A Discrete-Time Model for Spatio-Temporally Correlated MIMO WSSUS multipath Channels

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Abstract— **In this paper, a statistical discrete-time model is proposed for simulating wideband MIMO channels which experience spatially and temporally correlated, wide-sense stationary uncorrelated scattering (WSSUS) multipath Rayleigh fading. A new method is also presented to efficiently generate the correlated MIMO channel coefficients, which can be used for accurate simulation of physical continuous-time MIMO channels. The statistic accuracy of the discrete-time MIMO channel model is rigorously verified through theoretical analysis and extensive simulations in different criteria.**

I. Introduction

Multiple-input multiple-output (MIMO) communication architecture has recently emerged as a new paradigm for high data rate wireless cellular communications. It was shown [1] that the MIMO capacity can scale linearly with the number of antennas in independent Rayleigh flat fading channels. However, for a wideband MIMO wireless systems in the real world, subchannels of a MIMO wireless system have spatial correlation and time dispersion, and the fading of each subchannel has temporal correlation. These factors may substantially affect the MIMO performance [2]. Further researches in this field necessitate a realistic and efficient MIMO channel simulation model to investigate, evaluate and test new algorithms and performance of MIMO wireless systems under realistic fading scenarios.

Although numerous channel models have been established for single-input single-output (SISO) and single-input multiple-output mobile radio systems (see [3], [4] and references therein), there are very few channel models for MIMO wireless systems [5]-[7]. All of the previous MIMO channel models are continuous-time based models, which requires significant computational effort when the number of multiple delayed fading paths is large and/or the differential delay between paths is small [8].

The main objective of this paper is to establish a discrete-time MIMO channel model, which is statistically accurate and computationally efficient to characterize the continuous-time MIMO Rayleigh fading channel that has spatial correlation, temporal correlation and time dispersion (or frequency selectiveness), in realistic fading scenarios. The discrete-time MIMO channel model will translate the effects of transmit filter, physical MIMO multipath channel fading and receive filter into receiver's sampling-period spaced stochastic channel coefficients, and no oversampling is needed to handle multiple fractionally-delayed fading paths. With the discrete-time channel model, the simulation of a MIMO system is carried out in a pure discrete manner. The statistic accuracy and computational efficiency of the discrete-time MIMO channel model is rigorously verified through theoretical analysis and extensive simulations in this paper.

II. MIMO Channel Description and Assumptions

The baseband representation of a MIMO channel with N transmit antennas and M receive antennas is depicted in Figure 1, where $p_{_T}(t)$ and $p_{_R}(t)$ represent the normalized transmit filter and receive filter, respectively, and $v_m(t)$ is AWGN with power spectral density N_0. The (m,n)th-subchannel connecting the nth-transmit antenna and the mth-receive antenna is denoted by its time-varying impulse response $g_{m,n}(t,\tau)$, with τ being the time delay. The received signal at each receive antenna is sampled at a period of $T_s = T_{sym}/\gamma$, where T_{sym} is the symbol period of the transmitted sequence $s_n(k)$ and γ is an integer. We define the combined impulse response (CIR) of the (m,n)th-subchannel as follows

$$h_{m,n}(t,\tau) = p_{_R}(\tau) \odot g_{m,n}(t,\tau) \odot p_{_T}(\tau), \tag{1}$$

where $\odot$ is the convolution operator. The sampled output of the received signal at the m-th receive antenna is given by

$$y_m(k) = \sum_{n=1}^{N}\sum_{l} x_n(k-l)h_{m,n}(k,l) + z_m(k), \tag{2}$$

where $h_{m,n}(k,l) = h_{m,n}(kT_s, lT_s)$ is the T_s-space sampled version of $h_{m,n}(t,\tau)$, and $z_m(k)$ is sampled from $z_m(t)$, which is the noise component of the receive filter output and has the form

$$z_m(t) = v_m(t) \odot p_{_R}(t). \tag{3}$$

$x_n(k)$ in (2) can be viewed as an oversampled sequence of the transmitted signal $s_n(k)$ and is given by

$$x_n(k) = \begin{cases} s_n(k/\gamma), & \text{if } k/\gamma \text{ is integer,} \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Two assumptions are made on the physical channel of a wideband MIMO wireless system, as follows:

