Hash Division Multiple Access

Lu Wang*,Xiaoke Qi†, Kaishun Wu* and Qian Zhang‡
*College of Computer Science and Software Engineering, Shenzhen University
†Institute of Automation, Chinese Academy of Science
‡Department of Computer Science and Engineering, Hong Kong University of Science and Technology

Abstract—**Recently, the utilization of dense constellation diagram are all welcomed in wireless standards, since it can boost the wireless capacity. The state-of-the-are research on dense constellation diagram mainly focuses on single link transmission. In this paper, we enable a new orthogonal dimension for multiple access by exploiting the redundancy in dense constellation diagram. We termed it as hash division multiple access (HDMA). By harnessing more constellation points with controlled symbol distance, HDMA ensures higher transmission date rate and better diversity gain against fading. In PHY layer, HDMA incorporates a orthogonal, linear and random encoder to construct orthogonal hash space for user separation. An AP-driven MAC protocol is then proposed to fully utilize this transmission concurrency for uplink and downlink multiple access. We verify the feasibility of HDMA via a GNU radio testbed, and further conduct trace-driven emulations to evaluate HDMA's multiplexing gain. The results reveal that HDMA provides a maximum number of 3 to 5 concurrent transmissions, and achieves a performance gain up to 131% and 39% compared to 802.11n and AutoMAC.**

I. INTRODUCTION

The ultimate goal of WiFi networks is to enable as many concurrent transmissions as they can to boost the network throughput. However, the growing demand for high speed high quality services along with the dense multi-user tenet contradict to the capacity limitations. Due to the shared nature of the wireless signal, only one transmission is allowed at any instant on any given frequency. Otherwise, collision happens and induces to transmission failure with high probability.

To enable spectrum sharing among multiple clients, extensive research has been carried on for decades. Multiplexing techniques emerge with a wide following, which combine multiple analog message signals or digital data streams into one signal over a shared medium. Some good representatives include time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA). Their essential idea is to construct orthogonality in various domain, and allocate each orthogonal sub-domain to a client for concurrent transmission. The existing multiplexing techniques share a common tradeoff between user capacity and quantity. We need to find a multiplexing domain that provides more concurrent transmissions with enured performance.

Recent advances in rateless codes facilitate the utilization of dense constellation, such as Strider [1] and Spinal [2]. Unlike the state-of-the-art encoding schemes that produce fixed code rate, rateless codes enable an self-adaptive code rate according to the channel condition at the receiver side. The key insight behind rateless codes is to control the minimum distance among nearby constellation points. As the number of retransmissions increases, the minimum distance increases, until the bit errors are tolerable and the data can be decoded. This distance control gives us full access to the constellation diagram. More constellation points with designated positions can be accommodated with ensured performance. Fig. 1 illustrates the constellation comparison between the 16-ary quadrature amplitude modulation (16QAM) and 16-ary spinal code. 16QAM adopts fixed and symmetric symbol set constellation. As the symbol rate increases, e.g., 64-ary QAM or 256-ary QAM, the constellation becomes denser, and the noise resistance capacity is degraded accordingly. In rateless codes, as illustrated in Fig. 1 via spinal, the encoded symbols are highly correlated and randomly distributed, so that even with dense constellation, the transmission rate can be guaranteed due to good resilience to noise and interference.

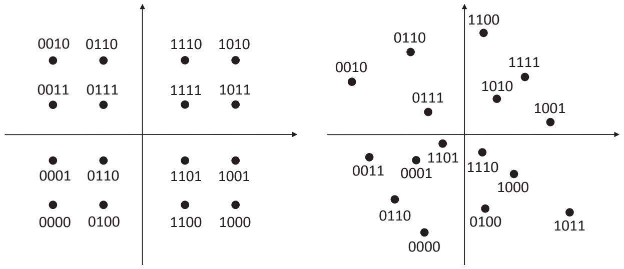


Fig. 1: Constellation comparison between 16-ary QAM and spinal codes. QAM adopts fixed and symmetric signal set constellation. In spinal codes, the constellation points are more flexible, giving us full access to the constellation diagram.

