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Overcoming Self- Interference in SM-OFDMA with ESINR and Dynamic Subcarrier Allocation

R. Nordin, S. Armour, and J.P. McGeehan

Centre for Communications Research

University of Bristol

Bristol, United Kingdom

Email: Rosdiadee.Nordin@bristol.ac.uk, Simon.Armour@bristol.ac.uk, J.P.McGeehan@bristol.ac.uk

Abstract— For a single user with multiple receive antennas, co-antenna interference can be the dominant source of impairment in a Spatial Multiplex Orthogonal Frequency Division Multiple Access (SM-OFDMA) system, particularly when correlation exists between spatial sub-channels. By exploiting knowledge of the channel response and combining it with Dynamic Sub-Carrier Allocation (DSA), the algorithm proposed in this paper aims to reduce the effect of interference, while providing fair gain and maximizing the SINR across all users. Simulation results reveal that the proposed algorithm considers self-interference that exists between multiple antennas and is capable of achieving a capacity gain for every user with improved BER performance compared to previous work.

Keywords- MIMO, OFDMA, ESINR, DSA

I. INTRODUCTION

Information theoretic results have shown the remarkable capacity potential of wireless communication systems using multiple antenna arrays at both transmitter and receiver. This system, known as Multiple Input Multiple Output (MIMO) has been shown by Foschini and Gans [1] to give significant capacity increase, which grows linearly with the minimum numbers of transmit and receive antennas when operating on a single link with Gaussian noise. Performance can be further improved in wideband scenarios by combining the MIMO architecture with OFDM(A).

OFDM is well suited in an environment where multipath is a major source of distortion and offers further advantages such as high spectral efficiency, better resistance against interference and simplified implementation. OFDMA further offers enhanced support for multi-user transmission through the ability to share channel resources with fine granularity in the frequency domain. As a result of the combined benefits of MIMO with OFDMA, this technology has been selected as the PHY Layer air-interface for WiMAX (802.16) whilst Third Generation Partnership Project (3GPP) has assumed OFDMA will be used as the downlink interface for the Long Term Evolution (LTE) network - an enhancement to existing 3G standards. The IEEE 802.20 Working Group has also nominated OFDMA as its packet-based air interface for future Mobile Broadband Wireless Access (MBWA) [2].

The capacity of a system employing a MIMO architecture has been shown by Gesbert *et al.* [3] and Andrews *et al.* [4] to decrease as the number of transmit antennas increases if the spatial interference is not suitably addressed.

This paper will investigate the capacity performance of a SM scheme since the main challenge in interference-limited situations described in this SM scheme is to maximize the capacity.

SM aims to achieve maximum capacity by achieving higher spectral efficiencies, i.e., more bits/s/Hz of bandwidth. This is achieved by dividing the high rate data stream input into parallel independent data streams with each sub-stream being transmitted over different antennas, thus increasing the viability of high data rates by a factor of $\min(N_t, N_r)$ [3].

There are three types of interference in MIMO systems. Consider a cellular network with M Base Stations (BS) adjacent to each other with N_t antennas. The source of interference for a single MS can be determined by $M \times N_t$ interfering signals if there are M non-negligible neighbouring base stations. This effect is known as *intra-cell interference*, or *other cell interference* (OCI) [4]. As opposed to OCI, interference that comes from other users within a single cell is known as *self-cell interference*. The third source of interference is called *co-antenna interference*, also known as self-interference resulting between the spatial multiplexing data streams of a single user. Self-interference can be measured using an effective signal-to-interference-and-noise-ratio (ESINR) metric [5]. This indicates the channel quality from the knowledge of self-interference caused by the mismatch between the spatial sub-channels.

In this paper the ESINR metric is used in combination with the dynamic subcarrier allocation algorithm proposed in [6] to allocate the 'best' subcarriers to different users in a multiuser scenario where the ESINR metric is used to determine the subcarrier quality; thereby taking into account both spatial sub-channel quality and self interference.

The proposed algorithm thus attempts to (i) utilise the multi-user channel to mitigate channel fading and exploit it as a source of diversity, (ii) consider the interference that exists between spatial sub-channels, and (iii) provide fair benefit to all users.

