Receive and Transmit Array Antenna Spacing and Their Effect on the Performance of SIMO and MIMO Systems by using an RCS Channel Model

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Abstract—In this paper, the effect of receive and/or transmit antenna spacing on the performance (BER vs. SNR) of multiple-antenna systems is determined by using an RCS (Radar Cross Section) channel model. In this physical model, the scatterers existing in the propagation environment are modeled by their RCS so that the correlation of the receive signal complex amplitudes, i.e., both magnitude and phase, can be estimated. The proposed RCS channel model is then compared with classical models.

Keywords—MIMO system, Performance of system, Signal correlation, SIMO system, Wireless channel model.

I. Introduction

CONVENTIONAL studies of multiple-antenna systems usually have considered independent Rayliegh fading channel for each pair of transmit and receive antennas, i.e., receive signals are assumed independent. Although by this assumption, multiple-antenna systems show significant improvement in link performance and capacity over single antenna systems [1], [2], this assumption is not applicable under realistic conditions. In real environments, considerable correlation can exist among receive signals which affects the gains obtained from multiple antennas [3], [4], [5]. Different channel models are suggested to overcome the consequences of this simplified assumption by modeling correlation of receive signals.

The frequently used channel model for investigating correlation of receive signals is the Jakes model [6]. The Jakes model is based on plane-wave propagation and formulate the correlation coefficients with a closed form formula.

Other models like Lee model [7] and Clarke model [8] describe macrocell environments that base station antennas are placed on a higher height than the mobile station's.

In the proposed RCS channel model, physical characteristics of environment like distance between TX and RX antennas, TX and RX antenna configurations, number of scatterers and their scattering properties which is quantitatively included in the RCS parameter of each scatterer and delay spread of the channel have been taken into account. These parameters can be chosen according to a given scenario.

Conventional channel models can be used for linear array antennas, while the RCS model can be used for any configuration of antenna elements. By using RCS model, characterization of phase correlation of receive signals is also possible.

The goal of this work is to determine the correlation coefficient of receive signals in SIMO systems by using the RCS channel model and Jakes model and compare them. The performance of SIMO snd MIMO systems is then evaluated under different correlation conditions (different distance between receive and between transmit antennas). Effect of correlated receive signals on degradation of diversity gain of SIMO and MIMO systems is studied.

In Section 2, correlation coefficient diagram and channel matrix of MIMO systems (SIMO systems are considered as especial cases of MIMO systems) are obtained by using the Jakes model.

In Section 3, the RCS channel model is described and correlation coefficient diagram of SIMO system by using this model is obtained.

Finally, by using these models the performance of a SIMO and MIMO system is evaluated.

II. Classical Channel Modeling

The Jakes model defines the correlation coefficient between two antennas by θ_{mk}

$$\theta_{mk} = J_0(2\pi \frac{d_{mk}}{\lambda}), \qquad m \neq k \quad (1)$$

where $J_0(x)$ is the zeroth order Bessel function, and d_{mk} is the distance between antenna m and k. Fig. 1 shows the correlation coefficient between receive antennas vs. d/λ by using the Jakes model. For characterizing MIMO systems,

channel matrix must be determined by using this model. By assuming zero correlation between receive and transmit antennas, an $n_R \times n_R$ correlation coefficient matrix, denoted by θ_R, for the receive antennas and an $n_T \times n_T$ correlation coefficient matrix, denoted by θ_T, for the transmit antennas are obtained from Jakes model by considering appropriate distance between each pair of transmit and each pair of receive antennas. These matrices can be represented as

$$\theta_T = \mathbf{k}_T \mathbf{k}_T^H$$
$$\theta_R = \mathbf{k}_R \mathbf{k}_R^H \qquad (2)$$

In which K_R and K_T are $n_R \times n_R$ and $n_T \times n_T$ lower triangular matrices, respectively, with positive diagonal elements. K_R and K_T can be obtained from respective correlation matrices θ_R and θ_T, using Cholesky decomposition. A correlated MIMO channel matrix, denoted by H_c can be represented as

$$H_C = K_R H K_T \qquad (3)$$

Where H is the channel matrix with uncorrelated Gaussian entries. For SIMO Channel, channel matrix H_c is changed to channel vector H_c.

