TRANSMISSION DIVERSITY AMBIGUITIES AND ADAPTIVE CHANNEL TRACKING

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Abstract– This paper studies the error propagation effect that is caused by some ambiguities in joint data detection–channel tracking algorithm for transmission diversity schemes. Some remedies to avoid or to overcome these error propagations are suggested. In this paper, a ST receiver is used that is based on the Maximum *A Posteriori* (MAP) method. It takes into account the channel estimation error assuming the unknown channel to have a given complex multivariate Gaussian probability density function (pdf) (*i.e.*, a Ricean channel). An adaptive algorithm which is capable of efficiently tracking a fast Raleigh fading channel is used for iterative channel estimation. However, the occurrence of two types of ambiguities during deep fades result in error propagation. Some solutions called Space-Time Ambiguity Remedies (STAR) are proposed to prevent error propagation; a new time VArying Space-Time (VAST) coding is suggested as an efficient method to combat these ambiguities. Simulation results confirm the validity of each proposed technique.

I. INTRODUCTION

IN this paper, we show that there exist some ambiguities when the data detection and the channel tracking is done jointly in some efficient ST coding schemes. The general form of possible ambiguities is determined by the structure of the ST code. The error propagation phenomena can be caused by these ambiguities. We identify two types of ambiguities namely: 1) the Phase Ambiguity (PA) and 2) the PErmutation Ambiguity (PEA). The PA 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 multiple of 90 degrees; therefore, 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 PEA can happen because of the structure of the ST coding scheme and the joint detector-estimator. Of course when the PEA happens phases can also be randomly rotated. Several STARs are outlined to combat the error propagation. In particular, we stress to show that a suggested enhanced estimation algorithm or an enhanced ST coding can resolve the error propagation in some situations. However, each STAR has some advantages and disadvantages; therefore a combination of these STARs could be used in practice to achieve the best performance.

Simulation results show that the error propagation is always initiated in deep fades, when the signal energy to be transmitted is very low. To prevent these ambiguities to occur, we suggest an enhanced tracking algorithm. This method estimates not only the Channel State Information (CSI), but also the speed of variations of CSI and uses these speeds to improve identification of the trajectory of the CSI. The use of these speeds not only improves the performance of the channel tracking but more importantly reduce the probability of random permutation or random rotation of the estimated parameters. Consequently, the error propagation becomes less probable. We also recommend a new time VAarying Space-Time (VAST) coding scheme to resolve the crossover drawback. The VAST scheme is basically to modulate different columns of a conventional ST code with a set of simple and different known time varying modulation, *i.e.*, different frequency shifts. It is easy to see that all advantageous properties of the code and the receiver are preserved when the channel is known at the reciever. Using the VAST scheme, the receiver perceives the same set of signals if we are able to modulate different channel gains, respectively. Of course, this idea can be easily extended to generate many new VAST codings by using proper time varying signals like sinusoids and Pseudo Noise (PN) sequences.

The paper is organized as follows. In Section II the system structure is discussed and some references are addressed for more details. The before-mentioned impairments that occur in time-varying channels at low SNRs are addressed in section III. The general form of these ambiguities is derived for a special case of dual transmit diversity system. An adaptive tracking method to combat permutation ambiguity (PEA) is proposed here. In this section the new VAST coding scheme is also proposed as another STAR to combat ambiguities in a more efficiently way. The achieved improvement over the conventional scheme using VAST shows that the error propagation is a serious problem for ST codes and the resolution of ambiguities results in a significant improvement in wireless communication system. Some concluding remarks and conclusions are discussed in Section IV.

II. SYSTEM STRUCTURE

The received signal vector, R, for a transmit diversity scheme can be described as follows [2]:

$$R = SH + N, \tag{1}$$

where S is the transmitted code that 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 vector representation of the Additive White Gaussian Noise (AWGN). For example, in our simulations we consider the Dual Transmit Diversity (DTD) technique that is proposed in [1]. This scheme can be described as follows:

$$\begin{cases} r_1 &= h_1\, s_1 + h_2\, s_2 + n_1, \\ r_2 &= -h_1\, s_2^* + h_2\, s_1^* + n_2, \end{cases} \tag{2}$$

where $R = [r_1, r_2]^T$ for $i = 1, 2$. In this work, we have used a MAP receiver [8,9] jointly connected to a Baysian estimator [8,10] in order 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 and Table II summarize the detection algorithm and estimation algorithm, respectively. The joint performance of these two systems is also studies in [8].

