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Adaptive Kalman Receiver for OFDM Systems with Transmit Diversity in Mobile Wireless Channels*

Abstract
A new joint channel tracking and symbol detection scheme is proposed in this paper for pilot symbol assisted transmit diversity OFDM systems by exploiting the correlation of the adjacent subchannels. Modelling the channel frequency response of every subcarrier corresponding to each transmit antenna as random processes, we employ Kalman filters for both channel tracking and subsequent decoding with diversity gain. Among different stochastic models, the AR model is adopted herein for channel dynamics. Since the proposed adaptive receiver uses two Kalman filters to track the variations of the channel and subsequently to detect the information symbols, they are combined in the coupled receiver structure. Finally the performance of the proposed method is studied through experimental results.

By Adnan Sen[1],
Hakan A. Cirpan[2],
and Erdal Panayirci[1]

Index Terms
OFDM, Kalman filter, channel tracking, diversity

1. Introduction

The dramatic growth of broadband services usage is strengthening demands for the collocation of high-data rate and high quality digital transmission over the wireless medium. In order to satisfy the high-data rate demand and efficiently support high quality wireless services, the modulation and coding must be much more spectrally efficient and flexible than those used in current mobile systems, with greater immunity against severe frequency selective fading.

Holding great promise to use the frequency resources as efficiently as possible, OFDM is a strong candidate to provide substantial capacity enhancement for future wireless systems [1, 2]. OFDM is therefore currently being adopted and tested for many standards, including terrestrial digital broadcasting (DAB and DVB) in Europe, and high speed modems over Digital Subscriber Lines in the US. It has also been implemented for broadband indoor wireless systems including IEEE802.11a, MMAC and HIPERLAN/2. In OFDM, the entire signal bandwidth is divided into a number of narrow bands or orthogonal subcarriers, and the signal is transmitted in the narrow bands in parallel. Therefore, it reduces intersymbol interference (ISI) and obviates the need for complex equalization thus greatly simplifies the channel estimation/equalization task [2, 3, 4]. Moreover, its structure also allows efficient hardware implementations using the fast Fourier transform (FFT) and polyphase filtering [1].

On the other hand, the dispersive property of the wireless channel causes deep fades for those subchannels. Hence, diversity techniques have to be used to compensate for the frequency selectivity. Transmitter diversity is an effective technique for combatting fading in mobile wireless channels. More recently, transmit diversity using space-time coding (STC) has been developed for high data-rate wireless communications [5]. However, for systems with transmit diversity, the received signal is a superposition of the different transmitted signals from all transmit antennas and consequently, channel estimation becomes more complicated.Sophisticated parameter estimation approaches are therefore required for transmit diversity systems. Fortunately, the combined application of OFDM modulation and transmit diversity with space-time coding allows us to avoid the complexity of channel estimation/equalization and therefore yields a unique reduced-complexity physical layer capabilities [6].

This paper focuses on the important issue of joint channel tracking and decoding in the STOFDM transmitter diversity setting. We propose an adaptive Kalman receiver for both channel tracking and subsequent equalization which are combined in the coupled estimator structure. The stochastic approach has been used to describe channel's variations in a general vector AR framework. Fortunately, the AR modelling lends itself to a state-space representation that enables the application of Kalman filtering for tracking channel variations. We therefore propose Kalman filtering to derive minimum variance estimators for fading coefficients yielding an adaptive channel tracking algorithm. However, this requires the knowledge of the transmitted symbols. This implies that an iterative method should be sought to obtain alternatively either channel or transmitted symbols. To complete the detection-tracking algorithm for transmit diversity OFDM systems with the distributed training, a linear Kalman filter equalization technique [10] is therefore proposed for the detection of transmitted symbols.

The rest of the paper is organized as follows. In Section 2, Alamouti's transmit diversity scheme for OFDM systems is described and received signal model is presented. In Section 3, multipath channel statistical characterization is explained. Section 4 first associates modeling of the fading channel taps with an AR process and then gives Kalman-based channel tracking and symbol detection algorithms. In Section 5, the proposed Kalman based receiver structure is briefly discussed. Finally, we present some numerical examples that illustrate the performance of the proposed Kalman-based receiver in Section 6 and conclusions are drawn in Section 7.

