

Non-Linear Precoding for Next Generation Multi-User MIMO Wireless LAN Systems

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Abstract— Multi-user MIMO has been recently proposed as a required technology for next generation 802.11 WLAN systems. This new system which will be called 802.11ac, will provide at least 1Gbps of multi-station throughput and at least 500Mbps of single station throughput. While linear precoding can be readily used to achieve this with little complexity, we explore the possibility of employing the non-linear scheme called dirty paper coding. Dirty paper coding is of recent interest in MIMO systems due to the possibility of achieving capacity. We show through simulations that dirty paper coding is promising as an alternative precoding scheme for 802.11ac.

Keywords— Dirty paper coding, 802.11 systems, multi-user MIMO, Tomlinson-Harashima precoding.

I. INTRODUCTION

The next generation standard of 802.11 very high throughput (VHT) wireless LAN systems is currently on development [1]. This new standard, which will be called 802.11ac, promises to provide over 500Mbps of single station throughput- a five-fold increase compared to the previous 802.11n standard [2]. The recently ratified 802.11n standard uses both Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) technologies to provide higher throughput compared to the older 802.11a standard. This time, 802.11ac for the first time will also employ downlink multi-user MIMO (MU-MIMO) technology that is capable of further increasing the total capacity when a single access point shares the wireless channel between a number of stations. With MU-MIMO, 802.11ac promises to deliver more than 1Gbps of multi-station throughput for use with the ever increasing demand of wireless connectivity.

MU-MIMO allows simultaneous transmission from one access point (AP) to multiple stations (STA) in contrast to the time sharing nature of carrier sense multiple access (CSMA) currently used in legacy 802.11n systems. This simultaneous transmission however can only be effectively done when the downlink channel state information (CSI) is available to the transmitter prior to transmission. The optional beamforming feature found in 802.11n works similarly but due to noncooperation between the receive antennas of different users, MU beamforming is a much more difficult task compared to SU beamforming. Beamforming and precoding

while have different nuances in meaning will be used interchangeably in this paper.

Conventional linear beamforming schemes like zero forcing (ZF) and minimum mean square error (MMSE) cannot achieve MU-MIMO capacity [3]. It is of particular interest therefore to use a precoding scheme that achieves capacity. It was reported in [4] that MU-MIMO capacity is achievable by employing dirty paper coding (DPC) originally proposed by Costa in [5]. Since [4], many implementations of DPC with varying complexity and proximity with known capacity [6]–[9] appeared in the literature. In [6], the authors used a vector perturbation approach to minimize the required transmit power of a multiuser transmission. In the dirty paper sense, the perturbation vector is similar to a 'dirt' that even though unknown to the receivers, the original symbols are still properly decoded. The main problem with this implementation is that finding the perturbation vector is similar to a multi-dimensional integer lattice least squares problem which is NP-hard. In [8], the authors used lattice reduction to decrease the complexity required in the computation of the perturbation vector.

A much simpler approach to DPC is to use a non-linear Tomlinson-Harashima Precoder (THP) combined with a unitary matrix linear precoder. In contrast to the vector precoding in [6], THP based DPC is one dimensional and hence has very little complexity. While THP is a suboptimal implementation it was shown in [10] that it is capable of approaching the sum-rate capacity of MU-MIMO by ordering the rows of the channel matrix optimally before transmission.

This paper explores the possibility of using the THP based DPC as an alternative precoding scheme for 802.11ac. Many of the papers in literature are based on hypothetical and simplified systems which makes it hard to assess the practicality of its application in consumer grade systems such as 802.11 WLAN. As such, the contribution of this paper is the study of the feasibility of DPC in 802.11 based WLAN systems. We propose a transmitter and receiver architecture that enables the use of DPC without too much additional complexity. We also present simulation results that show the advantages and disadvantages of DPC with linear precoding schemes.

For a more introductory reference to MU-MIMO systems including DPC, the reader is referred to [11].

The rest of the paper is organized as follows. In section II, we discuss the conventional linear precoding schemes as well as the DPC scheme. In section III, we describe our proposed architecture for dirty paper coded MU-MIMO systems. Simulations comparing linear schemes and DPC scheme are shown in section IV. Finally, we conclude this paper in section V.

