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多天線系統下在多點傳輸服務同時傳送多個單點傳播服務

HybridCast：Enable Concurrent Multicast and Unicast Services Transmission in Multiple Antenna System

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本論文係吳柏賢君（R01942055）在國立臺灣大學電信工程學研究所完成之碩（博）士學位論文，於民國 103 年 07 月 30 日承下列考試委員審查通過及口試及格，特此證明

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摘要

隨著科技的演進，將來的裝置和基地台將會擁有許多天線，目前已經有許多多用戶多輸入多輸出的協定已經被提出，這些協定運用了多天線特性來達到多路傳輸的增益，然而，目前的多點傳輸服務中，現存的協定像是 LTE 和 802.11ac 並沒有探索多天線所提供的可能增益，目前多點傳輸服務都是以最低的傳輸速率來確保所有的用戶端都能成功接收到服務。這篇論文中，我們提出 HybridCast，一種多用戶多輸入多輸出的協定，可以允許多個單點傳播服務使用共同資源同時和多點傳輸服務一起傳送，我們利用了多天線所提供的自由度和的連線餘裕 (link margin) 來同時傳送多個單點傳播服務並確保本來的多點傳輸服務不會受到任何影響及干擾。同時我們也設計了能和現今 LTE 和 802.11ac 系統相容的傳輸機制，從實驗和大規模的模擬中，我們展示了 HybridCast 比起一般的單一多點傳輸服務和強制為零波束協定確實能夠獲得更大的吞吐率的增益。

Abstract

In the future, AP and devices will equip with more antennas. There are several multiuser MIMO (MU-MIMO) protocol have been propose to allow multiple nodes to exploit the MIMO capability by transmitting concurrently. However, in single multicast session transmission, those existing protocol such as LTE and 802.11ac do not utilize the MIMO capability. The current mechanism just use the lowest rate to transmit the multicast session to make sure all clients can receive successfully. This paper introduces HybridCast, a MU-MIMO protocol that enables concurrent multicast session and unicast streams transmission. We fully utilize the degree of freedom (DoF) provided by multiple antenna and available link margin to transmit the unicast streams concurrently while doing no harm to multicast session. We also design the transmitting mechanism which is compatible with current 802.11ac and LET system. We show that HybridCast leverages the link margin and MIMO capability to provide more throughput gain than simple multicast or ZFBF protocol via testbed experiment and large scale simulation.

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Chapter 1

Introduction

Nowadays, the devices and base stations are equipped with more and more antennas. The current standard, such as 802.11ac and LTE-Advance, enable concurrent transmission of multiple unicast streams using MIMO technology. However, those standards transmit the single multicast session without utilizing the advantage of multiple antennas. Besides, the multicast traffic is usually sent at the lowest rate. The received SNR is usually higher than the required SNR. In this paper, we want to harvest throughput gain in the single multicast session transmission by leveraging multiple antenna and link margin to send multiple streams.

Motivation: Since DoF is underutilized and link margin is unused, our goal is to enable concurrent multicast and unicast streams to fully utilize the DoF and available transmitted power. To enable the HybridCast design, we need to consider the following two challenges.

Challenge 1: How to maximize the number of concurrent streams?

The naive solution is to treat a multicast stream as multiple unicast streams, and apply ZFBF to include additional unicast streams. For example, a 4-antenna base station can serve four clients when applying ZFBF. If there are three multicast receivers, ZFBF can include additional one unicast stream. However, in some cases, such a simple idea is not always work. For example, if there is a 4-antenna AP which needs to server five multicast receivers, ZFBF cannot work obviously.

Challenge 2: How to concurrent transmit unicast streams without harming multicast clients?

Concurrent transmission of multiple streams will introduce interference. Although ZFBF can avoid the interference from other streams, it only allows client to use single antenna to decode the signal, which may reduce the performance since receive diversity is waste. How to protect the multicast transmission while leveraging multiple antennas to improve the rate is a big challenge.

Contributions: We propose HybridCast, a joint multicast and unicast beamforming scheme that delivers unicast streams concurrently with the multicast session. To achieve this goal, we propose a method that can schedule maximum number of concurrent unicast streams. Further, we propose a precoding and decoding scheme that can fully utilize the available DoF. We also design a multicast beamforming scheme and power control mechanism to leverage the link margin.

We build our prototype using USRP-N200 platform over a 10MHz channel operating on 2.4GHz range. The experimental results show that HybridCast indeed harvest throughput gain by combining unicast streams transmission. In the link margin experiment, we show that the multicast beamforming scheme enlarges the available link margin. We also evaluate the performance of video transmission. We use the multicast transmission to send the video stream. The final result shows that HybridCast will do no harm to the multicast session while concurrent unicast transmission since our design will null the unicast interference to all multicast clients.

The rest of this paper is organized as follows. Chapter 2 summarizes related works. Chapter 3 gives a simple illustrative example of our scheme. Chapter 4 and 5 describe the proposed HybridCast protocol and address some practical issues. Chapter 6 shows the experimental and simulation results. Finally, we conclude the paper in Chapter 7.

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Chapter 2

Relative Work

(a)Multicast beamforming in MIMO system: There are some papers aim to provide better performance to single multicast transmission by utilizing the MIMO capability. [14] proposes two optimization problems to improve single multicast session: minimize transmitted power which subjects to received SNR constraint and maximize the minimum received SNR which subjects to transmitted power. Since both problems are NP-hard, they approximate the solution by semidefinite relaxation (SDR) and use randomization technique to satisfy the constraint. But the SDR approach is too computationally and may not apply to hardware platform, [7] presents a faster algorithm by iterative updating the multicast precoding to a better direction to achieve slightly better performance than SDR-based method. [5] divides the problem into subproblem. It first studies the optimal solution of two antennas BS for MIMO single multicast. For the arbitrary antennas BS, they propose a method by iterative transforming the original problem into the two-antenna one and improve the solution. [4] proposes an adaptive switch mode between spatial multiplexing mode and spatial diversity mode depending on whether received SNR is high or low to provide better performance. ADAM [2] presents a joint adaptive beamforming method and

MAC layer scheduling design to improve the multicast system in wireless LANs. They also use software define radio platform to demonstrate the performance gain. All those papers mentioned above only consider how to improve the single multicast transmission. However, some multicast services only use the lowest rate to transmit. All those methods will not get much benefit since the lowest transmission rate is enough. Instead, not only improving the multicast session, our HybridCast also combines the unicast transmission to harness the throughput gain.

(b)Multi-user MIMO: Multi-user MIMO protocol allows multiple clients to communicate with a single or multiple AP concurrently. There are many theoretical works have shown the promising gain of multi-user MIMO [17] [8] [3]. There are also some systems that try to realize and demonstrate the feasibility of multi-user MIMO in [18] [13] [16]. [18] presents a scalable MIMO architecture that enable real time signal processing when there are tens or hundreds of antennas. Argos [13] and SAM [16] allow multiple single antenna clients to communicate concurrently with a multiple antenna AP. JMB [11] tries to utilize multiple AP to form a large virtual MIMO node and serves multiple clients concurrently. OpenRF [9] presents a cross layer design architecture to manage multiple AP to communicate with multiple clients concurrently by leveraging MIMO techniques to void interference. Turborate [12] deals with the rate adaption problem in uplink when multiple clients transmit to AP concurrently. Our HybridCast is also a multi-user MIMO protocol. However, we deal with the problem to transmit concurrent unicast streams while protecting the multicast session since we utilize single multicast transmission to send multiple stream concurrently.

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Chapter 3

Illustrative Example

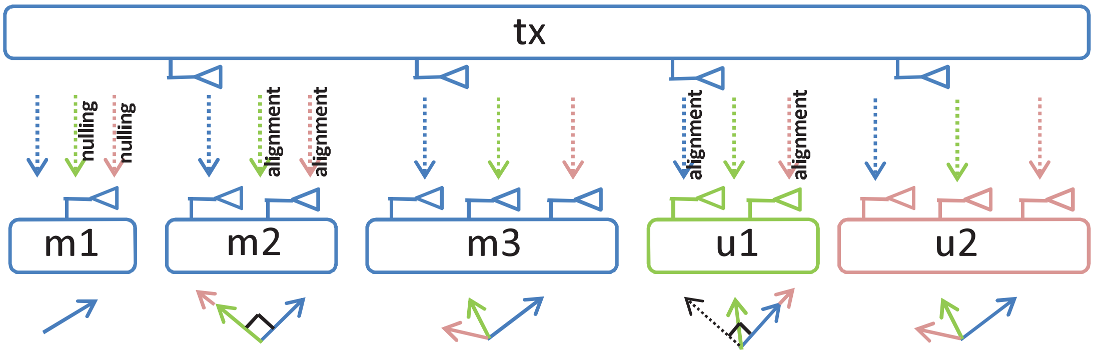

Figure 3.1: **Motivating example:** A 4-antenna AP wants to send a single multicast session and two unicast streams concurrently shown in the figure. The receivers $m1$, $m2$ and $m3$ belong to the multicast group. The receiver $u1$ wants to receive the unicast stream x_1^u (green). The receiver $u2$ wants to receive the unicast stream x_2^u (red).

Before we start to introduce HybridCast design, let us illustrate a simple example to tell you how we enable the concurrent multicast and unicast streams transmission. Consider the scenario shown in Fig. 3.1. There is a 4-antenna AP transmitting a multicast session. There are two unicast receivers, i.e., $u1$ and $u2$, which have downlink traffic want to join the transmission. In this scenario, AP has ability to transmit two unicast streams and the multicast session concurrently.

