OFDM-MIMO COMMUNICATION SYSTEMS WITH IMPERFECT CHANNEL ESTIMATES IN A RAYLEIGH FADED ENVIRONMENT

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ABSTRACT*

This paper presents the performance of mobile orthogonal frequency division multiplexing (OFDM) multiple-input multiple-output (MIMO) communication systems with imperfect knowledge of the channel matrix. MIMO systems typically require a channel matrix, which can be determined initially from a training sequence. However, mobile communication systems exhibit a time-varying channel matrix and have time and frequency selective fades which result in performance degradation of the MIMO system. Channel tracking methods can be used to estimate the time-varying channel matrix but cannot in practice be error free. This paper presents results of V-BLAST (Vertical Bell Laboratories Layered Space-Time) MIMO simulations using the Geometric Wide-band Time-varying Channel Model (GWTCM) with Rayleigh faded environments and imperfect channel matrix knowledge. Flat fading is assumed for each OFDM subcarrier. OFDM-MIMO architectures such as OFDM coupled with V-BLAST can be easily implemented by exploiting the built-in and flexible multi-channel architectures of advanced Software Defined Radios (SDR).

1. INTRODUCTION

Recent research has shown that a rich scattering environment is capable of significant communication capacity due to the multipath diversity inherent in the rich scattering environment. MIMO techniques, such as V-BLAST, have demonstrated spectral efficiencies of 20-40 bps/Hz in an indoor environment [1]. Consequently, a lot of interest has developed in MIMO systems. Most forms of MIMO such, as V-BLAST requires a reliable estimate of the channel matrix, H. V-BLAST uses successive interference cancellation techniques to remove the effect of undesired transmit channels and hence the channel matrix, H, is required for effective performance.

In practice, several methods may be used to estimate the channel. The method that we focus on in this paper is the use of a training preamble that consists of known data to both the MIMO transmitter and receiver. The OFDM frames that follow the training preamble do not have pilot subcarriers or other means to track the channel dynamically from OFDM frame to frame. The channel is estimated periodically when a training period occurs. The computed channel estimate is then used without modification for following OFDM frames until a new training period updates the channel estimate. Thus, under mobile, conditions where the channel is dynamically changing, the channel estimate for each OFDM frame incurs some error, resulting in degradation of the MIMO communication system.

We use two approaches to analyze and simulate the behavior of a MIMO system that has periodic training intervals. The first method, assumes that the channel varies according to a first-order auto-regressive (AR) Gauss-Markov fading channel model [2][3]. Using this method, we compute the simulated effective SNR with a channel with specified channel coherence length.

The second approach uses a Geometric Wide-band Time-varying Channel Model (GWTCM) [4] to predict the degradation due to inaccurate channel estimates. The GWTCM was developed specifically for simulating OFDM-MIMO applications. The GWTCM uses an elliptical boundary to limit multipath spread and implements wideband channel modeling by partitioning the spectrum into multiple flat channels.

This paper is organized as follows. Section 2 provides a description of the MIMO training and data format used. Section 3 describes the Gauss-Markov fading channel model. Section 4 provides a discussion of the GWTCM

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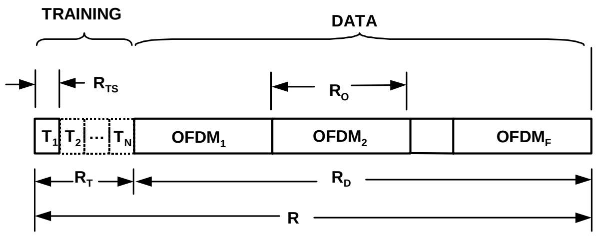

Figure 1. MIMO Training and Data Format for Transmit Antenna 1

channel model**.** Section 5 provides simulations results and a conclusion is given in section 6.