The design of rateless codes gives us an insight to exploit dense constellation for multiple access. We observe that there exists certain redundancy in the dense constellation diagram. With the term "constellation redundancy", we mean the constellation diagram is capable to accommodate a much greater number of symbols that has not been used yet. With appropriate design, such constellation redundancy can be utilized for more concurrent transmissions. Motivate by this, we propose hash division multiple access (HDMA), a novel multiplexing technique for wireless networks. HDMA enables a new multiplexing domain, hash domain. The core idea behind HDMA is to construct orthogonality in hash space with ensured transmission data rate. To achieve this goal, HDMA incorporates an encoder that possesses the following properties: 1) Randomness that maintains resilience to noise and interference; 2) Orthogonality that guarantees a simple structure for user separation; and 3) Linearity that enable a practical decoder whose time and space complexity is polynomial. These three principles provide transmission concurrency in the PHY layer. We further propose a novel MAC layer protocol to fully utilize this concurrency for uplink

978-1-5090-1328-9/16/$31.00 ©2016 IEEE

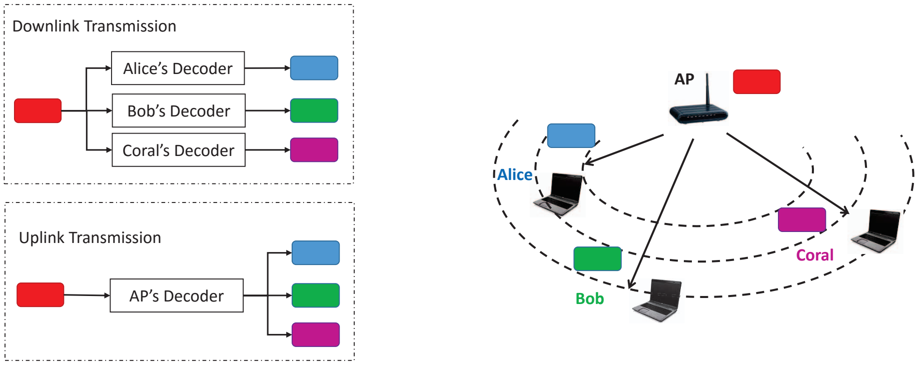


Fig. 2: Illustration of downlink and uplink transmission by Hash Division Multiple Access. A typical WLANs cell with a AP and 3 clients transmit concurrently.

and downlink multiple access.

We have implemented HDMA on a GNU Radio testbed. Experiments with our software radio prototype illustrate that the HDMA can sustain 3 to 5 concurrent transmissions. We also conduct trace-driven emulations to elaborate the performance of HDMA with channel access. The results demonstrate that HDMA improves the throughput up to 131% and 39% compared with 802.11n and AutoMAC. The performance gain stems from HDMAs ability to exploit the constellation redundancy, and encourage more concurrent transmissions.

II. RELATED WORK

A. Multiplexing Techniques

In the past few years, the demand for wireless spectrum has started to surpass the spectrum availability. Numerous techniques have been studied to improve the spectrum efficiency and increase the number of users that can be accommodated. Multiplexing techniques, oriented from the pioneering contributions of Shannon [3], are proposed to combine multiple analog message signals or digital data streams into one signal over a shared medium [4]. Time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA) are three fundamental techniques used in wireless communication systems. Their essential idea is to construct orthogonality in time, frequency and code domain for user separation. Afterwards, numerous advanced multiplexing techniques has emerge. Interleaver Division Multiple Access (IDMA) [5] is a special form of CDMA. It treats the interleaving index sequences as multiple access codes, and adopts a simple chip- by-chip iterative multi-user detector with low decoding complexity. Although the above multiplexing techniques support concurrent transmission, the data rate is rarely high due to the limited capacity allocated to each user.

