Impact of Spatial Correlation towards the Performance of MIMO Downlink Transmissions

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***Abstract*—There are two known MIMO transmission scheme in the wireless link-level research: Space-Time Coding (STC) and Spatial Multiplexing (SM). STC aims to achieve maximum antenna diversity and improve wireless link reliability, while SM, on the other hand provides a capability for increasing the data rate by higher spectral efficiencies, i.e. more bits/s/Hz of bandwidth. Most MIMO simulations consider ideal transmission spatial subchannels condition, whereby the fading correlation between each spatial subchannel is uncorrelated with uniform Rayleigh's distribution. However, in a more realistic propagation environment, spatial correlation does exist between antenna pairs and affects the MIMO transmission link, resulting in reduced capacity and loss of Bits Error Rate (BER). The main aim of this paper is to investigate the effect of spatial interference due to spatially correlated MIMO subchannels by employing a dynamic subcarrier allocation, based on the Orthogonal Frequency Division Multiple Access (OFDMA) transmission scheme. Focus is given in the downlink path, since the Mobile Station (MS) is expected to benefit from the rich multiuser diversity gain given from the dynamic subcarrier allocation. From the simulation results, the BER performance between both the STC and SM scheme will be analyzed to further understand the limitation in transmission under different spatial correlation.**

***Index Terms*—correlated channel, dynamic subcarrier allocation, MIMO, self-interference, spatial multiplexing, space-time coding, spatial subchannel**

I. Introduction

Transmission over the wireless medium is the fundamental challenge in a broadband wireless communications network. The transmission medium is impaired by many factors, such as building obstacles, noise and interference. OFDM is one of the effective mitigation techniques to combat the channel impairments in a wireless network. The fundamental feature of OFDM is to convert the single carrier transmission to multi-carrier transmission.

The multiuser version of OFDM, known as OFDMA consists of multiplexing different users in the time and frequency domains by assigning subsets of subcarriers to individual users, thus allowing efficient and flexible resource allocation. OFDMA transmission technology can be further enhanced by the addition of the multi-antenna techniques, known as MIMO, which can further be classified into two techniques. The first technique, Space-Time Coding (STC) aims to achieve full transmit diversity and reliable communication links. While another scheme, Spatial Multiplexing (SM) aims to increase the spectral efficiency by transmitting independent parallel data streams over multiple antennas.

However, the multiplexing gain is dependent on the number of transmit-receive antenna, which are subjected to uncorrelated fading. In other words, the spectral efficiency that can be exploited in a MIMO scheme depends strongly on the statistical behavior of the spatial fading correlation, also known as the effect of self-interference. MIMO schemes rely on the linear independence between the channel responses corresponding to each pair of transmit-receive antennas. As the spatial correlation increases, cross-correlation will occur between the spatial subchannels. Consequently, MIMO schemes suffer considerably from self-interference, resulting in ill-conditioned matrices, which cause degradation of system capacity.

The aim of this paper is to investigate the effect of self-interference towards transmission in both MIMO schemes. This paper compares the performance of both STC and SM schemes in different correlation scenarios by employing a dynamic subcarrier allocation (DSA) scheme, which takes advantage of independent channel variations across users to improve the network performance through frequency diversity.

The rest of the paper is organized as follows. The problem of self-interference is discussed in Section II. The DSA scheme is presented in Section III. In Section IV, simulation environment and network parameters are presented. In Section V, the BER performance of both MIMO schemes is further simulated and analyzed in different correlation environments and Section VI concludes this paper

