A Review on Multiplexing Schemes for MIMO Channel Sounding

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Summary
There are three multiplexing schemes for Multi-Input Multi-Output (MIMO) channel sounder Time-division multiplexing (TDM), Code-division multiplexing (CDM) and Frequency-division multiplexing (FDM). The purpose of this paper is comparison overview of multiplexing schemes for MIMO channel sounder. In this paper TDM, FDM and CDM techniques for MIMO channel sounding are considered. TDM, FDM and CDM multiplexing schemes have pros and cons in different aspects. The comparison between multiplexing techniques has been considered in terms of real-time measurement, hardware cost effectiveness and major drawbacks.

Keywords:
MIMO, Channel Sounder, CDM, TDM, FDM, Loosely Synchronous Code.

1. Introduction

MIMO (multiple input multiple output) wireless communication system is an innovative solution to improve the bandwidth efficiency by exploiting multipath-richness of the propagation environment. The degree of multipath-richness of the channel will determine the capacity gain attainable by MIMO deployment. MIMO antenna systems have recently gained considerable interest as they offer high data throughput and significant enhancement in link reliability over single antenna systems without requiring additional power or bandwidth [1, 2]. There can be various MIMO configurations. For example, a 2x2 MIMO configuration is 2 antennas to transmit signals and 2 antennas to receive signals.

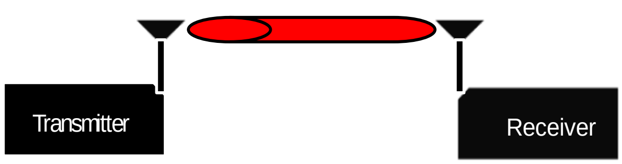

Figure 1(a): Single Input Single Output (SISO)

The benefits of MIMO system are; higher capacity (bits/s/Hz) (spectrum is expensive, number of base stations limited), better transmission quality (BER, outage), increased coverage and improved user position estimation [3, 6]. According to the following issues MIMO is preferable:

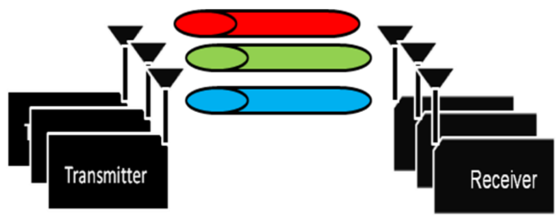

Figure 1(b): Multiple Input Multiple Output (MIMO)

(i) Spatial multiplexing gain - Capacity gain at no additional power or bandwidth consumption obtained through the use of multiple antennas at both sides of a wireless radio link.
(ii) Diversity gain-Improvement in link reliability obtained by transmitting the same data on independently fading branches.
(iii) Array gain
(iv) Interference reduction.

Capacity describes the amount of bits that can be sent over the channel in one cycle or second per Hertz. It can also be defined by maximizing the mutual information, defined below, of the input and output of the system [26].

$$I(X,Y) = \sum_{X,Y} f_{X,Y} \log_B \left(\frac{f_{X,Y}}{f_X f_Y} \right) \quad \text{......................(1)}$$

Where $f_{X,Y}$ is the mutual probability distribution function (pdf) of the input and output of the system and f_X and f_Y are the pdf of the input and output respectively. B is equal to 2 when speaking about bits.
It is realized at the below equation for mutual information after assuming zero-mean circular symmetric complex Gaussian (ZMCSCG) input and output and a power restraint at the transmitter, meaning the trace of the covariance of the input is equal to ρ. I represent the identity matrix, H represents the MIMO channel, and Rx represents the autocorrelation of the input.

$$I(X,Y) = \log_2 \det \left[\mathrm{I} + \mathrm{H} \mathrm{R}_x \mathrm{H}^H \right] \quad \text{..................(2)}$$

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The generalized Shannon Capacity describes the upper bound of error-free capacity for different antenna configuration schemes [14, 26].

$$Capacity = \max_{R_x} \log_2 \det \; [\mathrm{I} + \mathrm{HR}_x\mathrm{H}^H] \text{……….(3)}$$

The capacity of Single-input Single-output as follows:

$$Capacity = \log_2(1+\rho\chi_2^2) \text{ ………… ……..…… (4)}$$

Where ρ is equal to the average received SNR and χ_2^2 is a chi-squared random variable with 2 degrees of freedom.

The capacity of Multiple-input Single-output as follows:

$$Capacity = \log_2(1+\rho\chi_{2M}^2) \text{ …………….….…. .(5)}$$

Where ρ is equal to the average received SNR and χ_{2M}^2 is a chi-squared random variable with 2M degrees of freedom, while M is the number of transmit antennas.

