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Channel Estimation Model for Multi-carrier System in Fast Random-varying Channel with Optimum Spectral Utilization

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ABSTRACT— ***This paper proposes a novel channel estimation model for multi-carrier system like orthogonal frequency division multiplexing (OFDM) to attain optimum spectral utilization in a fast random-varying wireless channel. To achieve optimal balance between spectral utilization and maintaining target quality of reception, the estimation process switches between pilot based and non-pilot based estimation techniques depending on temporal correlation between frequency domain channel state information (CSI) of two successive OFDM blocks. This paper also evaluates the performance of proposed model with different correlation measuring techniques. The simulation results show that the proposed estimation model provides the quality close to the pilot based system while the spectrum utilization is as high as non-pilot based estimation technique.***

Keywords— Orthogonal frequency division multiplexing, pilot added channel estimation, decision-direct channel estimation, spectral efficiency.

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1. INTRODUCTION

The next generation wireless standards like IEEE802.16 and Long Term Evaluation (LTE)-Advanced adopts multi-carrier access techniques like orthogonal frequency division multiplexing (OFDM) which brings feasibility of broadband data transmission without increasing either the transmitting bandwidth or power. It divides the frequency selective channel into narrow band frequency flat orthogonal sub-channels and transmission is done in parallel in order to maintain high data rate and eliminates the inter symbol interference (ISI) by help of cyclic prefix [1]. Unlike single carrier system, in OFDM the effect of channel is multiplicative in each sub-carrier and is compensated by sub channel scaling by one-tap gain adjustment network which need complete channel state information (CSI) in frequency domain at detection end. The estimation of channel state information (CSI) is the key to the quality of reception [2].

For fast-varying channel, the CSI has to be estimated more frequently. The comb-type pilot added channel estimation (PACE) is the most suitable estimation technique where the pilot symbols are interleaved with data symbols in the frequency domain in each OFDM block to cope with the rapid change in CSI [3-4]. The CSI corresponding to the pilot bearing sub-channels are estimated first using least square (LS) or minimum mean square estimation (MMSE) and the CSI corresponding to payload sub-channels are obtained by interpolating along the frequency axis [5]. However, the spectrum utilization in this model is limited as each OFDM block has to carry pilot overhead. To enhance the spectrum utilization, non-pilot based scheme like decision direct channel estimation (DDCE) has been utilized which exploits the quasi-invariance nature of the channel between two consecutive OFDM symbols and utilizes the information symbols to estimate the channel [6-8]. Though much higher spectral efficiency is registered, this method undergoes severe performance degradation due to error propagation. The error propagation can be mitigated by periodically updating the estimate by inserting pilot bearing blocks [9]. Interval of pilot based channel updation depends on the rate of change in CSI, a function of Doppler shift of the channel.

However neither of the estimation model had simultaneously provide best quality of service and highest spectral utilization as a fixed pilot insertion scheme does not work well in realistic random-varying channel where the rate of change of instantaneous CSI is random and depends on dynamics of the channel; the instantaneous Doppler shift fluctuates in a wide range [10-11]. With the periodic insertion of pilot symbols, the spectral utilization efficiency decreases during slow-variation in channel and for a fast-varying channel, waiting for the next training block for updating the estimate may degrade the performance. To achieve optimal spectral utilization with maintaining the target quality of reception, there has to be an adaptive pilot insertion scheme depending on the channel dynamics and noise statistics [12].

In this paper, the dynamics of the channel is studied and is quantified based on temporal correlation between frequency domain channel transfer function (CTF) of two successive OFDM blocks. A novel adaptive channel estimation concept has been proposed to achieve optimal balance between spectral efficiency and maintaining target quality of reception in a realistic wireless mobile channel based on adaptive switching between pilot based and non-pilot based estimation techniques where the mode selection takes place adaptively, depending on channel dynamics and noise statistics. The performance of the proposed scheme is evaluated through simulations with various correlation techniques: product-moment based correlation (Pearson's correlation), distance based correlation and RV coefficient based correlation. The proposed method achieves the spectral utilization efficiency close to that of periodic PAC/DDC model while maintaining the quality of reception same with the pilot based model. The paper is organized as follows: Section 2 describes channel estimation schemes for an OFDM system. Section 3 contains the proposed estimation model for achieving optimum spectral efficiency. Section 4 presents the performance evolution through simulation and section 5 draws the conclusion.

