage vector of signal sources. In most communication systems, the power constraint is dependent on the transmit power P_0 of the signal sources. The transmit power constraint can be expressed as [21]

$$E\left[\mathbf{v}_x^H\mathbf{v}_x\right] \leq 4R_0P_0 = K_t, \tag{2}$$

where $E[\cdot]$ is the expectation operation and K_t is the mean square limitation of the signal voltages. Prior works commonly assumed constant radiated power to avoid the impact of mutual coupling of transmit antenna on SNR and thereby channel capacity [9]. However, the coupling between transmit antennas will demand signal sources to output more power, that is, a higher transmit power, to guarantee a constant radiated power, while the cost of improving the signal sources' transmit power is expensive. Thus, that constant radiated power limitation is obviously critical.

Because the mismatch between signal sources and coupled transmit antennas causes a reflection which may seriously reduce the gain realized by the antennas and interact with the signal sources to cause unstable operation of these components, a transmit matching network with Z-parameter matrix $\mathbf{Z}_{m,t}$ is used to compensate the impact of coupling between transmit antenna arrays on the MIMO performance. Given the multiport nature of the RF system, the impedance matrix of the transmit matching networks is represented using a block impedance matrix description as

$$\mathbf{Z}_{m,t} = \begin{bmatrix} \mathbf{Z}_{ss,t} & \mathbf{Z}_{sa,t} \\ \mathbf{Z}_{as,t} & \mathbf{Z}_{aa,t} \end{bmatrix}, \tag{3}$$

where the subscriber "a" and "s" refer to antenna and RF system ports as in Figure 1, respectively. Thus the input impedance matrix of matched transmit antenna array is $\mathbf{Z}_{s,t} = \mathbf{Z}_{ss,t} - \mathbf{Z}_{sa,t}(\mathbf{Z}_{a,t} + \mathbf{Z}_{aa,t})^{-1}\mathbf{Z}_{as,t}$.

The current vector on the antenna ports can be related to signal source voltages as

$$\mathbf{i}_{a,t} = \underbrace{\left[(\mathbf{Z}_{a,t} + \mathbf{Z}_{aa,t})^{-1} \mathbf{Z}_{as,t} \right] (R_0 \mathbf{I} + \mathbf{Z}_{s,t})^{-1}}_{\mathbf{T}_t} \mathbf{v}_x, \tag{4}$$

where $\mathbf{Z}_{a,t}$ is the impedance matrix of transmit antenna array, and $\mathbf{T}_t$ is the transfer function relating source voltages to antenna currents. When the transmit antenna array is directly connected to the sources, $\mathbf{T}_t = (R_0 \mathbf{I} + \mathbf{Z}_{a,t})^{-1}$.

The radiate electric fields $\mathbf{E}_{tx}(\mathbf{k}_t)$ in the far-field region of the transmitter can be related to the current $\mathbf{i}_{a,t}$ on the n_t antenna ports using the radiate electric pattern $\mathbf{E}_{a,t}(\mathbf{k}_t)$ as [22]

$$\mathbf{E}_{tx}(\mathbf{k}_t) = \sum_{n=1}^{n_t} \mathbf{e}_{n,a,t}(\mathbf{k}_t) \mathbf{i}_{n,a,t} = \mathbf{E}_{a,t}(\mathbf{k}_t) \mathbf{i}_{a,t}, \tag{5}$$

where $\mathbf{k}_t = [\theta_t \ \phi_t]^T$ represents a direction in solid angle with elevation θ_t and azimuth angels ϕ_t, respectively. The function $\mathbf{e}_{n,a,t}(\mathbf{k}_t)$, which is the nth column of $\mathbf{E}_{a,t}(\mathbf{k}_t)$, represents radiate electric wave fields represented in $\mathbf{k}_t$ for unit driving current ($\mathbf{i}_n = 1$) with all other antenna element ports open-circuited. The radiate fields in the far-field region is normalized by the spherical wave factor $e^{-jk_0 r_t}/r_t$, with k_0 the free-space wave number, and r_t is the distance from the center of the sphere to the $\mathbf{r}_t$ point, so the radiate electric patterns depend only on the observation angle [23].

The characteristics of propagation channel can be represented by the transfer function $\mathbf{\Gamma}_{rt}(-\mathbf{k}_r, \mathbf{k}_t)$ relating the inward wave fields impinging receive antenna arrays to the output forward wave fields from transmit antenna arrays as [12, 22]

$$\mathbf{E}_{rx}(-\mathbf{k}_r) = \oint_{\mathbf{k}_r} \mathbf{G}_{rt}(-\mathbf{k}_r, \mathbf{k}_t) \mathbf{E}_{tx}(\mathbf{k}_t) d\mathbf{k}_t, \tag{6}$$

where $\mathbf{E}_{rx}(-\mathbf{k}_r)$ denotes the inward signal wave fields in receive solid angle $-\mathbf{k}_r$, and the minus sign "−" before $\mathbf{k}_r$ denotes that the wave is toward the receiver.

We represent the radiate pattern of the mth coupled receive element referenced to the receive coordinate origin as $\mathbf{e}_{m,a,r}(\mathbf{k}_r)$. By reciprocity, the open-circuited voltages on receive antenna ports are then given as [10, 22]

$$\mathbf{v}_{a,r}^{(o)} = -j \frac{4\pi}{k_0 \eta} \oint_{\mathbf{k}_r} \mathbf{E}_{a,r}^T(\mathbf{k}_r) \mathbf{E}_{rx}(-\mathbf{k}_r) d\mathbf{k}_r, \tag{7}$$

where $\mathbf{E}_{a,r}(\mathbf{k}_r)$ represent the $2 \times n_r$ dimension matrix with mth column $\mathbf{e}_{m,a,r}(\mathbf{k}_r)$, and η is the characteristic wave impedance.

Terminate the coupled receive antenna array with receive matching network $\mathbf{Z}_{m,r}$, which composes of block matrix $\mathbf{Z}_{ss,r}$, $\mathbf{Z}_{sa,r}$, $\mathbf{Z}_{as,r}$, $\mathbf{Z}_{aa,r}$ in a similar way with transmit matching network. The open-circuited voltages on the receive ports are

$$\mathbf{v}_{s,r}^{(o)} = \mathbf{Z}_{sa,r} (\mathbf{Z}_{aa,r} + \mathbf{Z}_{a,r})^{-1} \mathbf{v}_{a,r}^{(o)}, \tag{8}$$

where $\mathbf{Z}_{a,r}$ is the impedance matrix of receive antenna array.