Changing TX and RX antenna distance in the correlated channel matrix can show the effect of RX and TX antenna correlation on the performance of 2×2 MIMO systems with linear receiver, i.e., zero forcing (ZF) receivers, and optimum nonlinear receiver, i.e., Maximum Likelihood (ML) receiver. By using the channel vector, effect of receive antenna distance on the performance of SIMO system with MRC (Maximal Ration Combiner) is also studied by simulation.
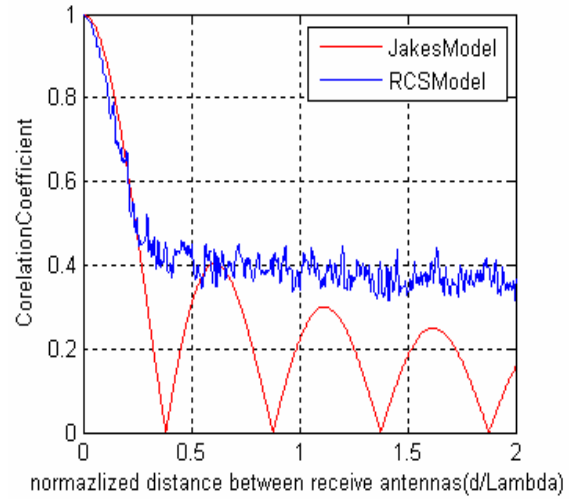

Fig. 1 Comparison of correlation coefficientof receive signals in a 1×2 SIMO system by using Jakes and RCS model

III. RCS CHANNEL MODELING

In this model, a flat and slow fading channel is assumed. Scatterers are distributed uniformly in an ellipse with diameters a and b related to τ_{rms} (delay spread of the channel) and distance between TX and RX antennas (D) according to following equations

$$a = \frac{c\tau_{rms}}{2}$$
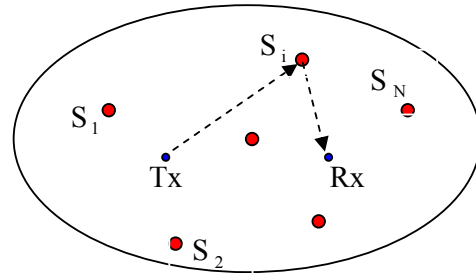$$b = 0.5\sqrt{c^2\tau_{rms} - D^2} \qquad (4)$$

Fig. 2 Shape of multipath environment

In which c is the speed of light. Depending on their shape and material, scatterers reflect different fractions of transmitted power. This characteristic is modeled with a random variable known as RCS of the scaterrer. Note that RCS is a real value with the unit of square meter. In this model, we assume that the RCSs of the scatterers have uniform distribution between zero and a certain value.

Moreover, each scatterer imposes a phase change on the

transmitted signal which is denoted by "scatterer phase." Because of both effects, the scattered signal is affected by "scatterer phase" and RCS. Superposition of the received signals from different paths at the position of the receive antenna can be constructive or destructive depending on phase differences caused by path lengths and scatterer phases. The open-circuit voltage of the receive antenna is given by:

$$V_{oc} = \sum_{i=1}^{N_c} \left(\sqrt{\frac{p_t}{4\pi d_i^2} G_t \sigma_i \frac{1}{4\pi d_i'^2} \frac{\lambda^2}{4\pi} G_r} \, e^{-jk_0(d_i+d_i')} e^{-j\phi_i} \right)$$

(5)

In which P_t is the transmitted power, G_t and G_r are transmit and receive antenna gains, respectively, N_s is the number of scaterrers, d_i and d_i' are distance of scatterers form transmit and receive antennas, respectively, σ_i is the i-th scaterrer's RSC, and ϕ_i is the i-th scatterer phase.

By using this model, the receive signal of two neighboring antenna in a 1×2 SIMO system and then their correlation coefficient is obtained. Fig. 1 shows the obtained result for antenna seprated by a distance d/λ. As can be seen, unlike the approximate Jakes model, the RCS model shows a stronger correlation which must be included in BER analysis. In next section, the performance of SIMO and MIMO systems is evaluated by using the RCS channel model.

