selective fading and the improvement due to correlative coding in MIMO-OFDM.

II. METHODS AND MATERIAL

A. System Model

Consider a MIMO-OFDM system with N_t transmit antennas, N_r receive antennas, and N_s subcarriers which employs binary phase shift keying achieved through the frequency-domain polynomial F(D) = 1 – D [Zhao 1998.], (BPSK) modulation. Input symbols $a_i \in \{1, -1\}$ are assumed to be i.i.d. with normalized energy. The correlative coding to encode a_i is which generates a new sequence $b_i = ai - a_{i-1}$ with $E[b_i] = 0$ and otherwise.

$$E[b_i b^*_j] = \begin{cases} 2E[a^2_i] = 2, & i = j \\ E[a^2_i] = -1, & |i - j| = 1 \\ 0 & \end{cases} \qquad (1)$$

It is well known that the general form of MIMO-OFDM over slowly fading channels (i.e., the channel is time-invariant over several OFDM symbol periods) can be expressed as [Stuber, 2004]

$$\mathbf{y}_k = \mathbf{\Lambda}_k \mathbf{x}_k + \mathbf{n}_k \qquad (2)$$

where $\mathbf{x}_k$ and $\mathbf{y}_k$ represent, respectively, the transmitted and received data for all antennas on subcarrier k, $\mathbf{\Lambda}_k$ is an $N_r \times N_t$ matrix whose (i, j)th element, $\{\mathbf{\Lambda}_k\}_{ij}$, denotes the channel frequency response between transmit antenna j and receive antenna i, and $\mathbf{n}_k$ is an $N_r \times 1$ vector denoting the zero-mean AWGN with covariance $\sigma^2_n \mathbf{I}_{Nr}$ for all antennas on subcarrier k.

B. Effects of Time-Selective Fadin

In a time-selective fading environment, the $N_sN_r \times N_sN_t$ spatiotemporal channel matrix H in one OFDM symbol period is expressed as

$$\boldsymbol{H} = \begin{Bmatrix} \mathbf{H}_0(0) & \cdots & \mathbf{H}_{L-1} & \cdots & \mathbf{H}_1(0) \\ \vdots & & \ddots & & \vdots \\ \mathbf{0} & \cdots \boldsymbol{H}_{L-1}(N_s - 1) & \cdots & \boldsymbol{H}_0(N_s - 1) & \end{Bmatrix} \qquad (3)$$

where L is the number of resolvable paths and 0 is an $N_r \times N_t$ zero matrix. Each non-zero block of **H** contains the $N_r \times N_t$ channel matrix $\mathbf{H}_l(n)$ for path l at time nT_s (T_s is the data symbol period).

Assuming a WSSUS channel, all elements of $\mathbf{H}_l(n)$ are modeled as independent complex Gaussian random variables with zero mean and equal variance. The channel is assumed to have an exponential power-delay profile $\theta\ (_{Tl}) = e^{-Tl/Trms}$, where $_{Tl}$ is the delay of the lth path and $_{Trms}$ is the rms delay spread. Since the channel is time-variant, the relationship between the channel coefficients for path l at times nT_s and $(n + m)T_s$ can be described as [Zheng, 2004]

$$\{\mathbf{H}_l(n + m)\}_{ij} = \alpha_m \{\mathbf{H}_l(n)_{ij} + \beta_{l,ij}(n + m) \qquad (4)$$

Where

$$\alpha_m = \frac{E[\{H_l(n)\}_{ij}\{H_l(n + m)\}*_{ij}]}{e^{-Tr/Trms}} = J_0(2\pi m f_d T_s) \qquad (5)$$

fd is the maximum Doppler shift and βl,ij(n) are independent complex Gaussian random variables with zero mean and variance e – $(1 - \alpha^2_m)$.

