Channel Estimation in MIMO-STBC Systems

Literature Review

Shubhhi Singh

Department of Electrical Engineering
Indian Institute of Technology Bombay

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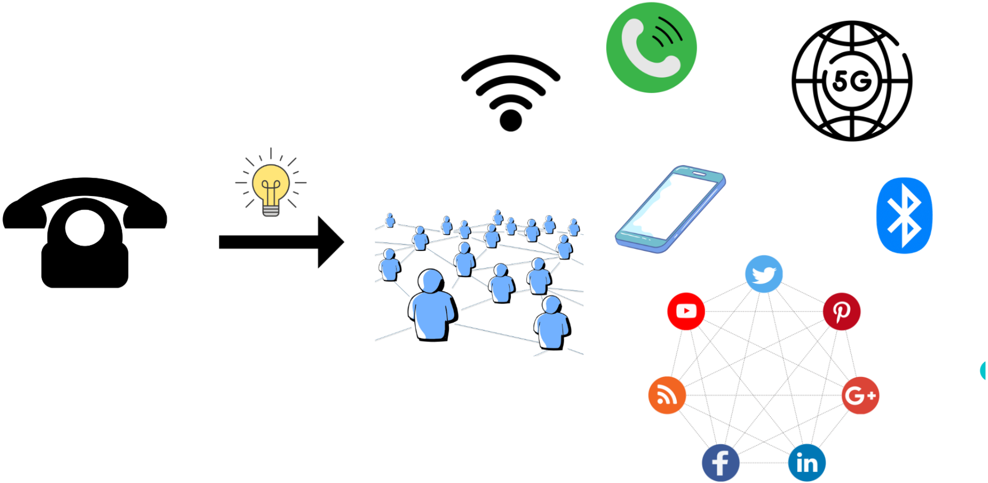
Introduction



Introduction

- Multiple-Input Multiple-Output Space-Time Block Coding (MIMO-STBC) systems are extremely important in fourth-generation (4G) wireless communication; They first started being used in 3G
- In MIMO communication, multiple antennas are used at both transmitter and receiver; This allows for multiple simultaneous data streams to be transmitted
- It enables **higher data rate**, **extended coverage**, **improved reliability** by enhancing the **robustness of links** and **mitigating interference**
- At the same time it doesn't increase total transmission power or bandwidth
- However, a key issue on the effectiveness of MIMO communication depends on efficient and accurate estimation of wireless channel

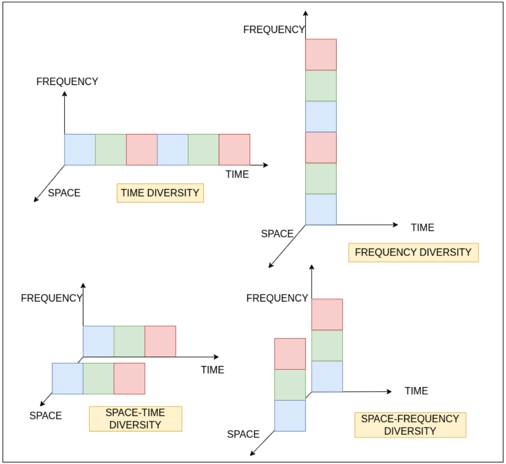
Channel Estimation

- Providing a reliable link for wireless communication is extremely important for a wide range of applications including but not limited to mobile network
- Robust channel estimation of **channel state information**(CSI) is particular important for coherent demodulation at the receiver in MIMO systems
- The challenges in accurate channel estimation are due to the dynamic and time-varying nature of the wireless channel
- It is also important to mitigate effects of signal fading, multi-path propagation and interference to ensure efficient data detection at receiver
- One common approach is to insert symbols known to both transmitted and receiver, called **pilot symbols**, to estimate the channel characteristics
- There also have been works to design matrix decomposition-based **semi-blind channel estimation** techniques with data detection having reduced complexity and near-optimal performance
- Channel estimation is an active area of research in wireless communication and recent works have been in the direction of utilising advanced signal processing and machine learning techniques