Similar with the transmitter, we assume the receive sinks are identically independent and the input impedances are R_0, then the voltages $\mathbf{v}_{x,r}$ and $\mathbf{v}_{n,r}$ on receive loads induced from inward waves and receiver noises, respectively, can be expressed as [11]

$$\mathbf{v}_{x,r} = \underbrace{(R_0 \mathbf{I} + \mathbf{Z}_{s,r})^{-1} [\mathbf{Z}_{sa,r} (\mathbf{Z}_{aa,r} + \mathbf{Z}_{a,r})]}_{\mathbf{T}_r} \mathbf{v}_{a,r}^{(o)}, \tag{9a}$$

$$\mathbf{v}_{n,r} = -G_r \mathbf{i}_n, \tag{9b}$$

where $\mathbf{Z}_{s,r} = \mathbf{Z}_{ss,r} - \mathbf{Z}_{sa,r}(\mathbf{Z}_{a,r} + \mathbf{Z}_{aa,r})^{-1} \mathbf{Z}_{as,r}$ is the impedance matrix of the matched receive antenna array as in Figure 1, $\mathbf{T}_r$ is the transfer function relating open-circuited voltages on antenna ports to voltages on receive loads, G_r represents the matched gain of the receive sinks, and $\mathbf{i}_n$ is the effective noise-source current vector of the receive sinks [11].

Following the above, the system model of MIMO system can be described as

$$\underbrace{\mathbf{v}_y}_{\mathbf{y}} = \underbrace{\mathbf{T}_r \mathbf{H}_0 \mathbf{T}_t}_{\mathbf{H}} \underbrace{\mathbf{v}_x}_{\mathbf{x}} + \underbrace{(-G_r \mathbf{i}_n)}_{\mathbf{n}}, \tag{10}$$

where $\mathbf{H}_0 = \oint_{\mathbf{k}_r} \oint_{\mathbf{k}_t} \mathbf{E}_{a,r}^T(-\mathbf{k}_r) \mathbf{G}_{rt}(-\mathbf{k}_r, \mathbf{k}_t) \mathbf{E}_{a,t}(\mathbf{k}_t) d\mathbf{k}_t d\mathbf{k}_r$ is the transfer function between the currents on the transmit antenna ports and the open-circuited signal voltages on the receive antenna ports, $\mathbf{n}$ denotes the noise. $\mathbf{y}$ and $\mathbf{x}$ represent the received and transmitted signals, respectively. While $\mathbf{H}$ is changed with different transmit and/or receive matching networks, $\mathbf{H}_0$ is not changed for given transmit and receive antenna arrays terminated with different matching networks.

3. Impacts of Mutual Coupling on BER Performances of Layered Space-Time Coding MIMO Systems

3.1. Mutual Coupling and Multiport Matching Networks. Tight mutual coupling in conjunction with closely spaced antennas results in significant gain reduction caused by power mismatch. The gain reduction decreases the antenna arrays' ability to transmit energy to or extract energy from the fields. The MIMO systems require dissipation of large amounts of transmitted power to guarantee the SNR. A potential solution to the problem would be to apply transmit and receive matching networks leading from signal sources/sinks to the coupled antenna arrays thereby to avoid the effects of mismatch. Prior works have revealed the impacts of receive matching networks on channel capacity. In this paper, impacts of both transmit and receive matching networks on BER performances of SM MIMO systems are studied.

The investigations of the BER performances of MIMO system, which is dependent on the transmit and receive matching networks, would be incomplete without considering the optimal matching networks. These decouple and match the impedances of the transmit and receive antenna arrays to the characteristic impedance of RF system, that is, to make $\mathbf{Z}_{s,t/r} = R_0\mathbf{I}$. Insertion of a lossless receive matching network between the receive antennas and sinks can increase the power collected when $\mathbf{Z}_{a,r} \neq R_0\mathbf{I}$. And similarly, insertion of a lossless transmit matching network between the transmitters and the transmit antennas can also decrease the required transmit power of signal sources when fixed (but arbitrary) driving antenna currents $\mathbf{i}_{a,t}$ (and thereby the transmit fields) are demanded when $\mathbf{Z}_{a,t} \neq R_0\mathbf{I}$. For the antenna arrays' ability to transmit and receive power to/from fields is improved, the BER performances of MIMO systems with matched transmit and receive antenna arrays are also better than that with unmatched antenna arrays.

The section firstly presents a significantly simplified proof that when the impedances of transmit and receive antenna arrays are decoupled and matched to characteristic impedance of the RF system, the equivalent impedances on the transmit and receive antenna ports towards the matching networks are intrinsically equal to the conjugates of impedances of transmit and receive antenna array respectively. Then, the section provides the assertion that when optimal transmit and/or receive matching networks are used, the collected power on the loads is maximized for arbitrary fixed inward wave fields $\mathbf{E}_{rx}(-\mathbf{k}_r)$ to the receiver, and the required signal sources' transmit power is minimized for transmit currents $\mathbf{i}_{a,t}$ on the transmit antenna ports.

Lemma 1. *Consider the optimal matching networks that satisfy $\mathbf{Z}_{s,t/r} = \mathbf{Z}_{1,t/r} = R_0\mathbf{I}$, the optimal matching networks intrinsically maintain that*

$$\mathbf{Z}_{2,t/r} = \mathbf{Z}^H_{a,t/r}, \tag{11}$$

where $\mathbf{Z}_{1,t/r}$ and $\mathbf{Z}_{2,t/r}$ are the respective impedances on the transmit/receive matching networks and antenna ports towards to the matching networks as shown in Figure 1.

Proof. The input impedance of the matched transmit/receive antenna array on RF system ports can be expressed as

$$\mathbf{Z}_{1,t/r} = \mathbf{Z}_{ss,tr} - \mathbf{Z}_{sa,t/r}\left(\mathbf{Z}_{a,t/r} + \mathbf{Z}_{aa,t/r}\right)^{-1}\mathbf{Z}_{as,t/r} = R_0\mathbf{I}. \tag{12}$$

Assuming $\mathbf{Z}_{as,t/r}$ and $\mathbf{Z}_{sa,t/r}$ are invertible (it omits the cases that $\mathbf{Z}_{as,t/r}$ and $\mathbf{Z}_{sa,t/r}$ are singular. Results pertaining to the singular case can be obtained in the limit of vanishing added loss. Henceforth, we shall make no explicit reference to singular cases), we draw

$$\mathbf{Z}^H_{a,t/r} = \mathbf{Z}^H_{sa,t/r}\left(\mathbf{Z}^H_{aa,t/r} - R_0\mathbf{I}\right)^{-1}\mathbf{Z}^H_{sa,t/r} - \mathbf{Z}^H_{sa,t/r}. \tag{13}$$

