CUTS: Improving Channel Utilization in Both Time and Spatial Domains in WLANs

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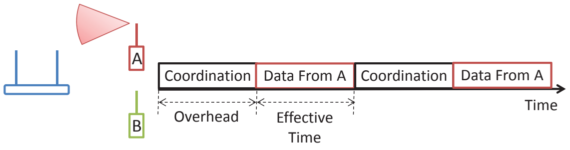
***Abstract*—Improving channel utilization is a well-known issue in wireless networks. In traditional point-to-point wireless communication, significant efforts had been made by the existing study on enhancing the utilization of the channel access time. However, in the emerging wireless network using MU-MIMO, considering only the time domain in channel utilization is not sufficient. As multiple transmitters are allowed to transmit packets simultaneously to the same AP, allowing more antennas at AP would lead to higher channel utilization. Thus the channel utilization in MU-MIMO should consider both time and spatial domains, i.e., the channel access time and the antenna usage, which has not been considered in the existing methods. In this paper, we point out that the fundamental problem is lacking of the antenna information of contention nodes in channel contention. To address this issue, we propose a new MAC-PHY architecture design, CUTS, to utilize the channel in both domains. Particularly, CUTS adopts interference nulling to attach the antenna information in channel contention. Meanwhile, techniques such as channel contention in frequency domain and ACK in frequency domain using self-jamming are adopted. Through the software defined radio based real experiments and extensive simulations, we demonstrate the feasibility of our design and illustrate that CUTS provides better channel utilization with the gain over IEEE 802.11 reaching up to 470%.**

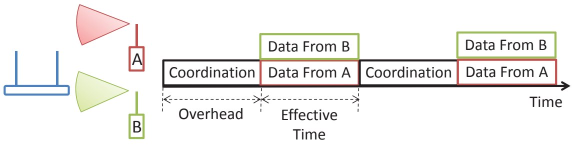
I. INTRODUCTION

Improving channel utilization is a well-known issue in wireless networks. In traditional point-to-point wireless communication, simultaneous transmissions may collide and lead to degradation of the system performance. Multiple access control thus is needed. However, such coordination consumes the limited channel resources, e.g., channel time, and only part of the channel time is used to send data. A lot of previous research thus focus on improving the channel utilization in time domain, either by increasing the proportion of time on data transmission [2] or reducing the time overhead on coordination [4] [5] [6] [14].

In recent years, Multiuser Multiple-Input-Multiple-Output (MU-MIMO) has attracted attention in wireless communication [1] [7] [8] [9]. By using the MU-MIMO technique, multiple transmitters are allowed to send packets to a same receiver simultaneously without affecting each other at the receiver, i.e., the receiver can still receive and decode all the packets successfully, as long as the total number of antennas at the receiver is not less than the sum of antennas of all transmitters. In [1], Tan et al even shed light on its feasibility in practical use by building the first working system to enable MU-MIMO in WLAN environment. However, since the transmissions are no longer limited to traditional point-to-point communication, considering the channel utilization only in time domain may not be sufficient anymore in MU-MIMO.



(a) Allowing only one stream in MU-MIMO



(b) Allowing two streams for transmission in MU-MIMO

Fig. 1: An illustrative example of wasting resources by considering only time domain for channel utilization in MU-MIMO.

Fig.1 shows an illustrative example by using a two-antenna AP with two single antenna nodes under two scenarios. Obviously, the efficiencies in time are the same for both two scenarios even though the second one doubles the amount of effective data of the first one. Indeed, the difference is induced by the antenna usage at the receiver. Allowing more antennas for transmission at the receiver can significantly improve the throughput and thus the channel utilization. Therefore, despite of the channel time, the antenna usage should be also considered as a channel resource in MU-MIMO to utilize. The unused antennas at the receiver should then be viewed as a waste of the channel. Such a channel waste would be even worse in today's network when more antennas are equipped in Access Point (AP). Due to the limitation of size, energy consumption and portability concern, most of today's mobile devices only have one or two antennas while AP has no such requirements and generally has more antennas, e.g., AP with IEEE 802.11ac allows up to 8 antennas. It is then essential to utilize the antenna usage by ensuring more simultaneous streams sent to the AP.

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Thus, channel utilization in wireless network by adopting MU-MIMO should consider both the time and spatial domain, i.e., the channel time and antenna usage at AP. As further observed, though some existing channel utilization methods in point-to-point wireless network can effectively increase the time efficiency, they cannot be applied in MU-MIMO since they just allocate one winner node at a channel time in the channel contention without considering the antenna usage, even though the AP has much more antennas than the senders. On the other hand, the MU-MIMO technique itself only provides a method for simultaneous transmission for multiple transmitters but cannot ensure its happening, i.e., allocating as many as possible simultaneous streams in a transmission. In fact, the fundamental problem of the existing methods is that they do not provide the antenna information of each contention nodes in the channel contention.

Motivated by this, in order to utilize the channel in MU-MIMO considering both time and spatial domains, we propose a new MAC-PHY design, called CUTS (Channel Utilization in Time and Spatial Domains), to allow effective MU-MIMO in practice for uplink traffic by providing the antenna information of contention nodes in channel contention. It is however, non-trivial to effectively and reliably provide extra information in channel contention. By observing that antenna itself actually provides a new dimension for use, CUTS makes use of the interference nulling technique to create different signal pattern at the AP's antennas for encoding the antenna information in channel contention. Leveraging these information, the AP can thus allocate as many as possible simultaneous streams sent from multiple transmitters to maximize the antenna usage. In addition, in order to send multiple ACKs from AP using least channel resource, CUTS combines multiple ACKs in the frequency domain by using self-jamming technique and transmit them at the same time to different associated clients. Moreover, CUTS equips channel contention in frequency domain to further improve the time efficiency. By effectively integrating the above three techniques, CUTS is able to utilize the channel in both time and spatial domains for the wireless network by adopting MU-MIMO.