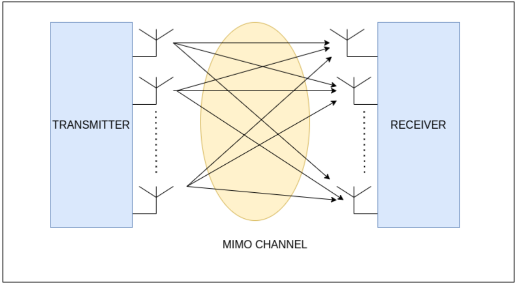
MIMO Systems and STBC

- 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
- Unlike time or frequency diversity techniques, spatial diversity does not require additional time and frequency resources
- Space-Time Block Codes (STBC) encodes a data stream over different transmission antennas and time slots, thereby 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
- One of the most well-known and earliest STBC schemes is the **Alamouti code**, proposed by S. M. Alamouti in 1998 wherein two consecutive symbols are transmitted over two time slots using two transmission antennas and by exploiting orthogonal coding, it achieves full diversity with a simple decoding scheme at the receiver

MIMO Systems and STBC



(a) Time, Frequency and Spatial Diversity



(b) MIMO System Model

MIMO Communication System

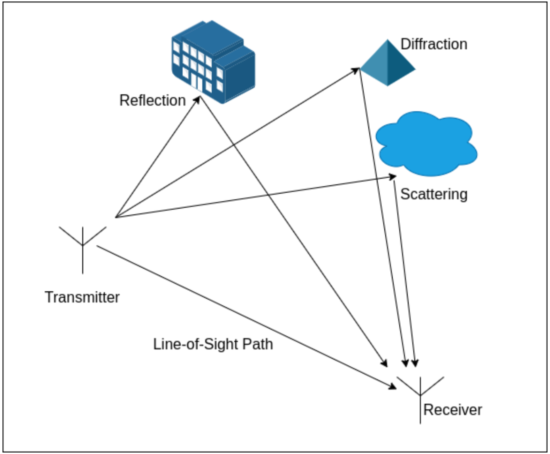
- The primary MIMO channel model we will consider is the **quasi-static, frequency non-selective, Rayleigh fading** channel model which can be modeled as :

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

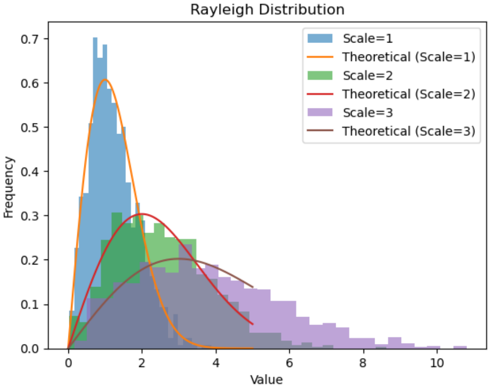
  Where h_{ij} is the complex channel gain (the attenuation and the phase shift) between transmitter j and receiver i and are independently identically distributed (i.i.d) zero mean complex Gaussian random variables with unit variance

- We can represent the MIMO signal model as $\vec{r} = H\vec{s} + \vec{n}$
  Where, the system has N outputs and M inputs and H is an $M \times N$ matrix r is channel matrix of size $M \times N$, 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 white gaussian noise (AWGN) of mean 0 and variance σ^2

Multi-path Fading Model



(a) Multi-path Fading



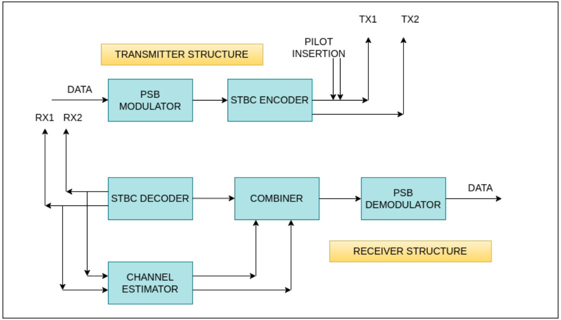
(b) Rayleigh Distribution Probability Density

