COORDINATED BEAMFORMING FOR MUTUALLY INTERFERING MULTI-ANTENNA WLAN NETWORKS WITH MULTIPACKET RECEPTION

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ABSTRACT

This paper presents the design of multiple-input multiple-output (MIMO) coordinated beamforming (CBF) techniques that greatly decrease packet decoding failure due to collisions at co-channel 802.11 WLAN access points (APs). Specifically, we advocate a new WLAN paradigm that promotes the sharing of channel state information (CSI) and uplink precoders between co-channel APs that are capable of multipacket reception (MPR). PHY-layer MIMO CBF design algorithms based on joint and sequential computation that satisfy network-wide MPR conditions are presented. Numerical examples illustrate that the proposed CBF schemes greatly outperform uncoordinated methods in terms of successful packet detection.

Index Terms— MIMO precoding, interference cancellation, MPR, 802.11 WLAN.

1. INTRODUCTION

The mutual interference due to simultaneous operation of networks in an uncoordinated manner becomes a critical obstacle in achieving high data rates for wireless communications. The problem of interference nullifies the potential increase in spectral efficiency promised by advanced physical-layer technologies such as channel bonding and multiple-input multiple-output (MIMO) technology.

A relevant example is the mutual interference caused by IEEE 802.11 WLAN networks deployed randomly in close proximity to each other. For a concentrated density of WLAN networks, it is impossible to find orthogonal, interference-free operating channels for each of them in either 2.4GHz or 5GHz, resulting in mutual interference in an overlapping basic service set (OBSS) scenario [1]. In conventional OBSS operation, simultaneous transmissions are not allowed due to packet collisions, which greatly increases communication latency and reduces spectrum efficiency. This motivates the design of coordinated beamforming (CBF) techniques that mitigate interference and greatly decrease packet error rates at co-channel WLAN access points and terminals or stations (STAs). CBF represents a major paradigm shift for IEEE 802.11, since it currently has no provision for inter-AP coordination.

In this work, we devise MIMO coordinated beamforming or precoding techniques that are based on the sharing of channel state information (CSI) between co-channel WLAN APs that are capable of multipacket reception (MPR). MPR-capable APs can decode multiple packets that are received simultaneously, analogous to the concept of successive interference cancelation (SIC) in cellular radio [2]. Prior work on MPR in single-antenna systems includes [3]-[4], where the emphasis was on characterizing the throughput and probability of successful MPR in random-access networks, and [5], which proposed a coarse two-level power control method for ensuring MPR. Cross-layer studies on MIMO MPR at a single AP appear in [6]-[9], where the STAs independently employ space-time Alamouti codes without coordination and the AP must contend with imprecise CSI. In sharp contrast, this paper presents CBF methods that span multiple APs, who collaboratively exchange CSI and design channel-dependent STA precoders so as to ensure each of them successfully performs MPR. Finally, a crucial difference from CBF schemes in MIMO cellular radio (for e.g., 3GPP LTE-A) is that they generally treat interference as Gaussian noise and assume single-user detection at receivers [10], whereas the methods in this paper exploit the interference cancelation opportunities afforded by MPR. While it is well known that non-linear interference cancellation outperforms linear interference suppression in MIMO receivers, the design of optimal transmit precoders that ensure successful SIC has received comparatively less attention, which is the focus of this work.

The remainder of this paper is organized as follows. The mathematical model of the network and definition of MPR conditions are given in Sec. 2. The details of the proposed joint and sequential MIMO CBF schemes are provided in Sec. 3. Several numerical examples comparing CBF with uncoordinated transmission are shown in Sec. 4, and we conclude in Sec. 5.

2. SYSTEM MODEL

2.1. Network Model

We describe in detail the proposed method for two MIMO-OFDM based WLAN cells or basic service sets (BSSs) operating on the same channel and causing asynchronous interference to each other. In other words, their transmitted packets collide and have a partial to total overlap in time. The default DCF protocol in 802.11 seeks to avoid such situations by applying the principle of CSMA/CA, but this can inhibit efficient usage of the spectrum. The BSSs can have near-simultaneous transmissions by design to maximize spectral efficiency (for e.g., through contention-free PCF/HCCA scheduling by the APs [1]), or in an OBSS scenario. By default we study the moderate to high interference scenario where uncoordinated co-channel transmissions almost always result in packet decoding failure.