In summary, in this paper we have made the following contributions. First, we analyze the channel utilization problem under an emerging wireless network MU-MIMO and point out the fundamental problem of the existing methods is lacking of antenna information in channel contention. Second, we propose a new MAC-PHY design, CUTS, to utilize the channel both in channel time and antenna usage by using interference nulling for attaching the antenna information in channel contention in frequency domain combined with the technique ACK in the frequency domain using self-jamming. Third, we have conducted experiments using USRP2s on a software radio testbed to verify the feasibility of CUTS. Forth, we also analyze the collision probability of CUTS and build a customized simulator to evaluate its performance in a large scale network. From the experimental results, the performance gain of CUTS over IEEE 802.11 can reach up to around 470%. To the best of our knowledge, we are the first work to point out the channel utilization in MU-MIMO should consider both the effective time and antenna usage.

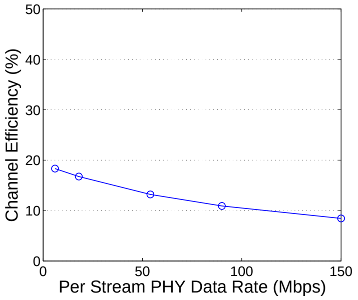

Fig. 2: Channel efficiency of 802.11 under different per stream data rate.

The rest of the paper is organized as follows. In Section II, we will introduce the background and challenges on CUTS design. Then the detail design of CUTS will be presented in Section III. In Section IV, the system implementation and results of our experiments will be presented. In Section V, we will give the related work. And we will conclude our work and make some suggestion for future research in Section VI.

II. BACKGROUND AND CHALLENGES

In this section, we explain in details the irrationality of considering only channel time for utilization and demonstrate the inefficiency of the current methods on channel utilization if MU-MIMO is allowed. Then the design challenges are presented in order to address the existing problems.

A. Inefficiency of existing methods on channel utilization

In wireless communication, channel utilization is formally defined by using the data throughput efficiency [16], i.e., the ratio between the actual network throughput and the ideal network throughput calculated using PHY data rate. It can be expressed as:

$$\eta = \frac{T_{actual}}{T_{ideal}} \tag{1}$$

where T_{actual} is the actual network throughput and T_{ideal} is the ideal network throughput. In the traditional network which only allows communication between single node pair, T_{actual} and T_{ideal} can be further expressed as follows respectively:

$$T_{actual} = t_{data} \cdot v_{PHY} \tag{2}$$

$$T_{ideal} = t_{cycle} \cdot v_{PHY} \tag{3}$$

where t_{data} is the time for effective data transmission in one cycle and t_{cycle} is the time of one transmission cycle and v_{PHY} is the underlying PHY data rate. Thus the channel utilization is usually expressed in the form of time efficiency:

$$\eta = \frac{t_{data}}{t_{cycle}} \tag{4}$$

However, this is generally not appropriate if MU-MIMO is used. In MU-MIMO, the client nodes are able to transmit simultaneously without affecting each other as long as the number of current streams in the air is less than the number of

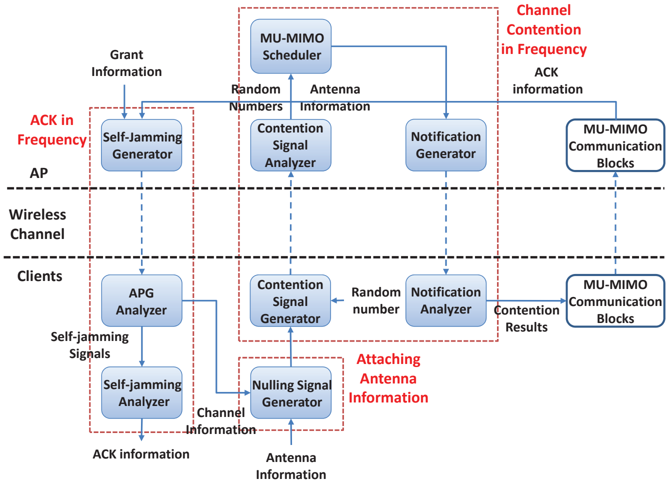

Fig. 3: System architecture of CUTS.

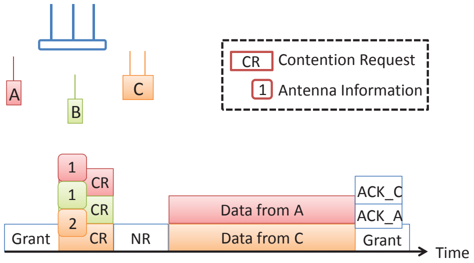

Fig. 4: An illustrative example of communication in CUTS.

antennas at AP. Apparently, even though the time used for data transmission are the same compared with the communication between single node pair, the actual data sent by using MU-MIMO is much more than the traditional one. Indeed, the intrinsic difference is induced by the usage of antennas at AP and the antenna should also be viewed as a channel resource and the not used antennas in the AP should be considered as a waste of channel.