IV. RESULTS OF SIMULATION

In a first step, we used RCS model for a SISO system. As Fig. 3 shows the performance of a BPSK modulation in this channel is completely compatible with the analytical formula for the performance of BPSK modulation in a Rayleigh fading channel.

In the second step, by means of RCS channel model, the performance of SIMO systems with MRC was evaluated. In this simulation, RCS model is used in the same conditions as Jakes model assumptions, i.e., receive antennas are arranged as a linear array and the environment is densely scattered and distance between receive antennas is equal to the wavelength, as it is clear from Fig. 1 at $d/\lambda = 1$ the correlation coefficient of both models are almost equal. Because of this agreement in the assumptions the results of two models must be compatible, which is confirmed by Fig. 3.
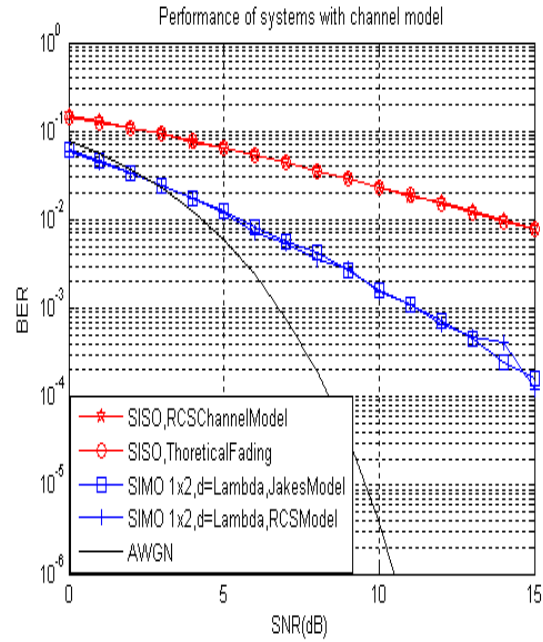

Fig. 3 Comparison RCS and Jakes Channel model

Implementing the RCS model for 1×2 SIMO systems with BPSK modulation shows that increasing the distance of the receive antennas, i.e., decreasing receive signal correlation, monotonicly improve the performance.

As Fig. 4 shows in an 1×2 SIMO system, if the distance between receive antennas becomes more than 0.5λ, the performance of system is almost like an ideal 1×2 SIMO system with independent receive signals.

Diversity gain manifests itself in improving the slope of BER vs. SNR curve [10]. It is clear from Fig. 4 that by increasing correlation of receive antennas, diversity gain decreases.

If the distance becomes as low as 0.01λ, the received signals are completely correlated. In this condition, the performance is poorer than an ideal 1×2 SIMO system with independent receive signals but it is still 3-dB better than a SISO (single-input single-output) system in fading channel.

The reason for this 3-dB improvement in the performance can be explained by the characteristic of MRC receiver. At MRC receiver the SNRs of different branches add with each other[9]. If the correlation coefficient of receive signals become high, their SNRs are almost the same, so by adding with each other at MRC, there is only 3-dB improvement in overal SNR of the system with no improvement in the slope of the curve (no diversity gain).

As the distance between receive antennas vary between 0.5λ to 0.01λ, the BER diagram vary between the result of a 1×2 SIMO system with ideal independent receive antennas and completely correlated receive antennas (3-dB improvement over SISO channel).
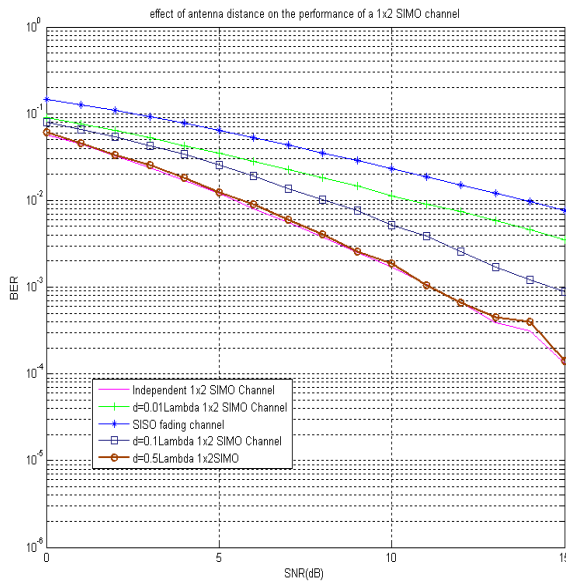
Fig. 4 Effect of antenna spacing on a 1×2 SIMO system using the RCS channel model

In the third step, by means of the RCS channel model, the performance of MIMO systems with SM (Spatial Multiplexing) with ZF and ML receivers was evaluated. Implementing the RCS model shows that tighter arrangement of transmit (and/or receive) antennas, i.e., increasing their correlations, degrades the performance.

