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AN EXTENSIVE REVIEW OF SIGNIFICANT RESEARCHES ON CHANNEL ESTIMATION IN MIMO-OFDM

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ABSTRACT

In communication systems, Multiple-Input Multiple-Output (MIMO) plays a major role because of its high performance. In MIMO systems, multiple antennas are used in both transmitter and receiver to improve the communication performance, whereas the orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation method. MIMO-OFDM is commonly used for communication systems due to its high transmission rates and robustness against multipath fading. In MIMO-OFDM, channel estimation plays a major role and channel estimation is the estimation of the transmitted signal bits using the corresponding received signal bits. While designing the channel estimator for wireless OFDM systems, two main problems will occur. The first problem is the arrangement of pilot information, in which pilot is the reference signal employed by both transmitters and receivers, whereas the second problem is the design of an estimator with both less intricacy and excellent channel tracking ability. In this paper an extensive review on different channel estimation methods used in MIMO-OFDM like pilot based, least square (LS) & minimum mean square error method (MMSE), least mean square (LMS) & recursive least squares (RLS) methods and also other channel estimation methods used in MIMO-OFDM was discussed with their achieved results.

Key words: *MIMO. OFDM, channel estimation, LS and MMSE, LS and RLS, blind channel*

1. INTRODUCTION

In the communication system, the signals are transmitted using several techniques, such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) [21]. The two different characteristic networks used in the communication system are wired and wireless [111]. In Wired technology, the transmission and its carrier waves are limited within the medium and a channel is formed for communication [109]. Whereas, the Wireless communication is a robust data communication system, which is used as an extension to or as an alternative for wired communication [110]. MIMO technology is a most significant method, which is employed to improve the signal to noise ratio for wireless technologies [6]. MIMO wireless technology increases the spectral efficiency through spatial multiplexing gain, and due to antenna diversity gain, it enhances the link reliability [57]. MIMO systems are a natural extension of developments in antenna array communication [9]. Combining OFDM with MIMO can increase the diversity gain as well as improve the system capacity on time-variant and frequency-selective channels [12].

OFDM is a promising technology for achieving high data rates, which is a digital multi-carrier modulation scheme [12]. OFDM is employed in several OFDM-based transmission standards, such as the digital audio broadcasting (DAB), digital video broadcasting (DVB), worldwide interoperability for microwave access (WiMAX), Integrated Services Digital Broadcasting-Terrestrial (ISDB-T) and Digital Terrestrial/Television Multimedia Broadcasting (DTMB) and high-speed wireless broadband local area networks (WLAN) [15] [25]. In wireless access systems with fading in the channels of signal distribution like Wi-MAX systems, receiving and transmission diversity is used [6].

Channel estimation is an important task in wireless communication systems [50]. The channel estimation can be done in two ways: 1) placing the pilot tones into all of the sub carriers of OFDM symbols with a certain period, or 2) placing the

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pilot tones into each OFDM symbol [49]. The data received is in the form of MIMO Channel Matrix [3]. This channel matrix can be determined by using statistical, measurement based or site-specific deterministic techniques [7].

In this paper, we present a comprehensive review of extremely important researches available in the literature for channel estimation in MIMO-OFDM system, using different methods. The reviewed researches are classified according to the type of channel estimation methods. The remaining part of the paper is organized as follows: Sections 1.1, 1.2 and 1.3 describes MIMO, OFDM and channel estimation in detail respectively. A broad review of channel estimation methods is presented in section 2. Directions for future research are briefly outlined in section 3 and section 4 concludes the paper.

1.1. Multiple-Input Multiple-Output System

In MIMO system, the use of multiple antennas at both sides of the wireless link provides a most promising solution to enhance the bandwidth efficiency and system reliability without using any additional bandwidth or transmitting more power into the channel [1] [5]. Numerous researches are going on MIMO systems formed by multiple transmit and receive antennas for receiving its attractive capability to increase the capacity of wireless communication system [2]. The ways for transmitting data from multiple users over the same frequency/time channel employing multiple antennas at the transmitter and receiver end are described by MIMO [3].

MIMO technology is also utilized to maximize the signal to noise ratio for wireless technologies, particularly in mobile WiMAX where there is a non-line-of-site situation and it needs to be adjustable to change the signal to noise ratio [6]. It is clearly exposed that MIMO systems has the potential to provide higher capacity than the single-input single-output (SISO) counterparts [7]. The advantages of MIMO communication, which uses the physical channel between several transmit and receive antennas, are currently receiving much attention [9]. Moreover, the system capacity can be considerably improved if multiple transmit and receive antennas are used to generate MIMO channels [10].

Advantages of MIMO systems are

- It has the competence to turn the multipath propagation, usually a drawback of wireless transmission, into an advantage for the user.
- Also, it has the potential to code and decode the multiple streams simultaneously as those are intended to the same user [108].

Applications of MIMO system are

- WiFi
- WiMAX
- 3G / 4G

Combination of MIMO wireless communication systems with OFDM has received a great interest and appears to be a hopeful technique for future wireless communications [13].

1.2. Orthogonal Frequency Division Multiplexing

OFDM is widely recognized as a robust modulation technique for wireless communication [14]. OFDM is a promising multi carrier transmission technique for the broadband wireless communication systems, which offers an efficient way to control the multipath and frequency selective fading without complex equalization [15]. OFDM/QAM systems are efficient for multipath channels because the cyclically prefixed guard interval is included between consequent symbols to remove inter symbol interference (ISI) [16].

OFDM necessitates time and frequency synchronization to sustain its orthogonality between sub carriers and also it is very sensitive to frequency offset which can be caused either by Doppler shift due to relative motion between transmitter and receiver or by the difference between the frequencies of the local oscillators at the transmitter and receiver [17] [18]. In OFDM implementation is performed using fast Fourier transform (FFT)/ inverse fast Fourier transform (IFFT) algorithms, and it is robustness against frequency-selective fading channels that are acquired by converting the channel into flat fading sub channels [19].

OFDM employs N overlapping (but orthogonal) sub bands, each carrying a baud rate of 1=T and they are spaced 1=T separately [21]. The modulation and demodulation are performed based on the application of the efficient IFFT and FFT, respectively [22]. In OFDM implementations, various issues appear that interrupt the orthogonality including:

- Carrier frequency offset
- Sampling frequency offset
- Timing jitter [23].

