Medium Access Protocol to Address Hidden Terminals in MU-MIMO WLANs

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***Abstract*—We exploit available Degrees of Freedom resulting from the deployment of mutiple antennas both at Access Points and Clients to address the Hidden Terminal problem in Multi User (MU) Multiple Input Multiple Output (MIMO) Wireless Local Area Networks (WLANs). This approach yields in concurrent transmissions in the Hidden Terminal scenario which is in contrast to the popularly used RTS/CTS solution. We treat concurrent transmissions as an integral part of our design and extend the traditional Point Coordination Function (PCF). Specifically, contention free period of the traditional PCF is used in uplink and downlink. A seamless channel sounding process obtains Channel State Information (CSI) at Access Points (APs) which becomes instrumental in determining the transmission opportunity based on Degrees of Freedom (DoF). The concurrent transmissions are maintained by precoding vectors calculated by Zeroforcing technique. Simulation shows that concurrent transmissions provide a remarkable network capacity gain of 4-5 times in comparison to traditional RTS/CTS scheme with only slightly higher signaling overhead. Besides, our simple fairness algorithm provides a fair share in the throughput among APs with the Jain Fairness Index greater than 90%.**

***Index Terms*—Hidden Terminals, Precoding Vector, Degrees of Freedom, Transmission Opportunity, Concurrent Transmissions.**

I. INTRODUCTION

While the IEEE802.11 Distributed Coordination Function (DCF) has become a de-facto mechanism to avoid collision of signals in Wireless Local Area Networks (WLANs), there exist inherent limitations as to how it treats interference at the receiver related to the carrier sensing at the transmitter. However, the fact is that successful transmissions mostly depend on the interference free condition at the receiver. Experimental works on CSMA/CA [1] show that the CSMA/CA mechanism degrades performance due to poor spatial reuse. Besides, it also fails to address the Hidden Terminal (HT) nodes [2] issue. While the RTS/CTS scheme proposed by Kran as a part of MACA in 1970s [3] has been very popular to address the HTs, experimental results show that RTS/CTS signicantly reduces the overall throughput [4].

HT nodes (that do not sense each other's transmission though they interfere with each other at the intended receiver causing decoding failure) are an inevitable phenomena in WLANs and their impact on network capacity cannot be overlooked. The study in [5] reveals that HTs lead to about 40-42 % of collision loss.

In early years, a receiver initiated busy tone scheme was proposed to solve the HT problem for Packet Radio Networks (PRN) [2]. However, the scheme required a dedicated channel for the busy tone which is not desirable in wireless networks.

A recent study proposed a lightweight wireless handshake [6] where the header of the payload and ACK are separated and designed to act like RTS/CTS. Nonetheless, packet decoding in dynamic channels is a fundamental question for that approach. An alternative technique like zigzag decoding [7] analyzes collisions of packets which shows a significant packet reduction loss from 72.06 % to about 0.7% in a testbed of 14 USPRs nodes. However, it needs to have a collision free chunk to bootstrap decoding in an irregular traffic pattern such as in WLAN scenarios.

Moreover, the use of multiple antennas both at Access Points (APs) and clients have turned many HT solutions inadequate as they fail to exploit the extra Degrees of Freedom (DoF) provided by an excess service antennas in today's Multi User Multiple Input Multiple Output (MU-MIMO) WLAN settings.

In this paper, we present a Wireless Access protocol to deal with the HT problem. Unlike, its precursors [2],[3],[6],[7] our design works on a dynamic MU-MIMO settings. Specifically, we exploit the extra DoF provided by multiple antennas and use Zeroforcing (ZF) precoding vectors to get rid of collision loss. Besides, the design maintains a constant capacity gain with respect to RTS/CTS by multiple simultaneous transmissions without interference to others. Furthermore, our design provides a fair share in terms of throughput among APs with Jain Fairness Index greater than 90%.