2. MIMO TRAINING AND DATA FORMAT

Figure 1 shows the periodic time sample training and data format used for our OFDM-MIMO simulations for transmit antenna 1. The MIMO system consist of M receive antennas and N transmit antennas. Training for each of the N transmit antennas is performed individually using R_{TS} samples. For example, the training sequence, T_1 is transmitted by transmit antenna 1. The remaining transmit antennas transmit the training samples individually in sequence. The total training samples required for N transmit antennas is R_T. Multiple frames of OFDM, F, follow the training sequence. Each OFDM frame consist of R_O samples, thus the total number of data bearing frames is R_O x F = R_D. The OFDM frames contain data carriers and null carriers only for the simulations in this paper. In practice, pilot carriers may be included in the OFDM frames so that tracking updates may be made to the time-varying channel matrix, H. These experiments assume that no tracking of the channel is performed and that the most current training estimate of H is used at the V-BLAST receiver to process each OFDM frame.

The total number of time samples required for training and data transmission is R_T + R_D=R. Some loss of data rate is incurred since the training interval, R_T, does not carry data samples. Define an efficiency parameter, k, as,

$$k = \frac{R_D}{R} = \frac{R_O \times F}{R} \qquad 0 \le k \le 1. \qquad (1)$$

The variable k measures the loss due to overhead of the training sequence. A value of k=1, describes a system with no overhead due to training. A value of k=0, describes a system with training only. A practical value of k is $0.5 \le k \le 1$, depending on the coherence length of the channel.

3. THE GAUSS-MARKOV FADING CHANNEL MODEL

For the trained modulation approach, space-time coding algorithms often assume that the receiver knows the channel, which is estimated by the receiver using known transmit symbols. The channel estimate is used for decoding subsequent symbols over which the channel is assumed to be constant. However, under sufficient mobile speeds, the channel estimate can become stale, and thus affect demodulation performance due to sufficient error between the estimate and actual channel transfer function. OFDM VBLAST MIMO systems for mobile channels require channel state information (CSI) to be estimated at the receiver to facilitate the zero-forcing successive interference cancellation process. For wideband transmissions, this requires an estimate across both time and frequency, because both time and frequency variation will exist.

The fading channel can be modeled using a Gauss-Markov fading channel model [2]. The analysis assumes that the channel matrix $\boldsymbol{H}_t$ is utilized r samples after the estimated (trained) channel $\boldsymbol{H}_{ref}$. For a single reference channel, we assume that $\boldsymbol{H}_t$ varies from the reference channel according to a first-order auto-regressive (AR) model written as $\boldsymbol{H}_t$ = $\sqrt{\alpha_r}\, \boldsymbol{H}_{ref}$ + $\sqrt{1-\alpha_r}\, \boldsymbol{E}_t$, where $\boldsymbol{H}_{ref}$ and $\boldsymbol{E}_t$ are i.i.d. and $\boldsymbol{E}_t$ is independent from symbol to symbol. If α_r = 1 the channel is time-invariant, and if α_r = 0 the channel is considered to be completely time-varying. If T is the number of time instants in a transmitted space-time symbol block, $r \approx FT$ is trained modulation, with demodulation based on a channel estimate obtained F>1 symbols in the past. Using the AR parameter α_r we can relate the behavior to the second order statistics of models based on actual physical propagation mechanisms. Solving the Yule-Walker equation ($\boldsymbol{H}_t$) above, and relating it to the autocorrelation function of the channel, $r_{hh}(t)$, where $r_{hh}(t)$ = $J_0(2\pi ft)$ [5] we can find

$$\alpha_r = \left[\frac{r_{hh}(t)}{r_{hh}(0)}\right]^2 = J_0^2(2\pi rf), \qquad (2)$$

where f=f_dT_s, f_d is the maximum Doppler frequency in the fading channel and T_s is the sampling period. The AR model is an appropriate approximation to Jakes' model for small values of f when using maximum likelihood decoders that depend on a single reference channel. Excellent agreement was found in [2] when the performance was analyzed using the AR model, but simulated using Jakes' channel model.