Assumption 1: The (m,n)th-subchannel of a MIMO system is a wide-sense stationary uncorrelated scattering (WSSUS) [9] Rayleigh fading channel with zero mean and its autocorrelation is given by

$$E\left\{g_{m,n}(t,\tau)g^*_{m,n}(t-\xi,\tau')\right\} = J_0(2\pi f_d \xi)G(\tau)\delta(\tau-\tau'), \tag{5}$$

where $(\cdot)^*$ is the conjugate operator, $J_0(x)$ is the zeroth-order Bessel function of the first kind, and $G(\tau)$ is the delay power profile with $\int_{-\infty}^{\infty} G(\tau)d\tau = 1$.

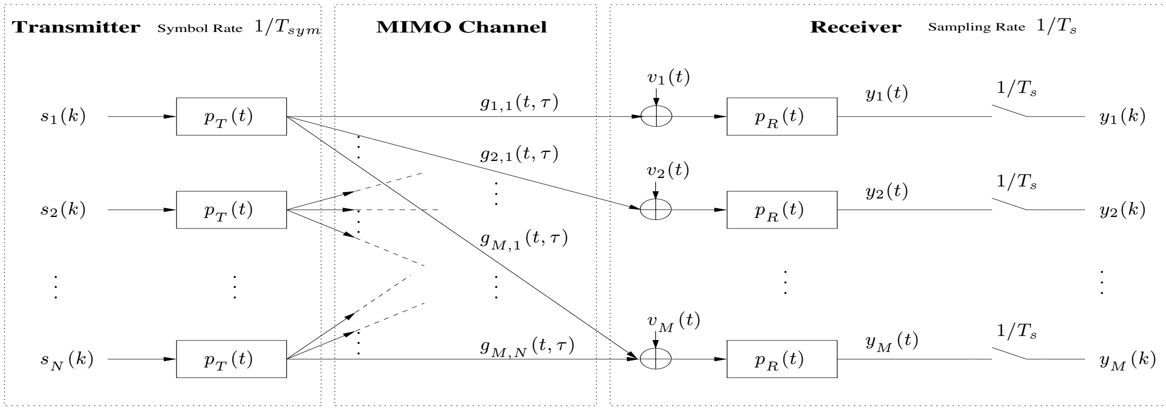

Fig. 1. A conventional continuous-time baseband MIMO channel model.

It is important to note that Assumption 1 is commonly employed for SISO channels in the literature [8], [10], [11], and in the wireless standards documents [12], [13] for both TDMA-based GSM and EDGE systems, and CDMA-based CDMA2000 and UMTS systems.

Assumption 2: The spatial correlation between any two subchannels of the MIMO system is given by

$$E\left\{g_{m,n}(t,\tau)g^*_{p,q}(t-\xi,\tau')\right\} = \rho^{(m,p)}_{Rx}\cdot\rho^{(n,q)}_{Tx}\cdot J_0(2\pi f_d\xi)\cdot G(\tau)\cdot\delta(\tau-\tau'), \quad (6)$$

where $\rho^{(m,p)}_{Rx}$ is the receive correlation coefficient between receive antennas m and p, and $\rho^{(n,q)}_{Tx}$ is the transmit correlation coefficient between transmit antennas n and q. Both of them satisfy $0 \le \left|\rho^{(n,q)}\right| \le \rho^{(n,n)} = 1$. They can be calculated by mathematical formulas [2]or obtained from experimental data.

This assumption is a straightforward extension of the MIMO Rayleigh flat fading case in [14] to the MIMO WSSUS multipath Rayleigh fading case. It should be pointed out that Assumption 2 may not be extendable to Rice fading MIMO channels [15].