2. Alamouti's Transmit Diversity Scheme for OFDM Systems

In this paper, we consider OFDM systems with transmitter diversity using a space-time block coded transmit diversity scheme first proposed by Alamouti [8]. The Alamouti's scheme can be generalized for OFDM systems as follows. At each time slot n, the data symbols, $a_l(n; k)$ $l = 1, 2$ $k = 0, 1, ..., N-1$ modulated by the k'th subcarrier(tone) during the OFDM symbol time, are simultaneously transmitted from the two antennas $l = 1, 2$. They are assumed to have unit variance and be independent for different k's and n's. Since the phase of each subchannel can be obtained by the channel estimator, coherent phase-shift keying(PSK) modulation is used here to enhance the system performance. The wireless channel is assumed to be quasi-static so that path gains are constant over a frame of L_{frame} and vary from one frame to another. The channel frequency response for the k'th tone corresponding to the l'th transmitter antenna and the receiver antenna is defined by channel attenuations $H_l(k)$ $l = 1, 2$ $k = 0, 1, ..., N-1$. They are correlated samples, in frequency, of a complex Gaussian process. For the k'th tone, Alamouti's encoding scheme maps

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1 Department of Electronics Engineering, ISIK University, Istanbul, Turkey
2 Department of Electrical Engineering, Istanbul University, Istanbul, Turkey

every consecutive symbol $a(2n, k)$ and $a(2n + 1, k)$ to the following 2×2 matrix:

$$\begin{array}{c} \quad space \rightarrow \\ time \downarrow \begin{bmatrix} a(2n,k) & a(2n+1,k) \\ -a^*(2n+1,k) & a^*(2n,k) \end{bmatrix} \end{array} \tag{1}$$

whose rows are transmitted in successive time intervals with the first and second symbol in a given row sent simultaneously through the first and second antenna respectively. $(.)^*$ denotes conjugation. Since the Alamouti's two branch transmit diversity scheme with one receiver is employed here, for $n = 0, 1, 2, ..., L_{frame}/2 - 1$, ($L_{frame}$ is even integer), under the assumption that fading is constant across two consecutive symbols, we can write each pair of the two consecutive received signals as:

$$\begin{aligned} y(2n,k) &= a(2n,k)H_1(k)+a(2n+1,k)H_2(k)+v(2n,k) \\ y(2n+1,k) &= -a^*(2n+1,k)H_1(k)+a^*(2n,k)H_2(k)+v(2n+1,k) \end{aligned} \tag{2}$$

where $v(2n, k)$ and $v(2n + 1, k)$ are independent samples of an additive Gaussian noise with variance σ^2 representing the additive white Gaussian noise entering the system.

Equation (2) shows that the information symbols $a(2n)$ and $a(2n + 1)$ are transmitted twice in two consecutive time intervals through two different channels. Without imposing any structure on Hi(k), i = 1; 2, to recover $a(2n)$ from the received data $y(2n, k)$ with transmit diversity gain is an ill-posed problem. Since for every two incoming received samples, two extra unknowns $H_1(k)$ and $H_2(k)$ appear in addition to the unknown symbols $a(2n)$ and $a(2n + 1)$. Fortunately, many wireless channels exhibit structured variations and hence fit into some frequency evolution model. Among different models, the AR model is adopted herein for channel dynamics. In this paper, we then apply alternatively Kalman filtering to acquire the channel and decode the information symbols with diversity gains.

3. Channel Characteristics

The impulse response of the mobile wireless channel can be described as [2]

$$h(t,\tau)=\sum_m \gamma_m(t)\delta(\tau-\tau_m) \tag{3}$$

where τ_m is the delay of the m'th path, γ_m is the corresponding complex gain, $\delta(\tau)$ is the Dirac Delta function, and the index i is omitted for simplicity. The frequency response at time t is then

$$H(t,f)\overset{\Delta}{=}\int_{-\infty}^{+\infty} h(t,\tau)e^{-j2\pi f\tau}d\tau=\sum_m \gamma_m(t)e^{-j2\pi f\tau_m} \tag{4}$$

The path gains $\gamma_m(t)$ are modelled as independent wide-sense stationary narrowband complex Gaussian processes due to the motion of the vehicle with the time domain correlation defined by the Doppler spectrum. Furthermore, the frequency domain correlation of the channel is defined by the channel power delay profile $\theta(\tau_l)$. Hence, the channel frequency response can be expressed with tolerable leakage as

$$H(n,k)\overset{\Delta}{=}H(nT_s,k\Delta f) \tag{5}$$

where T_s is the total OFDM symbol interval and Δf is the tone spacing of the OFDM system.