This paper is organized as follows. Section II describes the PHY Layer model of the OFDMA system and the proposed DSA-ESINR algorithm for the MIMO-SM architecture. In Section III, the simulation setup and system parameters are explained and in Section IV the results from the numerical simulation and information theoretic analysis are presented. Section V concludes the paper.

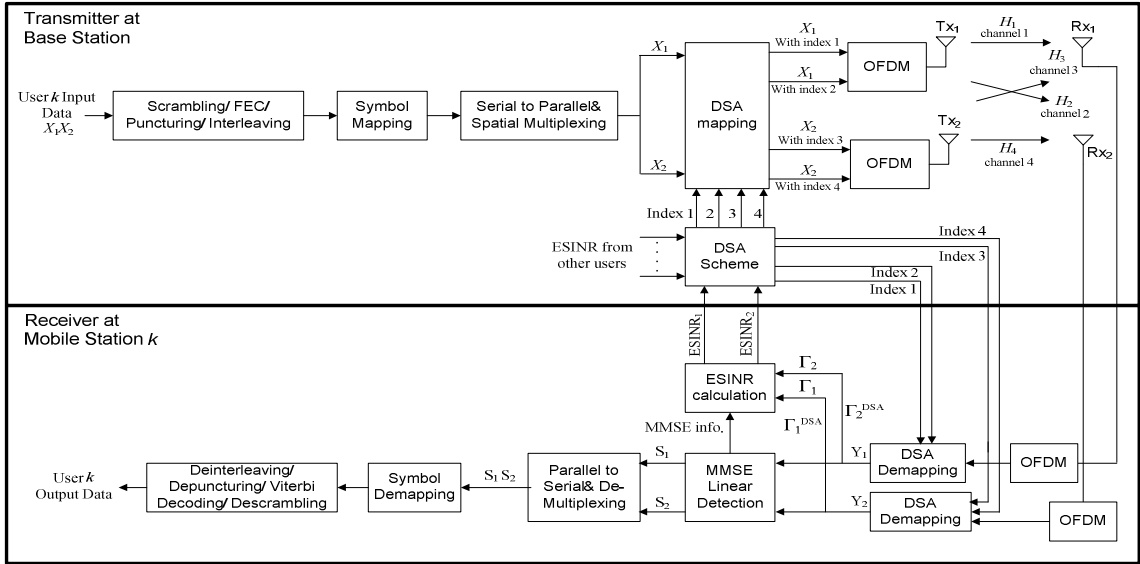


Figure 1. Block Diagram of DSA-ESINR with SM-OFDMA Architecture

II. SYSTEM MODEL

A. OFDMA System

In this paper, the downlink path of an OFDMA system is considered for multiple users to exploit diversity. Thus OCI is not considered.

In a single cell, one Base Station (BS) establishes communication with multiple Mobile Stations (MS) simultaneously and each MS experiences independent fading channels. For each MS, a single sub-channel is allocated, consisting of a number of OFDMA subcarriers and each subcarrier is subjected to a flat Rayleigh-fading narrowband channel with independent fading coefficients for each path. All users are assigned with the same number of subcarriers in each sub-channel.

The physical layer of a single link is presented as a block diagram in Figure 1. The BS transmits data streams to all MSs and applies independent bit level error control coding, symbol mapping and serial to parallel conversion. The DSA mapping process allocates the parallel data symbols to suitable subcarriers from the subcarrier indexes generated from the allocation algorithm. OFDM modulation is implemented by means of an inverse Fast Fourier Transform (IFFT) with subsequent guard interval (GI) insertion to combat ISI due to multipath delay. The GI is appended by means of a cyclic extension. When the GI is longer than the excess delay of the channel, ISI is eliminated.

At the MS, the resultant coded/ multiplexed symbol streams are assigned to appropriate subcarriers as indicated by the DSA algorithm. The allocated subcarriers are then extracted from the given MS's sub-channel. Each MS receiver extracts the GI, applies a parallel-to-serial conversion and a Fast Fourier Transform (FFT). Equalisation and soft de-mapping yield bit-level information which is subject to error control. This paper considers a 2x2 MIMO architecture, but the analysis is readily extendable to higher MIMO orders.

