A Comprehensive Review on Various Estimation Techniques for Multi Input Multi Output Channel

Awwab Qasim Jumaah Althahab **Sameer Abdul Kadhim Alrufaiaat**

Department of Electrical Engineering, Collage of Engineering, University of Babylon, Babylon,Iraq

eng.awwab.qasim@uobabylon.edu.iq, awwabq@yahoo.com samirabdcathem@yahoo.com

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Abstract

The problem of wireless channel estimation has been evolving due to some undesirable effects of channel physical properties on transmitted signals. At the receiver end, distortions, delays, attenuations, interferences, and phase shifts are the most issues encounter together with the received signals. In order to overcome channel effects and provide almost a perfect quality of data transmission, channel parameter estimation is needed. In Multiple Input-Multiple Output systems (MIMO), channel estimation is a more complicated step as compared with the Single Input-Single Output systems, SISO, because of the fact that the number of sub-channels that needs estimate is much greater than SISO systems. The fundamental objective of this research paper is to go over the famous and efficient algorithms that have been innovated to solve the problem of MIMO channel estimation in wireless communication systems. In this paper, these techniques have been classified into three groups: non-blind, semi-blind and blind estimation. For each group, a brief illustration is presented for familiar estimation algorithms. Finally, we compare between these techniques based on computational complexity, latency and estimation accuracy.

Keyword: Adaptive channel estimation, Blind source separation, Artificial neural networks and Hybrid optimization algorithms.

1. Introduction

The physical environment of a wireless communication channel between a transmitter and receiver can affect transmitted signals in a complicated manner. Diffraction of the electromagnetic waves, signal scattering and reflections due to large objects such as infrastructures, mountains and other obstruction are the most interactions that signal transmitted suffer from. Therefore, signals received at the receiver end have different phase shifts, distortions, interferences, delays …etc. Furthermore, a relative movement between the receiver and transmitter or the nature of time variation in the wireless communication channel generates what so called a Doppler shift, which is another implementation in the wireless channel. A model for the multipath effect in the wireless communication channel can be shown in Fig. 1 [1]. As illustrated from the Fig. 1, each signal transmitted from the mobile users, remote dominant reflector and local scatters arrives at the base station as multipath signals. They have a different phase shift, Doppler shift, amplitude and time delay [2]. Therefore, diversity using multiple independent communication channels has been proposed to overcome the effects of multipath fading. A MIMO system that has been one of the modern technologies provides full transmission diversity (reliable communication and wide coverage). The reason is that its receptivity for multiple broadcast features, robustness against multipath fading and interference, high data transmission rate as well as spatial multiplexing reuse [3].

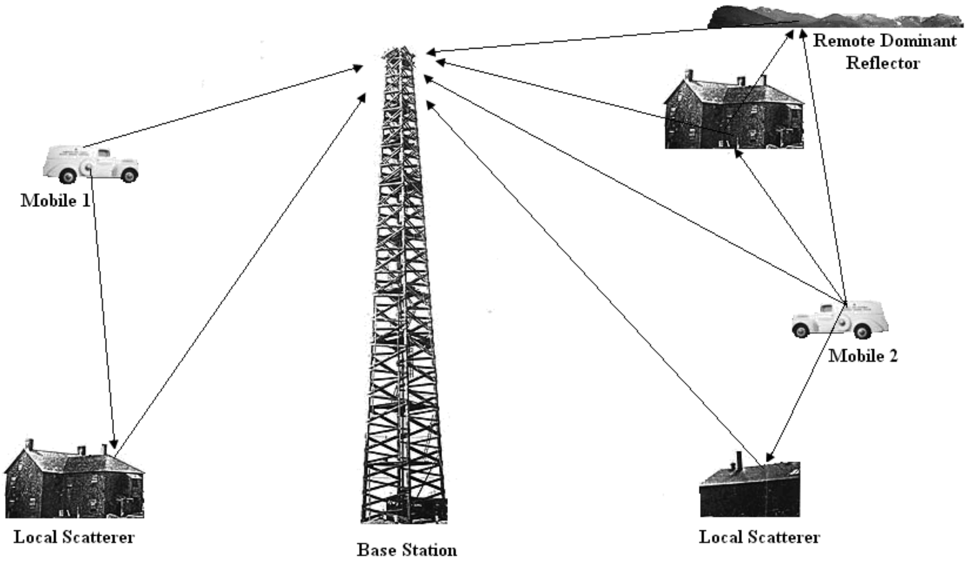

Figure 1: A typical wireless communication channel with Multipath propagation [1]

