Optimal Pair-Wise SUS Scheduling Algorithm for Multiuser MIMO

Aleksandra Panajotović[1], Nikola Sekulović[2] and Daniela Milović[3]

Abstract – **In this paper we present an optimal pair-wise semi-orthogonal user selection (SUS) scheduling algorithm for multiuser multiple-input multiple-output orthogonal frequency division multiplexing (MU-MIMO-OFDM) system. Based on the perfect channel state information (CSI), zero-forcing beam forming (ZFBF) precoding is applied to cancel inter- and intra-user interferences. Presented simulation results demonstrate benefit of proposed user selection algorithm in comparison to generalized multicarrier semi-orthogonal user selection algorithm (GMSUS), both applicable to IEEE 802.11ac.**

Keywords – **IEEE 802.11ac, MU-MIMO-OFDM, User scheduling algorithm, ZFBF.**

I. Introduction

Wi-Fi standard IEEE 802.11n has launched the technique known as multiple-input multiple-output (MIMO) enabling the system to arrange multiple data streams on the same channel which results in higher channel capacity. In addition, orthogonal frequency division multiplexing (OFDM) is one more feature incorporated into IEEE 802.11n. It is effective technique to mitigate intersymbol interference in frequency-selective channel by transforming a broadband frequency-selective channel into series of non-interfering narrowband sub-channels [1]. Capacity increment realized by proposed MIMO technique is limited by minimum number of transmit (N_T) and receive antennas (N_R) [2]. Therefore, a new IEEE 802.11ac standard, known as Gbps Wi-Fi, suggests using multiuser MIMO (MU-MIMO) technique. In MU-MIMO, an access point (AP) transmits simultaneously to several compatible mobile stations (MSs), i.e. users over the same spectrum. Therefore, this technique does not increase the performance that MSs will see, but allows the network to increase its utilization by transmitting to multiple clients simultaneously.

In order to maximize capacity in MU-MIMO, the optimal strategy consists of dirty paper coding (DPC) in combination with user scheduling and power allocation [3]. Unfortunately, DPC technique is impractical because of complicated encoding and decoding schemes even for a moderate number of users. Therefore, some alternative and more practical precoding techniques have to be applied, such as zero-forcing beamforming (ZFBF) [4] and block diagonalization (BD) [5].

[1]Aleksandra Panajotović is with the Faculty of Electronic Engineeering at University of Niš, Aleksandra Medvedeva 14, Niš 18000, Serbia, E-mail: aleksandra.panajotovic@elfak.ni.ac.rs.

[2]Nikola Sekulović is with the College of Applied Technical Sciences, Aleksandra Medvedeva 20, Niš 18000, Serbia.

[3]Daniela Milović is with the Faculty of Electronic Engineeering at University of Niš, Aleksandra Medvedeva 14, Niš 18000, Serbia.

It is known that ZFBF cancels inter- and intra-user interferences, while BD just cancels inter-user interference leaving intra-user cancellation to subsequent beamforming or equalization processes. Analysis which of these techniques is the most appropriate from sum-rate point of view is done in [6].

The number of users that AP can serve simultaneously is equal to or less than the number of antennas in AP. So, a fundamental problem arising in MU-MIMO system is how AP should choose a subset of users to be served. The optimal schedule is found by exhaustive search, i.e. achieved sum rate is evaluated for all combination of users and the user combination providing the maximal sum rate is scheduled. However, in the case when number of the users, N_u, is large, exhaustive search cannot be used any longer, since the size of search space, $\sum_{i=1}^{N_T}\binom{N_u}{i}$, becomes prohibitively large. Therefore, authors in [4] propose semi-orthogonal user selection (SUS) algorithm which in combination with ZFBF gives the performance reasonably close to that of DPC under practical values of N_u. That algorithm is adapted to multi-stream multicarrier users transmitting using OFDM as generalized multicarrier semi-orthogonal user selection (GMSUS) algorithm applicable to IEEE 802.11ac [7-9]. Modified version of SUS algorithm suitable for massive MIMO is described in [10] as massive MIMO pair-wise SUS algorithm.

In this paper we propose a new algorithm, acceptable to IEEE 802.11ac, based on both pair-wise and optimal scheduling algorithms. Simulation results show that proposed algorithm outperforms performance of its counterpart also based on SUS. The price paid for performance improvement is a bit greater complexity from practical point of view.

This introduction ends with notational remarks. Vector and matrices are denoted by lower- and upper-case bold letters, respectively, while scalars are represented with non-bold letters. $(\cdot)^T$ and $(\cdot)^H$ denote transpose and complex transpose, correspondingly, $D(x)$ is a (block) diagonal matrix with x at its main diagonal, $|Q|$ is the cardinality of subset Q, $\boldsymbol{I}_L$ is $L \times L$ identity matrix, $\|\boldsymbol{a}\|$ represents the Euclidian norm of a vector $\boldsymbol{a}$, and R and C are the set of real and complex numbers, respectively.