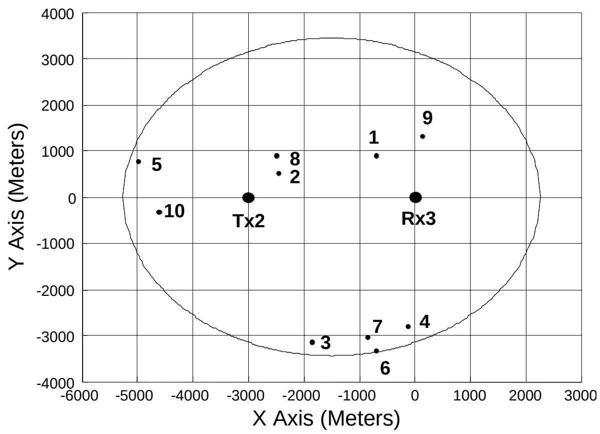

Figure 2. 3x2 MIMO Baseline Geometry

The model presented above [2] works well for narrowband channels but does not account for frequency selectivity. However, for our model we utilize OFDM, which allows us to parallelize the wideband channel into multiple narrowband fading channels. In this work we assume perfect interleaved sub-carriers such that fading is independent across all sub-carriers. This allows us to utilize the model from [2] to predict the amount of performance degradation to a wideband OFDM VBLAST system in a mobile channel. The process that is utilized to generate the channel fading coefficients is accomplished by combining the imperfect estimate [2] with our geometric model that will be mentioned in the next section.

In general, the AR parameter, α_r, induces an effective SNR, which is distinctly different depending on the training interval and mobile velocity. This will allow us to visualize the penalty incurred when changing the training interval given a fixed number of transmit elements. We assume that the channel is estimated during the first symbol of a F-symbol frame. The effective SNR is defined as,

$$ESNR = \rho\left(p_i^2\right), \tag{3}$$

where,

$$p_i = \sqrt{\frac{\alpha_r}{1+(1-\alpha_r)\rho\dfrac{R}{N}}}, \tag{4}$$

and where ρ is the SNR.

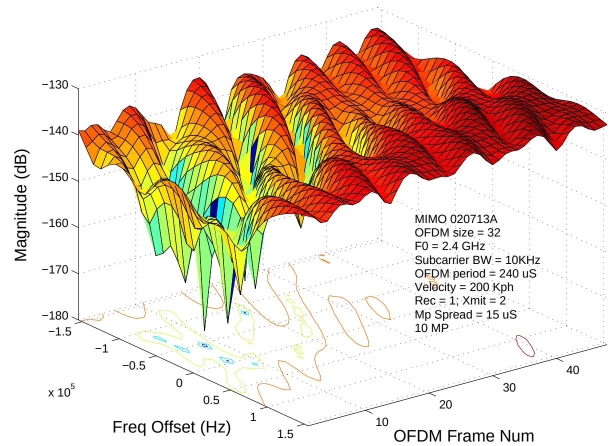

Figure 3. MIMO-OFDM Time-Frequency Plane Generated from GWTCM Channel Model

4. THE GWTCM CHANNEL MODEL

The channel model that we used for simulations is referred to as the Geometric Wide-band Time-varying Channel Model (GWTCM) [4]. The GWTCM was developed specifically for simulating OFDM-MIMO applications. The GWTCM uses an elliptical boundary to limit multipath spread, implements wideband channel modeling by partitioning the spectrum into multiple flat channels, provides for mobility of objects and can calculate the AOA and fading envelopes from the received signal. The GWTCM uses a single bounce model for the multipath components but can be extended to more reflections to reduce the standard deviation of the prediction error [6]. This model most closely follows that of Liberti's GBSBEM [7]. The model also is similar to ray tracing models developed by Fette [8] and Valenzuela [9].

Figure 2 shows the baseline simulation GWTCM geometry that we used for a 3x2 MIMO communications system consisting of M=3 isotropic receive antennas and N=2 isotropic transmit antennas. K=10 multipath reflectors are placed inside of an ellipse that represents the loci of multipath reflectors with a multipath delay of $\tau_m = 25$ µsec.

The transfer function, $H(m,n,t,f_s)$, is computed with the following equation,

$$H(m,n,t,f_s) = A_{mn} e^{\frac{-j2\pi d_{mn}}{\lambda_{mn}}} + \sum_{k=1}^{K} B_{mkn} e^{\frac{-j2\pi d_{mkn}}{\lambda_{mkn}}}, \tag{5}$$

where m is the receive antenna number, n is the transmit antenna number, t is the OFDM frame number and f_s is the subcarrier frequency.

