Addressing Hidden Terminals in WLANs with Zero Forcing Coordinated Beamforming

Sanjeeb Shrestha*, Gengfa Fang*, Eryk Dutkiewicz* and Xiaojing Huang†
*Department of Engineering, Macquarie University
Sydney, Australia
†CSIRO, Australia
Email: sanjeeb.shrestha@mq.edu.au

Abstract—**We present here a new technique that can be used to address a well-known Hidden Terminal problem in Wireless Local Area Networks. Specifically, Zero Forcing Coordinated Beamforming can be applied, in a hidden terminal scenario, in order to null the signal of the interfering transmitter so that desired transmission can take place without collision at the receiver. Basically, a precoding range of a receiver is used as a determinant in order to take a nulling decisions based on the notion that a successful transmission depends on the interference free condition at the receiver. We demonstrate the feasibility of the approach in an USRP2/GNURadio test-bed prototype. Our scheme improves the SNR and Effective SNR from about 5 to 11 dB in a hidden terminal scenario and maintains collision free simultaneous transmissions.**

Keywords-Hidden Terminals, Precoding Vector, Precoding Range, Nulling.

I. Introduction

Unlicensed spectrum backed with inexpensive access points and easy deployment have made wireless networks under the IEEE802.11standard almost ubiquitous (e.g. in home, workplace, college campuses, parks etc). This trend is to continue in years to come [1] due to the enterprise dependency on Wireless Local Area Networks (WLANs) for mission critical networks, the growing use of multimedia services with heterogeneous hardware such as iphones, ipads, tablets etc and the Bring Your Own Device (BYOD) trend. As a result, WLANs have become dynamic in topologies, complex in irregular traffic pattern and challenging from the architectural view point. In this context, collisions of frames are inevitable. Cheng et. al showed that transmission loss due to interference among 50 % of sender receiver pairs suffers 2.5 % probability of transmission loss [2]. While IEEE802.11 CSMA/CA with RTC/CTS has become a de-facto mechanism to avoid collisions, 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. Theoretical and experimental works on CSMA/CA [3][4] showed that CSMA/CA mechanism degrades performance due to poor spatial reuse and also fails to address the Hidden Terminal (HT) [5] and the capture effect [6] issues. However, HT nodes (that do not sense each others transmission though they interfere with each other at the intended receiver causing decoding failure) is an inevitable phenomena in WLANs 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. Additionally, the impact of HTs is significant. The study in [7] reveals that HTs lead to about 40-42 % of collision loss. This loss seems severe and alarming from the viewpoint of the maximum retransmission attempts, resulting in resource overutilization without increase in throughput.

In early years, a receiver initiated busy tone scheme was proposed to solve the HT problem for Packet Radio Networks (PRN) which was found to be effective in eliminating collisions caused by HTs [5]. However, the scheme required a dedicated channel for the busy tone which is not desirable in wireless networks. Later, Karn proposed the RTS/CTS mechanism as a part of MACA [8] to address the HT problem, however, experimental results show that RTS/CTS significantly reduces the overall throughput [9] and is disabled by Access Point (AP) manufactures by default. The handshaking process in RTS/CTS mechanism consumes a lot of of air-time and could be prohibitively expensive when the medium available for transmission is short. This gave rise to the discussion about turning on RTS/CTS only when the potential gain would outweigh the associated overhead for a scenario, adding to further computational complexity. A recent study proposed a lightweight wireless handshake [10] where the header of the payload and ACK are separated and designed to act like RTS/CTS. However, packet decoding in dynamic channels is a fundamental question for that approach. Addressing the HT in WLANs using CDMA is not viable as it requires tight power control and special codes [11] and at high SNRs the performance is degraded. An alternative technique like zigzag decoding [12] analyzes collisions of packets with strategically selected collision patterns, showing a significant packet reduction loss from 72.06 % to about 0.7%. However, it needs to have a collision free chunk to bootstrap decoding in an irregular traffic pattern such as in WLAN scenarios. Besides, the scheme works only for certain type of collision patterns, thus it is practically limited.

We present here a novel approach to deal with the HT problem. Unlike its precursors [5][8][10][12], our scheme utilizes precoding vectors with zero-forcing in order to get rid of collisions loss in the HT scenario.

For instance, lets take an example of Alice and Bob under

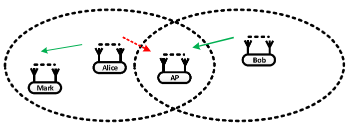

Fig. 1. Hidden Terminal

HT scenario in Fig.1, who are both out of the carrier sensing range of each other and who transmit at the same time to their respective APs. Bob transmits to the AP whereas Alice transmits to Mark. Since, Alice and Bob cannot sense each other they suffer collision at the AP. The green and the dotted red arrow indicate the desired and the interference signal respectively.