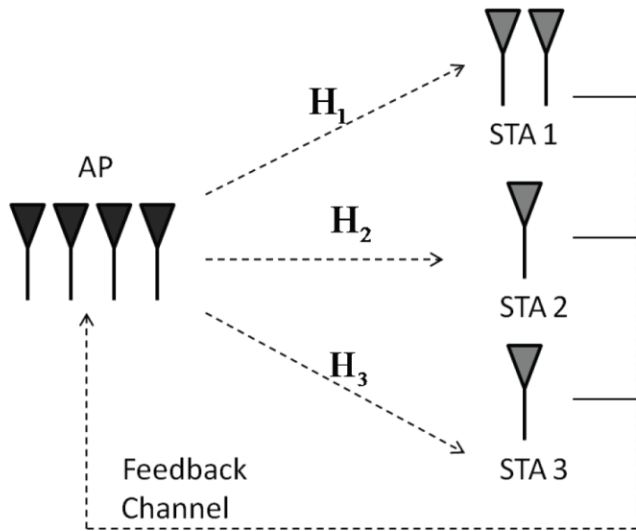


Figure 1. Multi-user MIMO scenario

II. PRECODING ALGORITHMS

A MU-MIMO WLAN scenario based on 802.11n is shown in Fig. 1. This setup consists of an AP with four antennas and $K=3$ STAs with two, one and one antennas respectively. Inherent in most MU-MIMO implementation as well as beamforming capable systems, is the assumption of channel state information (CSI) being available causally in the transmitter. The transmitter computes a beamforming weight matrix that will prevent signals of one STA to interfere with other STAs. In Fig. 1 for example, without proper precoding, the signals arriving for STA 1 includes signals from STA 2 and STA 3. This inter-user interference degrades the total network capacity and can even make any communication impossible.

Without loss of generality, we assume that all STAs receive single stream signals. Multiple streams for one STA can be thought of as two or more virtual STAs and can be treated as separate STAs. The only drawback with this model is that it has no option for doing block diagonalized linear precoding [12]. This scheme is out of the scope of this paper. In general, the received signal of the i^{th} user can be expressed as

$$y_i = \mathbf{H}_i \mathbf{x} + w_i \quad (1)$$

where \mathbf{H}_i is a $1 \times K$ row vector for the channel of the i^{th} STA's channel, $\mathbf{x} = [x_1, x_2, \dots, x_K]^T$ is the transmit signal vector, and w_i is the noise from the receiver. We assume that for each of the K users, this noise is identically distributed, independent, equal variance and zero mean Gaussian noise. Hence $\mathbf{R}_w = E[\mathbf{w}\mathbf{w}^H] = \sigma_w^2 \mathbf{I}$.

A. Linear Precoding

Linear SU-MIMO decoding algorithms employing space division multiplexing (SDM). SDM schemes traditionally use full channel receiver side CSI in order to decode the streams which due to the MIMO channel, mutually interfered with each other. In MU-MIMO case, full channel CSI is unavailable because the STAs cannot or rather impractical to cooperate to share these informations. Instead, each of the STAs sends its portion of the channel matrix (i.e. \mathbf{H}_i in (1)) to the AP who precodes the data in such a way that the receivers won't experience interference from each other.

The easiest precoding scheme called zero forcing precoding is expressed as.

$$\mathbf{x} = \frac{\mathbf{H}^{-1} \mathbf{u}}{\gamma_{ZF}} \quad (2)$$

where \mathbf{u} is the vector of symbols intended for the K users while \mathbf{x} is the precoded transmit symbol vector. The denominator $\gamma_{ZF} = \mathbf{u}^H (\mathbf{H}\mathbf{H}^H)^{-1} \mathbf{u}$ normalizes the transmit power to a constant value. It was shown in [3] that ZF while simple has very poor scaling of capacity when K is large. A better algorithm uses knowledge of the noise variances σ_w^2 to avoid severe attenuation of \mathbf{u} in (2) when the SNR is low. This precoding scheme is called Minimum Mean Square Error (MMSE) precoding and is done using

$$\mathbf{x} = \frac{\mathbf{H}^H (\mathbf{H}\mathbf{H}^H + \alpha \mathbf{I})^{-1} \mathbf{u}}{\gamma_{MMSE}} \quad (3)$$

where $\alpha = K\sigma_w^2$

Note that MMSE precoding doesn't perfectly remove the interference because of the additive term $\alpha \mathbf{I}$. Intuitively speaking, MMSE precoding does a more intelligent job compared to ZF by relaxing interference cancellation when the noise is actually higher than the interference itself. The result is that the receive signals from each user actually enjoys maximum signal plus interference ratio compared to any linear precoding scheme.