II. System model

We consider the downlink of MU-MIMO-OFDM system with N_T transmit antennas at AP and N_u users each equipped with N_R $(N_T \geq N_R)$ receive antennas. The system operates over N_c OFDM subcarriers, out of which N_d are used to transmit data while rest of them correspond to pilots and guard band.

Let $\mathbf{H}_u[q] \in C^{N_R \times N_T}$ represents MIMO propagation channel between AP and u-th user over q-th subcarrier. Singular value decomposition (SVD) applied on $\mathbf{H}_u[q]$ results into

$$\mathbf{H}_u[q] = \mathbf{U}_u[q]\mathbf{\Sigma}_u[q]\mathbf{V}_u^H[q], \quad (1)$$

where $\mathbf{U}_u[q] = [\mathbf{u}_{u,1}[q], \ldots, \mathbf{u}_{u,N_R}[q]] \in C^{N_R \times N_R}$ and $\mathbf{V}_u[q] = [\mathbf{v}_{u,1}[q], \ldots, \mathbf{v}_{u,N_T}[q]] \in C^{N_T \times N_T}$ are unitary matrices containing the left and the right singular vectors of $\mathbf{H}_u[q]$ and $\mathbf{\Sigma}_u[q] = D(\sigma_{u,1}[q], \ldots, \sigma_{u,N_R}[q]) \in R^{N_R \times N_T}$ is a diagonal matrix which elements on main diagonal are singular values of $\mathbf{H}_u[q]$. In order to eliminate interference ZFBF post-processing is applied at receiver, so now the equivalent channel matrix for u-th user on q-th subcarrier is defined as

$$\tilde{\mathbf{H}}_u[q] = \mathbf{U}_u^H[q]\mathbf{H}_u[q] = \mathbf{\Sigma}_u[q]\mathbf{V}_u^H[q]. \quad (2)$$

Since $N_R \le N_T$ and $\mathbf{H}_u[q]$ is full rank matrix, $\mathbf{\Sigma}_u[q]$ contains N_R non zero values, so there is a potential to transport N_R spatial streams. By treating each spatial stream as a virtual user with single antenna, now the system can be considered as a multiuser multiple-input single-output (MU-MISO) with $K = N_u N_R$ virtual users. Now, equivalent channel gain corresponding to k-th virtual user on q-th subcarrier is $\tilde{\mathbf{h}}_k[q] = \sigma_k[q]\mathbf{v}_k^H[q]$, where $k = n + (u-1)N_R$ and $n \in \overline{1, N_R}$. Assuming perfect frequency synchronization between transmitter and receiver and a cyclic prefix duration exceeding the channel delay spread, the received signal at the k-th virtual user on subcarrier q for an arbitrary OFDM symbol may be written as

$$\tilde{y}_k[q] = \tilde{\mathbf{h}}_k[q]\mathbf{x}_k[q] + \eta_k[q], \; k = \{1, \ldots, N_u N_R\}, \quad (3)$$

where $\mathbf{x}_k[q] \in C^{N_T \times 1}$ is the vector of transmitted symbol from AP antenna on subcarrier q. $\tilde{\eta}_k[q]$ is n-th element of vector $\tilde{\boldsymbol{\eta}}_u[q] = \mathbf{U}_u^H[q]\boldsymbol{\eta}_u[q]$, where $\boldsymbol{\eta}_u[q]$ is a zero-mean circularly symmetric complex Gaussian vector with covariance matrix $\mathbf{R}_\eta = \sigma_\eta^2 \mathbf{I}_{N_R}$. Since $\mathbf{U}_u[q]$ is unitary matrix, it holds $\tilde{\boldsymbol{\eta}}_u[q] : CN(0, \sigma_\eta^2 \mathbf{I}_{N_R})$.