Thus in MU-MIMO, the channel utilization should not merely consider only the time domain, but also the spatial domain, i.e., the usage of the antenna in AP. Let n_i be the total number of antennas used for data transmission in AP in the i-th cycle, m be the number of total cycles in the communication life time, N_{AP} be the total number of antennas in AP and v_{PPHY} be the per stream PHY data rate, the channel utilization should now be expressed as:

$$\begin{aligned}\eta' &= \frac{\sum_m t_{data} \cdot v_{PPHY} \cdot n_i}{t_{cycle} \cdot m \cdot v_{PPHY} \cdot N_{AP}} \\ &= \frac{t_{data}}{t_{cycle}} \cdot \left(\frac{1}{m} \cdot \sum_m \frac{n_i}{N_{AP}} \right)\end{aligned} \tag{5}$$

Then we define the efficiency in time domain as η_{time} and the efficiency in spatial domain as η_{space}, i.e., the usage of the antenna, as following, respectively:

$$\eta_{time} = \frac{t_{data}}{t_{cycle}} \tag{6}$$

$$\eta_{space} = \frac{1}{m} \cdot \sum_m \frac{n_i}{N_{AP}} \tag{7}$$

Thus, the channel utilization can finally be defined as the combination of efficiency in both time and spatial domain, i.e.,

$$\eta' = \eta_{time} \cdot \eta_{space} \tag{8}$$

Therefore, since MU-MIMO is practical in use, a better channel utilization scheme in wireless network should not only maximize the efficiency in time domain, but also need to maximize the efficiency in the spatial domain, i.e., the usage of the antennas of AP in each transmission cycle. Fig.2 shows the channel efficiency of IEEE 802.11 calculated using Equation.(8) with the different per stream PHY data rates using a 4-antenna AP and 10 single antenna clients.

Obviously, the current standard reveals very low channel efficiency and there is a large potential for improvement. In order to address this issue, we propose a new MAC-PHY architecture design, CUTS, to improve the efficiency in both time and spatial domain.

B. *Design challenges*

As discussed, the fundamental problem comes that no antenna information is provided while nodes contenting for the channel. Therefore, designing a new communication system for achieving high channel utilization is indeed not trivial and brings about many practical challenges.

First, the success of CUTS highly depends on whether the antenna information can be reliably delivered and identified in the contention. The false message of antenna information may lead to the overloading of AP's capability and in contract waste the channel resource. Since this is essential for the MU-MIMO transmission, we need to carefully design a method to reliably deliver the antenna information.

Second, sending extra information consumes extra channel resource, which turns out to be an overhead. Even though providing antenna information can enhance the antenna usage, it may add overhead in time and reduce the total efficiency. Thus, how to effectively deliver such information with least extra resource requires a careful design.

Third, due to that MU-MIMO allows multiple nodes transmit packets to AP simultaneously, the AP on the other hand, needs to send back multiple ACKs to those transmitters. Simply sending ACKs one by one may be slow and lead to a low efficiency. Thus, how to effectively send multiple ACK to the client nodes without costing extra resource is also a challenge in CUTS design.

In the next section, we will elaborate how to address each of these challenges in the CUTS design.

III. CUTS DESIGN

In this section, we first introduce the overview of the system architecture. And then we elaborate the design details of each new components in CUT and demonstrate how they together work to effectively improve the channel utilization.

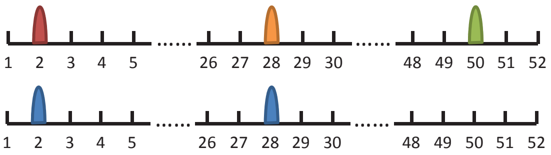

Fig. 5: An illustrative example of channel contention in frequency domain.

A. Overview of the system design

CUTS is a new MAC-PHY architecture design to provide the antenna information in channel contention with an effective way to ensure and utilize MU-MIMO. To achieve this, based on the MU-MIMO communication blocks, we introduce three new components in CUTS, i.e., channel contention in the frequency domain, attaching antenna information in channel contention and ACK in the frequency domain. The first component can effectively reduce the time for channel contention while the second one provides the antenna information in channel contention and can ensure using as more antennas as possible in MU-MIMO. The third one can further save the time for acknowledgement leading to better channel efficiency. Fig.3 illustrates the design blocks in each component of the architecture of CUTS.

For better illustration, consider a simple scenario with 3 clients A, B and C and a three-antenna AP shown in Fig.4. When these three nodes have packets to send, they need to wait until receiving a grant from AP and starts transmitting the requests to the AP for contenting the channel simultaneously in frequency domain. And these requests are attached with antenna information. Based on all contention information, the AP picks up a number of winners according to its capability and some pre-defined regulation. For example here, if the winners are A and C, nodes A and C will then transmit packets at the same time without affecting each other at AP. Upon successfully receiving all packets, the AP sends two ACKs which combine together in frequency with a grant for new transmission cycle. While the ACKs are received by nodes A and C, all the nodes including A and C can also receive the grant successfully and starts a new channel contention.

B. Channel contention in the frequency domain

Channel contention in the frequency domain is based on Orthogonal Frequency Division Multiplexing (OFDM) PHY scheme, which has been widely spread over the world and adopted by many wireless standards, e.g., IEEE 802.11a/g/n [13]. It divides the spectrum into multiple narrow sub-channels, named subcarriers, which are orthogonal to the each other. Specifically, in IEEE 802.11, a 20 MHz band implementation of OFDM has 52 subcarriers while a 40 MHz band has 114 subcarriers.