B. Dirty Paper Coding

Dirty Paper Coding as used in MU-MIMO literature is actually a blanket term for many non-linear precoding schemes that applies the original dirty paper coding scheme developed by Costa. The easiest implementation which is usually called zero forcing-dirty paper coding (ZF-DPC) or sometimes zero forcing-Tomlinson-Harashima precoding (ZF-THP) uses an LQ (i.e. \mathbf{L} =lower diagonal matrix, \mathbf{Q} = unitary matrix) decomposition of the channel matrix then apply THP. THP can be thought of as dirty paper coding in one dimension.

When \mathbf{Q}^H is applied as a linear precoder for system,

$$\begin{aligned} \mathbf{x} &= \mathbf{Q}^H \mathbf{z} \\ \mathbf{y} &= \mathbf{H}\mathbf{x} + \mathbf{w} \\ &= \mathbf{L}\mathbf{z} + \mathbf{w} \end{aligned} \quad (4)$$

$$\begin{bmatrix} y_1 \\ \vdots \\ y_K \end{bmatrix} = \begin{bmatrix} l_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ l_{K1} & \cdots & l_{KK} \end{bmatrix} \begin{bmatrix} z_1 \\ \vdots \\ z_K \end{bmatrix} + \begin{bmatrix} w_1 \\ \vdots \\ w_K \end{bmatrix}$$

where the elements of vector \mathbf{z} are intermediate values of \mathbf{x} precoded from \mathbf{u} . It can be seen from the equation (4) that STA 1 doesn't experience any interference. STA 2 on the other hand receives interference from STA 1. In general, STA i receives interference from STAs $i-1, i-2$ until STA 1 because of the effective channel L matrix. This is where dirty paper coding comes in. In order to remove the interference of STA 1 from STA 2 receive signal, the following encoding from \mathbf{u} to \mathbf{z} can be done

$$\begin{aligned} z_1 &= u_1 \\ z_2 &= u_2 - z_1 \frac{l_{21}}{l_{22}} \\ z_i &= u_i - \sum_{k=1}^{i-1} z_k \frac{l_{ik}}{l_{ii}} \end{aligned} \quad (5)$$

However, just by looking at z_2 , it is obvious that it needs more average transmit power compared to u_2 due to the additional term. This additional transmit power can be significantly reduced by using the modulo operation. z_2 in (5) now becomes

$$z_2 = u_2 - \text{mod} \left(z_1 \frac{l_{21}}{l_{22}}, \tau \right) \quad (6)$$

where

$$\text{mod}(z, \tau) = z - \left\lfloor \frac{z + \frac{\tau}{2}}{\tau} \right\rfloor \tau \quad (7)$$

Note that in order to recover the receive signals despite THP, τ must be $\tau > 2(|c|_{\max} + \Delta/2)$, where $|c|_{\max}$ is the maximum amplitude of constellation used while Δ is the spacing between two closest constellation points. In QPSK for instance having the constellation alphabet $[1+j, 1-j, -1+j, -1-j]$, $\tau = 4$ for the real and imaginary components of the constellation. Just like the linear ZF, the ZF-DPC discussed here has an MMSE-DPC version that improves the performance of the algorithm by incorporating the noise variance information into the precoding matrices [9].

Whenever THP is applied in the transmitter, it also becomes a necessity to apply the same modulo operation in the receiver [13].