Notations: The bold faced letter $\mathbf{A}$ represents vector. E{.} denotes the expectation operation. $Tr(.)$ is trace operation, $\|.\|$ is Euclidian norm.

2. CHANNEL ESTIMATION FOR OFDM SYSTEM

Consider an ODFM based communication system where each OFDM block is transmitted with *N* sub-carriers. Let $X_n[k]$ is the frequency domain information symbol present in *k-th* sub-carriers in *n-th* OFDM block. The frequency domain signal received at *k-th* tone of *n-th* OFDM block is [13]

$$Y_n[k] = H_n[k].X_n[k] + Z_n[k], \tag{1}$$

where $H_n[k]$ and $Z_n[k]$ are the temporal CTF and the frequency domain representation of noise respectively associated with in *k-th* sub-carrier of *n-th* OFDM block. In vector notation,

$$\mathbf{Y}_n = \mathbf{H}_n \mathbf{X}_n + \mathbf{Z}_n, \tag{2}$$

where $\mathbf{Y}_n$, $\mathbf{X}_n$, $\mathbf{H}_n$ and $\mathbf{Z}_n$ are the response vector, the input signal vector, the channel vector and the noise vector respectively of size (N X 1). Let $\hat{\mathbf{H}}_n$ be the estimate of channel vector $\mathbf{H}_n$ **.** The Least-Square (LS) estimation method finds the estimate by minimizing the cost function,

$$J(\hat{\mathbf{H}}_n) = \left\| \mathbf{Y}_n - \mathbf{X}_n \hat{\mathbf{H}}_n \right\|^2 \tag{3}$$

by equating the derivative of the cost function with respect to $\hat{\mathbf{H}}_n$ to zero,

$$\frac{\partial J(\hat{\mathbf{H}}_n)}{\partial \hat{\mathbf{H}}_n} = \frac{\partial \left\| \mathbf{Y}_n - \mathbf{X}_n . \hat{\mathbf{H}}_n \right\|}{\partial \hat{\mathbf{H}}_n} = 0 \ . \tag{4}$$

And the estimation is obtained as

$$\hat{\mathbf{H}}_n = \mathbf{X}_n^{-1} \mathbf{Y}_n \ . \tag{5}$$

The estimate of *k-th* sub-carrier can be expressed as

$$\hat{H}_n[k] = \frac{Y_n[k]}{X_n[k]} \ . \tag{6}$$

Pilot Added Channel Estimation (PACE):

In this estimation process *a priori* known pilots are inserted as periodically spaced sub-carriers and CTF of corresponding sub-carriers are estimated by (6) which are used for frequency-domain interpolation to estimate CTF of data bearing sub-carriers by exploiting the correlation between successive sub-carriers. The quality of estimation is good when the pilot spacing is less than the coherence bandwidth of the channel. The estimate of *k-th* sub-carrier is given by

$$\hat{H}_n[k] = \hat{H}_n[k^+] + \frac{\hat{H}_n[k^+] - \hat{H}_n[k^-]}{k^+ - k^-}(k - k^-) \, . \tag{7}$$

Here k^- and k^+ are the location index of the pilot sub-carrier just before and after the *k-th* sub-carrier respectively. For a frequency selective channel, the frequency separation between two successive pilots must be less than the inverse of the delay spread. The performance of estimation can be improved by eliminating the effect of noise outside the maximum channel delay by using DFT-based estimation smoothing technique. Taking estimated channel to time domain we have

$$\{\hat{h}_n\} = IDFT\{\hat{H}_l\} = \{h_n\} + \{z_n\} \ . \tag{8}$$

The channel component outside the maximum channel delay is due to noise only and DFT-based estimation process ignores these components,

$$\{\hat{h}_n\}_{DFT} = \begin{cases} \{h_n\} + \{z_n\}, n = 0,1,2,\ldots, L-1 \\ \mathbf{0}, else \end{cases} \ . \tag{9}$$