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To meet the quality of service requirements of future multimedia applications, OFDM has being used in diverse environments of broadband wireless systems, and being one of the robust technologies for wireless communications [24] [26]. Orthogonal transmission techniques such as TDMA, FDMA and CDMA are highly suboptimal as effectively BS will be transmitting to a single user over a particular resource [27]. Since OFDM is often used because of its superior performance in multipath environments, and capable to manage the interference and noise, it is not perfect for environments where adversarial elements purposely try to jam communications, such as tactical scenarios [28]. An OFDM is applied in order to transform the time-variant frequency-selective channel into a group of parallel time-variant frequency-flat sub carriers [41].

Advantages of OFDM are

- It can easily produce optimal "bit-loading", i.e., allocating different power and constellation size to each sub-carrier to improve the capacity of the system.
- It is powerful in avoiding the effects of narrow-band interference because such interference affects some of the sub-carriers.
- It allows efficient implementation of FFT algorithm

Applications of OFDM are

- ❖ Fix-wire network
- ❖ Broadcasting
- ❖ WLAN
- ❖ WMAN [55]

Block diagram of MIMO-OFDM is shown in the below figure.

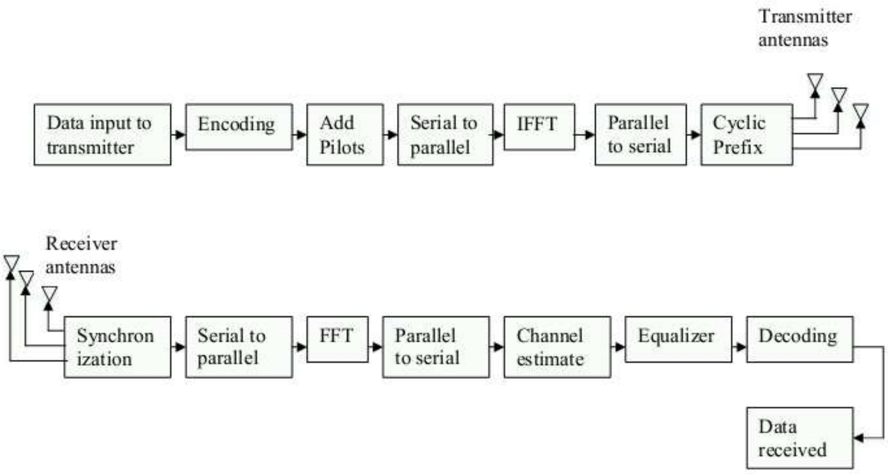

Figure 1: Block Diagram Of MIMO-OFDM System

OFDM transmission always needs an estimation of the channel frequency response [29]. Hence, an exact and efficient channel estimation that allows the realization of coherent demodulation is very significant to produce reliable data recovery [30].

1.3. Channel Estimation

Channel estimation is an important task in coherent communication systems [32]. As well as it is a major issue for coherent OFDM systems [33]. As compared to the SISO systems, channel estimation is more difficult because of the increased number of channels to be estimated [34]. Based on the signals correlation and MAI suppression, the channel estimation method is developed. Estimation of the signal amplitude and the propagation delay of each user are performed [36]. Also the effect of channel estimation is utilized in diversity combination and optimization of the receiver performance [37]. The quality of the channel estimation method has a severe impact on the overall Bit Error Rate (BER) performance of the receiver [38].

In adaptive MIMO detectors, channel estimates based on the preceding data block are employed for demodulation of the current block after being combined with phase tracking [39]. The time domain channel estimator with a priori knowledge of channel impulse response (CIR) length can offer amply improved channel estimates for MIMO-

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OFDM systems, but in practice the required CIR length is often approximated by the length of the cyclic prefix, and if the approximated CIR length is much larger than the real CIR length, then the time domain channel estimation performance is decreased considerably [40]. Accurate channel estimation can be used in OFDM systems to enhance their performance by permitting for coherent demodulation [35]. The performance of the LTE OFDMA systems is enhanced by effectively using the channel estimation (CE) [31].

There are two major types of channel estimation schemes namely, 1) pilot-assisted schemes, where a portion of the bandwidth is assigned to training symbols and 2) blind approaches, which can be implemented by using the statistical properties [42]. At a receiver, the channel estimation can be done by adding pilot signals into the transmitted signals [43]. Generally, channel estimation uses pilot signals that have a known pattern and that are discrete in terms of time and frequency [44]. Along with OFDM, pilot tones are used as a part of the OFDM symbol to estimate the channel and then simple linear equalization is employed to eliminate the multi path interference [45]. When pilot symbols are exist on some sub-carriers, initial estimates are easily obtained and can be enhanced by frequency- and time-domain interpolation [46].

A pilot assisted estimation algorithms utilize an interpolation method with fixed parameters (2-D or double 1-D) to estimate the frequency domain CIR by employing channel estimates acquired at the lattices assigned to the pilot tones [47]. Block-type pilot arrangements and comb-type pilot arrangements are basically the two types of pilot insertions [48]. Under the assumption of slow fading channel, the block type pilot channel estimation has been established, whereas the comb-type pilot channel estimation has been developed to fulfill the need for equalizing when the channel changes even in one OFDM block [49].

The least squares (LS) estimation is a common technique for pilot-based channel estimation, since it provides superior performance with reasonable complexity [50]. LSE has low complexity because it does not necessitate channel statistics but its performance is reduced that can be enhanced by using LMMSE, having more complexity because it exploits the autocorrelation matrix and the noise variance of the channel [51]. The channel at the pilot frequencies can be estimated based on Least Square LS or Linear Minimum Mean-Square-Error (LMMSE). As compared to LS, LMMSE has better performance [52].

Channel estimation can be performed even though no training sequence is available, by using a technique called blind channel estimation [53]. Blind channel estimation that depends on the utilization of statistical information of the received symbol has the advantage of bandwidth-savings [54]. Blind channel estimation techniques attempt to estimate the channel without using any knowledge of the transmitted data [29]. Majority of the channel estimation approaches may be viewed as DFT-based approaches, where LS (Least square) channel (frequency response) estimates are provided to IFFT block to obtain time domain channel impulse response estimate, and then processed properly and converted back to frequency domain by FFT [56].

Advantages of channel estimation are

- It allows performing coherent demodulation.
- It permits the receiver to estimate the impulse response of the channel and describe the performance of the channel.