III. PROPOSED ARCHITECTURE

The architecture of the proposed MU-MIMO system is based on the currently developed 802.11Tgac system which in itself is based on the 802.11n system. In the proposed transmitter architecture shown in Fig. 2, due to the user streams being received independently by different receivers,

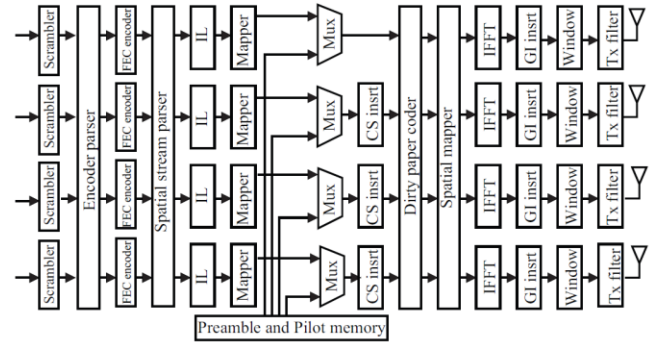


Figure 2. Transmitter Model for 802.11Tgac with Dirty Paper Coding

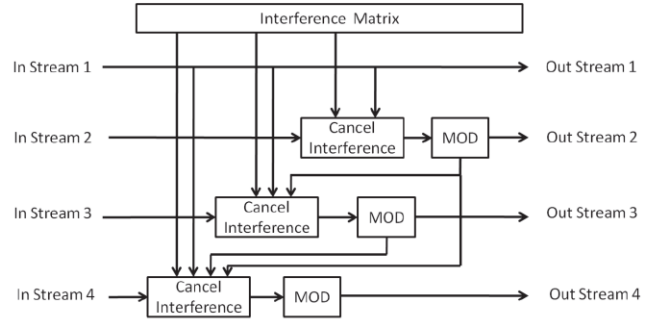


Figure 3. Dirty Paper Coder

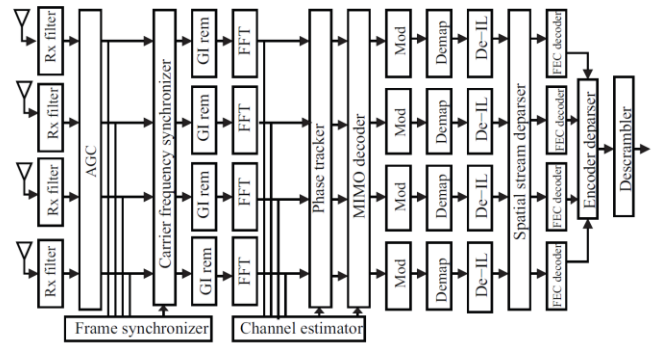


Figure 4. MU-MIMO Receiver Model

the minimum number of scramblers, forward error correction (FEC) blocks and interleavers are also dictated by the number of active STAs K . In the figure, the only block added that relates to the implementation of DPC is the dirty paper coder block. This implements all the equations discussed in section II-B. This DPC block consisting of a number of interference canceller blocks and modulo blocks is shown in Fig. 3. The interference canceller block is simply an implementation of (5) while the modulo block is (7). For the receiver as shown in Fig. 4, only the modulo block is related to the implementation of DPC. The rest of the blocks in Figs 2 and 4 are common component blocks and is present regardless of precoding algorithm used. In linear precoders, only one weight matrix is relevant for beamforming. In the case of ZF, only the channel inverse matrix \mathbf{H}^{-1} is necessary for effective beamforming. In 802.11n, the beamforming matrix is an input to the spatial

expansion block in the transmitter. That is, if beamforming is enabled, the beamforming matrix is used. Otherwise, the transmitter uses an identity or pseudo-identity matrix. For DPC on the other hand, both the L and Q components of the channel are necessary. The \mathbf{L} matrix which we call the interference matrix is passed into the dirty paper coder block while the \mathbf{Q}^H matrix goes into the spatial expansion block.

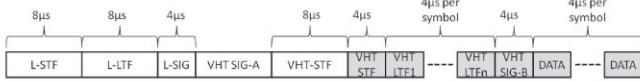


Figure 5. TGac Mixed Mode Packet Format

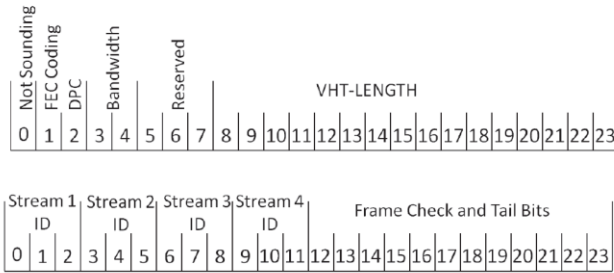


Figure 6. VHT-SIG-FIELD-A bit information

The rest of the architecture functions exactly like in the 11n architecture. In order to save space the reader is referred to [2] for the functions of these blocks.