From high level view, our proposed scheme makes Alice null her signal at the AP while transmitting to Mark so that Bob can transmit his signal to the AP. Specifically, we use the precoding vector to null the signal of Alice to AP while she is transmitting to Mark so that Bob can have collision free transmission to the AP at the same time. In this scenario neither of the HT nodes have to listen and wait before transmission as in the case when using RTS/CTS nor the receiver does have to re-encode any former decoded chunk as in the Successive Interference Cancellation (SIC) scheme.

The rest of the paper is arranged as follows: Section II presents the System model whereas Section III illustrates our scheme in the HT scenario. Section IV describes our experimental set up and Section V presents the performance evaluation of our scheme. In Section VI conclusion is presented. Notation:The superscript $(.)^H$ denotes the Hermitian transpose of the matrix whereas the operators $\mathrm{E}[.]$ and $\|.\|$ denote expectation and the Euclidean norm respectively. The matrix, vectors and scalar are defined next, as they are used.

II. SYSTEM MODEL

In this section, we present our system model for the HT problem. We consider a HT scenario where K HT transmitter-receiver pairs who are out of carrier sensing range of each other are transmitting simultaneously. Clearly at one of the jth receivers, we have collision of signals that are coming from K HT nodes. For simplicity and ease of discussion we take the jth HT-AP pair as a reference as shown in Fig.2. We consider N transmitting antennas at the transmitter and M receiving antennas at the AP.

We illustrate the concept of the collision of a signal in Fig.2 for K HT nodes transmitting at the same time. Without loss of generality, the received signal at the jth AP is now 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 transmitter to the jth receiver, $\mathbf{h}_{ij} \in \mathbb{C}^{N\times M}$ 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 the HT nodes satisfy a transmit power constraint of P, i.e.,

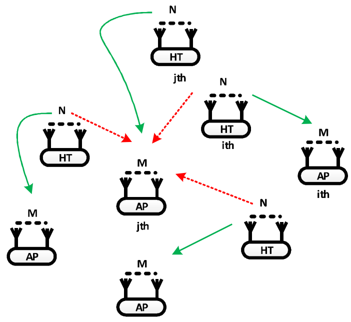

Fig. 2. K Hidden Terminal nodes colliding at jth (AP)

$E\left[\|\mathbf{x}\|^2\right] \leq P$. The concatenation of channels at the jth AP 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 ith row equal to the channel of the ith HT node to the jth AP with M numbers antennas.

III. THE SCHEME

In this section we describe our scheme in reference to the jth transmit-receive pair. Specifically, the precoding vector $\mathbf{v}_j \in \mathbb{C}^{N\times 1}$ obtained by applying Zero Forcing Coordinated Beamforming (ZFCB) is multiplied with the transmitting symbols of the jth HT nodes.Thus, the transmitted signal is given by $\mathbf{x}_j = \mathbf{v}_j s_j$.

Similarly, all the $K-1$ HT nodes will have a precoding vector given by ZFCB which nulls the interfering signals at the jth AP, leaving behind only the desired signal. While nulling the signal at the jth AP, the AP leverages its precoding range which will be discussed further.

We define a precoding range of the jth AP because the jth AP sends the Channel State Information (CSI) which is necessary for ZFCB and apparently for precoding vectors. Based on this information, interferences nulling from all $K-1$ HTs are possible because for ZFCB, each K HT nodes require to know only its own channels $\mathbf{h}_{i1}, ..., \mathbf{h}_{iK}$ to compute the beamforming vectors [13]. Thus, the interfering links $\mathbf{h}_{ij}$ are sent by the jth AP within precodng range by the channel estimation process described in Section IV.B.

Basically, we take precoding range as a determinant for making nulling decisions. Based on this, three scenarios can be studied in consideration with the jth AP. Case I: HT nodes are inside and outside precoding range of the jth AP as in Fig.3. Case II: All HT nodes are inside precoding range of the jth AP as in Fig.4. Case III: All HT nodes outside the precoding range of the jth AP.