The channel estimation process is a major challenging task in any wireless communication system. This process gives important information about different interactions happened to signals when they pass through the channel. Therefore, it is utilized for delicate decoding, signal demodulation as well as equalization processes. The overall wireless communication performance, such as capacity, signal to noise ratio (SNR) and bit error rate (BER), relies on the precise estimation of channel parameters at the receiver. How perfectly update the channel parameter is based mainly on estimators used [4]. Recently, channel estimation has been applied for the MIMO system to receive signals with the minimum error rate at the receiver side using a variety of estimation techniques. Many researchers have addressed this problem and developed a numerous amount of techniques for estimating wireless channel parameters to provide what is called channel state information, which is abbreviated as CSI, at the receiver ends: hence, a huge loss in SNR can be prevented. A review of some recent methods for estimating wireless communication channel parameters are discussed in this review paper.

The structure of this review article is as follows: Section 2 describes MIMO channel models based on fading phenomena. In Section 3, preview works of channel estimation techniques are presented. Finally, remarks concluding the survey are given in Section 4.

2. MIMO Channel Model

In a wireless communication system, a high data rate can be accomplished when transmitter and receiver have multiple antennas. A system is referred as a MIMO when it comprises of multiple antennas at the transmitter side as well as multiple antennas at the receiver side. This system provides a high capacity for wireless systems, and it is directly proportional to the number of antennas. Meaning, as the number of antennas increases, the capacity increases as well. Another important feature of the MIMO system is improving the signal quality and reducing the Bit Error Rate (BER) using suitable diversity encoding technique. Many categories of diversity techniques have been found. One of them seeks to maximize spatial diversity in order to promote the power efficiency. Space-Time-Block-Code (STBC) and Space-Time-Convolutional-Code (STCC) are the most popular diversity techniques within this category. However, the second one aims to increase the system capacity by utilizing a layered approach using Vertical-Bell –Layered-Space-Time (VBLAST) in which a full spatial diversity is usually not achieved. Historically, the evolution of wireless cellular systems has been fueled by the need for increased throughput. The necessity for a more considerable data rate drove to combine multi-carrier modulation techniques such as OFDM, OFDMA, BFDM, FBMC and GFDM along with the MIMO system [5-7].

MIMO system composes of a transmitter, a channel and a receiver, and their notations are as follows: TX, H and RX, respectively. In this paper, N_t and N_r is the number of antenna elements at the sender and receiver, respectively, as can be illustrated in Fig. 2 [5-6].

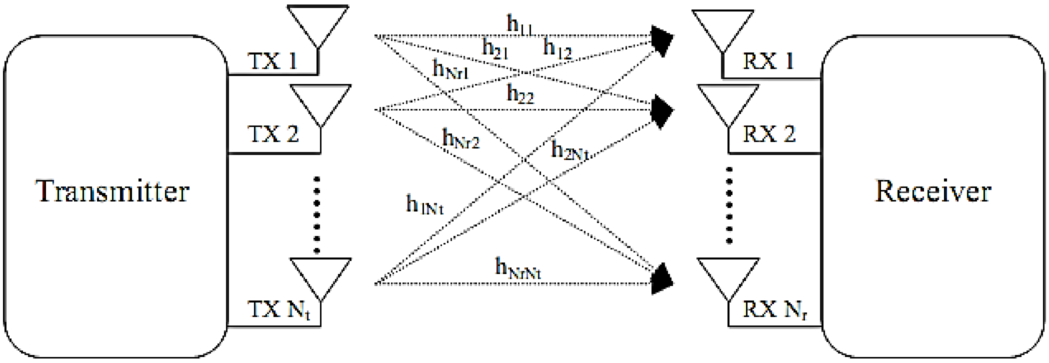

Figure 2: Basic block diagram of MIMO system [5]

The channel matrix H having $N_r \times N_t$ dimensions can be written as:

$$H = \begin{pmatrix} h_{11} & \cdots & h_{1N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r1} & \cdots & h_{N_rN_t} \end{pmatrix} \quad (1)$$

Where each entry h_{ij} defined in equation (2) represents the attenuation α_{ij} and delay τ_{ij} between the j^{th} transmitter and the i^{th} receiver [7].

$$h_{ij} = \alpha_{ij} e^{-j\omega\tau_{ij}} \quad (2)$$

MIMO channel is said to be a quasi-stationary channel when it cannot vary within a transmission time whereas it randomly changes between a block to block. The transmission time is referred to be a coherent time. A quasi-stationary can be achieved by keeping the block length less than or equal the coherence time [8].

3. MIMO Channel Estimation Techniques

In the MIMO channel, the observed signal received at the receiver side is often deformed due to the channel characteristics. A process of channel estimation provides enough information about any distortion occurred to the signals transmitted through the channel. The wireless system performance depends mainly on the updated and accurate estimation of channels, which then can be used for an equalization process, signal demodulation process and decoding process [9-10].

