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JOINT CHANNEL TRACKING AND SYMBOL DETECTION IN MIMO SYSTEMS VIA MULTIPLE MODEL METHODS

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ABSTRACT

We propose a new semi-blind joint channel tracking and symbol detection for spatial multiplexing MIMO system. The proposed algorithm is based on the Generalized Pseudo Bayesian algorithm (GPB) and Probability Data Association (PDA). The purpose of the GPB algorithm is to control the size of the filtering tree and the Gaussian approximation idea behind PDA is applied to each time instant to reduce the model size. Simulation results are given to demonstrate the effectiveness of the new algorithm.

1. INTRODUCTION

Accurate knowledge of the channel state information (CSI) plays a key role in the detection of the symbols in MIMO systems. The conventional training-based approaches transmit time-multiplexed training sequences and information sequence periodically in one block. The channel state is estimated from the training sequence which is known to the receiver and is used for the symbol detection of the information symbol sequence. The periodical transmission of training sequence incurs a loss in spectral efficiency. An alternative is a semi-blind approach where the training sequence is only sent at the beginning of each transmit block. The initial channel state is estimated from the training sequence and then joint channel tracking and symbol detection is performed for the information sequence.

There are two uncertainties in the joint channel tracking and symbol detection problem. One is the channel state uncertainty which is a time varying continuous random process. Another is the observation model (transmit symbol vector) uncertainty which is a discrete random value.

Conventional non-iterative solutions follow a decision based estimation strategy, i.e. perform symbol detection first and then run a single filter to estimate the channels based on the hard/soft output of the symbols. The drawback of this kind of methods is that possible symbol detection errors are not fully accounted for in the channel estimation.

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A similar problem has been perceived and widely explored in maneuver target tracking field [1] which is called there a hybrid estimation problem.

The MMSE-optimal solution for such hybrid estimation can be obtained by Bayesian full-hypothesis-tree (FHT) [1]. However, the FHT solution is infeasible because of its exponentially growing computation and memory with time [1]. Suppose the MIMO system has N_T transmit antennas and a modulation symbol alphabet with N symbols. FHT will operate $(N_T)^{Nk}$ filtering models in parallel at kth time instant.

Many suboptimal approaches have been proposed to control the size of the exponentially growing filtering tree and a recent detailed review is given in [2]. Amongst most prominent algorithms are:

1. Merging/Collapsing based algorithms, which refers to Multiple Model approach, including Generalized Pseudo Bayesian (GPB) algorithm [3][1] and Interacting Multiple Model algorithm [4]. Multiple Model approach aim to provide state estimation (channel estimation) and parameter identification (symbol detection) simultaneously.

2. Pruning/Selection based algorithms, such as Multiple Hypothesis Tracking [1] and Viterbi algorithm,

3. Iterative based algorithms via Expectation Maximization [5] or Sequential Monte Carlo Methods [6].

The iterative based solutions have been widely applied to the joint channel tracking and symbol detection problem of wireless communication systems[7]. However, such algorithms always require many iterations to converge and then the computation cost is typically higher than that of on-line type Multiple Model method.

Multiple Model methods has been presented for blind multiuser detection in MIMO system with Alamouti encoding in [8].

In this paper, we will use a first order GPB (GPB1) algorithm to the joint channel tracking and symbol detection problem for spatial multiplexing MIMO system. GPB1 operates $(N_T)^N$ filtering models parallel and combines the filtering results from those models at each time instant by a soft decision. Furthermore, Gaussian approximation (aka Probability Data Association (PDA) [1] [9]) are introduced to additionally reduce the number of the filtering models from $(N_T)^N$ to $N \times N_T$ at each time instant.

The paper is organized as follows. Section 2 describes the system model. Section 3 presents a decision based estimation algorithm via PDA and Kalman filter (PDAKal). PDAKal algorithm is originally proposed for Multiuser detection for asynchronous CDMA with imperfect CSI [10]. Here we present it for joint channel tracking and symbol detection for MIMO system, i.e., perform symbol detection via PDA considering the channel uncertainty first and then run a single Kalman filter to estimate the channels based on the soft output of the symbols, which is decision based estimation algorithm. Section 4 will give the joint channel tracking and symbol detection algorithm based on the PDA and Multiple Model algorithm (PDAMM). Section 5 compares the performance of PDAMM and PDAKal algorithm via Monte Carlo simulation. We conclude the paper in section 6.