2. REVIEW OF SIGNIFICANT RESEARCHES ON CHANNEL ESTIMATION IN MIMO-OFDM

An extensive range of research methodologies is employed for channel estimation in MIMO-OFDM is presented here. The reviewed works are classified different channel estimation methods such as pilot based, blind channel, RLS & LMS, LS & MMSE and other channel estimation methods.

2.1. Pilot Based Channel Estimation Methods

A low complexity, bandwidth efficient, pilot-symbol-assisted (PSA) channel estimator for multiple transmitter OFDM systems was proposed by King F. Lee *et al*. [75]. In order to allow simultaneous sounding of the multiple channels, the pilot symbols are constructed to be non-overlapping in frequency. A set of estimates acquired through periodically transmitted pilot symbols have been interpolated to find the time varying channel responses. The efficacy of the proposed estimator has been verified and its limitations have been analyzed by using the simulation results. Moreover, it has shown that the PSA channel estimator has a less computational complexity and enhanced performance when compared to existing decision directed minimum mean square error MMSE channel estimator for OFDM transmitter diversity systems.

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A pilot-aided channel estimation algorithm for estimating OFDM wireless channels in the presence of synchronous noise was presented by Aleksandar Jeremic *et al*. [76]. They have confirmed that the use of a priori available information regarding the interference structure can considerably reduce the number of covariance parameters in the synchronous case. They have modeled the user and interference channel responses using basis functions for further minimizing the number of unknown parameters. Consequently for the above approximations, a structured covariance model with smaller number of parameters has been obtained without any significant loss in detection efficiency. Then these parameters have been estimated by deriving the MLE and asymptotic MLE algorithms. The unknown interference parameters have been estimated by asymptotic MLE using a residual method of moments (RMM) estimator which is invariant to the user channel parameters resulting in a computationally competent non-iterative algorithm. Also, the performance of three algorithms such as, ordinary least squares, asymptotic MLE, and unstructured MLE has been compared.

A robust semi-blind technique for jointly estimating the CFOs and channels of an uplink multiuser MIMO–OFDM system was proposed by Yonghong Zeng *et al*. [77]. The CFOs and channels have been found simultaneously based on the SOS of the received signal and one specially designed pilot OFDM block. Also, the signals corrupted by the CFOs have been recovered by using a fast equalization technique.

The MMSE pilot-aided channel estimation for broadband OFDM systems was discussed by Carlos Ribeiro *et al*. [78]. A simplified time-domain (TD) MMSE estimator has been developed by the careful design of OFDM symbol. By finding the Fourier properties of the symbol, the investigated method eliminates the use of direct or inverse discrete Fourier transforms (DFT/IDFT) before the channel estimation, by utilizing the TD received symbol samples as the input to the MMSE filter. Furthermore, performing the estimation in TD (where CIR energy is mainly limit to a small set of samples), provides way to a simple, and efficient estimation of the filter parameters. When compared with the ideal situation (a priori knowledge of the channel correlation and noise variance), the performance of the channel estimation scheme, using the estimated parameters have presented a tolerable degradation and revealing a very low computational load.

The channel estimation method based on comb type pilot arrangement by using channel estimation method at pilot frequencies and then the CFR at data frequencies have been estimated by the mean of interpolation was presented by Hala M. Mahmoud *et al*. [79]. One advantage of using comb type pilots arrangement is it has the capacity to find the variation of channel in time. Simulation results have revealed that comb type pilot based channel estimation with low-pass interpolation has performed better among all other interpolation techniques. Hence the mean square error has been reduced by the low pass interpolation. Kalman estimation has enhanced performance than LS estimation. The estimators perform about the same for SNR lower than 10 dB.

A Pilot-aided and semi-blind joint data detection and frequency offset/channel estimation schemes for the uplink MIMO-OFDMA systems was proposed by Kyeong Jin Kim *et al*. [61]. Parallel Schmidt Kalman filter has been used by the proposed schemes to decompose the multiuser estimation problem into more adaptable sub problems, each of which copes with only one desired user. After the decomposition, the Schmidt Rao-Black wellized particle filter has been utilized to find the time varying channel and CFO of the desired user in each sub problem. Simulation results have exposed that the resulting scheme can give accurate CFO and channel estimates at reasonable computational complexity.

A pilot-aided algorithm for the estimation of fast time-varying channels in OFDM transmission was proposed by Tareq Y. Al-Naffouri *et al.* [80]. Unlike several existing OFDM channel estimation algorithms, their proposed algorithm performs channel estimation in the frequency domain, to use the structure of the channel response (such as frequency and time correlations, and bandedness). Moreover, the pilot group size has been optimized and performing most of the calculations offline resulting in high performance at considerable complexity reductions.

A channel estimation method for multiband OFDM ultra wideband (UWB) systems in multipath time varying wireless channels was proposed by Riazul Islam *et al*. [81]. Two-stage approach has been applied to achieve this purpose. In initial stage, Winner-Hopf filtration has been utilized for the interpolation of unknown channel state information (CSI) using comb-type known pilots. In second stage, interpolated channel statistics has been modeled as autoregressive (AR) process and fed into kalman filter. Also, an ICI

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mitigation filter is combined with kalman filter in order to eliminate the inter carrier interference (ICI). A mathematical framework has been given for the realization of their proposed system. Link level simulation (LLS) has exposed that their method can perform exact channel tarcking and provides enhanced SER performance.

The design of preamble for channel estimation and pilot symbols for pilot-assisted channel estimation in OFDM system with null subcarriers was studied by Shuichi Ohno *et al.* [82]. Both the preambles and pilot symbols have been designed for reducing the l_2 or the $l\infty$ norm of the channel estimate MSE in frequency-selective environments. A convex optimization method has been used to identify optimal power distribution to the preamble by casting the MSE minimization problem into a semi definite programming problem. Then, they iteratively select the placement and optimally distribute power to the selected pilot symbols by using the designed optimal preamble as an initial value. Design examples reliable with IEEE 802.11a and IEEE 802.16e have been provided to show the better performance of the proposed method over the equi-spaced equi-powered pilot symbols and the partly equi-spaced pilot symbols.

