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OPTIMIZING CHANNEL ESTIMATION IN MIMO-OFDM SYSTEMS USING SWARM INTELLIGENCE ALGORITHMS AND HYBRID PILOT-BASED METHODS

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Abstract:

With the increasing demand for high data rates and reliable communication in modern wireless systems, MIMO-OFDM has become a critical technology to address these needs. However, the accuracy of channel estimation remains a significant challenge in MIMO-OFDM systems, particularly due to the complexity introduced by multiple antennas and fading channels. This paper explores the application of swarm intelligence optimization algorithms, particularly the Bald Eagle Search Optimization Algorithm (BESOA), for enhancing channel estimation in MIMO-OFDM systems. We combine BESOA with traditional pilot-based methods like Block Type and Comb Type pilots to address the computational complexity and improve estimation accuracy. Additionally, the paper investigates the use of Time-Frequency Training (TFT) techniques, which integrate time and frequency domain training symbols for more precise channel estimation. The performance of the proposed hybrid approach is evaluated through simulations comparing it with traditional Least Squares (LS) and Minimum Mean Square Error (MMSE) methods. Results demonstrate that the BESOA-optimized MIMO-OFDM system significantly outperforms conventional methods in terms of Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and computational efficiency, showcasing the potential of swarm intelligence in optimizing communication systems. This study paves the way for future advancements in MIMO-OFDM optimization strategies.

Keywords: MIMO-OFDM**,** Channel Estimation**,** Pilot-Based Methods**,** Time-Frequency Training (TFT)**,** Swarm Intelligence Algorithms**,** Bald Eagle Search Optimization Algorithm (BESOA)**,** Optimization**.**

INTRODUCTION

MIMO technology has garnered interest in the telecommunications sector due to its potential to boost data transmission rates without increasing either the required bandwidth or the transmit power. Improvements in OFDM performance are expected thanks to recent advances in MIMO methods. The performance advantages of OFDM technology are achieved by delivering data independently from many antennas, which necessitates a large number of antennas at both ends of the wireless networks. The MIMO-OFDM combines MIMO with orthogonal frequency division multiplexing, which greatly simplifies equalisation in MIMO systems and allows for the inclusion of additional antennas. Enabling MIMO-OFDM combines MIMO with orthogonal frequency division multiplexing, which significantly simplifies equalisation in MIMO systems and allows for the inclusion of additional antennas.Integration of MIMO and Orthogonal Frequency Division techniques MIMO - OFDM systems, which use multiplexing technology, allow for data speeds for indoor wireless systems of hundreds of Mbps and spectral efficiency of tens of bits/Hz/s, both of which would be impossible with traditional single-input single-output systems(Karam et al. 1995).

In order to implement MIMO-OFDM with N subcarriers, separate data streams must first undergo IFFT at the OFDM modulators, then undergo parallel-to-serial conversion. The transmitted OFDM symbols have a cyclic prefix appended to them before being sent to the OFDM demodulators, where the CP is removed and an N-point FFT is performed(Wang et al. 2012). The OFDM demodulators' primary outputs are isolated and decoded. The MIMO systems provide potential answers to the dilemma of rising requirements for high-quality, high-bit-rate communication. The receiver's ability to recognise the broadcast signal efficiently depends on its familiarity with Channel State Information. Secure information for coherent detection of message symbols is a difficulty in MIMO-OFDM systems. Different estimation procedures, including as training-based, blind, and semi-blind estimation of the channel, are used to estimate the channel's state. The only-receiver-knows-what-they'redoing blind estimate is used for teaching symbols or pilot tones(Knievel & Hoeher 2012). In order to estimate the channel, these training symbols are multiplexed with the data stream. To achieve channel estimate, semi-blind methods use a mix of traditional blind channel estimation plus training using pilot carriers. Such pilot sequences are the unmodulated data which transmit data, and such pilots are used for the estimation of a channel and its synchronization. There are more pilots that are efficiently estimated and can increase the capacity of the channel. But the increase in the pilot also increases the overhead. The MIMO-OFDM scheme that is spectrally efficient will be identified as the TFT-OFDM (Kristam & Doss 2014).

