Cooperative Precoding and Beamforming in Co-working WLANs

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ABSTRACT

The interference among multiple access points (APs) that co-exist in the same location, limits the capacity of co-working wireless local area networks (WLANs). In this paper, we propose a practical cooperative transmission scheme to mitigate the interference in co-working WLANs. In particular, we combine Tomlinson Harashima precoding (THP), joint transmit-receive beamforming based on SINR (signal-to-interference-plus-noise-ratio) maximization, and an adaptive precoding order to eliminate co-working interference and achieve bit error rate (BER) fairness among different users. We consider the design of the system when partial channel state information (CSI) (where each user only knows its own CSI) and full CSI (where each user knows CSI of all users) are available at the receiver respectively. We prove analytically and by simulation that the performance of our proposed scheme will not be degraded under partial CSI. The simulation results show that the proposed scheme considerably outperforms both the existing non-cooperative and cooperative transmission schemes and is only 2 dB away from an interference-free channel under the same configuration.

I. INTRODUCTION

In wireless local area networks (WLANs), multiple access points (APs) run by different operators may co-exist in the same frequency band and in the same geographical location. Ideally, to achieve maximum capacity, the operators would like their APs to transmit simultaneously to their respective station without interfering with each other. In reality, however, these co-working APs do interfere with each other [1]. The co-working interference (CI) comes from either a hidden AP or an exposed AP. In WLANs, APs sense the spectrum before transmission. A hidden AP causes interference to other APs since its transmission cannot be sensed by other APs. An exposed AP, on the other hand, prevents parallel transmission by other APs since these APs will sense the transmission of the exposed AP. These two problems are illustrated in Fig. 1.

In open literature, only coexistence mechanisms between different technologies such as Bluetooth (BT) with WLANs have been investigated. Several approaches have been developed, including automatic frequency selection based on the received signal strength indicator (RSSI) [2], sub-carrier symbol erasure [3] and media access control (MAC) level interference avoidance [4], [5]. However, applying these approaches to mitigate CI in WLANs requires extra resources such as additional frequencies or time slots. It is more efficient for APs to transmit cooperatively without interfering with each other. This "coexistence" challenge is similar to a broadcasting problem. The major difference however, lies in the objective of the system design where now the aim is how to ensure performance fairness among the operators instead of maximizing sum-capacity in the broadcast service.

Recently, cooperative transmission that combines zero forcing (ZF) with dirty paper coding (DPC) [6] for a multi-user wireless network has been shown to substantially improve system performance [7]. This method however, is only applicable in a network with multiple antennas at the transmitter and a single receive antenna at each user’s terminal. The extension of ZF that optimizes transmit-receive beamforming for the case of multiple antennas at the receiver was considered in [8]. This work was further extended in [9] by combining ZF with dirty paper coding (DPC) to maximize sum-capacity. Three issues are likely to arise when the cooperative schemes above are used in co-working WLANs. First, the implementation of DPC in a practical system is very complex. Second, the bit error rate (BER) performance for the cooperative schemes varies from user to user. This BER variation is not desirable since co-working APs are deployed by different operators. Third, the multi-antenna receiver at each station needs either the transmitter (i.e., APs) to send the receiver weights information or needs to know the complete channel state information (CSI) of all users to estimate the receive weights. In reality, each user only knows its own CSI (partial CSI) which can be obtained during the training symbol period [10].

In this paper, we propose a cooperative transmission scheme among co-working APs to eliminate CI and address the three problems stated above in multiple-input-multiple-output (MIMO) orthogonal-frequency-division-multiplexing (OFDM) WLANs. We develop a practical precoding algorithm combining the Tomlinson Harashima precoding (THP) scheme [11], [12] with transmit-receive beamforming based on signal-to-interference-plus-noise-ratio maximization (SINRM) [13], [14], [15]. The transmit-receive beamforming weights are derived by using the SINRM design criteria. To get similar BER performance across all stations and further improve the overall BER, we implement an adaptive precoding order (APC) at the transmitter. We then show how our proposed scheme can
overcome the third issue above by using partial CSI without performance loss. Simulation results show that at BER=10^-4, the performance of the proposed cooperative transmission scheme significantly outperforms the performance of the cooperative scheme [9] and conventional non-cooperative schemes [13], [15] and is only 2 dB away from the performance of an interference-free channel under the same configuration. 