The packet format of 802.11ac which is adopted in this paper is shown in Fig. 5. The non-shaded area is always single stream and is transmitted omnidirectionally while the shaded area is generally multi-stream and is precoded for downlink MU-MIMO beamforming. Here, L-STF, L-LTF and L-SIG fields are all for the purpose of compatibility with legacy 11a/n devices. VHT-SIG-A while omnidirectional is important for MU-MIMO beamforming to inform the participating STAs of the parameters of the directional portion of the packet. VHTSTF is a training field whose primary purpose is for MIMO data power computation. This is necessary because huge power variation can occur between the single stream and multi-stream portions of the packet which necessitates the reset of the AGC. VHT-LTFs on the other hand are used to compute the MIMO Channel. The computed channel is either sent back to the AP during sounding or used for symbol detection when receiving a MU transmission.

In section II, we presented a simplistic introduction to linear precoding and DPC. By considering that OFDM is a parallel transmission of single carrier signals, the equations in section II can be applied on a per subcarrier basis along with the needed normalization. Looking at Fig. 1, the receiving STAs will need to know which position in the MU-MIMO stream are they located. For this reason VHT-SIG-A must contain an indication field on which STAs streams 1 to K are for. Note that this applies to both linear and DPC precoders. In the receiver side, due to the necessary modulo operation needed to be performed in the receiver whenever DPC is applied, the transmitter needs to inform the STAs that DPC is applied. This can be done by the addition of DPC indication

bit in the VHT-SIG-A Field. The VHT-SIG-A contents may look like Fig. 6. Depending on the features supported by the system, VHT-SIG-A bits may vary or may even need additional symbols. Over the 48 bits available in the VHT-SIG-A field, note that only one bit which we arbitrarily placed in the 2nd bit of the first symbol needs to be reserved to enable DPC.

Regardless of precoding scheme, the stream fields in Fig. 6 is needed to identify both the order and number of streams allotted to STAs 1-4. Information regarding user specific modulation and coding rates schemes (MCS) and per user DATA field lengths on the other hand are present in the per station beamformed VHT-SIG-B field seen in Fig. 5.

IV. SIMULATION RESULTS

In this section, we investigate the performance of linear precoding schemes vs. DPC. Particularly, we compare ZF vs. DPC as discussed in section II. In all of the simulations, we use a 40MHz MU-MIMO OFDM system based on the 802.11TGac following the architecture described in section III. The sampling rate used is 80MHz while the channel used is the TGn Channel D modified to provide MU-MIMO channels. The OFDM parameters like FFT sizes, null, pilot and data subcarrier indices all follow the 802.11n 40MHz mixed mode frequency parameters. Table 1 shows additional default simulation parameters.

TABLE I
SIMULATION PARAMETERS

Transmit Antennas	4
Number of Users	4
Streams per User	1
Modulation	16QAM
Channel Estimation	Linear MMSE
CFO/IQ imbalance/Phase Noise	off
Frame Synchronization	ideal
Iterations	1000
SNR	45 dB

The first metric we are going to use is the peak to average power ratio of the transmit signals. PAPR is roughly synonymous to the magnitude vs. time dynamic range of the transmit signal packet. Due to the non-linearity of the power amplifier (PA) in the transmitter, high PAPR results in distortions that are very hard to equalize. The PAPR of a signal is defined as

$$PAPR = 10 \log \left[\frac{\max(|x(n)|^2)}{\text{mean}(|x(n)|^2)} \right] \quad (8)$$

Due to precoding, the transmitted MU-MIMO packet is expected to exhibit higher PAPR compared to non-precoded packets. Figure 7 shows the cumulative frequency distribution of the PAPR for both ZF and DPC. At 95% percentile the PAPR of DPC precoded symbols is 0.6dB less than ZF. Using the same PA, a 0.6dB additional power back-off translates to a decrease in PA power efficiency of about 13%. This is significant considering the PA is one of the most power hungry component in a transceiver [14]. In this figure, we

assume that equal back-off is applied to the 4 PAs in the transmitter. The reduced PAPR of DPC comes from the fact that the precoding matrix for DPC is a unitary matrix as opposed to the linear precoders which uses the inverse of the general channel matrix.