III. The Discrete-time MIMO Channel Model

A discrete-time MIMO channel model is presented in this section with its statistical properties analyzed in details. These statistical properties are further used to build a discrete-time MIMO channel simulator with high computational efficiency and accurate statistics compared to its counterpart in the continuous-time domain.

A. The Discrete-Time Channel Model

The time varying CIR $h_{m,n}(k,l)$ is normally non-causal with infinite impulse response (IIR), because the transmit and receive filters are of infinite time duration in theory to maintain limited frequency bandwidth. However, in practice, the time-domain tails of the filters are designed to fall off rapidly. When $|l|$ exceeds a certain value, $|h_{m,n}(k,l)|$ will be so small that its effects on the channel output are negligible. Therefore the IIR channel can be truncated to a finite impulse response (FIR) channel. Without loss of generality, we assume that the coefficient index, l, is in the range of $[-L_1, L_2]$, where L_1 and L_2 are non-negative integers, and the channel length is L with $L \le L_1 + L_2 + 1$.

Based on the above discussion and equation (2), we can now describe the input-output relationship of the MIMO channel in the discrete-time domain as follows:

$$\mathbf{y}(k) = \sum_{l=-L_1}^{L_2} \mathbf{H}_l(k)\cdot\mathbf{x}(k-l) + \mathbf{z}(k), \quad (7)$$

where the vectors $\mathbf{x}(k) = [x_1(k), x_2(k), \cdots, x_N(k)]^t$, $\mathbf{z}(k) = [z_1(k), z_2(k), \cdots, z_M(k)]^t$ and $\mathbf{y}(k) = [y_1(k), y_2(k), \cdots, y_M(k)]^t$ are the input vector, noise vector and output vector at time instant k, respectively, with $(\cdot)^t$ being transpose operator; $\mathbf{H}_l(k)$ is the lT_s delayed channel matrix at time instant k, and the element on the m-th row, n-th column of $\mathbf{H}_l(k)$ is $[\mathbf{H}_l(k)]_{(m,n)} = h_{m,n}(k,l)$. The block-diagram of this discrete-time MIMO channel model is shown in Figure 2.

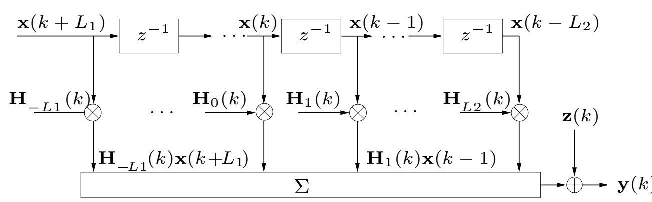

Fig. 2. The equivalent discrete-time MIMO channel model.

B. Statistical Properties of the Discrete-Time Channel

It is noted that there are (MNL) stochastic channel coefficients, and an M-element random noise vector in this MIMO Rayleigh fading model (7). Since all of them are complex-valued Gaussian random variables, the first-order and second-order statistics will be sufficient to fully characterize the MIMO channel.

The statistics of the noise vector $\mathbf{z}(k)$ can be directly derived from (3). $\mathbf{z}(k)$ is zero-mean Gaussian distributed with auto-covariance matrix $\mathbf{R}_{\mathbf{zz}}(k_1-k_2)$ given by

$$\begin{aligned}\mathbf{R}_{\mathbf{zz}}(k_1-k_2) &= E\left[\mathbf{z}(k_1)\cdot\mathbf{z}^h(k_2)\right]\\ &= N_0\cdot R_{p_R p_R}\left[(k_1-k_2)T_s\right]\cdot\mathbf{I}_M, \quad (8)\end{aligned}$$

where $(\cdot)^h$ stands for Hermitian operation, $R_{p_R p_R}(\xi)$ is the auto-correlation function of the receive filter $p_R(t)$, and $\mathbf{I}_M$ is an $M\times M$ identity matrix.

