Time-Varying Coding for Space-Time Ambiguities

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Abstract–This paper first formulates the error propagation effect that is caused by certain ambiguities in joint data detection/channel tracking algorithms for Space-Time (ST) schemes. The occurrence of any combination of two types of ambiguities, Phase Ambiguity (PhA) and Permutation Ambiguity (PeA), initiated in deep fades, produces error propagation in joint channel estimation/data detection for Dual Transmit Diversity method. A new Time-Varying Space-Time coding (TVST) scheme is suggested as a bandwidth efficient method to combat the PeA impairment. This coding scheme, in conjunction with a differential detector, can resolve the ambiguity problem. At the end, some remedies are used to prevent error propagation are listed. These remedies are called Space-Time Ambiguity Remedies (STARs).

I. Introduction

Time-varying multipath fading makes reliable wireless transmission expensive and difficult [1]. To improve data communication quality (*e.g.*, to reduce the effective error rate) in a multipath fading environment, it is crucial to successfully reduce the effect of fading at both mobile units and base stations. In most scattering environments antenna diversity is a practical and efficient technique to reduce the effect of multipath fading [2]. These schemes employ pre-coding, namely Space-Time Coding (STC), which is appropriate for multiple antenna systems [3].

Although in the presence of small errors in channel state information, STCs still result in an improved bandwidth efficiency over classical transmitting schemes [9], a considerable degradation is observed when the channel estimation error increases. This is improved by sending more pilot symbols (training symbols) during the transmission at the cost of losing some bandwidth efficiency [4]. The performance of existing receivers for STC methods degrades dramatically in time-varying channels [8], and an efficient channel tracking algorithm is required to provide accurate Channel State Information (CSI). Hence, robust detection algorithms are needed for good operation when the CSI is not exactly known. An almost neglected issue when employing joint adaptive channel estimation - data detection in a system with multiple antennas is the error propagation due to some ambiguities [10]. These ambiguities which are initiated in deep fades can be divided into two categories: PhA , and PeA. Ambiguities take place because of the structure of the STC scheme and the channel estimator.

In Section II the system structure is discussed (see [10] for more detailes) and two types of ambiguities that occur in time-varying channels at low SNRs are addressed. In Section III, the general form of these ambiguities is derived for the Dual Transmit Diversity (DTD) [2]. Several STARs are outlined to combat the error propagation. In particular, we show that the new proposed TVST coding scheme, in conjunction with conventional differential coding, can resolve the error propagation problem in a joint detection-estimation context. This scheme is bandwidth efficient. The achieved improvement over the conventional scheme shows that the error propagation is a serious problem for ST codes, and that the resolution of ambiguities results in a significant improvement. Some concluding remarks are discussed in Section IV.

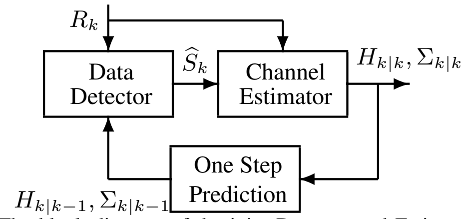

Fig. 1. The block diagram of the joint Detector and Estimator, where $H_{k|k}$ and $\Sigma_{k|k}$ represent the estimated CSI and $\widehat{S}$ is the detected symbol.

II. System Structure

The received signal vector, R, for a transmit diversity scheme equals $R = SH + N$, where the transmitted code S is a function of a block of symbols $s_1, s_2 \cdots, s_l$, H is the vector of channel gains, and N is the Additive White Gaussian Noise (AWGN). For instance, in our simulations and calculations we consider the Dual Transmit Diversity (DTD) technique that is proposed in [2]. This scheme is described as follows:

$$\begin{cases} r_1 &= h_1\, s_1 + h_2\, s_2 + n_1, \\ r_2 &= -h_1\, s_2^* + h_2\, s_1^* + n_2, \end{cases} \qquad (1)$$

where $R = [r_1, r_2]^T$ for $i = 1, 2$. Figure 1 shows the structure of a MAP receiver [10] jointly connected to a Baysian estimator [10] used to have joint estimation and detection over a fast rayleigh fading channel. The receiver takes into account the channel estimation error while the estimator is efficiently capable to track a fast rayleigh fading channel. Table I summarize the detection algorithm and estimation algorithm, respectively. The joint performance of these two systems is also studied in [10]. It is to be noted that throughout this paper $(.)_{k|k-1}$ and $(.)_{k|k}$ denote *a priori* and *a posteriori* estimates of $(.)_k$ at time k, respectively.