Since we investigate channel estimation for transmitter diversity OFDM systems by exploiting only the corresponding correlation of the adjacent subchannel responses in this paper, we now briefly describe the correlation function of the subchannel responses:

$$r(f,f')=E\left[H(f)H^*(f')\right]. \tag{6}$$

For an OFDM system with tone spacing Δf, the discrete correlation function for different tones can then be written as

$$r_f(m)=E\{H(k)H^*(k+m)\}. \tag{7}$$

A more frequently used channel model could be explicitly derived by using an exponentially decaying power delay profile $\theta(\tau_l) = Ce^{-\tau_l/\tau_{rms}}$ and special delays τ_l that are uniformly and independently distributed over the length of CP. In [2], it is shown that the normalized exponential discrete channel correlation for different subcarriers is

$$r_f(m)=\frac{1-\exp\left(-L\left(1/\tau_{rms}+2\pi jm/N\right)\right)}{\tau_{rms}\left(1-\exp\left(-L/\tau_{rms}\right)\right)\left(1/\tau_{rms}+2\pi jm/N\right)}. \tag{8}$$

Furthermore, the uniform channel correlation between the attenuations $h(k)$ and $h(m)$ can be obtained by letting $\tau_{rms} \to \infty$ in (8), resulting in

$$r_f(m)=\frac{1-\exp\left(2\pi jLm/N\right)}{2\pi jk/N}. \tag{9}$$

Note that the correlation function of the channel taps for different frequencies depends, in general, only on the multipath delay spread and is separated from the effect of Doppler frequency. By exploiting the frequency correlation in the channel estimation task, we attempt to find a reduced complexity channel estimator for transmitting by diversity OFDM systems.

4. Channel Estimation and Equalization

In this paper the algorithm to be used to estimate the variations of the channel and to decode the information symbols is based on the Kalman recursive state estimation algorithm. The Kalman filter is a useful algorithm when the state-space model used matches closely the variations of the parameter to be estimated. To build a channel model for the multipath fading channel, we match the spectral characteristics of the multipath fading with an AR process.

4.1 Channel Estimation

To parametrize variations of a wireless channel adequately, only the first few correlation terms are important. Therefore low-order AR models or even a simple Markov model can capture most of the channel tap dynamics [7, 9]. So, as in common practice we model channel's variations as a random process and use an AR model, order p, to model its variations.

4.1.1 AR Model considerations

We approximate the fading effect in transmit diversity OFDM system with a general AR process order p with a *priori* known structure,

$$H_i(k)=-\sum_{j=1}^{p} c_{i,j}H_i(k-j)+w_i(k) \tag{10}$$

where $k = 0, 1,...,N - 1$; $i = 1, 2$ and $H_i(k)$ is the multiplicative multipath fading effect on the signal transmitted from the i'th transmitter antenna, $w_i(k)$ is a random, additive white Gaussian noise and c_{ij} is the j'th AR coefficient. The coefficients c_{ij} are closely related physical parameters of the underlying fading process and can be acquired solving the following Yule-Walker equations:

$$r_f(m)=\begin{cases}-\sum_{j=1}^{p} c_{i,j} r_f(m-j) & m\geq 1 \\ -\sum_{i=j}^{p} c_{i,j} r_f(-j)+\sigma_w^2 & m=0\end{cases}. \tag{11}$$

Once the AR coefficients are calculated, Kalman filter idea may be employed to track the channel variations. Since a Kalman filter would require a state-space representation of the channel, we will now formulate the state-space representation of fading channel based on AR model parameters.