It is observed that the channel matrix H in (4.3) is no longer a block circulant matrix as the case of slowly fading channels. Consequently, G = (U ⊗ INr) H (U ⊗ INt)H is no longer a block diagonal matrix, where U is the unitary DFT matrix with

$$\{\boldsymbol{U}\}_{ij} = 1/\sqrt{N_s} e^{(\sqrt{-2} \quad -1/Ns)ij}$$

$0 \leq i, j \leq N_s - 1$. This shows that time-selective fading causes ICI, which is $0 \leq i, j \leq N_s - 1$. This shows that time-selective fading causes ICI, which is represented by the off-diagonal blocks of **G.** Let $\mathbf{G}_{ij}$ denote the (i, j)th block of **G**.

Eq. (4) can be rewritten as

$$y_k \sum_{\substack{k'=0\\k'\neq k}}^{N_s-1} G_{kk}x_k + G_{kk}'x_k' + n_k,\ k = 0, , N_s - 1. \tag{6}$$

Let Υ_{ij} be an $N_s \times N_s$ matrix given by

$$\Upsilon_{ij} = \begin{pmatrix} var(\{G_{00}\}_{ij}) & \ldots var(\{G_{0,Ns-1}\}_{ij}) \\ \vdots \quad \ddots & \vdots \\ var(\{G_{Ns-1,0}\}_{ij}) .. & var(\{G_{Ns-1,Ns-1}\}_{ij})^{(k)} \end{pmatrix}, 1 \le i\ N_r, 1 \le j \le N_t. \tag{7}$$

As shown in APPENDIX A, Υ_{ij} has a circulant structure, Note that in this case CIR is the same for all subcarriers and is independent of the channel power-delay profile as well as the number of resolvable paths. Obviously, $C_{corr} \ge C, \forall k$.

Therefore, correlative coding effectively increase CIR. Note worthily, from (5), it is easy to see that although C_{corr} is different for different subcarriers, the difference diminishes as N_s increases. As indicated earlier, when frequency-domain correlative coding with F(D) = 1 – D is used, the signals modulated on subcarriers are identical with alternate mark inversion code and $\{a_i\}$ can be recovered by using a ML sequence detector.

III. RESULTS AND DISCUSSION

In obtaining the numerical results, we consider a system with two transmit antennas and two receive antennas which employs BPSK modulation and adopt the “SUI-5” channel model [Falconer, 2002]. The time-selective Rayleigh fading channel is assumed to have three resolvable multipath components occurring at 0, 5, and 10μs. These paths are modeled as independent complex Gaussian random variables and the rms delay spread of the channel is 3.05μs. The maximum Doppler shift is calculated based on a carrier frequency of f_c = 2GHz.

CIR levels versus T_s calculated using Eqs. (4) and (5) are plotted in Fig.1, where the vehicle speed applied is v_s = 100Km/h. CIR curves of the MIMO-OFDM system with different number of subcarriers in one OFDM symbol (Ns = 8, 24, and 128) are compared

Table 1. PARAMETER VALUES USED IN THE SYSTEM SIMULATIONS

Cell Geometry	Hexagonal Array with side R = 1000 m
Carrier Frequency	fc = 2 GHz
System Bandwidth	W = 5 MHz
Path Loss Exponent	r = 3.7
Vehicle speed	30km, 60km, 100km, 200km
Subcarriers	Ns 8, 24 and 128
Shadow Fading	Lognormal, with Standard Deviation _ = 8 dB
Multipath Fading	Rayleigh (K-factor = 0)
Antenna Pattern	Omnidirectional or Uniform over 120
Thermal Noise Density	N0 = −174 dBm/Hz
Mobile Station’s Noise Figure	NF = 8 dB
Transmit Power	PT = 5 W for fc = 2 GHz PT = 31.25 W for fc = 5 GHz
Median Cell-Boundary SNR	p = 20 dB
Transmit Antenna Array (BS) Length	BS = 3 m
Receive Antenna Array (MS) Length	lMS = 0.1 m
AoD Statistics (at the Base Station)	Laplacian Power Angular Spectrum with Angular Spread _BS = 15_ = Il/12
AoA Statistics (at the Mobile Station)	Laplacian Power Angular Spectrum with Angular Spread _MS = 45_ = 11/4

In obtaining the numerical results, I consider a system with two transmit an-tennas and two receive antennas which employs BPSK modulation and adopt the “SUI-5” channel model. The time-selective Rayleigh fading channel is assumed to have three resolvable multipath components occurring at 0, 5, and 10μs. These paths are modeled as independent complex Gaussian random variables and the rms delay spread of the channel is 3.05μs. The maximum Doppler shift is calculated based on a carrier frequency of f_c = 2GHz.