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III. AMBIGUITIES IN SPACE-TIME CODES

This section discusses about the general form of ambiguities in ST codes and some STARs are introduced to combat them as modifications on both channel tracking algorithm or ST coding scheme. We categorize these STARS in two main groups 1) Methods to modify the channel tracking algorithm and 2) Methods to modify the ST coding scheme. Then, we give detailed examples for each group. We fist separately introduce each ambiguity.

Phase Ambiguity It is easy to see that the received signals r_1 and r_2 in (2) remain invariant by transforming the quadruplet (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, this property leaves ambiguous, which we shall call Phase Ambiguity (PA), in determination of the phase $e^{j\phi}$ when only r_1 and r_2 are observed in order to estimate this quadruplet. 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 the equivalent of 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 PA 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 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. Therefore, another alternative to overcome this problem is to use differentially coded modulation schemes (*e.g.*, see [3–5] and references therein for more details). In these schemes the information is embedded 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.

Permutation Ambiguity In (1), it is clearly seen that the received signal R 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 practice 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; therefore the channel estimation algorithm will track $(h_2, -h_1)$ instead of (h_1, h_2). After the crossover event, the algorithm fails to recognize that the situation has changed 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 and an improved tracking scheme for the channel vector, 2) by periodic use of one or two training symbols, 3) by the use of differential STC coding methods, *e.g.* [3–5], or 4) by a combination of these methods. This permutation mostly happens in low SNRs when both (or one) of channels are in deep fades (see Figure 1).

Figure 1 shows the effect of the permutation ambiguity on the channel tracking. After a joint deep fade, we see that 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 before, this phenomenon happens because of the structure of the estimator and the coding scheme. In other words, coding scheme along with the constellation set allows the chance that the detected signals to be exchanged while this exchange is not observed from received signals. After a joint deep fading point, the channel tracking algorithm takes the exchanged (detected) data as the transmitted data and remains confused. In other words, after the permutation point, $|h_1|$ follows $|h_2|$ and vice versa. This permutation is more clearly illustrated in Figure 2.

Channel Tracking with Speed Estimation In Table III, an improved tracking algorithm is suggested that is based on the estimation of variation speed of H_k [6, 7]. This algorithm also detects probable crossovers by comparing $|h_{1,k|k} + h_{2,k|k}|$ with a small positive threshold $\epsilon > 0$, and if there is any crossover probability, the channel parameters are updated by using only the estimated speeds from previous iteration. This algorithm decreases the probability of the permutation phenomenon to a great extent (and also

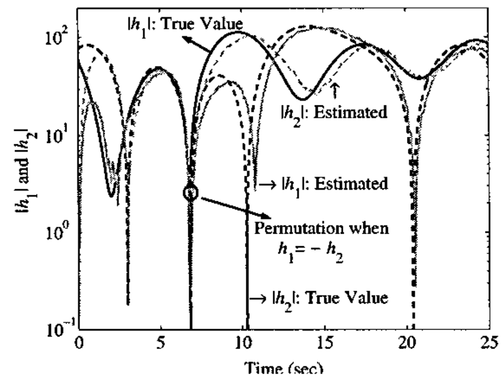

Fig. 1. Effect of permutation ambiguity on channel tracking performance. The simulation is done for SNR=5dB, 10 training pairs, when $\omega_d = 0.01$ rad/sec. In a low SNR, the algorithm is unable to continue tracking correctly beyond the crossover point.

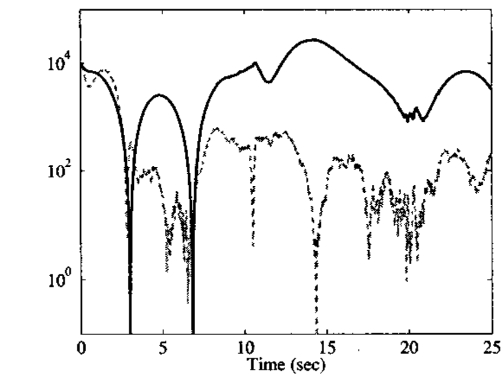

Fig. 2. Absolute value of the error between estimated channels and true channels; Solid: $\|H_k - H_{k|k}\|^2$; Dashed: $\left\|H_k^T - \left[-h_{2,k|k}, h_{1,k|k}\right]\right\|$.

