Defeating Heterogeneity in Wireless Multicast Networks

Eugene Chai, Kang G. Shin
University of Michigan – Ann Arbor
{zontar, kgshin}@eecs.umich.edu

Sung-Ju Lee, Jeongkeun Lee, Raul Etkin
Hewlett-Packard Labs – Palo Alto
{sjlee, jklee, raul.etkin}@hp.com

***Abstract*—The growing demand for real-time streaming video on portable devices has increased the importance of multimedia multicast in mobile wireless networks. A defining characteristic of such multicast networks is its heterogeneity in both the channel states and the MIMO capabilities of its clients. However, current wireless multicast schemes adapt poorly to such heterogeneity. We introduce *Procrustes*, a multimedia multicast scheme that is built upon a novel PHY-layer rateless code. Unlike bit-level rateless codes (such as Raptor [14] codes), Procrustes clients automatically adjust the PSNR of the received multicast video stream to match both the instantaneous channel state and the number of active receive antennas. We demonstrate the performance of Procrustes in a simulated environment.**

I. Introduction

The ubiquity of high-bandwidth MIMO wireless networks has created a high demand for real-time multicast video streaming applications on mobile devices. Examples include group video conferencing between participants from multiple sites and live broadcast of the Olympic games to multiple devices in an airport lounge. Such networks predominantly consist of energy-constrained, heterogeneous MIMO mobile wireless devices. Hence, the development of a power-efficient video multicast schemes is necessary and important.

Heterogeneity. A key requirement for video multicast over mobile MIMO networks is the ability to trade off gains between transmit/receive diversity and spatial multiplexing at all clients to maintain an acceptable PSNR while consuming as little energy as possible. Unfortunately, the current video multicast scheme cannot fully exploit this diversity-multiplexing tradeoff because of the PHY-layer heterogeneity in both the channel state and the number of antennas of the clients.

(a) Channel state. Heterogeneity of the time-varying channel conditions at different mobile clients forces the multicast scheme to conservatively select a diversity-multiplexing operating point to ensure that the BER is acceptable for the client with the lowest SNR. For example, in order to maintain a minimum video quality to all clients, transmit diversity may have to be increased at the expense of additional independent streams due to a client with a low-SNR channel. This unfairly penalizes clients with higher-SNR (i.e., better) channels that can otherwise receive the video at a higher bitrate.

(b) Number of receive antennas. Due to the heterogeneity of the number of receive antennas, the spatial multiplexing gain of the entire multicast group is unfairly upper-bounded by the device with the fewest number of antennas. The cost of tracking the hardware capabilities of all mobile clients can be excessive in the presence of a high client churn. Hence, the multicast transmitter must be conservative in employing additional spatial dimensions to improve the multimedia quality and bitrate.

Bit-level rateless codes for video streaming [1], [14] can mitigate the undesirable effects of channel heterogeneity. Such fountain codes adapt their rates to match the instantaneous SNR of the wireless channel — bit errors that occur due to bursts of interference/noise can be recovered from other code words from the fountain. However, since they are independent of the underlying PHY mechanism, they cannot overcome the channel degradation from antenna heterogeneity.

Multicast group management. An important challenge to efficient multicast operation is group managment: the transmitter must partition clients into groups with similar channel qualities [10]. This grouping can be done only if the transmitter knows the channel state to every downstream client [3]. However, obtaining this information typically involves probing the channel to every client — a potentially expensive step that adds a significant overhead to the multicast operation.

Antenna heterogeneity adds an additional dimension of complexity to this grouping process. Clients must now be grouped not just by their channel states but also by their number of receive antennas. This can increase the number of multicast groups, thereby increasing the number of separate multicast transmissions necessary to send a single frame.

Key insight. Rateless coding in the *antenna domain* generates a stream of coded symbols that are agnostic to the number of antennas at the receiver. The transmitter no longer has to (a) probe the state of channel to every client, or (b) ensure that clients are grouped by antenna count. This is important since current wireless networks increasingly include devices of varying numbers of antennas. For example, most smartphones have only one WiFi antenna because of space and energy constraints, while laptops have three or more antennas. Hence, the inability to compensate for antenna heterogeneity severely limits the video multicast capacity.