An efficient technique for the estimation of OFDM channels in a time-frequency-selective fading environment using Kalman filter was proposed by Allam Mousa *et al.* [83]. An AR model of the channel has been assumed to model the fading process of a time-varying channel. Based on comb-type pilot frequencies arrangement, the estimation has been performed. The channel coefficients that belong to the pilot subcarriers have been estimated and then these estimates are interpolated. As compared with other methods, Low-pass interpolation method has given improved performance and also this technique reduces the mean-square error between the interpolated points and their ideal values. Doppler frequency will destroy the orthogonality between subcarriers, and so this will produce ICI, which reduces the performance of the estimation process.

2.2. Blind Channel Estimation Methods

Two semiblind methods for multiuser MIMO channel estimation were proposed by Shahram Shahbazpanahi *et al.* [84]. These methods are useful when OSTBCs are used for data transmission. The proposed methods are based on the extension of the concepts of the popular Capon and MUSIC methods to the problem of multiuser MIMO channel estimation. An intrinsic structure of OSTBCs has been developed to blindly calculate the subspace which contains the user channel matrices, and then only a few training blocks have been used to extract the user channels from this subspace. The proposed methods require only less training blocks as compared to the standard non blind LS-based channel estimator, and so, the bandwidth efficiency has been improved.

A subspace-based blind channel estimation method for MIMO OFDM systems using the second order statistical analysis was developed by Feifei Gao *et al.* [85]. One advantage of the proposed method is that it is competent to apply channel estimation, even though the number of the transmit antennas is greater than or equal to the number of the receive antennas, where the conventional subspace-based algorithms could not be applied. They have considered the channel estimations with matrix ambiguity as well as with scalar ambiguity. Simulation results have clearly shown the efficiency of the proposed algorithm under different scenarios.

A robust subspace (SS) based blind channel estimation for MIMO OFDM systems were proposed by Feifei Gao *et al.* [86]. With an appropriate re-modulation on the received signals, an effective way has been found to apply the SS method for the CP based MIMO-OFDM system when the number of receive antennas is greater than the number of transmit antennas. Most of the problems related to the SS method have been studied for this proposed modulation, such as channel identifiability, order over-estimation, MSE of the channel estimation as well as the CRB of the channel estimation. Since the proposed method uses the blind channel estimation for the CP based MIMO OFDM, it is flexible for several existing standards and the future 4G wireless communication standards.

A subspace technique for blind channel estimation in OFDM systems over time-dispersive channel was developed by Xiaodong Yue *et al.* [87]. The proposed blind estimation method performs satisfactorily with a small number of received OFDM blocks by using the block Toeplitz structure of the channel matrix. Numerical simulations have demonstrated the enhanced performance of the proposed algorithm over methods reported earlier in the literature. A high spectral efficiency has been achieved by their proposed method because the method does not require a cyclic prefix (CP).

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A blind channel estimation algorithm and its lower complexity algorithm based on cyclostationarity properties induced by the cyclic prefix in OFDM system was proposed by Wensheng Zhu *et al*. [88]. In the proposed algorithm, the spectrum information of send and receive signal at the single frequency has been analyzed for identifying the channel individually. As compared to the previous Two-Cyclic algorithm, the proposed algorithm has better performance. Moreover, a lower complexity algorithm has been developed, which considerably minimize the computational complexity.

2.3. LMS and RLS Channel Estimation Methods

An LMS and RLS based adaptive channel estimation for orthogonal STBC-OFDM systems with three transmit antennas was proposed by Berna Ozbek *et al*. [89]. The BER results that are obtained using the proposed RLS algorithm approach have shown that the channel coefficients are perfectly recognized at three-transmitter side with a reasonable degree.

An adaptive channel estimation techniques such as normalized least mean (NLMS) square and RLS for the MIMO-OFDM systems was proposed by Masud Rana *et al.* [90]. An adaptive estimator has been used by these CE techniques, and it has the ability to update the parameters of the estimator constantly and thereby the knowledge of channel and noise statistics are not needed. The proposed NLMS/RLS CE algorithm necessitate only the knowledge of the received signal. Their simulation results have proved that the RLS CE technique has superior performance than the NLMS CE technique for MIMO OFDM systems. Moreover, a higher performance has been achieved through the utilization of more multiple antennas at the transmitter and/or receiver than with fewer antennas.

A pilot based channel estimation techniques for OFDM communication over frequency selective fading channels was proposed by Elangovan *et al.* [91]. The channel responses have been estimated by mainly using three prediction algorithms in the equalizer such as, LMS, NLMS and RLS algorithm. Fading occurred due to multi path delay has been cancelled by using three equalization techniques such as, LMS, NLMS and RLS. Using the SNR vs BER plot, graphs for each equalization technique has been plotted and analyzed. The tracking efficiency of algorithms has been shown evidently by plotting the original and predicted values of channel co-efficients.

Three adaptive channel estimation algorithms, RLS, LMS and Kalman-Filtering in terms of performance, MSE and SER, and complexity were compared by Saqib Saleem *et al.* [92]. The performance has been measured for several filter lengths and multipath channel taps. Among all the LMS techniques, Leaky-LMS has shown better performance with less computation time. Also, Kalman-Filtering has shown better performance than both LMS and RLS algorithm. 4-5 CIR samples and any number of channel taps can be used for optimized channel estimator utilizing Kalman Filtering in wireless communication system. But, channel taps should be less than 10 for less complexity.

2.4. MMSE and LS Channel Estimation Methods

A channel estimation algorithm based on a time-frequency polynomial model of the fading multipath channels was proposed by Xiaowen Wang *et al.* [93]. The correlation of the channel responses in both time and frequency domain has been used by this algorithm and so it minimizes more noise than the methods using only time or frequency polynomial model. Also, the estimator is more efficient than the existing methods based on Fourier transform. The simulation has shown that it has more than 5 dB enhancement in terms of mean-squared estimation error under some practical channel conditions. The algorithm requires some previous knowledge regarding the delay and fading properties of the channel. The algorithm can be implemented recursively and can change itself to follow the variation of the channel statistics.

An iterative receiver algorithm for MIMO systems in frequency-selective fading channels was proposed by Maja Loncar *et al.* [58]. The proposed algorithm performs iterative channel estimation, soft interference cancellation with MMSE post-filtering and soft-in soft-out (SISO) MAP decoding. An extrinsic and a-posteriori log-likelihood ratio of coded symbols in each iteration has been calculated by the decoder. LMMSE channel estimator that uses soft estimates of all the data symbols has been derived. The estimator has been initiated by using the pilot symbols, and updated in each iteration using the a-posteriori based soft data decisions obtained from the decoders' output. They have presented two approximate channel estimators, based on LMMSE and LS solution and their performance has been compared by simulations.