In this section, a review of various channel estimation techniques that have been efficiently developed and evolved recently for the use in MIMO communication systems is presented. The estimation techniques can be divided into three groups that include non-blind, semi-blind and blind estimation. The following sub-sections illustrate an adequate overview of each category.

3.1 Non-Blind Channel Estimation

In this type of technique, pilot symbols are employed to estimate the channel response. The transmitter and receiver should have full information about those pilots. It is important to position the pilot symbols as much as the coherence time, so that time-varying channel characteristics can be kept tracked. However, the drawback of using the pilots is the minimization of the throughput. Consequently, these techniques are unsuitable when the bandwidth is rare [11].

The notion behind the non-blind estimators is positioning a pilot symbol sequence, let say T, at the inception of each transmitted frame of symbols. Then these sequences can be used by channel estimator to estimate the channel matrix H consisting of fading coefficients, during the estimation period. Finally, maximum ratio combiner MRC receives them such that the received signal can be decoded as depicted in Fig. 3. This type of approach is very functional for a quasi-stationary MIMO channel due to the fact that the channel matrix H is constant. However, this technique needs pilots to be transmitted together with data symbols and what the cause is a reduction in the transmission efficiencies. To overcome this problem, the number of pilots must be reduced, whereas inefficient performance is achieved using short training sequences [5] and [11]. There are several non-blind estimation algorithms. The most popular estimators will be explained in the next sub-sections.

a) Algebraic Estimator

The matrix T consisting of pilot symbols is selected to be a diagonal matrix in this estimator, and it can be expressed as in equation (3).

$$T = \begin{bmatrix} T_1 & 0 & \cdots & 0 \\ 0 & T_2 & & \\ \vdots & & \ddots & \vdots \\ 0 & & \cdots & T_{N_T} \end{bmatrix} \quad (3)$$

At the first time slot, pilot symbol T_1 is transmitted through the first antenna while the transmission of other antennas is inactive; thus the received signal at the jth antenna is:

$$r_j = h_{j1}T_1 + Noise_j \rightarrow h_{j1} \cong r_j/T_1 \quad (4)$$

At the second time slot, pilot symbol T_2 is transmitted through antenna number 2 while the transmission of the rest of antennas is idle ➔$h_{j2} \cong r_j/T_2$ and so on [12].

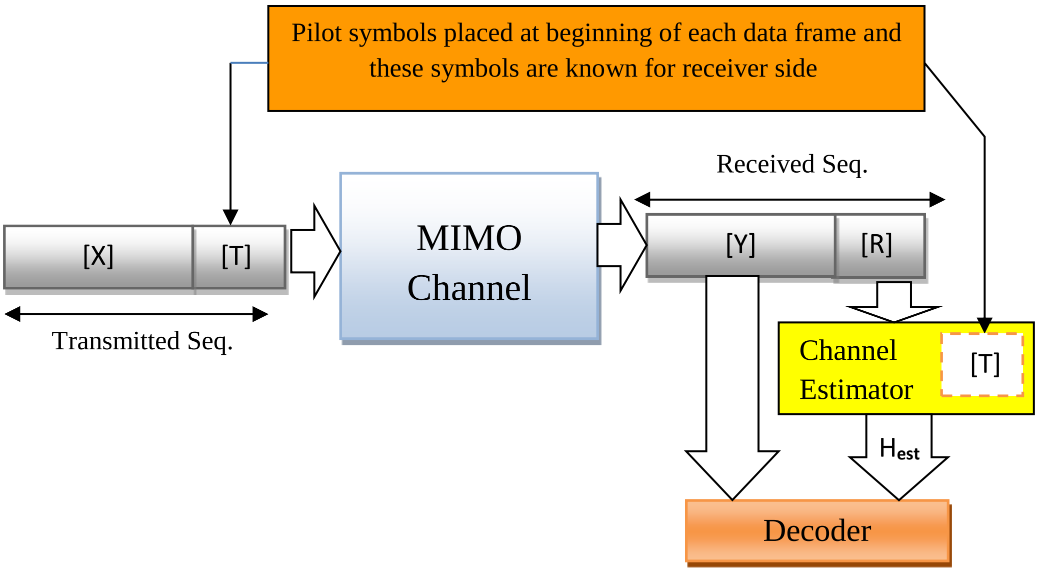

Figure 3: non-blind channel estimation process [12]

b) Least-Square Channel Estimation (LS)