TFT-OFDM

TFT-OFDM refers to the acronym for Time and Frequency Training Orthogonal Frequency Division Multiplexing. The term "it" pertains to the temporal training sequence and the pilots that are grouped together in the frequency domain. The TFT-OFDM scheme is considered to be highly efficient, exhibiting superior performance compared to alternative schemes.

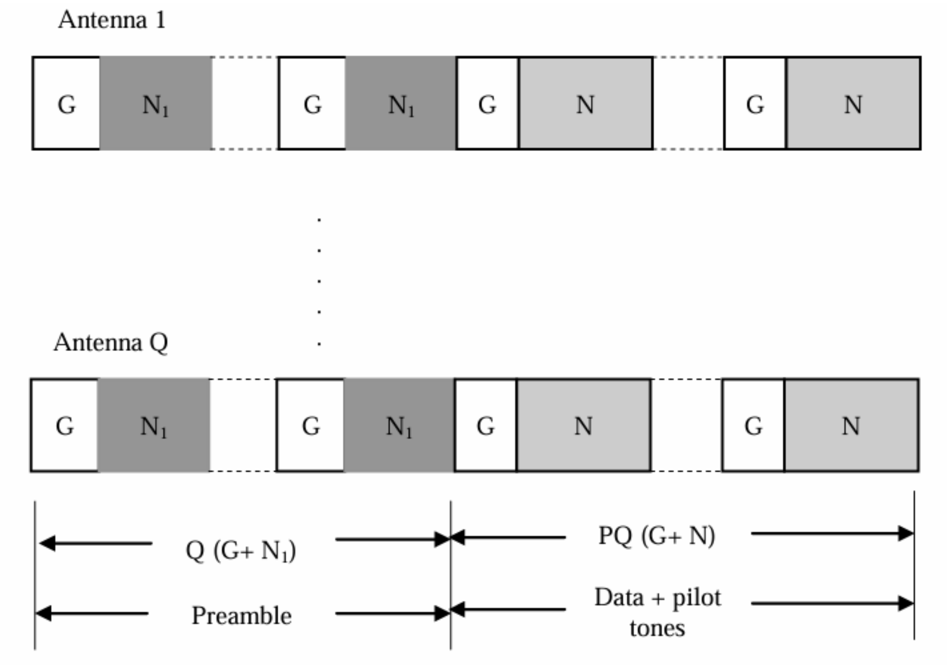
The channel estimation technique utilised in Time-Frequency-Division Multiplexing (TFT-OFDM) is based on a dual-domain approach, as described by Das & Bansode (2016). The primary use of the Training Sequence (TS) is in estimating the value of the channel route delay and parameters in the frequency domain. The TS is located within the time domain. The interference resulting from these time slots may be eliminated if the channel estimation is accurate. In order to obtain an accurate estimation of the channel, it is necessary for the OFDM data block to possess random characteristics and remain unknown (Ali & Aghdam 2019). This issue of estimation is decoupled into the antennas. But in case of the enhanced training based techniques, the correlation among several antennas is considered. This does not mean that such enhanced methods of training in case of smaller subgroups will receive antennas that are not used or used as a means of another approach where the performance may not be similar. An optimal method is found for this channel estimation, and this has a high computation cost.

Limitations

A proper estimation of a channel is needed for performing this efficiently as a measure for the receivers. Matrix inversion is incorporated to this resolution, and this is incorporated into that resolution, and a popular Least-Squares or the Minimum Mean Square Error estimator is not proficient and a Maximum Posterior Probability (MAP) is shown to generating the channel estimation algorithms and their optimal results compared to the LS or the MMSE techniques. Such computational complexity is very high when the MAP is applied to that of the MIMO-OFDM systems making a poor choice of mobile devices. Solving issues of the real world problems is a challenging task and the proposed tools of optimization are used to find solutions. Therefore such issues may be sorted out using a trial and error method with many such techniques of optimization.(Aboulfotouh et al. 2022)