The performance of MIMO channel estimation techniques using the training sequences was

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analyzed by Mehrzad Biguesh *et al.* [94]. They have considered the well-known linear LS and MMSE approaches and proposed a scaled LS (SLS) and relaxed MMSE methods. These methods require only less knowledge of the channel second-order statistics and/or have enhanced performance than the conventional LS and MMSE channel estimators. The optimal choice of training signals has been examined for the aforesaid techniques. In the case of multiple LS channel estimates, the best linear unbiased estimation (BLUE) scheme for their linear combining has been introduced and studied.

An alternative technique for minimizing the computational time for MIMO-OFDM channel estimation algorithms was proposed by Reza Abdolee *et al*. [95]. The QR decomposition (QRD) as an alternative mathematical expression to lessen the computational complexity of those complex algorithms which require matrix inversion has been analyzed. Here, the channel estimation algorithm which is targeted to simplify is LS method. Their results have proved that QR decomposition can significantly decrease the complexity of LS channel estimation. Moreover, it has achieved more than 77% of reduction in computational complexity while it keeps the performance efficacy of the system at the same level.

LS channel estimation scheme in time domain for pilot tones based MIMO-OFDM systems was proposed by Han Wang *et al.* [96]. Here, the time-domain channel responses have been estimated by using the time-domain signals generated by pilots of the transmitter and the receiver. They have presented an optimal pilot sequences (OPS) regarding the mean square error (MSE) of LS channel estimation and it has shown that the OPS are equi-powered, equi-spaced, and position orthogonal. The maximum guard band-width (MGB) regarding MSE has been developed, since virtual subcarriers are not used for transmission. If the guard bandwidth of MIMO-OFDM system is less than or equal to the MGB, then the OPS can be evaded from the guard band by changing the initial position of OPS. From the simulations, it has revealed that the OPS which are derived have performed better than the conventional OPS in terms of MGB and MSE.

The performance of OFDM/TDM using MMSE-FDE with practical channel estimation in a fast fading channel was evaluated by Haris Gacanin *et al*. [97]. A tracking against fast fading has been enhanced by an efficient pilot-assisted channel estimation that employs time-domain first-order filtering on a slot-by-slot basis and frequency-domain interpolation. The MSE of the channel estimator using time-domain first-order filtering and frequency-domain interpolation has been derived and then, they have discussed a tradeoff between improving the tracking ability against fading and the noise reduction. It has revealed that the OFDM/TDM using MMSE-FDE gives a lower BER and an excellent tracking ability against fading in comparison with conventional OFDM while keeping the same data-rate transmission.

The design and implementation of an end to end MIMO system was discussed by Sudhakar Reddy *et al.* [98]. 2x2 MIMO systems have been implemented by using LS channel estimation and QPSK techniques. MIMO model has been generated using Verilog and synthesized for area, power and speed. The HDL code for 2x2 MIMO systems has been simulated, synthesized and implemented on Virtex2Pro FPGA board and the results have been validated against MATLAB. The design is targeted on 7 and 30 million gate Virtex for comparing its hardware performance. Based on the results obtained, hardware constraints for ASIC implementation have been derived and implemented using Synopsys ASIC flow. Channel estimation and QPSK models have the maximum delay, and the important paths in these models have been found and redesigned to reduce the delay using buffer insertion method. The results have been verified for its functionality. With the modifications performed the frequency of operation is increased to 13.388MHz from 7.27MHz.

A Single carrier Ultra-wideband (SC-UWB) transmission scheme with MSE channel estimation was proposed by LI Yuhong *et al.* [99]. Mainly, a Direct sequence Binary phase shift keying (DS-BPSK) has been used by this scheme to support high to moderate data rate applications that differentiates from Multi-band OFDM and Impulse radio (IR) UWB systems. Simulation results have demonstrated that, with base band time-frequency signal processing algorithms, the BER performance of the SC-UWB system over the IEEE 802.15.3a UWB Channel model III (CM3) is about 10^{-5} at E_b/N_0 of 10.5dB. Also, the SC-UWB system exhibits a low power consumption and low implementation complexity because of its low Peak-to-average ratio (PAR) and modulation characteristics. It is clear that the proposed scheme is a good candidate for short range communications, particularly for low power and low cost applications for e.g., mobile terminals.

A low complexity partial-sampled MMSE channel estimation for compromising between

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complexity and performance was presented by Savitri Galih *et al*. [100]. The MMSE weight matrix has been sampled partly to minimize the MMSE channel estimation complexity. The simulation results have shown that the BER performance and equalized signal constellation scatter plot has considerably improved over the LS channel estimation and has comparable BER performance with MMSE channel estimation. Also, depending on the size of sampling, the computational complexity has been decreased to 57% from 64%.

The channel state information for both SISO and MIMO systems using pilot aided arrangement was analyzed by Kala Praveen Bagadi *et al*. [101]. The estimation of channel at pilot frequencies with conventional LS and MMSE estimation algorithms has been performed through MATLAB simulation. The performance of MIMO OFDM and SISO OFDM has been evaluated in terms of BER and MSE level. Further improvement of performance could be achieved by means of maximum diversity Space Time Block Coding (STBC) and Maximum Likelihood Detection at transmission and reception ends respectively.

MIMO-OFDM channel estimation technique based on a Decision Directed Recursive Least Squares (RLS) algorithm in which pilot symbols need not to be included in the data after a short initial preamble was presented by Patric Beinschob *et al*. [102]. The innovation and key concept of the proposed technique is the block-wise causal and anti-causal RLS processing, which produces two independent processing's of RLS along with the related decisions. The receiver operates with soft information due to the usage of low density parity check (LDPC) channel code, and so it allows them to introduce a modification of the Turbo principle and also simple information combining approach based on approximated a posteriori log-likelihood ratios (LLRs). At lower SNR values the performance is still better than the simple RLS-DDCE algorithm, although the applied zero forcing equalizer forbid a better performance.