And for the matching network is lossless, that is,

$$\begin{bmatrix} \mathbf{Z}_{aa,t/r} & \mathbf{Z}_{as,t/r} \\ \mathbf{Z}_{sa,t/r} & \mathbf{Z}_{ss,t/r} \end{bmatrix} + \begin{bmatrix} \mathbf{Z}_{aa,t/r} & \mathbf{Z}_{as,t/r} \\ \mathbf{Z}_{sa,t/r} & \mathbf{Z}_{ss,t/r} \end{bmatrix}^H = 0. \tag{14}$$

We get $\mathbf{Z}_{aa,t/r} = -\mathbf{Z}^H_{aa,t/r}$, $\mathbf{Z}_{aa,t/r} = -\mathbf{Z}^H_{ss,t/r}$, and $\mathbf{Z}_{sa,t/r} = -\mathbf{Z}^H_{sa,t/r}$, thus

$$\mathbf{Z}^H_{a,t/r} = \mathbf{Z}_{aa,t/r} - \mathbf{Z}_{as,t/r}\left(\mathbf{Z}_{ss,t/r} + R_0\mathbf{I}\right)^{-1}\mathbf{Z}_{sa,t/r}. \tag{15}$$

The impedance towards matching networks on the antenna ports is

$$\mathbf{Z}_{2,t/r} = \mathbf{Z}_{aa,t/r} - \mathbf{Z}_{as,t/r}\left(\mathbf{Z}_{ss,t/r} + R_0\mathbf{I}\right)^{-1}\mathbf{Z}_{sa,t/r}. \tag{16}$$

Thus we can draw the conclusion that when the matching network that transfer the antenna impedance to $R_0\mathbf{I}$ is connected to the RF systems, the impedance towards matching networks on the antenna ports is equal to the conjugate of the impedance of coupled antenna array as

$$\mathbf{Z}_{2,t/r} = \mathbf{Z}^H_{a,t/r}. \tag{17}$$

□

Firstly, we consider the effect of optimal receive matching networks on the sum collected power on the loads. For any given inward wave fields $\mathbf{E}_{rx}(-\mathbf{k}_r)$, the characteristics of the antenna array can be represented with equivalent source voltages $\mathbf{V}^{(0)}_{a,r}$ and impedance matrix $\mathbf{Z}_{a,r}$. The received power on the sinks is

$$P_r = \frac{\left(\mathbf{T}_r\mathbf{v}^{(o)}_{a,r}\right)^H \mathbf{T}_r\mathbf{v}^{(o)}_{a,r}}{2R_0}. \tag{18}$$

According to the maximum power transfer theorem that the output power is maximized when the impedance matrix of the terminations is equal to the conjugate of the impedance matrix of the sources [21], and noting the optimal receive matching networks are lossless, we derive

$$P_r\left(\mathbf{Z}_{m,r,\mathrm{opt}}\right) \geq P_r\left(\mathbf{Z}_{m,r}\right). \tag{19}$$

Secondly, we consider the effect of optimal matched matching networks on required transmit power of the signal generators. For any given currents $\mathbf{i}_{a,t}$ on the transmit antenna ports, the required transmit power of the signal generators satisfies

$$P_x\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right) = \frac{\mathbf{v}^H_x\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right)\mathbf{v}_x\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right)}{4R_0}, \tag{20}$$

where $\mathbf{v}_x(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}) = \mathbf{T}^{-1}_t(\mathbf{Z}_{m,t})\mathbf{i}_{a,t}$ denotes the voltage vector of signal generators as to excite the antenna currents $\mathbf{i}_{a,t}$ with transmit matching network $\mathbf{Z}_{m,t}$.

According to [21], the exchangeable power of the signal sources can be expressed as

$$P_e\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right) \geq P_x\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right) \tag{21}$$

Because the transmit matching networks are passive, the outputted power of the transmit amplifiers must be not less than the radiated power [21]. According that, exchangeable power is the maximum power that can be delivered from the signal sources, we get correctness.

$$P_e\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right) \geq \frac{\mathrm{Re}\left\{\mathbf{i}^H_{a,t}\mathbf{Z}_{a,t}\mathbf{i}_{a,t}\right\}}{2}. \tag{22}$$

For the maximum power will be outputted when the impedance matrix of the terminations is equal to the conjugate of source impedance matrix, and the optimal transmit matching network is lossless, we get

$$P_e\left(\mathbf{Z}_{m,t,\text{opt}}, \mathbf{i}_{a,t}\right) = P_x\left(\mathbf{Z}_{m,t,\text{opt}}, \mathbf{i}_{a,t}\right) = \frac{\text{Re}\left\{\mathbf{i}_{a,t}^H \mathbf{Z}_{a,t} \mathbf{i}_{a,t}\right\}}{2}, \quad (23)$$

where $P_x(\mathbf{Z}_{m,t,\text{opt}}, \mathbf{v}_{a,t})$ is the transmit power of the signal sources on the transmit antenna ports when the optimal matching network $\mathbf{Z}_{m,t,\text{opt}}$ is applied to excited currents $\mathbf{i}_{a,t}$.

Relating (23) and (24), we derive that

$$P_e\left(\mathbf{Z}_{m,t}, \mathbf{i}_{a,t}\right) \geq P_e\left(\mathbf{Z}_{m,t,\text{opt}}, \mathbf{i}_{a,t}\right). \quad (24)$$

This shows that the matching networks not only maximize the received power but also minimize the required transmit power. Thus, it is also deserved that the matching networks will improve the BER performance of SM MIMO systems with compact antenna arrays, which is studied in the following.

3.2. Configurations of Numerical Simulations. To demonstrate applications of the analysis framework developed in the paper and illustrate the impacts of mutual coupling and matching networks on channel capacity of MIMO systems between coupled antenna arrays, the simulation constructs the MIMO systems using network framework to explore the possible gain from matching networks as compared to the systems without matching networks.

At first, the section provides the representative parallel dipole antenna arrays, construction of optimal matching networks, and path-based channel model and then demonstrates how to calculate the channel transfer function connected with these models. After the transmit power limitation is set according to the SNR of a reference SISO system, the BERs of the SM MIMO systems with different spaced antennas are calculated with numerical simulation. The configuration of the modulation schemes and detection methods is also presented.