CUTS makes use of the subcarriers for channel contention as following. When a client N_i wants to transmit a packet, it generates a random number n_i at the channel contention round in the range of $[1, N_c]$, where N_c is the total number of available subcarriers. It then transmits a pre-defined signal through Subcarrier n_i. Meanwhile, the AP will listen instead and receive all signals among subcarriers. Upon the contention round finishes, AP then chooses w smallest subcarriers with signals and notifies the corresponding clients as winners by transmitting pre-defined signal back through these w chosen subcarriers. The number w here depends on the number of antennas at AP, i.e., m, and the distribution of nodes. The sum of the antennas of all these w clients, i.e., s, should be as close as m but with $s \leq m$. Such antenna information delivery relies on the technique introduced in the next section. Then those clients who receive signal back at their chosen subcarriers know they are the winners and start transmitting while the others wait for the next round for contention.

For example, if there are three single antenna clients N_1, N_2 and N_3 contending for the channel with their random number n_1, n_2 and n_3 respectively, a 2-antenna AP then receives signals at Subcarrier n_1, n_2 and n_3 respectively. If $n_3 < n_1 < n_2$, AP will then pick up the Subcarriers n_3 and n_1 for transmitting signals back to indicate N_3 and N_1 as the winners. By receiving the signals back from Subcarrier n_3 and n_1, N_3 and N_1 then start to transmit packets. Fig.5 demonstrates this example by having $n_1 = 28$, $n_2 = 50$ and $n_3 = 2$.

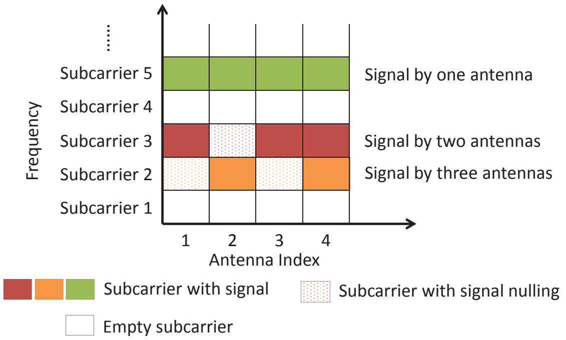

Fig. 6: An illustrative example of attaching antenna information by using interference nulling.

C. Attaching antenna information in channel contention

As discussed, it is essential to reliably and effectively attach the antenna information in channel contention. As observed, for a MIMO node, despite of using the dimension of frequency for contention, the space using multi-antenna indeed forms a new dimension. In CUTS design, we exploit such an opportunity to attach the antenna information in channel contention by leveraging a MIMO technique, interference nulling. Interference nulling allows a transmitter to zero out the signals received at one or more antennas at the receiver side and thus provides us a way to encode the antenna information while contenting the channel. Specially, for a client node with the number of antennas to be n, in the channel contention round, the signal it transmits through the chosen subcarrier should nulling $n - 1$ antennas at the AP. By making use of the number of nulling antennas, we can encode the number of antennas of nodes in channel contention. AP can then decode such information easily by examining the number of

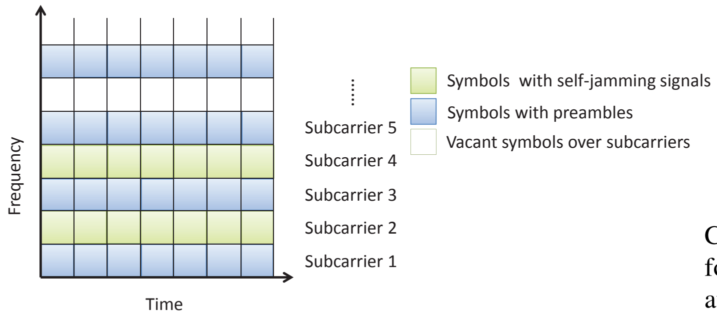

Fig. 7: An illustrative example of ACK in the frequency domain.

nulling antennas. Fig.6 shows an example with a 4-antenna AP and three clients equipped with one, two and three antennas respectively.

For more details, the interference nulling works as following. Take a communication pair with two antennas as an example. Let h_{ij} be the channel coefficients at a subcarrier from the i-th antenna at the transmitter to the j-th antenna at the receivers. If at the transmitter, the signal sample at the first antenna is $p[t]$ while the second antenna is $q[t]$, the received signal at the j-th antenna of this subcarrier, i.e., $y_j[t]$, can be expressed as:

$$y_1[t] = h_{11}p[t] + h_{21}q[t] \tag{9}$$

$$y_2[t] = h_{12}p[t] + h_{22}q[t] \tag{10}$$

If we randomly pick the first antenna at the receiver to zero out the signal, then the signal at that antenna would become:

$$h_{11}p[t] + h_{21}q[t] = 0 \tag{11}$$

Accordingly, the signal $q[t]$ can be expressed in the form of $p[t]$ as:

$$q[t] = -\frac{h_{11}}{h_{21}}p[t] \tag{12}$$

Thus, in order to create a null at the antenna of AP, if the signal sent from the first antenna at the transmitter is $p[t]$, then the signal $q[t]$ sent from the second one should be $\alpha p[t]$ with:

$$\alpha = -\frac{h_{1j}}{h_{2j}} \tag{13}$$

where j is the antenna chosen to null at the AP. By using the same philosophy, this can in fact be easily generalized to different numbers of antennas at the client node and AP.