Channel estimation technique for MIMO systems based on orthogonal matrix triangularization with better performance and reduced complexity was presented by Mohammad Tariqul Islam *et al*. [62]. As compared with LS channel estimation, the proposed technique has shown a wide improvement in terms of BER performance. Furthermore, a detailed analysis and simulations have proved that the computational complexity of the proposed channel estimation is much lower than the conventional LS estimation. The complexity of the proposed technique has been increased almost linearly regarding the number of transmit antenna, but for LS method it has been increased exponentially at much higher rate.

The performance of OFDM system with generalized fading model of $\alpha-\mu$ distribution with and without estimation was analyzed by Neetu Sood *et al.* [103]. The simulation results have clearly shown the non-linearity added in propagation medium, and the BER has been considerably reduced by varying α from 1 to 7. However, higher values of α has been employed for further reductions in BER. It is evident from the simulation result that the substantial enhancement has been achieved by applying the phase estimation using trained symbols.

A complexity structure of receiver and that the LS technique and linear interpolation have been employed for initial channel estimation was proposed by Manwinder Singh *et al*. [104]. Here, the LSM iterative algorithm uses the channel estimation of last iteration in current estimation. Moreover, channel estimation performance can be enhanced when an LMS iterative algorithm is added to the system. For enhancing the accuracy of channel estimation, LMS iterative algorithm has been added to receiver that includes a feedback of output and enhances the BER performance of system, which is almost close to the ideal channel performance.

A particle swarm optimization (PSO) to optimize both placement and power of pilot tones, which are utilized for LS channel estimation algorithm based on comb-type pilot tones in MIMO-OFDM systems, was proposed by Muhammet Nuri Seyman *et al.* [105]. The simulation results have proved that, the optimized pilot tone derived by PSO has performed better than the orthogonal and random pilot tones in terms of MSE and BER. Simulations have been performed over channels with diverse Doppler shifts values, in order to exhibit the effect of Doppler shifts on various pilot tones performance.

The performance and complexity of two algorithms, such as LSE and LMMSE in terms of MSE and SER, based on CIR samples and channel taps was evaluated by Saqib Saleem *et al.* [106]. LMMSE has the capability to improve the performance by making use of previous information of noise and channel. But this enhanced performance appears at the cost of more complexity. Although the performance can be

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improved by increasing CIR samples or channel taps, after a certain value of these factors, only the complexity has been increased and no further enhancement has been made in the performance. But, LSE has been made more efficient both in terms of performance and complexity by increasing CIR samples than the LMMSE. They have also shown that SNR value does not affect the performance of LSE for diverse channel taps. The performance and complexity can also be optimized by using other channel estimation techniques namely Transform-based and Kalman filtering based algorithms.

The two linear channel estimation methods, such as LSE and LMMSE along with their modified versions, to minimize the complexity for LTE-Advanced which is based on MIMO-OFDM technology was discussed by Saqib Saleem *et al.* [107]. LMMSE provides better performance but it has more complexity than LSE since it necessitates channel and noise statistics. The LSE and LMMSE techniques have been modified to optimize the performance and complexity. Based on CIR samples and multi-path channel taps, these algorithms have been evaluated. MATLAB Monte –Carlo Simulations have been used to optimize their performance in terms of MSE, BER and Frame Error Rate (FER) for 2 × 2 MIMO System. Simulation parameters have been taken according to the physical layer of LTE Advanced as given in Release-10 by 3rd Generation Partnership Project (3GPP).

2.5. Other Channel Estimation Methods

The optimum training-sequence design and simplified channel estimation for enhancing the performance as well as for reducing the complexity of channel parameter estimation was proposed by Ye (Geoffrey) Li [65]. The optimal training sequences simplify the initial channel estimation and achieved an excellent estimation performance. Whereas the simplified channel estimation considerably reduces the complexity of the channel estimation at the expense of small performance degradation. The simulation of an OFDM system with two-transmit and two-receive antennas have shown the efficiency of the techniques. The space-time coding with 240 information bits per codeword has been employed for transmit diversity. Moreover, the simulation results have exposed that, the required SNR is only about 9 dB for a 10% word error rate for a channel with the typical urban- or hilly-terrain delay profile and a 40-Hz Doppler frequency.

Reduced complexity channel estimation for an OFDM system with space–time coding in time-varying, dispersive multipath fading channels was proposed by Hlaing Minn *et al.* [66]. Particularly, their aim is to minimize the complexity in the matrix inversion required for every OFDM data symbols. The technique has been developed based on a channel with relatively small delay spread. Complexity reduction has been achieved by decoupling the channel responses from several transmit antennas. Specifically, the size of the matrix inverse and the FFTs needed in the channel estimation for each OFDM data symbol has been reduced by half. The simulation results have shown that the cost for the complexity reduction is just a slight BER degradation for channels with relatively small delay spreads.

An iterative receiver for a joint data-detection and channel-estimation scheme in OFDM system, which includes iterative decoding in the receiver, was presented Seung Young Park *et al.* [67]. In the proposed scheme, a maximum a posteriori-based decoder and a channel estimator have provided more dependable information on the coded bits for each other in an iterative manner. Initially, they have considered a practical implementation issue for the optimal minimum mean squared error two-dimensional (2-D) channel estimator as an important element in the iterative receiver. In order to minimize the complexity of the 2-D estimator as suitable to the iterative receiver, they have focused on examining the design aspect of a separable estimator, in order that its design framework may become asymptotically equivalent to that of the optimal 2-D estimator.

A delay spread estimation algorithms for OFDM systems was proposed by Tevfik Yucek *et al.* [68]. Initially, the PDP of the channel has been estimated by the proposed algorithm and then from this estimation, the dispersion parameters have been calculated. It has found that when the channel frequency estimates are used directly, then an estimation error floor has been caused by the timing error and this problem is defeated by using the magnitude of the channel estimates. Furthermore, the channel magnitude- based algorithm has been extended to a method, which utilizes the received signal power in the frequency domain when the transmitted symbols have a constant envelope. The channel and received signal-magnitude based algorithms have been performed well under different situations and the performances of the proposed algorithms have been evaluated using computer simulations. Also, the CRLB for the RMS

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delay spread parameter has been derived and it is used to verify the performance of the proposed methods.