MIMO-OFDM

Using OFDM, the frequency-selective MIMO channel may be converted into a set of parallel flat-frequency subchannels. The first stage in an N-subcarrier MIMO-OFDM system is to pass the data streams via separate OFDM modulators. This method first involves a parallel-to-serial conversion, and then an Inverse Fast Fourier Transform (IFFT) is performed on blocks of length N. The given requirement must be satisfied by the length of the cyclic prefix L Lcp . Every transmitter antenna starts to send out OFDM signals with an approximate length of N + Lcp simultaneously. Disturbance among OFDM signals may be eliminated and linear convolution can be converted to circular convolution with the use of a protective interval called a cyclic prefix (CP). Using Fast Fourier Transform (FFT) in circular convolution, which is the channel may be diagonalized. After arriving at the destination, each of the signals undergo OFDM demodulators, typically remove the cyclic prefix and run N-point Fast Fourier Transform. Separation and decoding of the OFDM signal's outputs take place(Bana et al. 2019).



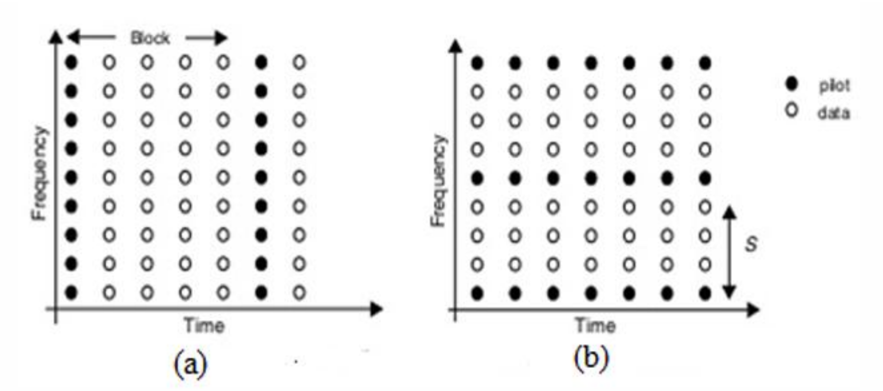
Frame structure for the MIMO-OFDM system

shows the frame structure of a typical MIMO-OFDM system.

Channel Estimation

In a comprehensive framework, a channel can be delineated as a physical conduit through which radio signals are conveyed from an origin to a destination. The channel model is characterised by a mathematical framework that provides a depiction of the transfer properties of the physical medium (Tang et al. 2019). The development of channel models has been undertaken by analysing the signal characteristics detected in the received signals, as outlined by Negi et al. in their 1998 publication.The primary objective of channel estimation is to analyse and describe the properties of the physical medium and its influence on a given input sequence. The fundamental goal of this approach is to minimise the mean square error while simultaneously ensuring a low level of complexity.

In the context of channel estimation, a common approach involves the integration of pilot symbols into the subcarriers of the orthogonal frequency-division multiplexing (OFDM) signal. The practise of incorporating pilot symbols into designated subcarriers, in conjunction with the aforementioned approach, is widely known as pilot-based block type estimate. This methodology is commonly utilised in a channel with slow fading.The channel estimation strategy that employs a comb-type methodology entails the placement of pilot symbols within the subcarriers of each orthogonal frequency division multiplexing (OFDM) symbol. Alternative approaches, such as linear interpolation, spline cubic interpolation, and temporal domain interpolation, utilise similar methodologies.



Basic Pilot Pattern (a) Block Type pilot (b) Comp Type pilot

In order to maintain consistency across a limited number of OFDM symbols and block fading channels, a channel will be uniformly incorporated across all subcarriers for the OFDM blocks, including their respective pilots (Marzetta et al. 2016). The pilot arrangement depicted in Figure (3.4a) is of the block type. In case of a channel alteration, the rapid fading channels during the pilot times will be conveyed with spacing on subcarriers that signify a comb-shaped pilot arrangement, as illustrated in Figure (3.4b). The pilot subcarriers are to be interpolated with the data subcarriers to estimate the channel (Dong et al. 2019). The subsequent segment delves into the evaluation of the channel in the context of a pilot arrangement utilizing block type methodology. The pilot subcarriers will incorporate the channel coefficients, which will be evaluated using the least squares (LS) technique.