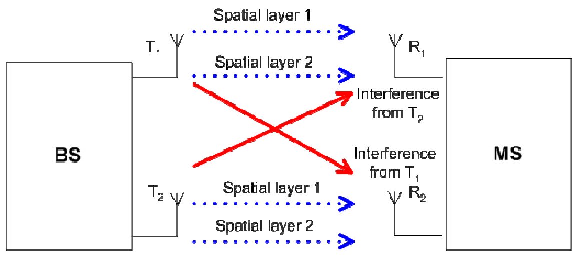

Figure 1. Example of self-interference in 2×2 MIMO system

II. PROBLEM BACKGROUNDS

A. Introduction to MIMO

Imperfections in the wireless channel can be overcome by applying different forms of diversity. One of the forms of diversity is MIMO transmission and it is often classified into two schemes namely STC and SM. STC aims to improve the link reliability so that the effect of fading can be reduced. Implementation of STC schemes comes in two forms: Space-Time Trellis Codes (STTC) and Space-Time Block Codes (STBC). STTC, originally proposed by Tarokh *et al.* [1], requires heavy, non-linear Viterbi decoder implementation since it relies on the Viterbi decoder at the receiver, whereby the complexity increases exponentially as the number of antennas and the order of the trellis is increased. In an effort to reduce the decoder complexity of STTC, Alamouti [2] proposed a simple transmit diversity scheme, known as STBC. STBC requires linear processing of the received signals for decoding. By encoding the data over both the temporal and spatial domains, STBC provides spatial diversity and robustness against fading.

Spatial Multiplexing (SM) provides a capability for increasing the data rate by higher spectral efficiencies, i.e. more bits/s/Hz of bandwidth, at no additional power or bandwidth expenditure [3], [4]. This is achieved by separating the data stream input into parallel independent data streams, whereby each data stream transmitted over different antennas, thus increasing the nominal spectral efficiencies by a factor of N_t. Under suitable channel conditions, SM is useful for high data rate applications, particularly when combined with appropriate channel coding, puncturing and interleaving [5]. The transmitted data streams are not separated in time or frequency, but they are emitted in different antennas.

B. MIMO and Self-Interference

In a realistic propagation environment, the effect of self-interference does exist in MIMO transmission, thus affects the MIMO capacity. Previous works in [5], [6] and [7] have suggested that the existence of a correlation between antenna elements is one of the main challenges in MIMO implementation. The potential capacity gain is highly dependent on the multipath richness, since a fully correlated MIMO channel offers only single effective channel over a SISO system, while a fully de-correlated channel offers the multiple capacity benefits, which increases linearly as the number of antenna increases. SM schemes rely on the linear independence between each transmit antenna.

Consequently, such schemes suffer considerably from spatial correlation, resulting in an ill conditioned MIMO channel matrix [5]. This can cause degradation of system capacity, whereby retransmission does not improve the BER performance. As the correlation increases between the spatial subchannels, cross-paths from the adjacent spatial subchannel will occur, resulting in an effect known as self-interference in Gesbert *et al.* [5].

Self-interference occurs due to a variety of factors, such as insufficient antenna separation [9], small angular spread (AS) and angle of arrival (AoA) [5], [10]. In addition, the height of the base stations antennas, the condition of signal path clearance and scatterers surrounding the base stations have also been identified as key factors contributing towards the effect of self-interference as identified by Catreux *et al.* [6].

In a highly correlated environment, the simultaneous transmission of independent data symbols from multiple antennas is perceived as similar symbols at the receiver and makes stream detection and decoding a difficult task for the receiver. As a result, MIMO receiver failed to adapt and extract the nonzero capacity that is present in the highly correlated channel. This effect can be illustrated by Fig. 1, whereby spatial subchannel 1 from T_2 acts as an interferer for the desired signal to be transmitted between T_1 to R_1, and the same occurs between the T_2 and R_2 antenna.

C. Correlation Coefficient

Theoretically, a MIMO scheme can achieve its maximum capacity in the uncorrelated channel scenario, provided with proper detection and error correction coding. However, the capacity can be reduced when the spatial subchannels of the MIMO channel affected by self-interference. The spatial correlation matrix of the MIMO channel can be derived from the Kronecker model [7], a well-known correlation analytical model.

Spatial correlation matrices between BS and MS, are given by:

$$\mathbf{R}_{MIMO} = \mathbf{R}_{MS} \otimes \mathbf{R}_{BS} \quad (1)$$

where ⊗ represents the Kronecker product, and $\mathbf{R}_{MS}$ and $\mathbf{R}_{BS}$ are $N_r \times N_r$ and $N_t \times N_t$ matrices corresponding to transmit and receive covariance matrices.