Transmiting the multicast session: At the beginning, AP will transmit the single

Variable define	
M	number of transmitted antennas of AP
k	number of concurrent unicast streams
V^m	A set that contains all multicast receivers
$\lvert V^m \rvert$	number of multicast receivers
N_i	number of antennas of receiver i
H_i	the channel matrix from AP to receiver i
W_m	the precoding vector of multicast session
W_i	the precoding vector of unicast stream i
R_i	the decoding vector of receiver i

Table 3.1: **Variable definition in the paper**

multicast session. When multicast session is transmitted, each receiver belongs to multicast group can learn the multicast signal in their antenna space. To decode the symbol, they project on the direction that they receive the multicast session. We say this direction is the wanted space of multicast receivers. In Fig. 3.1, blue line is the wanted space of $m1$. For the receivers that do not want to receive the multicast session, they project on the direction that orthogonal to the multicast stream. For example, in Fig. 3.1, the dotted black line in $u1$ is its wanted space and the multicast stream in blue line is its unwanted space.

Transmitting the first unicast stream: Now, we want to join the first unicast stream. It is a challenge to transmit a unicast stream without introducing the interference to those receivers which belong to multicast group. To address this problem, we leverage the MIMO techniques called interference nulling and interference alignment [3]. In Fig. 3.1, when $u1$ joins the transmission, the unicast stream transmitted for $u1$ needs to perform interference nulling at the antenna of $m1$. To see how interference nulling operates, let us see what $m1$ receives. Let x_m and x_1^u denote the symbols of multicast session and the first unicast stream, respectively, and let H_{m1} be the channel from AP to receiver $m1$. $m1$ can receive the signal y_{m1}:

$$y_{m1} = H_{m1}^T x_m + H_{m1}^T x_1^u + n_{m1}$$

where T means matrix transpose operation and n_{m1} is the gaussian white noise observed at $m1$. When we apply precoding vector W_m and W_1 to multicast session and the first unicast stream respectively, y_{m1} becomes:

$$y_{m1} = H_{m1}^T W_m x_m + H_{m1}^T W_1 x_1^u + n_1$$

There are two terms in y_{m1}. The first term $H_{m1}^T W_m x_m$ is the wanted signal of receiver $m1$. The second term $H_{m1}^T W_1 x_1^u$ is the interference. To null the unicast interference of $u1$, the following constraint must meet :

$$H_{m1}^T W_1 = 0 \tag{3.1}$$

By satisfying the constraint Eq. 3.1, we can ensure that $m1$ will not be interfered by unicast stream x_1^u. Now, let us see what happens to $m2$ when we transmit the multicast session and the first unicast stream concurrently. Since $m2$ has two antennas, it has ability to decode the multicast session and the first unicast stream. However, if we want to join the second unicast stream, there will be total three streams which occupy the 2-dimensional antenna space of $m2$. $m2$ will not be able to decode all the signals successfully. In this situation, we need to apply some MIMO techniques to help receiver $m2$ decode its signal. If we directly apply interference nulling at $m2$, there will be total two constraints needed to be satisfied because the first unicast stream need to be canceled at the two antennas of $m2$. But, instead interference nulling, if we perform interference alignment at $m2$, there will be only one constraint needed. Let us see what $m2$ receives :

$$y_{m2} = R_{m2}^T H_{m2}^T W_m x_m + R_{m2}^T H_{m2}^T W_1 x_1^u + n_{m2}$$

Recall that the multicast session is first transmitted. After $m2$ learns the projection of multicast session, it will directly project the decoding vector R_{m2} on the direction that along with the multicast session. Therefore, The decoding vector R_{m2} is determined by.

$$R_{m2} = (H_{m2}^T W_m)^\dagger$$

where † denotes matrix hermitian transpose operation. Substitute this term into the equation, the received signal of $m2$ becomes :

$$y_{m2} = (W_m^T H_{m2})^* H_{m2}^T W_m x_m + (W_m^T H_{m2})^* H_{m2}^T W_1 x_1^u + n_{m2}$$

where $*$ means conjugate operation. Since AP knows the channel term H_{m2} and multicast precoding vector W_m, the interference alignment can be achieved by solving the Eq. 3.2.

$$(W_m^T H_{m2})^* H_{m2}^T W_1 = 0 \tag{3.2}$$

From the above result, we can see that we need to satisfy only one constraint when we apply interference alignment. The first unicast precoding vector W_1 can be calculated by solving the simultaneous equations Eq. 3.1 and 3.2. Since there all total two constraints and AP has four available DoF, this simultaneous equations has infinite solution except for the $\vec{0}$ vector. The $\vec{0}$ vector solution is unacceptable because it prevents AP to transmit the first unicast stream.

Transmitting the second unicast stream: We will show that how we concurrent transmit the second unicast stream. When the second unicast stream joins the transmission, $m1$ will receive the additional interference signal :

$$y_{m1} = H_{m1}^T W_m x_m + H_{m1}^T W_1 x_1^u + H_{m1}^T W_2 x_2^u + n_{m1}$$

$H_{m1}^T W_1 x_1^u$ has been canceled in previous step. However, when we add the second unicast stream, there will exist an addition interference term. To prevent the interference of second unicast stream, we use the interference nulling again as we mentioned before in previous step. The following constraint we will have if we apply interference nulling:

$$H_{m1}^T W_2 = 0 \tag{3.3}$$

Now, let us consider the receivers $m2$ and $u1$ which do not want to receive the second unicast stream too. Since those two receivers have multiple antennas, we perform interference alignment on those receivers to align the interference to their unwanted received space. We will have the following two constraints needed to be satisfied when we perform alignment at $m2$ and $u1$:

$$R_{m2}^T W_2^T H_{m2} = 0 \tag{3.4}$$

$$R_{u1}^T W_2^T H_{u1} = 0 \tag{3.5}$$

Let us check whether we can find a solution for the unicast precoding vector W_2.

Since there are total three constraints from Eq. 3.3, 3.4 and 3.5 and AP has total four DoF available, the unicast precoding vector W_2 has infinite solution. We can pick arbitrary one except for the $\vec{0}$ vector as its solution.

Zero-forcing and successive interference cancellation: Now, let us consider how $m3$ and $u2$ decode their signal. Since those receivers have number of antennas no less than the number of concurrent transmission streams. They have ability to decode all the signals. In this case, we apply Zero-forcing and successive interference cancellation (ZF-SIC) decoder on those receivers. The main idea of ZF-SIC decoder is to decode all the interference signals first. Then, re-encode the interference to construct original interference signal and remove it from the received signal. Finally, we can decode the desired signal as if the interference does not exist. The general rule to apply the ZF-SIC decoder is when the number of antennas of the receiver is no less than the number of concurrent transmission streams. The reason for this limitation is that, in this case, the receiver has available DoF no less than the number of concurrent streams. Receiver has the ability to decode all the transmitted streams. Therefore, we can decode all the interference and cancel them.

Chapter 4

HybridCast Design

4.1 Overview

We consider a network where an AP is equipped with M antenna and transmits a multicast session. The multicast session x^m can apply mulitcast precoding vector W_m to serve a group of multicast receivers, V^{m}. Each receiver $m \in V^m$ is equipped with N_m antennas and it can apply decoding vector R_m to decode the signal. The AP use total P power to transmit the signal. The signal received by each multicast receiver $m \in V^{\mathrm{m}}$ is given by

$$\mathbf{y}_m = \sqrt{P} R_m^T H_m^T W_m x^m + n_m, \forall m \in V_m,$$

where x^m is the multicast symbol transmitted by the AP, H_m is the $M \times N_m$ channel matrix for receiver m, W_m is the $M \times 1$ precoding vector of multicast session x^m, R_m is the $N_m \times 1$ decoding vector of receiver m and n_m represents the additive white Gaussian noise at the receiver m. Each multicast receiver m can achieve an SNR SNR_m, depending on the channel matrix H_m, the AP's precoding strategy, and the decoder it applies. Assume that the multicast session is transmitted at the bit-rate r, which requires at least $SNR(r)$ to ensure successful decoding. We define the link margin of receiver m as $\Delta_m = SNR_m - SNR(r)$. The AP can hence exploit the minimum link margin $\Delta = \min_{m \in V^m} \Delta_m$ to deliver concurrent unicast streams.

Let V^{u} denote the set of users that have downlink traffic and could potentially join concurrent transmissions, and each user $u \in V^{\mathrm{u}}$ has N_u antennas. Given a selected multicast session, our goal is to determine: (*i*) how many unicast streams from V^{u} can be transmitted concurrently with the multicast session, (*ii*) how to transmit concurrent unicast streams without harming the multicast receivers, i.e., ensuring $SNR_m \geq SNR(r)$ for all $m \in V^{\mathrm{m}}$, (*iii*) how to decode the wanted signal in each client to avoid interference, and (*iv*) how to allocate the transmitted power and utilize the available link margin Δ for unicast streams. We will explain in the next four sections how we achieve the above goals.