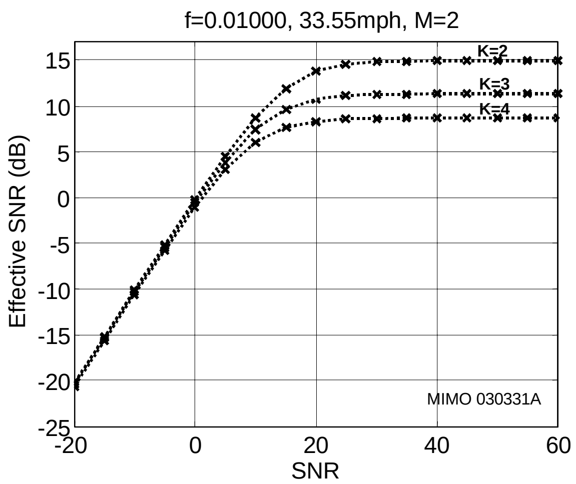

Figure 4. ESNR versus received SNR at 33.55 mph, M = 2, and F=2, 3, 4.

For the case of mobile transmit antenna n and static receive antenna m and multipath reflector k the Doppler shift, υ_{mkn}, can be found by [10]

$$\upsilon_{mkn} = \frac{v}{\lambda_s}\cos(\phi_i - \phi_v)\,, \tag{6}$$

where v is the velocity of transmit antenna n, λ_s is the wavelength of subcarrier frequency, f_s, φ_i is the AOA at receive antenna n, and φ_v is the relative angle of travel for transmit antenna n. The receive frequency, f_m, at antenna m, is thus

$$f_m = f_s + \upsilon_{mnk}\,, \tag{7}$$

then the received wavelength, λ_{mnk}, is

$$\lambda_{mnk} = \frac{C}{f_m}\,. \tag{8}$$

The plot in Figure 3 shows the antenna 1 receive power as a function of frequency and OFDM frame number for the case where the transmit power, P_T, for transmit antenna, n = 2, is 0 dBm, and the transmit array moved in the NE direction with a velocity, v = 200 Kph. The geometry of the experiment is shown in Figure 2. An OFDM size of 32 with a center frequency of 2.4 GHz was used. The OFDM subcarrier bandwidth was 10 KHz and the OFDM symbol time was 240 *u*sec. Note the deep time and frequency selective fades at OFDM frame number 8 in Figure 3.

5. SIMULATION RESULTS

We studied the effective SNR, given a fixed mobile speed, and a varied received SNR. Figure 4 shows the results with an RF frequency of 2 GHz and sampling rate of 1e4 for M = 2 transmit elements, respectively. In this plot, given a fixed mobile speed, we see that reasonable "effective" SNRs occur only at high received SNRs, but the flooring effect is present due to the training interval and mobile speed.

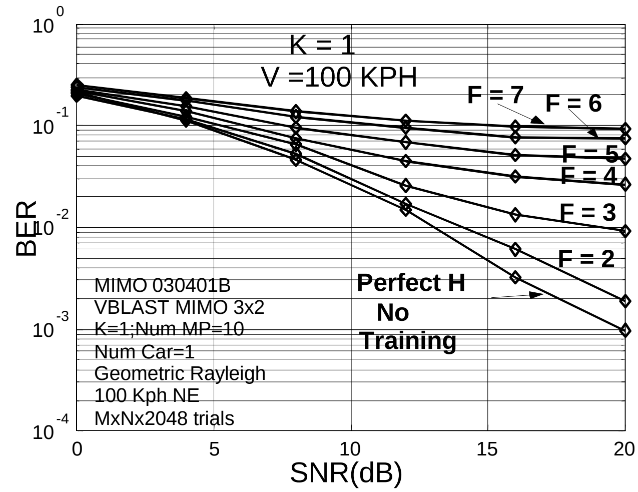

Figure 5. 3x2 MIMO BER Vs. Number of OFDM Frames for k=1.0

In this case the effective SNR can only be improved by reducing the mobile speed or through optimal placement and tracking of the channel between training intervals. Optimal tracking and placement versus transmit-receive configuration is not considered in this paper, but may be applied as suggested in [3][11][12].