2. SYSTEM MODEL

Consider a spatial multiplexing MIMO system with N_T transmit antennas and N_R receive antennas. The channel is assumed to be time selective. At each time instant k, the system model will be:

$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{x}(k) + \mathbf{n}(k) \quad (1)$$

where $\mathbf{H}(k)$ is the $N_R \times N_T$ Rayleigh flat fading channel matrix with $h_{ij}(k)$ as its (i,j)th entry, which is the channel gain from transmit i to receive antenna j; $i = 1, \ldots, N_R$ and $j = 1, \ldots, N_T$; N_T symbols $\mathbf{x(k)} \equiv [x_1(k), \ldots, x_{N_T}(k)]^T$ ($[*]^T$ means transpose), taken from a modulation constellation $A = \{a_1, a_2, \ldots, a_N\}$, are transmitted from each antenna; $\mathbf{n}(k)$ is a $N_R \times 1$ zero-mean complex circular symmetric Gaussian noise with covariance matrix $\sigma_n^2\mathbf{I}$ ($\mathbf{I}$ is the identity matrix).

The first order AR model is widely used for modeling the time selective fading channels [11] and it will be adopted:

$$h_{ij}(k) = \alpha h_{ij}(k-1) + v_{ij}(k) \quad (2)$$

where the noise $v_{ij}(k)$ is zero-mean complex circular symmetric Gaussian noise with covariance σ_v^2.

3. DECISION BASED ESTIMATION ALGORITHM VIA PDA-KALMAN

First rewrite Eq.(1) as follows:

$$\mathbf{y}(k) = \mathbf{h}_j(k)x_j(k) + \sum_{l=1, l\neq j}^{N_T} \mathbf{h}_l(k)x_l(k) + \mathbf{n}(k) \quad (3)$$

where $\mathbf{h}_j(k)$ is the jth column of $\mathbf{H}$. The interference noise term $\mathbf{N}_j(k) \equiv \sum_{l\neq j} \mathbf{h}_l(k)x_l(k) + \mathbf{n}(k)$ is approximated as Gaussian distribution according to [9].

Suppose we have got the channel estimation $\hat{\mathbf{h}}_j(k-1|k-1)$ and covariance matrix $\mathbf{P}_j(k-1|k-1)$ at time instant $k-1$, the predictions at time instant k will be:

$$\hat{\mathbf{h}}_j(k|k-1) = \alpha\hat{\mathbf{h}}_j(k-1|k-1); \quad (4)$$

$$\mathbf{P}_j(k|k-1) = \alpha^2\mathbf{P}_j(k-1|k-1) + \sigma_v^2\mathbf{I}; \quad (5)$$

The symbol probability of antenna j will be computed as follows:

$$\begin{aligned} &\hat{p}(x_j(k)|\mathbf{Y}_1^k) = \phi_j^s(k)/\sum_s \phi_j^s(k) \\ &\phi_j^s(k) = \exp\Big(-\big(\mathbf{W}_j^s(k)\big)^H \big(\mathbf{\Gamma}_j^s(k)\big)^{-1}\mathbf{W}_j^s(k)\Big) \\ &p(x_j(k))/\left|\det(\mathbf{\Gamma}_j^s(\mathrm{k}))\right| \end{aligned} \quad (6)$$

where $\mathbf{W}_j^s(k)$ and $\mathbf{\Gamma}_j^s(k)$ are given by:

$$\mathbf{W}_j^s(k) = \mathbf{y}(k) - \hat{\mathbf{h}}_j(k|k-1)a_s - \sum_{l\neq j}\hat{\mathbf{h}}_l(k|k-1)\bar{x}_l(k) \quad (7)$$

$$\begin{aligned} \mathbf{\Gamma}_j^s(k) = {} & ||a_s||^2\mathbf{P}_j(k|k-1) + \sigma_n^2\mathbf{I} + \sum_{l\neq j}\Big(\gamma_l(k)\hat{\mathbf{h}}_l(k|k-1) \\ & \hat{\mathbf{h}}_l^H(k|k-1) + \big(\bar{x}_l(k)^2 + \gamma_l(k)\big)\mathbf{P}_l(k|k-1)\Big) \end{aligned} \quad (8)$$