D. ACK in the frequency domain

In order to let the AP effectively transmit multiple ACKs back, we make use of the trick induced by the channel correlation. Due to the channel correlation, the channel estimation of a subcarrier can be interpolated with the neighboring ones and thus using only half of the subcarriers in preambles to send pilots is sufficient for channel estimation [17]. We can then further use those vacant subcarriers to encode the ACK information by adopting self-jamming technique. Self-jamming technique generates some dedicated signals and sends through the corresponding subcarriers for indication. Currently in our design, we assign the first 8 vacant subcarriers for ACK purpose due to that the maximum number of antennas at existing commercial AP is 8 and thus the maximum number of ACK the AP needs to send is 8 with all clients using one antenna. The rest of vacant subcarriers are reserved for other purpose which we will introduce in the next subsection. Since upon receiving the notification from AP, the clients can know their orders in the contention by detecting the signals in subcarriers, the order of the 8 reserved vacant subcarriers is then mapped to the order of the winners, e.g., the first vacant subcarrier is used to send ACK to the winner nodes with least subcarrier number in channel contention. And we use the existence of the jamming signal over some symbols to indicate the ACK. No signal received over all symbols at the vacant subcarrier can then indicate a failed packet. Fig.7 shows an illustrative example by using self-jamming over the first and second vacant subcarriers to indicate the ACKs for the corresponding clients.

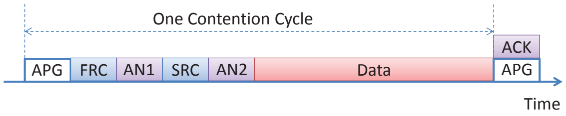

Fig. 8: Multiple access method in CUTS

E. Multiple access method

In this section, we demonstrate how the above three new components together effectively improve the wireless channel utilization in both time and spatial domain in MU-MIMO.

Consider a single AP scenario. Fig.8 shows the Multiple Access Control (MAC) Protocol in CUTS. The cycle starts by AP sending a grant for channel contention (APG). The APG is simply a preamble with self-jamming in the preserved vacant subcarriers to indicate its ID. The APG serves for two purposes. First, it can notify those nodes who has already subscribed to this AP to start channel contention. Second, it allows those nodes to make use of the preambles for channel estimation, which can further be used to perform interference nulling in the channel contention. Upon receiving the APG, the first round contention (FRC) starts and each of the subscribed clients generates a random number and contends in the frequency with its antenna information. By receiving all the contention information, the AP selects the winners according the mechanism described in Section III-B and notifies them in AN1. Here, we introduce another round of contention (SRC) for further alleviating collisions. In SRC, those winners in the first round contention start a same channel contention procedure and the AP then notifies the final winners in AN2. Those final winners can then start the simultaneous transmissions by using different MU-MIMO technique, e.g., chain-decoding in [1]. Once finishing, the AP starts the second transmission cycle by sending a new APG with the ACK attached in the reserved vacant subcarriers. If the AP wants to send packets, it simply sends the packet immediately without sending APG. Since the transmission of CUTS is AP-based,

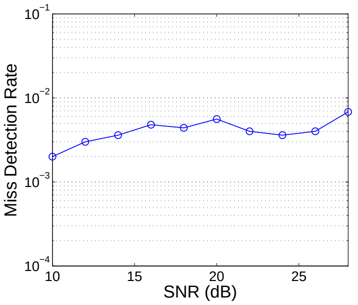

Fig. 9: Miss detection of using interference nulling for attaching antenna information.

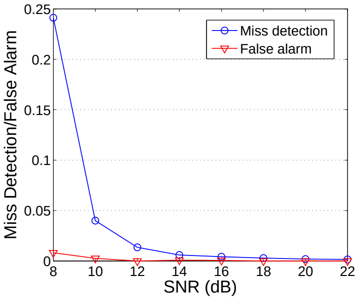

Fig. 10: Miss detection and false alarm of using self-jamming for ACK in the frequency domain.

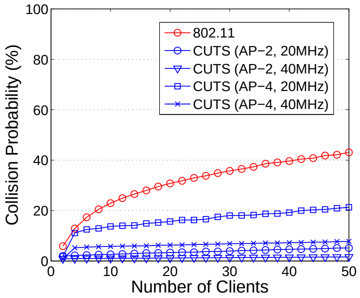

Fig. 11: Collision probability under different number of clients (AP-n refers to an AP with n antennas)

i.e., each client only responds to the APG of its subscribed AP, CUTS is easily extended to the multiple collision domains.

IV. EXPERIMENTAL EVALUATION

In this section, we evaluate the feasibility of CUTS and compare its performance against the existing IEEE 802.11 and SAM's designs. We first give our system implementation and start our experiments by examining the feasibility of CUTS using our implementation on an indoor tested consisting of USRP2 nodes. Then in order to get an insight into the behavior of CUTS under a large scale wireless network, we also build a customized simulator to study its performance.

A. Implementation

We implement the design of CUTS using Software Defined Radios (SDRs), which are from the open source GNU Radio project [10] and implement the signal processing blocks of wireless communication system in software. Each node in our testbed is equipped with Universal Software Radio Peripheral 2 (USRP2) [12] boards and XCVR2450 daughterboards, which operate in 2.4-2.5GHz range. Since USRP2 boards cannot support multiple daughterborads, in order to build MIMO nodes with multiple antennas, we combine multiple USRP2 by using an external clock [11]. These experiments are all run in our laboratory with a room size $5m \times 8m$.

In our evaluation, we implement the following components of our design: contention in the frequency domain, attaching the antenna information by using interference nulling and ACKing in the frequency domain by using self-jamming. However, due to the timing constrain induced by GNURadio, we evaluate the contention in the frequency domain and attaching the antenna information by using interference nulling independently from ACKing in the frequency domain by using self-jamming.