The autocorrelation of the channel coefficients $h_{m,n}(k,l)$ and $h_{p,q}(k,l)$ can be obtained by using eqn (1) and Assumptions 1 and 2, and it is given by

$$\begin{aligned}E\left[h_{m,n}(k_1,l_1)h^*_{p,q}(k_2,l_2)\right] &= \rho^{(m,p)}_{Rx}\rho^{(n,q)}_{Tx}c(l_1,l_2)\\ &\quad\cdot J_0\left[2\pi f_d(k_1-k_2)T_s\right], \quad (9)\end{aligned}$$

where

$$c(l_1,l_2)=\int_{-\infty}^{+\infty}R_{p_T p_R}(l_1T_s-\tau)R^*_{p_T p_R}(l_2T_s-\tau)G(\tau)d\tau, \quad (10)$$

with $R_{p_T p_R}(\xi)$ being the convolution of $p_T(t)$ and $p_R(t)$.

For convenient discussion, we define the MIMO channel coefficient vector $\mathbf{h}_{vec}(k)$ as follows:

$$\mathbf{h}_{vec}(k)=\left[\mathbf{h}_{1,1}(k),\cdots,\mathbf{h}_{1,N}(k)\mid\cdots\mid\mathbf{h}_{M,1}(k),\cdots,\mathbf{h}_{M,N}(k)\right]^t, \quad (11)$$

where the row vector $\mathbf{h}_{m,n}(k)$ is the (m,n)th-subchannel's FIR coefficients at time k, and given by

$$\mathbf{h}_{m,n}(k)=\left[\begin{array}{ccc} h_{m,n}(k,-L_1) & \cdots & h_{m,n}(k,L_2)\end{array}\right]. \quad (12)$$

The statistics of $\mathbf{h}_{vec}(k)$ is given by the following theorem.

Theorem 1: The channel coefficient column vector $\mathbf{h}_{vec}(k)$ is zero-mean Gaussian distributed, its covariance matrix is given by

$$\begin{aligned}\mathbf{C}_{\mathbf{h}}(k_1-k_2) &= E\left\{\mathbf{h}_{vec}(k_1)\cdot\mathbf{h}^h_{vec}(k_2)\right\}\\ &= \left(\mathbf{\Psi}_{Rx}\otimes\mathbf{\Psi}_{Tx}\otimes\mathbf{C}_{SISO}\right)J_0\left[2\pi f_d(k_1-k_2)T_s\right], \quad (13)\end{aligned}$$

where $\otimes$ denotes the Kronecker product [16], $[\mathbf{\Psi}_{Rx}]_{(m,n)}=\rho^{(m,n)}_{Rx}$, $[\mathbf{\Psi}_{Tx}]_{(m,n)}=\rho^{(m,n)}_{Tx}$ and $[\mathbf{C}_{SISO}]_{(l_1,l_2)}=c(l_1,l_2)$.

Proof: With eqns (9) and (11), this theorem can be proved. Details are omitted here for brevity.

C. Generation of Discrete-Time MIMO Channel Fading

Based on subsection III-B, the stochastic fading channel coefficients $\mathbf{h}_{vec}(k)$ can be efficiently generated for computer simulations of MIMO systems, using the following theorem.

Theorem 2: The zero-mean time-varying Rayleigh fading channel vector $\mathbf{h}_{vec}(k)$ can be generated by

$$\begin{aligned}\mathbf{h}_{vec}(k) &= \mathbf{C_h}^{1/2}(0)\cdot\mathbf{\Phi}(k)\\ &= \left(\mathbf{\Psi}^{1/2}_{Rx}\otimes\mathbf{\Psi}^{1/2}_{Tx}\otimes\mathbf{C}^{1/2}_{SISO}\right)\cdot\mathbf{\Phi}(k), \quad (14)\end{aligned}$$

where $\mathbf{X}^{1/2}$ is the square root of matrix $\mathbf{X}=\mathbf{X}^{1/2}\cdot\left(\mathbf{X}^{1/2}\right)^h$; $\mathbf{\Phi}(k)$ is an $(MNL)\times 1$ vector, whose elements are uncorrelated Rayleigh flat fading, and $E\left[\mathbf{\Phi}(k_1)\cdot\mathbf{\Phi}^h(k_2)\right]=J_0\left[2\pi f_d(k_1-k_2)T_s\right]\cdot\mathbf{I}_{MNL\times MNL}$.

