Channel Estimation in MIMO-STBC Systems

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***Abstract*—Multiple Input Multiple Output (MIMO) systems are the cornerstone technology which led to evolution of 3G, 4G-LTE and 5G. Space-Time Block Coding (STBC) emerged as the fundamental technique to enhance performance of MIMO systems in wireless communication. To get accurate description of channel state information (CSI) for coherent demodulation, channel estimation plays a crucial role in reliable data transmission. This report focuses on one of the earliest channel estimation techniques of pilot-based estimation using Alamouti-STBC. The efficiency of this method in mitigating effects of fading, enhancing spectral efficiency and improving robustness of links is discussed. Integration of other techniques along with pilot-based approach to address the shortcomings is discussed. Moreover, opportunities for future work in advancing channel estimation is also highlighted. Through a thorough analysis this report aims to analyse the current state of channel estimation in wireless communication and propose future innovations.**

***Index Terms*—Alamouti code, channel estimation, fading, MIMO, pilot-based, STBC.**

I. Introduction

MIMO systems play a pivotal role in wireless communication by significantly improving the data coverage and spectrum efficiency. By taking advantage of spatial diversity by using multiple antennas at both transmitter and receiver, MIMO systems enable the simultaneous transmission of multiple data streams over the same frequency band which increases the capacity of channel. The spatial diversity helps to achieve performance in a dense multipath scattering and fading environment like urban cities. To ensure reliable data transmission, the receiver needs to have accurate description of CSI. Efficient channel estimation techniques have been developed to ensure optimal performance of communication systems.

The channel model can be assumed as quasi-static (approximately constant or infinitesimally slow variation over the duration of a frame length), frequency non-selective (channel exhibits similar response to all frequencies in a given bandwidth) and Rayleigh-fading (the amplitude decays as a Rayleigh distribution due to multi-path fading) as proposed in [1]. For a MIMO system with M inputs (transmitters) and N outputs (receivers), the channel is modelled as $M \times N$ matrix where entry h_{ij} is the complex gain between the i^{th} tramsitter and the j^{th} receiver. The complex gain reflects both the amplitude and phase shift in the signal. The channel gains are independent and identically distributed (IID) zero mean gaussian random variable. Due to independence of channels we can model that arbitray white gaussian noise (AWGN) is IID added to each channel. Thus, the MIMO system is modelled as $\vec{r} = H\vec{s} + \vec{n}$ where H is the channel gain matrix, $\vec{s}$ is the transmiited signal vector, $\vec{n}$ is the added noise and $\vec{r}$ is the received vector.

Alamouti code, proposed by S.M Alamouti in 1998 in [2], is one of the earliest space-time block code. It uses two transmit antennas and M receive antennas and achieves full diversity order of 2M. In this method, in the first time slot s_0 is transmitted by first transmission antenna and s_1 by the second transmission antenna and then in the next time slot the first transmission antenna transmits $-{s_1}^*$ and the second transmission antenna transmits ${s_0}^*$, where x^* represents complex conjugate of x. Since this approach involves diversifying the signal in both space and time domain, it is referred as space-time coding. A maximum likelihood (ML) decoder is used at the receiver after combining the received signal r_0 and r_1 in the two time slots. In order to obtain accurate channel estimate, pilot symbols which are known to both transmitter and receiver are inserted into the data stream. They provide a reference of the amplitude, frequency and phase shift in the signal over the transmission in the channel. By constructing STBC and orthogonal pilot symbols and periodically inserting them into the data stream and transmitting across multiple antennas, we can obtain a channel estimate. However, certain intricacies are an area of research like optimal pilot placement strategies, pilot sequence design, power allocation to pilot symbols and joint channel estimation [3].

This paper provides a comprehensive discussion of the importance of channel estimation in wireless communication, suitable model for channel fading and multipath propagation, space-time block coding, pilot-based channel approach and also highlights the relevant areas of research. This paper focuses on pilot-based channel estimation approach using Alamouti STBC [4] and suggesting further improvements and integration in the technique. The paper also suggests about semi-blind matrix based decomposition [5], [6] and joint channel estimation using mutual information [7], [8] between the transmitted and received signal. It also highlights using deep learning and reinforcement learning to estimate complex channel estimates [9] particularly in a fast time-varying and dense scattering environment.

The remainder of paper is organised as follows. Section II describes the model and set-up of the system. It provides the necessary literature survey and background and presents the pilot-based channel estimation technique. It also presents the future scope in addressing the limitations. Section III provides the conclusion for the paper.