where $\bar{x}_l(k)$ and $\gamma_l(k)$ are the mean and variance of estimates of symbol probability $\hat{p}(x_l(k)|\mathbf{Y}_1^k)$ of antenna l:

$$\begin{aligned} \bar{x}_l(k) &= \sum_{s=1}^{N} a_s\hat{p}(x_l(k)|\mathbf{Y}_1^k) \\ \gamma_l(k) &= \sum_{s=1}^{N}\big(a_s - \bar{x}_l(k)\big)^2\hat{p}(x_l(k)|\mathbf{Y}_1^k) \end{aligned} \quad (9)$$

where $\mathbf{Y}_1^k$ are all the observations up to time k.

Then a soft decision of symbols of antenna j $\bar{x}_j(k)$ will be calculated via Eq.(9) and used for channel tracking via Kalman filter:

$$\hat{\mathbf{h}}_j(k|k) = \hat{\mathbf{h}}_j(k|k-1) + \bar{\mathbf{K}}_j(k)\bar{\mathbf{W}}_j(k) \quad (10)$$

$$\mathbf{P}_j(k|k) = \mathbf{P}_j(k|k-1) - \bar{\mathbf{K}}_j(k)\bar{\mathbf{\Gamma}}_j(k)\bar{\mathbf{K}}_j^H(k) \quad (11)$$

$$\bar{\mathbf{K}}_j(k) = \mathbf{P}_j(k|k-1)\bar{x}_j^H(k)\bar{\mathbf{\Gamma}}_j(k)^{-1} \quad (12)$$

where $\bar{\mathbf{\Gamma}}_j(k)$ and $\bar{\mathbf{W}}_j(k)$ are computed via Eq.(7)-(8) with a_s replaced with $\bar{x}_j(k)$.

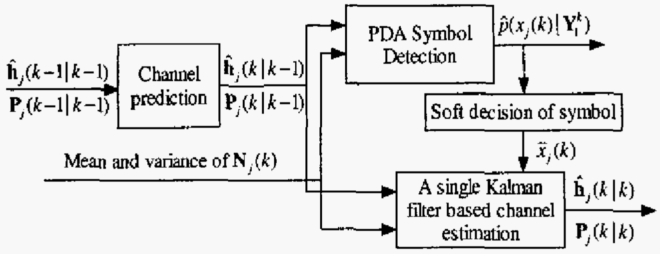

Fig. 1. Illustration of PDAKal algorithm for antenna j.

The above process of computing symbol probability and channel estimations related to antenna j is illustrated in Fig.1. The mean of $\mathbf{N}_j(k)$ is $\sum_{l\neq j}\hat{\mathbf{h}}_l(k-1|k)\bar{x}_l(k)$ in Eq.(7) and its variance is $\sigma_n^2\mathbf{I}+\sum_{l\neq j}\Big(\gamma_l(k)\hat{\mathbf{h}}_l(k|k-1)\hat{\mathbf{h}}_l^H(k|k-1)+(\bar{x}_l(k)^2+\gamma_l(k))\mathbf{P}_l(k|k-1)\Big)$ in Eq.(8).

PDAKal will work as follows for kth time instant:

1. Predict the channels $\hat{\mathbf{h}}_j(k|k-1)$ and variance $\mathbf{P}_j(k|k-1)$ using Eq.(4)-(5),
2. Set $\bar{x}_j(k)=\bar{x}$ and $\gamma_j(k)=\gamma$ for $j=1,2,\ldots,N_T$, where $\bar{x}$ and γ are the mean and variance of alphabet A,
3. For $j=1,2,\ldots,N_T$:
   (a) Compute $\hat{p}\big(x_j(k)|\mathbf{Y}_1^k\big)$ using Eq.(6)-(8),
   (b) Compute new $\bar{x}_j(k)$ and $\gamma_j(k)$ via Eq.(9),
4. For $j=1,2,\ldots,N_T$:
   (a) Replace $\hat{\mathbf{h}}_l(k|k-1)$ with $\hat{\mathbf{h}}_l(k|k)$ and $\mathbf{P}_l(k|k-1)$ with $\mathbf{P}_l(k|k)$ while $l<j$ and compute symbol probability $\hat{p}\big(x_j(k)|\mathbf{Y}_1^k\big)$ of antenna j using Eq.(6) -(8),
   (b) Compute new $\bar{x}_j(k)$ and $\gamma_j(k)$ via Eq.(9),
   (c) Update the channel state $\hat{\mathbf{h}}_j(k|k)$ and its variance $\mathbf{P}_j(k|k)$ using Eq.(10)-(12) with $\bar{x}_j(k)$.