Equation (1) assumes that receive and transmit antenna are correlated independently and assumes the presence of scatterers near both antenna elements. The simplicity of

TABLE I
PHYSICAL LAYER PARAMETER FOR OFDM SYSTEM

Parameter	Value
Operating Frequency	5 GHz
Available Bandwidth (BW)	100 MHz
Transmit Information Duration (T_{tx})	10 ns
FFT size (N_{FFT})	1024
Useable subcarriers (N_{sub})	768
Subcarrier spacing (Δ_f)	97.66 kHz
Useful Symbol duration (T)	10.24 μs
Guard Interval (GI)	176
Total Symbol Duration (T_s)	12.00 μs

TABLE II
MODULATION AND CODING SCHEME (MCS) FOR THE MIMO-OFDMA SYSTEM

Modes	SM 1	ST 1	SM 2	ST 2
Modulation	BPSK	QPSK	QPSK	16QAM
Coding Rate	1/2	1/2	3/4	3/4
Data bits per OFDM symbol	768	1536	2304	2304
Total Bit per OFDM symbol	1024	2048	3072	3072
Target Bit Rate [Mbps]	**64**	**64**	**192**	**192**

the Kronecker model makes it an attractive channel model in the analysis of any space-time processing technique. The Kronecker model allows separate optimization at both ends, so that receive and transmit correlations can be dealt separately since the correlation properties at both transmit and receive antennas are independent of each other.

III. DYNAMIC SUBCARRIER ALLOCATION

Both of the MIMO schemes employ the subcarrier allocation strategies, known as the Dynamic Subcarrier Allocation (DSA). In this scheme, the allocation offers fair subcarrier allocation across all users; however, it did not consider any spatial correlation that occurs between antenna elements. The allocation process allows the user with the lowest channel gain to have the next best of subcarrier gain, thus able to achieve the desired balance between fairness and system capacity.

The allocation procedure can be described as follows:

(1) Initialization
Set $\mathbf{P}_{k,q}$=0 for all users, u =1,…, U ; Set $\mathbf{C}_{k,s,q}$=0 for all users u =1,…, U and spatial subchannels q={1,2,…, Q};
Set s =1

(2) Main process
While $N_q \neq 0_{Nsub}$
{ (a) Make a short list according to the users that have less power. Find the user u satisfying:

$$P_{u,q} \leq P_{i,q} \quad \text{for all } i,\ 1 \leq i \leq u$$

(b) For the user u got in (a), Find sub-carrier n satisfying:

$$|\, h_{u,n,q}| \geq |\, h_{u,j,q}| \quad \text{for all } j \in N$$

(c) Update $\mathbf{P}_{u,q'}$, N_q and $\mathbf{C}_{u,s,q'}$ with the s from (b) according to

$$\mathbf{P}_{u,q} = P_{u,q} + |\, h_{u,n,q}|^2$$
$$N_q = N_q - s$$
$$\mathbf{C}_{k,s,q} = n$$
$$s = s + 1$$

(d) Go to the next user in the short list got in (a) until all users are allocated another subcarrier. }

where $\mathbf{P}_{k,q}$ represents the average received power for user u at the q-th spatial subchannel and q={1,…,Q}, where Q is the effective number of spatial subchannels considered by the allocation process. U is the total number of users, N_{sub} is the total number of useable subcarriers, N is an Q by N_{sub} matrix where each row is a vector containing the useable subcarrier indices for corresponding spatial subchannel. The $h_{u,n,q}$ is the channel response for user u, subcarrier s and subchannel q and $\mathbf{C}_{k,s,q}$ is a matrix which contains the location of allocated subcarriers for user u. In this scheme, the subcarrier allocation is performed independently between each spatial subchannel.