Dipole antennas as very basic antenna element are used to construct the antenna arrays as in Figure 2. All antenna properties (i.e., active gain, pattern, and self- and mutual-coupling impedance) of parallel dipoles are calculated by a standard electromagnetic simulator software tool [24]. To minimize the effects of mismatch for the reference single antenna element, the length of the dipole with a 0.01λ diameter is adjusted to about 0.47λ to make the reactance of the dipole nearly equal to 0 with a real resistance about $R_0 = 72$ ohm, where λ is the wave length. The VSWR of the isolated antenna is less than 1.05 in the carrier frequency. The transmit and receive antenna arrays have the same array configuration for all results presented here, and the largest spacing between the antenna elements is L while the distance between adjacent antenna elements is d as shown in Figure 2. The matching networks that satisfy $\mathbf{Z}_{s,t/r} = R_0\mathbf{I}$ are used to construct the transmit and receive optimal matching networks as addressed in [25]. Specifically, $\mathbf{h} = j\mathbf{I}$ is chosen.

When the transmit and receive arrays and scattering objects are all in the farfield of one another, a single path-based model can be used to approximate the channel. In flat

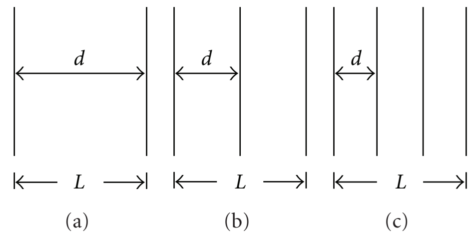

Figure 2: Configurations of the parallel dipoles.

fading channel, the channel transfer function relating receive wave fields to transmit wave fields is described as [12]

$$\mathbf{G}_{rt}(-\mathbf{k}_r, \mathbf{k}_t) = \sum_i \boldsymbol{\beta}_l \delta(\mathbf{k}_r - \mathbf{k}_{l,r}, \mathbf{k}_t - \mathbf{k}_{l,t}), \quad (25)$$

where δ represents the delta function, and

$$\boldsymbol{\beta}_l = \begin{bmatrix} \beta_{\theta\theta,l} & \beta_{\theta\phi,l} \\ \beta_{\phi\theta,l} & \beta_{\phi\phi,l} \end{bmatrix}. \quad (26)$$

The Cross Polarization Discrimination (XPD) is defined as

$$\text{XPD} = \frac{E\left\{\sum_l \left[\beta_{\theta\phi,l}^2 + \beta_{\phi\theta,l}^2\right]\right\}}{E\left\{\sum_l \left[\beta_{\theta\theta,l}^2 + \beta_{\phi\phi,l}^2\right]\right\}}. \quad (27)$$

Thus, incorporating with active radiate patterns of transmit and receive antenna arrays, the channel response $\mathbf{H}_0$ is

$$\mathbf{H}_0 = \sum_l \mathbf{E}_{a,r}^T(\mathbf{k}_{l,r}) \boldsymbol{\beta}_l \mathbf{E}_{a,t}(\mathbf{k}_{l,\mathbf{t}}). \quad (28)$$

In the computations, 1000 random realizations of the path-based, clustered channel model [26, 27] are generated based on a parameter set for 2.5 GHz to model a typical indoor channel for mobile communications, refer to (28).

Because the SNR is affected by the antenna arrays and the matching networks, the normalized SNR assumption is not appropriate. In this paper, the power constraint that limits the output power of signal generators is applied as shown. The single-input single-output system between standard dipoles is used as the reference system. The transmit power limitation is obtained as

$$K_0 = E\left[\mathbf{v}_x^H \mathbf{v}_x\right] = \gamma_1 \frac{\sigma_n^2}{E\left[H_1 H_1^H\right]}, \quad (29)$$

where γ_1 is the assumed SNR of the reference SISO system, H_1 is the channel transfer function of SISO system according to the random channel realizations, and $E(\cdot)$ is the expectation operation.

In the simulations, the power limitations are constrained by the number of the transmit antennas (individual data streams), that is, $K_t = n_t K_0$. The details of the configurations are listed in Table 1.

In each realization of the channel model, a frame consisting of 50 signal symbols in each individual antenna

Table 1: Configurations of the simulation.

n_t/n_r	Source code	Modulation	Bit rate	Power
2	Gray code	4QAM	2	$2P_0$
3	Gray code	4QAM	3	$3P_0$
4	Gray code	4QAM	4	$4P_0$

is transmitted, that is, an information sequence of 100 bits for 4QAM modulation constellation is adopted. Type of mapping employed for mapping symbols to ideal constellation points is Gray code scheme. For the BER performances of MIMO systems are also relative to the receive schemes, maximum likelihood (ML) [28], that is, spherical-decoding scheme [29], and/or zero forcing (ZF) [30], detection methods are employed to detect and decide the received information respectively in receivers.

3.3. Simulation Results. The BER performances of the SM MIMO systems are affected by the spacings between the used linear antenna arrays. When the spacings are large enough to make the mutual coupling between adjacent antennas be ignorable, the MIMO systems work quite good. But when the spacings are less than $0.5\,\lambda$, the mutual coupling reduces the transmit and receive power efficiencies and distorts the radiation patterns, thereby deteriorate the performance of space-time coding MIMO systems.

In Figure 3, the BER performances of space-time coding MIMO systems relative to SNR with $n_t = n_r = 2, 3, 4$ and $d = 0.1, 0.2, 0.3\,\lambda$ are considered. As shown, matching networks improve the performance of SM MIMO systems significantly. When matching networks are not used, the differences of BER performances are significant when different spacings d are considered. However, when matching networks are used, the BER performances of the SM MIMO systems with different antenna arrays are nearly same for the multiport matching networks can compensate the power mismatch caused by mutual coupling. The SM MIMO systems employing matching networks outperform the systems without matching networks, for example, the MIMO systems with $d = 0.1\,\lambda$, and matching networks even perform better than the MIMO systems with $d = 0.3\,\lambda$ but without matching networks.

As in Figures 3(a) and 3(b), when $n_r = n_t = 2$ and $d = 0.1\,\lambda$, the SNR gain of matching networks are about 7 and 7.2 dB for 10^{-3} bit error probability with $K = 0$ and $K = 10$, respectively, where K is the K-factors of Ricean channel [20]. And when $n_r = n_t = 2$ and $d = 0.2\,\lambda_0$, the SNR gain of matching networks are about 1.5 dB and 1 dB for 10^{-3} bit error probability with $K = 0$ and $K = 10$. When d is increased, the SNR gain of matching networks is decreased for the impact of mutual coupling between antennas are less serious. When the numbers of the transmit and receive antennas increase, the SNR gains of the matching networks become more significantly. As in Figures 3(c) and 3(d), the SNRgains of matching networks are about 7 dB and 5 dB with $d = 0.2\,\lambda_0$ spaced antennas when $K = 0$ and $K = 10$. In Figures 3(e) and 3(f), the SM MIMO systems with $n_t = 4$ and $n_r = 4$ are considered. The SNR gains of matching networks for MIMO systems with $d = 0.2\,\lambda$ is 8 and 9 dB for $K = 0$ and $K = 10$. When matching networks are employed, the MIMO systems with $d = 0.1,\ 0.2$, and $0.3\,\lambda$ nearly have the same BER performances, which are much better than the performance of MIMO systems without matching networks.