4.2 Achievable Number of Concurrent Unicast Streams

How do we enable the concurent umulticast and unicast session transmission? The simplest way is directly apply the Zero-Forcing Beamforming (ZFBF) technique [19] [1]. ZFBF allows M-antenna AP to transmit M independent streams. Therefore, M-antenna AP has ability to serve M clients simultaneously. The idea of ZFBF is to beamform the wanted signal to its intended client and null the unwanted signal at that client. Hence, each client can receive the desired signal without being interfered by other streams. In our scenario, when AP applies ZFBF, it can treat multicast receivers as $|V^m|$ independent unicast clients, and leave the remaining $M - |V^m|$ DoF to transmit the unicast streams. Consider the example shown in Fig 3.1, where there is a 4-antenna AP which serves three multicast clients $m1$, $m2$ and $m3$. When AP applies ZFBF, it will treat those multicast clients as three independent unicast receivers. The remaining one DoF can be use to send unicast stream x_1^u to receiver $u1$.

However, when the number of antenna of AP M is no more than the number of multicast clients $|V^m|$, This naïve ZFBF approach can not transmit any unicast stream concurrently. For example, an 4-antenna AP can not serve four multicast clients and one unicast client concurrently by ZFBF technique. However, in some cases, it is possible to include this unicast client . That is because this naïve ZFBF approach cannot efficiently utilize all the available DoF. Note that it neglects the fact that some clients has ability to decode all streams. Consider the example in Fig. 3.1, we have explained that by applying naïve ZFBF, the AP could serve three multicast receivers, and one unicast client, $u1$, concurrently. However, in this example, it is possible to further include the second unicast stream x_2^u. We observe that receiver $m3$ has three antennas and can recover three streams. The AP hence does not need to do beamforming for $m3$, and hence can save one DoF for including the second unicast stream. Specifically, when applying ZFBF, the AP only need to perform beamforming for the other four clients $m1$, $m2$,$u1$ and $u2$. The receiver $m3$ can overhear the three streams (x^m, x_1^u and x_2^u) and use its three antennas to decode the multicast signals x^m. Unlike naïve ZFBF, which allows an M-antenna AP to serve M client at most, such a modified ZFBF, enables an M-antenna AP to transmit more unicast streams simultaneously than naïve ZFBF.

The key to add more concurrent unicast streams is that some clients have ability to decode all transmitted streams. Therefore, it is not necessary to exploit $|V^m|$ degrees of freedom to beamforming the multicast streams for each of multicast members. Note that the multicast receiver with a sufficient number of antennas can recover the multicast stream from the interfering unicast signals. As a result, in modified ZFBF, AP does not need to cancel the unicast interfernece for those receivers, and it can save some DoF to send the extra unicast streams.

Let us give a general rule to maximize the number of concurrent transmission unicast streams. Consider the scenario, say AP wants to transmit k concurrent unicast streams. We define the receivers with more than $(k+1)$ antennas as *strong users* because they can use their antennas to decode $(k+1)$ concurrent streams, i.e., k unicast and 1 multicast. On the contrary, all the other receivers with no more than k antennas are called *weak users*. We collect all the weak receivers belong to multicast group as a set V_k^m. Since the *strong users* can recover $(k+1)$ concurrent streams, the AP only needs to cancel the interfering unicast signals for those *weak users* but ignore the *strong users*. Therefore, unlike naïve ZFBF, which treats all the multicast receivers as unicast clients, modified ZFBF can improve antenna efficiency by only beamforming the multicast signal toward those *weak users*. Since sending k unicast streams requires k degrees of freedom, the M-antenna AP can only use the rest $(M-k)$ degrees of freedom to null for the *weak users*. Hence, the M-antenna AP can send k unicast streams only if $M - k \geq |V_k^{\mathrm{m}}|$. Hence, the maximum number of the concurrent unicast streams K^* is constrained by the number of weak users, and can be found by

$$K^* = \arg\max_k \left(k : M - k \geq V_k^M\right) \tag{4.1}$$

Consider again the example in Fig. 3.1. If AP wants to transmit two unicast streams, then both m_1 and m_2 are weak users, i.e., $|V_2^m| = 2$. The AP has four antennas and hence $M - k = 4 - 2 \geq |V_2^m| = 2$ holds. However, if AP wants to further send the third unicast stream, then the set of weak users becomes $V_3^{\mathrm{m}} = \{m1, m2, m3\}$. The constraint in Eq. 4.1 now does not hold, i.e., $M - k = 4 - 3 \ngeq |V_3^m|$. The maximum number of concurrent unicast streams in this case is hence $K^* = 2$.

4.3 Unicast Precoding: joint multicast and unicast interference nulling alignment

To make sure the achievable rate of multicast session will not reduce due to the concurrent transmission of unicast streams, we propose a Joint Multicast and Unicast Interference Nulling Alignment scheme, call JMU-INA. We have illustrated a simple example in Chapter 3 to explain our precoding scheme. In this section, we will tell you how we calculate the precoding vector that enables concurrent multicast and unicast transmission without harming the multicast receivers in general scenario. Assume there are k unicast streams join the transmission. Our goal is to find all k unicast precoding vectors.

Step 1: Protected receivers assignment. The first step to calculate the unicast precoding vector is that we need to know which receivers we need to protect when we transmit the additional unicast stream concurrently. In other word, those receivers will receive interference if we do nothing for them when unicast streams join the transmission. Take an example, from Fig. 3.1, when we want to transmit the first unicast stream x_1^{u} concurrently, we need to protect $m1$ and $m2$. The simplest way to find all those receivers is to find the receivers with antenna less than $k+1$, i.e., k unicast and 1 multicast. Such receivers we define as weak users. We collect all those weak users as a set G. If we want to transmit the unicast stream i, the receivers that unicast stream i needs to protect are $G - \{u_i\}$. The reason to exclude $\{u_i\}$ is that the unicast receiver u_i which wants to receive the unicast stream i does not need the protection.

Step 2: JMU-INA constraints. Now, we have a list that which receivers we need to protect when transmitting the unicast stream i. Each weak receiver in the list will give a limitation for the precoding vector of unicast stream i. For the weak user j with single antenna $N_j = 1$, we need to perform interference nulling to user j because it cannot avoid any interference. For the weak user n with multiple antenna, i.e., $N_n > 1$, we align the unicast interference at its unwanted receiving space. Hence, when the weak user n decodes along with its wanted space, it will not receive the interference introduce by unicast stream i. We list the three types of constraints that unicast precoding needs to satisfy at below:

- **Interference nulling constraint:** The unicast precoding vector i which needs to perform interference nulling to those receivers needs to satisfy:

  $$H_j^T W_i = 0 \tag{4.2}$$

  where j belongs to the weak users with $N_j = 1$.

- **Interference alignment constraint:** The unicast precoding vector i needs to align the interference to the unwanted space of those weak users by satisfying:

  $$R_n^T H_n^T W_i = 0 \tag{4.3}$$

  where n belongs to the weak users with $N_n > 1$.

- **Equal precoding vector constraint:** In some cases, the two or more unicast precoding vectors may be the same. We use a simple example to illustrate how this situation happens. Assume all receivers which belong to multicast group are weak users. There are two unicast receivers join the transmission and those two unicast users does not belong to weak users. The unicast precoding vectors of these two unicast streams will be equal because they have the same nulling and alignment constraints. To avoid this situation happen, we need to add additional constraint to prevent the equal unicast precoding vector occur. Therefore, the below constraint also needs to be considered:

$$W_i \neq W_l \tag{4.4}$$

where l belongs to all prior scheduled unicast receiver.

Step 3: Calculating the precoding vectors. In previous step, we list all the constrains that unicast precoding must satisfy. Then, how do we calculate the precoding vector of unicast stream i ? This task is simple. We can combine all the nulling, alignment and equal precoding constraints to form a matrix equation shown below:

$$\begin{bmatrix} H_j^T & \dots & R_n^T H_n^T & \dots & W_l^T & \dots \end{bmatrix} W_i = 0$$

where, j belongs the weak users with $N_j = 1$, n belongs the weak users with $N_n > 1$ and l belongs all the prior scheduled unicast clients. The solutions of this matrix form equation are the null basis of the matrix:

$$W_i = null(\begin{bmatrix} H_j^T & \dots & R_n^T H_n^T & \dots & W_l^T & \dots \end{bmatrix})$$

We can pick any one of the null basis as the solution of unicast precoding vector i. The detail algorithm for unicast precoding calculation is in Algorithm 1.

Algorithm 1 : Unicast precoding vector calculation

```
Input: $k$, $G$, $H$, $R$, $schedule\_unicast\_array$
Output: $W_i$
Initial $W_s \to \{\}$;
for each unicast receiver $i \in schedule\_unicast\_array$ do
    Initial $C_i \to \{\}$;
    for each weak user $j \in G - \{i\}$ do
        if $Nj == 1$ then
            $C_i = C_i \cup \{H_j^T\}$
        else
            $C_i = C_i \cup \{R_j^T H_j^T\}$
        end if
    end for
    $C_i = C_i \cup W_s$;
    $W_i = null(Ci)$;
    if $Ni \geq k$ then
        $W_s = W_s \cup \{W_i^T\}$ ;
    end if
end for
```

4.4 Decoding

In this section, we discuss how those receivers decode their wanted signal and avoid the interference. We define the terms wanted space F^{w} and unwanted space F^{n}. Wanted space is the projection of decoding vector in receiver's received antenna space. On the other hand, unwanted space is the null space of wanted space $\mathrm{F}^{\mathrm{n}} = \mathrm{null}\left(\mathrm{F}^{\mathrm{w}}\right)$. From the previous subsection, JMU-INA will alignment all the unicast interference to reciever's unwanted space. As long as the receiver decodes along with the wanted space, it can avoid the interference from other unicast streams. Now, we will tell you how those receivers decide their wanted space. We divide all the receivers into three groups: 1) single-antenna nodes, i.e., the receivers equipped with single antenna, 2) weak nodes, i.e., the receivers with $1 < N_i \leq k$ antennas and 3) strong nodes, i.e. the receivers with more than k antennas. We use different decoding strategies in those three groups.