B. Rateless Codes

Recently, researchers have investigated more advanced coding and modulation schemes for wireless communications. Among which, rateless codes have displayed a desirable paradigm for rate adaptation [1] [2]. In a rateless code enabled communication system, the sender generates a potentially limitless number of output rateless symbols from a fixed number of message symbols, so that the receiver can continue collecting the rateless symbols until all the message symbols are successfully decoded. Rateless codes are robust against noise and interference, and thus they encourage a number of research on concurrent transmissions. AutoMAC [6] leverages rateless property along with interference cancellation to ensure a simple, low overhead MAC for concurrent transmissions. However, the capacity is also restricted by the interference level. Unlike the previous research, HDMA aims to construct a new orthogonal dimension for multiple access, and thus the multiplexing gain could be maximized.

III. HASH DIVISION MULTIPLE ACCESS

In this section, we describe the overall architecture of Hash Division Multiple Access, which leverages the dense constellation diagram to enable a new multiplexing domain.

A. Overview and Design Challenge

HDMA's design targets at wireless LANs with one access point (AP) and several clients. Fig. 2 illustrates the basic idea of HDMA in a typical WLAN cell, where 3 clients, Alice, Bob and Coral are transmitting concurrently with the AP. HDMA adopts a AP driven MAC protocol. All the transmissions are scheduled by the AP.

The most challenging task in HDMA is how to achieve the above-mentioned multiple access control with minimum overhead and ensured per-user throughput. To solve this problem, HDMA leverages recent work on rateless codes to enable a new multiplexing domain, hash domain for multiple access. The encoding scheme based on sequential hashing provides a simple and robust structure to use dense constellation against noise and interference. However, when come to multiple access scenario, this non-linear property also makes the multi-user detection impossible. Also, as there is no orthogonality among different clients, the collided packets are inseparable. If we want to harness the constellation redundancy to enable multiple concurrent transmissions, we need a linear, orthogonal and invertible encoder in hash space.

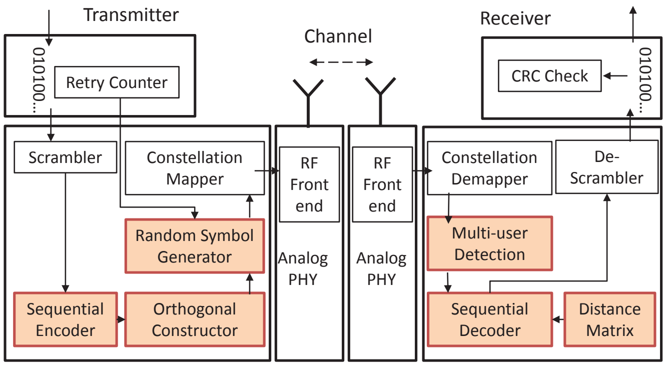


Fig. 3: HDMA Block Diagram. The colored blocks are HDMA extensions to 802.11. Some other standard operations such as OFDM modulation are not included.

As shown in Fig. 3, HDMA offers three components to achieve the PHY layer encoder: sequential encoder and random symbol generator that maintains the rateless property to against noise and interference, and orthogonality constructor that provides transmission concurrency in hash space. Accordingly, it provides a practical decoder based on soft information. In MAC layer, a polling based scheduled MAC is proposed to fully utilize this concurrency for multiple access.

B. PHY Layer Encoder

The design of HDMA's PHY layer encoder follows three principles: 1) Randomness: This principle is the core idea to leverage dense constellation diagram. Otherwise, the resilience to noise and interference will be greatly reduced; 2) Orthogonality: To guarantee a simple structure for multi-user separation, we need to construct orthogonality in hash space; 3) Linearity: It is critical to enable a practical decoder with polynomial time and space complexity. Therefore, a linear encoder under multi-user scenario is indispensable. We will detail our design to meet these principle.

HDMA inherits many advantages from rateless codes. In particular, with the use of a hash function, HDMA manages to produce a random, nonlinear mapping between message bits and coded bits (e.g. spine value) to ensure the resilience to noise and interference. Also, the coded bits are mapped to a dense constellation symbol set to convey as many information as possible. To embrace multiple concurrent transmissions, HDMA constructs orthogonal spine value in hash space. The original encoded bits, or orthogonal spine value, is segmented into several sectors. Each client is allocated one sector as its own spine space. After sequential encoding, a user zero-pads its spine value into orthogonal spine value according to the allocation. Thus, the messages from various clients are orthogonalized in hash space.