Although simulation results for ML receiver (Fig. 5) imply that receive or transmit correlation have approximately the same degradation effect on the performance of ideal 2×2 MIMO systems with independent receive and transmit antennas, it still performs better than a single fading channel (note that because of SM, MIMO system's bit rate is twice rather than SIMO and SISO systems). Simultaneous existence of receive and transmit antenna correlation degrades the performance considerably such that the performance becomes poorer than a single fading channel.
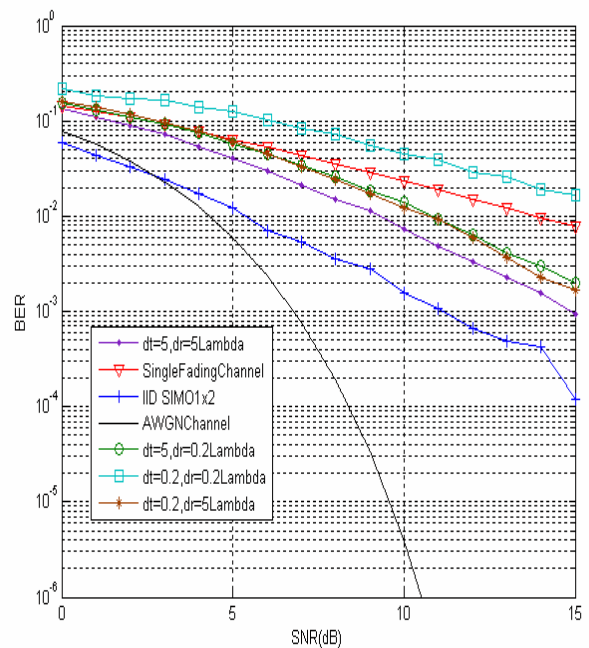

Fig. 5 Effect of antenna spacing on a 2×2 MIMO system with ML receiver, BPSK modulation

For ZF receiver (Fig. 6), without any correlation, the performance is already worse than single fading channel in the expense of increasing the bit rate and simplicity of receiver. With transmit and/or receive correlation the performance degrades sharply.
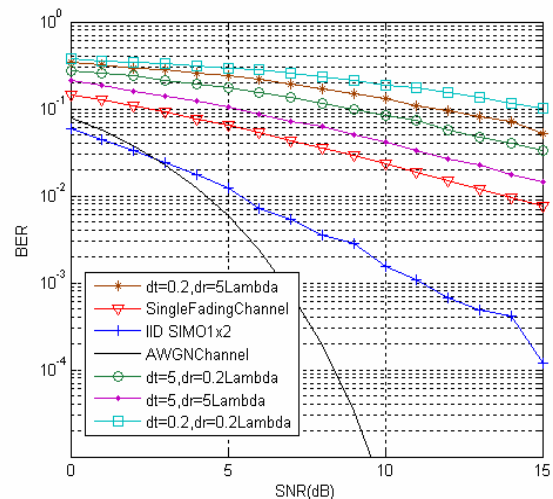

Fig. 6 Effect of antenna spacing on a 2×2 MIMO system with ZF receiver, BPSK modulation

V. CONCLUSION

In this paper, by means of the RCS channel model, the correlation coefficient of receive signals in SIMO systems is

determined. In comparison to the classical Jakes model, the RCS model can provide us with information more than the correlation coefficient, such that it can be used for determination of the average received power for a specific transmit power and a given transmitter-receiver distance.

The effect of signal correlation on the performance of SIMO system with MRC and MIMO system with ZF and ML receivers was investigated by using the RCS model. Effect of receive signal correlation on diversity gain degradation is clear by decreasing the slope of BER diagram.

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