In this technique, the pilot symbols matrix T is chosen to be an orthogonal matrix. The least-square algorithm detects the estimated channel matrix H_{LS} so that the cost function $|| R - H_{LS}T||^2$ is minimized. If the cost function tends to zero then [6] and [13].

$$H_{LS} = RT^H(TT^H)^{-1} \quad (5)$$

c) MAP Channel Estimation

An alternative estimation method is Maximum A Posteriori (MAP) that has reliable performance in the Rayleigh fading channel. A knowledge of channel covariance, pilot sequence, and noise covariance is required at the receiver in this type of estimator. The system of MAP estimation is similar to that described for LS estimation. A posteriori probability density function, which is$p(H|r,X)$, is maximized by the MAP estimation, leading to

$$H_{MAP} = (T^H C_n^{-1} T + C_h^{-1})^{-1}(T^H C_n^{-1} R) \quad (6)$$

where C_n , C_h are the covariance matrix of noise and channel, respectively [6].

3.2Adaptive Semi-Blind Channel Estimation

In a non-blind estimator, good performance is obtained when a pilot sequence length is high, but the consequence is reduced in the transmission efficiencies. Semi-blind estimator needs fewer pilots, which is called training symbols, while its performance can be better during adaptation as displayed in Fig. 4. The semi-blind channel estimation techniques based on superimposing periodic training sequences require known inherent information of the transmitted signal like signal constellations, first order statistics, etc. [14-17]. The well-known adaptation techniques utilized in the semi-blind channel estimator are

- ML: Maximum Likelihood channel estimator.
- LMS: Least-Mean-Square channel estimator.
- MMSE: Minimum-Mean-Square-Error channel estimator.
- RLS: Recursive-Lest-Square channel estimator.
- Channel estimator based on Artificial Neural Network (multilayer perception (MLP), MAXNET ANN, etc.)

