# Time Domain Estimation of Mobile Radio Channels for OFDM Transmission

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**Abstract.** Time domain synchronous OFDM (TDS-OFDM) is a kind of orthogonal multicarrier transmission, where a guard period between consecutive parts of useful information is filled with a pseudorandom noise that acts as a training sequence. This sequence can be used both for synchronization and channel estimation. The paper presents a new estimation procedure for mobile channel recovery, that is based on the time domain training sequence and utilizes the compressive sensing approach. The proposed solution does not require any additional help from any deliberately deployed training information in the frequency domain (pilot tones). The method is experimentally explored in a simulated doubly selective sparse transmission environment. The quality metrics, obtained for an uncoded OFDM transmission system with implementation of the proposed estimation method, are compared to the ones that were obtained in case of ideal channel state information as well as the time-frequency training method.

**Keywords:** mobile channels, OFDM modulation, time domain estimation, compressive sensing.

## 1 Introduction

Time Domain Synchronous Orthogonal Frequency Division Multiplex (TDS-OFDM) transmission belongs to the broad family of orthogonal multicarrier modulation schemes that use IFFT/FFT as the key processing method. The specific feature that distinguishes it from the others OFDM techniques is a pseudorandom noise sequence with good autocorrelation property inserted between consecutive information symbols [1]. Although this modulation type is less popular than the cyclic prefix OFDM (CP-OFDM) [2–4], the one has been successfully applied in the Chinese digital television network [5].

The guard time is part and parcel of any OFDM transmission. It is a period of time, that splits the transmitted information conveyed by the consecutive OFDM symbols into independent data parts, provided that its duration is longer than the delay spread of the channel impulse response. Fulfillment of this condition

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eliminates inter-block interference (IBI) and is obligatory for effective transmission. In the case of TDS-OFDM modulation, content of the guard period is known to the receiver, so it can be used as a training sequence for synchronization and channel estimation. Because majority of the initialization process may be based on the time-domain training in this case, an additional support form the frequency domain pilot (training) signals may be reduced as compared to CP-OFDM systems. This better utilization of the frequency spectrum for data transmission improves spectral efficiency about 10 % [6].

In the paper, the main attention is directed at channel estimation problem in TDS-OFDM transmission system, so synchronization will be assumed as perfect. Characteristics of the considered channels are doubly selective, i.e. they are dynamic both in the time and frequency domains. From practical point of view, relation between the Doppler frequency $f_D$ and the duration of the OFDM symbol $T$ usually meets condition [7]

$$f_D T \leq 0.1 \ . \tag{1}$$

For example, for the carrier frequency of 500 MHz and the relative speed of transmission's participants of 150 $\frac{\text{km}}{\text{h}}$, the OFDM symbol should span less than 1.4 ms. For comparison purposes, this symbol duration can corresponds to a 8K mode OFDM symbol (8192 samples of data plus 2048 samples of the guard time) of the digital terrestrial television system DVB-T2.

Beside the time-frequency variability, sparsity in the time domain is another important channel feature adopted here. It means that only a few propagation paths between transmitter and receiver have significant impact on transmission. The scientific reports show that the sparsity phenomenon is inherent feature of many wireless environments [8]. For instance, the COST 207 TU-6 propagation model consists of only six resolvable paths.

Simulation analysis of a new channel estimation procedure, that uses only pseudorandom training sequence of the TDS-OFDM symbol, even in the case of doubly selective channels, is the main contribution of this paper. The remainder of this paper is organized as follows. Section 2 presents the selected approaches to channel estimation for TDS-OFDM systems. Their short description acts as background for presentation of the new one in Sect. 3. The method performance is evaluated in Sect. 4 and conclusion are in Sect. 5.