For instance, let's take the ith network, AP2, and the jth network, AP1, in Fig.1. Due to the nature of dynamic topologies, non-isotropic nature of the wireless transmission range, mix-mode 802.11b/g/n usages, dense deployments, decentralized control etc., they are both out of the carrier sensing range of each other but their transmissions overlap. As a result when APs transmit to their desired clients (AP2 to 'Frank' and AP1 to 'Bob'), the undesired clients ('Bob' for AP2 and 'Frank' for AP1) suffer collision of signals from their respective Hidden APs i.e., AP2 for 'Bob' and AP1 for 'Frank'. The green and the dotted red arrow indicate the desired and the undesired signals respectively. From high level view, our proposed design makes AP2 null its signal at 'Bob' while transmitting to 'Frank' so that AP1 can transmit to 'Bob'. Similarly, AP1 nulls its signal to 'Frank' while transmitting to 'Bob' so that AP2 can transmit to 'Frank' simultaneously. In this scenario, neither of APs have to listen and wait before transmission as in the case when using RTS/CTS nor do the receiver clients have to re-encode any former decoded chunks as in the Successive Interference Cancellation (SIC) scheme.

Notation:

The superscript $(.)^H$ denotes the Hermitian transpose whereas the operators $\mathrm{E}[.]$ and $\|.\|$ denote expectation and the Euclidean norm respectively. The matrices, vectors and scalars are defined, as they are used.

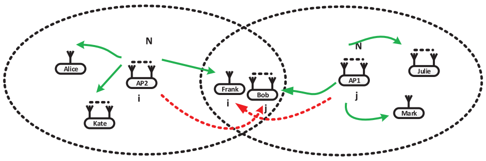

Fig. 1. Hidden Terminals.

II. SYSTEM MODEL

We present our system model for K APs. The number of antenna at APs and the client are considered to be N and M respectively. Now, the received signal at a client in the overlapping (HT) region is given by

$$\mathbf{y} = \sum\nolimits_{i=1}^{K} \mathbf{h}_{ij}^{H} \mathbf{x}_i + \mathbf{w} \tag{1}$$

where the received signal is $\mathbf{y} \in \mathbb{C}^{M\times 1}$, $\mathbf{h}_{ij}$ is the channel associated with the ith AP to the jth Client, $\mathbf{h}_{ij} \in \mathbb{C}^{N\times M}$ and transmitted signal $\mathbf{x}_i \in \mathbb{C}^{N\times 1}$. The noise term is represented by $\mathbf{w} \in \mathbb{C}^{M\times 1}$ which is circularly symmetric additive white Gaussian noise with zero mean and σ^2 variance. All APs satisfy the transmit power constraint P, i.e., $E\left\|\mathbf{x}_i^2\right\| < P, \; for\, i = 1.....K$. The concatenation of channels at the jth client is given by

$$\mathbf{H} = \left[\mathbf{h}_{1j}^{H}, \mathbf{h}_{2j}^{H}, ...\mathbf{h}_{jj}^{H}, ...\mathbf{h}_{K-1j}^{H}, \mathbf{h}_{Kj}^{H}\right] \tag{2}$$

where $\mathbf{H}$ is a $[M \times KN]$ matrix with the jth row equal to the channel of the K APs to the jth antenna elements of the jth client with M antennas.

III. THE PHYSICAL LAYER

The physical layer of our protocol exploits DoF (provided by MIMO) and maintains multiple concurrent transmissions in a network. Traditional protocols in WLANs work on time division basis and are unable to do so.

Fig.1 where two APs, AP1 and AP2 (i.e., K=2), and the jth reference client 'Bob' are taken into consideration, the nulling of signal by AP2 is assisted by the precoding vector. As a matter of fact, the calculation of the precoding vector at AP2 is vital as it not only removes interferences to undesired clients but also maintains concurrent transmissions among the desired clients.

A. Precoding Vector

The precoding vectors at APs are such that they maximize the desired transmissions, while nulling interferences at the undesired clients. The choice for the best ZF beamforing vector for any ith AP2 is given by solving the following optimization problem for $i \in \{1, ...K\}$

$$\begin{aligned} \max_{\mathbf{v}_i} \log\left(1 + \frac{\left\|\mathbf{h}_{ii}^{H}\mathbf{v}_i\right\|^2}{\sigma_i^2}\right) & \\ s.t \left\|\mathbf{h}_{ij}^{H}\mathbf{v}_i\right\|^2 &= 0 \,\forall j \neq i \\ \left\|\mathbf{v}_i\right\|^2 &\leqslant P_i \end{aligned} \tag{3}$$