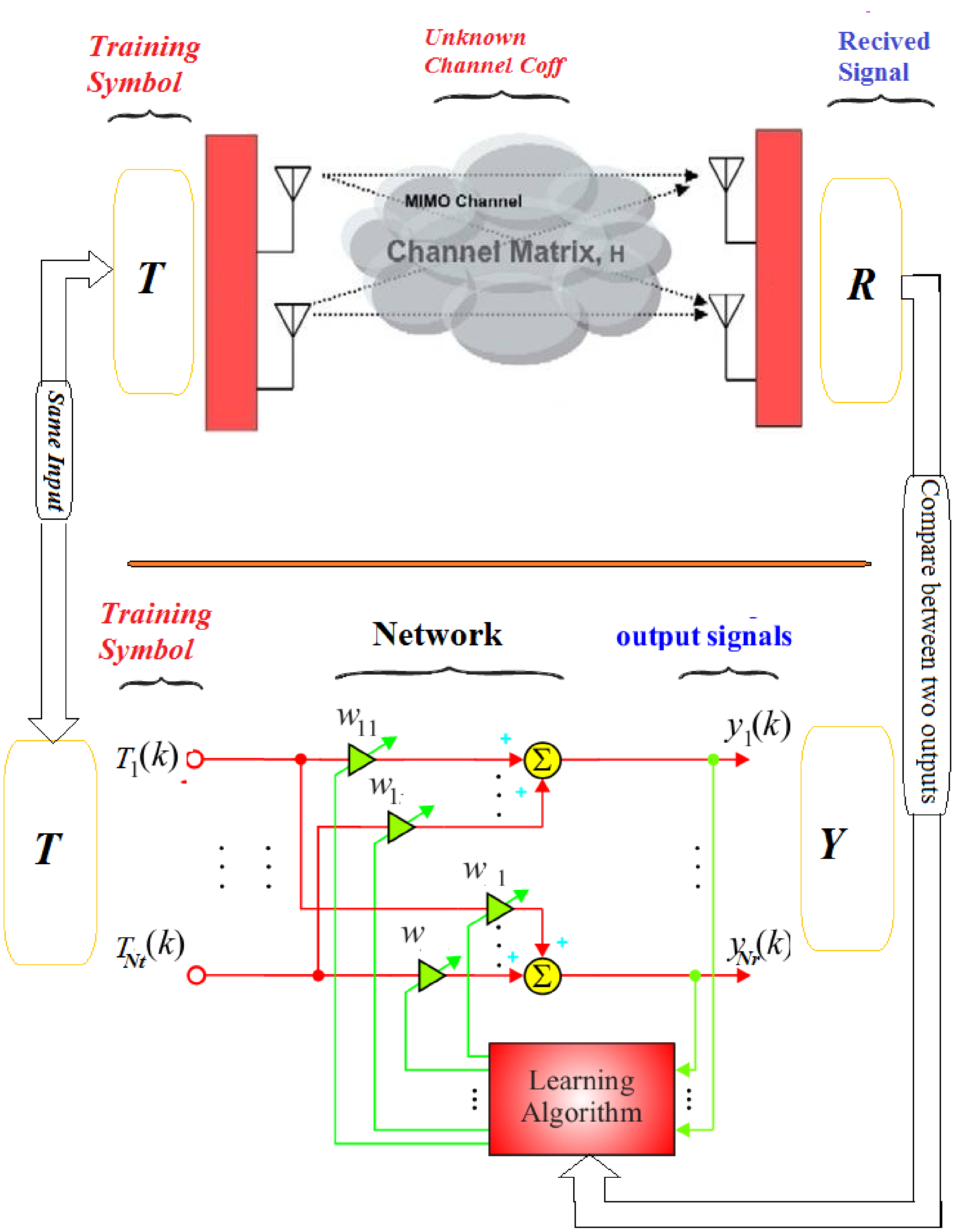

Figure 4: The process of Semi-blind channel [17]

All these algorithms are based on an adaptation of the network weights (w_{ij}) until the error (mean square error or Euclidean distance) between Y and R ($\|R - Y\|$) approaches zero. The common steps for these algorithms are:

1- Random initialization for weight matrix$W$.
2- Find output of network: $Y = WT$.
3- Update the network weights using the following equation:

$$w_{ij}(new) = w_{ij}(old) + f\left(T_j, y_i, d_{ij}, \eta, \mu, \dots\right) \quad (7)$$

Where: $\eta, \mu, \dots$ are some constants depending on algorithm type?
4- Find $\|R - Y\|$.
5- $If\ \|R - Y\| \le Threshold$, go to step 2, else stop update and go to step 6.
6- The estimate channel coefficient$H = W$.

One of the popular techniques is Zero-Forcing (ZF) detector, which is very efficient semi-blind estimation for MIMO channel. This technique demands awareness of the channel state information (CSI), which is usually not obtainable in practice. The estimated vector of transmitted symbols using ZF can be prescribed as:

$$R = G(HT + n) = T + Gn \quad (8)$$

Where $G = (HH^H)^{-1}H^H$ denotes the pseudo-inverse operation [14-15].

On the other hand, an artificial neural network used as a semi-blind estimator is adopted in recent researches to solve the problem of channel estimation in a blind manner. Finally, theses algorithms have been employed across a variety of applications in the wireless communication systems, including parameter estimation as well as data detection and equalization for linear and nonlinear channels. Up to date, these algorithms are still considered open topics to researchers, since they provide acceptable performance and complexity while error and latency mainly depend on optimization techniques used [16].

3.3Blind Channel Estimation

If Channel State Information (CSI) is not a priori known at a receiver, this type of estimator is referred to be blind channel estimator. The blind techniques do not need training symbols, while the structural properties of transmitted signals and the inherent information, obtained in the signals received, can be used together for estimating channels. Since a blind estimator needs no training symbol, it provides a full throughput. Lately, researchers have evolved numerous algorithms to solve the problem of blind channel estimation and to precisely recover digitally modulated signals. In the blind estimation, there are two main strategies used.

A. Statistical based methods using High order statistic (HOS), Second order statistic, independent component analysis (ICA) and blind signal separation BSS.

B. Artificial Intelligence techniques, which can be divided into two classes

i. Artificial Neural Network ANN. For instance, Multi-layer perception (MLP), Self-organized Map SOM and Radial Basis ANN.

ii. Global Optimization Techniques. For example, Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Fruit Fly Optimization Algorithm(FFOA), Gravitational Search Algorithm (GSA) and Invasive Weed Optimization Algorithm (IWO).

3.3.1 Statistical Based Blind Channel Estimation

In the literature, the statistical blind estimation approaches can be, in general, categorized based on higher order statistics (HOS) or second order statistics (SOS). Earlier, the blind methods for estimating channel coefficients depends mainly on the HOS of observed signals. Such works found in [17-20]. Since these methods that exploit the higher order statistics require huge information of data samples, they experience high computational complexity. Therefore, blind methods based only on the SOS have been invented and developed in [21-22] under the condition that channel outputs should be an over sampled.

Statistics-based methods try to extract source signals $\boldsymbol{X}$ from noisy mixtures received signals Y without any prior knowledge of channel characteristic or source signal. This issue is called a Blind Source Separation. Most of the pervious works start with the equation $\boldsymbol{Y} = H\boldsymbol{X} + N$ where H is referred to as a mixing matrix as shown in Fig. 5 [13], [17] and [23].