The WLAN STAs and APs are equipped with N_S and N_A antennas respectively, and employ OFDM modulation. The APs are capable of multipacket reception, which implies that a packet collision at the receivers does not necessarily lead to packet loss. Under MPR the APs can decode and cancel interfering packets as long as their SINR is above some threshold, to yield a cleaner signal for the desired packet. When the adjacent WLAN networks operate near-

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simultaneously, the transmitter(s) from one network will cause unintentional interference to the receiver(s) of the other network, and vice versa. An example is shown in Fig. 1, with one active WLAN client in each BSS.

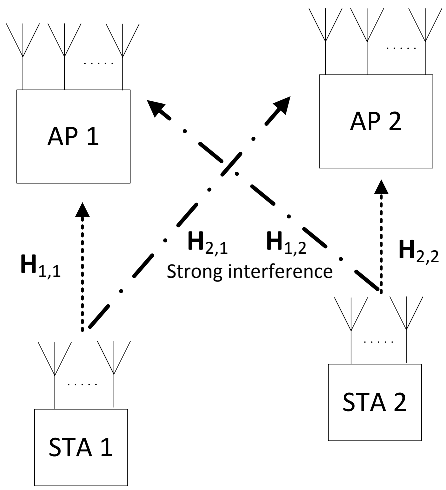

Fig. 1. Mutually interfering WLAN BSSs with multiple transmit and receive antennas.

Without loss of generality we describe the CBF process for an arbitrary OFDM subcarrier and therefore suppress the subcarrier index for convenience. The received signals at the two APs is written as

$$\mathbf{y}_1 = \mathbf{H}_{1,1}\mathbf{x}_1 + \mathbf{H}_{1,2}\mathbf{x}_2 e^{-j\frac{2\pi m_2 \tau_2}{T}} + \mathbf{n}_1 \tag{1}$$

$$\mathbf{y}_2 = \mathbf{H}_{2,2}\mathbf{x}_2 + \mathbf{H}_{2,1}\mathbf{x}_1 e^{-j\frac{2\pi m_1 \tau_1}{T}} + \mathbf{n}_2 \tag{2}$$

where $\mathbf{H}_{i,j} \in \mathbb{C}^{N_A \times N_S}$ are the complex channel matrices from STA j to AP i, $\mathbf{x}_1$ and $\mathbf{x}_2$ are the transmitted STA signals with possibly random time offsets τ_1 and τ_2 (smaller than the cyclic prefix duration) with respect to the unintended APs, the WLAN OFDM symbol index is m_i and symbol duration is T, and $\mathbf{n}_i$ is colored zero-mean complex additive white Gaussian noise with covariance matrix $\mathbf{Z}_i, i = 1, 2$. The channel matrices can be written as $\mathbf{H}_{i,j} = \sqrt{d_{i,j}^{-\alpha}}\tilde{\mathbf{H}}_{i,j}$, where $d_{i,j}^{-\alpha}$ represents the path-loss of exponent α between STA j and AP i, and $\tilde{\mathbf{H}}_{i,j}$ is a full-rank matrix that captures the effects of small-scale fading.

The STA transmit signals $\mathbf{x}_i$ are designed based on MIMO precoding techniques discussed in the next section, with transmit covariance matrices

$$\mathbf{Q}_i = E\left\{\mathbf{x}_i\mathbf{x}_i^H\right\},\ i = 1, 2,$$

and average transmit power constraints $\mathrm{Tr}(\mathbf{Q}_i) \le P_i$. This can be transformed into a linear matrix precoding structure by setting $\mathbf{x}_i = \mathbf{T}_i\mathbf{s}_i$, where $\mathbf{s}_i$ is the STA data vector with $E\left\{\mathbf{s}_i\mathbf{s}_i^H\right\} = \mathbf{I}$, and precoding matrix $\mathbf{T}_i$ is obtained from the eigenvalue decomposition of $\mathbf{Q}_i = \mathbf{U}_i\mathbf{D}_i\mathbf{U}_i^H$, and applying $\mathbf{T}_i = \mathbf{U}_i\mathbf{D}_i^{1/2}$.