Normally PDA algorithm will converge after 2 iterations with perfect CSI. Therefore, one iteration of PDA algorithm is firstly performed for symbol detection with predicted CSI, then joint channel tracking and symbol detection method is used in the second iteration.

4. MULTIPLE MODEL BASED PDAMM ALGORITHM

Eq.(3) can be regarded as an observation model:

$$\mathbf{y}(k)=\mathbf{X}_j(k)\mathbf{h}_j(k)+\mathbf{N}_j(k) \qquad (13)$$

where $\mathbf{X}_j(k)=x_j\mathbf{I}$ for $j=1,2,\ldots,N_T$ and $x_j\in A$.

Now we can apply GPB algorithm to such a system with state model Eq.(2) and multiple observation models Eq.(13).

The estimation according to observation model s where $x_j=a_s$ for $s=1,2,\ldots,N$ via Kalman filter will be:

$$\hat{\mathbf{h}}_j^s(k|k)=\hat{\mathbf{h}}_j(k|k-1)+\mathbf{K}_j^s(k)\mathbf{W}_j^s(k) \qquad (14)$$

$$\mathbf{P}_j^s(k|k)=\mathbf{P}_j(k|k-1)-\mathbf{K}_j^s(k)\mathbf{\Gamma}_j^s(k)(\mathbf{K}_j^s(k))^H \qquad (15)$$

$$\mathbf{K}_j^s(k)=\mathbf{P}_j(k|k-1)a_s^H\mathbf{\Gamma}_j^s(k)^{-1} \qquad (16)$$

where $\mathbf{W}_j^s(k)$ and $\mathbf{\Gamma}_j^s(k)$ are computed via Eq. (7)-(8).

The update of model probability, i.e. the symbol probability of antenna j is as follows:

$$p(x_j(k)|\mathbf{Y}_1^k)=p\big(\mathbf{y}(k)|x_j(k),\mathbf{Y}_1^{k-1}\big)p(x_j(k))/Z(k) \qquad (17)$$

where $Z(k)$ is a normalizing constant and $p\big(x_j(k)\big)$ is the prior information of antenna j for $j=1,2,\ldots,N_T$. In GPB algorithm, it is assumed that the likelihood in the numerator is Gaussian given all previous measurements. Hence the likelihood of model s of antenna j is:

$$p\big(\mathbf{y}(k)|x_j(k),\mathbf{Y}_1^{k-1}\big)\sim\mathcal{N}\big(\mathbf{W}_j^s(k);0,\mathbf{\Gamma}_j^s(k)\big) \qquad (18)$$

and $\hat{p}(x_j(k)|\mathbf{Y}_1^k)$ is computed via Eq.(6).

The update of channel estimation and covariance are as follows:

$$\hat{\mathbf{h}}_j(k|k)=\sum_s\hat{\mathbf{h}}_j^s(k|k)\hat{p}\big(x_j(k)|\mathbf{Y}_1^k\big) \qquad (19)$$

$$\begin{aligned}\mathbf{P}_j(k|k)=\sum_s\Big(&\mathbf{P}_j^s(k|k)+\big(\hat{\mathbf{h}}_j^s(k|k)-\hat{\mathbf{h}}_j(k|k)\big)\\&\big(\hat{\mathbf{h}}_j^s(k|k)-\hat{\mathbf{h}}_j(k|k)\big)^H\Big)\hat{p}\big(x_j(k)|\mathbf{Y}_1^k\big)\end{aligned} \qquad (20)$$

In Eq.(20), the extra term which is added to $\mathbf{P}_j^s(k|k)$ is known as the 'spread-of-the-means' [1].