The remainder of this paper is organized as follows. Section II presents the system model. Sections III and IV present the transceiver design and the system design with partial CSI respectively. Section V shows the simulation results and the discussion. Finally, the conclusion is drawn in Section VI.

The notations used in this paper are as follows. We use boldface lower case letters to denote vectors, boldface upper case letters to denote matrices, and E for expectation. The superscripts $H$, $T$, and $Diag()$ denote conjugate transpose, transpose, $K \times K$ identity matrix, and diagonal matrix respectively. $C_a \times b$ indicates a complex matrix with $a$ rows and $b$ columns. $[x]$ is the greatest integer smaller than $x$. LoT($A$) is defined as the operation to extract the lower triangular components of $A$ and to set the other components to zero. UpT($A$) is defined as the operation to extract the upper triangular components of $A$ and to set the other components to zero. DiT($A$) is defined as the operation to extract the diagonal components of $A$ and to set the other components to zero. In addition, sub-carrier notation is also omitted for simplicity, since the analysis is essentially the same for all sub-carriers.

II. SYSTEM MODEL

In this paper, we consider a co-working WLAN system, where $K$ APs communicate with $K$ stations. APs and stations are each equipped with $N_T$ and $N_R$ antennas respectively. We consider a MIMO-OFDM system for each AP and station. All APs cooperate with each other to transmit to their respective station via $K N_T$ antennas. Each of these transmissions is defined as link $j$.

A. Channel Model under consideration

Let $h_j = (h_{1,N_T}(t), \ldots, h_{N_R,N_T}(t))$ where $h_{n_t,n_r}(t)$ is the channel response between the antenna $n_t$ and antenna $n_r$ at the receiver of link $j$ at time $t$. $h_j$ is characterized by an $N$-path frequency selective Rayleigh fading channel with a power exponential delay profile. The frequency selectivity of the channel is controlled by the normalized maximum channel delay $u \Delta$ and normalized rms delay spread $\Delta$. $\Delta$ and $u$ are defined as the ratio of rms delay spread $\tau_{rms}$ over OFDM symbol period $T_T$ and the ratio of maximum channel delay over $\tau_{rms}$ respectively. The channel response between antenna $n_t = 1, \ldots, K N_T$ and antenna $n_r = 1, \ldots, N_R$ at the receiver of link $j$ is given by

$$h_{n_t,n_r}(t) = \sum_{l=0}^{N-1} \alpha_{n_t,n_r}^l \delta(t - \frac{l u \Delta}{N-1}).$$

Channel amplitude for each path is modelled as a zero mean complex Gaussian random variable $\alpha_{n_t,n_r}^l$. The power exponential delay profile for the above channel is given by

$$\sigma_l^2 = \sigma_0^2 e^{-\frac{l}{\Delta}} \text{ subject to } \sum_l \sigma_l^2 = 1.$$  

The frequency response coefficient matrix for each sub-carrier for link $j$, $H_j \in C^{N_R \times K N_T}$ can then be obtained using Discrete Fourier Transform operation of $h_{n_t,n_r}(t)$.

B. Transmitter Structure

The transmitter for the proposed cooperative transmission using precoding and beamforming is shown in Fig. 2. Let $x = [x_1 \ldots x_k \ldots x_K]^T$ be the symbols transmitted to $K$ stations where $x_k$ is the symbol for station $k$ taken from $M$-ary rectangular constellation. The transmitted symbols are first permuted by a matrix $P$. We call this process APC. As shown later, APC can maintain BER fairness across links and improve system performance by rearranging the order of $x$ based on their respective SINR. APC selects a suitable $P \in \{0,1\}^{K \times K}$ for the permutation operation. Let $u = Px = [u_1 \ldots u_j \ldots u_K]^T$ be the symbols after permutation where $u_j$ is the symbol for link $j$. After APC, $x_k$ for $k$ station is permuted into $u_j$ which will be transmitted in link $j$.