The work reported in this paper was supported in part by the NSF under Grant CNS-1160775

978-1-4673-5946-7/13/$31.00 ©2013 IEEE

Our Solution: Procrustes[2]

We introduce Procrustes, a wireless video multicast scheme that is built upon a novel PHY-layer rateless code. Procrustes maintains the efficiency of broadcast-based multicast while allowing each mobile node to exploit both diversity and multiplexing gains for energy-efficient video reception.

Antenna-domain rateless coding. Procrustes is based on the observation that each OFDM symbol received by an antenna of a MIMO device is a linear combination of multiple transmitted symbols due to the MIMO channel. Procrustes is rateless as the transmitter can generate an infinite stream of random linear combinations. The Procrustes receiver only needs to collect a sufficient number of linearly independent combinations to recover the transmitted symbols. This is more efficient than the usual practice of retransmitting the entire erroneous frames.

An important consequence of antenna-domain rateless coding is that the number of transmit and receive antennas are no longer limiting factors in PHY-layer transmissions. Each receive antenna can be regarded as an independent "collector" of linear equations to be used by the decoder. Similarly, each transmit antenna can be regarded as a simple sender of coefficients that is combined linearly by the MIMO channel. The larger the number of receive antennas, the faster the rate at which linear equations can be collected. However, successful decoding can still occur with fewer equations. The BER simply scales with receive antenna count and channel state and no explicit TX-RX antenna coordination is now necessary.

Simplified multicast grouping. The diversity and multiplexing gain no longer have to be conservatively selected to match that of the client with the fewest antennas or the noisiest channel. Instead, the transmitter simply sends a stream of coded linear combinations to all clients in the multicast group. Clients then decode the transmissions as soon as they have collected a sufficient number of equations. This simplifies the multicast grouping restrictions and reduces the number of channel accesses needed to reach all downstream clients.

We discuss related work in §II and describe Procrustes in §III. We demonstrate its performance using simulations in §IV and conclude in §V.

II. Related Work

MU-MIMO [2], [6], [7] constructs multiple indepedent and parallel channels from the transmitter to each of its clients. Unfortunately, MU-MIMO suffers from similar limitations: the channel state of all downstream clients must be known to the transmitter the number of parallel channels that can be supported is limited to the number of transmit antennas available. Procrustes does not suffer from such scalability problems as it relies mainly on broadcasting rateless coded symbols. Hence, the coding overhead depends on the number of spatial streams and the number of transmit antennas (which are not necessarily equal), and is independent on the number of multicast clients.

[2]Conformist blacksmith of ancient Greece.

Bit-level rateless codes such as Spinal codes [11] and Raptor codes [14] provide resilience to random fluctuations in channel state. Unlike Procrustes, these codes do not exploit the MIMO channel state and thus are not able to mitigate the effects of antenna heterogeneity. However, the fact that these codes operate on bits, and not PHY-layer symbols means that they are orthogonal to and can be used in conjunction with Procrustes.

PHY-layer rateless codes [8], [13] operate on PHY-layer symbols. Strider [8] is a layered code that combines a PHY-layer code with a bit-level channel code. Although this combination offers the adaptability that comes with cross-layer rateless coding, it is not designed for multicast and thus does not address the issue of antenna heterogeneity. Procrustes reduces multicast overhead due to heterogeneous devices. The authors in [13] describe a rateless coding over MIMO approach that builds upon diagonal D-BLAST space-time codes. This is similar to our work in that it exploits the MIMO channel for rateless code construction, but it does not take advantage of antenna heterogeneity that is present in multicast networks.

Space-time block codes (STBCs) [9], [15] are fixed rate codes that exploit multiple antennas to improve transmit and receive diversity. STBCs inherit the afore-mentioned limitations associated with fixed-rate codes. This fixed-rate nature of STBCs extends to its PHY-layer operation — all transmitted code words must be used in the decoding process to recover the original transmitted symbols. Moreover, the STBC code words are necessarily constructed according to an agreed-upon TX and RX antenna configuration. Hence, STBC cannot adapt to client antenna heterogeneity as the number of TX and RX antennas must be known before coding commences.