enhances the performance of the channel tracking) and therefore improves the performance of the data detection. In other words, this algorithm enhances the performance not only by improving the channel tracking performance but also by decreasing the probability of occurrence of the ambiguities. Obviously, it is assumed that the channel is an smooth random process. Figure 3 illustrates the simulation results using this algorithm. Comparing Figures 3 and 1, we observe that this channel tracking algorithm resolves the occurrence of the permutation ambiguity in deep fades. As this algorithm is a second-order dynamical system with imaginary poles [6, 7], its response exhibits a second order fluctuating response. The parameter, γ, plays a role in positioning the poles of this system. As a rule of thumb, we can introduce an approximation for this value as $\gamma = \omega_d$ to guarantee a good performance, where ω_d is the maximum Doppler frequency shift in rad/sample. In this figure, the value of this parameter is set to be 0.01. Although this tracking algorithm results in significant performance improvement, the ambiguities still might occur in low SNRs in joint deep fades. This is why other solutions are required also to further reduce combat the ambiguities.

Time VArying ST (VAST) Coding Scheme In this section, we introduce a new time VArying Space-Time (VAST) Coding scheme to contest the problem for the general form of Space-Time

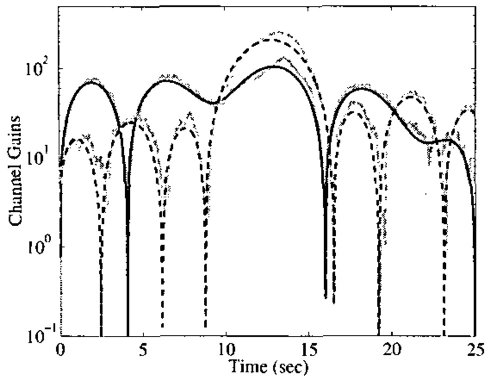

Fig. 3. Channel gains, $|h_1|$ and $|h_2|$, and their estimated values when SNR=0dB: Solid: $|h_1|$; Dashed: $|h_2|$. The simulation condition is the same as Figure 1.

AmbiguiTies (STAT). We will show that this new coding method allows to separate the spectrum of different channels coefficients by modulating them into different frequency bandwidths. This scheme is a reliable solution to the STAT problem for STCs that can be easily extended to the general case.

General From of Space-Time AmbiguiTies (STAT) Consider the received signal $R_k = S_k H_k + N_k$ 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 pair of input and the channel. To find all ambiguities for this scheme, we note that any pair of the form $(S_k W, W^{-1} H_k)$ results the same received signal. So, we call the pair $(S_k W, W^{-1} H_k)$ ambiguous with (S_k, H_k) if $S_k W$ could be generated by any other sequence taking its values from the constellation points set, *i.e.*, all STATs are solutions of $B(\mathbf{s}_k) W \in B(\mathcal{C}^M)$. It means that the structure of $S_k = B(\mathbf{s}_k)$ and $S_k W$ are the same for STATs. In brief, STATs are those transformations for which the ST code remains invariant. For example, for the QAM modulation in the case of a 2×2 ST coding matrix (Alamouti's scheme), the general form of STAT is presented by:

$$W = \begin{bmatrix} w_1 e^{j\varphi_1} & w_2 e^{j\varphi_2} \\ -w_2 e^{-j\varphi_2} & w_1 e^{-j\varphi_1} \end{bmatrix}, \tag{3}$$

where $\{w_i, \varphi_i\}_{i=1}^{2} \in \mathbb{R}$. For example for a 4QAM modulation, this general solution gives the Phase Ambiguity when, $w_1 = 1, w_2 = 0$ with $\varphi_1 \in \{\pi/2, \pi, 3\pi/2\}$. The proposed equation also gives the Permutation Ambiguity when, $w_1 = 0, w_2 = 1$ with $\varphi_2 \in \{\pi/2, \pi, 3\pi/2\}$. Hence, for a 4QAM modulation, totally there is 7 STATs 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 IV offers a new VAST coding 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 low pass signals with a given bandwidth of ω_d, this modulations allows 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 S_k at the transmitter, *i.e.*, the signal $V_k = S_k \mathrm{diag}[1, e^{j\omega_0 k}, \cdots, e^{j(M-1)\omega_0 k}]$ is transmitted instead of S_k. For example, for the DTD scheme we transmit the following time VArying Space Time (VAST) Coding scheme instead of the conventional code:

$$V_k = \begin{bmatrix} s_{1,k} & e^{j\omega_0 k} s_{2,k} \\ -s_{2,k}^* & e^{j\omega_0 k} s_{1,k}^* \end{bmatrix}. \tag{4}$$