Proof: This theorem can be proved by using two identities of matrices [16]: $[A\otimes B][C\otimes D]=[AC]\otimes[BD]$ and $[A\otimes B]^h=A^h\otimes B^h$. Details are omitted.

It is emphasized here that the generation of the channel coefficients is done through the Kroneker product of the square roots of three small matrices rather than the square root of a very large matrix $\mathbf{C_h}(0)$ of size $(MNL)\times(MNL)$. This significantly reduces the computational complexity, and certainly leads to much better numerical computation accuracy.

The generation of multiple uncorrelated Rayleigh flat fading waveforms is a classic topic with new challenges for the number (MNL) of multiple faders being large. It has been commonly postulated in the literature [6], [11] that can be done by Jakes' original simulation model [17], which is computational efficient compared with noise-filtering models [8]. Unfortunately, there are two problems in the original Jakes' simulation model. First, Jakes' model is a deterministic model, it has difficulty to directly generate three or more uncorrelated Rayleigh flat fading waveforms. Second, and more importantly, Pop and Beaulieu [18] showed recently that Jakes' model is even not stationary in the wide sense. They further proposed in [18] an improved Jakes' model to remove the WSS problem. However, the improved Jakes' model along with the original Jakes' model have significant deficiency in their statistical properties as pointed out by Xiao, Zheng and Beaulieu in [19], and this statistic deficiency was removed by a generalized Rayleigh fading model developed in [20]. Furthermore, Zheng and Xiao [21] developed new and efficient simulation models for the generation of multiple uncorrelated Rayleigh flat faders, which have exactly the same statistics as what is required by Theorem 2, therefore, we adopt these models of [21] to generate the $(MNL)\times 1$ vector $\mathbf{\Phi}(k)$.

IV. Simulation Experiments

Several simulation experiments are carried out in this section to evaluate the performance of the discrete-time MIMO model from different criteria.

A. Spatial-Temporal Statistics

Consider a MIMO system consisting of 2 antennas at the base station as the transmitter and 2 antennas at the mobile station as the receiver, then the correlation coefficient matrices $\mathbf{\Psi}_{Tx}$ and $\mathbf{\Psi}_{Rx}$ can be calculated by the formulas derived in [2] under certain spatial parameters. For example, if the BS and MS antennas are spaced by 15λ and λ, respectively, where λ is the wavelength, the angle of arrival is 90^0 and the angular spread is 10^0, then we get the two matrices as follows:

$$\mathbf{\Psi}_{Tx}=\left[\begin{array}{cc}1.0000 & -0.1964\\ -0.1964 & 1.0000\end{array}\right],\ \mathbf{\Psi}_{Rx}=\left[\begin{array}{cc}1.0000 & 0.2203\\ 0.2203 & 1.0000\end{array}\right]. \quad (15)$$

If the delay power profile is exponentially decaying [8] and given by $G(\tau)=A\cdot\exp(\tau/\mu s)$ for $0\le\tau\le 5\mu s$, and $G(\tau)=0$ otherwise; the transmit filter is a linearized Gaussian filter with time-bandwidth product 0.3 [22], the receive filter is a square root raised cosine (SRC) filter with a roll-off factor 0.3, the sampling period T_s is $3.69\mu s$, then the elements $c(l_1, l_2)$ of the matrix $\mathbf{C}_{SISO}$ obtained by (10) is shown in Table 1.