The channel estimator for LS shall be denoted by Equation (3.1).

$$\hat{H}_{LS} = X_d^{-1} Y \qquad (3.1)$$

In which $X_d = diag\{X(0), X(1)\ldots,.X(k-1), Y = [Y(0), Y(1), \ldots., Y(k-1)]$

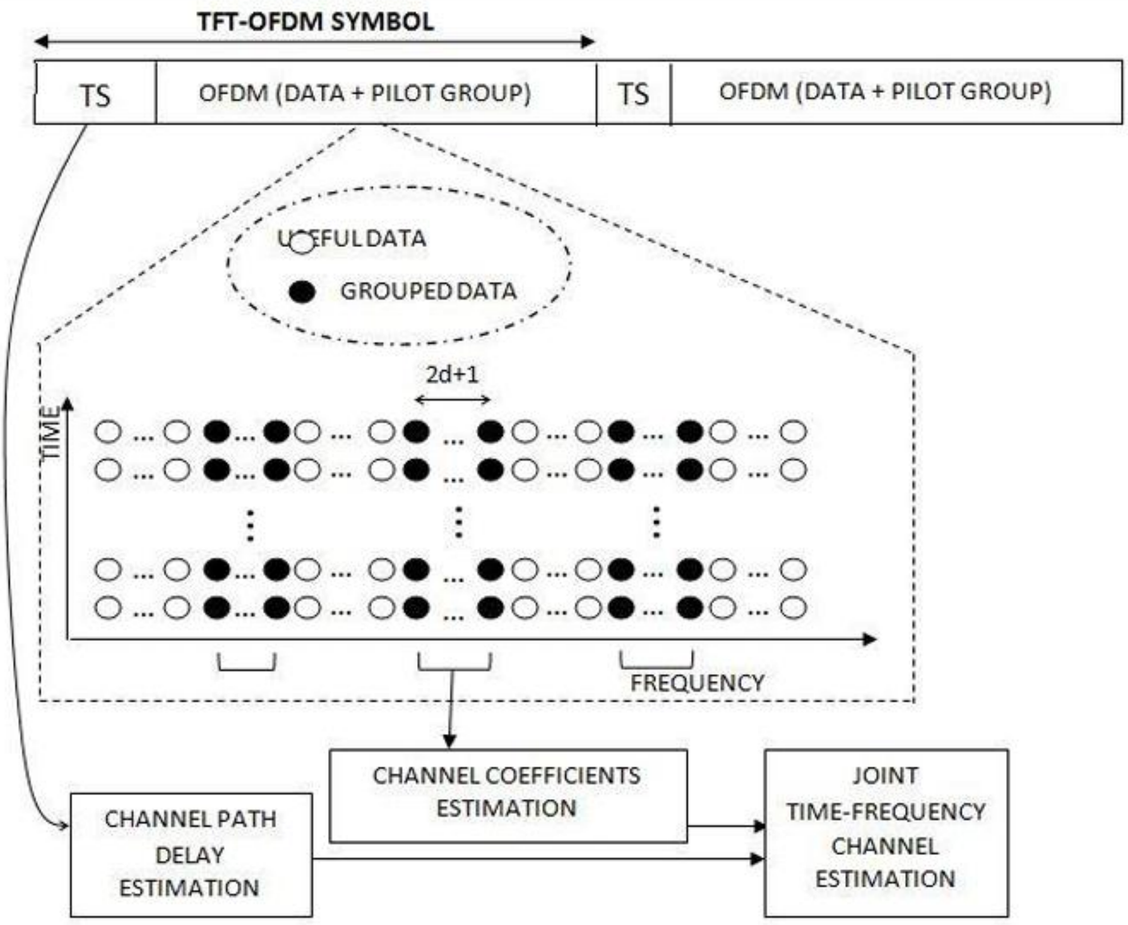
In the case of the MIMO-OFDM system, an LS channel estimation between the NT transmitter and the NR receiver antenna has been defined as

$$\hat{H}_{LS}^{(\hat{N}_T,\hat{N}_R)} = \left(X^{(N_T)}\right)^{-1} Y^{N_R} \qquad (3.2)$$