Remark 1: (Phase Ambiguity) The received signals r_1 and r_2 in (1) remain invariant by transforming (s_1, s_2, h_1, h_2) into $(e^{j\phi}s_1, e^{-j\phi}s_2, e^{-j\phi}h_1, e^{j\phi}h_2)$, assuming that elements of this quadruplet are unknown and only r_1 and r_2 are observed in order to estimate this quadruplet. In this situation, the determination of the phase $e^{j\phi}$ remains ambiguous, which we shall call PhA. This ambiguity depends on the set of alphabets, $\mathcal{C}$. For example, using a 4QAM modulation scheme, we have $e^{j\phi} \in \{\pm 1, \pm j\}$. In this case the receiver must know $e^{j\phi}$, which is equivalent to two bits or one symbol. To resolve this ambiguity, the direction of one of the components of this quadruplet must be determined. One way to resolve this PhA is to control the set of alphabets $\mathcal{C}$ for s_1 and s_2. For instance, using one pair of training symbols might enable this problem to be resolved. If the phase varies slowly enough with

TABLE I. Summary of Estimation and Detection Algorithm

Detection Algorithm:

$$H_{k|k} = H_{k|k-1} + \frac{1}{\sigma^2}\Sigma_{k|k} C_{p,q}^H \big(R_k - C_{p,q} H_{k|k-1}\big),$$
$$M(C_{p,q}, R_k) = \log|\Sigma_{k|k}| + H_{k|k}^H \Sigma_{k|k}^{-1} H_{k|k},$$
$$\widehat{S}_k = \arg\max_{c_p, c_q \in \mathcal{C}} M(C_{p,q}, R_k)$$
$$\Sigma_{k|k}{}^{-1} = \alpha_{p,q} I + \Sigma_{k|k-1}^{-1},$$
$$\alpha_{p,q} \triangleq \frac{\|c_p\|^2 + \|c_q\|^2}{\sigma^2} = \frac{|C_{p,q}|}{\sigma^2}, \quad C_{p,q} \triangleq \begin{bmatrix} c_p & c_q \\ -c_q^* & c_p^* \end{bmatrix}.$$

Channel Estimation Algorithm

$$H_{k|k} = H_{k|k-1} + \mu \Sigma_{k|k} \widehat{S}_k^H \left(R_k - \widehat{S}_k H_{k|k-1}\right),$$
$$H_{k+1|k} = H_{k|k}, \quad \Sigma_{k+1|k} = \Sigma_{k|k} + \eta I.$$

time, it can be tracked accurately after the first initialization. However, a sudden rotation of the channel coefficients results in a dual rotation of the detected data after that event. Another alternative to overcome this problem is to use differentially coded modulation schemes (see [6, 7] and references therein). In these schemes the information is embedded in the transmitted sequence in such a way that after decoding the effect of $e^{j\phi}$ is cancelled, usually at the expense of about 3dB noise augmentation. The PhA is the result of a random rotation of one constellation point to another constellation point. This is similar to the propagation phenomena that occurs in a QAM modulation scheme where the set of constellation points is invariant under any rotation of multiples of 90 degrees. If for any reason the channel phase is unknown then the error propagation can happen when data detection and channel tracking are jointly done. The general form of possible ambiguities is determined by the structure of the ST code. The error propagation phenomena are caused by these ambiguities. In Remark 2, we will identify a second type of ambiguity, Permutation Ambiguity, which can happen because of the structure of the STC scheme. When the PeA occurs, phases can also rotate randomly.