In Case I, HT nodes inside the precoding range would null the signal to the jth AP and HT node outside the precoding range would transmit to the jth AP. The received signal at the jth AP is given by

$$\underbrace{\mathbf{y}_j}_{\text{received signal}} = \underbrace{\mathbf{h}_{jj}^{H}\mathbf{v}_j^{o}s_j}_{\text{desired signal}} + \sum_{i\neq j}^{K-1} \underbrace{\mathbf{h}_{ij}^{H}\mathbf{v}_i s_i}_{\text{interferences}} + \underbrace{\mathbf{w}_j}_{\text{noise}}. \tag{3}$$

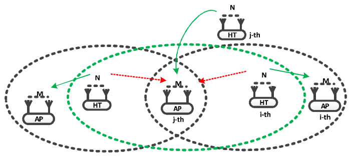

Fig. 3. Case I where HT nodes are inside and outside the precoding range of the jth AP

The precoding vector $\mathbf{v}_j^o$ in (3) simply contains unit vectors of size $N \times 1$ because the jth HT node is outside the precoding range of the jth AP. However, since all other $K-1$ HTs are inside the precoding range of the jth AP the corresponding ZFCB vectors $\mathbf{v}_i$ are associated with it. In order to get the desired signal at the jth AP, all the unwanted interferences i.e. $\mathbf{h}_{ij}^H \mathbf{v}_i s_i$, for all $i \neq j$ should be zero. For this to happen, each pair of the AP and the HT nodes should satisfy $M < N$. This provides the required degree of freedom in the signal space of the each HTs which can be used to project the signal orthogonal, i.e. $\mathbf{h}_{ij}^H \mathbf{v}_i = 0$ to the desired transmission of the jth AP. In this case, the choice of precoding vector $\mathbf{v}_i$ should be orthogonal to the interfering link at the jth AP, i.e.,$\mathbf{v}_i \perp \mathbf{h}_{ij}$. Now, precoding vectors for all $K-1$ HTs are given by the principle of ZFCB

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

where $\prod_{\mathbf{h}_{ij}}^{\perp} = \mathbf{I} - \mathbf{h}_{ij} (\mathbf{h}_{ij}{}^H \mathbf{h}_{ij})^{-1} \mathbf{h}_{ij}{}^H$ denotes 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). $\mathbf{U} \in \mathbb{C}^{M \times 1}$ is a unit vector acting as a demultiplexer where $\mathbf{U}^H \mathbf{U} = 1$.The choice of the precoding vector $\mathbf{v}_i$ for each $K-1$ HTs are such that it maximizes its own desired transmission, however nulls its interferences to the undesired jth AP.

For instance, let's take an example where the ith HT is in the proximity of the ith i.e., desired and the jth i.e. undesired AP, the choice of $\mathbf{v}_i$ will result in $\mathbf{h}_{ii}^H \mathbf{v}_i = \mathbf{h}_{ii}^H \left(\frac{\prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii}}{\left\| \prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii} \right\|} \mathbf{U} \right)$ and $\mathbf{h}_{ij}^H \mathbf{v}_i = \mathbf{h}_{ij}^H \left(\frac{\prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii}}{\left\| \prod_{\mathbf{h}_{ij}}^{\perp} \mathbf{h}_{ii} \right\|} \mathbf{U} \right)$ respectively.

The term $\mathbf{h}_{ij}^H \mathbf{v}_i$ is the interferences which need to be zero for the collision free transmission of the jth HT. With the precoding vector $\mathbf{v}_i$ at the ith HT node, the interferences at the jth AP become zero, because $\mathbf{h}_{ij}^H \mathbf{v}_i = 0$ for $i \neq j$. This applies to all the HTs inside the precoding range of the $j$the AP, resulting in collision free transmission to the jth HT-AP pair. The $\mathbf{h}_{ii}^H \mathbf{v}_i$ is the desired signal at the ith AP. The interference nulling, however, cost one degree of freedom to the ith HT.

For ease of discussion, we have taken only the jth HT outside the precoding range of the jth AP, though there can be many nodes outside. It is because, due to the neighboring nodes outside the precoding range of the jth AP, traditional carrier sense can manage to get only one jth node to transmit at a time.

Case II as shown in Fig.4, considers K HTs with N antennas inside the precoding range of the AP with M antennas. The basic idea for managing collision free transmission is identical as in Case I, i.e., ZFCB except the fact that the precoding vector is available at the desired HT i.e., jth HT which can transmit to the jth AP. Thus, the received signal at the jth AP is given by