III. Procrustes Design

Objective. Procrustes is built upon a novel rateless code that instantaneously adapts to both antenna and channel heterogeneity of the downstream multicast clients. Procrustes aims to (a) reduce multicast coordination overhead and (b) maximize the energy-efficiency of of the multicast stream, while keeping the absolute video bitrate above the target threshold.

Overview. Procrustes consists of two main components: the encoder and the decoder The encoder and the decoder are employed at the transmitter and the receiver, respectively. The encoder selects a code rate and generates ratelessly-coded symbols at that chosen code rate; the decoder collects these coded symbols and attempts to recover the original symbols once a sufficient number of coded symbols have been received.

A. Procrustes Encoder

Given a Procrustes transmitter with N_T transmit antennas, the code rate of the Procrustes encoder is governed by two parameters: the number of spatial streams per subcarrier, N_D, and the number of blocks, N_B. Let N_{SC} be the number of OFDM subcarriers in each frame.

Figure 1 shows a high-level overview of the encoder. A stream of uncoded *data symbols* is packed into one or more uncoded OFDM *frames*. Each OFDM frame consists of N_{sym} OFDM *symbols*. For simplicity, we illustrate the case of

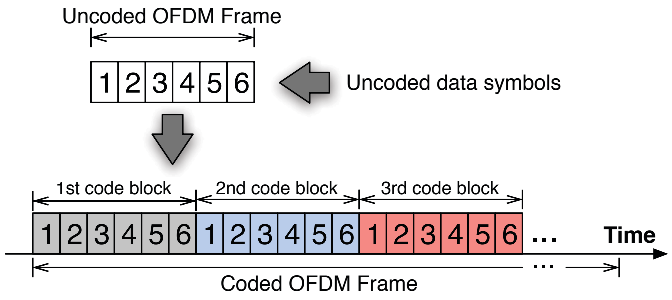


Fig. 1: Procrustes encoder.

$N_{sym} = 6$. Each uncoded OFDM symbol is then replicated across multiple code blocks using the rateless code to form a fully coded OFDM frame.

Let $\mathbf{X}_n$ be an $N_D \times N_{sc}$ matrix that represents the n^{th} OFDM symbol, where $n \in \{1, \ldots, N_{sym}\}$. Each of the N_{SC} columns of $\mathbf{X}_n$ represents a subcarrier that is used to transmit N_D data symbols in separate spatial streams. Also, let $\mathbf{x}_{n,s}$ where $s \in \{1, \ldots, N_{SC}\}$ be the s^{th} column vector of $\mathbf{X}_n$. Note that $\mathbf{x}_{n,s}$ also represents the N_D data symbols mapped to the s^{th} subcarrier of the uncoded OFDM frame. Thus, we can write $\mathbf{X}_n = [\mathbf{x}_{n,1}, \ldots, \mathbf{x}_{n,N_{SC}}]$. Unless otherwise indicated, all vectors are column vectors.

Let $\mathbf{Y}_{n,b}$ be the n^{th} coded OFDM symbol in the b^{th} block where $b \in \{1, \ldots, N_B\}$ and can be expressed as

$$\mathbf{Y}_{n,b} = \mathbf{K}(\mathbf{P}_b \mathbf{X}_n^T)^T = \mathbf{K}\mathbf{X}_n\mathbf{P}_b^T \tag{1}$$

where $\mathbf{K}$ is an $N_T \times N_D$ complex-valued antenna mapping matrix, $\mathbf{P}_b$ is an $N_{SC} \times N_{SC}$ subcarrier permutation matrix and $(\cdot)^T$ indicates a non-Hermitian transpose. Note that to avoid distorting the transmit power of the original data symbols, each column and row of K must have a norm of 1. This encoding process can be understood to proceed in two steps:

Step 1. Subcarrier permutation. The permutation matrix cyclically rotates the columns of $\mathbf{X}$ such that

$$\mathbf{X}_n\mathbf{P}_b^T = [\mathbf{x}_{n,b}, \ldots \mathbf{x}_{n,N_{SC}}, \mathbf{x}_{n,1}, \ldots \mathbf{x}_{n,b-1}].$$

This permutation step ensures that each data symbol in the OFDM symbol is transmitted over different subcarriers in different coded blocks. In frequency-selective fading channels, the channel state of different subcarriers can differ significantly. Hence, this increases the probability that the different linear combinations of the OFDM symbol from different coded blocks are independent. Note that the constraint $N_B \leq N_{SC}$ is necessary to prevent any repeated permutations.