1) single-antenna nodes: Since receivers in this group have only one antenna, they can

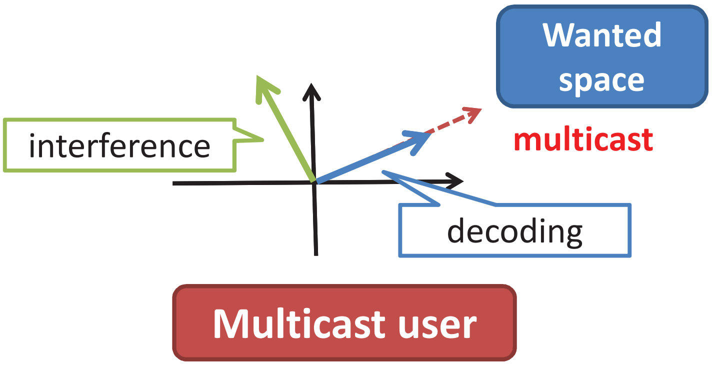

Figure 4.1: Antenna space of weak nodes in multicast group.

only decode the received signal from their single antenna without choice. Fortunately, JMU-INA will null all the interference to those receivers. They can just use standard SISO decoder to get the desired signal.

2) weak nodes: Receivers in this group have multiple antennas. However, they still have no ability to decode all the streams. The key point is how those receivers decide their decoding vectors. Since all the unicast interference will align to the unwanted space by JMU-INA scheme, those receivers will not receive the unicast interference. The remaining multicast stream will act an important role to decide the decoding vector depending on whether the multicast stream is the interference or not. For the weak nodes which belong to multicast group, multicast stream is their wanted signal. They can apply MRC decoder and decode along with the projection of multicast stream shown in Fig.4.1. For the weak nodes which belong to unicast receivers, multicast stream is their interference. When learning the multicast projection, they will pick a decoding direction that orthogonal to multicast stream shown in Fig.4.2. Since all unicast interference will project on the unwanted space of those weak nodes, they can decode the wanted signal without interference.

3) strong nodes: For the strong nodes, they are capable of recovering all the $k+1$ streams. JMU-INA scheme will not precode for them. However, if they directly decode the wanted

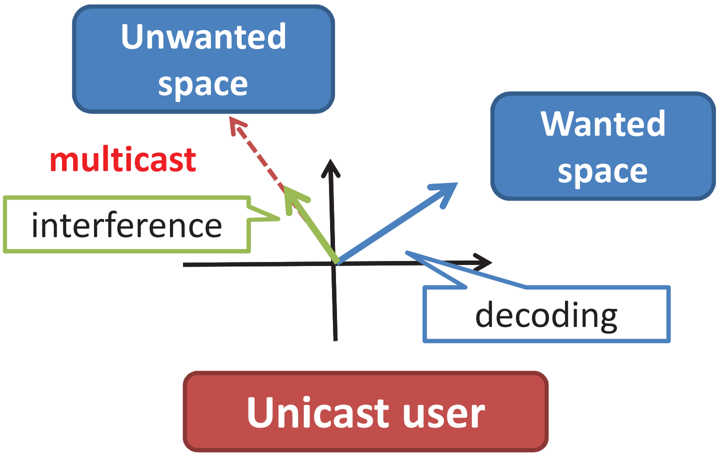

Figure 4.2: Antenna space of weak nodes in unicast receivers.

stream by projecting the decoding vector along with the direction that orthogonal to all interference streams. The projected SNR is unpredictable and AP has no idea how to select the best transmitted rate to transmit their stream. Therefore, instead of using ZF decoder, we apply zero-forcing with successive interference cancellation (ZF-SIC) decoder for strong nodes. The main feature of ZF-SIC decoder is that it enables strong nodes to decode the desired signal after removing all the interference streams and strong nodes can directly apply MRC decoder to decode the signal as if the interference does not exist. Let us illustrate a simple example. Consider the scenario that there are three concurrent transmitted streams. A strong node wants to decode the third stream. At the beginning, it will decode the first interference stream by projecting the receiving vector along with the direction orthogonal to the plane which is formed by the second and third stream. Then, it re-encodes the first stream and substrates the first stream from the received signal. Afterward, it decodes the second stream and substrates the second stream from the received signal. Finally, only the third stream stays in the received signal and we can apply MRC decoder to decode the third stream. Since ZF-SIC decoder removes all the interference, the achievable SNR will not decrease by the interference streams.

Algorithm 2 : Decoding vector R calculation

```
Input: $k, V^m, schedule\_unicast\_array, W_m, H$
Output: $R$
for each multicast client $i \in V^m$ do
    if $N_i \leq k$ then
        $R_i = conj(H_i^T W_m)$;
    else
        Use ZF-SIC decoder;
    end if
end for
for each unicast client $i \in schedule\_unicast\_array$ do
    if $N_i \leq k$ then
        $R_i = null(H_i^T W_m)$;
    else
        Use ZF-SIC decoder;
    end if
end for
```

4.5 Link Margin Adaption

In this section, we will explain how we utilize the link margin. Since in current standard, such as 802.11 or LET, the multicast session is transmit at the lowest rate to make sure most of the receivers can receive the service successfully, the received SNR of each receiver is usually much higher than the minimum required SNR for decoding. Assume the lowest transmitted rate requires at least $SNR(low)$ to ensure successful decoding and the worst receiver m which has the lowest SNR in the multicast group received $SNR(m)$.

$$SNR(m) = \min_{k \in V^m} 10 \log \frac{\|x^m\|^2 \left\| H_k^T \vec{1} \right\|^2}{\sigma^2}$$

The available link margin is $\Delta_m = SNR(m) - SNR(low)$. We can lower the transmitted power of multicast session but we need to satisfy $\Delta_m \geq 0$ because we must ensure all receivers can decode the multicast session successfully after power control. Therefore, since the total transmitted power is P, we only need to allocate P_m to transmit the multicast session.

$$P_m = P\frac{SNR(low)}{SNR(m)}$$

The remaining power $P - P_m$ can be utilized to transmit the unicast streams. By transmitting the multicast session using power P_m, we can make sure all receivers which belong to multicast group can still decode successfully and we have available power to transmit unicast streams.

However, in some protocols, the multicast session uses the best rate to transmit. It means that the transmitting rate is depending on the worst receiver. In this case, we do not have any available link margin because lowering the transmitted power will lead to fail decoding of the worst receiver. However, we can try to improve the worst receiver by applying multicast precoding W_m. We can enlarge the link margin by maximizing the SNR of the worst receiver. This problem is an optimization problem with the form max min $SNR(m)$, where m belong to the worst receiver in multicast group. This is a NP hard problem [14] and it is unrealistic to be implemented on real system. Instead of using such complicated solution, we propose a simple multicast beamforming method by finding a proper multicast precoding vector that enlarges the worst SNR in the multicast group. The idea of this method is to find the best precoding vector b_i for each multicast receiver i. Each receiver i will get the maximum achievable SNR when applying the best precoding vector b_i. However, $|V^m|$ multicast receivers will have $|V^m|$ best precoding vectors but we can only select one precoding vector for multicast precoding. Therefore, we try to find a sub optimal solution by combining all b_i precoding candidates. For example, we can add a weighting a_i for each multicast precoding candidate b_i and a_i is the inverse of maximum SNR of receiver i if we use precoding vector b_i to transmit. The detail algorithm of propose multicast beamforming method is in Algorithm. 3.

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Algorithm 3 : multicast beamforming method

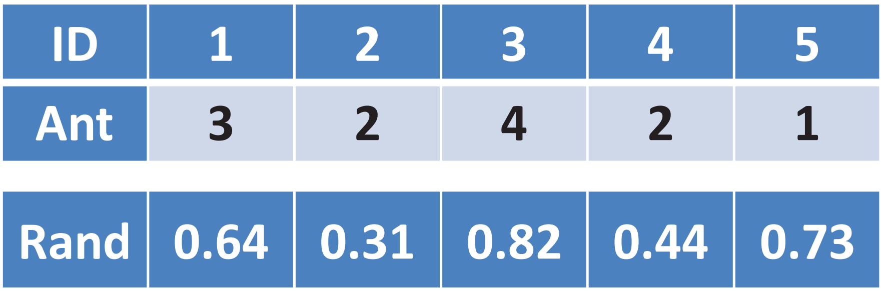
```
Input: $V^m$, $H$
Output: $W_m$
Initial $b_i$, $a_i$;
for each multicast client $i \in V^m$ do
    if $N_i == 1$ then
        $b_i = conj(H_i)$;
    else
        $b_i$ is the eigenvector with the biggest eigenvalue of $H_i H_i^*$;
    end if
    $a_i = \frac{1}{\left\| H_i^T b_i \right\|}$;
end for
$W_m = \sum_{i=0}^{|V^m|-1} a_i b_i$;
Normalize $W_m$
```

Chapter 5

Additional Issues

Selection of unicast candidates: When there are many unicast clients have downlink traffic but AP cannot serve all of them, we need a mechanism to select which unicast receivers can be served concurrently in every round. How does AP select unicast clients among unicast candidates? Since we wish that all unicast candidates have equal probability to be served, our method needs to satisfy the property of fairness. At the beginning, AP will give every unicast candidates a random number. Based on the random number, the unicast candidates with the bigger random number will have the higher priority to be served. For example, from Fig. 5.1, the unicast candidates 3 has the biggest random number, so it is the first one to be scheduled. The unicast candidate 5 is the second. However, we will not allow unicast candidates 5 to join the concurrent transmission since unicast candidates 5 only has single antenna. From section 4.4, we know that all the interference will align to the unwanted space of receiver and receiver can decode the desired signal on its wanted space without being interfered. But unicast candidates 5 only has single antenna which means unwanted space does not exist and it cannot avoid any interference. Therefore, we do not allow any single antenna unicast candidate to join the transmission.