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

In order to get the desired signals at the $j$the AP, we leverage the approach of ZFCB among the K HTs transmitting at the same time. Specifically, at each HTs, the interferences to the undesired receivers are eliminated by ZFCB. The choice for the best ZF beamforing vector for any transmitter j is given by sloving the following optimization problem for $j \in \{1, ...K\}$

$$\max_{\mathbf{v}_j} \log \left(1 + \frac{\left\| \mathbf{h}_{jj}^H \mathbf{v}_j \right\|^2}{\sigma_j^2} \right) \tag{6}$$

$$s.t \quad \left\| \mathbf{h}_{ji}^H \mathbf{v}_j \right\|^2 = 0 \, \forall i \neq j \tag{7}$$

$$\left\| \mathbf{v}_j \right\|^2 \leqslant P_j \tag{8}$$

The $\left\| \mathbf{h}_{ji}^H \mathbf{v}_j \right\|^2 = 0$ is the ZF leakage constraint of transmitter j to receiver i. The optimization problem has the non-trivial solution given by $\mathbf{v}_j^{ZF} = c \prod_{[h_{j1}, ...h_{jj-1}, h_{jj+1} ......h_{jK}]}^{\perp} \mathbf{h}_{jj}$, where c is the scalar satisfying the transmit power constraint.The necessary condition for the non-trivial solution is $N > M$.

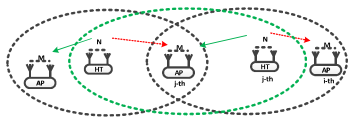

Fig. 4. Case II where all the HT nodes are inside the precoding range of the AP

Case III where all HT nodes are outside the precoding range of the AP, does not have any clear solution as there is no interaction from the AP to the HTs for channel feedback. This case can largely be avoided by proper power adjustments at the HTs and the APs when setting up the network.

IV. EXPERIMENTAL SETUP

A. The USRP2/GNURadio platform

We implemented our scheme on the hardware platform made of Universal Software Radio Peripheral2 (USRP2) [14], RFX2400 daughter-boards and Jackson labs equipments. The standard GNURadio libraries [15], C++ and python were used in the Ubuntu 11.04 environment as software. The experiment was carried out in the indoor environment with operating frequency of 2.45GHz, FFT length 64 and occupied subcarriers 48.

B. Implementations

We implemented Case I with four USRP2 nodes equipped with RFX2400 daughter-boards. Two USRP2 were configured to work as a single node consisting of two antennas, i.e Alice in our case and the rest were used as a single antenna node as the AP and Bob. An external clock was provided by Jackson labs equipment along with an external GPS antenna to fine tune the reference guide for the external clock. Care was taken to avoid the capture effect [6] among the terminals while setting up the HT scenario.

Our system requires a feedback mechanism in order to calculate the suitable precoding vector at the HT node. Before calculating the precoding vector we need to have the Channel State Information (CSI). We use Time Division Duplexing (TDD) and acheive the CSI as follows. First, the transmitter sends a packet with three known preambles. Second, the receiver receivers the packet and update the preambles to the host PC. Third, the host PC calculates the channel frequency response as shown in Fig.5 and feeds it back to the HT(In our prototype setting we used the University's DHCP server for feeback purpose). After getting the CSI at the HT, the HT calculates the precoding vector. The precoding vector is then multiplied with the transmitting symbols of the interfering HT which nulls its interference at the AP. Since interferences are removed at the AP, it receives the desired signal and logs the results to the host PC. The host PC with offline decoding using Matlab® extracts raw received signals.

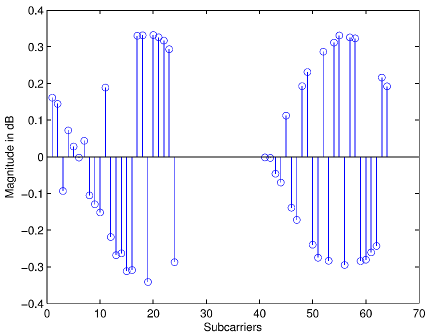

Fig. 5. Channel Frequency Response

C. Channel Feedback time

Timely channel feedback to the transmitter is vital as stale channel state information would degrade the performance in terms of interference management. Thus, we first measured the feedback delay time (T_f) of our test-bed environment (which was found to be 4.871ms) and then compared it with the standard Coherence Time (CT), 21.2ms, measured by MacLeod et al in [16] for ISM wireless indoor environments. The T_f is about five times less than the standard CT, which ensures that the precodng vector is up to date with respect to the change in channel conditions. The comparison of (T_f) and the standard CT is made because the measurement of the standard CT and our experimental environment are similar.

V. PERFORMANCE EVALUATION

A. Analysis from raw received signal

In the HT condition, the collision of the signals is shown in Fig.6 where the AP is totally flooded with the signals from Alice and Bob. The observed y-axis shows a real part of the signal. The signal lie within the range of -0.2 to +0.2 however with some irregularities and spikes, which may have come form the collided signals adding up constructively and destructively at the AP. After applying our scheme the raw received signals obtained at the AP is shown in Fig.7.