The channel characteristics of OFDM communication system by using the worst case H∞ approach was estimated by Naganjaneyulu *et al.* [69]. Their estimation criterion is different from kalman filter. These two algorithms are not succeeded because of more updating parameters such as V, W and Q. So, they have proposed this worst case H-infinity approach for estimating the signal without updating factors, where the V and W are taken as worst case values. Here, the parameters V and W has been updated only once for the whole recursive estimation process. From the simulation results, they have concluded that with an increase in input SNR, the mean-square-error performance of worst case H∞, H∞ and Kalman estimation algorithms has been improved.

A joint channel-estimation technique for the desired and interfering channels for cell edge users in reuse-1 cellular OFDM systems was developed by Raghavendra *et al.* [70]. They have made some assumptions in proposing the algorithm: i) The desired and interferer's channel multipath delays do not overlap; ii) the same pilot sequence should be sent from the desired and interfering base stations (BSs); and iii) reuse-3 preamble symbols, as in the preamble structure in IEEE 802.16d/e (Wimax) systems, are used to obtain initial channel estimates with no interference. If they make these assumptions, then it is possible to estimate the desired and interfering channels, even with reuse-1 pilots. Simulation results have shown that the performance of the proposed channel-estimation method is better than the LS-based channel estimation technique, when used in conjunction with INC and MMSE-DC detectors.

Two schemes for efficient channel estimation in OFDM-based systems operating in the presence of narrowband interference were proposed by Michele Morelli *et al.* [71]. The latter is modeled as a Gaussian process and its power has been averaged out from the likelihood function using an inverse-gamma distribution. Iterative solutions based on either the expectation-maximization or the Jacobi-Newton algorithms have been used to avoid the direct maximization of the likelihood function over a multidimensional domain. The two schemes such as EMCE and JNCE have used some dedicated pilot sub carriers and provided a channel estimates with less complexity. A comparison has been done with the Cramer-Rao bound and with the conventional channel estimation approach that does not consider NBI into account. An ideal scheme using perfect knowledge of the interference-plus-noise power has also been used as a benchmark. Simulations have proved that the proposed methods are intrinsically robust to NBI and can efficiently be utilized in a severely interfered scenario.

A 2D low-pass interpolation based channel estimation of fast varying OFDM channels was proposed by Mahmut Yalcin *et al.* [72]. This technique has very low complexity. Also, their proposed technique has performed better than the conventional methods and approaches for high mobility environments. It has also been shown that SERs of Zero-Forcer are decreased because of ICI effect or noise enhancement for all cases. They have concluded that the OFDM receiver should be improved using channel encoders for high mobility applications to attain low SERs.

The lower bounds for various parametric mobile wideband MIMO-OFDM channel models were presented by Michael D. Larsen *et al.* [59]. These bounds have been derived using vector formulations of the Cramer–Rao lower bound for the functions of parameters for both biased and unbiased estimators. The Fisher information matrices in the Cramer-Rao Bound (CRB) formulations have been used to obtain a simple block structure allowing for proper representation and computation of the bounds. Numerical evaluations of these bounds have shown some remarkable features about the estimation and prediction of MIMO-OFDM channels.

The performance of OFDM- BPSK & QPSK based system with and without channel estimation in Nakagami-m fading channels was analyzed by Neetu Sood *et al.* [73]. Nakagami-m variants have been produced by the decomposition of Nakagami random variable into orthogonal random variables using Gaussian distribution envelopes. Also, they have evaluated the performance of OFDM system in Nakagami channel. An optimum value of m based on BER and SNR has been obtained from the results. The channel estimation over flat fading has also been measured by using this optimum value of m. From the simulated graphs, it has been shown evidently that channel estimation has further decreased the BER. Moreover, threshold value of m has played an important role during channel estimation.

Various physical layer research challenges in MIMO-OFDM system design as well as channel modeling, space time block code techniques, channel estimation and signal processing

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algorithms, used for performing time and frequency synchronization in MIMO-OFDM system was investigated by Chitra *et al*. [74]. The transmitter and receiver in OFDM combined with antenna arrays can enhance the diversity gain as well as improve the system capability on time variant and frequency selective channels, resulting in MIMO configuration. The proposed system was simulated in MATLAB and analyzed in terms of BER with SNR. They have also evaluated the difference of BER for coded and uncoded MIMO system.

For estimating the LTV channels of MIMO/OFDM systems using superimposed training technique was developed by Xianhua Dai *et al*. [60]. Initially the LTV channel coefficients have been modeled by the truncated DFB, and then a two-step approach has been examined where they have estimated the channel by using the user-specific training sequence. A weighted average procedure has been proposed by using the estimated channel from the first step, in order to improve the channel estimates over multiple OFDM symbols. Moreover, they have presented a performance analysis of the channel estimation approach and derived a closed-form expression for the channel estimation variances. It has been shown that the estimation variances, unlike conventional superimposed training schemes, approach to a fixed lower-bound can only be minimized by increasing the pilot power.

The performance of a MIMO system using a Mismatched Maximum Likelihood Detector (MMLD) with that using a Generalized Likelihood Ratio Detector (GLRD) in the presence of channel estimation errors was compared by Meriam Rezk *et al*. [63]. Two sources of error have been considered such as errors due to noise and errors due to time variations caused by Doppler effects. The MMLD depends on the obtainable channel estimate, while the GLRD combines the channel estimate with a block of received data and employs a joint channel-symbol estimation approach to solve for the transmitted symbols. The GLRD performs better than the MMLD whenever errors in channel estimation are acquired and the performance gap relies on the amount of error. Moreover, the GLRD provides a combined receiver structure which can be used to differentially encoded MIMO systems as well as used in situation where no channel estimate is available as in blind MIMO. The enhanced performance of the GLRD has produced an increased computational complexity. This problem has been addressed by search efficient algorithms based on the branch-estimate-bound optimization framework. They have examined the performance of the GLRD and provided a tight upper bound on the BER of the system at high SNR. Simulation results have been shown for a 2 × 2 MIMO system.

A MIMO-OFDM based channel estimation technique was proposed by Deeparani Mishra *et al.* [64]. The MIMO system has been developed using multiple antennas, where the Space Time Block Coding (STBC) has been examined over Rayleigh's flat fading channel. The concept for wireless communication using MIMO-OFDM has been considered and tested step-by-step. They have evaluated the noise analysis, BER, and Symbol Error Rate (SER). The comparison result of LS method and MMSE method has shown the performance for slow fading environment that leads to further improvement.