For each new round, AP will assign a new random number to each unicast candidates.



ID	1	2	3	4	5
Ant	3	2	4	2	1
Rand	0.64	0.31	0.82	0.44	0.73

(a) Before prioritizing

ID	3	5	1	4	2
Ant	4	1	3	2	2
Rand	0.82	0.73	0.64	0.44	0.31

(b) After prioritizing

Figure 5.1: Unicast candidates prioritizing

Transmitted mechanism compatible with 802.11ac and LTE: 1)802.11ac: We illustrate the transmit mechanism in Fig. 5.2. At the beginning, AP will broadcast NDP Announce (NDP-A) frame to tell all clients to begin the channel estimation phase. NDP-A frame also contains the information that which clients need to feedback the Channel State Information (CSI). Then, AP will send NDP frame which contains the common information that all clients and AP know. Clients can use NDP frame to estimate the channel fading between AP and their receiving antennas. When all clients calculate the CSI by estimation, multicast receiver can feedback the CSI using dedicated subchannel. For unicast receiver, AP will use polling method to ask them to feedback their CSI. After the channel estimation process completes, AP will transmit the preambles which contain the information that how all the streams are precoding. Clients will know how to decode their desired signal by learning the preambles. And then, AP can start to transmit the data streams concurrently. Finally, to make sure all the unicast stream are transmit successfully, AP will use polling method to ask unicast clients to feedback ACK by Block ACK Request (BAR) frame. 2)LTE: Since LTE is a central control system, we can use the original channel estimation mechanism existing in LET system to feedback the CSI of all clients via dedicated channel. After channel estimation process completes, AP will start to transmit the preamble to tell all clients how all the stream are precoded. Then, AP will start to transmit all data streams concurrently. When the data transmission is finish, unicast clients can feedback ACK in dedicated channel assigned by AP.

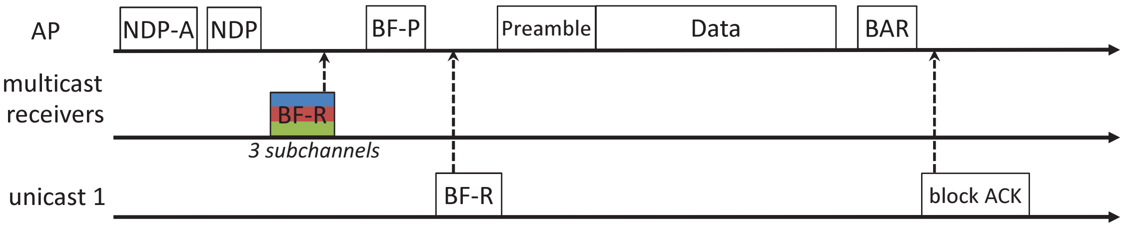


Figure 5.2: Transmitted mechanism in 802.11ac

Estimation of the best bit rate: We need to determine the best transmitted bit rate of every stream when concurrent transmission occurs. How do we cope with this problem? Since AP knows the channel state information and the direction of decoding projection of each client, it can estimate the SNR in each OFDM subcarrier among those clients. Then, AP needs to translate the SNR to the effective SNR(ESNR). Why we need the ESNR? That is because the ESNR considers the impact of frequency selective channel of multiple OFDM subcarriers. Therefore, It will be more accurate to use ESNR instead of SNR to map the best transmitted bit rate [6]

Time synchronization: In OFDM system, we need to synchronize all nodes within a cyclic prefix time of an OFDM symbol. To further cope with the delay due to the hardware processing time and channel propagation, we scale both the cyclic prefix and OFDM FFT size by the same factor. This action will not introduce additional overhead because the percentage of transmitted data and cyclic prefix is remaining constant. Moreover, this action allow the system to tolerate synchronization error since cyclic prefix are scale up [15].

Frequency offset: To avoid the inter-carrier interference, every client in the system should have the same frequency offset with respect to AP. We apply the mechanism propose in [10] [15] to compensate the frequency offset of those clients. When the AP transmits the preamble, every client naturally estimates the frequency offset with respect to the AP. Then, every client can synchronize their frequency domain by compensating the offset.

Chapter 6

Performance Evaluation

We evaluate HybridCast using both testbed experiments and large scale simulations.

6.1 Experimental results

We implement our design using N200 software define radio, each node is equipped with RFX2400 daughterboard and communicates on a 10MHz channel. We operate our experiment in 2.4GHz range. We construct a MIMO node using MIMO cable and extern clock for synchronization. Further, we build our prototype based on GNURadio OFDM code. We also implement the following component: Unicast scheduler, interference nulling, in-

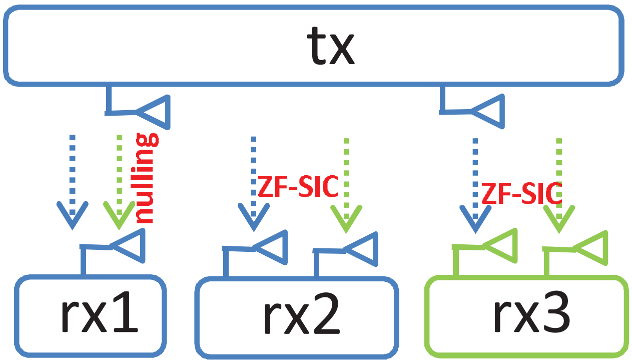


Figure 6.1: **Experiment scenario1:** A 2-antenna BS can transmit 1 multicast and 1 unicast streams concurrently.

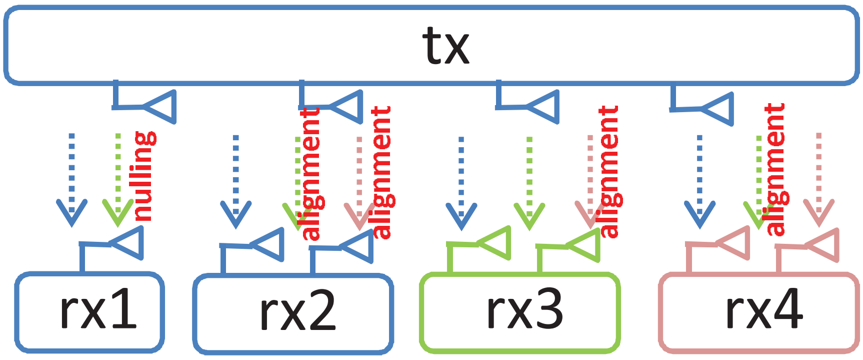


Figure 6.2: **Experiment scenario2:** A 4-antenna BS can transmit 1 multicast and 2 unicast streams concurrently.

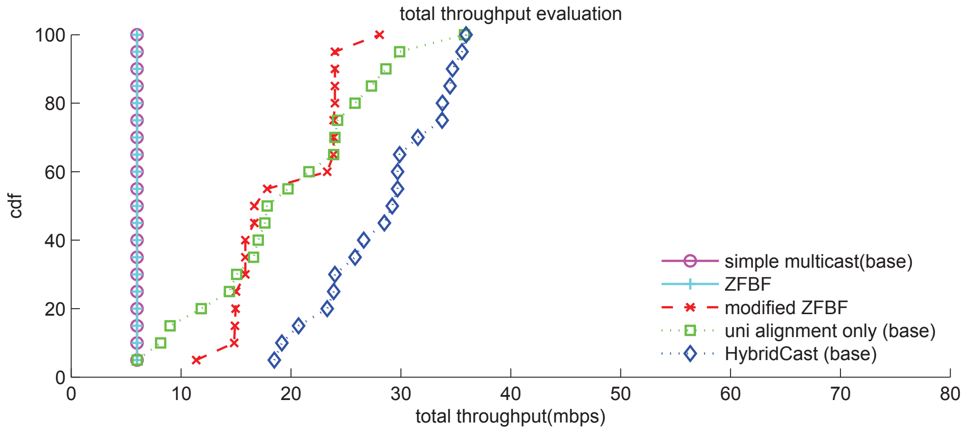
terference alignment, ZF-SIC decoder, MRC decoder, power controller and bitrate selection based on SNR. We change bitrate by using different modulation scheme and coding rate supported by 802.11 system.

We implement total six scheme in our experiment.