B. ESINR Metric

The mathematical model for a received signal in an SM-OFDMA system, after FFT and guard removal is described as follows:

$$Y_k^s = H_k^s X_t^s + N_k^s \quad (1)$$

where the subscript k denotes MS index, s denotes the subcarrier index, H_k^s is the channel matrix containing MS k 's frequency responses of the channels between N_t transmit and N_r receive antennas at subcarrier s and applied to the subcarriers of the OFDMA signal on a cluster basis, while N_k^s denotes a complex circular symmetric colored noise with invertible covariance matrix and X_t^s denotes $N_t \times 1$ matrix containing transmit signals.

At the receiver, the proposed OFDMA system adopts a linear MMSE configuration:

$$G_k^s = \left((H_k^s)^H H_k^s + SNR^{-1} I \right) (H_k^s)^{-1} \quad (2)$$

The MMSE filter has the ability to mitigate self-interference whilst not adversely amplifying the received noise. The MMSE filter is also able to separate the spatial layers of the MIMO structure [5]. As a result, different spatial layers can be allocated to a different MS to achieve an additional spatial multi-user diversity gain. On the other hand, this increases the amount of feedback by the number of spatial layers. The received signal is multiplied by an MMSE filter given by (2):

$$G_k^s Y_k^s = G_k^s Y_k^s X_t^s + G_k^s N_k^s \quad (3)$$

MS k then computes the ESINR at every data stream for every subcarrier [5] (the subcarrier index, s , is omitted):

$$ESINR_k^q = \frac{|(G_k H_k)_{qq}|^2 E_s}{|(G_k H_k)_{qj, j \neq q}|^2 E_s + (|G_k|_{qq}^2 + |G_k|_{qj, j \neq q}^2) N} \quad (4)$$

where q is the spatial sub-channel at every subcarrier, E_s denotes the average symbol energy and $|\cdot|_{qj}$ denotes the element located in row q and column j . The ESINR metric aims to compute self-interference from the data stream component, $|\cdot|_{qq}$ and self-interference component, $|\cdot|_{qj, j \neq q}$ from the other transmitted data streams within the same channel.

The data rate of each subcarrier for MS k in the frequency domain can be calculated as [5]:

$$r_k^q = \log_2(1 + ESINR_k^q) \quad (5)$$

For comparison purposes, the feedback capacity for the ESINR metric is compared with *effective* SNR (ESNR). ESNR considers the eigenvalues of the MIMO channels to indicate the channel quality from every MS:

$$ESNR_k^q = \frac{|D_k|_{qq}^2 |(V_k^H)_{qq}|^2 E_s}{|D_k|_{qq}^2 |(V_k^H)_{qj, q \neq j}|^2 E_s + N} \quad (6)$$

where D_k is a diagonal matrix and V_k is the unitary matrix obtained by applying the Singular Value Decomposition (SVD) to H_k^s . Capacity feedback of each subcarrier for MS k in frequency domain is:

$$r_k = \sum_q^{N_s} \log_2(1 + ESNR_k^q) \quad (7)$$

C. DSA Algorithm

Each MS provides feedback information¹ to the BS and the DSA algorithm then allocates subcarriers to the MSs. The DSA algorithm is based on previous work of Peng [6], which considers five different schemes to predict the performance in correlated and uncorrelated channels. This paper only considers DSA-Scheme 1, whereby subcarrier allocation at each spatial layer is treated independently in an uncorrelated channel. The use of the ESINR metric proposed in this paper is an alternative method for mitigating interference to those methods used by schemes 2-5 in [6].

The algorithm ranks users from the lowest to highest data rate at each spatial layer. Consequently, the next best subcarriers are allocated to users in rank order, allowing users

with the lowest data rate at that particular spatial layer to have the best data rate that is available for the next transmission.