4.1.2 State-space representation

When a Kalman filter is used for estimating a process, the model which describes the dynamics of the process and the observation is formed using the state-space representation. If we define

$$\mathrm{H}_i(k)=\left[H_i(k),H_i(k-1),\ldots,H_i(k-p)\right]^T,$$

and

$$\mathrm{H}(k)=\left[H_1^T(k),H_2^T(k)\right]^T,$$

then (11) can be written in state-space form

$$\mathrm{H}(k)=\begin{bmatrix}\bar{\mathrm{F}}_1 & 0_{pxp} \\ 0_{pxp} & \bar{\mathrm{F}}_2\end{bmatrix}\mathrm{H}(k-1)+\mathrm{Bw}(k) \tag{12}$$

where

$$\bar{\mathrm{F}}_i=\begin{bmatrix}-c_{i,1} & -c_{i,2} & \cdots & -c_{i,p} \\ 1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ 0 & 0 & 1 & 0\end{bmatrix}, \quad \mathrm{w}(k)=\begin{bmatrix}w_1(k) \\ w_2(k)\end{bmatrix} \tag{13}$$

B is a $(2px2)$ dimensional matrix and $\mathbf{B}(1,1)=\mathbf{B}(p+1,2)=1$, other elements are zero. $w_1(k)$ and $w_2(k)$ are mutually independent zero mean Gaussian noises and $\mathbf{w}(k)$ has the covariance matrix **Q**.

In order to obtain the measurement equation, define.

$$\tilde{\mathrm{a}}_1(k)=\left[a(2n,k),-a^*(2n+1,k)\right]^T,$$
$$\tilde{\mathrm{a}}_2(k)=\left[a(2n+1,k),a^*(2n,k)\right]^T,$$
$$\mathrm{A}(k)=\left[\tilde{\mathrm{a}}_1(k),\,0_{2x(p-1)},\tilde{\mathrm{a}}_2(k),0_{2x(p-1)}\right]_{2x2p}$$

Then equation (2) can be written as

$$\mathrm{y}(k)=\mathrm{A}(k)\mathrm{H}(k)+\mathrm{v}(k) \tag{14}$$

where $y(k)=[y(2n,k),y(2n+1,k)]^T v(k)=[v(2n,k),v(2n+1,k)]^T$. We also assume that $v(2n,k)$ and $v(2n+1,k)$ are zero mean Gaussian measurement noises and the covariance of $\mathbf{v}(k)$ is **C**.

Equations (12) and (14) offer a state-space representation of the multiplicative multipath fading model with transition matrix **F** which is assumed to be known in this section. Based on this representation, the algorithm for mean square estimation of the state vector, i.e., the conditional expectation of **H(k)** given $\{A(k),y(k)\}_{k=0}^{N-1}$ can be computed from Kalman filtering. The recursions are summarized in **Table 1**.

Table 1: Kalman-Based channel tracking algorithm

Initialization	$\mathbf{H}(0\|-1)=\mathbf{0},\ \mathbf{S}(0\|-1)=\mathbf{0}$
Ricati Equations	$\mathbf{S}(k\|k-1)=\mathbf{FS}(k-1\|k-1)\mathbf{F}^T+\mathbf{BQB}^T$ $\mathbf{K}(k)=\mathbf{S}(k\|k-1)\mathbf{A}^T(k)(\mathbf{C}+\mathbf{AS}(k\|k-1)\mathbf{A}^T)^{-1}$ $\mathbf{S}(k\|k)=(\mathbf{I}-\mathbf{K}(k)\mathbf{A}(k))\mathbf{S}(k\|k-1)$
State Estimation Update	$\hat{\mathbf{H}}(k\|k-1)=\mathbf{F}\hat{\mathbf{H}}(k-1\|k-1)$ $\hat{\mathbf{H}}(k\|k)=\hat{\mathbf{H}}(k\|k-1)+\mathbf{K}(k)(\mathbf{y}(k)-\mathbf{A}(k)\hat{\mathbf{H}}(k\|k-1)$

Matrices $\mathbf{K}(k)$ and $\mathbf{S}(k|k)$ denote the Kalman filter gain and covariance of the state vector $\mathbf{H}(k|k)$ respectively.