Remark 2: (Permutation Ambiguity) It is clearly seen that the received signal $R = SH + N$ remains invariant if the quadruplet (s_1, s_2, h_1, h_2) is transformed into $(s_2, -s_1, h_2, -h_1)$. Therefore, in a non-stationary environment, if h_2 passes by $-h_1$, the receiver might detect $(s_2, -s_1)$ instead of (s_1, s_2). In other words, the receiver ignores the crossover which results that the channel estimation algorithm tracks $(h_2, -h_1)$ instead of (h_1, h_2). After the crossover event, the algorithm fails to recognize the change of situation and continues to consider $(s_2, -s_1, h_2, -h_1)$ instead of (s_1, s_2, h_1, h_2). This phenomenon can be resolved: 1) by the detection of crossovers by an improved tracking scheme for the channel vector, 2) by periodic use of one or two training symbols, 3) by using DSTC methods, *e.g.* [6, 7], or 4) by a combination of these methods. This permutation mostly happens in low SNRs when both channels are in deep fades.

Figure 2 shows the effect of the PeA on the channel tracking. After a joint deep fade, the estimates of h_1 and $-h_2$ are permuted, and the estimated gain for the first channel, $|h_1|$, follows the second channel gain, $|h_2|$, and vice versa. As pointed out in Remarks, this phenomenon happens because of the structure of the estimator and the coding scheme. In other words, the coding scheme along with the constellation set allows for the chance that the detected signals be exchanged, even though this exchange is not observed from the received signals. After a joint deep fading point, the channel tracking algorithm takes the exchanged (detected) data as the transmitted data and remains confused. Thus, after the permutation point $|h_1|$ follows $|h_2|$ and vice versa.

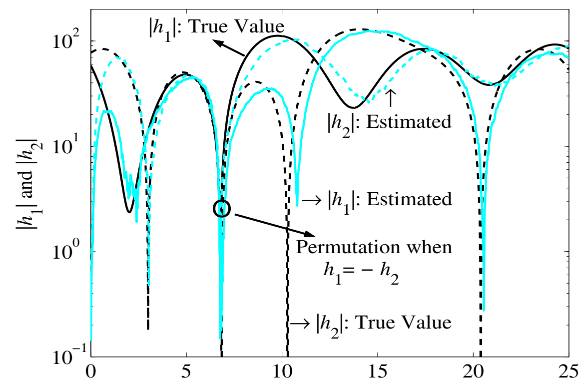

Fig. 2. Effect of PeA (Remark 2) on channel tracking performance. The simulation is done for SNR=5dB, 10 training pairs, when $\omega_d = 0.01\frac{\text{rad}}{\text{sample}}$, $\mu = 3.5$. In a low SNR, the algorithm is unable to continue tracking correctly beyond the crossover point; Solid: $\|H_k - H_{k|k}\|^2$; Dashed: $\left\|H_k^T - \left[-h_{2,k|k}, h_{1,k|k}\right]\right\|$.

III. Ambiguities in Space-Time Codes

In this section, the general form of ambiguities in STCs and some STARs are introduced as modifications on either the channel tracking algorithm or the STC scheme. Remarks 1 and 2 introduce two types of ambiguities occurring in deep fades which result in serious error propagation. We categorize these STARs in two main groups: 1) Methods to enhance the channel tracking algorithm, and 2) Methods to modify the STC scheme. As as instance of the first category, we have suggested an improved tracking algorithm in [10] that estimates not only the CSI, but also the speed of variations of CSI. The algorithm uses these speeds to improve identification of the trajectory of the CSI. Using these speeds not only improves the performance of the channel tracking, but more importantly reduces the probability of random permutation or random rotation of the estimated parameters. Details of a new Time-Varying ST coding scheme are proposed in the next part, as an example of the second category of STARs to combat the PeA.