where $\left\|\mathbf{h}_{ij}^{H}\mathbf{v}_i\right\|^2 = 0$ is the ZF leakage constraint of the ith AP2 to the j clients. The optimization problem has the non-trivial solution given by $\mathbf{v}_i^{ZF} = c\prod_{[h_{i1},.......h_{ii-1},h_{ii+1}.......h_{iK}]}^{\perp} \mathbf{h}_{ii}$, where c is the scalar satisfying the transmit power constraint. The necessary condition for the non-trivial solution is $N{>}M$. Specifically, the precoding vector for AP2, $\mathbf{v}_i \in \mathbb{C}^{N\times 1}$, is given by

$$\mathbf{v}_i = \left(\frac{\prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii}}{\left\|\prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii}\right\|}\mathbf{D}\right) \tag{4}$$

where $\prod_{\mathbf{h}_{ij}}^{\perp} = \mathbf{I} {-} \mathbf{h}_{ij}({\mathbf{h}_{ij}}^H\mathbf{h}_{ij})^{-1}{\mathbf{h}_{ij}}^H$ denotes the projection onto the orthogonal complement of the column space of $\mathbf{h}_{ij}$. $\mathbf{I}_N$ represents the identity matrix of size N(the subscript is omitted when unnecessary). $\mathbf{D} \in \mathbb{C}^{M\times 1}$ is a unit vector acting as a demultiplexer where $\mathbf{D}^H\mathbf{D} = 1$.

In a general network scenario, where there can be mismatch among the desired and undesired clients, there is a need to make a concurrent transmissions without interfering with each other. In such a context, the expression for the precoding vector in (4) still remains valid, except that we deal with $N \times PM$ channel realizations for P undesired (i.e., $\mathbf{h}_{ij}$) clients and $N \times QM$ channel realizations for Q desired clients (i.e., $\mathbf{h}_{ii}$). The condition $N > PM$ has to be satisfied in order to take the left inverse. From the standpoint of the jth client 'Bob', the received signal is given by

$$\underbrace{\mathbf{y}_j}_{\text{received signal}} = \underbrace{\mathbf{h}_{jj}^{H}\mathbf{v}_j s_j}_{\text{desired signal}} + \underbrace{\sum_{i=1,i\neq j}^{K-1} \mathbf{h}_{ij}^{H}\mathbf{v}_i s_i}_{\text{interferences}} + \underbrace{\mathbf{w}_j}_{\text{noise}}. \tag{5}$$

IV. MEDIUM ACCESS CONTROL

The challenge of MAC design is three folds. First, the CSI associated with APs and clients should be acquired and the procoding vector (steering vector) for concurrent transmission should be obtained. Second, the signalling overhead (i.e., handshaking process) for completing the first process should be as minimal as possible for capacity increment of the network. Third, the fairness in transmission should be maintained among APs with heterogeneous antennas. Other important aspect is to move the complexity of signal processing to APs.

1) Acquiring CSI associated with transmitter and clients: The channel sounding is initiated by those APs, who have packets in queue for transmission. Since APs need to find the channels associated with Q desired and P undesired clients, they first broadcast an announcement frame so that clients within APs' transmission range can report their channels to APs. The frame formats used in channel sounding are shown in Fig.2. The Null Data Packet (NDP) announcement control frames, each having 25 bytes in length, are transmitted by APs. APs assign an Association Identifications (AIDs) to the Q clients upon association which are included inside the 12 Least Significant Bits (LSB) of Station Information (STA info) . The second step is to send the training symbols by APs for channel measurement. This is done by the NDP frames which have the same format as Very High Throughput (VHT) PPDUs without a data field. Each client analyzes the training symbols in the PLCP header (of the NDP) and measures the channel between APs and themselves. It is obvious that clients within the overlapping region would hear multiple NDP announcements. Each client responds to the channel request on First In First Out (FIFO) basis in the uplink. Owing to the limited feedback channel, the channels (in the form of the matrices) are compressed as VHT Compressed Beamforming frames and only clients having AIDs with APs will respond. The remaining clients wait to be polled by APs. Fourth, APs sent a 12 byte long Beamforming Report Poll frame after SIFS to poll and retrieve the additional channel matrices from the subsequent clients within the range. Hence, by the end of the channel sounding all APs in the network get access to the channels from the desired and the undesired clients within the range. Fig.2 shows the basic diagram of the frame formats and the channel measurement process for APs in the typical ith network, AP2 and two clients, each from the ith and jth networks.