## 2 Channel Estimation Essentials for TDS-OFDM

Concatenation of the information data sequence $x_i$ of length $N$ and the pseudorandom noise training sequence $c_i$ of length $M$ forms $N + M$ samples of the $i$-th TDS-OFDM symbol in the time domain. The vector $x_i$ is IFFT transform of $N$ complex numbers $X_i$ coming from a QAM signal constellation. The two parts of the OFDM symbol are independent each other as opposed to the CP-OFDM symbol, where a copy of $M$ samples from the end of $x_i$ is transmitted during the guard period. Preservation of the subcarriers orthogonality precludes immediate use of $N$-point FFT even on properly synchronized received signals until the mutual channel interference between $y_i = x_i * h_i$ and $d_i = c_i * h_i$ are eliminated and the cyclic property reconstruction of $y_i$ is made. Symbol "$*$" is the convolution operator and $h_i$ denotes a channel impulse response. This overlapping phenomenon is presented in Fig. 1, where every beginning part of the received data sequence $y_i$ as well as the received training sequence $d_i$ is distorted by the tail of the preceding component. The only way to obtain the "pure" $y_i$ for further Fourier transformation is to eliminate $d_i$ and $d_{i+1}$ from the received signal. This processing step is feasible only if the channel impulse responses $h_i$ and $h_{i+1}$ are known to the receiver.

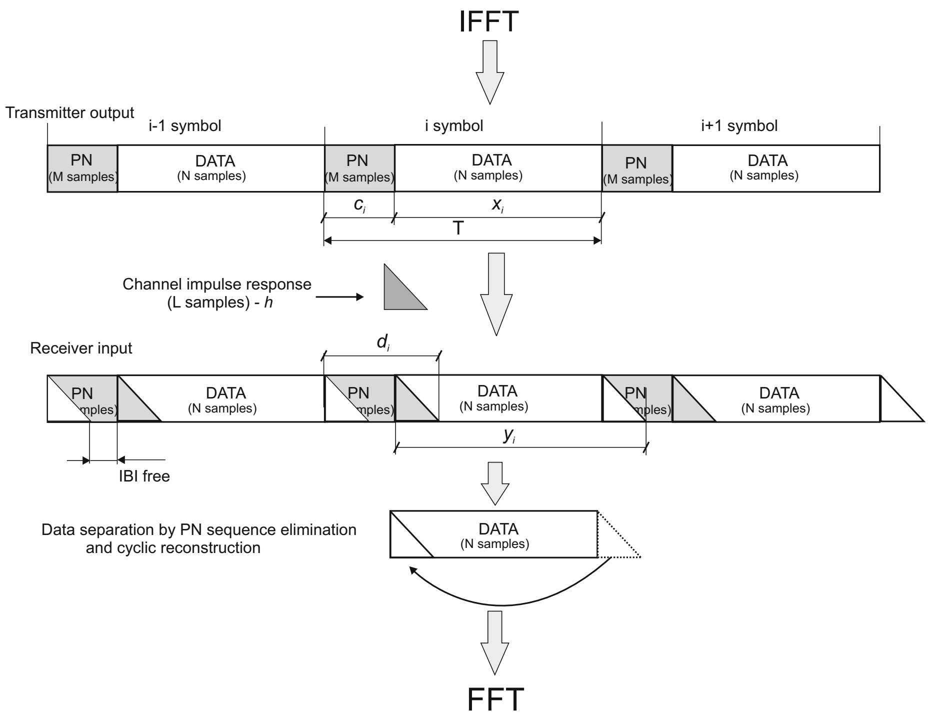


**Fig. 1.** Time domain processing steps in TDS-OFDM transmission

The method of channel impulse response estimation in TDS-OFDM system, that only employs the pseudorandom training sequence, is called iterative cancellation algorithm [1]. The first supposition about a current channel characteristic comes from the linear extrapolation of the channel coefficients, that were estimated during the previous two OFDM symbols. Thus, channel variability over one symbol duration should be small enough, that is typical for slow fading frequency selective channels only. Next adjustments of the recovered channel parameters are carried out in iterative manner using sequentially estimated $x_i$ $(X_i)$ and $d_i$ vectors.

For better tracking of the channel time variability, the time domain training sequence can be supported by pilots in the frequency domain as proposed in Time-Frequency Training OFDM (TFT-OFDM) transmission scheme [7]. The number of pilots depends on complexity (sparsity) of the channel impulse response and its dynamic. The channel estimation method distinguishes two separate stages. The first one uses the time-domain training sequence only for paths delay estimation. The second one, that is carried out in the frequency domain, determines the paths gains for the delays selected before.

## 3 Compressive Sensing Time Domain Estimation

### 3.1 Outline

Main weakness of the iterative method [1] is assumption that the propagation environment is static, i.e. changes occurring throughout duration of at least one OFDM symbol may be ignored. Additionally, slow channel variation should be well approximated by linear interpolation within three consecutive OFDM symbols. Those restrictions are somewhat relaxed in TFT-OFDM transmission, but this is done at a cost of the frequency-domain training [7].