This method is simple to implement for ST codes. For VAST scheme, $R_k = S_k \left(\mathrm{diag}[1, e^{j\omega_0 k}, \cdots, e^{j(M-1)\omega_0 k}] H_k\right) + N_k$. Obviously, the receiver can perceive this as modulating different rows of H_k, *i.e.*, $\left(\mathrm{diag}[1, e^{j\omega_0 k}, \cdots, e^{j(M-1)\omega_0 k}] H_k\right)$ represents the channel instead of H_k.

As we want to separate the spectrum of different rows of H_k in frequency domain, the rows of $\mathrm{diag}[1, e^{j\omega_0 k}, \cdots, e^{j(M-1)\omega_0 k}] H_k$ should not have overlapping bandwidth in spectrum. Therefore we should have: $2\omega_d \leqslant \omega_0$. Thus, ω_0 should fit in the below inequality

$$2\omega_d \leqslant \omega_0 \leqslant \frac{2(\pi - \omega_d)}{M}, \tag{5}$$

in which ω_d is the maximum doppler frequency in (rad/sec). In addition, the centered frequencies should be enough 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. In order to analyze the proposed TVST scheme in the case of permutation ambiguity, we rewrite the observation equation as $R_k = S_k^{\mathrm{eq}} \Psi_k H_k^{\mathrm{eq}}$. The observation equation is invariant when the pair of (S_k, H_k) maps to the pair of $(S_k^{\mathrm{eq}} = S_k W, H_k^{\mathrm{eq}} = \Psi_k^{-1} W^{-1} \Psi_k H_k)$ occurs, *i.e.*, $R_k = (S_k W)\Psi_k(\Psi_k^{-1} W^{-1} \Psi_k H_k)$. Using this approach and looking at the estimated values of H_k, if a permutation occurs, the algorithm instead tracks the permuted channel, *i.e.*, $\Psi_k^{-1} W^{-1} \Psi_k H_k$. Therefore, permuted components will be perceived bandpass signals instead of H_k that is a lowpass process unless if $W = I$. Obviously, the adaptive algorithm could only track the slow variations of $\Psi_k^{-1} W^{-1} \Psi_k H_k$. In other words, the adaptive algorithm converges rapidly to its mean; *i.e.*, zero. Consequently, the algorithm will go back automatically to the right tracking when the first true detection occurs. As an example for a DTD system and in the case of a permutation ambiguity, the algorithm tries to track H_k^{eq}, *i.e.*, $-e^{j\omega_0 k} h_{2,k}$ and $e^{-j\omega_0 k} h_{1,k}$ that is a bandpass vector.

The VAST coding can be extended for general MIMO systems. For the DTD, the detection and estimation structures will remain unchanged as long as $S_k^H S_k$ is fixed. The only change in the estimation algorithm is to replace $\widehat{S}_k$ by the new VAST code $\widehat{V}_k$ as summarized in Table IV.

Overview of STARs to Resolve Error-Propagation

- Periodic use of short training sequences.
- Using two or more different conventional ST codes at different time instances: In this approach, different ST codes are used periodically. These codes should not share any ambiguity matrices.
- Redundant ST Coding (RSTC): One may extend a code by adding redundancy to resolve the ambiguity. For example, instead of the conventional, we can use

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \\ s_1 s_2 & s_2 \end{bmatrix} \tag{6}$$

  as the coding matrix. In this method, the transmitted code provides the opportunity to correct errors, and improve the channel estimation.
- Differential ST Coding (DSTC) (*e.g.*, see [3-5] and references therein): In these schemes the information is embeded the transmitted sequence in a such a way that after decoding the effect of $e^{j\phi}$ is cancelled, usually at the expense

TABLE I. Summary of Detection Algorithm

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

TABLE II. Summary of Channel Estimation Algorithm

$$\begin{aligned} H_{k|k} &= H_{k|k-1} + \mu \Sigma_{k|k} \widehat{S}_k^H \left(R_k - \widehat{S}_k H_{k|k-1}\right), \\ \Sigma_{k|k}^{-1} &= \tfrac{1}{\sigma^2} \widehat{S}_k^H \widehat{S}_k + \Sigma_{k|k-1}^{-1}, \\ \widehat{S} &\triangleq \begin{bmatrix} \widehat{s}_{1,k} & \widehat{s}_{2,k} \\ -\widehat{s}_{2,k}^* & \widehat{s}_{1,k}^* \end{bmatrix} \text{ from Table I.} \end{aligned}$$

$$H_{k+1|k} = H_{k|k}, \quad \Sigma_{k+1|k} = \Sigma_{k|k} + \eta I.$$

of about 3dB increase in noise. Thus, these codes don't suffer from the PA which is seen in conventional ST codes.