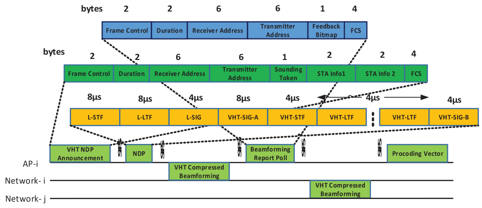

Fig. 2. Frames formats suited for our protocol for channel measurement.

2) Transmission opportunity for APs with heterogeneous antennas: All APs in the network have to calculate their corresponding precoding vectors for concurrent transmissions. Thus, APs go for Channel Sounding and acquire CSI from Q desired (i.e., $\mathbf{h}_{ii_d}$) and P undesired (i.e., $\mathbf{h}_{ij_u}$) clients in their transmission range, where $\underset{i_d \neq j_u}{i_d} \in \{1......QM\}$ and $\underset{j_u \neq i_d}{j_u} \in \{1......PM\}$. Since ZF precoding is used to address the HT problem, APs make decision for transmission opportunity (TXOP) (i.e., choose to remain in the 'Active' or the 'Silent' Mode) if $i \geqslant j_u$ for the ith reference AP where $i \in \{1.....N\}$. Otherwise, APs end up with causing interference to other clients. Suppose that we have 3 APs in a network having N_1, N_2 and N_3 antennas respectively. Each of these APs has I_1, I_2, I_3 undesired clients in the overlapping region. The 3 APs satisfying $N_1 > I_2 + I_3$, $N_2 > I_1 + I_3$ and $N_3 > I_1 + I_2$ will have TXOP and will remain in the 'Active' mode, otherwise, APs will not have TXOP and remain in the 'Silent' mode at that instant. Thus, the TXOP among APs are decided on the available DoF for a particular AP at the particular time.

3) Fairness Algorithm: It appears that, the criteria for TXOP according to the available DoF, favors APs with a larger number of antennas resulting in a deep unfairness among APs having a fewer numbers of antennas. In order to ensure fairness in terms of throughput among APs with heterogeneous antennas, we present a simple fairness algorithm that runs at APs in MU-MIMO WLANs. We describe the algorithm as follows. We assign APs with two types of credit counters (i.e.'S_Counter' and 'F_Counter', initialize to 0) and a credit threshold (i.e.'C_threshold', set to a constant value). Each time when APs get the TXOP, the 'S_counter' will be incremented otherwise the 'F_Counter' will be increased. If the 'F_Counter' crosses the 'C_threshold', the corresponding AP directly qualifies for TXOP. The basic pseudocode is given below.

Algorithm 1 Fairness

```
procedure FAIRNESS
initialization  S_counter=0; F_counter=0; C_threshold.
    if $i \geqslant j_u$ then
        $S\_counter \leftarrow S\_counter + 1$.
        if $S\_counter == 2 * C\_threshold$ then
            Reset S_counter to 0.
    else
        $F\_counter \leftarrow F\_counter + 1$.
        if $F\_counter == 2 * C\_threshold$ then
            Reset F_counter to 0.
    if $S\_counter \leqslant C\_threshold$ then
        Wins TXOP 'Active' Mode.
    else
        'Silent' Mode.
    if $F\_counter \leqslant C\_threshold$ then
        ('Silent' Mode).
    else
        'Active' Mode.
```

4) Fairness Index of the Algorithm: We evaluate the Fairness Index of our fairness algorithm according to the Jain Fairness Index [8] which fundamentally studies the quantitative measure to any resource sharing or allocation problem. We consider 3 APs with 2, 3 and 4 antennas among which the fairness in the throughput is studied. We assume each AP after winning TXOP, at least have one stream for transmission and at most have transmission streams equal to the number of antennas at the AP. For instance, a three antennas AP has at least one transmission stream and at most have three transmission streams after TXOP.