Here L is the memory of the channel. The improved DFT-based estimate is obtained by transforming the remaining L elements onto the frequency domain,

$$\hat{H}_n^{DFT}[k] = DFT\{\{\hat{h}_n\}_{DFT}\} \ . \tag{10}$$

Non-Pilot based estimation:

DDCE is most convenient approach of non-pilot based channel estimation where the *l-th* received OFDM block $Y_l[k]$ can be equalized by the estimate of *(l-1)-th* block

$$X_l[k] = \frac{Y_l[k]}{\hat{H}_{l-1}[k]} \ . \tag{11}$$

This information is used to find the estimate of the *l-th* OFDM block which is to be utilized at (*l*+1)-*th* block.

$$\hat{H}_l[k] = \frac{Y_l[k]}{\overline{X}_l[k]} , \tag{12}$$

where $\overline{X}_l[k]$ is the hard-decision value for the channel-equalized signal $\hat{X}_l[k]$. Channel estimation using this method undergoes severe performance degradation due to error propagation which may be overcome by updating the estimate by periodically inserting pilot bearing blocks.

3. PROPOSED ESTIMATION MODEL

In this proposed model, the estimation method switches between pilot based and non-pilot based estimation techniques depending on temporal correlation between frequency domain channel transfer function (CTF) of two successive OFDM blocks. The block diagram of the proposed model is presented in Fig. 1.

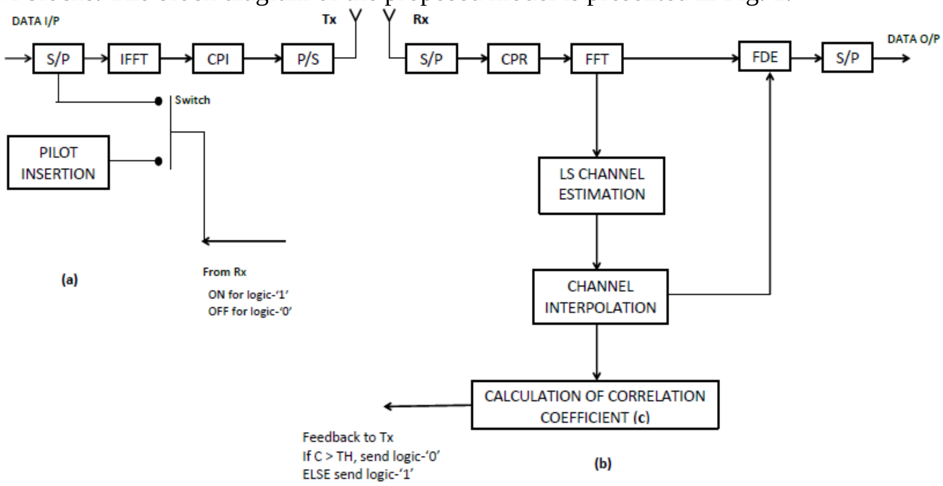

Fig. 1. Proposed system model, CPI: Cyclic prefix insertion, CPR: Cyclic prefix removal, FDE: Frequency domain equalizer

The correlation coefficient is computed during each block. The process remains non-pilot based as long there is a strong correlation between CTFs. In the proposed method, the estimate of CTF begins with a long preamble during 1st OFDM block which is utilized to equalize the received signal during next OFDM block in non pilot based mode and CTF during same block is estimated. The statistical correlation between CTF during two successive blocks in terms of correlation coefficient is computed and compared with the threshold value, a pre-defined value used for mode switching. Consider C_l as the correlation coefficient between CTFs during (l-1)-*th* and that of l-*th* OFDM block; if it is above the threshold, the receiver generates a feedback signal of LOGIC-**0** indicating no mode switching, the process remains non-pilot based mode for (l+1)-*th* OFDM block. Else generates LOGIC-**1** to initiate mode switching by changing pilot insertion switch present at transmitter to '**ON**' position. Hence considering lower correlation with previous block, a fresh estimation is made by inserting pilots on (l+1)-*th* OFDM block. The switching is quasi-stable in nature with non-pilot based mode as its stable mode; the process switches automatically to non-pilot based mode making pilot insertion switch to '**OFF**' providing optimal utilization of spectrum. This scheme ensures the avoidance of unwanted pilot insertion during slow variation of channel and the unwanted delay for pilot insertion during fast variation of channel. The choice of threshold value is critical for given target quality of reception. The proposed algorithm is summarized below.