At the APs, the received signal is first post-processed with a decoding matrix $\mathbf{W}_i \in \mathbb{C}^{N_s \times N_A}$, followed by decoding operations on the resulting signal $\mathbf{W}_i\mathbf{y}_i$. It is assumed that the APs employ suboptimal zero-forcing (ZF) receivers that are functions of the direct channels only for simplicity, represented by

$$\mathbf{W}_i = \left(\mathbf{H}_{i,i}^H\mathbf{H}_{i,i}\right)^{-1}\mathbf{H}_{i,i}^H. \tag{3}$$

The assumption of ZF receivers greatly reduces the complexity of the CBF design since $\mathbf{W}_i$ is independent of the covariance matrix from the co-channel interferer. Otherwise, if optimal linear MMSE receivers were adopted by the APs, then an iterative solution that alternately optimizes $\{\mathbf{Q}_i\}_{i=1,2}$ and $\{\mathbf{W}_i\}_{i=1,2}$ would be required. While a MF receiver ($\mathbf{W}_i = \mathbf{H}_{i,i}^H$) would also avoid this pitfall, the ZF receiver has the additional advantage of diagonalizing (inverting) the main channel carrying the desired signal and removing inter-stream interference of the target STA, which facilitates data detection.

In the remainder of this work, we focus on the optimal and suboptimal coordinated design of STA signal covariance matrices $\mathbf{Q}_1$ and $\mathbf{Q}_2$ (equivalently, STA precoding matrices $\{\mathbf{T}_i\}$) so that both APs can successfully perform MPR to cancel out interference and subsequently decode their respective desired packets.

2.2. MPR Conditions

Multiple-packet reception (MPR) schemes use interference cancellation techniques to receive and decode multiple packets that arrive simultaneously and are known to be very efficient. In principle, even if multiple packets are received near-simultaneously (i.e., they collide), they can be decoded individually and cancelled out if their individual SINRs are above a minimum *capture* threshold [4]. In a MIMO system, we define signal and interference-plus-noise powers in terms of the Frobenius norms of the corresponding terms in eq. (1), and the SINR is the ratio of these Frobenius norms.

After arbitrary receiver-side post-processing, the MPR conditions at AP 1 are written as

$$\frac{\mathrm{Tr}\left(\mathbf{W}_1\mathbf{H}_{1,2}\mathbf{Q}_2\mathbf{H}_{1,2}^H\mathbf{W}_1^H\right)}{\mathrm{Tr}\left(\mathbf{W}_1\left(\mathbf{H}_{1,1}\mathbf{Q}_1\mathbf{H}_{1,1}^H + \mathbf{Z}_1\right)\mathbf{W}_1^H\right)} \ge \gamma_1 \ \text{(step 1)} \tag{4a}$$

$$\frac{\mathrm{Tr}\left(\mathbf{W}_1\mathbf{H}_{1,1}\mathbf{Q}_1\mathbf{H}_{1,1}^H\mathbf{W}_1^H\right)}{\mathrm{Tr}\left(\mathbf{W}_1\mathbf{Z}_1\mathbf{W}_1^H\right)} \ge \gamma_2 \ \text{(step 2)} \tag{4b}$$

with SINR capture thresholds γ_1 and γ_2 needed for successful packet decoding. Note that the interfering packet is decoded first and cancelled out, since we are focusing on the strong interference regime. In other regimes, the decoding order may be dynamic. In practice, it may be useful to set $\gamma_1 > \gamma_2$ such that the CBF optimization ensures successful SIC in the first step. Similarly, the MPR conditions at AP 2 can be written as

$$\frac{\mathrm{Tr}\left(\mathbf{W}_2\mathbf{H}_{2,1}\mathbf{Q}_1\mathbf{H}_{2,1}^H\mathbf{W}_2^H\right)}{\mathrm{Tr}\left(\mathbf{W}_2\left(\mathbf{H}_{2,2}\mathbf{Q}_2\mathbf{H}_{2,2}^H + \mathbf{Z}_2\right)\mathbf{W}_2^H\right)} \ge \gamma_1 \ \text{(step 1)} \tag{5a}$$

$$\frac{\mathrm{Tr}\left(\mathbf{W}_2\mathbf{H}_{2,2}\mathbf{Q}_2\mathbf{H}_{2,2}^H\mathbf{W}_2^H\right)}{\mathrm{Tr}\left(\mathbf{W}_2\mathbf{Z}_2\mathbf{W}_2^H\right)} \ge \gamma_2 \ \text{(step 2)}. \tag{5b}$$

3. MIMO CBF WITH MPR

3.1. CBF MAC Protocol

The proposed MIMO CBF schemes require the acquisition of global CSI ($\mathbf{H}_{1,1}, \mathbf{H}_{1,2}, \mathbf{H}_{2,1}, \mathbf{H}_{2,2}$) and noise covariance information at the entities that compute the optimal MIMO precoders. As noted previously, there is currently no provision for simultaneous transmission and inter-AP coordination in IEEE 802.11, which necessitates the design of a new MAC protocol in conjunction with the PHY-layer CBF schemes presented here. While the details are beyond the scope of this work, we note that an AP can broadcast suitably modified request-to-send (RTS) frames to first indicate the possibility of CBF to an OBSS AP and to later exchange CSI/precoders, while the clear-to-send (CTS) responses from the STAs allow APs to estimate their own direct and cross channels.