Time-Varying ST (TVST) Coding Scheme: In this section, we introduce a Time-Varying Space-Time (TVST) coding scheme to contest the problem for the general form of Space-Time Ambiguity (STA) . The TVST scheme is basically the modulation of different columns of a conventional ST code with a set of simple and different known time varying modulations, *i.e.*, different frequency shifts. We will show that this new coding method allows to separate the spectrum of different channel coefficients by modulating them into different frequency bandwidths. This scheme is a consistent solution to the STA problem for STCs that can be easily extended to the general case.

General Form of STAs: Consider the received signal in the transmitter $R_k = S_k H_k + N_k$, where $S_k = B(\mathbf{s}_k)$ is a function of a vector of symbols $\mathbf{s}_k = [s_{1,k}\ s_{2,k}\ \cdots\ s_{M,k}]$ (*e.g.*, see Table I for $M = 2$) and $s_{i,k}$ takes its alphabet from the constellation points set $s_{i,k} \in \mathcal{C}$. The ST code is described by the function B and the constellation set. Consider the pair (S_k, H_k) as the input and the channel. To find all ambiguities for this scheme we note that any other pair of the form $(S_k W_k, {W_k}^{-1} H_k)$ results in the same received signal. Therefore, we call the pair $(S_k W_k, {W_k}^{-1} H_k)$ ambiguous with (S_k, H_k), if $S_k W_k$ can be generated by any other sequence taking its values from the constellation points set, *i.e.*, all STAs are solutions of $B(\mathbf{s}_k) W_k \in B(\mathcal{C}^M)$. This means that the structure of $S_k = B(\mathbf{s}_k)$ and $S_k W_k$ are the same for STAs. In brief, STAs are those transformations for which the ST code re-

TABLE II. Summary of TVST Coding Algorithm

$$
\begin{aligned}
R_k &= V_k H_k + N_k, \\
H_k &\sim \mathcal{N}(H_{k|k-1}, \Sigma_{k|k-1}), \;\; N_k \sim \mathcal{N}(0, \sigma^2 I_{2L}), \\
V_k &\triangleq \begin{bmatrix} s_{1,k} & e^{j\omega_0 k} s_{2,k} \\ -s_{2,k}^* & e^{j\omega_0 k} s_{1,k}^* \end{bmatrix}, s_{1,k}, s_{2,k} \in \{c_i\}_{i=1}^K . \\
\widehat{V}_k &= \arg \max_{c_p, c_q \in \mathcal{C}} M(C_{p,q}, R_k) \\
&= \arg \max_{c_p, c_q \in \mathcal{C}} \left[\log |\Sigma_{k|k}| + \widehat{H}^H \Sigma_{k|k}^{-1} \widehat{H} \right], \\
{\Sigma_{k|k}}^{-1} &= \alpha_{p,q} I + \Sigma_{k|k-1}^{-1}, \\
H_{k|k} &= H_{k|k-1} + \tfrac{1}{\sigma^2} \Sigma_{k|k} C_{p,q}^H \left(R_k - C_{p,q} H_{k|k-1} \right), \\
\alpha_{p,q} &\triangleq \tfrac{\|c_p\|^2 + \|c_q\|^2}{\sigma^2} = \tfrac{|C_{p,q}|}{\sigma^2}, \\
C_{p,q} &\triangleq \begin{bmatrix} c_p & e^{j\omega_0 k} c_q \\ -c_q^* & e^{j\omega_0 k} c_p^* \end{bmatrix}. \\
H_{k+1|k} &= H_{k|k}, \quad \Sigma_{k+1|k} = \Sigma_{k|k} + \eta I.
\end{aligned}
$$

mains invariant. For example, for the QAM modulation in the case of a 2×2 STC matrix (Alamouti's scheme) the general form of STA is presented by:

$$
W_k = \begin{bmatrix} w_1 e^{j\varphi_1} & w_2 e^{j\varphi_2} \\ -w_2 e^{-j\varphi_2} & w_1 e^{-j\varphi_1} \end{bmatrix}, \quad \{w_i, \varphi_i\}_{i=1}^2 \in \mathbb{R}. \quad (2)
$$

As an example, for a 4QAM modulation this general solution gives the PhA when $w_1 = 1, w_2 = 0$ with $\varphi_1 \in \{\pi/2, \pi, 3\pi/2\}$. The proposed equation also gives the PeA when $w_1 = 0, w_2 = 1$ with $\varphi_2 \in \{\pi/2, \pi, 3\pi/2\}$. Hence, for a 4QAM modulation there are a total of 7 STAs that can cause H_k to become confused with any of the following: $e^{j\varphi} H_k$ and $e^{j\varphi} \begin{bmatrix} -h_{2,k} \\ h_{1,k} \end{bmatrix}$, with $\varphi \in \{0, \pi/2, \pi, 3\pi/2\}$.