Using the GWTCM channel model, we devised a simulation to determine the loss of BER in a mobile environment as a function of the number of OFDM frames that follow a training sequence. Figure 5 shows the results of this experiment for the case where k=1, i.e. the training interval is R_T=0 time samples. Mobility was induced in the GWTCM channel model by moving the transmit antenna array at a velocity of 100 KPH in the NE direction. The position of the receive array and all multipath reflectors remained static. The plot in Figure 5 shows the BER degradation that results in a Rayleigh fading environment as we change the number of OFDM frames (F) per training period. Results show that a 3 dB penalty is incurred for F=2 OFDM frames at a BER of 1e-3. The plot in Figure 5 also shows that the curves bottom out at higher BER levels as F increases.

OFDM parameters for the simulation are as follows: The carrier frequency was set to 2.4 GHz. The OFDM size, R_O=320 samples at a sampling rate of 1.33 MSPS which gives an OFDM duration of 240 *u*sec. The 320 OFDM size consist of N=256 samples plus a 64 sample cyclic extension. The 1 MHz bandwidth OFDM signal consists of 190 subcarriers each spaced 5.1 kHz apart. The re maining 66 subcarriers are null carriers. The OFDM subcarriers are QPSK modulated which yields a data rate of 1.43 Mbps not including the training duration.

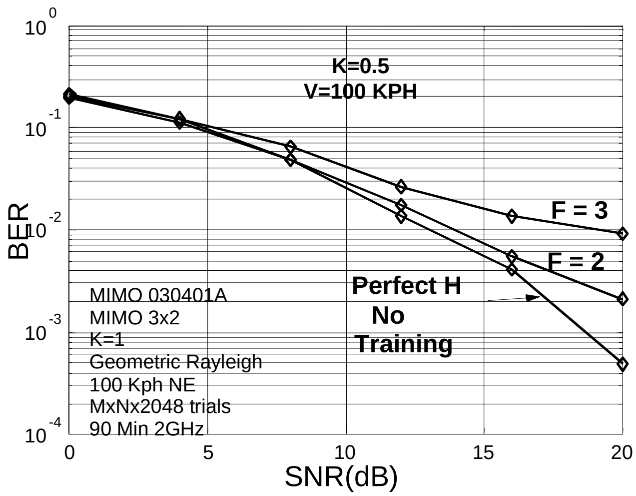

Figure 6. 3x2 MIMO BER Vs. Number of OFDM Frames for *k*=0.5

A similar simulation was performed for the case where *k*=0.5 and is shown in Figure 6. All other parameters are as indicated for Figure 5. Results will show that the performance is slightly degraded from the *k*=1.0 training parameter results shown in Figure 5. This supports the utilization of more optimal training procedures and sophisticated channel tracking methods.

6. CONCLUSION[#]

This paper has presented the performance of mobile orthogonal frequency division multiplexing (OFDM) multiple-input multiple-output (MIMO) communication systems with imperfect knowledge of the channel matrix. MIMO systems typically require a channel matrix, which can be determined initially from a training sequence. However, mobile wideband MIMO communication systems exhibit a time-varying channel matrix and have time and frequency selective fades which result in performance degradation of the MIMO system. Channel tracking methods can be used to estimate the time-varying channel matrix but cannot in practice be error free. The simulation model of the V-BLAST (Vertical Bell Laboratories Layered Space-Time) OFDM MIMO system accurately predicts performance degradations using the Geometric Wide-band Time-varying Channel Model (GWTCM) in a prescribed Rayleigh faded environment and imperfect channel matrix knowledge. We are able to predict performance degradations due to imperfect channel estimation in wideband mobile MIMO channels by combining the GWTCM with a Gauss-Markov narrowband fading channel model. The V-BLAST OFDM-MIMO architecture presented in this paper can be easily implemented by exploiting the built-in and flexible multi-channel architectures of advanced Software Defined Radios (SDR).

7. REFERENCES

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