The capacity of Single-input Multiple-output as follows:

$$Capacity = \log_2(1+\rho\chi_{2N}^2) \text{ …………..………. (6)}$$

Where ρ is equal to the average received SNR and χ_{2N}^2 is a chi-squared random variable with 2N degrees of freedom, while N is the number of receive antennas.

The capacity of Multiple-input Multiple-output as follows:

$$Capacity > \sum_{k=M-N-1}^{M} Log_2(1+\frac{\rho}{M}\chi_{2k}^2) \text{ ……..….. (7)}$$

Where ρ is equal to the average received SNR and χ_{2k}^2 is a chi-squared random variable with 2k degrees of freedom.

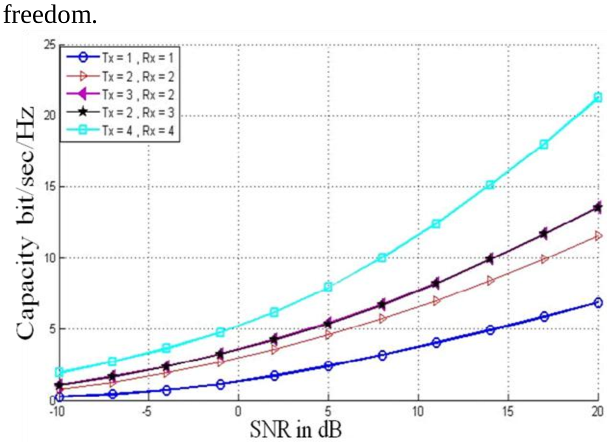

Figure 2: The Capacity of a MIMO channel

In figure 2 the Capacity of a MIMO channel with Tx transmit antenna and Tx receive antenna is analyzed [24].

It is observed that, single transmit and Receive antenna capacity is lower the multiple antennas with same SNR. For more transmit and receive antenna capacity increase with same SNR accordingly.

2. MIMO Channel Sounder

The characteristic of the MIMO channel is the vital issue to determine performance of the MIMO system. The accurate knowledge of channel behavior is most important for efficient mobile communication system [17].

The MIMO channel is considered to be parameterized by time-delay, complex path weight, direction of arrival (DOA), direction of departure (DOD), which can be obtained by analyzing measurement data. So, the accuracy of MIMO channel measurement is an important issue in many aspects like simulation, system design, and performance analysis. Channel sounders should therefore provide the temporal and spatial characteristics of the MIMO channel with accuracy and resolution high enough to befit the design purpose. In the conventional TDM based MIMO channel sounding technique [22, 23], the number of antennas at both transmitter and receiver limits its capability, with a trade-off between spatial resolution and time resolution. However, for the sake of reduced cost and complexity, most of the commercial MIMO channel sounders use single, time multiplexed, transceiver architecture [12].

MIMO Channel Response - Typical environment for MIMO channel sounding, considering m_s-transmitting (Tx) array antenna and m_r-receiving (Rx) array antenna. The channel is superposition multipath components. Each path is departed from the transmitting array with an azimuth angle θ_i^s and is arriving at the receiving array with an azimuth angle θ_i^r , where i is an index of multipath components. Between Tx and Rx, each path has a delay time τ_i and complex amplitude γ_i that is function of scattering and propagation co-efficient. A $m_r \; x \; m_s$ channel matrix H ∈ C $^{m_r \; x \; m_s}$ at the center frequency of f_c can be expressed as [16]

$$\mathrm{H} = \sum_i \gamma_i(t)e^{-j2\pi f_c\tau_i} a_r(\theta_i^r)(a_s(\theta_i^s))^T \text{ ….(8)}$$

Where $a_s(\theta)$ and $a_r(\theta)$ transmitting and receiving array response vectors for the plane wave impinging from an azimuth angle θ. The observable signal is only the superposition of contributions from all transmitting

antennas. Therefore some kind of multiplexing technique is needed to implement the MIMO channel sounder.
MIMO Channel Matrix