II. Methods

A. Channel Model for Wireless Communication

In a wireless medium, there are multiple paths between the transmitter and the receiver which causes multiple versions

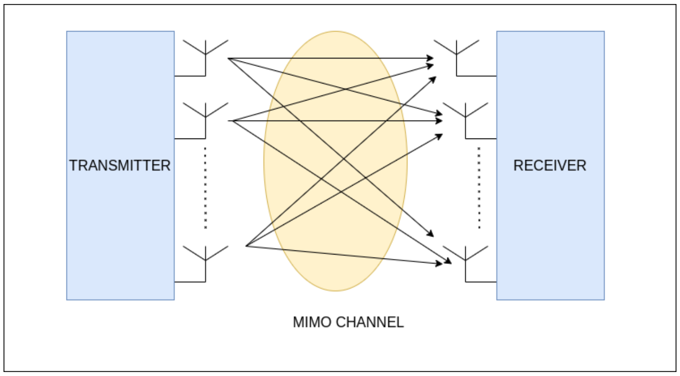

Fig. 1. MIMO Channel Model [1]

of the signal to be received. The primary MIMO channel model we will consider mostly in this paper is the quasi-static, frequency non-selective and Rayleigh fading channel model. It means that the channel remains constant or has infinitesimally small variation over the length of transmission of a frame, the channel response is same for all frequencies in a given bandwidth and the amplitude decays as a Rayleigh distribution due to multipath fading. This model is quite appropriate description in many application. For an M transmitters and N receivers, the channel can be modeled as :

$$H = \begin{bmatrix} h_{11} & .... & h_{1N} \\ h_{21} & .... & h_{2N} \\ ... & .... & ... \\ h_{M1} & .... & h_{MN} \end{bmatrix} \tag{1}$$

Where h_{ij} is the complex channel gain (the attenuation and the phase shift) between the transmitter i and receiver j and are IID zero mean complex Gaussian random variables with unit variance We can represent the MIMO signal model as $\vec{r} = H\vec{s} + \vec{n}$; where, H is an $M \times N$ matrix r is received vector of size $N \times 1$, s is the transmitted vector of size $M \times 1$, and n is the noise vector of size $N \times 1$. We can model noise as AWGN of mean 0 and variance σ^2. Figure 1 demonstrates the MIMO system model.

Due to dense scattering, reflection, refraction and diffraction, multiple copies of the signal which are delayed in time reach at receiver. Figure 2 demonstrates that the path travelled by the signal is rarely the line-of-sight path but rather multiple copies reach the receiver. Rayleigh distribution is commonly used to describe the nature of the envelope of the statistical time-varying fading signal or a multipath component. The Rayleigh distribution is a continuous probability distribution for positive-valued random variables.

The probability density function (PDF) of the Rayleigh distribution is given by:

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}, \quad x \geq 0 \tag{2}$$

where $\sigma > 0$ is the scale parameter.

The cumulative distribution function (CDF) of the Rayleigh distribution is:

$$F(x;\sigma) = 1 - e^{-\frac{x^2}{2\sigma^2}}, \quad x \geq 0 \tag{3}$$

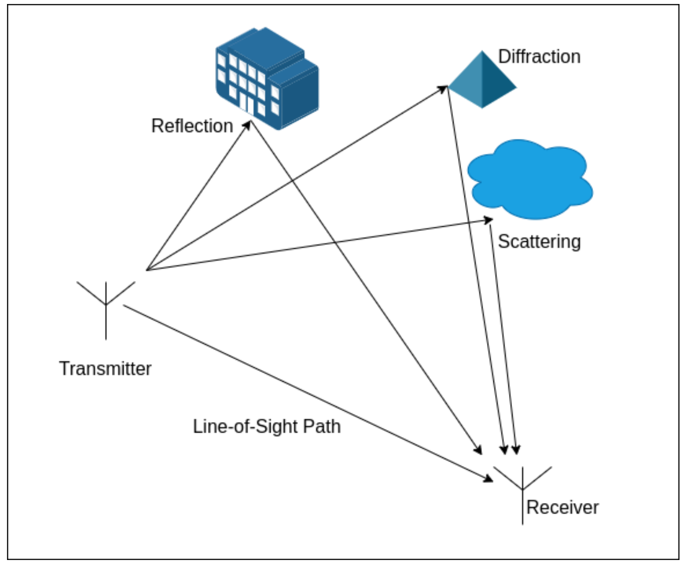

Fig. 2. Multipath Fading in Wireless Communication [1]