- Enhanced Tracking Algorithms (ETA): *e.g.*, the algorithm suggested in Section III.
- Time-varying schemes: *e.g.*, the proposed VAST 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 for the trivial solution of $W = I$). Note, that free ambiguity ST codes 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 ST codes. An enhanced channel tracking algorithm is suggested to resolve the permutation ambiguities. The

TABLE III. Enhancement of Channel Tracking Algorithm for Resolution of Permutation Ambiguity

$$\begin{aligned} H_{k|k} &= H_{k|k-1} + \mu T_k \Sigma_{k|k} \widehat{S}_k^H \left(R_k - \widehat{S}_k H_{k|k-1}\right), \\ \Sigma_{k|k} &= \left(\tfrac{1}{\sigma^2} \widehat{S}_k^H \widehat{S}_k + \Sigma_{k|k-1}^{-1}\right)^{-1} + \eta I. \end{aligned}$$

Speed Estimation ($\gamma \gtrsim 0$, *e.g.*, $\gamma = 0.05$):

$$\dot{H}_k = (1-\gamma)\dot{H}_{k-1} + \gamma\left(H_{k|k} - H_{k-1|k-1}\right).$$

Prediction: $H_{k+1|k} = H_{k|k} + \dot{H}_k.$ $\Sigma_{k+1|k} = \Sigma_{k|k} + \eta I.$

Cross-Over Detection ($\epsilon > 0$ is a small, fixed threshold):

$$T_{k+1} = \begin{cases} 0, & \text{if } \left|\left[H_{k+1|k}\right]_1 + \left[H_{k+1|k}\right]_2\right| < \epsilon \\ 1, & \text{otherwise.} \end{cases}$$

TABLE IV. Summary of VAST Coding Algorithm

$$R_k = S_k H_k + N_k,$$

$$V_k \triangleq \begin{bmatrix} s_{1,k} & e^{j\omega_0 k} s_{2,k} \\ -s_{2,k}^* & e^{j\omega_0 k} s_{1,k}^* \end{bmatrix}, s_{1,k}, s_{2,k} \in = \left\{c_i \in \mathbb{C}^L\right\}_{i=1}^K,$$

$$H_k \sim \mathcal{N}(H_{k|k-1}, \Sigma_{k|k-1}), \quad N_k \sim \mathcal{N}(0, \sigma^2 I_{2L}).$$

Detection: $\widehat{V}_k = \arg\max_{c_p, c_q \in \mathcal{C}} M(C_{p,q}, R_k),$

$$\Sigma_{k|k}{}^{-1} = \alpha_{p,q} I + \Sigma_{k|k-1}^{-1},$$

$$H_{k|k} = H_{k|k-1} + \tfrac{1}{\sigma^2}\Sigma_{k|k} C_{p,q}^H \left(R_k - C_{p,q} H_{k|k-1}\right),$$

$$\alpha_{p,q} \triangleq \tfrac{\|c_p\|^2 + \|c_q\|^2}{\sigma^2} = \tfrac{|C_{p,q}|}{\sigma^2}, \quad C_{p,q} \triangleq \begin{bmatrix} c_p & e^{j\omega_0 k} c_q \\ -c_q^* & e^{j\omega_0 k} c_p^* \end{bmatrix}.$$

Prediction: $H_{k+1|k} = H_{k|k},$ $\Sigma_{k+1|k} = \Sigma_{k|k} + \eta I.$

algorithm estimates the speed of the channel variations and identifies deep fades and probable crossovers. In critical cases, the channel is updated using previously estimated speeds and during critical periods, very noisy received signals are not used for channel adaptation. By this way, the channel estimator is enhanced and also is prevented to track wrong trajectories; therefore, the error propagation is prevented to a great extent.

The VAST scheme is proposed as a major remedy for the problem of ambiguities. Using the VAST, the tracking algorithm automatically tracks the true channel if the channel is a low-pass random process.

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