To maintain the rateless property, the orthogonal spine value needs to be randomized in each transmission round. However, the non-linear random number generator will destroy the orthogonality we have constructed. Besides, the non-linearity makes the sum of any two codewords not necessarily a valid codeword. Therefore, the decoding algorithm becomes computational impossible when there are multiple concurrent transmissions. To overcome this obstacle, we adopt linear random number generator to generate rateless symbols in each transmission round. Linear congruential generator and its variants [7] are good choices. With proper parameters, they achieve pair-wise independence and universal randomness. Thus, the orthogonal spinal values are randomly and uniformly distributed among the entire constellation diagram.

As depicted in Fig. 3, after receiving a packet from the upper layer, the encoder divides a packet into multiple message blocks. Each message block M has a length of $(n-16)$. A 16-bit CRC is computed and inserted at the end of each M to construct a link-layer frame. The encoder consists of one hash function h, one padding function p and one Linear Random Number Generator (LRNG). It takes every k message bits $\vec{m_i}$ ($\{0,1\}^k$) from block M, and encodes them into one rateless symbol according to the following equations:

$$h : \{0,1\}^k \times \{0,1\}^v \rightarrow \{0,1\}^v \tag{1}$$

$$p : \{0,1\}^v \times \mathbf{P} \rightarrow \{0,1\}^{L*v} \tag{2}$$

$$LRNG : \{0,1\}^{L*v} \times \mathbf{N} \rightarrow \{0,1\}^c \tag{3}$$

where L is the total number of concurrent transmissions, $\{0,1\}^v$ is the spine value s_i of individual clients, and $\{0,1\}^{n*v}$ is the orthogonal spine value s'_i after padding. Equation (1) is used to generate spine s_i for message bits $\vec{m_i}$ by sequential hashing, and Equation (2) is to construct orthogonality among different clients. Finally, we get sequences of rateless symbols $r_{i,j}$ by applying $LRNG$ to s'_i repeatedly in each transmission round.

C. PHY Layer Decoder

In this section, we present the decoder design for HDMA. HDMA's decoding algorithm benefits from the sequential encoding structure. By searching over a tree based on maximum-likelihood (ML), we aim to find the branch with minimum cost. The key challenge is how to achieve a practical ML decoder with ensured performance and minimum computational overhead. Here we adopt a soft information based M-Algorithm to solve the problem, which helps to prune the tree fast and accurate.

Upon receiving a combined signal $\bar{y}$, the ML rule for sequential coding is as follows:

$$\hat{M} \in \arg \min_{M' \in \{0,1\}^n} \sum_{i=1}^{n/k} \|\bar{y}_i - \tilde{x}_i(s'_i)\|^2$$

Where $\bar{y}_i$ is decomposed $\bar{y}$ that contains symbols from spine value s_i, and $x_i(s'_i)$ is the replayed encoding symbols from s_i. Our job is to find a sequence of s'_i that closest to $\bar{y}$ in l_2 distance. It is noticed that this l_2 Euclidean is for AWGN channel. As for Binary Symmetric Channel (BSC), the distance is replaced by Hamming distance.

A common approach for ML decoding is to construct a tree and conduct brute-force searching, where the branches from all the concurrent transmissions are computed and compared. However, the computational complexity grows exponentially with the number of concurrent transmissions. Thanks to the linearity property of HDMA, a receiver only needs to construct its own decoding tree. In the downlink, assume that AP is transmitting to Alice, Bob and Coral concurrently. The received signal at Alice $\bar{y}_{a,i}$ is,

$$\begin{aligned}\bar{y}_{a,i} &= h_a(\tilde{x}_{a,i} + \tilde{x}_{b,i} + \tilde{x}_{c,i}) + n \\ &= h_a\tilde{x}_{a,i} + h_a\sum_{l=b,c}\tilde{x}_{l,i} + n \\ &= h_a\tilde{x}_{a,i} + \zeta_i \end{aligned} \tag{4}$$