The LS channel estimation method is widely used and well-known for its simplicity in estimation. It involves matrix inversion and is commonly employed in pilot symbol-based estimation. LS estimation requires only the multiplication of the received signal with a matrix, making it computationally efficient and suitable for real-time calculations. In wireless communication systems, the standard method employed is known as Cyclic Prefix OFDM (CP-OFDM). CP-OFDM utilizes a cyclic extension of the OFDM symbol, where a portion of the symbol is repeated and appended to the beginning. This cyclic prefix acts as a guard space, effectively eliminating both Inter-Symbol Interference (ISI) and Intercarrier Interference (ICI) that can occur due to channel effects. By mitigating these interferences, CP-OFDM ensures reliable communication and improves the system's robustness against multipath fading. An alternative variant of CP-OFDM is Zero-Padding OFDM (ZPOFDM). In ZP-OFDM, the non-zero cyclic prefix of CP-OFDM is replaced with zero-padding. This modification allows for better equalization performance by utilizing zero samples, which help mitigate distortion caused by the channel. The inclusion of zero samples can improve the overall quality of the received signal and enhance the system's performance in challenging wireless environments. However, both CP-OFDM and ZP-OFDM rely on the use of domain pilots for channel estimation and synchronization. Pilots are specific symbols inserted in the transmitted signal, which carry known information. These pilots serve as reference signals and are utilized to estimate the communication channel's characteristics and synchronize the receiver with the transmitter. While effective, the reliance on pilot symbols comes at a cost to spectral efficiency since valuable bandwidth is allocated to carrying the pilot information.

JOINT CHANNEL ESTIMATION IN THE TIMEFREQUENCY DOMAIN

The channel tracking process for TFT-OFDM involves utilizing the time-frequency joint channel estimation method to derive the channel information from the time-frequency training symbol (Sun et al. 2020). This is achieved through a series of sequential steps. One possible topic of study is the utilization of time-series (TS) methodology for the estimation of path delay (Prasad et al. 2011). A method of estimating path gain using pilot signals. Figure 3.5 depicts the schematic representation of a joint estimation approach in the time-frequency domain.



Time – Frequency Joint Channel Estimation

The Training Sequence of ith TFT-OFDM symbol received has been defined as (3.3)

$$d_i = \sum_{p=1}^{N_t} \left(h^{(p)}_{-i,ISI} \, z_i^{(p)} + h^{(p)}_{-i,IBI} \, x^{(p)}_{i,N-M:N-1} \right) + v_i \qquad (3.3)$$

and in the second term, the received TS in the di is contaminated by an IBI, through preceding the OFDM data blocks. Even without the cancellation of the interference, a path delay is considered as leading to an inaccurate estimation. On the basis of the wireless channels in which the variation the path delay slower than that of the path gains (Zhang et al. 2021), the actual averaged path delay and its estimation for the β adjacent TFT-OFDM symbols taking β are considerably (> 10). This averaged path delay, and its estimation is shown as (Figure 3.6), and their path gains are discarded directly as it is inaccurate owing to the absence of cancellation of interference (Ren et al. 2021).

$$\bar{h}_i^{(p)} = \frac{1}{\beta} \sum_{u=i-\beta+1}^{i} \bar{h}_i^{(p)} = \frac{1}{\beta M} z_u^{(p)} \otimes \left(\sum_{u=i-\beta+1}^{i} d_u \right) \qquad (3.4)$$