Pseudo code of the Algorithm

Step 1: Estimate the CSI during 1st block by use of long preamble.
Step 2: Equalize the 2nd block using the estimate of previous block.
Step 3: Estimate the CSI during 2nd block with non-pilot based method.
FOR *i*=2: Number of OFDM blocks to be transmitted
Step 4: Compute correlation coefficient (C) between CSI during (i-1)-*th* and i-*th* block at receiver and send the feedback signal to transmitter.
Step 5: **IF** (C> th) Feedback =**LOGIC-0**
Pilot Insertion Switch=**OFF**
Estimate CSI during (i+2)-*th* block using non-pilot based method
ELSE Feedback= **LOGIC-1**
Pilot Insertion Switch=**ON**
Add pilot to (i+2)-*th* block and estimate CSI using pilot based method.
Estimate CSI during (i+3)-*th* block using non-pilot based method
i = i+1.
END

The spectral utilization is quantified as efficiency given by

$$Spectral\,Utilization\,Efficiency = \frac{no\,of\ Total\ Data - no\,of\ Pilot\ Data}{no\,of\ Total\ Data} \quad (13)$$

The spectrum utilization efficiency of various methods is listed in table-1.

Table-1 Spectrum utilization efficiency

PACE	Periodic PAC/DDC	Proposed Model
$\frac{ps-1}{ps}$	$1-\frac{1}{pbs\times ps}$	$\frac{no\,of\ Total\,Data - \frac{N.(no\_switching)}{ps}}{no\,of\ Total\,Data}$

ps: pilot spacing; *pbs*: pilot bearing block separation; $no\_switching$: the number of mode switching takes place
Following correlation measurement technique has been considered in this work:

Classical Correlation

It is product-moment based correlation called Pearson's correlation where the correlation coefficient between CTFs of two successive OFDM block is a measure of strength and direction of linear relationship between two. The Pearson's correlation coefficient (C_l^P) between CTFs of l-*th* (H_l) and (l-1)-*th* (H_{l-1}) block is [13]

$$C_l^P = \frac{\text{cov}(H_l, H_{l-1})}{\sigma_{H_l}.\sigma_{H_{l-1}}}, \quad -1 \le C_l^P \le 1 \quad (14)$$

Here σ_X is the standard deviation of random variable X. For realistic channel as the sub-carrier gains are not clustered around their mean values,

$$C_l^P = \frac{\sum_{k=0}^{N-1} H_l[k] H_{l-1}[k]}{\left[\sum_{k=0}^{N-1} H_l^2[k] \sum_{k=0}^{N-1} H_{l-1}^2[k]\right]^{\frac{1}{2}}} \quad (15)$$

RV coefficient

It is an excellent measure of correlation representing a multivariate generalization of the squared Pearson correlation coefficient based on measurement of closeness of two sets of points by computing scalar covariance and scalar variances. The RV correlation coefficient (C_l^R) between CTFs of *l-th* (H_l) and (*l*-1)-*th* (H_{l-1}) block is [14]

$$C_l^R = \frac{sc\_Cov(H_l, H_{l-1})}{[sc\_Var(H_l).sc\_Var(H_{l-1})]^{\frac{1}{2}}}, \qquad 0 \le C_l^R \le 1 \ . \quad (16)$$

Here the scalar covariance is

$$sc\_Cov(\mathbf{H}_l, \mathbf{H}_{l-1}) = Tr\left(\mathrm{E}\left\{\mathbf{H}_l{}^H \mathbf{H}_{l-1}\right\}\right)$$

and the scalar variances is

$$sc\_Var(\mathbf{H}_l) = sc\_Cov(\mathbf{H}_l, \mathbf{H}_l) \, .$$

Distance Correlation

It is a distance based correlation computes a non-negative correlation coefficient, with its value equals to 0 for two CTF having absolute independence. The distance correlation coefficient between CTFs during two successive OFDM blocks is [15]

$$C_l^D = \frac{dCov(\mathbf{H}_l, \mathbf{H}_{l-1})}{[dVar(\mathbf{H}_l).dVar(\mathbf{H}_{l-1})]^{\frac{1}{2}}}, \qquad 0 \le C_l^D \le 1 \, . \quad (17)$$