B. Detection of contention nodes and antenna information

The success of CUTS mainly relies on the detection accuracy of the following three aspects, i.e., the contention nodes in the frequency domain, the antenna information using interference nulling and the ACK information using self-jamming. Any misbehavior of one of the above may lead to a collision or retransmission and thus affects the effectiveness of CUTS. Since [4] and [6] have already demonstrated the high accuracy of the first aspect, in this paper, we only present the results of the latter two to show the feasibility of CUTS.

The detection accuracy of the antenna information is composed by the miss detection and the false alarm of the signal pattern induced by interference nulling. In order to measure it, we build 2×2 MIMO nodes by using an external clock and conduct experiments as following by using a communication pair under different channel conditions. The transmitter creates nulling signal at an antenna of the receiver interleaved with the normal intense signal for channel contention. We call such interleave signals with 40 symbol each as a group of testing signals and in each run we transmit 2500 groups of such testing signals. And for each SNR value in the range [10, 28] dB, we repeat the above procedures 10 times.

Fig.9 plots the miss detection rate as a function of the SNR of the intense signals for channel contention. We observe from the figure that the miss detection rate of interference nulling is controlled within a low level, i.e., less than 0.8%, under different channel conditions. Though, the changing of the missing detection does not have a specific pattern as the SNR increases. We infer this uncertain variance may be induced by the external interference while the intrinsic miss detection rates are very small ideally. In addition, from our experiment results, we also find that there is no false alarm, i.e., 0%.

The detection accuracy of the ACK using self-jamming is also essential for the whole performance of the system. For evaluating it, we have conducted experiments using 5 USRP2s with one transmitter and four receivers. The transmitter broadcasts the preambles with the ACK encoded by self-jamming in four different vacant subcarriers. The receivers then detect the jamming signals in their corresponding vacant subcarriers respectively. For each run, we send 3000 groups of preambles for testing and for each SNR value in the range of [8, 22], we repeat the experiments for 10 times.

Fig.10 shows the miss detection and false alarm of self-jamming under different channel contention. As observed, when the SNR is large than 14 dB, the miss detection rate keeps less than 1% while the false alarm is close to 0%, leading to a high detection accuracy. Together with the high detection accuracy of interference nulling, it is then feasible to use CUTS in practical use.

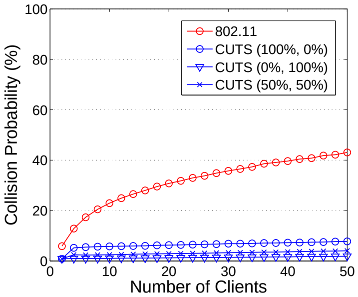

Fig. 12: Collision probability under different number of clients. (n_1,n_2) refers to the percentage of node distribution. n_1 is 1-antenna nodes and n_2 is 2-antenna nodes.

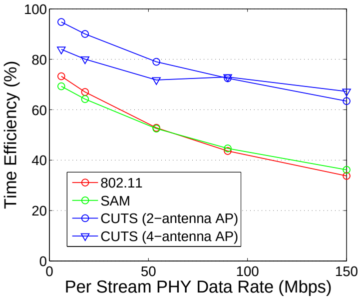

Fig. 13: Time efficiency under different per stream data rates (10 clients, each with single antenna).

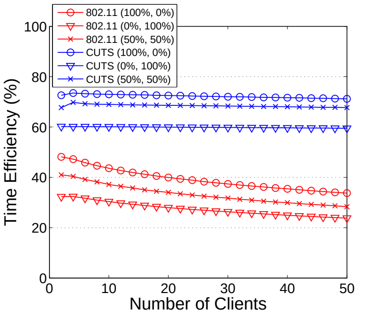

Fig. 14: Time efficiency under different number of clients. (n_1,n_2) refers to the percentage of node distribution.

C. Collision probability analysis

Collisions among transmitters lead to a waste of the channel resources and dramatically decrease the channel utilization. Thus, it is essential for CUTS to avoid collisions while consuming least extra channel resources.

Assuming at the second contention round, AP chooses the k smallest indexes of subcarriers as the winners. Collision happens when at least one of these k smallest indexes of subcarriers corresponding to more than one clients. Let N_o be the number of contention nodes in the second round and N_c be the number of total available subcarriers, the probability without collision when the k-th smallest index of subcarrier is i, i.e., $P(i)$, can be expressed as:

$$P(i) = \binom{N_o}{k} k \binom{i-1}{k-1} \left(\frac{1}{N_c}\right)^k \left(\frac{N_c - i}{N_c}\right)^{N_o - k} \tag{14}$$

Then CUTS's collision probability P_c can be expressed as:

$$P_c = 1 - \sum_{i=k}^{N_c} [P(i)] \tag{15}$$

Note that a larger N_c leads to a small collision probability. In addition, N_o is further determined by the expectation of number of winner nodes in the first round, i.e., E_{FR}, which can be expressed as:

$$N_o = E_{FR} = E_1 + E_2 \tag{16}$$

where E_1 is the expectation of number of winners when the k-th smallest index of subcarrier is i with m nodes in those k smallest indexes of subcarriers, and E_2 is the expectation when all nodes choose the n smallest indexes of subcarriers and $n < k$. Then E_1 can be calculated as:

$$E_1 = \sum_{i=k}^{N_c} \sum_{m=k}^{N} m \cdot \frac{\binom{N}{m} k! S_2(m,k) \binom{i-1}{k-1} k^{m-k} C_{rest}}{N_c^N} \tag{17}$$

with N being the total number of clients in the network, $S_2(m,k)$ being the stirling numbers of the second kind and C_{rest} being the combination of nodes choosing the subcarriers larger than i:

$$S_2(m,k) = \left\{ \begin{matrix} m \\ k \end{matrix} \right\} = \frac{1}{k!} \sum_{j=0}^{k} (-1)^{k-j} \binom{k}{j} j^m \tag{18}$$

$$C_{rest} = \begin{cases} 1 \text{ if } N = m \\ (N-m)^{N_c - i} \text{ if } N > m \end{cases} \tag{19}$$