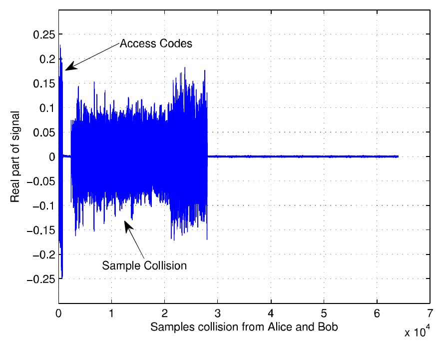

Fig. 6. Decoded raw samples form Alice and Bob in HT

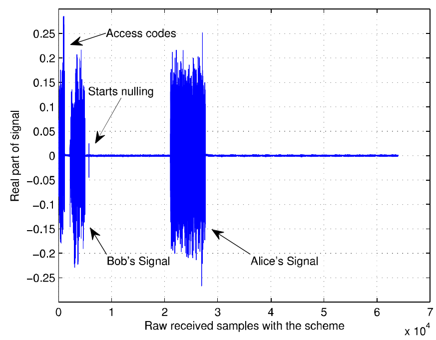

Fig. 7. Raw received signal after implementing the scheme

From Fig.7 the signal transmitted from Bob is clearly seen after implementing our scheme. This ensures error free reception of Bob's signal under the HT scenario. Besides we see the signal received from Alice as well. It is intentionally done so as to show that how Alice signal would look like if it was not nulled. It is the part of Alices signal where we purposely did not apply our scheme.

B. The impact on SNR

Comparing the SNR-in-HT condition with those obtained by implementing our scheme, Fig.8 shows a significant gain in SNR after applying our scheme. This improvement in SNR comes from the successive transmission of Bob's signal to the AP due to effective signal nulling operation of Alice. The gain in SNR is remarkable, because in the HT condition, the signal transmission was marred by interferences. However, implementing our scheme mitigated the interferences yielding a significant SNR gain.

C. Comparative study with collision free transmission

As seen in Fig.8, there is in average of about 4-5 dB difference in SNR per subcarrier between collision free transmission and with our scheme. The SNR gain in a collision free

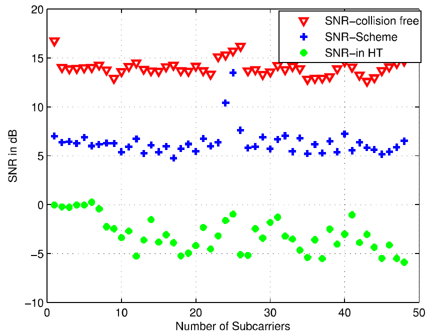

Fig. 8. SNR per subcarrier comparison with collision free Bob's transmission, our scheme and in HT condition

transmission is the upper bound that our scheme is supposed to achieve. Despite imperfections in nulling to the Alice's signal caused by hardware offsets and other implementation limitations, the SNR gain of our scheme still possesses an acceptable performance of about 6 dB on an average. Clearly, the gain is about 10dB in comparison to transmission in the HT scenario.

D. Analysis from Effective SNR (ESNR)

For multicarrier system like OFDM, subcarriers may undergo different levels of fading and these channel qualities cannot simply be represented by overall Received Signal Strength Indication (RSSI) due to frequency selectivity [17]. Thus, the ESNR can be used as an important matric for performance evaluation. The availability of CSI at the subcarrier levels as shown in Fig.5, allows us to measure the ESNR at the AP. From Fig.9, we clearly observe the rise in the ESNR value by about 10 dB for each modulation scheme after applying our scheme.

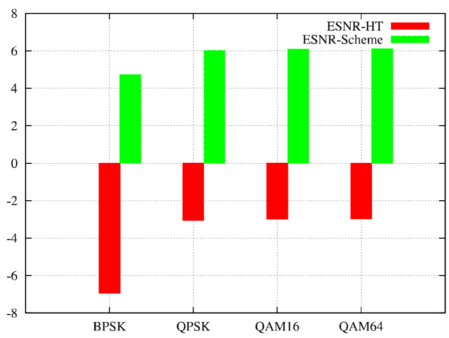

Fig. 9. ESNR comparison of different modulation schemes in Case I

VI. Conclusion

Collisions due to hidden terminal are inevitable in WLANs. This paper presents an effective technique that deals with the hidden terminal problem where receiver plays an important role for channel feedback in order to perform Zeroforcing Coordinated Beamforming(ZFCB). Specifically, ZFCB is calculated in HTs for percoding vector which is used to null the interfering signal from all undesired transmitters in HT scenarios. We showed via experimental results of the test-bed that our scheme effectively addressed the HT problem as we observed: collision free signal reception and significant gain in SNR and ESNR.

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