TABLE III
CHANNEL MODEL PARAMETERS

Parameters	SCM Urban Micro
Environment	Outdoor urban NLOS
Bandwidth	5 MHz
Excess Delay Spread	923 ns
Mean Delay Spread	251 ns
Carrier Frequency	2 GHz

IV. SIMULATION SETUP AND PARAMETERS

A. MIMO-OFDMA Design Parameters

In the simulation, the Alamouti-based STBC scheme is chosen as a representation of STC scheme due to its simpler block architecture with sub-optimal BER performance. The STBC scheme is then compared against SM scheme, using the sub-optimal V-BLAST architecture. The simulation is performed in an MIMO-OFDMA downlink environment. The OFDM parameters are summarized in Table I and Table II summarized the different modulation and coding schemes (MCS) employed by both MIMO schemes. Two target bit rates are used for comparison purposes: 64 Mbps and 192 Mbps. In order to achieve such target bit rates, the SM transmission scheme shall employ MCS labeled as SM 1 and SM 2, while STC shall employ ST 1 and ST 2 respectively.

The channel model for network simulation is adopted from the SCM 'Urban Micro' [11] standards. Urban Micro represents a very small cell in an ultra-high density urban area with cell radius of approximately less than 500m and BS antennas located at the rooftop level. The key parameters for the channel model are summarized in Table III.

A packet size of 54 bytes is considered throughout this

TABLE IV
CORRELATION MODES AND ITS COEFFICIENT

Correlation Modes	Correlation Coefficient	
	R_{BS}	R_{MS}
'Uncorrelated'	0.00	0.00
'HH'	0.91	0.91
'Full'	0.99	0.99

paper. In addition to that, 2000 i.i.d. quasi-static Rayleigh distributed channel samples per OFDM symbol are used in each simulation to achieve stable averaging over wide fading channel condition. 16 users are considered to exploit the multiuser diversity gain with a total of 768 useable subcarriers to be equally shared among the users with FFT size, N_{FFT}= 1024. A 2×2 antenna configuration is used for both the STC and SM scheme.

B. Correlated Channel Model

Different levels of spatial correlation will be considered: ranging from the ideal to the extreme correlation scenario. The correlation cases are derived based on practical wireless channel measurements from previous works as published in [12], [13] and [13] and it is summarized in Table IV.

'Uncorrelated' channel represents an ideal correlation scenario where the influence of self-interference is negligible, while 'Fully' correlated channel represents the worst-case scenario where the effect of self-interference is expected to be dominant and the effective capacity gain is equal to a SISO system. In realistic channel environments, partially correlated MIMO channels should be expected, especially in densely populated urban environments. Other than the ideal and extreme correlation case, additional correlation mode is introduced, namely 'HH', which consists of the combinations of High (H) correlation between BS and MS.

V. SIMULATION RESULTS & ANALYSIS

For the target rate of 64 Mbps, as shown in Fig. 2, the difference in BER improvement is obvious, whereby STBC performance is better by 6 dB at BER= 10^{-3} in an uncorrelated channel, compared to the SM scheme. As the correlation increases, the BER slightly degrades for the STBC case, however, not as severely as the SM scheme for which the BER degradation becomes very severe as channel correlation increases. In the fully correlated channel, STBC performance is slightly reduced by 2 dB at BER=10^{-3}, compared to SM, which suffers an error floor. The absence of error floors suggests the robustness of the STBC scheme against the effect of self-interference.

A similar observation can be found in Fig. 3 for SM and STBC with target rate of 196 Mbps. For example, in