As it is presented in Fig. 1, each data part $x_i$ of the $i$-th OFDM symbol is surrounded by the own training sequence $c_i$ and the sequence $c_{i+1}$ of the next symbol. A channel recovery method, that is proposed in this paper, focuses directly on the estimation of a current channel impulse response that is valid during transmission of the $c_{i+1}$ training sequence. The assumed sparsity property allows to use a compressive sensing method, e.g. Orthogonal Matching Pursuit (OMP), in order to find the elements of the channel impulse response [9]. The related works presented in [10, 11] use the compressive sensing approach for the path delays estimation only.

The channel is considered static during transmission of the training period, which is still much less than the duration of the OFDM symbol. Because the previous symbol, i.e. $i-1$, has been already recovered, there is assumed that the channel state information (CSI) in the time of the $c_i$ sequence is already known.

Consequently, having at receiver's disposal two estimates of the channel impulse response – valid right before and after the data part of the OFDM symbol – and taking into account the principle expressed in (1), the channel variation within data part of the symbol may be linearly approximated.

Next subsection presents a mathematical description of the proposed procedure.

### 3.2 Algorithm Details

The time domain interference between the $i$-th channel distorted data samples $y_i$ and the next channel distorted training sequence $d_{i+1}$ at the receiver's input, that occurs during the $i+1$-th guard period, can be expressed in matrix notation as follows:

$$\begin{bmatrix} y_{i,N-1} \\ y_{i,N}+d_{i+1,0} \\ y_{i,N+1}+d_{i+1,1} \\ \vdots \\ y_{i,N+L-1}+d_{i+1,L-1} \\ d_{i+1,L} \\ \vdots \\ d_{i+1,M-1} \end{bmatrix} = \begin{bmatrix} x_{i,N-1} & x_{i,N-2} & \ddots & x_{i,N-L} \\ c_{i+1,0} & x_{i,N-1} & \ddots & x_{i,N-L+1} \\ c_{i+1,1} & c_{i+1,0} & \ddots & x_{i,N-L+2} \\ \vdots & \ddots & \ddots & \ddots \\ c_{i+1,L-1} & c_{i+1,L-2} & \ddots & x_{i,N-1} \\ c_{i+1,L} & c_{i+1,L-1} & \ddots & c_{i+1,0} \\ \vdots & \ddots & \ddots & \ddots \\ c_{i+1,M-1} & c_{i+1,M-2} & \ddots & c_{i,M-L} \end{bmatrix} \begin{bmatrix} h_{i+1,0} \\ h_{i+1,1} \\ \vdots \\ h_{i+1,L-1} \end{bmatrix} , \quad (2)$$

where the matrix in the right side of the Equation (2) is called the measurement matrix according to terminology introduced in the compressive sensing theory [9].

Because the sought channel impulse response is considered sparse, the number of the active paths $S$ in the channel is significantly less than its delay spread $L$. The Orthogonal Matching Pursuit (OMP) algorithm works iteratively in two steps. The first step is to determine a single delay of a path and appends it to the delays estimated in the previous iterations. The second step is to estimate of the gains for uncovered paths using the LS (Least Squares) method. The number of iteration equals to the maximum number of resolvable paths in the channel. Two modes of sparse estimations are proposed:

– *direct* (dir) – all $M - L$ received samples in the IBI free region of the guard period, i.e. $[d_{i+1,L}, d_{i+1,L+1}, \cdots, d_{i+1,M-1}]^T$ are directly used by the OMP. It can be done because the corresponding submatrix of the measurement matrix in the Equation (2) is completely known to the receiver (it consists of the training sequence only). Estimation of the sparse vector representing the propagations paths is correct with high probability (about 99 %) if the following inequality is met [9]:

$$M - L > 2S \ln L \ , \quad (3)$$

– *iterative* (iter) – it applies when the condition (3) is false, i.e. the IBI free region is too short. The OMP algorithm is run for all received samples of the guard period but the end part of data sequence $x_i$ must be estimated first. It is done in an iterative manner using last results of channel estimation ($h_i$) as the first approximation of the current channel impulse response $h_{i+1}$. Then, the first estimate of the $x_i$ is calculated as follows:

$$\hat{x}_i^1 = \mathrm{IFFT}\left\{ \mathcal{Q}\left[\frac{\mathrm{FFT}\{\tilde{y}_i\}}{\mathrm{FFT}\{h_i\}}\right]\right\} \ , \quad (4)$$

where $\tilde{y}_i$ is the received data sequence of length $N$ that is cyclically reshaped according to the scheme outlined in Fig. 1. The $\mathcal{Q}[\cdot]$ refers to a hard decision operator that implements the minimum distance rule to find the likely values of the transmitted complex number in each OFDM subchannel. When the first estimate $\hat{x}_i^1$ is already known, the OMP begins to compute new values of the channel impulse response $h_{i+1}$.

The next estimates of $x_i$ (the iterative mode) as well as final one (the direct and iterative modes), are calculated assuming the linear interpolation of the respective gains in the channel impulse response within the $i$-th data sequence. The linear variation of the channel gain within data sequence for the $k$-th path is calculated as follows:

$$h(k)_{i,n}^t = \frac{h(k)_{i+1}^t - h(k)_i}{N} n + h(k)_i \quad \text{for} \quad n = 0 \dots N-1 \tag{5}$$

where $n$ is the discrete time index and $t$ is the current iteration number. The straightforward LS (Least Squares) estimate of the transmitted data is:

$$\hat{x}_i^t = \text{IFFT}\left\{\mathcal{Q}\left[\mathbf{G_i^{-1}}\text{FFT}\{\mathbf{\tilde{y}_i}\}\right]\right\} \ , \tag{6}$$

where $\mathbf{G_i}$ is the frequency domain channel matrix for the $i$-th OFDM symbol. The elements of $\mathbf{G_i}$, due to inter-channel interference produced by the channel time variability, are generally non zero out of the diagonal. Any $g_{p,q}$ element of the $\mathbf{G_i}$ matrix is calculated according to equation [7]:

$$g_{p,q} = \sum_k \left( \frac{1}{N} \sum_{n=0}^{N-1} h(k)_{i,n} e^{-j2\pi \frac{p-q}{N} n} \right) e^{-j2\pi q \Delta_k} \ , \tag{7}$$

where both $p$ and $q \in < 0 \dots N-1 >$, and $\Delta_k$ means the delay value of the $k$-th path in the channel impulse response.

## 4 Simulations

The simulation environment designed for analysis of the proposed method assumes as follows:

- the transmitted symbol of TDS-OFDM modulation consists of 1024 data samples and 64 or 128 samples of the pseudorandon noise training sequence in the guard period. No subcarriers are used as pilot tones. The 16-QAM constellation is used for data coding in the subchannels. The total number of the OFDM symbol transmitted during one simulation cycle is 300 (300x1024=307200 QAM data symbols for SER estimation);
- the model of the time and frequency selective wireless channel for terrestrial propagation in an urban area (COST 207) is considered in the investigations. It consists of six active path with the delay spread about 5 $\mu$s. According to the sampling frequency about 9 MHz (DVB-T), the delays of the active paths can be approximated by discrete time indices – [0,1,4,14,21,45];

– two cases of the channel time selectivity was considered – $f_dT = [0.1, 0.02]$;
– no additional error correction coding is used in order for a better understanding of the underlying capabilities of the proposed method;
– signal to noise ratio varies from 5 dB to 25 dB.

Both modes of the proposed method was explored regardless of the guard period duration. In fact, the direct one (marked as "dir" on the graphs) is intended for relatively long guard periods, where the condition (3) holds for the IBI-free area. This mode is designed so that it would not be necessary to use previous decoded data (full independence of reception of the consecutive OFDM symbols). But it does not preclude to support the estimation procedure with that information. On the opposite side, when the delay spread of the channel impulse response and the guard period are comparable in the time, there is advised to use the iterative mode.

Each aforementioned mode is explored for another two cases, that are related to operation principles of the OMP algorithm. The basic research assumes that both the paths delays and gains are estimated by the OMP. But, the delay evaluation (the first processing step in the OMP ) may be incorrect in high noisy environment, so in order to assess the influence of this inaccuracy on the final result, the operation of the OMP was evaluated in case of perfect information about the channel path delays.