The BER performance of MIMO systems with same array size is considered in Figure 4, where the length L of array is equal to $(n_r/n_t - 1 \times d)$ and referenced SNR is 16 dB. As shown, the BER probability of the SM MIMO systems without matching networks increases along the shrinking of spacings when spacings are less than $\sim 0.5\,\lambda$. However, the BER performances of MIMO systems with matching networks almost maintains when the spacings shrank. When the spacings d between adjacent antennas are larger than $0.5\ \lambda$, both the systems with and without matching networks have the similar performance. That is, matching networks are more likely to be used when closely spaced antennas are utilized.

4. Impacts of Polarization Diversity on BER Performance of Layered Space-Time Coding MIMO Systems

Although the matching networks can prove the BER performance of narrow band MIMO systems with compact arrays, the implementations of the matching networks are very difficult when the spacings between antenna elements shrink and will limit the application of matching networks on wideband MIMO systems [31]. To resolve the difficulty of constructing matching networks, the polarization diversity antennas are usually used in MIMO systems. The section studies the BER performance of MIMO systems with polarization diversity antenna and compares the performance with that of MIMO systems with linear arrays.

Polarization diversity Antennas are commonly used in communications for decades to obtain diversity gain [32], compensate the power loss causing from polarization mismatch [33], and so on. For the polarization diversity is adopted in addition to spatial diversity, the mutual coupling between polarization diversity antenna is reduced compared to linear arrays when the two kinds of antenna arrays occupy similar volumes. As in [12–14], the use of polarization diversity antenna is a potential solution to construct multiple antennas in volume constraint mobile terminals for mobile communications.

Though mutual coupling is reduced, the array gains of antenna arrays with polarization diversity are usually lessened compare to copolarization antennas. Thus, when the cross-polarization components of the propagation channel are not abundant, there is power loss caused from the reducing of array gain. To compare the performances of MIMO systems with copolarization and polarization diversity antennas when mutual coupling and matching networks are taken into account, in-depth and comprehensive simulations are carried out.

The paper adopts different dual-polarization antennas and linear arrays as shown in 0, which have the same sizes when the element numbers of the antenna arrays are same (The area that the antennas cover is indicated in gray.) as

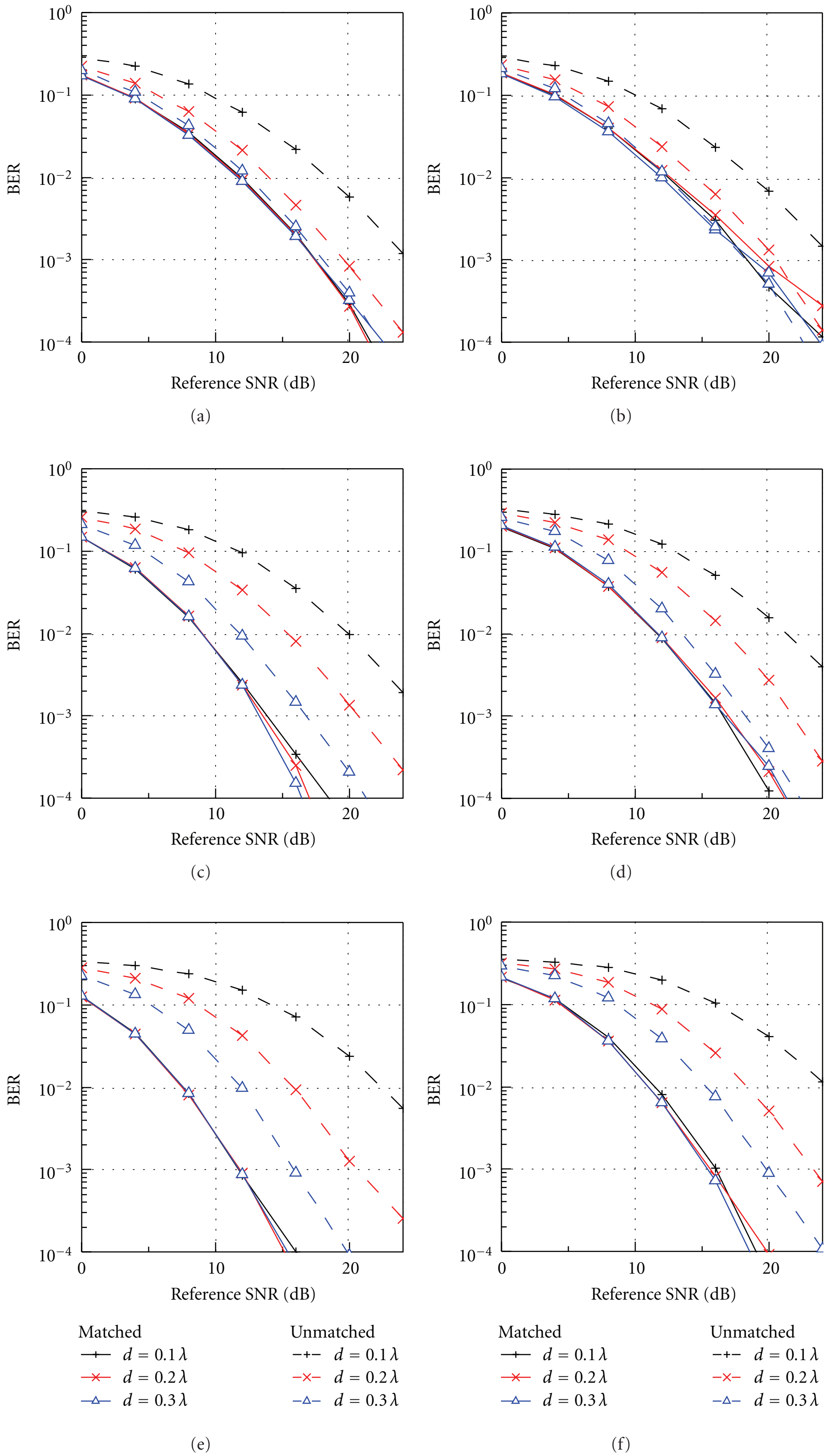

Figure 3: BER performances of the SM MIMO systems with linear arrays in Rayleigh and Rician scenarios: (a) $n_t/n_r = 2$, $K = 0$; (b) $n_t/n_r = 2$, $K = 10$; (c) $n_t/n_r = 3$, $K = 0$; (d) $n_t/n_r = 3$, $K = 10$; (e) $n_t/n_r = 4$, $K = 0$; (f) $n_t/n_r = 4$, $K = 10$.