4.2 Adaptive Kalman Equalization

The Kalman based adaptive channel estimation algorithm have to be coupled with an equalization technique in order to eventually compose a receiver. In this paper, we adopt an adaptive Kalman equalizer which was originally developed for FIR channel [10]. Therefore, we first summarize the adaptive Kalman equalizer in this section. If we assume an FIR channel model, the elements of the state vector would be the inputs to the channel i.e.,

$$\mathrm{a}_e(k)=\left[a(k),a(k-1),\ldots,a(k-d)\right]^T \tag{15}$$

where $(d+1)$ is the number of taps of the channel. Then the state equation becomes

$$\mathrm{a}_e(k)=\mathrm{F}_e\mathrm{a}_e(k-1)+ga(k) \tag{16}$$

where **Fe** is the $(d+1)\mathrm{x}(d+1)$ shift matrix, i.e,

$$\mathrm{F}_e=\begin{bmatrix}0 & 0 & \cdots & \cdots & 0 \\ 1 & 0 & \cdots & \cdots & 0 \\ 0 & 1 & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & 1 & 0\end{bmatrix}$$

and **g** is a vector with $(d+1)$ elements, $\mathbf{g}=[1,0,\ldots,0]^T$. Then the observation equation is

$$y(k)=\mathrm{a}_e^T(k)\mathrm{h}_e(k)+v(k) \tag{17}$$

where $h_e(k)=[h(k),h(k-1),\ldots,h(k-d)]^T$ is a vector with channel taps. Based on the state-space representation for FIR channel, adaptive Kalman equalizer recursions are summarized in [10].

The state-space equations (16) and (17) for adaptive Kalman equalizer can now be adopted to transmit diversity OFDM systems in a very simple form since OFDM overcomes ISI arising from channel memory and introduces just random atenuations on each tone. Thus, the state-space equations for transmit diversity OFDM systems becomes

$$\begin{aligned}\mathrm{a}_e(k)&=f\mathrm{a}_e(k-1)+\mathrm{a}_e(k) \\ \mathrm{y}_e(k)&=\hat{H}(k)\mathrm{a}_e(k)+\mathrm{v}(k)\end{aligned} \tag{18}$$

where f $(f=0)$ in (18) superficially introduced parameter in order to put (18) in a form given by (16),

$$\mathbf{a}_e(k)=\left[a(2n,k),a(2n+1,k)^T\right],$$
$$\mathbf{y}_e(k)=\left[y(2n,k),y^*(2n+1,k)\right]^T,$$
$$\mathbf{v}(k)=\left[v(2n,k),v(2n+1,k)\right]^T$$

measurement noise vector, which has mutually independent zero mean Gaussian noise components with covariance $\mathbf{C}e$, and finally

$$\breve{\mathrm{H}}(k)=\begin{bmatrix} h_1(k) & h_2(k) \\ h_2^* & -h_1^*(k) \end{bmatrix}. \tag{19}$$

Recursions of the the Kalman equalizer is summarized in **Table 2.**

Table 2: Adaptive Kalman Equalizer

Initialization	$a(1, 0)$, $a(2, 0)$ = Known pilot symbols
Ricati Equations	$\mathbf{S}_e(k\|k-1)=\mathbf{I}$ $\mathbf{K}_e(k)=\mathbf{S}_e(k\|k-1)\breve{H}^T(k)/\mathbf{C}_e+\breve{H}(k)\text{-}\mathbf{S}_e(k\|k-1)\breve{H}^T(k)$ $\mathbf{S}_e(k\|k)=(\mathbf{I}-\mathbf{K}_e)\mathbf{S}_e(k\|k-1)$
State Estimation Update	$\hat{\mathbf{a}}(k\|k-1)=\mathbf{K}_e(k)\mathbf{y}_e(k)$

In Table 2, $\mathbf{K}_e(k)$ is the Kalman gain, $\mathbf{S}_e(k|k)$ and covariance of the estimated state vector respectively.