Figures 2 and 3 present estimated Symbol Error Rate (SER) where "Symbol" in the metric name refers to the element transmitted in every subchannel. The SER expresses an average value over the one simulation cycle. The solid line without any markers on it, that is on every graph in Fig. 2 and 3 represents the absolute minimum of SER for the given instance of the channel. The perfect knowledge of the impulse response (perfect CSI) in every time sample was assumed to draw those lines. Because the simulation procedure reflects a deterministic approach, the level of the minimum may vary according to current

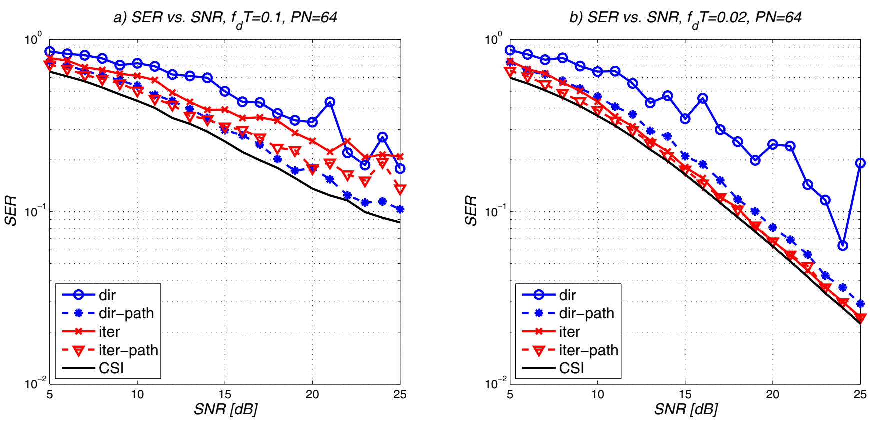


**Fig. 2.** SER vs SNR for 64 samples of the PN guard period and $f_dT$ a) 0.1 b) 0.02

channel realization. The lines with "path" suffix in the names refer to the simulation with the prior information about the correct path delays.

The iterative mode characterizes good estimation accuracy in case of relatively slow channel variability (Fig. 2b and 3b) regardless of the guard time duration. The risk of an initial fault estimation of the path delay is compensated by iterative procedure. It is seen especially for the short guard period, where the precise delay estimation has clear impact on SER, if the direct mode is used.

The high channel variability and the "short" guard time (64 samples) destroy effectiveness of the methods if the exact values of the paths delays are not known in advance (Fig. 2). The poor results of the iterative mode may come from error propagation in the estimated $x_i$ data sequence. The error correction coding of $x_i$ is probably the simplest way to improve the estimation accuracy. It should be noted that for the "long" guard time (128 samples) the iterative mode is no longer necessary regardless of the channel variability.