The above joint channel tracking and symbol detection of antenna j is illustrated in Fig.2. For kth time instant, PDAMM will work similar to PDAKal except that Step.4 will be replaced with:

1. Replace $\hat{\mathbf{h}}_l(k|k-1)$ with $\hat{\mathbf{h}}_l(k|k)$ and $\mathbf{P}_l(k|k-1)$ with $\mathbf{P}_l(k|k)$ while $l<j$ and compute $\mathbf{W}_j^s(k),\mathbf{\Gamma}_j^s(k)$ using Eq.(7)-(8) and $\hat{\mathbf{h}}_j^s(k|k),\mathbf{P}_j^s(k|k-1)$ using Eq.(14)-(16) for $s=1,\ldots,N$,
2. Compute symbol probability $\hat{p}\big(x_j(k)|\mathbf{Y}_1^k\big)$ using Eq.(6)
3. Update the channel estimation $\hat{\mathbf{h}}_j(k|k)$ and its variance $\mathbf{P}_j(k|k)$ using Eq.(19) -(20)
4. Compute new $\bar{x}_j(k)$ and $\gamma_j(k)$ via Eq.(9).

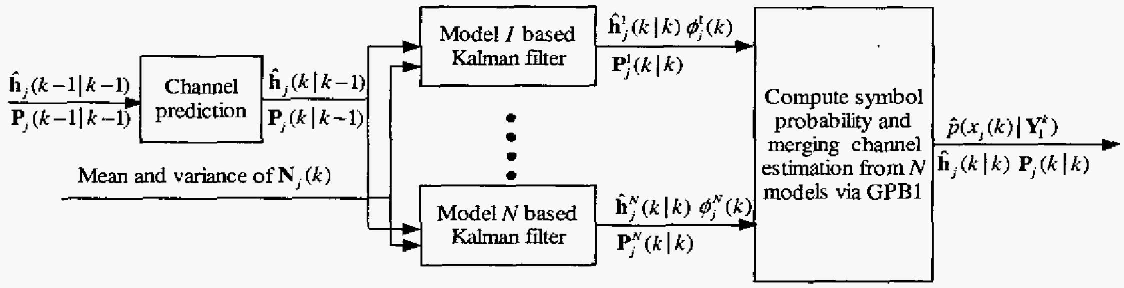

Fig. 2. Illustration of PDAMM algorithm for antenna j.

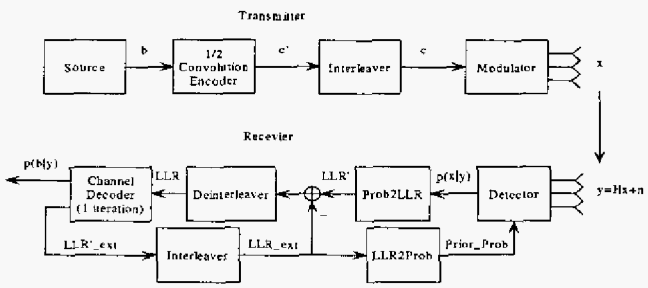

Fig. 3. System model.

5. SIMULATION RESULTS

In this section, we compare the performance of PDAKal algorithm proposed in section 3, PDAMM algorithm proposed in section 4, Genie-Aided method (performance bound) and the optimal A Posteriori Probability detector (APP) with perfect CSI (APPKnowChan) or initial channel estimation only (APPTrained).

In Genie-Aided approach, we estimate the channels using a random generated symbol sequence known to the receiver via Kalman filter and then detect the symbols via APP detector with the channel estimation.

The simulation is based on a turbo receiver system illustrated in Fig.3. The system is with $N_T = N_R = \{4, 8\}$ antennas and QPSK modulation. The rate 1/2 convolution code with generators 7 and 5 in octal notation are used in transmitter and the information bit block size is 1152 bits. For each SNR we randomly generated 10^4 blocks of data and for each block, the Rayleigh fading channel is generated by the Jake's model[12] with a normalized Doppler shift $Fd = \{1e-3, 1e-5\}$.

The initial channel estimation $\hat{\mathbf{H}}(0|0)$ for all the algorithms is computed from the training sequence via Maximum Likelihood estimation:

$$\hat{\mathbf{H}}(0|0) = \mathbf{Y}(0)\mathbf{X}(0)^H \tag{21}$$

where $\mathbf{X}(0)$ is a $N_T \times N_T$ orthogonal training sequence known to the receiver and $\mathbf{Y}(0)$ is the observation matrix at receiver. The initial channel estimation variance $C(0|0)$ for all channels. $\alpha \approx 1$ which can be estimated as detailed in [13]. We set $\sigma_v^2 = 2e-3$ for high Doppler shift case and $\sigma_v^2 = 2e-5$ for low Doppler shift case.