After the reordering, $u$ is then passed to the THP precoder, which performs precoding to $u$ at the transmitter [12], [11]. The THP precoding order of link $j$ is assumed to be $K - j + 1$. Thus, link $K$ is precoded first and link 1 is precoded last. This means THP treats the interference from link $j + 1, \ldots, K$ to link $j$ as known when $u_j$ is precoded. We let $v \in C^{K \times 1}$ be THP precoded symbols.

THP, however, cannot eliminate the interference from link $1, \ldots, j - 1$ at link $j$ since this interference is treated as unknown. This remaining interference needs to be suppressed by using transmit beamforming weights $T \in C^{K N_T \times K}$ at the transmitter and by using receive beamforming weights $r_j \in C^{N_R \times 1}$ at the receiver of link $j$. In this paper, we propose a SINRM method to jointly optimize these transmit-receive beamforming weights.

C. Receiver Structure

The receiver for each link is shown in Fig. 2. Note that there is no cooperation among these receivers. The received signals for these $K$ links pass through the channels, $H_1, \ldots, H_K$ and are given by

$$y = HTv + N$$

where $y = [y_1 \ldots y_K]^T \in C^{K N_T \times 1}$, $H = [H_1 \ldots H_K]^T$, $N = Diag(n_1, \ldots, n_K)$ and $T = [t_1 \ldots t_K]$, $y_j$, $n_j \in C^{N_R \times 1}$ and $
The proposed scheme, THP precoding cancels interference caused by link 1, ..., j − 1 at each link j respectively (e.g., jth rows of F). This remaining interference needs to be suppressed by SINRM beamforming.

It can be noted from Eqn. (7) that there is no interference for link 1. This means that the transmit beamforming weights for link 1 are not affected by other links, and hence can be designed independently. Here, we propose to design the transmit-receive beamforming weights in the order of link 1, ..., K. After obtaining the transmit-receive beamforming weights for link 1, the transmit-receive beamforming weights for link l = 2, ..., K are determined by treating transmit beamforming weights for link 1, ..., l − 1 as known weights. Since the SINRM algorithm maximizes the SINR for each link without forcing interference to zero, the interference still remains. This results in the highest and lowest interference in links K and 1 respectively.

The average SINR for link j can be calculated as

\[ SINR_j = \frac{r_j^H H_j t_j (H_j t_j)^H r_j}{r_j^H R_{N,j} r_j} \]  \hspace{1cm} (8)\]

where \( R_{N,j} \) is the interference correlation matrix defined as

\[ R_{N,j} = E[n_j n_j^H] + \sum_{i=1}^{j-1} H_i t_i (H_i t_i)^H. \]  \hspace{1cm} (9)\]

To maximize SINR for link j, the denominator of Eqn. (8) needs to be minimized while maintaining the unity gain for the numerator,

\[ \min_{r_j} r_j^H R_{N,j} r_j \]

subject to \( r_j^H H_j t_j = 1, \| t_j \| = 1. \)  \hspace{1cm} (10)\]

The optimum \( r_j \) can be derived using the standard Lagrange method and is given as

\[ r_j = \frac{R_{N,j} H_j t_j}{(H_j t_j)^H R_{N,j} H_j t_j}. \]  \hspace{1cm} (11)\]
The SINR can now be written as \[ \text{SINR}_j = \| \mathbf{t}_j \|^2 \mathbf{R}_{N,j}^{-1} \mathbf{H}_j \mathbf{t}_j \] (12)
with \( \| \mathbf{t}_j \| = 1 \). \( \text{SINR}_j \) is clearly upper bounded \[16\] by
\[ \mathbf{t}_j^H \mathbf{H}_j \mathbf{R}_{N,j}^{-1} \mathbf{H}_j \mathbf{t}_j \leq \lambda_1 \text{SINR}_j \] (13)
where \( \lambda_1 \text{SINR}_j \) is the maximum eigenvalue of \( \mathbf{H}_j \mathbf{R}_{N,j}^{-1} \mathbf{H}_j \).
The upper bound is achieved by selecting \( \mathbf{t}_j \) in the direction of the eigenvector associated with \( \lambda_1 \text{SINR}_j \).