5. Receiver Structure

The proposed receiver uses two Kalman filters to estimate the variations of the channel and subsequently to detect the information symbols. The Kalman filters are combined in the proposed estimator structure. Note that, when a faded, noisy signal received by the receiver both transmitted symbols $\mathbf{a}_e(k)$ and the channel's effect $\mathbf{H}(k)$ are unknown. With the knowledge of $a(2n, 0)$ and $a(2n+1, 0)$ and the observations $y(2n, 0)$ and $y(2n+1, 0)$, $\hat{\mathbf{H}}(0)$ can be obtained using Kalman recursions in Table 1. However, the detection of $\mathbf{a}_e(k)$, $k = 1, 2, ..., N-1$ relies on the estimates of $\mathbf{H}(k)$, $k = 1, 2, ..., N-1$ that in turn require the knowledge of $\mathbf{a}_e(k)$, $k = 1, 2, ..., N-1$. Therefore an iterative algorithm is employed in the proposed receiver to obtain alternatively either $\mathbf{a}_e(k)$ or $\mathbf{H}(k)$. According to this algorithm a coarse prediction of $\mathbf{H}(k|k-1)$ is obtained from the Table 1. i.e.

$$\hat{\mathrm{H}}\left(k\middle|k-1\right)=\mathrm{F}\hat{\mathrm{H}}\left(k-1\middle|k-1\right) \tag{20}$$

that is initialized by $\mathbf{H}(0|-1)$. Next, we use the coarse channel estimates in the adaptive Kalman equalizer to obtain coarse symbol estimates for $\hat{\mathbf{a}}_e(k)$ that are denoted by $\mathbf{a}_e^c(k)$. Subsequently these estimates are transformed into $\mathbf{a}_e^r(k)$ using the nearest neighbor criterion with a slicer. Next we use $\hat{\mathbf{a}}_e^r(k)$ to form $\mathbf{A}(k)$ and rely on the Kalman filter to obtain refined channel estimates $\hat{\mathbf{H}}(k|k)$. Thus we summarize our algorithm for channel tracking and symbol detection, in the following steps:

Initialization: Obtain $\mathbf{H}(0|0)$ using pilot symbols;
1. Obtain $\hat{\mathbf{H}}(k|k-1)$ using Table 1;
2. Use Kalman equalizer to decode $\mathbf{a}_e^c(k)$;
3. Use slicer to obtain $\hat{\mathbf{a}}_e^r(k)$ from $\mathbf{a}_e^c(k)$;
4. Perform Kalman channel estimation to retrieve $\hat{\mathbf{H}}(k|k)$ using $\hat{\mathbf{a}}_e^r(k)$;
5. Repeat steps 1 - 4 for $k \rightarrow k+1$.

Next, we test the performance of our joint channel tracker and equalizer through simulation.

6. Simulations

We now present the simulation results for the tracking of channel taps and decoding transmitted symbols in OFDM systems with Kalman filtering. We consider the scheme with 2 transmit and 1 receive antennas with the fading multipath channels between the transmitter and the receiver. The channels $H_l(k)$ have an exponentially decaying power delay profile and delays τ_l that are uniformly and independently distributed over the length of the cyclic prefix.

The scenario for our simulation study consists of a wireless QPSK, OFDM system employing the pulse shape as a unit-energy Nyquist-root raised-cosine shape with rolloff $\alpha = 0.2$ with a symbol period (Ts) of 0.167 µs. The transmission bandwidth (3.6MHz) is divided N = 256 tones. We assume that the multipath channel models consists of 5 impulses with uniformly spaced intervals of duration (Ts). Therefore the maximum channel delay is τ_{max} = 4 sample (0.668 µs).

Since the first order process provides a sufficiently accurate model for multipath fading channels, an AR(1) process is adopted in the development of state-space description. Of course computational complexity will increase as AR order increases. QPSK-OFDM sequence passes through channel taps and corrupted by AWGN. We use 2 pilot symbols for every 26 subcarrier in an OFDM symbol.

Finally, we wish to illustrate the performance of the proposed algorithms by plotting the tracking performance and symbol-error-rate results. In **Figure 1** and **2**, channel tracking performance for SNR = 10 dB and 20 dB are illustrated, respectively. In this figure the solid linesrepresents the true channel taps and the dashed lines represents the estimated taps. Moreover, SER performance of the proposed receiver is illustrated in **Figure 3**.