In downlink scenario with large number of users, the AP serves users with favourable channel conditions. Let $Q = \{u_1, \ldots, u_{|Q|}\}$ be the subset of those virtual users which be served by AP in a given time slot. Now, let define matrix collecting the channel coefficient of selected virtual users on subcarrier q as $\tilde{\mathbf{H}}_Q[q] = [\mathbf{h}_{u_1}^T[q] \ldots \mathbf{h}_{u_{|Q|}}^T[q]]^T \in C^{|Q| \times N_T}$. To totally suppress multiuser interference, linear precoding has to be carried out as

$$\mathbf{x}[q] = \mathbf{W}_Q[q]\mathbf{P}_Q^{1/2}[q]\mathbf{s}_Q[q], \quad (4)$$

where $\mathbf{W}_Q[q] = [\mathbf{w}_{u_1}[q] \ldots \mathbf{w}_{u_{|Q|}}[q]] \in C^{N_T \times |Q|}$ is ZFBF precoding matrix on subcarrier q, $\mathbf{P}_Q[q] = D(P_{u_1}[q], \ldots, P_{u_{|Q|}}[q]) \in R^{|Q| \times |Q|}$ is power allocation matrix which satisfies $\sum_{u_i \in Q} \|\mathbf{w}_{u_i}[q]\|^2 P_{u_i}[q] = \frac{P_T}{N_d}$, with P_T being total power available for all subcarriers and $\mathbf{s}_Q[q] = [s_{u_1}[q] \ldots s_{u_{|Q|}}[q]]^T \in C^{|Q| \times 1}$ being the vector which contains the information symbols sent to users from selected group Q. After pre- and post-processing, the received signal for selected virtual user $u_i \in Q$ on subcarrier q can be presented as

$$\tilde{y}_{u_i}[q] = \sqrt{P_{u_i}[q]}s_{u_i}[q] + \tilde{\eta}_{u_i}[q], \quad (5)$$

where optimal value of $P_{u_i}[q]$, obtained to provide maximum capacity, can be found using waterfilling method [4].

III. Optimal pair-wise SUS algorithm

The optimal scheduled user group can be found through exhaustive search. Such approach is not acceptable when number of users is large, especially when users are equipped with more than one antenna. Therefore, design of applicable scheduling algorithm is important issue in MU-MIMO systems. In [10], authors point out that the complexity of pair-wise SUS algorithm is smaller than its traditional counterpart [4]. For that reason, in this paper we propose optimal pair-wise SUS algorithm based on both pair-wise SUS algorithm and exhaustive search. The steps of the optimal pair-wise SUS algorithm are:

Step 1: Initialization

$$Q_0 = \{1, \ldots, K\}, \quad (6)$$

$$i = 1. \quad (7)$$

Step 2: Determine the degrees of orthogonality, $\beta_{l,p}$, between all virtual user pairs $l \ne p$:

$$\beta_{l,p} = \frac{|\tilde{\mathbf{h}}_l \tilde{\mathbf{h}}_p|}{\|\tilde{\mathbf{h}}_l\| \|\tilde{\mathbf{h}}_p\|}. \quad (8)$$

Step 3: Find the pair P_i from Q_{i-1} with the smallest degree of orthogonality

$$P_i = \{l, p\} = \arg \max_{l,p \in Q_{i-1}} \beta_{l,p}. \quad (9)$$

Step 4: Select i-th virtual user to be eliminated as follows

$$\pi(i) = \arg \min_{r \in P_i} \|\tilde{\mathbf{h}}_r\| \quad (10)$$

$$Q_i = \{ m \in Q_{i-1} | m \neq \pi(i) \}, \quad (11)$$

$$i \leftarrow i + 1. \quad (12)$$

If $|Q_{i-1}| > N_T$, go to Step 3.

Step 5: Apply exhaustive search, i.e. calculate the realized throughput for all combination of virtual users selected in Step 4 and find the combination providing maximal throughput.

$$Q_{opt} = \arg \max_{S \subset Q_{i-1}} T(S). \quad (13)$$

In IEEE 802.11ac system, only finite set of transmission modes, which consist of a combination of modulation alphabet and coding rate (MCS), is available [9]. Consequently, once the group of virtual users has been selected, fast link adaptation (FLA) carries out a procedure to allocate MCS to users in order to maximize system throughput while satisfying predetermined quality of service (QoS) constraints. Usually, QoS constraint is in the form of an outage probability of target packet error rate (PER_0). Since system packet error rate (PER) depends on the allocated MCS, the received SNR, packet length and channel realization, derivation and evaluation of analytical expression for PER is a awkward task. This problem can be solved using a look-up table which maps all those parameters onto a single link quality metrics (LQM) which is then associated to PER value. In this paper, LQM known as effective SNR (SNR_{eff}) is used [11]. Namely, the optimal MCS for particular conditions in the channel is determined using SNR_{eff}.

IV. Numerical Results

In order to show advantage of the proposed optimal pair-wise SUS scheduling algorithm in throughput point of view, this section presents simulation results obtained using parameters from IEEE 802.11ac standard. System operates on 5.25GHz carrier frequency with bandwidth of 20MHz that is divided into N_c = 64 subcarriers out of which N_d = 52 are used to carry data while the rest correspond to pilot signals and guard intervals. The AP has N_T = 4 transmit antennas, while all users are equipped with N_R = 2 receive antennas. Channel profile B from [12] is used in the simulations testbed to generate a space-time-frequency-selective fading channel. The values of parameters for FLA are taken from Table I in [9].