The proposed Dynamic Subcarrier Allocation (DSA) with ESINR metric algorithm can be described as below:

- 1) After the base station transmits data vector X_t^s , the k -th mobile station computes the MMSE filter given by (2).
- 2) The k -th mobile station then computes the ESINR (4) and data rate, r (5), of the q -th spatial sub-channel.
- 3) With the feedback information from the MS, the user with the lowest allocated data rate is allowed to have the next ‘choice’ of best subcarrier as follows:

- (a) Short list of users is generated, starting at user with least data rate, Γ . Find user k satisfying:

$$\Gamma_k^q \leq \Gamma_i^q \quad \text{for all } i, 1 \leq i \leq K$$

- (b) For the user k above, find the subcarrier n satisfying:

$$r_k^q \geq r_j^q \quad \text{for all } j \in N$$

- (c) Then r_k^q , N and $C_{s,k}$ are updated with k and n in (b) above according to the following relationships:

$$\begin{aligned} \Gamma_k^q &= \Gamma_k^q + r_{k,n}^q \\ N_q &= N_q - n \\ C_{s,k} &= n \end{aligned}$$

where N_q is a vector containing the indices of the useable subcarriers, $C_{s,k}$ is the allocation matrix to record the allocated subcarrier, n for user k and s is the cluster size.

- 4) Go to the next user in the short list defined in (a) above, until all users are allocated another subcarrier, $N \neq 0$.

The algorithm can be repeated when the channel changes.

In this algorithm, users are not allowed to share subcarriers, thus reducing the complexity of the algorithm. In the SISO case, Jiho and Kwang Bok [7] show that the capacity can be maximized if a subcarrier is only assigned to one user, as it helps to reduce the interference from other users’ signals that happens to share the same subcarrier. This paper extends the theory presented by Jiho and Kwang Bok *loc. cit.* [7] into the MIMO case, where the number of users sharing the same subcarrier is limited to the number of available spatial sub-channels (two spatial layers in the results below).

III. SIMULATION ENVIRONMENT AND PARAMETERS

The channel model employed for this paper is based on Channel E adopted by the ETSI-BRAN standard [8]. Channel E simulates the typical large open space outdoor environments for NLOS conditions, with excess delay spread of 1760ns, sampling period of 10ns and RMS delay spread of 250ns.

The key parameters for this paper and the transmission mode to simulate the OFDMA system are summarised in Table I.

¹ Refer to ESINR (4) or r (5). Either one can be used in this step

TABLE I. PARAMETERS FOR THE PROPOSED OFDMA SYSTEM

Operating frequency	5 GHz
Bandwidth	100 MHz
FFT Size	1024
Useful Subcarriers	768
Subcarrier spacing	97.656 KHz
Useful symbol duration	10.24 μ s
Total symbol duration	12.00 μ s
Channel Coding	Punctured $\frac{1}{2}$ rate convolution code, constraint length 7, {133, 171} _{octal}

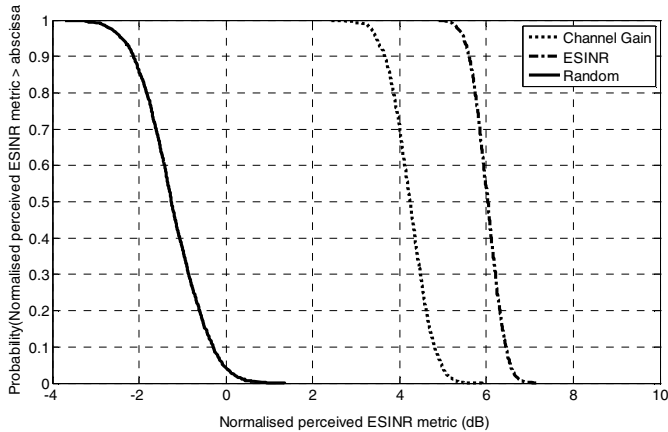


Figure 2. CCDF comparison of total ESINR metric between three different allocation strategies

2000 independent identically distributed (i.i.d.) quasi-static random channels samples per user are adopted in the simulation. The ESINR calculation is performed at MS level and the feedback information is sent to the BS.

The proposed algorithm is simulated for 16 MS users, where each of the MS is allocated a single sub-channel consisting of 48 useable subcarriers. It is assumed that the BS has perfect knowledge of the channel gain matrix and uses this to determine the subcarrier allocation.