Fig. 4-5 show the BER and channel estimation Mean Square Error (MSE) of different methods for $Fd = 1e-5$ with $N_T = N_R = 4$ after 4 iterations of Turbo receiver respectively. Fig.6-7 show the BER and channel estimation MSE of different methods for $Fd = 1e-3$ and $N_T = N_R = 8$ after 4 iterations of Turbo receiver for respectively.

It is seen that PDAMM performs better than APPTrained and single model based channel tracking method PDAKal.

6. CONCLUSIONS

We propose a new joint channel tracking and symbol detection algorithm based on multiple model estimation and Gaussian approximation for spatial multiplexing MIMO system. Simulation results demonstrates the effectiveness of the PDAMM algorithm over decision based estimation PDAKal algorithm.

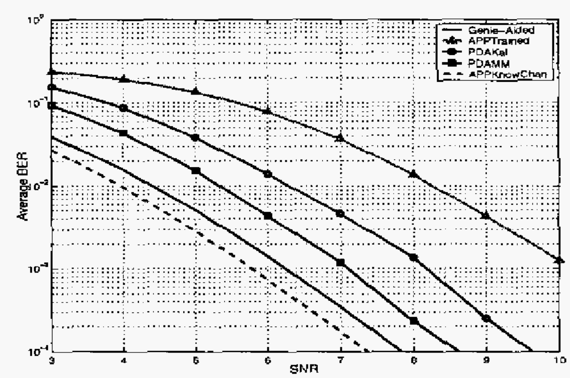

Fig. 4. BER after 4th Turbo iteration, $Fd = 1e-5$, $N_T = N_R = 4$.

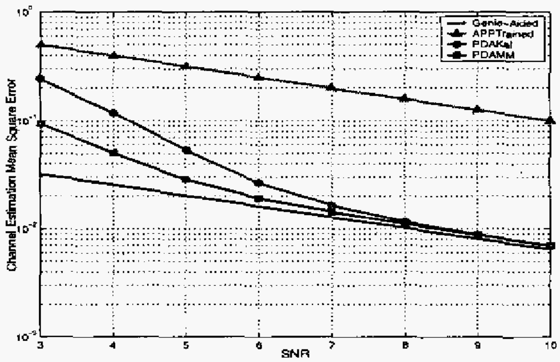

Fig. 5. Channel estimation MSE after 4th Turbo iteration ,$Fd = 1e-5, N_T = N_R = 4$.

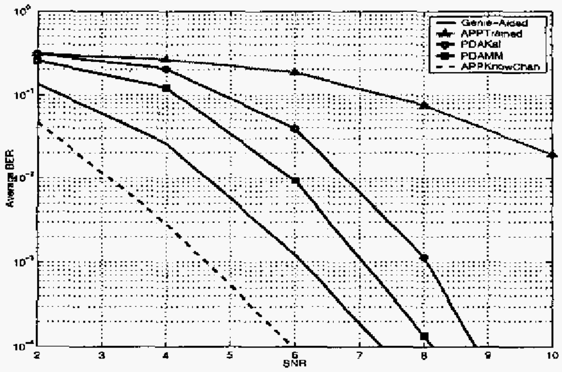

Fig. 6. BER after 4th Turbo iteration, $Fd = 1e-3, N_T = N_R = 8$.

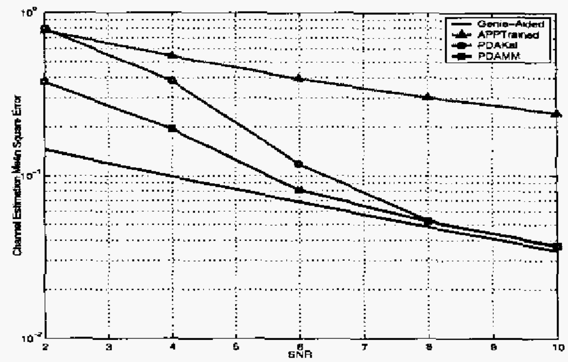

Fig. 7. Channel estimation MSE after 4th Turbo iteration ,$Fd = 1e-3, N_T = N_R = 8$.

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