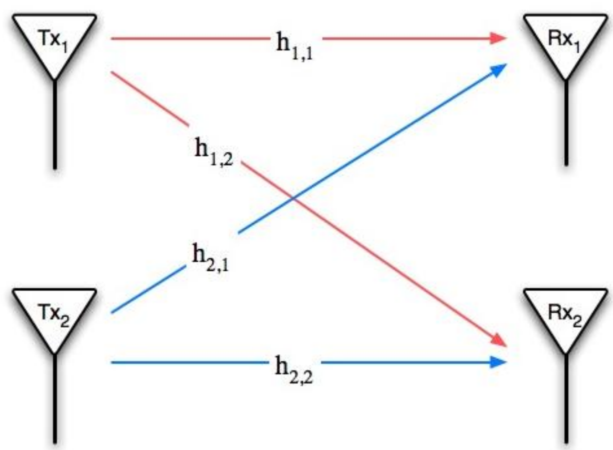

Figure 3: 2x2 Multi-input Multi-output system

The channel matrix for 2 X 2 MIMO system as follows:

$$\begin{bmatrix} X_1 \\ X_1 \end{bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}}_{H} = \begin{bmatrix} b_1 \\ b_1 \end{bmatrix} + Noise$$

$$\begin{bmatrix} \hat{b}_1 \\ \hat{b}_1 \end{bmatrix} = H^{-1} \begin{bmatrix} X_1 \\ X_1 \end{bmatrix}$$

The previous scheme for MIMO channel sounder is based on Time-Division Multiplexing(TDM) architecture that sounding signals from each transmit antenna are transmitted utilizing synchronized switch sequentially, not concurrently and uses PN sequence as a sounding signal. Although it has a merit of cost-effective in hardware implementation, but this scheme is not suitable for real-time channel measurement and has some major drawbacks such as the requirement of precise synchronization between transmitter and receiver and accuracy reduction during switching time as well. As a result, reformation about architecture of MIMO channel sounder is needed for overcoming these limitations of conventional TDM based MIMO channel sounder.
Another approach is CDM based MIMO channel sounding technique, which has the merit of real-time measurement [8].
In CDM architecture, sounding signals from all transmit antennas are transmitted simultaneously enables to measure the real-time MIMO channel parameters. The level of interference among different codes has a dominant effect on the performance of channel measurement [15]. However this scheme multiplexes transmit signals by using codes. Therefore it needs a code which has very low autocorrelation and cross-correlation values between different code sets for this CDM architecture.

2.1 TDM based Channel Sounder

TDM architecture of MIMO channel sounder uses a switch to connect one RF module with all antennas in each transmit and receive platform and utilizes PN sequence as sounding signals as shown in Fig. 4. The system uses M transmitter (Tx) and M receiver (Rx) antennas. Generated Pseudo-Noise (PN) code sequences for each transmission antenna propagates to MIMO channel [17, 18]. At the receiver, Channel Impulse Response (CIR) is observed after sliding correlation of Pseudo-Noise (PN) code sequences with the received signal.

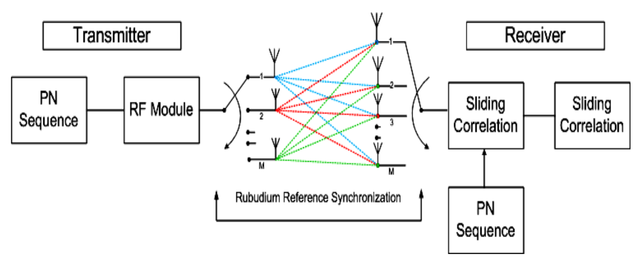

Figure 4: TDM Based Channel Sounder Architecture

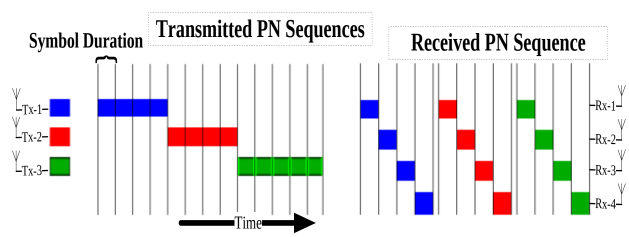

Figure 5: TDM-based signal transmission in time-varying channel

Specially, periodic transmission structure of signals from each Tx antenna in Fig. 5 makes it hard for signals in each Tx antenna to go through the same channel in fast fading channel environment. Because signals from all Tx antennas have to experience a temporal channel concurrently for the accurate measurement of MIMO spatial channel. The accuracy of MIMO channel sounding with TDM architecture is decreased in case that the time-variation of channel is larger or the number of Tx and Rx antennas increases.
To estimate the channel from the received signals the following correlation method is used [6]. When pseudo

random binary signal **x** is transmitted, received data **y** is expressed as:

$$\mathbf{y} = \mathbf{x} * \mathbf{h} + \mathbf{n} \quad \text{.....................................(9)}$$

Where h is impulse response of the channel and n is white noise from receiver. We can rewrite (9) using circular matrix X as

$$\mathbf{y} = \mathbf{X}^{H} \bullet \mathbf{h} + \mathbf{n} \quad \text{......................(10)}$$

2.2 CDM based Channel Sounder

CDM-based MIMO channel sounding technique is depicted in Fig.6. CDM architecture that sounding signals from all transmit antennas are transmitted simultaneously enables to measure the MIMO channel in real-time. A generated sounding signal adopting spread spectrum with low correlation codeset at the transmitter propagates to MIMO channel.