IV. PERFORMANCE ANALYSIS

In this section, results are presented for an OFDMA system with different allocation strategies. These are: random allocation, DSA using channel gain as the metric (from [6]), DSA using ESINR as the metric and DSA using ESNR as the metric. Equal power allocation is assumed for all allocation strategies.

The total normalised ESINR metric for all 16 users achieved by different algorithms are compared in Figure 2, which represents complementary cumulative distribution functions (CCDF) of all 2000 channel samples for the three allocation algorithms as described earlier.

It can be seen that DSA using the ESINR metric outperforms the random allocation strategies by up to 7 dB. DSA using channel gain as the metric has slightly lower gain; approximately 2 dB compared to DSA using the ESINR metric.

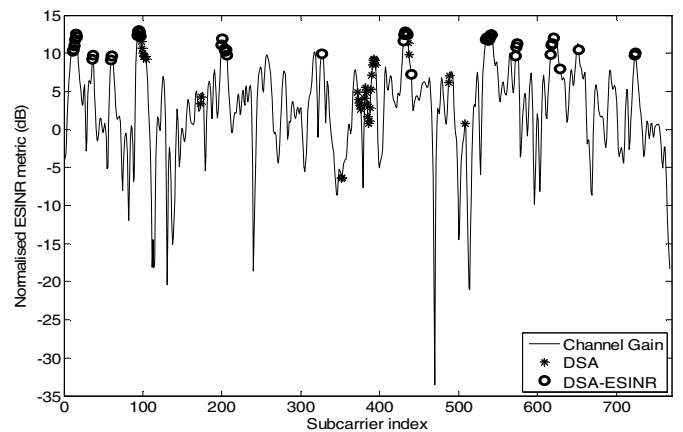


Figure 3. Example of allocated subcarriers for two different allocation algorithms across ESINR metric.

These effects can be justified by considering the instantaneous wideband channel response in the frequency domain for an arbitrary user and the corresponding subcarrier allocation achieved by three allocation algorithms as shown in Figure 3. This result illustrates the multi-user diversity benefit that the proposed algorithm is able to achieve. It can be seen that the subcarriers allocated based on the DSA-ESINR algorithm have consistent high ESINR metric (higher than the mean for the channel) and a flatter response than the actual channel. For DSA based on channel gain, it can be observed that some of the allocated subcarriers have a significantly lower ESINR metric, which shows that the DSA with channel gain does not consider the effect of self-interference (and its impact upon system capacity and BER) for the selected subcarriers.

Fairness gain across all users is investigated from the mean variance and average ESINR metric across users. The average gain and variance for all users is shown in Figure 4 and further simplified in Table II. DSA using the ESINR metric has the smallest variance compared to other types of allocation algorithm. DSA using the ESINR metric also has the largest average channel response, which shows that the proposed algorithm offers fairness to every user whilst maximizing the average channel gain of any given user without minimizing it in the other users.

Figure 5 compares the capacity between random allocation and DSA, which uses ESINR and ESNR metrics across the normalised SNR (E_b/N_0). Assuming perfect knowledge of the channel matrix, the SVD OFDM system capacity bound is also plotted for reference. At below 2 dB, both ESINR and ESNR system have almost identical data rate. As a consequence of the use of the DSA algorithm, the average data rate performance for both the ESINR and ESNR systems increases at approximately twice the capacity of random subcarrier allocation. The margin of improvement can be observed to increase significantly for system employing DSA-ESINR. This is due to the ability of MMSE receiver to minimize self-interference and noise. This result can be associated with observation from Figure 4, where the proposed algorithm is able to achieve the desired balance between fairness and system capacity.