Table II offers a new TVST scheme to resolve these ambiguities. The idea is based on separation of different wireless channel spectrums in frequency domain by modulating them with a tone of $(m-1)\omega_0$, in which $m = 1, 2, \cdots, M$ and M is the number of transmitters. As channel gains are lowpass signals with a given bandwidth of ω_d, these modulations allow us to make a clear distinction between them. This is done by applying the tone waveform, $e^{j(m-1)\omega_0 k}$, on the mth column of the transmitted matrix S_k at the transmitter, *i.e.*, the signal $V_k = S_k \Psi_k$ is transmitted instead of S_k, in which $\Psi_k \triangleq \text{diag}[1, e^{j\omega_0 k}, \cdots, e^{j(M-1)\omega_0 k}]$. For example, for the DTD scheme we transmit the following TVST instead of the conventional code:

$$
V_k = \begin{bmatrix} s_{1,k} & e^{j\omega_0 k} s_{2,k} \\ -s_{2,k}^* & e^{j\omega_0 k} s_{1,k}^* \end{bmatrix}. \quad (3)
$$

In TVST scheme, instead of transmitting the discrete-time signal S_k, the discrete-time signal of $V_k = S_k \Psi_k$ is transmitted. Since, V_k and S_k, both have identical flat spectrums in the discrete-time domain[1], converting them into continuous-time domain using a digital-to-analog converter produces identical spectrums in the continuous-time domain. Therefore, this scheme is bandwidth efficient and simple to implement for all existing STCs. For the TVST scheme the observed signal equals $R_k = (S_k \Psi_k) H_k + N_k$. The receiver can perceive this as modulating different rows of H_k, *i.e.*, in the absence of ambiguity the channel can be perceived as $\Psi_k H_k$ instead of H_k. As we want to be able to separate the spectrum of different rows of H_k in frequency domain, the spectrum of rows of $\Psi_k H_k$ should not have overlapping bandwidth. Therefore, ω_0 should fit in the below inequality