3.2. Joint and Sequential CBF

In one CBF scenario, the transmit covariance matrices $\mathbf{Q}_1$ and $\mathbf{Q}_2$ are designed jointly by an entity (one of the APs or STAs) which possesses complete CSI of the system. Without loss of generality assume the computations are done at the APs. The objective function is set as the minimization of the sum transmit power of the STAs in order to prolong their battery life, subject to the power constraints and MPR conditions in (4) and (5) being satisfied:

$$\begin{aligned} &\min_{\mathbf{Q}_1,\mathbf{Q}_2} \operatorname{Tr}\left(\mathbf{Q}_1+\mathbf{Q}_2\right) \\ &\text{s.t.} \mathbf{Q}_1 \succeq \mathbf{0}, \mathbf{Q}_2 \succeq \mathbf{0}, \\ &\quad \operatorname{Tr}\left(\mathbf{Q}_1\right) \leq P_1, \operatorname{Tr}\left(\mathbf{Q}_2\right) \leq P_2 \\ &\quad 4(a), 4(b), 5(a), 5(b) \text{ TRUE} \end{aligned} \tag{6}$$

Recall that the trace function is linear, and that the positive semidefinite constraints are convex. Therefore, (8) is a convex semidefinite program (SDP) with an efficiently-computable global optimal solution since the objective function and all constraints are convex. Either AP can perform the above computation and inform its neighbor of the transmit covariance matrix that should be used by its associated STA.

A sequential CBF mechanism can also be designed that operates as follows. AP i assumes a worst-case interference scenario[1] of $\mathbf{Q}_j = (P_j/N_A)\,\mathbf{I}$ and first designs $\mathbf{Q}_i$ to satisfy its individual power constraint P_i, the first (step 1) MPR condition at its neighbor, and the second (step 2) MPR condition for itself. AP i then sends its choice of $\mathbf{Q}_i$ to AP j, who then computes $\mathbf{Q}_j$ to satisfy its own individual power constraint, the first (step 1) MPR condition at its neighbor, and the second (step 2) MPR condition for itself. For example, if AP 1 moves first it solves

$$\begin{aligned} &\min_{\mathbf{Q}_1} \operatorname{Tr}\left(\mathbf{Q}_1\right) \\ &\text{s.t. } \mathbf{Q}_1 \succeq 0 \\ &\quad \operatorname{Tr}\left(\mathbf{Q}_1\right) \leq P_1 \\ &\quad 4(b), 5(a) \text{ TRUE} \end{aligned} \tag{7}$$

which is also a convex SDP and efficiently solvable. AP 2 then receives AP 1's choice of $\mathbf{Q}_1$ and designs $\mathbf{Q}_2$ using a similar SDP. In order to reduce latency and overhead, no further iteration is made by having AP 1 redesign $\mathbf{Q}_1$ based on AP 2's solution; since $\mathbf{Q}_1$ was designed under a worst-case assumption it still satisfies AP 1's MPR conditions with a high probability. Note that the APs still require global CSI in the sequential CBF case. The sequential CBF design is suitable for OBSS coordination with a master-slave configuration for the APs, or where the second BSS is intermittently active.

To gain further insight, we reexamine the MPR conditions of Sec. 2.2 in the strong interference regime. In this case, the cross-interference dominates the effective background noise; furthermore, applying the ZF conditions and denoting the effective cross-channels as $\tilde{\mathbf{H}}_{1,2} = \mathbf{W}_1\mathbf{H}_{1,2}, \tilde{\mathbf{H}}_{2,1} = \mathbf{W}_2\mathbf{H}_{2,1}$ yields

$$\frac{\operatorname{Tr}\left(\tilde{\mathbf{H}}_{1,2}\mathbf{Q}_2\tilde{\mathbf{H}}_{1,2}^H\right)}{\operatorname{Tr}(\mathbf{Q}_1)} \geq \gamma_1 \text{ (step 1)}; \quad \frac{\operatorname{Tr}(\mathbf{Q}_1)}{\operatorname{Tr}\left(\mathbf{W}_1\mathbf{Z}_1\mathbf{W}_1^H\right)} \geq \gamma_2 \text{ (step 2)}$$