In BSS literature, a pre-whitening operation is widely used to simplify this problem. The idea of the pre-whitening is constructing orthogonal independent signals $\boldsymbol{Z}$ from noisy mixtures received signals $\boldsymbol{Y}$ by using a linear transformation so that $\boldsymbol{Z} = \boldsymbol{PY}$ and$E(\boldsymbol{ZZ^H}) = I_m$. The matrix $\boldsymbol{P}$ is the pre-whitening transformation matrix. To estimate source signals $\boldsymbol{X}$ from orthogonal independent signals$\boldsymbol{Z}$, the following linear transformation is used:

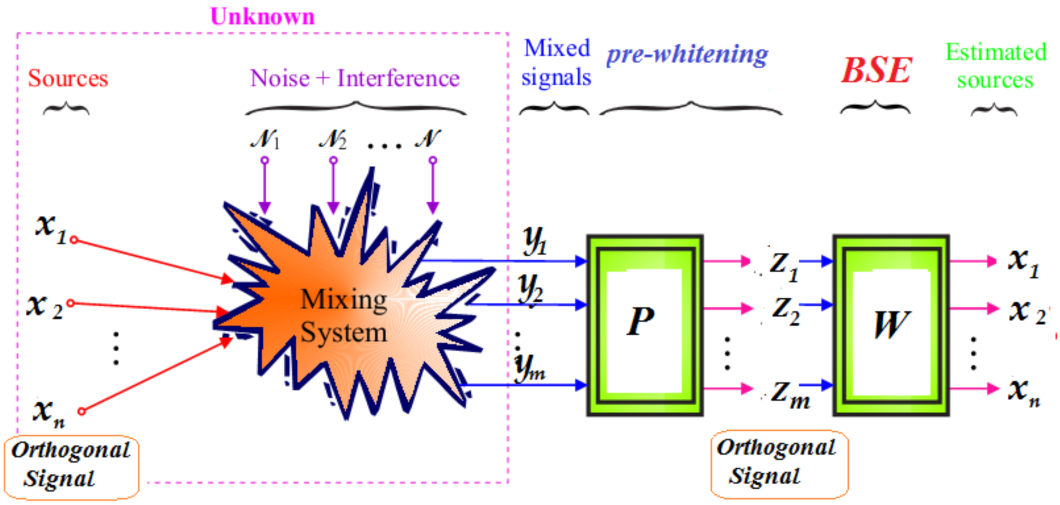

Figure 5: Statistic based-blind channel estimation process [17]

$$\boldsymbol{X} = \boldsymbol{WZ} \tag{9}$$

Where $\boldsymbol{W}$ is a de-mixing matrix? For all MIMO encoding systems, like V-BLAST, STBC, STCC, etc., the source signals $\boldsymbol{X}$ are orthogonal [5], [6], and [24]. It means $E(\boldsymbol{XX^H}) = I_n$, yielding:

$$\boldsymbol{WW^H} = I_m \text{ and } \|\boldsymbol{W}\| = 1 \tag{10}$$

This constraint will reduce the search space in the normalized unitary matrix only [23-25].

The notion behind all BSS algorithms is based on the Central Limit Theorem that states that "the sum of independent random variables usually has a distribution that is closer to Gaussian than any of the two original random variables". In other words, the fundamental concept to estimate de-mixing matrix, $\boldsymbol{W}$, bases on maximizing non-Gaussianty measuring of $\varphi(WZ)$. A function $\varphi(\cdot)$ is used to reduce noise effect and improve estimation quality. Many approaches are used for measuring of non-Gaussianty such as entropy, negative entropy, and kurtosis. The famous and simplest measure of non-Gaussianty is kurtosis, in which for a complex random variable b, the kurtosis could be defined as [26]:

$$Kurt(b) = \frac{E(|b|^4) - 2\left(E(|b|^2)\right)^2 - |E(b^2)|^2}{\left(E(|b|^2)\right)^2} \tag{11}$$

Thus, a random variable that is Gaussian having kurtosis equals to zero. Kurtosis is a very efficient tool in implementing the well-known BSS algorithms such as Fast ICA and Robust ICA. Other research papers in literature used entropy or negative entropy in measuring the non-Gaussianty. Some old ICA versions based on natural gradient approach [23-27].

3.3.2 Blind Channel Estimation Using Artificial Intelligence

During the past few years, Artificial Intelligence Technology has been recently developed and utilized in various digital signal processing applications including real time, nonlinear and adaptive signal processing. All researches that use the artificial intelligence technology for solving the problem of a channel estimation try to create algorithms that allow computers to do this function in an intelligent manner. The general issue of creating intelligence has taken two major ways that are illustrated in the next sub-sections.