In the uplink, assume Alice, Bob and Coral are transmitting concurrently with the AP. The received signal at AP $\bar{y}_{ap,i}$ is,

$$\begin{aligned}\bar{y}_{ap,i} &= h_a\tilde{x}_{a,i} + h_b\tilde{x}_{b,i} + h_c\tilde{x}_{c,i} + n \\ &= h_a\tilde{x}_{a,i} + \sum_{l=b,c} h_l\tilde{x}_{l,i} + n \\ &= h_a\tilde{x}_{a,i} + \zeta_i \end{aligned} \tag{5}$$

where n donates the Gaussian noise with mean zero and variance σ_n^2. h_a, h_b and h_c is the frequency channel responses from Alice, Bob and Coral. From Equation (4) and (5), the messages from other clients and noise are distortion ζ_i. From the central limit theorem, ζ_i can be approximated as a Gaussian variable. Therefore, Alice (or the AP) only needs to construct a single decoding tree for the desired message.

The tree decoding problem is not trivial in multi-user scenario. As the number of multiple access increases, the distortion becomes higher. Thus we cannot simple using M-Algorithm [8] to prune the tree with B best survivors as that in single user scenario. The discarded branches actually carry a significant amount of reliable soft-information. The extracted soft-information can be utilized improve the decoding accuracy with little computational overhead. The soft-information is also termed as Log-Likelihood Ratio (LLR). It indicates the certainty of each bit decision made by the decoder, can be obtained using the following equation,

$$LLR_0(i) = \frac{2y_i}{\sigma^2}, i = 1, ..., N. \tag{6}$$

In a decoding tree or trellis, the LLR is computed by the metric difference between the approximated maximum likelihood branch and the best C competitor that has opposite bit decisions from the discard branch. The soft-information is then used to correct the final decoding decisions.

D. MAC Layer Multiple Access

For multiple concurrent transmission, different clients normally experience diverse link quality. Therefore, the packet transmission time will not be equal. HDMA adopts a AP driven MAC protocol to schedule the downlink and uplink transmissions. The MAC protocol aims to fully utilize the transmission concurrency and provide ensured fairness.

The primary concern for any rateless code over commercial half-duplex radios is to address the tradeoff between the feedback overhead and accuracy. In HDMA, we divide the entire transmission round into multiple fine-grained subrounds, a transmitter pauses to wait for the feedback from its receiver after each subround. Traditional feedback using 802.11 ACK is known to be costly. In HDMA , correlated symbol sequence (CSS) is leveraged for efficient feedback delivery [9]. CSS can be easily detected by correlating it with the incoming samples. Thus, the control overhead (e.g., preamble, frame checksum, etc.) can be avoided and frame duration can be reduced. The use of CSS exempts the usage of preamble, and enables the symbol level synchronization. After CSS, an OFDM symbol is appended as the ACK payload. Each client is assigned a couple of subcarriers within the symbol to declare its decoding status using Binary Amplitude Modulation.

In the downlink, upon receiving the feedback from all the clients, the AP adopts an adaptive allocation algorithm to avoid redundant transmission and ensure fairness among all the clients. Assume that the total number of clients that needs to be transmitted is N, and the maximum number of concurrent transmissions is L, the allocation algorithm aims to achieve a fined-grained allocation without any knowledge on the AP side. The AP first numbers all the transmission request in ascending order starting from index 1 to N for initialization. Upon receiving a "1" from a client, the AP realizes that the message block for that client has been successfully decoded and deletes it from the table $queue$. Afterwards, the AP will pick up the first message block from the table $unfinished$ and put it into $queue$. This allocation is conducted cyclically until the $queue$ is full. This $queue$ is inserted in the packet preamble to keep all the clients in pace.