$$\frac{\operatorname{Tr}\left(\tilde{\mathbf{H}}_{2,1}\mathbf{Q}_1\tilde{\mathbf{H}}_{2,1}^H\right)}{\operatorname{Tr}(\mathbf{Q}_2)} \geq \gamma_1 \text{ (step 1)}; \quad \frac{\operatorname{Tr}(\mathbf{Q}_2)}{\operatorname{Tr}\left(\mathbf{W}_2\mathbf{Z}_2\mathbf{W}_2^H\right)} \geq \gamma_2 \text{ (step 2)}$$

as the MPR conditions at AP 1 and 2, respectively. When the joint CBF solution is feasible, the step 1 MPR constraints are likely to be 'tight' with high probability. Furthermore, the step 2 constraints shown above provide a lower bound for the minimum transmit power required for $\mathbf{Q}_1$ and $\mathbf{Q}_2$. Therefore, in the strong interference regime, it is expected that the optimal transmit directions of the STA precoders lie in the eigenspace of the effective cross-channels $\tilde{\mathbf{H}}_{1,2}^H\tilde{\mathbf{H}}_{1,2}$ and $\tilde{\mathbf{H}}_{2,1}^H\tilde{\mathbf{H}}_{2,1}$, with a suitable scaling to also satisfy the step 2 SINR constraint on the direct channel.

[1] Uniform spatial power allocation by a MIMO jammer without cross-CSI is known to cause worst-case interference.

4. NUMERICAL RESULTS

We now present simulation results obtained by averaging over 800 i.i.d. Rayleigh channel fading instances for several single-carrier network scenarios. We set the user distances as $d_{1,1} = 3, d_{2,1} = 4, d_{1,2} = 7, d_{2,2} = 5$ m, with a path-loss exponent of $\alpha = 2.5$, and assume equal STA transmit power constraints $P_1 = P_2 = P$. The MPR SINR capture thresholds are set as $\gamma_1 = 4$dB, $\gamma_2 = 2$dB, suitable for MCS 0 (BPSK/low code-rate). The normalized cross-channel time offsets $m_i\tau_i/T, i = 1, 2$, are assumed to be standard uniform random variables. The background additive noise is assumed to be spatially uncorrelated with $\mathbf{Z}_1 = \mathbf{Z}_2 = \mathbf{I}$. The convex programs are solved numerically using the CVX MATLAB toolbox [11].

As a baseline for comparison, a conventional leakage-minimizing CBF scheme and two uncoordinated schemes are also shown. The leakage minimization approach jointly designs $\mathbf{Q}_1, \mathbf{Q}_2$, to minimize the sum interference leakage to the adjacent AP, while satisfying SINR constraints for direct decoding of the desired packets, i.e., MPR is not applied and the APs continue to use ZF receivers. Formally, we can write

$$\begin{aligned} &\min_{\mathbf{Q}_1,\mathbf{Q}_2} \operatorname{Tr}\left(\tilde{\mathbf{H}}_{2,1}\mathbf{Q}_1\tilde{\mathbf{H}}_{2,1}^H + \tilde{\mathbf{H}}_{1,2}\mathbf{Q}_2\tilde{\mathbf{H}}_{1,2}^H\right) \\ &\text{s.t.} \mathbf{Q}_1 \succeq \mathbf{0}, \mathbf{Q}_2 \succeq \mathbf{0}, \\ &\quad \operatorname{Tr}\left(\mathbf{Q}_1\right) \leq P_1, \operatorname{Tr}\left(\mathbf{Q}_2\right) \leq P_2 \\ &\quad \frac{\operatorname{Tr}\left(\tilde{\mathbf{H}}_{1,1}\mathbf{Q}_1\tilde{\mathbf{H}}_{1,1}^H\right)}{\operatorname{Tr}\left(\mathbf{W}_1\left(\mathbf{H}_{1,2}\mathbf{Q}_2\mathbf{H}_{1,2}^H + \mathbf{Z}_1\right)\mathbf{W}_1^H\right)} \geq \gamma_1 \\ &\quad \frac{\operatorname{Tr}\left(\tilde{\mathbf{H}}_{2,2}\mathbf{Q}_2\tilde{\mathbf{H}}_{2,2}^H\right)}{\operatorname{Tr}\left(\mathbf{W}_2\left(\mathbf{H}_{2,1}\mathbf{Q}_1\mathbf{H}_{2,1}^H + \mathbf{Z}_2\right)\mathbf{W}_2^H\right)} \geq \gamma_1. \end{aligned} \tag{8}$$

In the uncoordinated schemes, each STA assumes an interference-free link and minimizes its individual transmit power subject to satisfying the step 2 conditions in $4(b)$ and $5(b)$, respectively. In other words, the uncoordinated STAs do not have knowledge of the interference covariance matrix at their APs, and APs do not perform MPR (i.e., they attempt to directly decode their desired packet in the first stage). In the first uncoordinated scenario which ignores interference at both STA and AP, the APs utilize ZF receivers. In the second uncoordinated scenario, each AP utilizes an optimal MMSE receiver.