C. Adaptive Precoding Order

Here with SINRM, we have the highest and lowest SINR in links 1 and \( K \) respectively leading to different BER performance. In order to maintain the BER fairness across \( K \) links, in this section we propose an APC scheme. APC arranges the order of \( K \) links by selecting an appropriate permutation matrix. There are two objectives to be achieved by APC; 1) to reduce the variation of bit-error-rate (BER) performance across \( K \) links 2) to improve the average BER of \( K \) links. Hence logically, to achieve our two objectives above, we need to improve SINR\(_K\). Hence we need to find a permutation matrix \( \mathbf{P} \in \mathbf{P} \) that gives maximum SINR\(_K\). This optimization process can be formulated as
\[ \mathbf{P} = \arg \max_{\mathbf{P}} \text{SINR}_K(\mathbf{P}) \] (14)
where SINR\(_K(\mathbf{P})\) is the SINR\(_K\) given that the permutation matrix \( \mathbf{P} \) is used.

IV. PARTIAL CSI

In the previous sections, we implicitly assume complete knowledge of \( \mathbf{H} \) at the receiver of each link. This means each receiver of link \( j \) is aware of its interference and has CSI from all stations. This is indicated in Eqn. (9) where the summation term of the interference correlation matrix, \( \mathbf{R}_{N,j} \) consists of interference from link 1, ..., \( j - 1 \). In reality, the receiver at link \( j \) will only know \( \mathbf{H}_j \), its own CSI. Hence we do not have information about the interference correlation matrix at the receiver. We also do not want APs to specifically transmit \( \mathbf{r}_j \) to each link \( j \) since this transmission will use extra resources. To mitigate this problem, in this section, we propose to find \( \mathbf{t}_j \) and \( \mathbf{r}_j \) that correspond to the sub-optimum interference correlation matrix, \( \mathbf{R}_{N,j} \) calculated from the estimation of the received signal \( \mathbf{y} \) at the transmitter. \( \mathbf{R}_{N,j} \) is given as
\[ \mathbf{R}_{N,j} = \mathbb{E}[\mathbf{y}_j \mathbf{y}_j^H] = \mathbb{E}[\mathbf{n}_j \mathbf{n}_j^H] + \sum_{l=1}^{K} \mathbf{H}_j \mathbf{t}_l (\mathbf{H}_j \mathbf{t}_l)^H \] (15)
Eqn. (13) and Eqn. (11) are then used to find \( \mathbf{t}_j \) and \( \mathbf{r}_j \) respectively. We still need to relay the \( \mathbf{r}_j \) information to the receiver of link \( j \). In a practical system, this can be implemented by using training symbols transmitted using \( \mathbf{t}_j \) at the beginning of each frame during the training period.

Note that the use of \( \mathbf{R}_{N,j} \) will not degrade the system performance. To prove that, we use the fact that in SINRM
\[ \text{SINR}_1 > \ldots > \text{SINR}_j > \ldots > \text{SINR}_K. \] (16)
This is so since in our SINRM beamforming design, links 1 and \( K \) have the lowest and highest interference respectively. Hence, we only need to prove that the \( \text{SINR}_K \) calculated either using \( \mathbf{R}_{N,K} \) or \( \mathbf{R}_{N,K} \) is the same. \( \mathbf{R}_{N,K} \) in Eqn. (15) can be rewritten as
\[ \mathbf{R}_{N,K}^{-1} = \mathbf{H}_K \mathbf{t}_K (\mathbf{H}_K \mathbf{t}_K)^H + \mathbb{E}[\mathbf{n}_j \mathbf{n}_j^H] + \sum_{i=1,i\neq K}^{K} \mathbf{H}_K \mathbf{t}_i (\mathbf{H}_K \mathbf{t}_i)^H \]
It then follows from Woodbury’s identity \[17\] that
\[ \mathbf{R}_{N,K}^{-1} = \mathbf{R}_{N,K}^{-1} \mathbf{H}_K \mathbf{t}_K (\mathbf{H}_K \mathbf{t}_K)^H \mathbf{R}_{N,K}^{-1} \frac{1}{1 + (\mathbf{H}_K \mathbf{t}_K)^H \mathbf{R}_{N,K}^{-1} \mathbf{H}_K \mathbf{t}_K} \] (17)
A substitution of \( \mathbf{R}_{N,K} \) in Eqn. (11) with \( \mathbf{R}_{N,K} \) and algebraic simplification leads to the same \( \mathbf{r}_K \) expression. This concludes the proof.