Let R_i be the ith AP that has TXOP and n be the number of such APs, thus, the Jain Fairness Index is given by

$$f\left(R\right) = \frac{\left|\sum_{i=1}^{n} R_i\right|^2}{\sum_{i=1}^{n} R_i^2},\ R_i \geq 0. \tag{6}$$

R_i is calculated as the ratio of the maximum throughput and the least expected throughput, i.e., for the AP with 3 antennas,

$$R_i = \frac{Throughput\ when\ three\ streams\ are\ used}{Throughput\ when\ single\ stream\ is\ used}. \tag{7}$$

Similarly, R_i can be calculated for the reminder APs. The Fairness Index for $n = 3$ (in our case), is calculated which is discussed further in $Section VI.C$.

5) Concurrency Algorithm: After winning the TXOP, APs in 'Active' mode need to decide which clients within the network are to be served concurrently. This is done by the concurrency algorithm which runs at APs. We discuss three popular approaches:First in First Out (FIFO), Brute Force and Best of the Two choices according to network capacity and fairness. For equal fairness, clients are served on the basis of FIFO packet queues, however, this approach is oblivious of the increment and the decrement of the network capacity. Brute force approach is the combinations of clients with queued packets which can maximize the throughput. However, it would undoubtedly end up with deep unfairness among clients who cannot maximize the throughput. Our choice is the remaining the Best of the Two choices where the first packet in the queue is always picked up to prevent starvation of clients and use a randomized design that exploits the Best of the Two choices, a standard approach for reducing the complexity of combinatorial problems [9]. This approach checks both fairness and throughput.

V. ACCESS TO THE MEDIUM

Since concurrent transmissions take place after the decision of TXOP, there is no contention among APs during concurrent transmissions. We exploit this fundamental attribute of the concurrent transmission and adopt and expand the IEEE802.11 Point Coordination Function (PCF) mode to address the concurrent transmissions.

A. Contention Free Period and Contention Period

Similar to the PCF in 802.11, we designate each APs in the network as point coordinators. We divide time into CFP and Contention Period (CP) as shown in Fig.3. The beginning of the CFP is marked by the transmission of beacon by APs. This sets the duration of the current CFP. During CFP, APs run the concurrency algorithms as described in $Section IV.4$ and selects clients for transmissions both at downlink and uplink. The CFP is followed by CP, during which any clients can contend for the medium using IEEE802.11 and point to point MIMO. The objective of the CFP is to manage the concurrent transmissions as much as possible so that the network throughput can be increased. The duration of CFP depends on the traffic congestion and may increase or decrease with the rise and fall of the traffic congestion. However, at CFP, APs at least serve one packet (on the downlink and uplink) to all clients that has pending traffic. In contrast, the duration of CP is constant. Similar to the IEEE802.11, we set the minimum length of the CP equivalent to the time required to transmit and acknowledge one maximum size frame. However, sometimes it is possible for the contention based service to run past the expected beginning of CFP which we call 'foreshortening' of CFP.

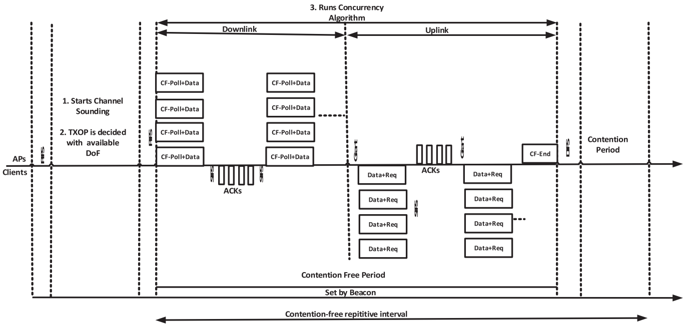

Fig. 3. Modified Point Coordination Function

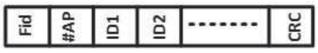

Fig. 4. Metadata structure

1) Medium Access to downlink: Fig.3 presents a series of events that takes place in this process. APs run the concurrency algorithm and select the group of clients for transmission at that instant. After that, APs transmit their downlink packets and poll clients for uplink data with the help of CF-Poll+Data frame. This process is similar to the existing PCF except that the current PCF polls the individual clients one by one whereas, with our MAC, APs poll a group of clients for uplink traffic which are selected by the concurrency algorithm.