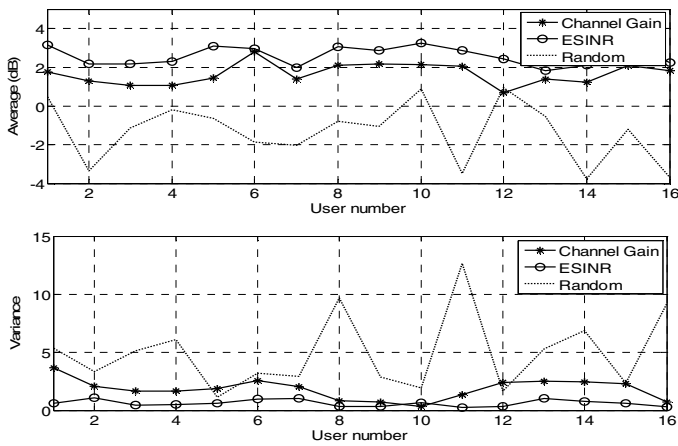


Figure 4. Average ESINR metric and mean variance across all users

TABLE II. AVERAGE NORMALISED ESINR METRIC AND VARIANCE (ACROSS ALL USERS) FOR THREE ALLOCATION ALGORITHMS

Algorithm	ESINR	Channel gain	Random
Mean (dB)	1.815	1.658	-1.336
Variance	0.6061	1.882	4.972

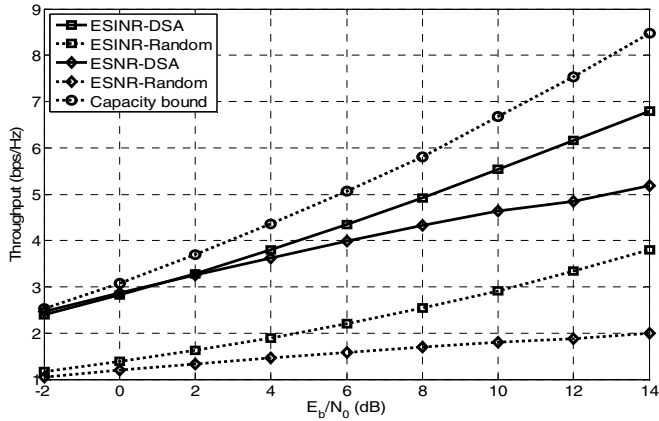


Figure 5. Feedback capacity comparison

Figure 6 shows the BER performance comparison between three allocation strategies (as described earlier) in a 2×2 SM-OFDMA system, using 64-QAM modulation and $3/4$ -rate coding, simulated in an uncorrelated channel environment. It can be seen that DSA using the ESINR metric has better performance than DSA using channel gain by 4 dB (at 10^{-5} BER), implying that DSA-ESINR has the additional benefit of minimizing the effect of self-interference while providing fair distribution of multiuser diversity benefits between users. Random allocation degrades much more severely and almost reaches an error floor, as there is no diversity exploited and self-interference severely affects the SM-OFDMA system.

The capacity gain and BER curves for the ESINR metric employing an MMSE receiver shows that it offers better performance compared to the DSA using channel gain and random allocation. This is due to the ability of MMSE receiver to minimize self-interference and noise.

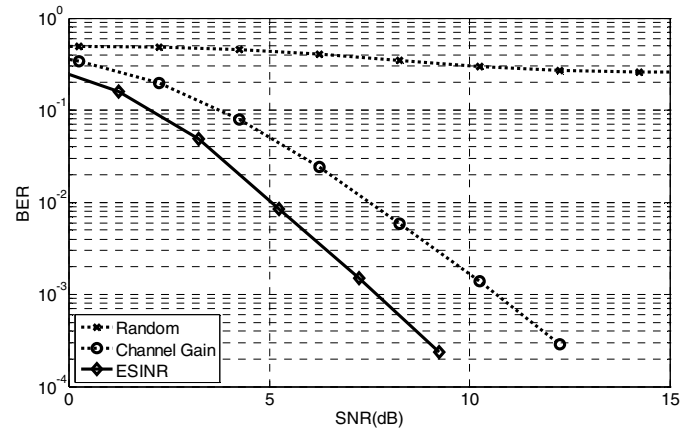


Figure 6. BER performance between three different allocation strategies

CONCLUSIONS

By employing the ESINR metric in combination with the DSA algorithm, initial investigation has revealed that the next generation of wireless system would be capable of improving the capacity performance while providing fair gain and improved BER performance. The proposed algorithm considers co-antenna interference within a SM-OFDMA system. Future work will focus on investigating BER and capacity performance of the system in correlated channels where the effect of self-interference is more dominant. Based on the initial results, the proposed algorithm can be expected to provide even greater benefits.

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