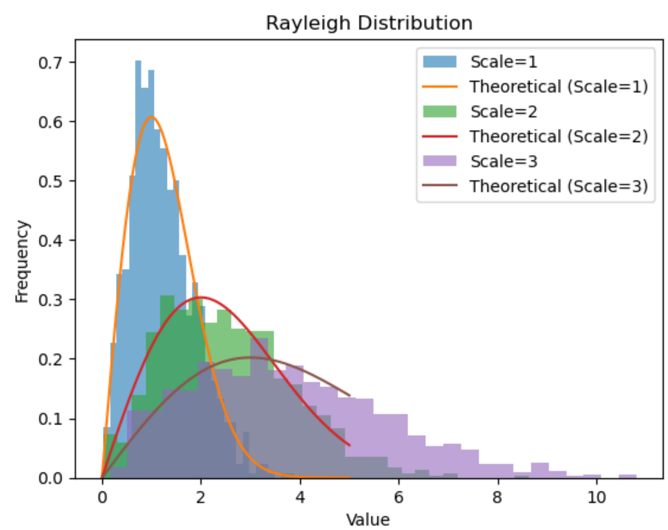

Fig. 3. Rayleigh Distribution Probability Density Function

Figure 3 shows the PDF of Rayleigh distribution.

B. Spatial Diversity in MIMO

Using multiple antennas at both transmitter and receiver, we can combine coding with spatial diversity and take advantage of spatially separating the antennas in a dense multi-path scattering environment [1], [4]. Unlike time or frequency diversity techniques, (wherein data is transmitted over multiple time or frequency slots respectively) spatial diversity does not require additional time and frequency resources STBC encodes a data stream over different transmission antennas and time slots. This allows allowing multiple redundant copies to be transmitted through independent fading channels ensuring reliable detection at the receiver. The same information can be transmitted from multiple transmission antennas and received at multiple antennas simultaneously such that it increases the probability of accurate detection. We exploit the idea that

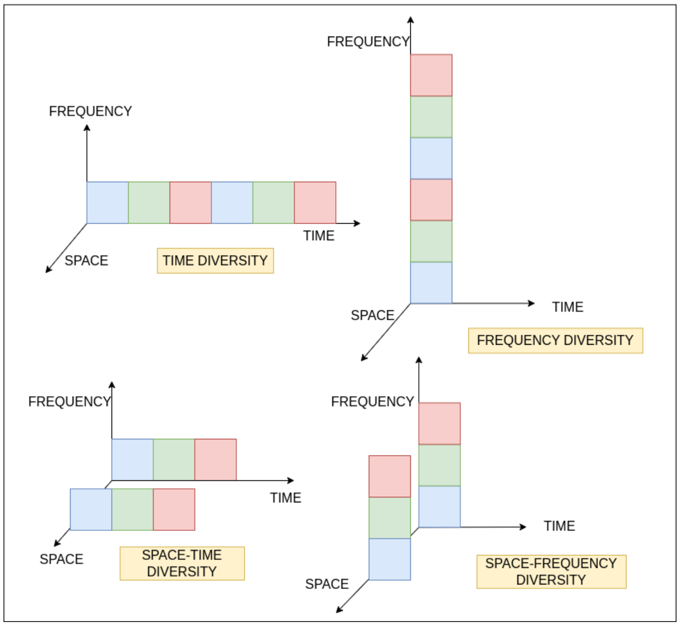

Fig. 4. Diversity in time, frequency and space [4]

since channels are statistically independent the probability that multiple channels simultaneously experience sharp fading is very low. Figure 4 demonstrates various diversity in space, time and frequency domain.

C. Pilot-based Channel Estimation using Alamouti STBC

As mentioned in [2], in Alamouti STBC, we consider two transmit antennas and one receive antenna (can be extended to M antennas). In this, the channel is assumed to remain constant over two time slots and the antennas transmit simulaneosly. In first time period Tx0 transmits s_0 and Tx1 transmits s_1 and in the next time period Tx0 transmits $-s_1{}^*$ and Tx1 transmits $s_0{}^*$ where x^* represent complex conjugate of x. Figure 5 shows the Alamoti STBC transmission scheme. By our model assumption that the two transmitters experience independent channels, the receiver can estimate the channel gain matrix by the received signal in the two time slot using ML decoding. We can estimate the channel by inserting known pilot symbols in block by block pattern for a particular frame length orthogonally between different transmit antennas. The mixed transmitted signals can be separated completely at the receiver due to their orthogonal nature. The gains values obtained in this process are then used as estimated channel values which provides the receiver with CSI needed for ML decoder to obtain the correct transmitted signal. Figure 6 shows the block diagram at transmitter and receiver while using pilot-based channel estimation [4]. PSK stands for phase shift keying which is an orthogonal coding scheme.