In Fig. 2, the probability that both APs successfully decode their desired packets is shown versus the maximum allowable STA transmit power P, for $N_S = N_A = 2$ antennas. The proposed MPR CBF schemes provide a very high probability of successful packet detection even in the strong interference regime (100% and 82% for joint and sequential CBF at $P = 35$dB), and significantly outperform the uncoordinated methods which either fail completely or provide 50%

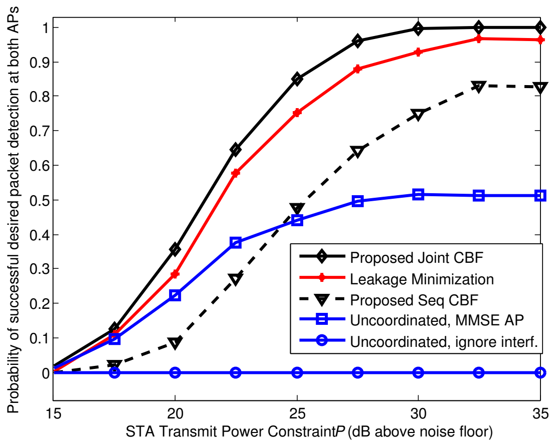

Fig. 2. Probability that both APs successfully decode their desired packets versus STA transmit power constraint.

packet detection rate at best. The leakage-minimizing CBF scheme without MPR outperforms the sequential CBF method over the entire range of P, illustrating that coordinated precoding with simple receivers is more valuable than sophisticated SIC reception without joint precoding. This result therefore provides a strong incentive for the introduction of coordinated transmission techniques in WLAN that exploit advanced PHY-layer capabilities such as MPR.

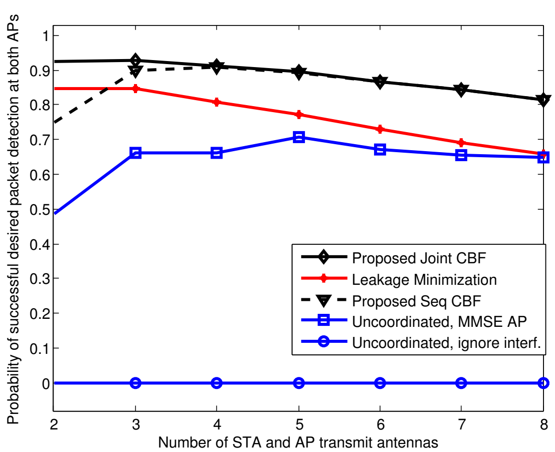

Fig. 3. Probability that both APs successfully decode their desired packets versus number of STA/AP antennas.

Fig. 3 depicts the AP packet detection rate as the number of STA and AP antennas vary, with $N_A = N_S$ and fixed $P = 30$dB. Once again, it is observed that the proposed CBF schemes handily outperform the uncoordinated methods for all array sizes, indicating that receiver-side MMSE interference suppression alone is not sufficient for co-channel operation in the strong interference regime. Interestingly, the sequential CBF method offers virtually the same performance as the joint CBF scheme, which validates the efficacy of the worst-case interferer model assumed for the semi-distributed precoder design algorithm. Leakage minimization approaches the MMSE-based uncoordinated scheme for increasing N, which implies that the increase in available spatial dimensions can be more effectively exploited with SIC.

5. CONCLUSIONS

In principle, the spectral efficiency of dense WLAN deployments can be increased by allowing simultaneous transmissions and exploiting SDMA methods based on MIMO transceivers and SIC. As a concrete example, we proposed two types of coordinated beamforming algorithms based on the exchange of CSI between OBSS APs. Numerical examples demonstrated that the proposed CBF schemes greatly outperform uncoordinated methods in terms of successful packet detection. While this work assumed perfect CSI at the APs, the CBF principles can be extended to robust methods that take into account imperfections due to estimation error and quantization.

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