Table 1. The matrix $\mathbf{C}_{SISO}$ for the exponential delay power profile

$c(l_1, l_2)$	$l_2 = -1$	$l_2 = 0$	$l_2 = 1$	$l_2 = 2$
$l_1 = -1$	0.0091	0.0426	0.0178	-0.0016
$l_1 = 0$	0.0426	0.3664	0.3407	0.0367
$l_1 = 1$	0.0178	0.3407	0.5583	0.1414
$l_1 = 2$	-0.0016	0.0367	0.1414	0.0602

The correlation statistics of the generated time-varying random channel coefficients are compared with the theoretical values as described by eqn (9) and Theorem 1, and only one of the results are shown in Figure 3. We have also compared the correlation statistics of all other channel coefficients to their theoretical ones, finding good agreement in all cases. Therefore, the statistic accuracy of the the discrete-time MIMO channel model is confirmed.

Before leaving this subsection, we have two remarks. First, Figure 3 indicates that the fading coefficients from different subchannels with different delays can be statistically correlated. This is quite different from the commonly used independence assumption in the literature [6], [24]. Second, the conventional continuous-time channel model needs a very high oversampling rate [8] to approximately simulate this continuous delay power profile $G(\tau)$, but this scenario can be efficiently and accurately simulated by our discrete-time channel model.

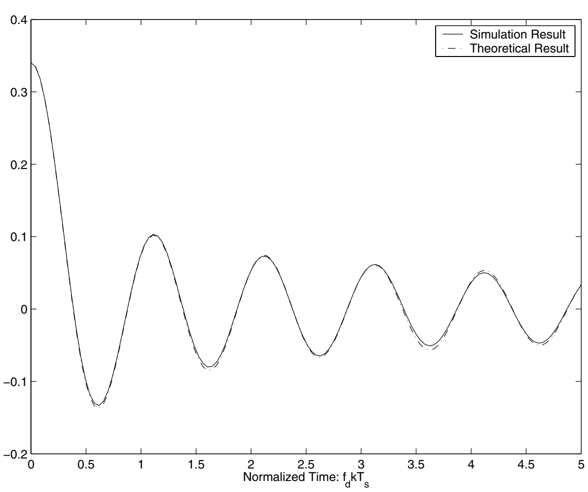

Fig. 3. Comparison of the theoretical and simulated cross-correlations of $h_{1,1}(k, 0)$ and $h_{1,2}(k, 1)$.

B. Bit Error Rate Comparison

The statistic equivalence of the discrete-time channel model to the conventional continuous-time channel model can be demonstrated by comparing their BER performances. We choose EDGE system [12], [22] as an example in this subsection. The delay power profile $G(\tau)$ used here is the reduced 6-path Typical Urban (TU) profile provided in [12]. The transmit and receive filters and the sampling period T_s are the same as those given in last subsection.

Assuming perfect channel estimation at the receiver for both discrete-time channel model and continuous-time channel model, and employing MLSE for channel equalization with truncated channel memory length 4, we have obtained the uncoded (raw) BER vs E_b/N_0 shown in Figure 4. Apparently, the BER performance of the discrete-time channel model is almost identical to that of the continuous-time channel model. This demonstrates that the discrete-time channel model is statistically equivalent to the continuous-time channel model. However, the discrete-time model needs only about 2.6% computations of the continuous-time model to generate the statistical fading channel coefficients in this SISO example. The computational saving is even more significant for MIMO discrete-time channels.

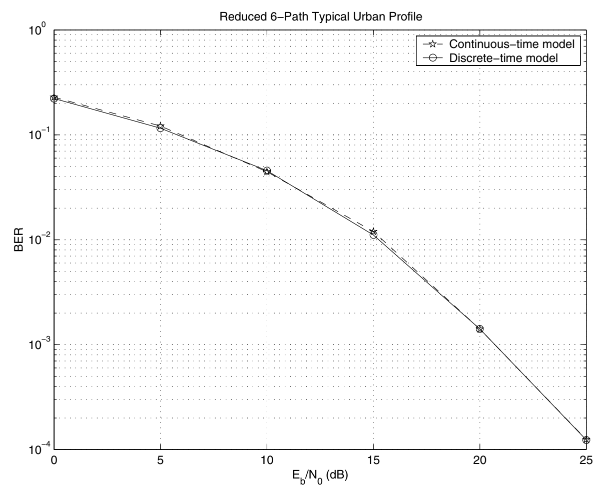

Fig. 4. Comparison of BER performance with discrete-time model and continuous-time model for EDGE mobile system under Typical Urban delay power profile.