The CF-Poll+Data frame contains two parts. The first part of the frame is shown in Fig.4 which contains IDs of clients that are selected as the result of the concurrency algorithm. The IDs are given to clients upon association. It also contains the frame ID, Fid, the address of APs and the checksum of their broadcast. APs and clients use this checksum to test whether or not the received data is correct. The second part of the frame is the list of concurrent downlink data of APs to clients. For instance, a downlink transmission of the AP with 4 antennas is given in Fig.3. Upon reception of data at clients in downlink, clients send the Acknowledgments (ACKs) to AP. The order in which they send these ACKs is the same order as the IDs in Data+Poll frame. Basically, clients send ACKs using the traditional MIMO. Thus, each received data frame at clients is acknowledged.

2) Medium Access to uplink: The uplink data transmission at CFP is initiated by the grant frame broadcast by AP. The grant frame consists of the IDs of clients which are determined by the concurrency algorithm that runs at APs. Clients in the uplink transmit Data+Req frame. This frame contains the uplink data and if there are more data in clients to send, it also contains a request frame. The request frame is for transmission of the new frame in the uplink. Upon reception of the Data+Req frame, AP decodes them by the standard decoding method. AP confirms the received data by the broadcast of the ACK frame within its transmission range. Clients in the transmission range receive the ACK frames. However, clients who are not selected for the uplink transmission discard the ACKs. Thus, clients are acknowledged for the successful reception of data in the uplink transmission. The end of the CFP is marked by the CF-End frame broadcast by APs. This frame indicates to clients the end of the CFP. This frame prepares APs and clients to go back to the contention mode.

3) When to initiate modified PCF?: Traditionally the HTs are managed by the RTS/CTS mechanism. Basically, the RTS threshold, set between the range of 0-2347, determines whether APs should use CSMA/CA or RTS/CTS mechanism to send the payload.

In contrast to this traditional scheme, we set the retransmission threshold at APs as $Re\_Threshold$. Generally, when the transmitted data are not acknowledged at APs either due to data or ACKs loss, APs retransmit the data and retry up to a certain count, Re_count. We compare Re_count and $Re\_Threshold$ and if $Re\_count > Re\_Threshold$, the modified PCF is initiated. This is because the presence of the HT scenario causes collisions of signals and there is a high possibility of occurrence of retransmissions. In such a context, our proposed modified PCF comes into play to address the HT scenario.

VI. PERFORMANCE EVALUATION

A. *Feasibility from PHY*

We check the feasibility of the solution of our PHY in a hardware platform made of Universal Software Radio Peripheral2 (USRP2) [10] with RFX2400 daughter-boards. The detailed description of our PHY solution is presented in [11]. Thus, we only present the main result of it.[1] The experimental result in Fig.5 showed that there is an average of about 5-6 dB gain in SNR per subcarrier due to our PHY solution. Besides, the collision free transmission is also shown which is the upper bound that our PHY solution is supposed to achieve. Despite imperfections in nulling caused by hardware offsets and other implementation limitations, the SNR gain of our PHY solution still possesses an acceptable performance of about 6 dB on average. Clearly, the gain in SNR is about 10 dB in comparison to transmission in the HT scenario.