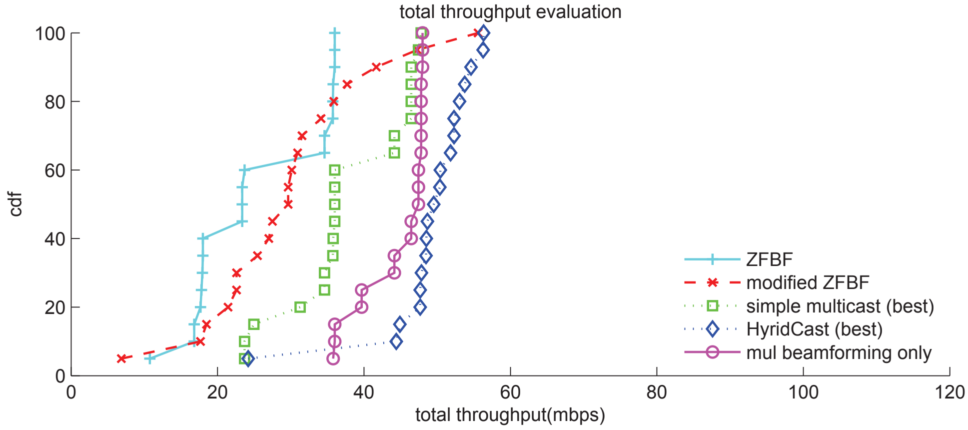
- **simple multicast:** use equal power allocation on each transmitted antenna to transmit single multicast session.
- **ZFBF:** use zero-forcing beamforming technique to transmit multicast session and unicast streams concurrently.
- **modified ZFBF:** modify ZFBF scheme to enable more unicast clients than ZFBF to join the transmission.
- **alignment only:** join the unicast clients by interference alignment to avoid the interference. This scheme transmits the multicast session using base rate.
- **HybridCast:** HybridCast scheme mentioned in paper.
- **mul beamforming only:** use multicast beamforming method mentioned in Algorithm 3 to improve the multicast session transmission. This scheme only transmits single multicast session.

In our experiment, AP can use base rate or best rate to transmit the multicast session. Base rate means AP uses the most robust and lowest rate to transmit the multicast session. Best rate means AP uses highest rate that all clients which belong to multicast group can still decode signal correctly to transmit the multicast session.

Throughput Comparison: We evaluate the total throughput gain using two different scenario shown in Fig 6.1 and Fig 6.2. In each scenario, we also evaluate the different requirement of transmitting rate in multicast session.



(a) Base rate



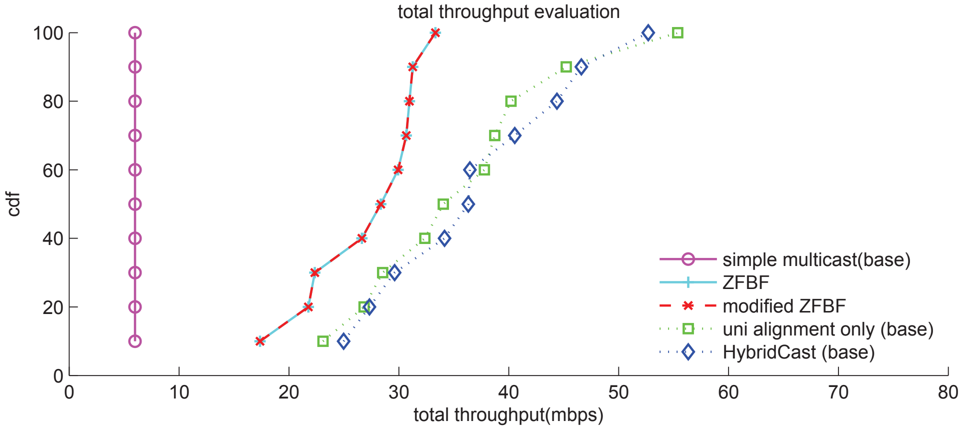
(b) Best rate

Figure 6.3: Total throughput comparison in scenario 1

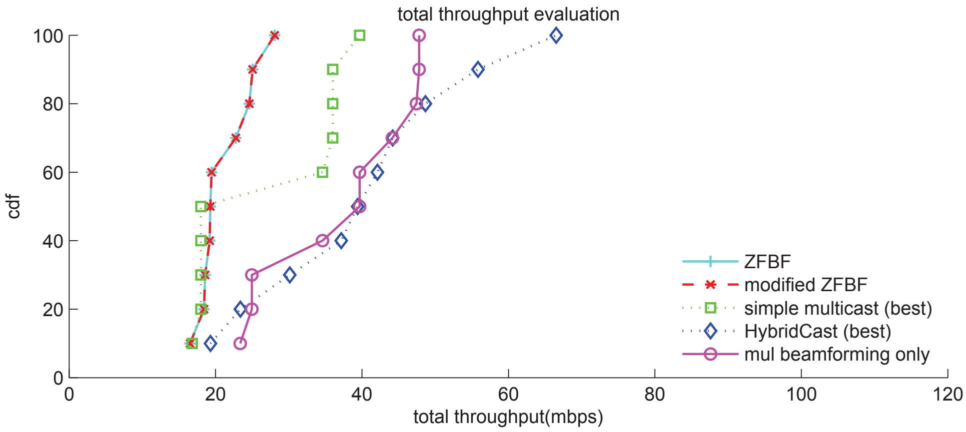
Experiment1: We use the scenario shown in Fig 6.1, where an 2-antenna AP serves two multicast clients and one unicast client have downlink traffic. We randomly assign each MIMO node in different location to make sure the accuracy of experimental results.

Result: Fig 6.3(a) plots the CDFs of total throughput of different schemes using base rate requirement of multicast session. From the experimental result, we can find that the CDFs of simple multicast and ZFBF overlap. That is because, in this scenario, simple multicast and ZFBF can only serve two multicast clients and multicast session is transmitted using base rate. Therefore, the total throughput in these two schemes are equal. Since modified ZFBF can transmit additional unicast stream compared with ZFBF, the total throughput of modified ZFBF is higher than ZFBF. Further, we can see that HybridCast outperforms than modified ZFBF and alignment only scheme. The reason is that modified ZFBF does not utilize the receive diversity and alignment only scheme does not explore the possibility to enlarge the link margin. However, HybridCast leverages both. The average total throughput are 6(mbps), 6(mbps), 19.443(mbps), 19.7305 (mbps) and 28.4419(mbps) for each scheme shown in Fig 6.3(a) respectively. In Fig 6.3(b), we use the best rate requirement of multicast session to evaluate the performance in same scenario. From the experimental result, in average, the total throughput of modified ZFBF is higher than ZFBF because modified ZFBF sends one additional unicast stream. NO surprisingly, HybridCast outperforms than modified ZFBF and simple multicast for the same reason that HybridCast leverages the advantage of receive diversity and link margin. Mul beamforming only scheme shows that, instead of using link margin to transmit the unicast stream concurrently, we can just enlarge the link margin to allow multicast session using higher rate to transmit. The average total throughput are 25.6063(mbps), 29.6878(mbps), 37.8856(mbps), 49.157 (mbps) and 44.6828(mbps) for each scheme shown in Fig 6.3(b) respectively.

Experiment2: We repeat the throughput evaluation experiment but in another scenario shown in Fig 6.4, where there is an 4-antenna AP which serves two multicast clients and



(a) Base rate

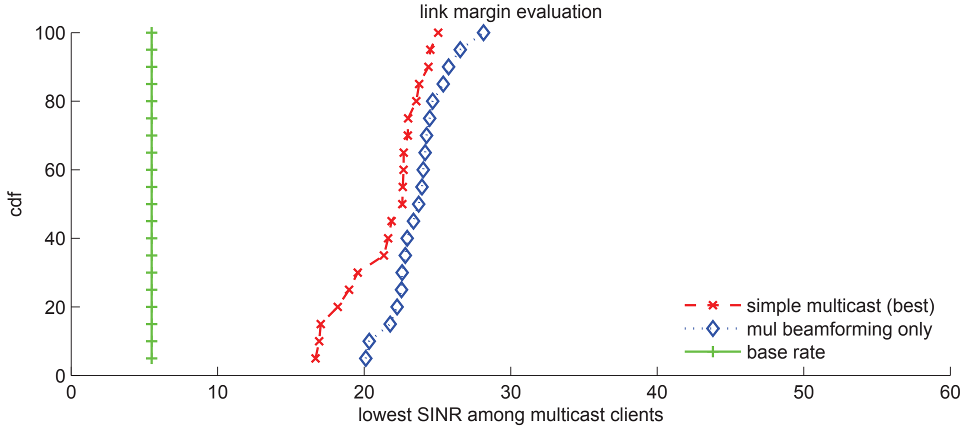


(b) Best rate

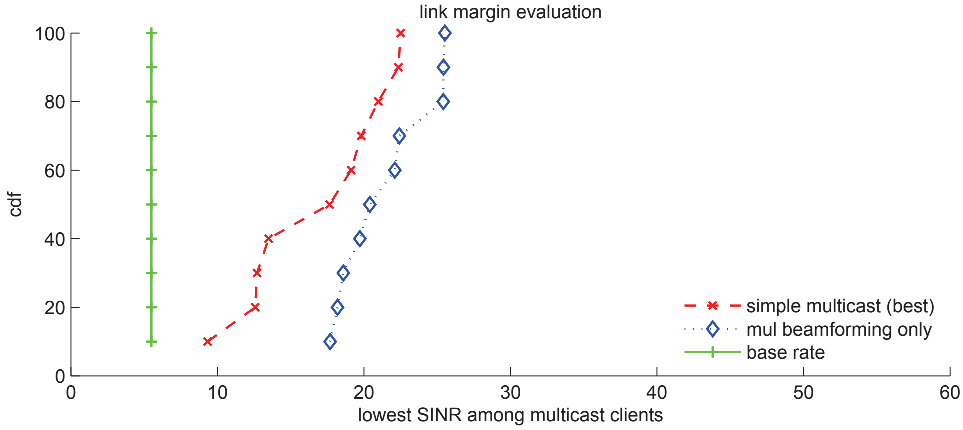
Figure 6.4: Total throughput comparison in scenario 2

two unicast clients have downlink traffic. We also evaluate two different requirement of multicast session in this scenario.