3.3.2.1 Complex-Valued Artificial Neural Networks

Blind Estimation can be accomplished by creating complex-valued neural networks whose architecture is identical to a MIMO channel. This architecture allows direct adaptive processing of complex-valued signals. This network is patterned to track the time-variant channel response by modifying its weights of coefficients and predict the behavior of the channel. Various structures, such as multilayer perceptron (MLP), self-organizing maps (SOMs), and radial basis function (RBF) networks, have been employed [24-32]

The structure of MLP is v widespread since they can efficiently solve the problem of channel estimation with (or without) memory. Several MLP structures have been suggested in the literature. For instance, either the MLP is fully connected, or it comprises of separable blocks, such as a linear block with memory followed by a memory less nonlinearity. Structures selected based on the estimation problem and the channel characteristics (type of nonlinearity, channel memory, etc.) [28-29].

Neural networks have the capability to be merged with other techniques like genetic algorithms, fuzzy systems, and linear adaptive filtering. This is because of their flexible structure and capability of self-organization and learning. The SOM is valuable when two dimensional signaling systems with high order constellations (MIMO-QAM) are employed. The capability of SOMs to self-organize allows them to be perfect candidates for blind or semi blind estimation of a time-varying wireless MIMO channel [29-30].

In literature, radial basis function (RBF) networks have been comprehensively utilized to address the problem of blind channel estimation since they consider to be powerful channel estimators. RBF depends on the statistical analysis of neural network estimation of a nonlinear or linear dynamical system. RBF networks have a real activation function as compared with the MLP. They have a simple structure, and they often supply more robust and faster solutions to estimation problems. Furthermore, the structure of the RBF neural network is identical to the optimal Bayesian symbol decision. Moreover, it has the capability of providing the cumulative density function (CDF) of the transmitted symbols. The network of RBF can be shown in Fig. 6 while its overall response $f(X)$ can be formulated using Gaussian RBF as [31]:

$$f(X) = \sum_{i-1}^{N} \omega_i \varphi(x_i)\ ,\ where\ \varphi(x_i) = exp\left(\frac{-\|x_i - a_i\|^2}{\sigma}\right) \qquad (12)$$

where $\varphi(x_i)$ is the RBF, a_i represents the RBF centers having the same dimensionality as the input vector X, ω_i is the RBF weight, σ is the RBF width with a positive constant value, and N is the hidden node numbers [31-32].

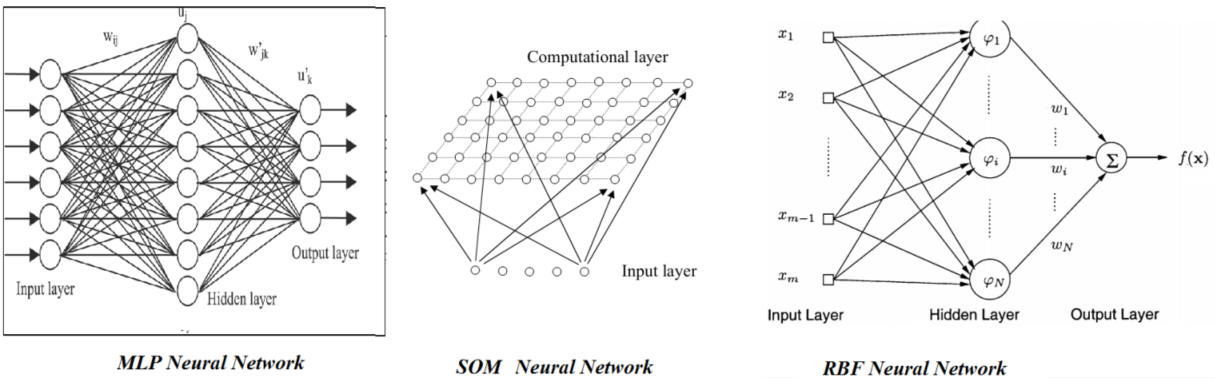

Figure 6: Architecture of well-known ANN used in blind estimation [28-32]

3.3.2.2 Global Optimization Techniques

The design of MIMO channel Estimator is typically expensive optimization tasks. Hence, researchers and engineers are motivated to develop efficient optimization techniques that can attain optimal estimation with affordable costs. Particle Swarm Optimization (PSO), Fruit Fly Optimization (FFO), Genetic Algorithms (GA), Gravitational Search Algorithm (GSA) and Invasive Weed Optimization algorithm (IWO) can provide efficient solutions to support and simplify the estimation in MIMO channel with low-complexity. All of these algorithms have many similarities, such as population and fitness value. An initialized population is randomly selected to start with, while a fitness function is used to speculate their population members. However, the major distinctions are the chosen of optimum solutions, the update of possible solutions or generation of new solutions. In general, it is really hard to compare between all of these algorithms in term of their performance, since they depend on the certain optimization problem. Such research papers that reported possible implementations with a similar set can be found in [33-34]. However, several research papers have concluded that the PSO algorithm is a more efficient approach in term of speed, computational complexity, accuracy, and convergence. Moreover, the PSO algorithm requires a fewer number of parameters [35-36].