B. *Signaling overhead and Capacity gain of MAC*

As shown in Fig.2, the payload is not transmitted until we get all the channels and calculate the precoding vectors for APs. This period is defined as the signaling period. In a typical HT scenario for 2 networks, we calculate the network capacity gain and the signaling overheads associated with different frames as shown in Fig.2. Since a PLCP preamble and a PLCP header are added to an MPDU to create a PLCP Protocol Data unit (PPDU), the transmission duration of the NDP announcement frame is given by $T_{NDP_{ann}} = PLCP\,frame + \left[\frac{25}{BpS(m)}\right].tSymbol = 40 + \left[\frac{25}{3}\right].4\mu s = 73.33\mu s$. The PLCP frame is the compatible frame with legacy standards and is defined in IEEE802.11ac standard, whereas $tSymbol = 4\mu s$ is the OFDM symbol interval. The type of modulation used is BPSK with data rate 6 Mbps and code rate $\frac{1}{2}$. The VHT NDP frame has the same format as the VHT PPDU except the data field, so the transmission duration $T_{NDP} = (8 \times 5) = 40\mu s$. Likewise, the time duration of Beamforming Report Poll is $T_{BR_{Poll}} = 40 + \left[\frac{20}{3}\right].4\mu s = 66.67\mu s$. We calculate the time duration of VHT compressed beamformimg assuming payload length $l = 200$octets, $T_{CB_{\text{Report}}=}40 + \left[\frac{5+l}{3}\right].4\mu s = 313.33\mu s$. Thus, for typical two network, $K = 2$, the signaling overhead is given by $T_{OH} = T_{NDP_{ann}} + T_{NDP} + 2 \times T_{CB_{\text{Report}}=} + T_{BR_{Poll}} + 5 \times SIFS = 886.66\mu s$, where $tSIFS = 16\mu s$. The traditional signaling overhead for RTS/CTS scheme is given by $T_{RTS/CTS} = T_{DIFS} + T_{RTS} + T_{CTS} + 2 \times SIFS = (34 + 50.33 + 42.33 + 2 \times 16) = 158.7\mu s$.

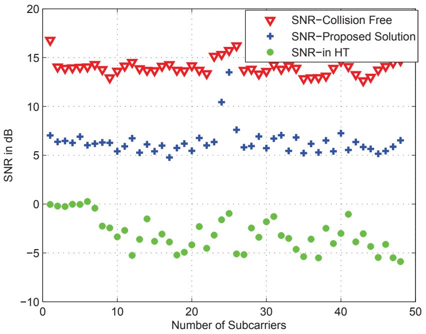

Fig. 5. SNR per subcarrier comparison with collision free transmission, our PHY scheme and in the HT condition.

Simulations are carried out based on the calculation above for a typical scenario with the ith network AP2 $N = 6$ in presence of the jth network clients $I = 2$ in transmission range. Thus, there are 4 clients inside the network to be served concurrently. We take an arbitrary air time $t = 20ms$ and compare the capacity gain for our MAC and RTS/CTS at 5, 15 and 25 dB respectively. Our simulation results in Fig.6 reveal that RTS/CTS scheme has an early gain in capacity at around $157.8\mu s$ whereas our MAC protocol does not gain in capacity until $886.66\mu s$. This is an expected behavior as our MAC protocol has higher signaling overhead than the RTS/CTS scheme. However, interestingly, we observe that our MAC protocol has about 4-5 times capacity gain compared to RTS/CTS scheme. The gain in capacity comes from the concurrent transmissions (made possible by precoding vector) that takes place once the handshaking process is completed.

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[1] The standard GNURadio libraries were used and the experiment was carried out in the indoor environment with operating frequency of 2.45GHz, FFT length 64 and occupied subcarriers 48.

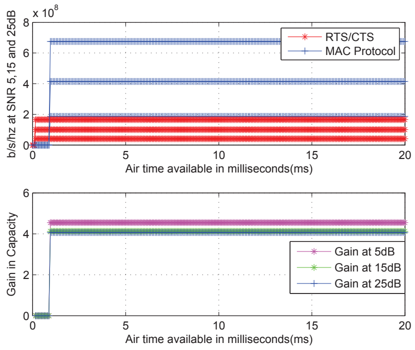

Fig. 6. Capacity comparison between RTS/CTS and our MAC protocol, air-time 20ms.

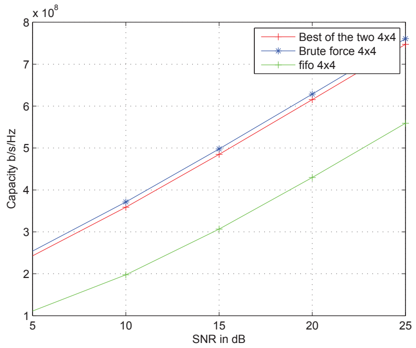

Fig. 8. Throughput comparison among FIFO, Brute Force and Best of the Two approach.