Result: Fig 6.4(a) plots the CDFs of total throughput of different schemes using base rate requirement of multicast session. It verifies that, by leveraging both receiver diversity and link margin, HybridCast has the highest throughput gain. We can also see that the total throughput of ZFBF and modified ZFBF are close. That is because, in this scenario, both ZFBF and modified ZFBF need to do beamforming to those four clients. Specifically, ZFBF and modified ZFBF transmit the signal using the same way. The average total throughput are 6(mbps), 27.2674(mbps), 27.2674(mbps), 36.2236(mbps) and 37.3146(mbps) for each scheme shown in Fig 6.4(a) respectively. In Fig 6.4(b), we use best rate requirement to transmit multicast session. For the same reason we mentioned in Fig 6.4(a), ZFBF and modified ZFBF using same way to transmit the signal. Therefore, the total throughput of these two scheme are equal. The experimental result also shows that we can utilize link margin to transmit unicast concurrently like HybridCast or just improve the multicast session like mul beamforming only scheme. The average total throughput are 21.2012(mbps), 21.2012(mbps), 27.1122(mbps), 40.6741 (mbps) and 37.4475(mbps) for each scheme shown in Fig 6.4(a) respectively.



(a) Scenario 1



(b) Scenario 2

Figure 6.5: Link margin evaluation

Link Margin Evaluation: We next study the link margin gain improved by multicast beamforming method mentioned in the paper. We evaluate the link margin gain in both scenario shown in Fig 6.1 and Fig 6.2.

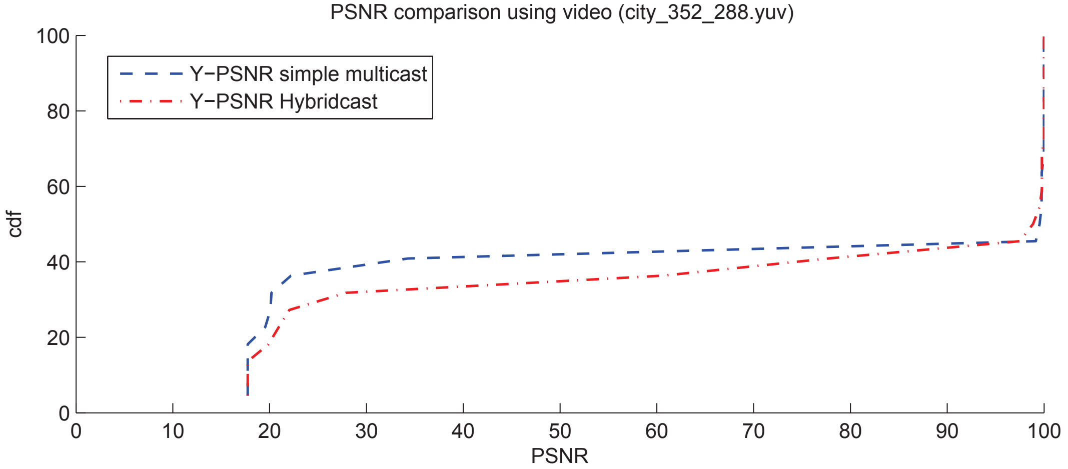


Figure 6.6: **video evaluation:** we use city_352 × 288.yui to evaluate simple multicast and Hybridcast.

In Fig 6.5(a), we compare the link margin of two scheme. We plot the lowest SINR of multicast receivers in both scheme because the available link margin in each scheme is the gap between decoding required SINR and minimum received SINR among multicast clients. In this scenario, we transmit the multicast session using base rate. Therefore, we plot the base rate required SINR in the figure (green line) to show how much link margin that each scheme has. From the experiment, we can see that mul beamforming only scheme has higher link margin compared with simple multicast. The reason is that the multicast beamforming method can larger the minimum SINR among multicast receivers. Hence, we can have more available link margin by applying multicast beamforming method. The average available margin of both scheme is 15.005dB and 18.1913dB respectively.

Fig 6.5(b) plots the link margin using scenario shown in Fig 6.2. In this scenario, we also show that multicast beamforming method indeed achieves larger link margin gain than simple multicast transmission. The average available margin in this scenario of both scheme is 11.5538dB and 16.0508dB respectively.

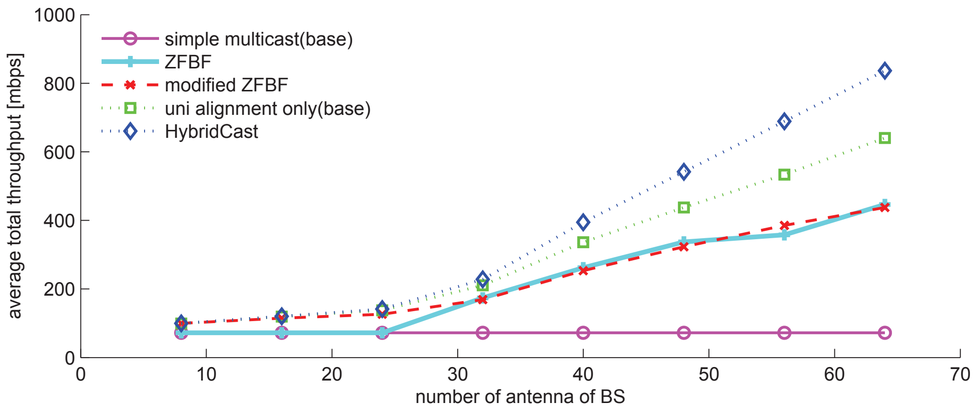
Video Transmission: We evaluate the HybridCast design using video transmission.

we use the video $\mathrm{city\_352 \times 288.yui}$ for multicast session. Our experiment scenario is shown in Fig. 6.1, where HybridCast will transmit multicast session and one unicast stream concurrently and simple multicast only transmits the multicast session. From the experiment result, we show that HybridCast does no harm to the multicast transmission while transmitting unicast stream concurrently since the PSNR is very close to the single multicast transmission. This means that the received video quality is no different from those two scheme. This experiment shows that HybridCast indeed protects the multicast transmission while harness the throughput gain from concurrent transmission. The average Y-PSNR of simple multicast and HybridCast is 67.5081db and 71.7031db respectively.

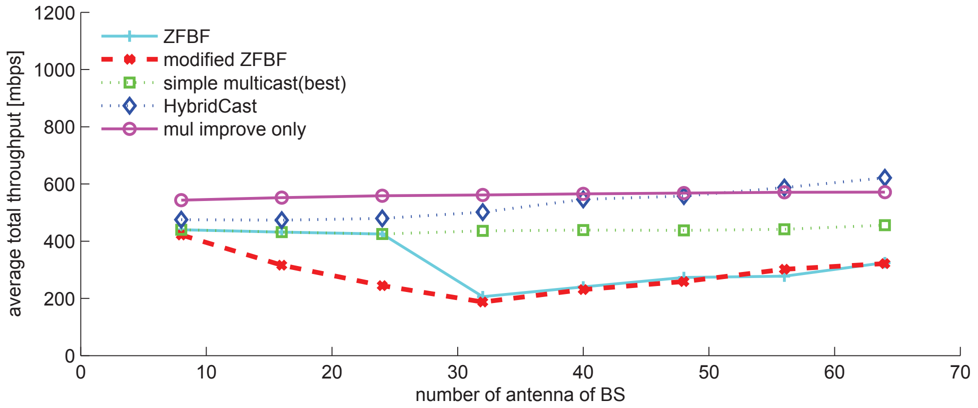
6.2 Simulation evaluation

We next evaluate our propose scheme in large scale simulation. We deploy all clients in $100m \times 100m$ area. Let max_rx_ant denotes the maximum number of antenna equipped on each client. Each clients will equip with antenna from 1 to max_rx_ant uniformly. We use i.i.d. complex Gaussian channel with zero mean and unit variance and use log-distance path loss model which the path loss exponent is 3 and the reference receive power is -25dBm. Our noise power is set to -95dBm and the maximum transmission power of the BS is 15dBm. In the simulation, we explore the influence of the number of antenna of BS and the number of multicast clients among different scheme.