And E2 can then calculated by:

$$E_2 = \frac{\binom{N_c}{k-1} \cdot (k-1)^N}{N_c^N} \cdot N \tag{20}$$

Moreover, the number of winners the AP chooses, i.e., k, is determined by the nodes distribution and the number of antennas at the AP. It can be bounded by:

$$1 \le k \le \left\lfloor \frac{N_{AP}}{N_{small}} \right\rfloor \tag{21}$$

where N_{AP} is the number of antennas at the AP and N_{small} is the smallest number of antennas at the clients.

Fig.11 plots the collision probability as a function of number of clients under different settings of AP with all nodes equipped with one antenna. Observe that when using a 4-antenna AP at 20MHz band, the collision probability of CUTS become larger than other settings, though it is still less than the collision probability of CSMA. This is mainly affected by a larger N_o. For the other three settings, CUTS can remain at a very low level, i.e., less than 8%, even at a dense network. CSMA in 802.11, instead, collides more frequently as the number of clients increases. Fig.12 further plots the collision probability under different nodes distribution with a four-antenna AP. Apparently, the collision probability of the scenario with all clients of 2 antennas is less than the one with 1 antennas when the number of antennas at AP is fixed.

D. Performance enhancement

Since the latency constraint of USRP2 disallows the real-time evaluation of the system, we then build a customized simulator in order to understand its efficiency in time and space respectively, and how they together affects the whole channel utilization. Since the focus of this experiment is on the system throughput, we assume the network is saturated and the failure of a packet transmission is only due to collisions. We mainly compare the results of CUTS with the CSMA of IEEE 802.11 and CCMA of SAM [1].

Equation.(6) and Equation.(7) discussed in Section II gives us a simple model for calculating the time efficiency and

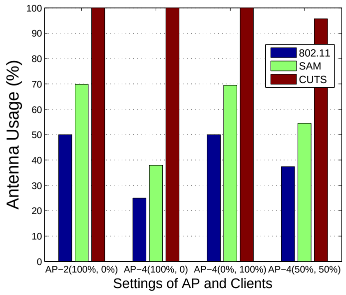

Fig. 15: Antenna usage with 20 clients. (n_1,n_2) refers to the percentage of node distribution.

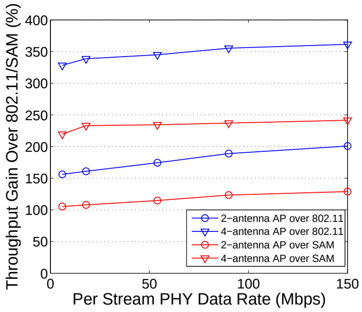

Fig. 16: Performance gain of CUTS over 802.11 and SAM under different data rates (10 clients, each with single antenna).

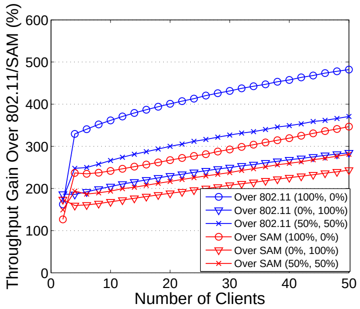

Fig. 17: Performance gain of CUTS over 802.11 and SAM under different number of clients with data rate 90 Mbps

antenna usage. By Equation.(8), the total efficiency can be calculated. For more details, the t_{cycle} for CUTS can be modeled as:

$$t_{cycle} = t_{APG} + 4 \cdot t_{Cont} + t_{preamble} + t_{data} \tag{22}$$

where t_{APG} is as long as an preamble and t_{Cont} should be at least one FFT window time in order to let the nodes successfully detects the signals in subcarriers. Thus we set:

$$t_{Cont} = t_{FFT} + 2 \cdot t_{prop} \tag{23}$$

where t_{FFT} is the time frame of an FFT window and t_{prop} is the propagation delay. Verified by [6], t_{Cont} is set to $5.2\mu s$.

Our simulations use the Maximal Transmit Unit (MTU) as the packet size for transmission, i.e., 1500 bytes, and model the transmission using different data rates under two bandwidths, i.e., 20 MHz and 40 MHz. Unless other specified, we choose the physical layer parameter values consistent with the IEEE 802.11 Standard [13].

Fig.13 plots time efficiency under different physical data rates with different antenna settings at AP. As observed, CUTS outperforms CSMA and CCMA under all per stream data rates in 802.11. This gain of CUTS increases as the data rate increases and is mainly introduced by its low coordination overhead and collision probability. The small efficiency increase of CUTS from 54 Mbps to 90 Mbps with 4-antenna AP is due to the large drop of collision probability induced by using more subcarriers for contention, as shown in Fig.11.