V. SIMULATION RESULTS

In this section, we study the performance of the proposed cooperative transmission scheme (THP-SINRM-APC) in terms of uncoded BER. Two MIMO-OFDM APs and two stations \( (K = 2) \) are considered. Each is equipped with two antennas \( (N_T = N_R = 2) \). APs have full CSIs since each AP can share its CSI with all other APs through backbone networks. Each link is transmitted at equal power. Rectangular 4-QAM \((M=4)\) modulation is used. The symbol period, guard period and number of sub-carriers are set to 3.2\( \mu \)s, 0.8\( \mu \)s, and 48 respectively. The number of paths, RMS delay spread and maximum channel delay are set to 10, 0.16\( \mu \)s, and 0.8\( \mu \)s respectively. The performance of cooperative APs in an interference-free channel and a non-cooperative scheme \[13\] under the same configuration are used as benchmarks in our simulations. THP-SINRM, with a fixed precoding order (THP-SINRM-FPC) that encodes link 2, then link 1, and a similar cooperative transmission scheme with \[9\] (THP-ZF-APC1) are also simulated for comparison purposes. In our discussion below, the comparison of the schemes is performed at \( \text{BER}=10^{-4} \).

A. Performance of the individual links

The result shown in Fig. 3 shows the BER for individual links. For THP-SINRM-FPC, link 1 has better performance than link 2 since the former has lower interference than the latter. The BER performance difference between link 1 and link 2 exceeds 4 dB. Once APC is incorporated (THP-SINRM-APC), the difference in BER between links 1 and 2 disappears. Here, the performance of link 2 is improved at the expense of link 1. This results in similar BER across all the links. Note that even though THP-ZF-APC1 \[9\] can properly eliminate the difference in BER, its performance is still worse than the proposed scheme by 3 dB.

B. Performance of the overall BER

Here, we studied the performance of the overall BER. Overall BER is defined as the average BER for \( K \) links. The
overall BER performance is shown in Fig. 4. The use of the adaptive precoding order (THP-SINR-APC) results in 3 dB gain over the fixed precoding order (THP-SINR-FPC). This gain is due to an additional degree of freedom provided by APC. THP-SINRM-APC also outperforms the non-cooperative scheme by more than 10 dB and is only 2 dB away from an interference-free channel. The large improvement in our proposed scheme over the non-cooperative scheme comes from an increase in transmit diversity (two to four), APC gain, as well as interference cancellation. Lastly, Fig. 4 also shows the performance of the proposed scheme when only partial CSI is available at the receiver (THP-SINR-APC-PCSI). It can be observed that its performance is very close to the performance of THP-SINR-APC with full CSI at the receiver. This confirms our earlier analysis in Section IV.

VI. CONCLUSION

This paper proposes a practical cooperative transmission scheme employing precoding, beamforming and an adaptive precoding order for co-working MIMO OFDM WLANS. The proposed design eliminates CI in co-working WLANS with only partial CSI available at the receiver of each station. The cooperative scheme among APs, first, combines THP with joint transmit-receive beamforming based on SINR maximization. An adaptive precoding order is then used to further improve overall performance and to ensure BER fairness among stations served by different APs. We prove analytically and by simulation that our proposed scheme will not degrade under partial CSI. The simulation results also show that our proposed scheme (THP-SINRM-APC) gives the optimum overall BER performance. The performance is only 2 dB away from an interference-free channel, is 3 dB better than the best known cooperative scheme and is 10 dB better than the best known non-cooperative scheme.

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