C. MIMO Channel Capacity

In this subsection, the MIMO channel capacity is evaluated using our discrete-time channel model to indicate the effects of spatial correlations, multipaths and number of antennas on the channel capacity. The channel capacity for a wideband MIMO channel can be computed from [25], [27]. The complementary cumulative distribution function (ccdf) of the random capacity C is used to evaluate the performance of the MIMO channel.

The wideband CDMA system, UMTS, is used as an example in this section. The delay power profile is chosen to be Vehicular Channel A profile specified in [13]. For convenient illustration purpose, the elements of the correlation coefficient matrices $\mathbf{\Psi}_{Tx}$ and $\mathbf{\Psi}_{Rx}$ are simply chosen to be exponential correlation matrix [23] as follows

$$\rho_{Rx}^{(m,p)} = r^{|m-p|}, \quad \rho_{Tx}^{(n,q)} = r^{|n-q|}, \qquad |r| \leq 1. \quad (16)$$

The capacity ccdfs of MIMO channels under different correlation coefficients, and different number of antennas are depicted in Figure 5. As can be seen, when $M = N$, the MIMO channel capacity is linearly growing with M when $r \leq 0.5$, and the growing rate depends on the value of r, the smaller for the r, the larger for the growing rate. This shows that the spatial correlation of the MIMO channel has a strong impact on the channel capacity. This observation for frequency selective channel is in a good agreement with the results presented in [14] for Rayleigh flat fading.

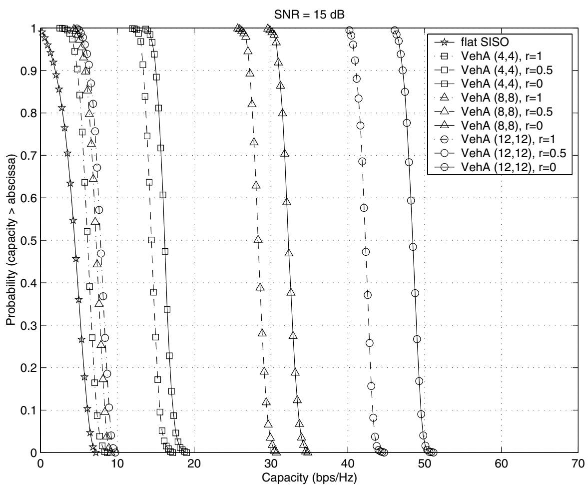

Fig. 5. The capacities of MIMO channels with different spatial correlation coefficients and $M = N$. Dash dot lines stand for $r = 1$, dash lines for $r = 0.5$, and solid lines for $r = 0$. Observation: The channel capacity is linearly scaling with M when $r \leq 0.5$, and the scaling rate is depending on the value of r.

Finally, it is remarked that the MIMO channel capacity with continuous-time models have also been evaluated by extensive simulations, and the results are all nearly identical to those obtained with the discrete-time model. This further verifies the statistic equivalence of the discrete-time and continuous-time channel model. However, with the discrete-time MIMO channel model, the outage capacity for MIMO channel can be easier and more efficiently evaluated.

V. Conclusions

We have proposed a new discrete-time channel model for MIMO systems over spatially and temporally correlated, frequency selective Rayleigh fading channels. The new model is computationally efficient to describe the input-output of MIMO channels, because it does not need to oversample the fractionally delayed multipath channel fading, the transmit filter and the receive filter, which, however, is necessary for continuous-time channel models. The statistic accuracy of the discrete-time channel model is rigorously confirmed by extensive simulations.

Acknowledgments

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