The distance co-variance is

$$dCov(\mathbf{H}_l, \mathbf{H}_{l-1}) = \left[\frac{1}{N^2} \sum_{j=0}^{N-1} \sum_{k=0}^{N-1} D_l^{j,k} . D_{l-1}^{j,k}\right]^{\frac{1}{2}},$$

and the distance variance

$$dVar(\mathbf{H}_l) = dCov(\mathbf{H}_l, \mathbf{H}_l) \, .$$

The pair-wise distance is given by

$$D_l^{j,k} = \left\| H_l[k] - H_l[j] \right\| \qquad j,k = 1,2,\ldots,N.$$

4. PERFORMANCE EVALUATION THROUGH SIMULATION

In this section the OFDM based communication is simulated with FFT size 512 and the length of cyclic prefix of 8. QPSK modulation is considered. The channel for simulation is considered as 6-tap COST-207 Typical Urban. The dynamic time varying nature of channel is analysed in Figure 2. The variation of channel response is quantified in terms of correlation coefficient between CTF of first OFDM block and that of successive blocks. The channel variation depends on the relative motion between transmitter and receiver which is the specific feature of realistic mobile channel and hence on maximum Doppler shift and Jakes Doppler spectrum is considered. Figure 2 demonstrates the change of channel correlation coefficient with time for systems having maximum Doppler shift 100Hz, 200Hz and 400Hz. It has been observed that the correlation between channels during successive block reduces; rate of reduction is proportional to the maximum Doppler shift in the channel.

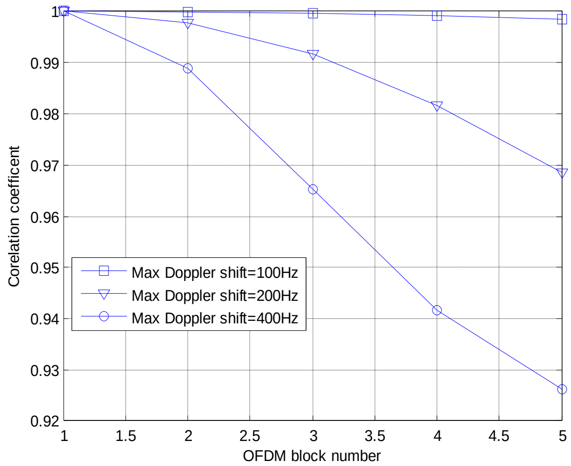

Figure 2.Change of channel correlation coefficient with time

Then the performance of the proposed channel estimation model is evaluated in random-varying channel. The maximum Doppler shift in channel is taken as 400Hz and Jakes Doppler spectrum is considered. The performance of following estimation methods are compared (a) by pilot based method where pilots are inserted in each block with separation of 4 sub-carriers (b) by periodic PACE/DDCE method where we insert pilots in every fifth OFDM block and do estimation of the remaining blocks using DDCE method and (c) by proposed model with discussed correlation coefficient measuring techniques: Pearson’s correlation, RV correlation and distance based correlation. Each case the mode switching threshold (*th*) is considered as 0.98 and 0.9. Fig.-3 shows the performance of spectral utilization efficiency of given methods with maximum. In both existing methods i.e. PACE based and periodic PAC/DDC based systems, the pilot patterns are constant and hence constant efficiencies are registered, 75% and 95% respectively. In proposed method the process switches between pilot based and non-pilot based schemes, depending on the value of correlation coefficient between CTF during successive blocks resulting improvement of spectral efficiency with signal-to-noise ratio. The proposed method registers much higher efficiency than that of PACE based method. It has been observed with mode switching threshold th=0.9 less number of switching occurred than that of th=0.98 showing higher efficiency and is very close to that of periodic PAC/DDC method. It has been observed that RV coefficient based measurement out-performs other techniques followed by distance correlation based measurement and Pearson’s correlation method.