D. Limitations and Future Scope

As mentioned in [10], there are certain shortcomings in the method suggested in previous subsection. If N_p denoted the

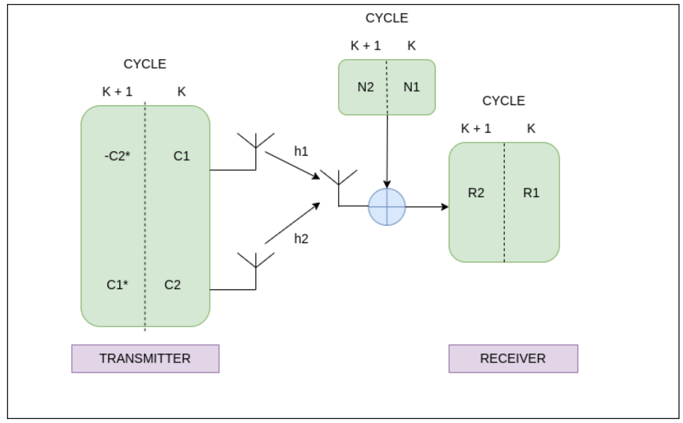

Fig. 5. Transmitted and received signals in Alamouti Space-time block code scheme [2]

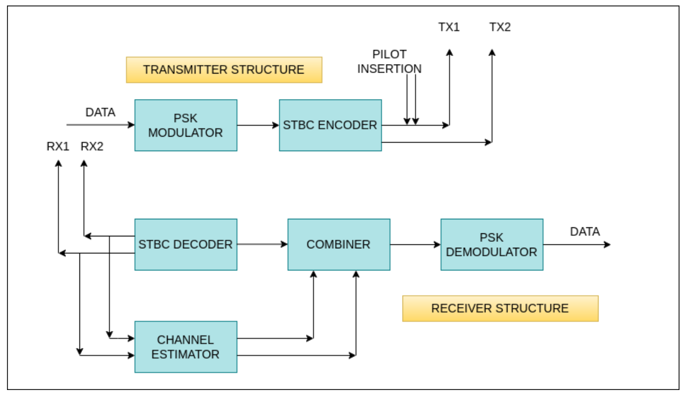

Fig. 6. Transmitter and receiver structure of STBC system with channel estimation [4]

number of pilot symbols inserted in a frame of length F, certain power is consumed as pilot signals are periodically inserted in blocks of transmitted signal and we can calculate the power loss as $10\log(\frac{F}{F-N_p})$ dB. Therefore,

$$SNR_{eff} = \frac{F - N_p}{F} SNR$$

where, SNR stand for Signal-to-Noise ratio.

We assumed a slow-varying channel model (quasi-static) which remained constant over a frame length however, if the channel is fast time-varying, then the ML decoding becomes highly complex as the channel varies on a symbol-to-symbol basis. Also, there is a significant scope of research in integrating deep learning and reinforcement learning to obtain real-time feedback and learn complex channel characteristics and optimize the transmission strategy [9]. Using information theory, we can develop advanced algorithms which exploit the correlation between the transmitted and received signal which would then jointly estimate the channel [7], [8]. There is also a need to optimize pilot sequence, pilot placement and power allocation [3].

III. Conclusion

MIMO systems are the cornerstone technology in wireless communication which increased throughput within the available spectrum, ensured reliable communication while mitigating the effects of interference. Channel estimation is an extremely essential process for ensuring reliable MIMO wireless communication. Pilot-based channel estimation using Alamouti space-time block coding provides a simple yet effective solution. It takes the advantage of orthogonal codes and spatial diversity. When implementing pilot-based channel estimation using Alamouti STBC, factors such as pilot placement, power allocation, and feedback mechanisms are important for optimizing performance and efficiency. Despite significant advancements, several challenges remain in channel estimation for MIMO systems and it is a highly relevant area of research.

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