Number of antenna of BS: In Fig. 6.7, we show the simulation results of average total throughput when the number of antenna of BS increases from 8 to 64. In each case, we run the simulation for 1000 times and we average the throughput result. There are 16 multicast clients, 8 unicast candidates and we set $max\_rx\_ant = 4$ in this simulation. We deploy the clients using the normal distribution. In Fig. 6.7(a), we use base rate to



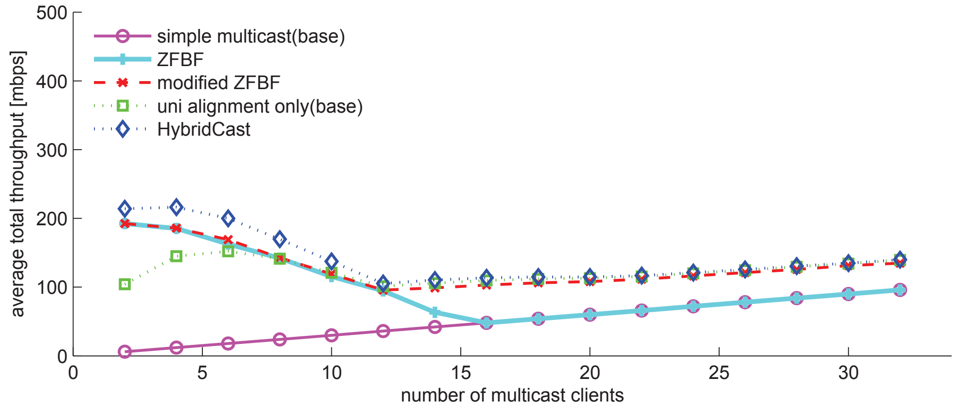
(a) Multicast using base rate



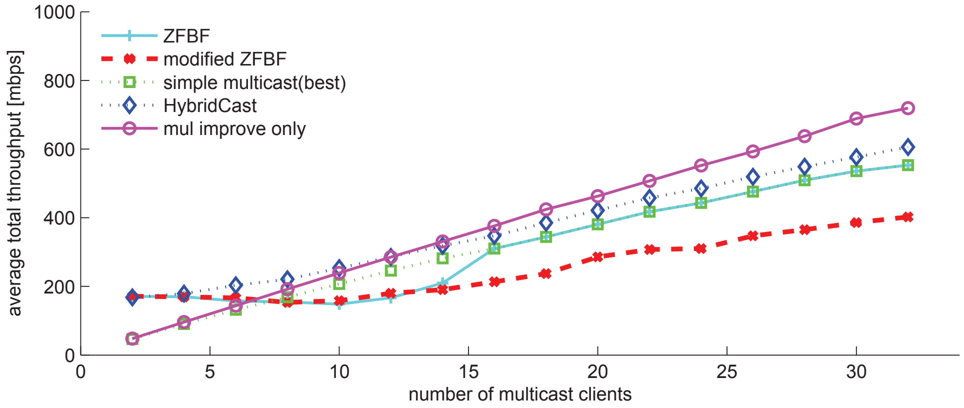
(b) Multicast using best rate

Figure 6.7: Simulation result with different number of antenna of BS

send the multicast session. The result shows that almost all schemes will increase the total throughput since the more available DoF allows them to send multiple streams. The total throughput of simple multicast remains constant because the multicast is sent with base rate and the number of multicast clients is fixing. This result demonstrates that HybridCast harness more throughput gain than other schemes since it fully utilize the DoF and link margin. In Fig. 6.7(b), we use best rate to send the multicast session. This result also shows that HybridCast achieves higher throughput gain than ZFBF and simple multicast scheme. Mul beamforming only scheme also harness more throughput gain than simple multicast since it utilizes link margin to improve multicast transmission. We also note that the ZFBF and modified ZFBF are worse than simple multicast. That is because when the number of multicast clients is too many, those two schemes can only transmit the multicast session. When number of antenna of BS increases, they have ability to send multiple concurrent streams. However, they only allow clients using single antenna to receive the signal. Compared with simple multicast, which utilizes receive diversity by MRC decoder, ZFBF and modified ZFBF has lower throughput gain.



(a) Multicast using base rate



(b) Multicast using best rate

Figure 6.8: Simulation result with different number of multicast clients

Number of multicast clients: We show the simulation results of average total throughput when the number of multicast clients increases in Fig. 6.8. There are total 8 unicast candidates and we fix the number of antenna of BS $M = 16$. In Fig. 6.8(a), we use base rate to send the multicast session. We find that the average total throughput will decrease when the number of multicast clients is less than 16. That is because when the number of multicast clients increase, BS must use more DoF to take care of those multicast clients and the number of concurrent streams will decrease. When the number of multicast clients is more than 16, the total throughput of all scheme increase since only the multicast session transmission remain and the number of multicast clients is increasing. In Fig. 6.8(b), we use best rate to send the multicast session. This simulation result shows that HybridCast and mul improve only scheme will achieve higher throughput than simple multicast and ZFBF scheme since those schemes can utilize link margin and DoF to send multiple streams or improve the multicast transmission. ZFBF and modified ZFBF scheme has lower throughput than simple multicast because those two schemes do not utilize receive diversity but simple multicast dose by using MRC decoder.

Chapter 7

Conclusion

We propose HybridCast, which enables concurrent multicast and unicast streams transmission. We fully utilize the DoF provided by the multiple antennas equipped on AP and clients by jointing multicast and unicast interference nulling alignment. We also use the available link margin to transmit the unicast streams concurrently without harming the multicast session transmission. Further, to harness more available link gain, we propose a simple multicast beaforming method to enlarge the link margin. In our real testbed experiment and large scale simulation, we demonstrate that HybridCast improve the throughput over simple multicast scheme or even ZFBF and modified ZFBF protocol.

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Bibliography

[1] E. Aryafar, N. Anand, T. Salonidis, and E. W. Knightly. Design and experimental evaluation of multi-user beamforming in wireless lans. MobiCom ’10, pages 197–208, New York, NY, USA, 2010. ACM.

[2] E. Aryafar, M. Khojastepour, K. Sundaresan, S. Rangarajan, and E. Knightly. Adam: An adaptive beamforming system for multicasting in wireless lans. In *Proceedings IEEE INFOCOM, 2012*, pages 1467–1475, March 2012.

[3] V. Cadambe and S. Jafar. Interference alignment and degrees of freedom of the k -user interference channel. *IEEE Transactions on Information Theory*, 54(8):3425–3441, Aug 2008.

[4] X. Chen, J.-N. Hwang, P.-H. Wu, H.-J. Su, and C.-N. Lee. Adaptive mode and modulation coding switching scheme in mimo multicasting system. In *2013 IEEE International Symposium on Circuits and Systems (ISCAS)*, pages 441–444, 2013.

[5] B. Du, Y. Jiang, X. Xu, and X. Dai. Transmit beamforming for mimo multicast channels. In *IEEE International Conference on Communications (ICC), 2012*, pages 3800–3805, 2012.

[6] D. Halperin, W. Hu, A. Sheth, and D. Wetherall. Predictable 802.11 packet delivery

from wireless channel measurements. SIGCOMM '10, pages 159–170, New York, NY, USA, 2010. ACM.

[7] R. Hunger, D. Schmidt, M. Joham, A. Schwing, and W. Utschick. Design of single-group multicasting-beamformers. In *IEEE International Conference on Communications, 2007. ICC '07.*, pages 2499–2505, 2007.

[8] S. Jafar and S. Shamai. Degrees of freedom region of the mimo x channel. *IEEE Transactions on Information Theory*, 54(1):151–170, Jan 2008.

[9] S. Kumar, D. Cifuentes, S. Gollakota, and D. Katabi. Bringing cross-layer mimo to today's wireless lans. SIGCOMM '13, pages 387–398, New York, NY, USA, 2013. ACM.

[10] H. Rahul, H. Hassanieh, and D. Katabi. Sourcesync: A distributed wireless architecture for exploiting sender diversity. SIGCOMM '10, pages 171–182, New York, NY, USA, 2010. ACM.

[11] H. S. Rahul, S. Kumar, and D. Katabi. Jmb: Scaling wireless capacity with user demands. SIGCOMM '12, pages 235–246, New York, NY, USA, 2012. ACM.

[12] W.-L. Shen, Y.-C. Tung, K.-C. Lee, K. C.-J. Lin, S. Gollakota, D. Katabi, and M.-S. Chen. Rate adaptation for 802.11 multiuser mimo networks. Mobicom '12, pages 29–40, New York, NY, USA, 2012. ACM.

[13] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong. Argos: Practical many-antenna base stations. Mobicom '12, pages 53–64, New York, NY, USA, 2012. ACM.

[14] N. Sidiropoulos, T. Davidson, and Z.-Q. Luo. Transmit beamforming for physical-layer multicasting. *IEEE Transactions on Signal Processing*, 54(6):2239–2251, 2006.

[15] K. Tan, J. Fang, Y. Zhang, S. Chen, L. Shi, J. Zhang, and Y. Zhang. Fine-grained channel access in wireless lan. SIGCOMM '10, pages 147–158, New York, NY, USA, 2010. ACM.

[16] K. Tan, H. Liu, J. Fang, W. Wang, J. Zhang, M. Chen, and G. M. Voelker. Sam: Enabling practical spatial multiple access in wireless lan. MobiCom '09, pages 49–60, New York, NY, USA, 2009. ACM.

[17] P. Viswanath and D. Tse. Sum capacity of the vector gaussian broadcast channel and uplink-downlink duality. *IEEE Transactions on Information Theory*, 49(8):1912–1921, Aug 2003.

[18] Q. Yang, X. Li, H. Yao, J. Fang, K. Tan, W. Hu, J. Zhang, and Y. Zhang. Bigstation: Enabling scalable real-time signal processingin large mu-mimo systems. SIGCOMM '13, pages 399–410, New York, NY, USA, 2013. ACM.

[19] T. Yoo and A. Goldsmith. On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming. *IEEE Journal on Selected Areas in Communications*, 24(3):528–541, March 2006.