Figures 1 and 2 present the system throughput as a function of average received SNR for MU-MIMO-OFDM in B channel which characterizes environment with little-to-moderate frequency selectivity. System throughput results achieved serving homogenous users selected by optimal pair-wise SUS algorithm are compared with ones achieved using GMSUS algorithm [9]. The GMSUS algorithm is built on SUS algorithm described in [4]. Namely, it is enhanced version of SUS algorithm suitable for IEEE 802.11ac. Parameter θ defines degree of orthogonality between selected virtual users. It has been shown that θ in range [0.4-0.6] maximizes sum-rate capacity [9]. In adaptive GMSUS algorithm, appropriate new value of θ that maximizes system throughput is selected

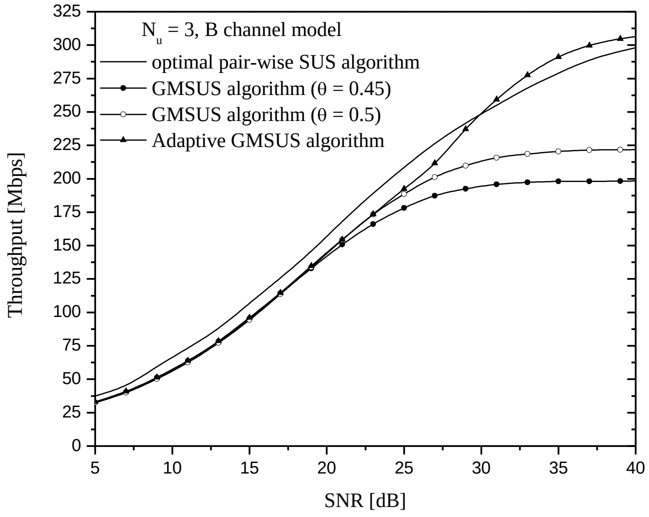

Fig. 1. Throughput comparison for different user scheduling algorithms for N_u = 3 users

for each considered value of SNR. It is evident that optimal

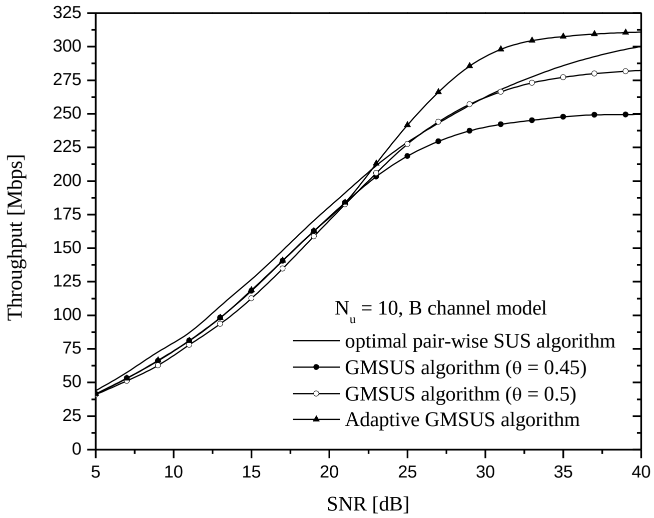

Fig. 2. Throughput comparison for different user scheduling algorithms for N_u = 10 users

pair-wise SUS algorithm provides the highest throughput for small and moderate SNR, while for large SNR the best throughput performance is achieved using adaptive GMSUS. It is known, that maximal data rate per spatial stream in IEEE 802.11ac system is 78Mbps. Therefore, maximal throughput that can be realized in considered IEEE 802.11ac system is 4*78Mb/s = 312 Mb/s. It has to be highlighted that maximal throughput can be achieved with optimal pair-wise SUS algorithm for large SNR even in a case when system should serve small number of users. In addition, it can clearly be noticed that existence of more users in the system, for all considered algorithms, leads to higher throughput thanks to the increased multiuser diversity that a larger N_u brings along.

V. CONCLUSION

This paper has proposed the optimal pair-wise SUS scheduling algorithm. The simulated throughput results have shown that this user scheduling algorithm can be accepted for application in MU-MIMO-OFDM systems complaint with IEEE 802.11ac standard. Namely, throughput performance of that system outperforms those ones realized using GMSUS and adaptive GMSUS algorithm for small and moderate SNR and achieves possible maximum for large SNR. The advantage of proposed algorithm is more significant for the case when AP serves small number of users. Further work will concentrate on modification of exhaustive search part of optimal pair-wise SUS algorithm in order to achieve performance improvement with slightly less complicated approach.

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