$$
2\omega_d \leqslant \omega_0 \leqslant \frac{\pi - \omega_d}{M}, \quad (4)
$$

in which ω_d is the maximum Doppler frequency in $\frac{\text{rad}}{\text{sec}}$. In addition, the centered frequencies should be sufficiently apart in comparison to the maximum Doppler spread, *e.g.*, a good value in practice for $\frac{\omega_0}{\omega_d}$ is at least 5. The received signal using TVST equals $R_k = S_k \Psi_k H_k + N_k$, where Ψ_k is a diagonal time varying matrix and $S_k \Psi_k$ is transmitted symbol instead of S_k. The above equation remains invariant if we replace the pair of (S_k, H_k) by $(S_k W_k, \Psi_k^{-1} W_k^{-1} \Psi_k H_k) = (S_k^a, H_k^a)$. Thus, the pair (S_k, H_k) is ambiguous with (S_k^a, H_k^a), where $B(\mathbf{s}_k) W_k \in B(\mathcal{C}^M)$. Therefore, if any ambiguity occurs, the channel estimator can track the wrong channel, *i.e.*, $H_k^a = \Psi_k^{-1} W_k^{-1} \Psi_k H_k$. Since the channel H_k follows the Clark's model, it is a lowpass random process. This means that the autocorrelation function of the correct channel is a lowpass signal, *i.e.*, the autocorrelation function $R_m = E[H_{k+m} H_k^H]$ is described by a Bessel function and is a lowpass signal. In contrast, the autocorrelation of the wrong channel H_k^a is $R_m^a = E[H_{k+m}^a H_k^{aH}] = \Psi_{k+m}^{-1} W_k^{-1} \Psi_{k+m} R_m \Psi_k^H W_k^{-1H} \Psi_k^{-1H}$. The wrong channel, H_k^a, represents a bandpass random process, except for the case that W_k is diagonal, *i.e.*, no permutation. Because the channel estimator is tuned to estimate the lowpass components of the channel process, the corresponding components rapidly converge to zero if any permutation occurs. In this mode the data is detected randomly. As soon as the first data is detected correctly, the correct channel is tracked. For instance, in a DTD system, and in the absence of PeA, *e.g.*, $W_k = I$, the algorithm tracks lowpass components: $h_{1,k}$ and $h_{2,k}$ and $R_m^a = R_m = J_0(m\omega_d) I_2$, in which ω_d is the maximum Doppler frequency. In the case of a PeA, *e.g.*, $W_k^{-1} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$, the algorithm tracks $H_k^a = \left[e^{j\omega_0 k} h_{2,k}, \; -e^{-j\omega_0 k} h_{1,k} \right]^T$ instead of $H_k = [h_{1,k}, \; h_{2,k}]^T$ and the autocorrelation of H_k^a is $R_m^a = J_0(m\omega_d) \begin{bmatrix} e^{j\omega_0 m} & 0 \\ 0 & e^{-j\omega_0 m} \end{bmatrix}$, representing a vector process that is not lowpass. The TVST is applied in the discrete-time domain and does not require extra bandwidth.

If an Orthogonal Space-Time Block Coding (OSTBC) scheme [5] is employed with TVST (*e.g.*, the DTD example employed in this paper), the orthogonality property of the code is preserved, *i.e.*, $V_k V_k^H = S_k \Psi_k \Psi_k^H S_k^H = S_k S_k^H$, where $\Psi_k \Psi_k^H = I$. Therefore, the TVST receiver takes advantage of orthogonal deigns of OSTBC, which has good performance and low decoding complexity. Note that a minor extra computational complexity results from generation of $V_k = S_k \Psi_k$ instead of S_k.

The TVST can be extended for general MIMO systems. The structures of the detector and the estimator using TVST will remain almost unchanged. The only change in the estimation algorithm is to replace $\widehat{S}_k$ by the TVST, $\widehat{V}_k$, as summarized in Table II. Figure 3 shows a sample tracking of the TVST coding scheme. As it is seen in the probable permutations, algorithm slows down the tracking procedure, help the system pass the critical place. Then, tries to catch up with the main time-varying channel. This result also introduces a compromise between the tracking speed and the tracking accuracy in the time-varying envi-

[1] The sequence $s_{i,k}$ is an i.i.d. sequence; hence, denoting $x_k \triangleq e^{j\omega_0 k} s_{i,k}$ we have $R_x[m] = E[x_k x_{k+m}^*] = E[s_{i,k} s_{i,k}^*] = \delta_m R_s(0)$. This means that $s_{i,k}$ and x_k have identical bandwidths of $2\pi \text{rad/symbol}$.

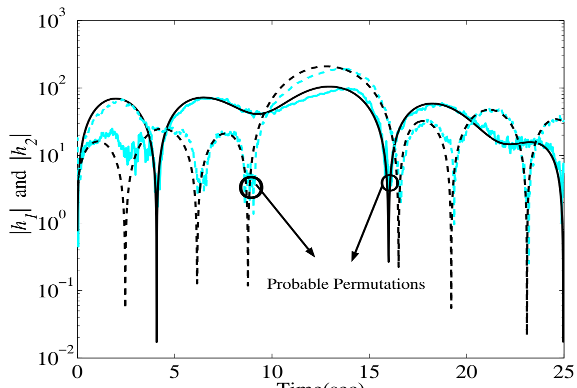

Fig. 3. TVST tracking shows the behavior of the algorithm, when detecting a permutation. Simulation is done for SNR=5dB, 1 percent training symbols, $\omega_d = 0.01 \frac{\text{rad}}{\text{sample}}$, $\omega_0 = 0.2 \frac{\text{rad}}{\text{sample}}$, $\eta = 180$, and $\mu = 8$.