7. Conclusions

In this paper we have developed a novel Kalman filter based scheme for joint iterative channel tracking and symbol recovery of pilot symbol assisted transmit diversity OFDM systems in multipath fading channels. Modelling the multipath fading channel

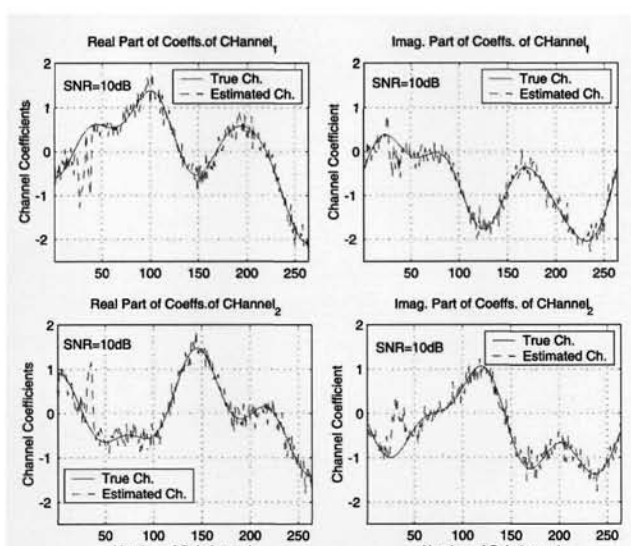

Fig. 1: Channel Tracking (SNR = 10 dB)

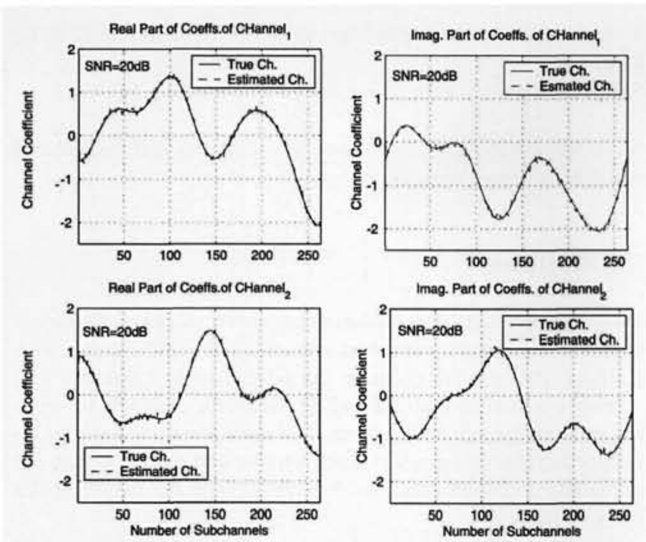

Fig. 2: Channel Tracking (SNR = 20 dB)

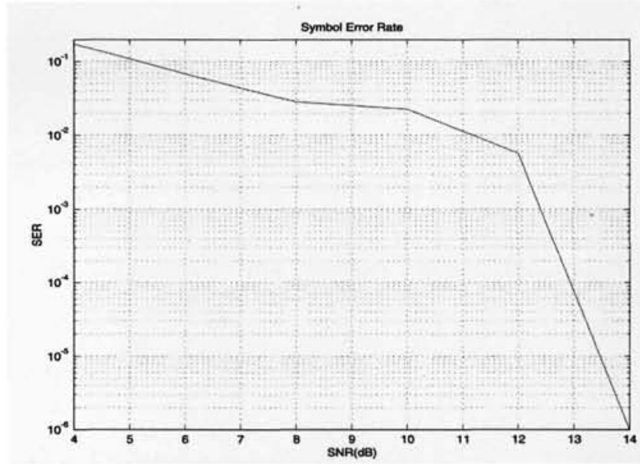

Fig. 3: Symbol Error Rate Performance

as AR processes, a Kalman filter was employed to track the variations of the channel. Moreover, to compose the joint iterative estimator structure, a linear Kalman filter equalizer with the corresponding state-space model was proposed for the recovery of the transmitted symbols. Although the adaptive Kalman equalizer does not yield minimum variance estimates, its structure is very simple. The simulation results show that the resulting algorithm is efficient and can be effectively employed in such applications. Future topics include blind estimation of the AR parameters.

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Adnan Sen
Erdal Panayirci
Department of Electronics Enginering
ISIK University
Maslak 80670, Istanbul
Turkey
e-mail: eepanay@isikun.edu.tr

Hakan A. Cirpan
Department of Electrical Engineering
Istanbul University
Avcilar, 34850 Istanbul
Turkey
fax: +90 (212) 4 73 70 64
e-mail: hcirpan@istanbul.edu.tr

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