These path gains are calculated for the significant taps Q that are lower than length of the channel which is L, i.e, Q <<L leading to the reduction in the unknown parameters of the $h_i^{(p)}$ from L to Q , where only a small size group pilots in the frequency-domain are sufficient to obtain a channel path gain (Zhang et al. 2021). The central pilots that are received owing to orthogonality of grouped pilots in different transmit antenna, is as per (3.5)

$$Y_{i,k} = \sum_{p=1}^{N_t} X_{i,k}^{(p)} H_{i,k}^{(p)} + W_{i,k} = H_{i,k}^{(p)} + W_{i,k}, \; k \in G^{(p)} \qquad (3.5)$$

In which the central pilot $X_{i,k}^{(p)} = 1$, $k \in G^{(p)}$ and $X_{i,k}^{(u)} = 0$, $u \neq p$, $k \in G^{(p)}$. A matrix form of the original Equation (3.6),

$$Y_i^{(p)} = F_N^{(p)} h_{i,\Gamma}^{(p)} + W_i^{(p)}, \; 1 \le p \le N_t . \qquad (3.6)$$

The comprehensive channel impulse response (CIR) $\{\hat{h}^{(p)}\}_{N_t}$ for all communication antennas N_t, as expressed in equation (3.7), is obtained through the integration of path delays derived from a time-domain obtained TS di, as well as path gains derived from a frequency-domain (20) obtained pilots

$$\left\{ \hat{Y}_i^{(p)} \right\}_{p=1}^{N_t} \cdot \; \hat{h}_{i,\Gamma}^{(p)} = \left(F_N^{(p)} \right)^{\dagger} Y_i^{(p)} = \left[\left(F_N^{(p)H} F_N^{(p)} \right) \right]^{-1} \left(F_N^{(p)} \right)^{H} Y_i^{(p)} \qquad (3.7)$$

BALD EAGLE SEARCH OPTIMIZATION ALGORITHM (BESOA) ALGORITHM

An example of a naturally-inspired optimization algorithm, the Bald Eagle Search Optimization Algorithm (BESO) is modelled after the strategies used by bald eagles during their hunts. In place of time-honored optimization strategies, Dr. Seyedali Mirjalili introduced it in 2015. Bald eagles are known for their hunting ability, which involves scanning large areas of land for prey, then diving down to capture it with precision and speed. BESO mimics this behavior by iteratively searching for the best solution to an optimization problem.

BESOA is inspired by the behavior of bald eagles, known for their excellent hunting skills and efficient searching strategies. The algorithm starts by initializing a population of potential solutions, representing different candidate solutions to the optimization problem. The population is divided into several subpopulations, called eagle nests, each containing a set of solutions. In each iteration, the algorithm performs three main steps: search, prey capturing, and nest updating. Search: Bald eagles search for prey by exploring the environment. In the algorithm, this corresponds to individuals in each nest searching for better solutions in their local search space. Prey Capturing: Bald eagles capture prey by evaluating the fitness of potential solutions. In the algorithm, this step involves evaluating the objective function of each solution in the population. Nest Updating: Bald eagles update their nests based on the captured prey. Similarly, in the algorithm, nests are updated by selecting and replacing inferior solutions with better ones.

Conclusion:

In this study, we explored the optimization of channel estimation in MIMO-OFDM systems using swarm intelligence algorithms, specifically the Bald Eagle Search Optimization Algorithm (BESOA), alongside hybrid pilot-based methods like Block Type and Comb Type pilots. The integration of Time-Frequency Training (TFT) further enhanced the accuracy and reliability of channel estimation. The BESOA-based approach demonstrated significant improvements over traditional methods such as Least Squares (LS) and Minimum Mean Square Error (MMSE), achieving superior performance in terms of Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and computational efficiency. These results underline the potential of combining optimization algorithms with MIMO-OFDM systems to address the complexities of modern wireless communications. The findings pave the way for future research into advanced optimization techniques that can further enhance MIMO-OFDM performance in dynamic and complex wireless environments.

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