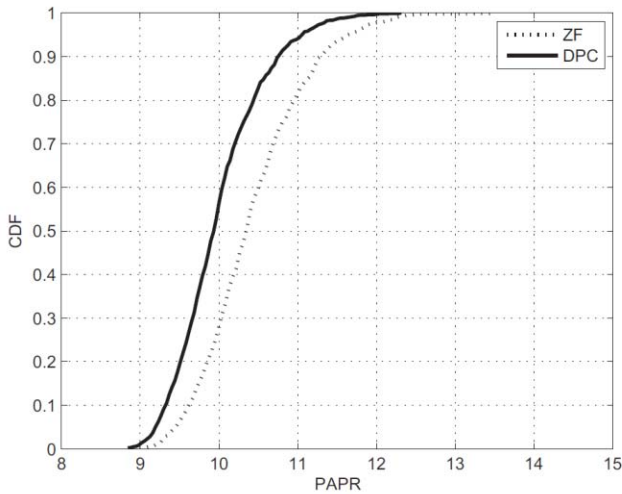


Figure 7. PAPR of Data Field

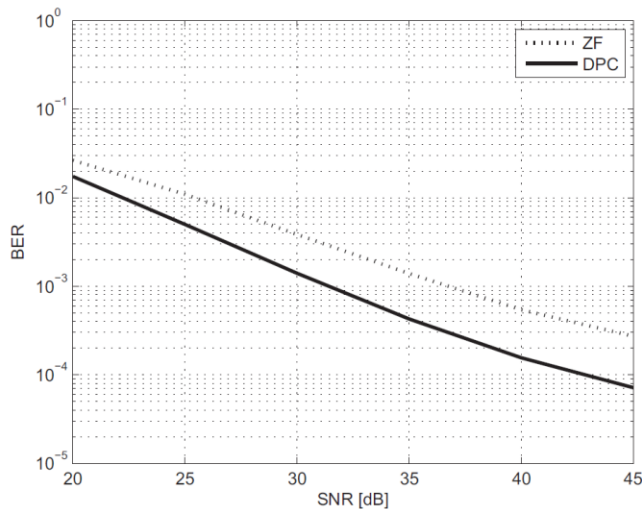


Figure 8. Uncoded BER Performance of ZF vs. DPC

The second metric we examined is the bit error rate (BER) performance. As shown in Fig. 8, the uncoded BER performance measured from STA 1 of DPC is better than ZF by more than 5dB. The simulation however doesn't implement user ordering such that STA 1 is always located into the first stream. Depending on the user algorithm used, each STAs may experience different link quality for every MU-MIMO transmission from the AP. This property can be exploited however to provide PHY level quality of service (QoS) implementation wherein high priority users are given better stream locations.

V. CONCLUSIONS

In this paper we investigated the performance of DPC compared to linear precoding. Theoretically, DPC can enable capacity approaching performance at the expense of huge complexity. This complexity doesn't only come from multidimensional dirty paper coding itself but also from the needed AWGN capacity approaching FECs like turbo codes or low density parity check coding.

While DPC is normally discussed in the context of capacity approaching schemes regardless of complexity, some developments in this relatively new research field though suboptimal can be used to provide additional performance compared to linear precoding. As shown through the simulation results in this paper, lower PAPR as well as better BER performance can be achieved by simply adding a DPC block which is mostly a modulo calculating circuit at the transmitter and receiver. Future work on this research includes implementation of a low complexity user ordering algorithm as mentioned in the Introduction. Also, the effects of impairments like CFO, phase imbalance, phase noise and other non-idealities are needed to be addressed when applying a non-linear algorithm as DPC. While this technology is still in infancy, we showed that very little hardware is necessary to incorporate DPC in 802.11ac based systems.

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