C. Computation of Fairness Index

We discuss the Fairness Index of our fairness algorithm considering three APs i.e., $n = 3$ with the number of antennas 2, 3 and 4 respectively. Fig.7 shows the system throughput with the credit counters where 'C_threshold' is arbitrarily taken 6. Also, we show the maximum and minimum streams based throughput of APs when the credit counter gradually increases to 'C_threshold'. Besides, we calculate the Jain Fairness Index according to (6) for three APs and present the Jain Fairness Index with the credit counters. It is shown that our fairness algorithm has Fairness Index greater than 0.9. Thus the use of our fairness algorithm provides more than 90% fair share among three APs in terms of throughput.

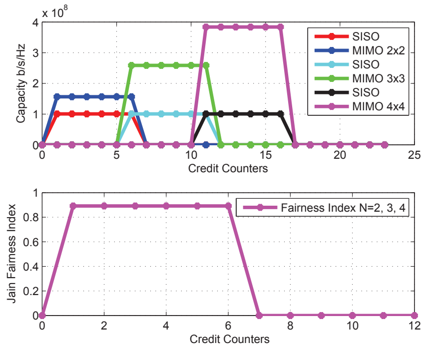

Fig. 7. Throughput of three APs with the fairness algorithm.

D. Performance of the concurrency algorithm

We check the throughput of the AP which has $N - I = 6 - 2 = 4$ concurrent transmissions to maintain, against three approaches discussed in $SectionIV, 5$. The simulation study shows that out of the three, Brute Force has higher throughput followed by the Best of the Two choices and FIFO. Empirically, fairness index among clients is in the reverse order to the network capacity of the algorithm.

VII. CONCLUSION

This paper presents a Wireless Access Protocol to solve the Hidden Terminal problem in MU-MIMO WLANs. With a modified Point Coordination Function, concurrent transmissions are managed which contributes to a network capacity gain despite some signaling overhead. The ZF precoding solution at the PHY layer is seen effective to deal with the HT problem as we can see the increment in the received SNR from 5 to 11 dB in our USRP2/GNURadio prototype testbed. In addition, our MAC layer simulation studies show a network capacity gain of 4-5 times, compared to RTS/CTS. Additionally, a simple fairness algorithm in terms of throughput among APs is presented which possesses the Jain Fairness Index greater than 90%.

REFERENCES

[1] X. Yang and N. Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, vol. 4, March 2005, pp. 2525–2535 vol. 4.

[2] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: part ii–the hidden terminal problem in carrier sense multiple-access and the busy-tone solution," *Communications, IEEE Transactions on*, vol. 23, no. 12, pp. 1417–1433, 1975.

[3] P. Karn, "Maca-a new channel access method for packet radio," in *ARRL/CRRL Amateur radio 9th computer networking conference*, vol. 140, 1990, pp. 134–140.

[4] P. C. Ng, S. C. Liew, K. C. Sha, and W. T. To, "Experimental study of hidden node problem in ieee 802.11 wireless networks," *Sigcomm Poster*, p. 26, 2005.

[5] A. Sheth, C. Doerr, D. Grunwald, R. Han, and D. Sicker, "Mojo: A distributed physical layer anomaly detection system for 802.11 wlans," in *In Proceedings of MobiSys*. ACM Press, 2006, pp. 191–204.

[6] K. Lin, Y.-J. Chuang, and D. Katabi, "A light-weight wireless handshake," *ACM SIGCOMM Computer Communication Review*, vol. 42, no. 2, pp. 28–34, 2012.

[7] S. Gollakota and D. Katabi, *Zigzag decoding: combating hidden terminals in wireless networks*. ACM, 2008, vol. 38, no. 4.

[8] R. Jain, D.-M. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," 1998.

[9] M. Mitzenmacher, "The power of two choices in randomized load balancing," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 12, no. 10, pp. 1094–1104, 2001.

[10] [Online]. Available: http://www.ettus.com/

[11] S. Shrestha, G. Fang, E. Dutkiewicz, and X. Huang, "Addressing hidden terminals in wlans with zero forcing coordinated beamforming," in *Proceedings of 14 th International Symposium on Communication and Information Technologies*, 2014.