Fig.14 further plot the time efficiency of CUTS over CSMA with different number of clients and different distribution of nodes at the per stream data rate 90 Mbps. They show that when the number of clients increases, the time efficiency of CSMA reduce obviously while CUTS just experiences a small drop from 2 clients to 50 clients' scenario, i.e., less than 2%. This is mainly because as the number of clients increases, the collision probability of CSMA increases to a relatively high level while in contrast, CUTS maintains a small collision probability. As observed, the node distribution also affects the time efficiency of CUTS. More 2-antenna nodes will lead to less time efficiency. This is because in such a case CUTS will allow less concurrent transmissions with a fixed setting of AP and the total data rate of a 2-antenna node is indeed larger and reveals a smaller transmission time per packet.

Fig.15 shows the antenna usage of CUTS, CSMA and CCMA under four different settings of AP and clients. From the results, we find that CUTS can maintain 100% antenna usage when the numbers of antennas of all clients are the same and the number of antennas at AP can be divided by that number. When the clients are mixed with different number of antennas of nodes, the antenna usage may not be fully utilized but still maintains above 96%. This happens because it may not be able to find out the best combination of winners that can fully utilize the antenna usage according to the order of channel contention winners. But the performance of CUTS is still better than CSMA and CCMA in all settings.

Fig.16 shows the total throughput gain of CUTS over CSMA and CCMA under different per stream data rates at different AP settings. As the per stream physical data rate increases, the performance gain of CUTS over CSMA and CCMA also increases by introducing a better time efficiency. Fig.17 further demonstrates the performance gain of CUTS with different number of clients and different node distribution at data rate 90 Mbps. Being benefit from the high time efficiency (by low collision probability and low coordination overhead) and the high antenna usage (by attaching the antenna information in channel contention), the performance gain of CUTS over CSMA and CCMA can even reach around 480% and 340% at high data rates in a dense network.

V. RELATED WORK

Improving channel utilization is a well-known issue in wireless networks for years. Traditionally, in WLAN, CSMA has been adopted by IEEE 802.11 Standard due to its fairness and effectiveness brought about by the randomized contention. However, its low efficiency becomes a problem as the physical data rate progressively increases nowadays. A lot of work has been proposed to address this problem.

The existing approaches are mainly classified into the following two categories. (1) Increasing the proportion of data transmission time: Data aggregation [13] belongs to this category but increases the delay of a packet and is generally not applied in the delay-sensitive scenario. In [2], the authors have proposed a fine grained channel access system to increase the data transmission time in each sub-channel. (2) Reducing the coordination overhead: [15] reveals the need for optimal CSMA by the experimental results. [14] has proposed a minimum controlled coordination by reducing the DCF overhead. [6] has moved the channel contention from time to frequency, making the time for channel contention become small and constant. [4] even eliminates the control overhead by allowing the data transmission and control message sent simultaneously. Although the existing work can improve the efficiency to some extent, they just focused on time domain and are generally not applicable on improving the antenna usage. CUTS instead considers the utilization in both domains.

The success of CUTS is based on the feasibility of MU-MIMO. SAM [1] is the first working system to enable MU-MIMO in wireless LAN environment. Though, it has limitations. SAM requires a special preamble scheme by limiting each transmitting antenna sends a separate preamble one-by-one and non-overlapping, which is not compatible with IEEE 802.11 and thus not practical. Meanwhile, since the focus of SAM is on the implementation of MU-MIMO technique, its MAC design only provides a chance to allow simultaneous transmission, but cannot ensure the simultaneous transmission in each transmission round. In addition, its MAC design is CSMA-based, which is proved to be with low time efficiency by the literature [4] [14]. In other words, SAM do not utilize the channel with respect to both time and spatial domain. In contrast, CUTS's focus is on the channel utilization and it argues that one should maximize the concurrent transmissions in each round while still maintaining high time efficiency. CUTS achieves this by providing a new MAC-PHY design and does not have the preamble limitation. In [3], the authors have also proposed a work to solve heterogeneous MIMO networks problem. It allows nodes who have more antennas than the current number of used degrees of freedom to contend for concurrent transmissions. However, it highly depends on the contention order and requires a large coordination overhead. CUTS instead does not have the order problem on contention. In [8] [18], the authors also improve the channel efficiency but with its focus on the downlink while our approach focuses on the uplink. [7] also works on the MU-MIMO by proposing a new rate adaptation for MU-MIMO with a different purpose of CUTS.

VI. CONCLUSION

Improving channel utilization is a well-known issue in wireless networks. In traditional point-to-point wireless communication, the existing methods on channel utilization mainly focus on the channel time. We argue that in the emerging wireless network using MU-MIMO, those approaches are not sufficient without considering the antenna usage with the fundamental problem being lacking of the antenna information in channel contention. To address this problem, we propose a new MAC-PHY architecture design, CUTS, to utilize the channel in both time and antenna usage by using interference nulling for attaching the antenna information in channel contention in frequency domain combined with ACK in frequency domain using self-jamming. Through the software defined radio based real experiments and simulations, we demonstrate the feasibility of our design and that it provides better channel utilization with the gain over 802.11 reaching up to 470%.

VII. ACKNOWLEDGEMENT

This research is supported in part by Guangdong Natural Science Funds for Distinguished Young Scholar (No.S20120011468), Guangzhou Pearl River New Star Technology Training Project (No.2012J2200081), Guangdong NSF Grant (No.S2012010010427), China NSFC Grant (No.61202454,60933011,61027009), Hong Kong RGC Grants HKUST617811 and HKUST617212, Science and Technology Planning Project of Guangdong Province, China(No.2011A011302001), NSFC-Guangdong Joint Fund (No.U1201252), the National Key Basic Research and Development Program of China (973)(No.2013CB329505).

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