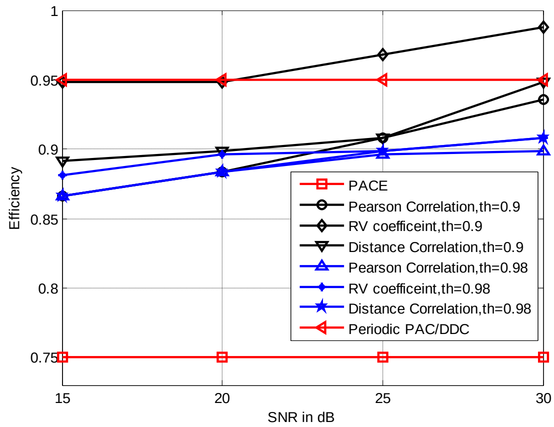

Fig-3 Spectral utilization efficiency performance of different channel estimation process

Fig. 4 shows the performance of mean squared error (MSE) in channel estimation process and fig. 5 shows the performance of bit error rate (BER) of uncoded signal of given methods. For both QoS parameters the performance of PACE based system is superior to that of periodic PACE/DDCE based method. The proposed method with th=0.98 performs much better than that of periodic PACE/DDCE method and close to that of PACE based method. The Pearson correlation technique provides best quality of reception followed by distance correlation and RV coefficient. The performance of proposed method with Pearson correlation technique with th=0.98 is very close to that of PACE method.

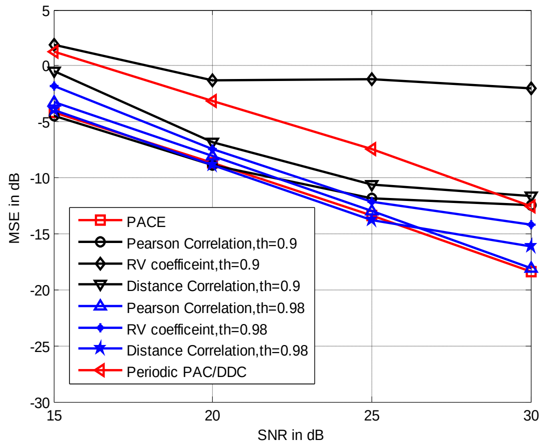

Fig-4 MSE of estimation process in dB performance of different channel estimation process

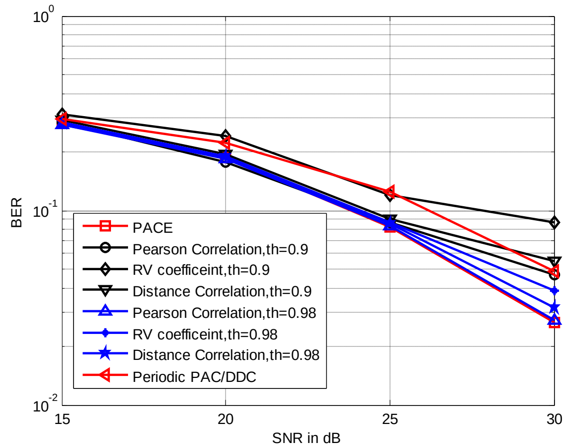

Fig-5 BER performance of different channel estimation process

Hence the proposed method is trade-off between spectral utilization and quality of reception. An optimal solution can be reached by carefully choosing the mode switching threshold value and correlation measurement technique. The proposed method with Pearson correlation technique with th=0.98 performs as good as PACE based method providing target quality of reception and with much higher spectral efficiency closer to that of periodic PACE/DDCE based method.

5. CONCLUSIONS

In this paper, the dynamics of realistic wireless channel is studied and quantified in terms of correlation coefficient between channel transfer function (CTF) of two successive OFDM blocks. Based on this, a correlation based adaptive estimation model for multi-carrier system for fast random-varying wireless channel has been proposed. In this model the optimal spectral utilization is achieved as the pilot insertion depends on dynamics of channel and noise statistics. This paper also investigates the performance of proposed model with different correlation measuring techniques. The performance of QoS parameters (BER and MSE) of proposed method with switching threshold th=0.98 is quite close to that of PACE method while the spectral efficiency of the proposed method is much higher than that of PSACE method and closer to that of periodic PAC/DDC estimation method. Implementation of proposed method for MIMO systems can be taken as direction of future research.

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