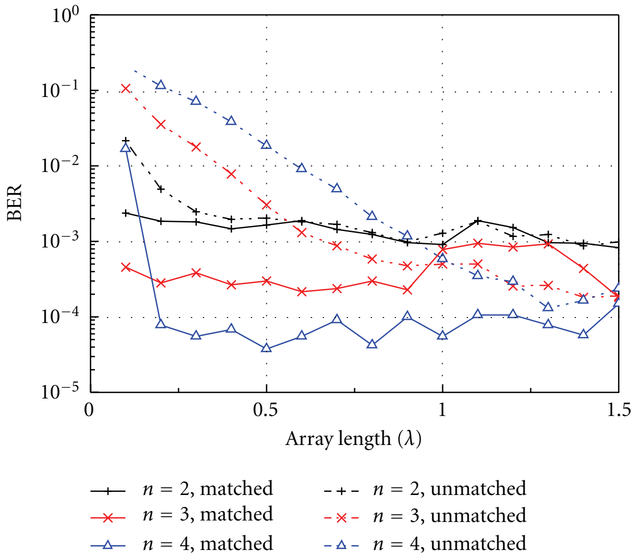

FIGURE 4: Imacts of spacings between antenna elements on BER performances of the SM MIMO systems with linear arrays in Rayleigh senarios.

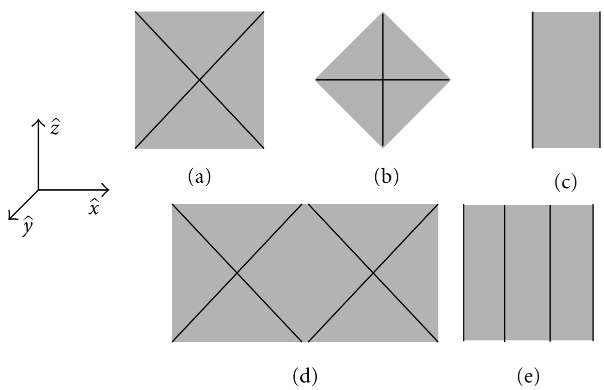

FIGURE 5: Schemes of Antenna Arrays.

shown in Figure 5. The sizes of the arrays are $l_0^2/2$ and l_0^2 when $n_{t/r} = 2$ and 4 respectively. XPD is used to measure the richness of cross polarization components in propagation channels.

4.1. Impacts of Polarization Diversity on BER Performances of MIMO Systems with ML and ZF Receivers. Firstly, the ML receive scheme is considered. The comparisons of the SM MIMO systems using polarization diversity and copolarization antennas are shown in Figure 6. The simulation results of XPD = 0 are shown in Figures 6(a) and 6(b). When matching networks are used, as in Figure 6(a), MIMO systems with linear arrays perform better than the systems with polarization diversity antenna. Considering the 10^{-3} bit error probability, the SNR gains of linear arrays are 3 and 2 dB compared to polarization diversity antenna when $n_{t/r} =$ 2 and 4. When matching networks are not used, the MIMO systems with linear array perform better than the systems with polarization diversity antennas when $n_{t/r} = 2$ but worse than that when $n_{t/r} = 4$. This is because the mutual coupling of linear arrays increases more significantly than that of polarization diversity antennas when the numbers of antennas increase. The simulation results of XPD = −6 dB are shown in Figures 6(c) and 6(d). For the cross polarization components of the propagation channel are short, the performance differences of matched MIMO system with linear array and polarization diversity antennas are larger than that when XPD = 0. The results are similar when matching networks are used.

Secondly, the ZF receive scheme is considered as shown in Figure 7. The simulation results of XPD = 0 is shown in Figures 7(a) and 7(b). When cross polarization components in the propagation channel are rich, the MIMO systems with polarization diversity antennas perform better than the systems with copolarization antennas no matter the matching networks are used or not. The simulation results of XPD = −6 dB is shown in Figures 7(c) and 7(d). When $n_{t/r} = 4$, MIMO systems with polarization diversity antenna perform much better than MIMO systems with copolarization antennas. When $n_{t/r} = 2$, the systems with polarization diversity and copolarization diversity perform similarly.

In general, when the number of antennas is small and the sizes of the arrays are not extremely limited, the use of polarization diversity in MIMO systems which employ ML receivers does not bring considerable benefits especially when matching networks are adopted. But when ZF receivers are adopted, the MIMO systems with polarization diversity antenna are more attractive.

4.2. Impacts of Antenna Orientation Randomness on BER Performances of MIMO Systems with Different Antennas. When applied in handheld devices, the main disadvantage of MIMO systems with arrays consisting of parallel dipoles is the sensitivity to polarization mismatch due to random orientation of devices. If the transmit and receive array are orthogonal, only the cross polarization components are received; thus, the SNR is very low. For polarization diversity antenna can receive inward fields with different polarization, the uses of polarization diversity antenna in MIMO systems are potential to compensate the effects of polarization mismatch [34, 35].

In the simulation, the orientations of the transmit antenna arrays are fixed, while the receive antennas are rotated against the center point randomly. Here, both the transmit and the receive antennas are matched. The radiation patterns of the rotated antennas are drawn by the Euler vector rotation formula as in [36].

As shown in Figure 8, the SM MIMO systems with polarization diversity antenna perform better than the SM MIMO system with parallel antennas. The BER performance of the SM MIMO systems with the randomly rotated receive antennas is similar with that with orientation-fixed antennas when polarization diversity antennas are adopted. However, when parallel dipoles are adopted, the BER performance of the SM MIMO systems with randomly rotated receive antennas deteriorates significantly than that with orientation-fixed antennas. That holds no matter when cross polarization components are rich (XPD = 0 dB) or lacking (XPD = −6 dB).