In the uplink, all the clients first send their transmission request to the AP, and the AP then constructs a table $unfinished$ as we mentioned before. In each subround, the transmission is scheduled by the AP according to its decoding results. Whenever a message block from client i is decoded, the AP deletes it from the $queue$, picking up the first message block from the $unfinished$ and puts it into $queue$. This table $queue$ is included in the feedback as the ACK payload.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of HDMA through extensive experiments and simulations. Our rateless-based PHY layer are built on top of 802.11 OFDM modules on GNURadio/USRP2 platform. The USRP2 uses the RFX2450 daughterboard as RF frontend, which operates in the 2.4-2.5GHZ range. The emulations are interconnected written in C++ and Matlab. Fixed-rate LDPC codes (802.11n) with perfect rate adaptation, rateless Spinal codes, and rateless enabled AutoMAC are selected as comparisons under different scenarios. In the following experiments, each run transfers 2500 packets, which are randomly generated with length of 1460 bytes. The channel bandwidth is 20MHz with 64-point FFT, where 48 subcarriers are used for data transmission, and 4 serves as pilots. The channel bandwidth is 20MHz, with 64-point FFT modulation. 48 subcarriers are used for data transmission, and 4 serves as pilots. We measure the

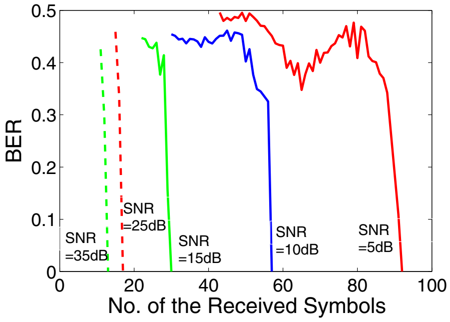


Fig. 4: The BER vs no.of the received symbol in HDMA. The BER threshold behavior verifies the rateless property of HDMA.

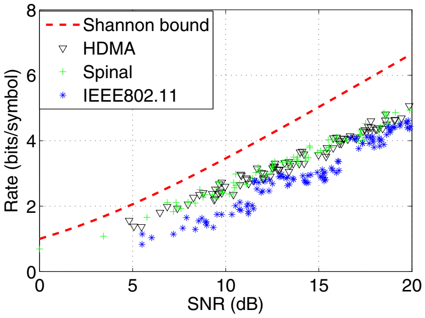


Fig. 5: The achieved data rate. HDMA has comparable performance with Spinal codes.

SNR range from 0dB to 35dB with 1dB interval. The channel models are AWGN channel and flat fading channel. Through extensive simulations, we can see that HDMA outperform AutoMAC in the entire SNR range. That is because HDMA has the ability to exploit the constellation redundancy and harness hash space orthogonality for multiple access. Without loss of generality, we use Shannon Bound in AWGN channel as the upper bound in all the channel models.

A. *HDMA's PHY Layer Performance*

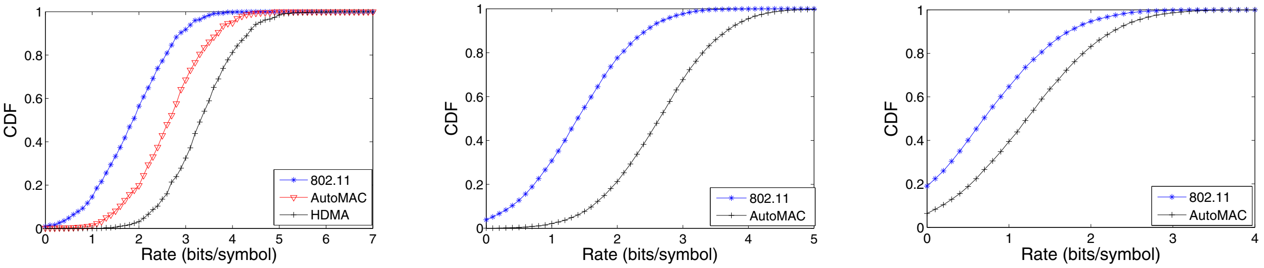
In this part, we conduct experiment to evaluate the feasibility of HDMA's PHY layer encoding and decoding scheme. We use one USRP node as AP and other node as client. The AP keeps transmitting packets to the client using LDPC, spinal and HDMA respectively. Our target is to prove that the orthogonal and linear encoder does not corrupt the randomness and rateless property, and the soft-information based M-algorithm achieves the capacity. To verify this point, we measure the BER as a function of the number of received symbols under different SNRs. As shown in Fig. 4, higher SNR leads to faster decoding. As the number of received symbol increases, BER decreases slightly, showing that the receiver are accumulating symbols for decoding. After receiving a certain number of symbols, BER quickly drops to 0, indicating that the message block is successfully decoded. This BER threshold behavior verifies that HDMA functions well as rateless codes, and does not waste any single symbol for decoding. Therefore, it can achieve the capacity at any channel condition. Next, we compare the performance of HDMA with LDPC codes and rateless Spinal codes. As shown in Fig. 5, the achieved data rate is depicted as a function of SNR. LDPC codes perform quite poorly due fading and multipath effect. On the contrary, thanks to the rateless property, both HDMA and spinal achieve desirable data rate even under poor channel condition, and outperform LDPC by 100%. Furthermore, HDMA achieves a comparable performance with spinal codes across the entire SNR range. This indicates that the linear random number generator also maintains universal randomness, and our constructed orthogonality upon spine value does not ruin the rateless property.