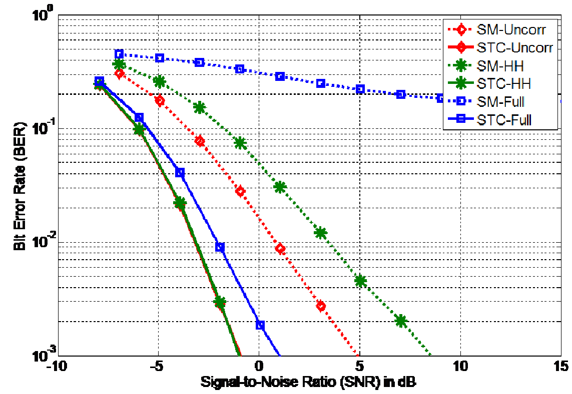

Figure 2. BER performance between STBC and SM with target rate of 64 Mbps

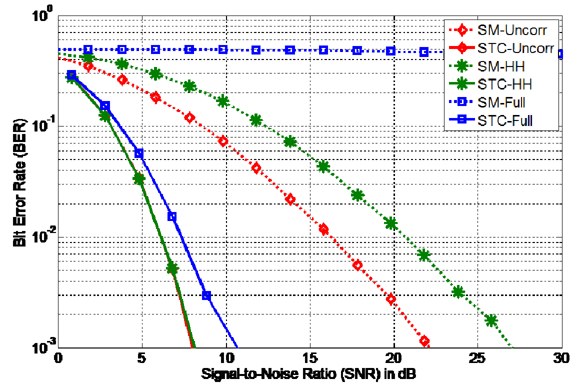

Figure 3. BER performance between STBC and SM with target rate of 196 Mbps

'CH' correlation mode, the BER performance of a STBC scheme employing MCS of QPSK, ½ rate outperformed SM scheme by close to 10 dB at BER = 10^{-2}, while the similar observation can be found in the STBC scheme with MCS of QPSK, ¾ rate, with approximately 20 dB at BER=10^{-2}. It can be observed that STBC scheme performance is robust across all correlation scenarios. In both MCS, it is noticeable that the BER performance of a 'fully' correlated channel has slightly reduced as the differences in BER performance are very minimal, ranges between 2-3 dB in both uncorrelated and fully correlated channel environments. In STBC transmission, a single data stream is replicated and transmitted over multiple antennas. The redundant data streams are each encoded using the mathematical algorithm. With such coding, each transmitted signal is orthogonal to the rest, reducing self-interference and improving the reliability of the receiver to distinguish between the multiple signals.

From the multiple transmissions of the coded data streams, there is increased opportunity for the receiver to detect a strong signal that is less adversely affected by the presence of correlation in the spatial subchannels. The ML detection scheme in Alamouti's STBC is likewise, known to be able to tolerate against the moderate level of correlation, which is approximately up to correlation coefficient, R_{MIMO} < 0.8, as shown by Gore *et al.* [15]. However, the implementation complexity of ML receiver needs to be considered, especially for small MS with low-power requirement and also when the delay spread of the channel is large. The complexity of a ML decoder depends on the number of receive antennas and the constellation size of the modulation scheme, whereby for an $Nt \times N_r$ MIMO system using M-QAM, the complexity is in the order of M^{Nr}.

The difference in BER performance of the SM scheme occurs due to the architecture of spatial multiplexing transmission, whereby the probability of the other spatial interferer to transmit the same subcarrier to the desired signal is very high as the spatial subchannel approaches full correlation. In other words, the existing SM scheme has poor ability to minimize the effect of self-interference. Other than that, the MMSE decoder employed at the receiver of a SM system offers a suboptimal solution for equalization at the receiver as it has poor ability to reduce the combined effect of interference in the fully correlated channel. In a highly correlated channel, the presence of self-interference becomes more dominant than the additive noise, thus the symbols' detection and decoding become a difficult task to the MMSE receiver. Therefore, in a highly correlated spatial subchannel, designing a proper downlink transmission strategy to minimize the effect of self-interference is desired, especially for the SM transmission scheme.

VI. Conclusions

In this paper, two practical MIMO strategy, namely STBC and SM are presented. From the simulation results, both STBC and SM suffer from the effect of self-interference, whereby the degree of impairment increases as the degree of spatial correlation increases. However, it can be seen that the effect of self-interference is highly dominant in SM architecture compared to STBC from the BER performance comparison. This is due to the cross paths that occur between the spatial multiplexing of data streams during SM transmissions.

Unlike SM, STBC is a robust MIMO technique against non-ideal operating conditions, especially in extreme spatial correlation. Other than spatial diversity, STBC offer better mechanisms in the spatial correlation correction from the ML codes. Future work will be focusing on the use of interference-aware performance metric to minimize the debilitating effect of self-interference inherent in the SM architecture.

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