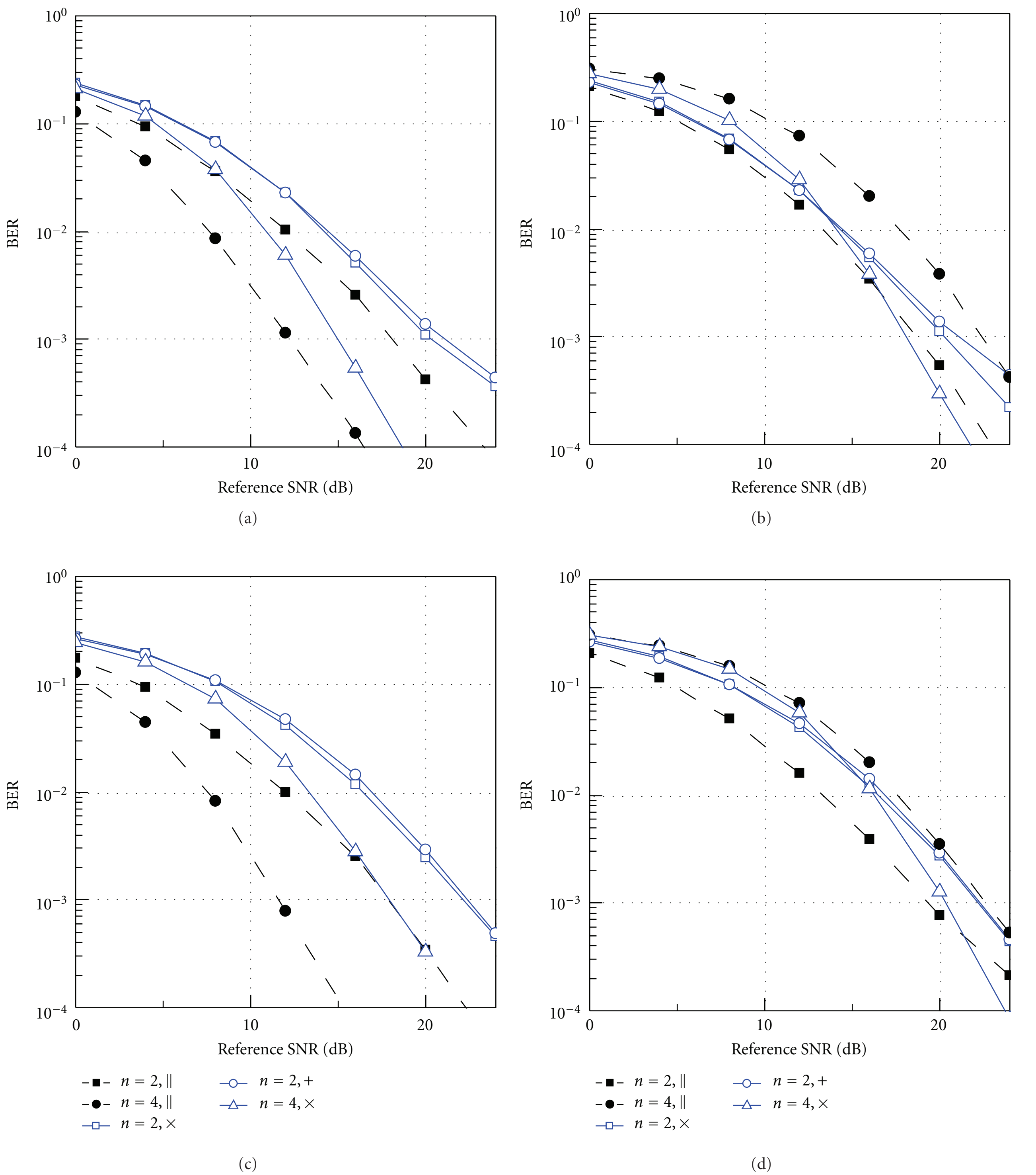

FIGURE 6: BER performances of maximum-likelihood receivers for the SM MIMO systems with polarization diversity when: (a) matched, XPD = 0 dB; (b) unmatched, XPD = 0 dB; (c) matched, XPD = −6 dB; (d) unmatched, XPD = −6 dB.

5. Conclusion

The paper adopts an accurate signal analysis framework based on circuit network parameters to investigate the transmit/receive characteristics of the matched/unmatched antenna array and the impact of matching networks on the BER performance of the SM MIMO systems. The numerical simulation results show that the matching networks can improve the BER performance of the SM MIMO systems when the antennas are closely spaced. And the narrow