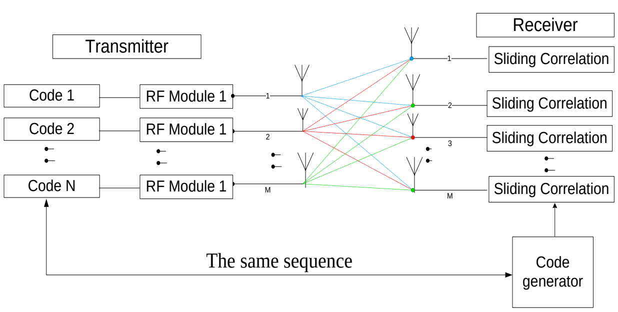

Figure 6: CDM Based Channel Sounder Architecture

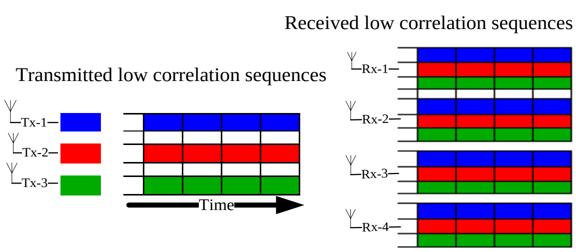

Figure 7: CDM-based signal transmission in time- varying channel

At the receiver, the channel characteristic is observed after sliding correlation of the received signal simultaneously. In this CDM architecture, the level of interference among different codes has a dominant effect on the performance of channel measurement because this scheme multiplexes transmit signals by using codes. Therefore it needs a code which has very low autocorrelation and cross-correlation values between different code sets for this CDM architecture.

2.3 FDM based Channel Sounder

MIMO channel sounder with FDM architecture enables all Tx antennas to transmit signals concurrently by allocating subcarriers that are orthogonal among them in frequency domain into each Tx antenna utilizing multiple carriers. When the total number of subcarriers is N and the number of Tx antennas is M, the number of the allocated subcarriers per each Tx antenna are N/M.

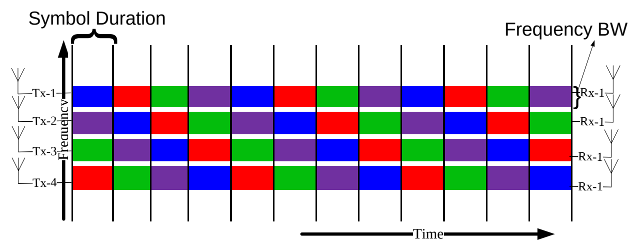

Figure 8: FDM-based signal transmission in time-varying channel

This subcarrier allocation method which is proposed in as a combination of comb type and block type [8] pilot allocation has a big advantage that it can measure all Tx signals simultaneously and all frequency areas by applying some interpolation methods in time domain as shown in Fig. 8.
The method to estimate the channel is as follows. When signal X generated in frequency domain is transmitted, received data is represented in time domain as [25],

$$\mathbf{y} = \mathrm{IFFT}(\mathbf{X}) * \mathbf{h} + \mathbf{n} \quad \text{..............(11)}$$

where h is impulse response of the channel and n is white noise from receiver. This equation is also transformed by using fast fourier transform as

$$\mathbf{Y} = \mathbf{X} \bullet \mathbf{H} + \tilde{n} \quad \text{...................................(12)}$$

Where **X**= $diag\,(\mathbf{x}(0), \mathbf{x}(1), ..., \mathbf{x}(N-1))$, **H**= $FFT(\mathbf{h})$ and $\tilde{n} = FFT(n)$. By using received signal **Y** and known transmitted signal **X,** thus changing the equation (11) in frequency domain by using IFFT can be estimated as follows:

$$\tilde{\mathbf{H}} = \mathbf{X}^{H} \bullet Y \quad \text{..(13)}$$

3. Technical Analysis

As a solution of conventional TDM based channel sounder limitations, code division multiplexing (CDM) based MIMO channel sounding architecture is considered. One of the efficient codes is loosely synchronous (LS) codes with excellent correlation properties based on Golay complementary codes proposed [20].