CIR levels versus T_s calculated using Eqs. (5) and (6) are plotted in Fig. 2 where the vehicle speed applied is v_s = 100Km/h. CIR curves of the MIMO-OFDM system with different number of subcarriers in one OFDM symbol (Ns = 8, 24, and 128) are compared. As shown in Fig. 1, frequency-domain correlative coding incorporated in this letter can effectively increase CIR and the improvement is proportional to the number of subcarriers. With N_s = 128, the improvement is observed to be as high as 3.0dB. The BER performances of MIMO-OFDM systems with and without frequency-domain correlative coding are compared in Fig.1., where $T_s = 5 \times 10^{-7}$s and v_s = 100Km/h are applied. The ML detection scheme is used when correlative coding is applied. The improvement in the BER performance is also found proportional to the number of subcarriers.

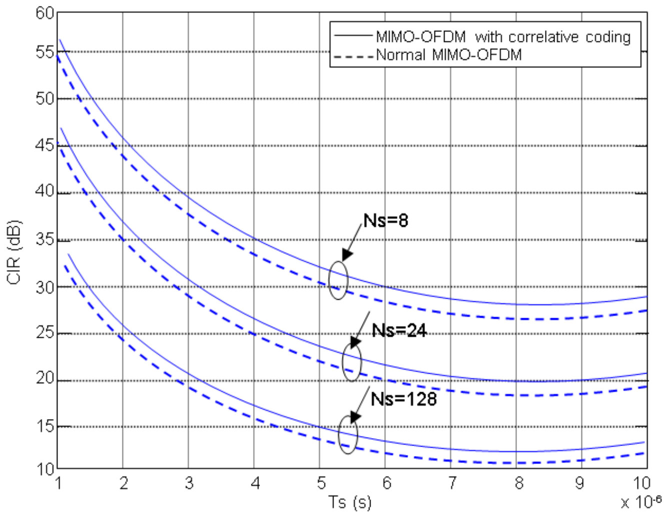

Figure 1. CIR curves of MIMO-OFDM systems with and without frequency-domain correlative coding.

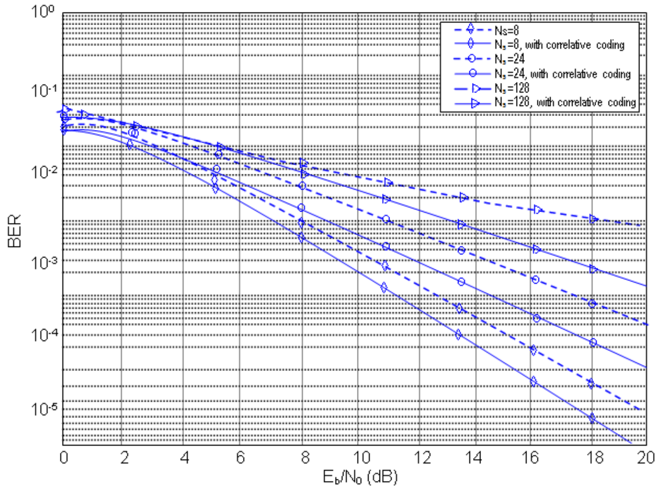

Figure 2. BER versus E_b/N_0 for MIMO-OFDM systems with and without frequency-domain correlative coding.

IV. CONCLUSION

We applied frequency-domain correlative coding to mitigate the effect of time-selective fading to the performance of MIMO-OFDM systems. We derived the analytical expression of CIR as a function of the maximum Doppler shift and power-delay profile of the channel, the number of subcarriers, and the OFDM symbol duration. The CIR expression can be used to quantify the amount of ICI caused by channel time variations. Numerical results indicate that a simple correlative coding scheme with correlation polynomial $F(D) = 1 - D$ can effectively increase CIR of a 128-subcarrier MIMO-OFDM system by as much as 3.0dB, and the improvement further increases as the number of subcarriers becomes larger.

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