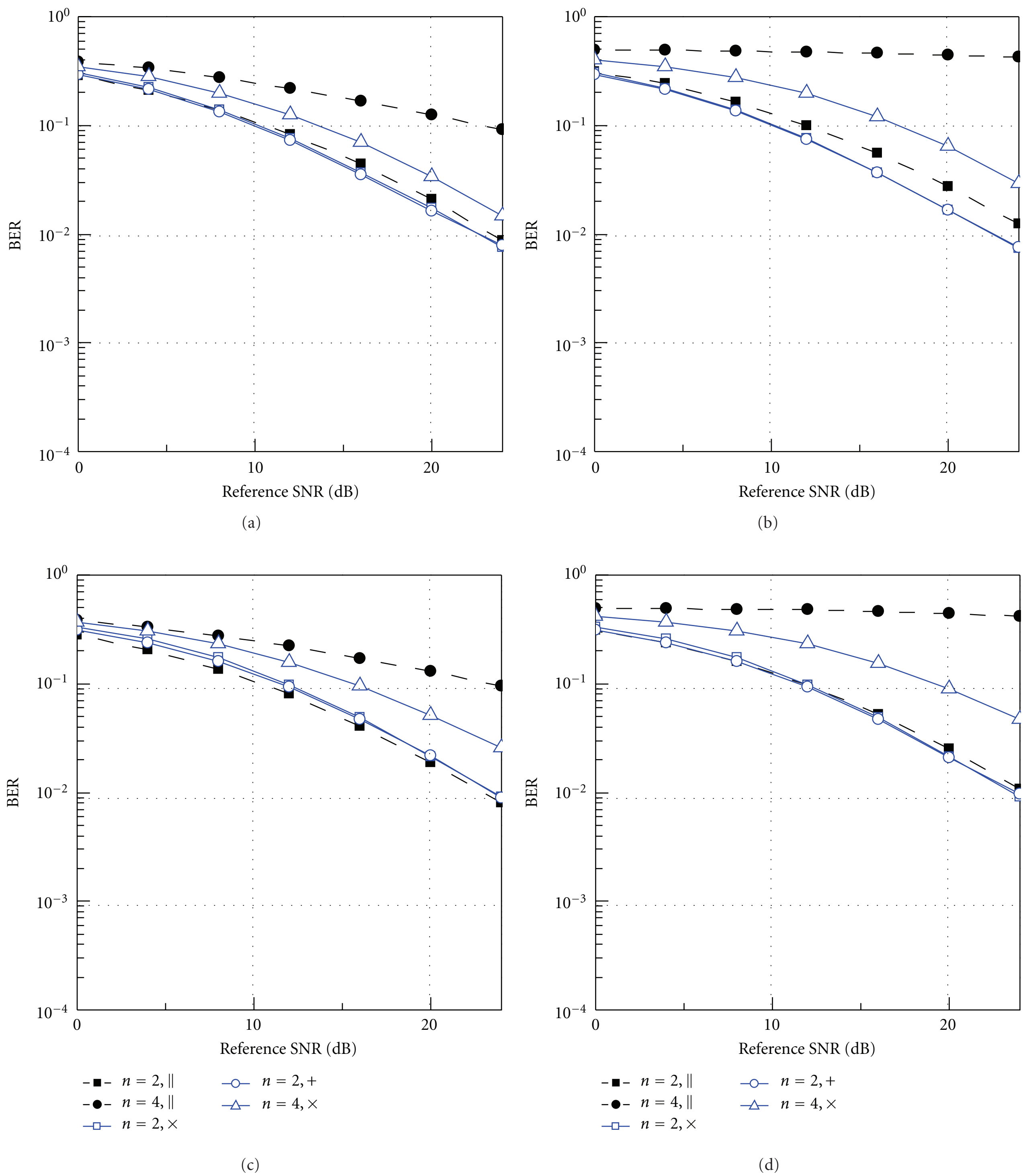

Figure 7: BER performances of zero-forcing receivers for space-time coding MIMO systems with polarization diversity when: (a) matched, XPD = 0 dB; (b) unmatched, XPD = 0 dB; (c) matched, XPD = –6 dB; (d) unmatched, XPD = –6 dB.

band MIMO systems with lossless matching networks will maintain the BER performance even when the spacings between antenna elements are around $0.1\,\lambda$.

The impacts of polarization diversity antennas on BER performance of the SM MIMO systems are also considered. It shows, when comparing to MIMO systems with matched antennas, the performance improvements due to polarization diversity antennas are not significant. But when antenna orientation randomness is present, the MIMO systems with polarization diversity antennas do perform better than MIMO systems with copolarization antennas whenever the antennas are matched or not matched.

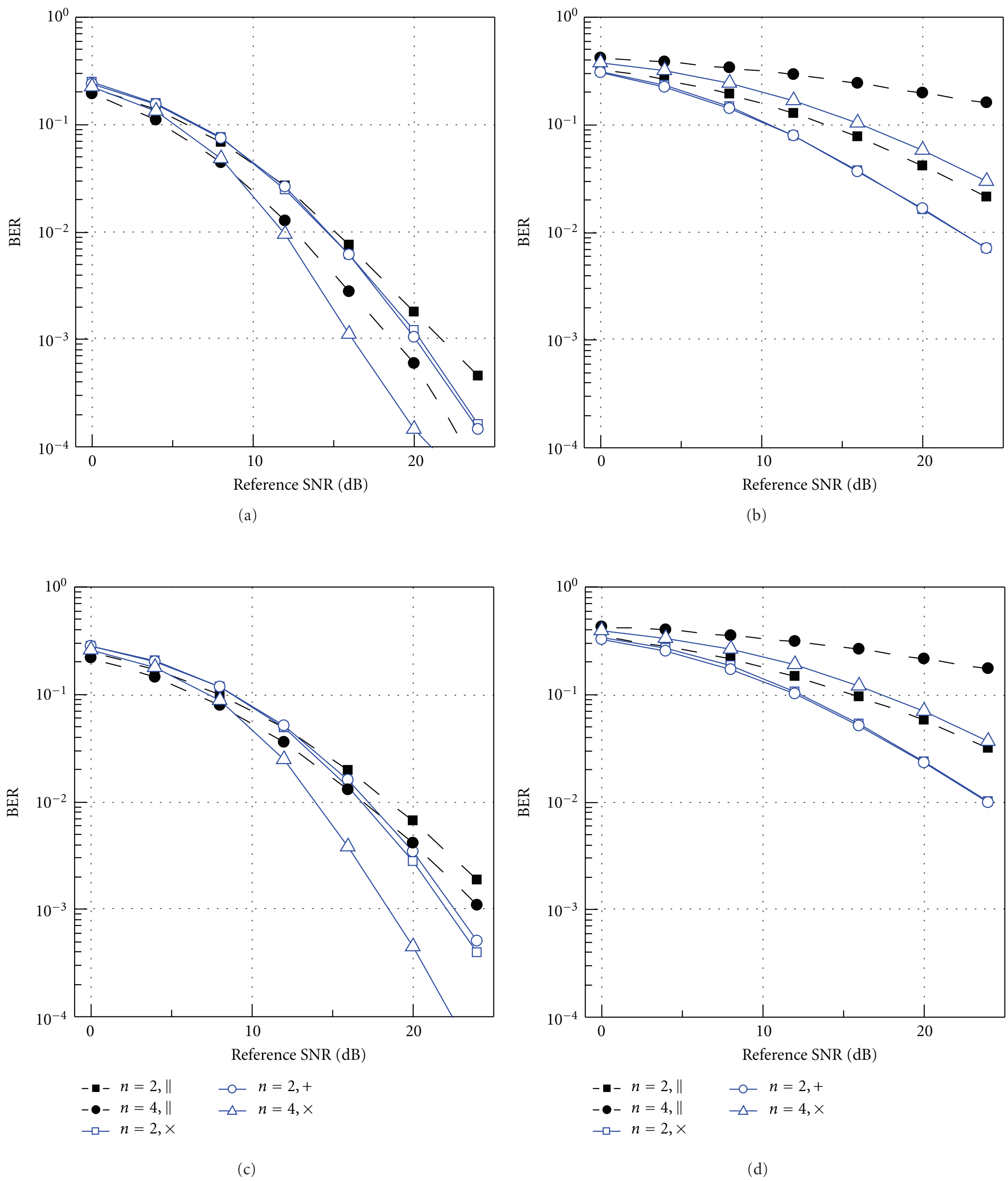

Figure 8: Impact of orientation randomness on BER performances of the SM MIMO systems with matching networks when: (a) XPD = 0 dB, ML receiver; (b) XPD = 0 dB, ZF receiver; (c) XPD = −6 dB, ML receiver; (d) XPD = −6 dB, ZF receiver.

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