The PSO algorithm cannot be applied for high dimensional issues, since it searches for a region surrounding the global optimum of small-specified volume in an N-dimensional space. Many different solutions are proposed to solve this problem [37]. To promote the realization of the original PSO algorithm, the PSO can be combined with other optimization algorithms, resulting hybrid optimization techniques such as GSA-PSO or IWO-PSO. To attain full convergence and reaching the global optimum, new solutions within this region are created by the hybrid algorithms, in which the update weight function is adapted to take these parameters into consideration [38-39].

4. Conclusions

This paper presents a review of channel estimation techniques includes; non-blind, semi-blind and blind techniques for the MIMO wireless communication systems. The major drawback of using the techniques that are non-blind is the low transmission rate since they depend mainly on the pilot symbols. Consequently, they are very efficacious to the applications that require a low transmission rate. However, their implementations are simple, and low computational complexity can be obtained. The problem of low transmission rate can be mitigated using semi-blind techniques due to the need for fewer training symbols. Although the semi-blind methods perform better than the non-blind, latency and high computational complexity are the significant limitations due to the fact that these methods require both pilots and statistical properties. Research papers have shown that the ZF estimator is the best within the family of semi-blind techniques. Despite the fact that the blind techniques that are statistically developed avert the use of the training symbols, a long record of data is required, resulting in high computational complexity as well as slow convergence. Global Optimization Techniques that are based on an artificial intelligence technology are still open topics for the researchers, since they are advantageous in term of complexity, convergence speed and accuracy. Furthermore, the GOT is capable of predicting the channel characteristics precisely. On the other side, the hybrid optimization techniques such as GSA-PSO or IWO-PSO have been newly found to overcome the PSO weakness mentioned in the previous sub-section. Finally, there is no such way that can say or judge which of estimation algorithm is better. An appropriate selection of estimation techniques depends on applications and engineering designers.

CONFLICT OF INTERESTS.

- There are no conflicts of interest.

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مراجعة شاملة لمختلف تقنيات التقدير لقناة ذات المدخلات والمخرجات المتعددة

أواب قاسم جمعة الذهب سمير عبد الكاظم خضير الرفيعات

قسم الهندسه الكهربائية، كليه الهندسة، جامعه بابل، بابل، العراق

samirabdcathem@yahoo.com eng.awwab.qasim@uobabylon.edu.iq, awwabq@yahoo.com

الخلاصة:

لقد تطورت مشكلة تقدير القناة اللاسلكية بسبب بعض التأثيرات غير المرغوب فيها للخواص الفيزيائية للقناة على الإشارات المرسلة. في نهاية المستقبل، التشوه، والتأخير، والتوهين، والتداخلات، ونوبات الطور هي أكثر المشكلات التي تواجهها مع الإشارات المستقبلة. من أجل التغلب على تأثيرات القناة وتوفير جودة كاملة تقريبًا لنقل البيانات، يلزم تقدير معلومات القناة. في أنظمة المخرجات متعددة المدخلات والمخرجات (MIMO)، يعتبر تقدير القناة خطوة أكثر تعقيدًا مقارنة بأنظمة المخرجات ذات المدخلات المفردة، SISO، نظرًا لأن عدد القنوات الفرعية التي تحتاج إلى تقدير أكبر بكثير من انظمة SISO. الهدف الأساسي من هذه الورقة البحثية هو مراجعة شاملة لاغلب الخوارزميات الشهيرة والفعالة التي تم ابتكارها لحل مشكلة تقدير قناة MIMO في أنظمة الاتصالات اللاسلكية. في هذه الورقة، تم تصنيف هذه التقنيات إلى ثلاث مجموعات: غير المكفوفين، شبه الأعمى وتقدير أعمى. لكل مجموعة، يتم تقديم توضيح مختصر لخوارزميات التقدير المألوفة. وأخيرًا، نقارن بين هذه التقنيات استنادًا إلى التعقيد الحسابي والكمون ودقة التقدير.

الكلمات الدالة: تخمين القناة المحسن، الفصل الاعمى للإشارات، شبكات الذكاء الاصطناعي، خوارزميات التحسين الهجين.