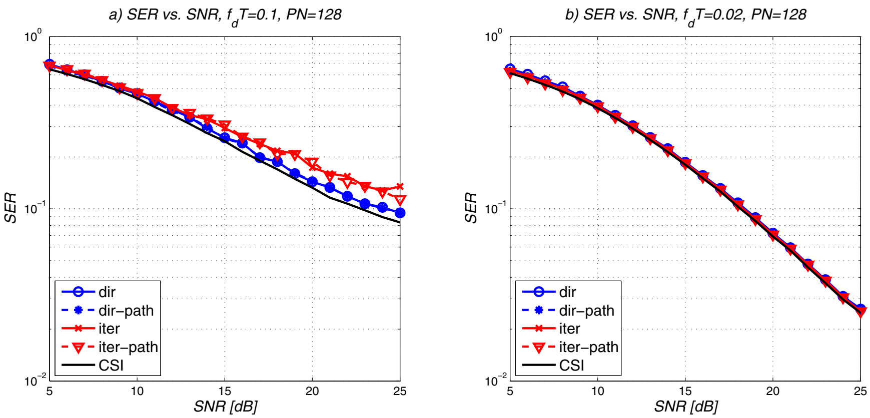


**Fig. 3.** SER vs SNR for 128 samples of the PN guard period and $f_dT$ a) 0.1 b) 0.02

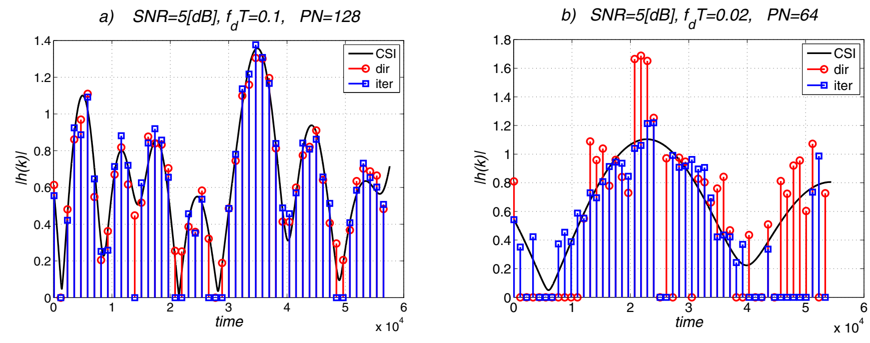


**Fig. 4.** Gain variability of the estimated channel path for the same exemplary delay and different channel properties and the guard period duration

To sum up, if the IBI free region in the guard time is large enough to find the parameters of the channel paths with the help of the OMP algorithm, then it is possible to use the direct mode. In the opposite situation, the iterative one with error correction should be used and better quality of the prior path delay estimation should be ensured.

If the obtained SER values are in the close vicinity of the one for the perfect CSI, the estimated paths coefficients should roughly approximate the perfect ones. It can be noticed in Fig. 4, that depicts the absolute gains values of the one of the estimated path (bars on the graphs) visible against the background of ideal channel path coefficients (solid line).

In TFT-OFDM system [7], the pilot tones are used for initial channel estimation. This algorithm was reconstructed here for comparison purposes. Fig. 5 presents that better initial performance (lower SER) achieves the proposed compressive sensing time domain method. The TFT one gets the worse results regardless of amount of pilots allocated in the OFDM symbol and type of impulse response interpolation within symbol duration.

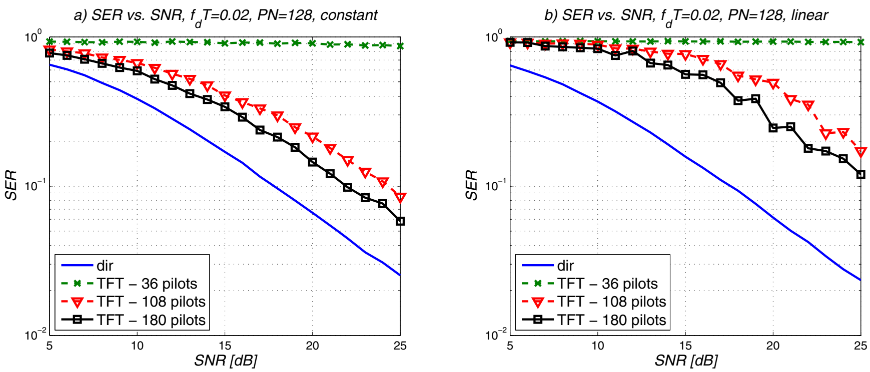


**Fig. 5.** Compressed sensing time domain estimation vs. time-frequency training for a) constant interpolation b) linear interpolation of the paths gain

## 5 Conclusions

Utilization of some subcarriers as the pilot tones for efficient estimation of the transmission channel is the standard approach used in the most OFDM systems. The high estimation quality is substantial for the transmission throughput, but undoubtedly, every pilot irrecoverable consumes some part of the system capacity on its own. Therefore, the pilot reduction is a serious challenge especially in case of the mobile radio environment, that usually requires more training information for the channel recovery, because of its dynamic properties both in the time and frequency domains. The guard time, as inherent part of every OFDM symbol, is another natural way for training delivery. It is successfully implemented in TDS-OFDM system by the pseudorandom noise sequence. Nonetheless, a support from pilot tones is still taken into consideration.

The paper presents the new channel estimation method that is based on the time domain training completely. No pilot tones is required to do so. The estimated channel is assumed sparse, which is confirmed in many practical situations. The latter property allows to use the compressed sensing method for channel paths acquisition. The simulation results with the OMP algorithm demonstrate fine estimation accuracy for mobile channels, even better than for the time frequency training method implemented in TFT-OFDM. The method was investigated for the fully implemented frequency domain channel matrix. Next research plans cover the issues of an improvement of the paths delay estimation and system analysis with error correction codes.

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