B. *HDMA's MAC Layer Performance*

In this part, we evaluate the multiplexing gain using HDMA. Due to the latency constraint of USRP2, we are not allowed to conduct the realtime evaluation for MAC layer protocol. Therefore, we conduct trace-driven emulations to evaluate the downlink and uplink concurrent transmissions. We use a typical WLAN configuration. Each AP-client link is assigned a channel model with different parameters. We select the public trace in SIGCOMM'08 [10] to ensure the simulations are repeatable. The trace is feeded into custom emulator interconnected written in C++ and with the HDMAs implementation. AutoMAC is chosen as our comparison, as it is the state-of-the-art work that leverages rateless codes for concurrent transmissions.

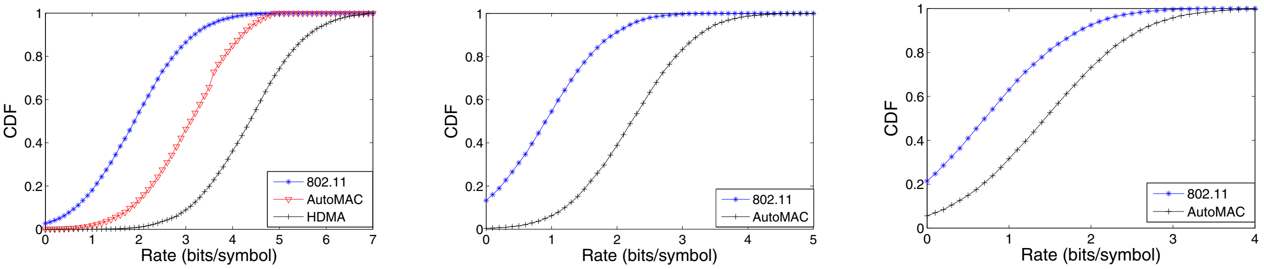
In the downlink, the AP encodes the message for a number of clients and broadcasts it into the air. Upon receiving the packet, each client decodes its own component and feedback to the AP. We choose the MAC layer received data rate as our basic performance metric, which is calculated by multiplying the bits per symbol with channel bandwidth, and subtracting MAC layer overheads. As we mentioned before, the maximum number of concurrent transmission supported in HDMA cannot exceed the shannon bound. That means with more concurrent transmissions, the per user throughput might become lower. Thus we need to find a good balance between concurrency and per user throughput. Fig. 6 depicts the cumulative distribution function of throughput gains in the downlink. The performance of HDMA, AutoMAC and 802.11 with perfect rate adaptation scheme are compared with difference number of concurrent transmissions. Both HDMA and AutoMAC outperform 802.11n in terms of the multiplexing gain. In particular, HDMA achieves up to 82% performance gain over 802.11n. HDMA also outperform AutoMAC by 39%. As AutoMAC only supports 3 downlink concurrent transmissions, HDMA can achieve more. As the number of concurrent transmission increases, there are more users with higher throughput. When the number exceed 5, the per user throughput begins to decline, indicating that it is better for HDMA to support 4 to 5 concurrent transmissions.