LS codes are defined as the combination of C and S subsequences, a Golay complementary pair, with zeros inserted to avoid overlapping between the two subsequences. If (C_0, S_0) and (C_1, S_1) are both Golay pairs of LS codes. As a result of inserted zeros, LS codes have features that aperiodic autocorrelation sidelobes and cross-correlations are zero within IFW zone [20, 21]. The main purpose of zeros insertion of the LS codes is to avoid the sequences C_0 and C_1 overlapping with the sequences

	Real-time Measurement	Hardware Cost	Major Drawback
TDM	Poor	Excellent	Synchronization between Tx and Rx
FDM	Good	Good	Frequency shift in Tx antennas
CDM	Excellent	Poor	Cross-correlation between codes

S_0 and S_1. Note that it is also necessary to insert enough guard intervals between sequences with length longer than the maximum delay of the multipath channel [6, 7].

The LS code tree generated by the above steps in figure 2 has the following properties [14, 21].

(a) All the codes on the same layer of the code tree make up an LS code set;

(b) The auto correlation of each LS code is zero at non-zero shift.

(c) The two codes in the same node are completely complementary, i.e. their cross correlation is zero everywhere.

(d) If two nodes share the same father node, the IFW length of any two codes from the two nodes is equal to the sub-code length of the codes in the father node.

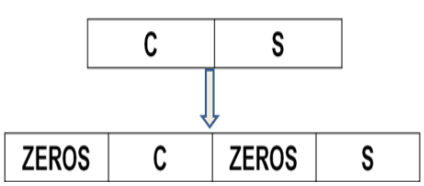

Figure 9: Formation of LS Code

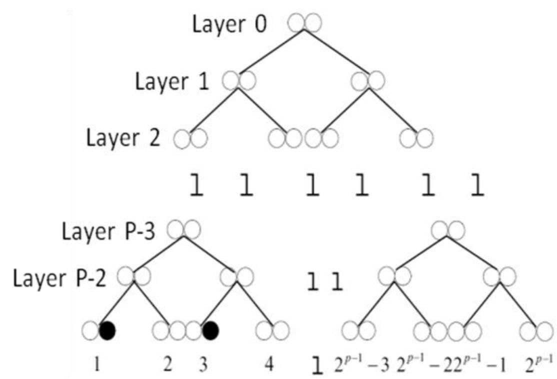

Figure 10: Structure of the LS code tree

4. Comparison Analysis:

Table 1: Comparison Table of TDM, FDM and CDM Technique

By using an analogy with multi-user communication scenarios, Time Division Multiplexing and Code Division Multiplexing techniques considered for channel sounding purpose in terms of real-time measurement, hardware cost effectiveness, and major drawbacks.

TDM based technique - Real-time Measurement of TDM technique is poor. Measurement which has MS times baseband signal period and furthermore guard interval and switching are needed. TDM based hardware cost is excellent. It is realizable only by changing one transmitter to the other antennas with a switch. Major Drawback of TDM based technique is absolute time synchronization between transmitter and receiver is required.

FDM Based Technique - Real-time measurement and hardware cost of FDM based channel sounding is good. Measurement period is MS times baseband signal period. It requires MS local oscillators and one signal generator. Major drawback of FDM based channel sounding technique is the data model needs to be modified, since the frequency sample points in each transmitting antenna are different.

CDM based technique - Real-time Measurement of CDM based channel sounding is excellent. Measurement period doesn't depend on MS. Hardware cost of CDM technique is poor. It needs ms transmitter channels. Major Drawback of CDM based technique is The length of sounding code depends on the number of antennas. For more transmit and receive antenna needs long code which need more bandwidth and memory of the hardware.

The major drawback of CDM based channel sounder has been solved by using Loosely Synchronous (LS) Code with zero cross correlation properties. CDM based channel sounder achieves real-time measurement and excellent cross correlation between codes. Therefore, the CDM based channel sounder is proposed.

5. Conclusion

In this paper, we have investigated FDM, TDM and CDM techniques in terms of real-time measurement, hardware cost and major drawback. By using CDM based MIMO channel sounder, we can overcome the major drawback of the conventional TDM-based MIMO channel sounder scheme. To overcome the main limitation of TDM scheme we propose, CDM based technique using LS code as sounding code with excellent correlation property. Having almost zero cross correlation property LS code is much better than conventional PN code sequence. Which is most important for a channel sounder to measure the channel parameters.

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