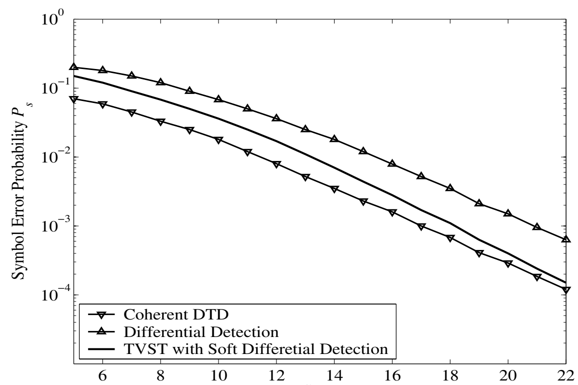

Fig. 4. SEP for fading channel using TVST with soft differential detection compared to the coherent method (upper curve) and conventional differential scheme. A soft differential detector is used to improve the 3dB loss due to noncoherent detection, $\omega_d = 0.01$, $\omega_0 = 0.3$, $\mu = 6$.

ronment. Figure 4 compares the performance of three schemes: 1) the TVST in conjunction with the conventional differential encoding: $s_{i,n} = s_{i,n-1} a_{2n-1+i}$ for $i = 1, 2$ and a soft decoder, where a_n is the 4QAM information sequence, 2) the coherent DTD proposed in [2] and 3) the non-coherent DSTC proposed in [7]. The TVST scheme can combat only the PeA; therefore, a conventional differential encoding is used to prevent the PhA and successfully prevent the error propagation. The TVST scheme outperforms the noncoherent DSTC. In other words, when an ambiguity and crossover occurs, the receiver using TVST goes back to normal tracking itself. This feature improves the tracking as well as the SEP.

Overview of STARs to Resolve Error-Propagation: The PhA introduces a simple phase rotation in the signal constellation. The PeA introduces a spatial exchange in STCs. Different methods including any of the following methods, or a combination of them, could be employed to combat and prevent error propagation:

• Periodic use of short training sequences or pilot assisted training scheme: The time interval between two successive training period should be small enough [4] to provide accurate CSI.

• Using two or more different conventional STCs at different time instances: In this approach different STCs are used periodically. These codes should not share any ambiguity matrices. In fact, this is another kind of TVST code in which constellations are time-varying.

• Redundant STC: One may extend a code by adding redundancy to resolve the ambiguity. For example, instead of the conventional DTD, we can use $\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \\ s_1 s_2 & s_2 \end{bmatrix}$ as the coding matrix to correct errors, and improve the channel estimation.

• Differential STC (*e.g.*, see [6, 7] and references therein).

• Enhanced Tracking Algorithms.

• Time-varying schemes: *e.g.*, the TVST scheme in Section III.

• Controlling the size of the constellation set: We sometimes limit the number of constellation points in a way that $S_k W_k \in \mathcal{C}$ will have no solution for all S_k. For instance, for an orthogonal modulation scheme, *e.g.*, $\mathcal{C} = \{1, j\}$, the ambiguity equation $B(\mathbf{s}_k) W_k \in B(\mathcal{C}^M)$ has no solution except $W_k = I$. Note that these free ambiguity STCs are not bandwidth efficient, but can be used instead of training sequences.

IV. Conclusions

To prevent error propagation caused by two types of ambiguities, some remedies (STARs) are outlined, along with the general form of them for STCs. An enhanced channel tracking algorithm is suggested to resolve the permutation ambiguities. The TVST scheme is proposed as a bandwidth efficient remedy for the problem of PeA. Using the TVST, the tracking algorithm automatically tracks the true channel as the channel is a lowpass random process. This bandwidth efficient scheme, in conjunction with differential schemes, can resolve the error propagation imperfection due to ambiguities.

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