Function $:= f(x;\sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}, \quad x \geq 0$, where σ is the scale parameter

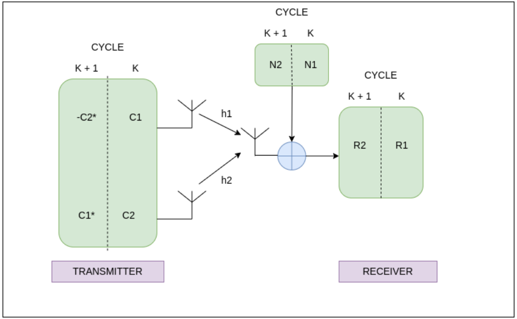
Pilot Assisted Channel Estimation Technique for Alamouti STBC

- Let's first look into the case for 2 transmit antennas (Tx0 and Tx1) and 1 receiving antenna (can be easily extended to M receiver antennas)
- In one period of symbol transmission, two antennas simultaneously transmit; 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 ${s_0}^*$
- We assume that the channel experienced by the two transmitters is independent of each other and also that the channel remains constant over two time slots
- **Maximum likelihood (ML) decoder** is used at the receiver (i.e given all symbols with equal probability it outputs the symbol from the code-book with minimum euclidean distance from the received signal)
- From the received signals in the two time slots, we can estimate the channel

Pilot Assisted Channel Estimation Technique for Alamouti STBC



(a) Transmitter and receiver structure of STBC system with channel estimation



(b) Transmitted and received signals in Alamouti Space-time block code scheme

Pilot Assisted Channel Estimation Technique for Alamouti STBC

- 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 channel is assumed to remain constant over a frame length and due to the orthogonality property, the mixed transmitted signals can be separated completely at the receiver
- The Rayleigh distributed channel response (h_{ij}) is estimated using the pilots at the receiver
- The gains are then used as estimated channel values which provides the receiver with channel state information (CSI) needed for ML decoder to obtain the correct transmitted signal
- Comparing with respect to bit error rate(BER), this performs considerably better than SISO; Hence we can claim that pilot-assisted MIMO technique provides accurate channel estimates
- The pilot symbol insertion in the transmitted block and detection at receiver can be viewed as sampling of a band-limited process and should satisfy the Nyquist criteria

Pilot Assisted Channel Estimation Technique for Alamouti STBC

There are certain shortcomings in this method:

- Let N_p denoted the number of pilot symbols inserted in a frame of length F, one crucial thing to note is that power is consumed as pilot signals are periodically inserted in blocks of transmitted signal and power loss $= 10\log(\frac{F}{F-N_p})$ dB
- Therefore, $SNR_{eff} = \frac{F-N_p}{F}SNR$
- 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
- There have been works to couple pilot-based channel estimation along with semi-blind and joint-typicality decoding

Directions for Future Work

- **Machine Learning for Channel Estimation:** Using deep learning and reinforcement learning and obtaining real-time feedback one can learn complex channel characteristics and optimize the transmission strategy
- **Joint Channel Estimation:** 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
- **STBC beyond 5G:** We can explore the possibility of STBC in IoT, vehicular communication, industrial automation which can enable ultra-reliable low-latency communication
- **Secure Communication:** An important and relevant area of research is to investigate use of STBC for enhancing security and privacy of wireless communication to prevent eavesdropping, interception and potential cyber-crimes and frauds

Conclusions

- 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 in MIMO systems is closely integrated with emerging technologies such as 5G, massive MIMO, and mmWave communication
- Pilot-based channel estimation using Alamouti space-time block coding provides a straightforward and elegant solution by taking advantage of orthogonal and spatial diversity
- When implementing pilot-based channel estimation using Alamouti STBC, considerations such as pilot placement, power allocation, and feedback mechanisms are crucial 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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