In the uplink, the AP is responsible for scheduling. Thus each client first sends its transmission request to the AP using PHY layer signalling. After the feedback from the AP,



(a) L=3 (b) L=4 (c) L=5

Fig. 6: Cumulative distribution function of throughput gains in the downlink with different number of concurrent transmission L. We compare HDMA with AutoMAC and 802.11 with perfect rate adaptation.



(a) L=2 (b) L=3 (c) L=4

Fig. 7: Cumulative distribution function of throughput gains in the uplink with different number of concurrent transmission L. We compare HDMA with AutoMAC and 802.11n with perfect rate adaptation.

the designated clients begin to transmit concurrently. Here we also use the MAC layer received data rate as our basic performance metric, and we would like to see the performance under different number of concurrent transmissions. As gauged in Fig. 7, the cumulative distribution function of throughput gains in the uplink is compared among HDMA, AutoMAC and 802.11n with perfect rate adaptation. Not surprisingly, HDMA outperforms 802.11n by enabling multiple concurrent transmissions. The performance gain is 118% for 2 concurrent transmissions, 131% for 3 concurrent transmissions and 92% for 4 concurrent transmissions. The performance degradation is expected, since the channel capacity cannot exceed the shannon bound. However, HDMA still outperform AutoMAC since AutoMAC can only support 2 uplink concurrent transmissions.

V. CONCLUSION

In this paper, we propose a novel multiple access scheme termed hash division multiple access (HDMA). HDMA leverages the recent advances on dense constellation diagram. By constructing orthogonality in hash space to leverage the constellation redundancy, HDMA enables a new multiplexing dimension. We first present the PHY layer encoder design in HDMA. A soft-information based decoding algorithm is proposed to achieve a practical and efficient decoder. We further present an AP driven MAC protocol to fully utilize the transmission concurrency. The experiment via GNU radio verifies the feasibility of HDMA. Extensive simulation results show that HDMA achieves a performance gain over 131% compared to traditional Wifi that picks the best bitrate.

ACKNOWLEDGMENT

The research was supported in part by grants from China NSFC under Grant 61502313,61472259,61202377, Shenzhen Science and Technology Foundation JCYJ20150324141711621, KQCX20150324160536457, Project 2016044 supported by SZU R/D fund, RGC under the contracts CERG 622613, 16212714, and 16203215, Program for New Century Excellent Talents in University (NCET-13-0908), Guangdong Talent Project 2014TQ01X238, 2015TX01X111 and GDUPS (2015).

REFERENCES

[1] A. Gudipati and S. Katti, “Strider: Automatic rate adaptation and collision handling,” *ACM SIGCOMM*, 2011.
[2] J. Perry, H. Balakrishnan, and D. Shah, “Rateless spinal codes,” in *ACM HotNets*, 2011.
[3] C. E. Shannon, “A mathematical theory of communication,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, no. 1, pp. 3–55, 2001.
[4] T. S. Rappaport *et al.*, *Wireless communications: principles and practice*. prentice hall PTR New Jersey, 1996, vol. 2.
[5] L. Ping, L. Liu, K. Wu, and W. K. Leung, “Interleave division multiple-access,” *Wireless Communications, IEEE Transactions on*, vol. 5, no. 4, pp. 938–947, 2006.
[6] A. Gudipati, S. Pereira, and S. Katti, “Automac: rateless wireless concurrent medium access,” in *Proceedings of the 18th annual international conference on Mobile computing and networking*. ACM, 2012, pp. 5–16.
[7] P. L’Ecuyer and T. H. Andres, “A random number generator based on the combination of four lcgs,” *Mathematics and Computers in Simulation*, vol. 44, no. 1, pp. 99–107, 1997.
[8] J. B. Anderson and S. Mohan, “Sequential coding algorithms: A survey and cost analysis,” *Communications, IEEE Transactions on*, vol. 32, no. 2, pp. 169–176, 1984.
[9] E. Magistretti, O. Gurewitz, and E. Knightly, “802.11 ec: collision avoidance without control messages,” in *ACM MobiCom*, 2012.
[10] A. Schulman, D. Levin, and N. Spring, “Crawdad data set umd/sigcomm2008 (v. 2009-03-02),” 2009.