2.6. The Performance Review

Best performance i.e. BER vs SNR obtained for different channel estimation methods in recent literature works are discussed below. In the above section more number of recent literature works is discussed for different channel estimation methods. The performance of the method was from older works to the most recent works, so that the performances of most recent works from each category of channel estimation methods are discussed below.

i. Channel estimation in OFDM using pilot based method [82].

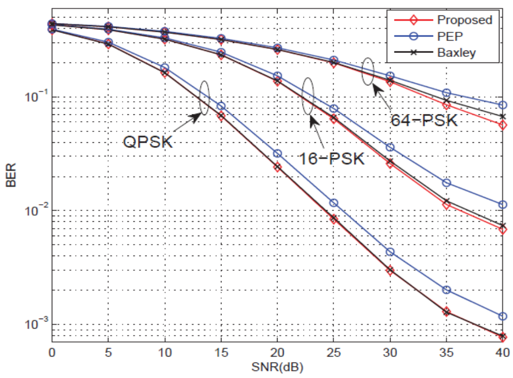

Figure 2: Comparison of the BER vs SNR performance graph for $N_p = 16$ (IEEE 802.16e)

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ii. Channel estimation in OFDM using RLS and LMS method [92].

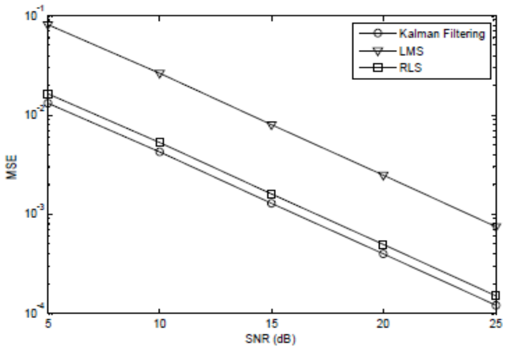

Figure 3: BER vs SNR graph for LMS, RLS and kalman based method.

iii. Channel estimation in OFDM using blind channel method [88].

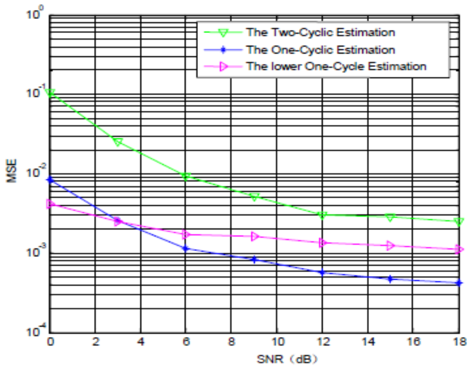

Figure 4: BER vs SNR graph for M=2, L=4, 1000M data.

iv. Channel estimation in OFDM using LSE and LMMSE method [106].

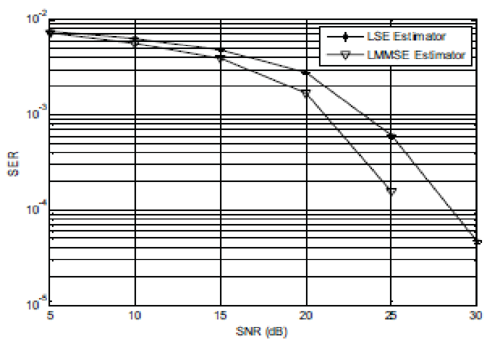

Figure 5: BER vs SNR graph LSE and LMMSE estimator

v. Channel estimation in OFDM using LSE and LMMSE [107].

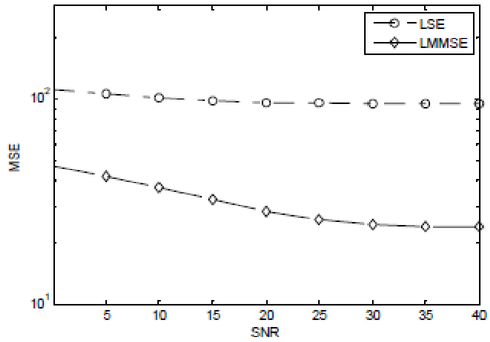

Figure 6: BER vs SNR graph LSE and LMMSE estimator for 2 x 2 systems.

vi. Channel estimation in OFDM using MMLD [63].

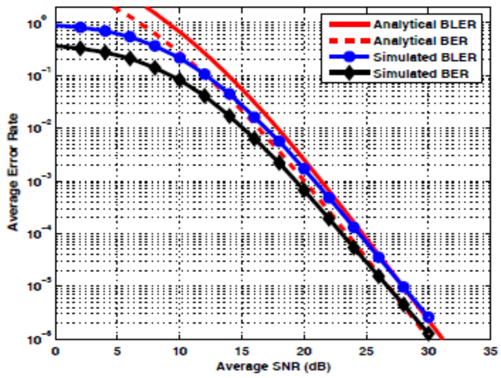

Figure 7: Analytical and Simulated BLER and BER for a GLRD with $P = 2$ and $\beta = 0$

3. DIRECTION FOR THE FUTURE WORK

In this review paper, different methods for computing the channel estimation in MIMO-OFDM system are presented. Analysis has been done based on pilot based, LS & MMSE method, LMS & RLS methods and other methods for channel estimation. Among the other methods, LS and MMSE methods are utilized mostly in which the error value is relatively lesser than the other methods. Hence in future, the scope of channel estimation methods would be more positively in enhancing the present LS and MMSE channel estimation method, so that estimation error can be made even further. This paper will be a healthier foundation for the budding researchers for identifying appropriate channel estimation techniques in the MIMO-OFDM.

4. CONCLUSION

In this paper, a broad review of the significant researches and techniques that exist for MIMO-

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OFDM channel estimation is pursued. Here the researches are first categorized in to MIMO, OFDM and channel estimation methods sections and are explained briefly. Then recent works related to different channel estimation methods like pilot based, LS & MMSE method, LMS & RLS methods and other methods used in channel estimation are reviewed and for more recent works performance of each channel estimation methods was analyzed. From the performance results it is clear that, the error value was low in LS and MMSE channel estimation methods. From the review, it can be concluded that further enhancements/modifications in the LS and MMSE channel estimation methods will improve the performance of the future channel estimation methods by obtaining very less estimation error. Thus, this review paves the path for the budding researchers to get acquainted with the various techniques existing in the channel estimation in MIMO-OFDM.

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