Step 2. Antenna mapping. The mapping matrix, $\mathbf{K}$, ensures that length-N_D vector of data symbols in each subcarrier is mapped onto N_T transmit antennas. This mapping step controls the spatial-multiplexing tradeoff at the transmitter. If $N_D = N_T$, the transmitter sends one data stream on each available spatial dimension. If $N_D < N_T$, transmit diversity is used in addition to spatial multiplexing. Note that $\mathbf{K}$ can be a fixed, pre-defined matrix, or generated using an RNG. It must be known to both the receiver and the transmitter for correct decoding.

B. Procrustes Decoder

PHY-layer rateless decoder. Consider a MIMO client with N_R antennas. Let $\mathbf{H}_s$ be the $N_R \times N_T$ channel state matrix of the s^{th} subcarrier. Procrustes assumes that the channel remains constant over the entire duration of the coded OFDM frame. We express $\mathbf{Y}_{n,b} = [\mathbf{y}_{n,b}^1, \ldots, \mathbf{y}_{n,b}^{N_{SC}}]$ where $\mathbf{y}_{n,b}^s$ is the s^{th} column vector of $\mathbf{Y}_{n,b}$.

For the sake of clarity, we describe the decoding process necessary to recover $\mathbf{x}_{1,1}$ — the N_D data symbols mapped to the first subcarrier of the first uncoded OFDM symbol. Let $M_B \leq N_B$ be the number of coded blocks that the Procrustes receiver uses to decode $\mathbf{x}_{1,1}$.

Due to the permutation step in the encoder, $\mathbf{x}_{1,1}$ is mapped to $\hat{\mathbf{Y}} = [\mathbf{y}_{1,1}^1, \mathbf{y}_{1,2}^2, \ldots, \mathbf{y}_{1,M_B}^{N_B}]$. The received linear equations corresponding to $\mathbf{x}_{1,1}$ can be written as

$$\begin{aligned}\mathbf{Z} &= \begin{bmatrix} \mathbf{H}_1\mathbf{y}_{1,1}^1 \\ \vdots \\ \mathbf{H}_{M_B}\mathbf{y}_{1,M_B}^{M_B} \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \vdots \\ \mathbf{n}_{M_B} \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{H}_1\mathbf{K}\mathbf{x}_{1,1} \\ \vdots \\ \mathbf{H}_{M_B}\mathbf{K}\mathbf{x}_{1,1} \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \vdots \\ \mathbf{n}_{M_B} \end{bmatrix} \\ &= \mathbf{H}\mathbf{K}\mathbf{x}_{1,1} + \mathbf{N} \end{aligned} \tag{2}$$

where $\mathbf{H} = [\mathbf{H}_1^T \ldots \mathbf{H}_{M_B}^T]^T$ is the composite channel state matrix and $\mathbf{N} = [\mathbf{n}_1^T \ldots \mathbf{n}_{M_B}^T]^T$ is the noise seen on all blocks. Hence, we can recover $\mathbf{x}_{1,1}$ according to

$$\hat{\mathbf{x}}_{1,1} = (\mathbf{H}\mathbf{K})^+\mathbf{Z} \tag{3}$$

where $(\cdot)^+$ is the Moore-Penrose pseudoinverse. This decoding process is repeated for every transmitted data symbol in the OFDM frame.

Decoder features. There are two key features that set Procrustes apart from other PHY-layer communication schemes. First, the number of coded blocks used for decoding, M_B, can be less than the number of transmitted coded blocks, N_B. Second, decoding can be successful even if $N_R < N_T$ and $N_R < N_D$. This means that the antenna configurations of both the receiver and transmitter do not need to be known to each other in advance. Hence, the receiver independently adapts its diversity and multiplexing gains to maximize the video quality without full coordination from the transmitter.

C. Channel Estimation

The receiver must know $\mathbf{H}$ before it can recover the transmissions according to (2). In practice, this is done by inserting known training sequences for each antenna into the frame header, similar to the approach adopted by 802.11n. The receiver can estimate the channel state $\mathbf{H}$ via correlation against the known sequenes.

IV. Experimental Evaluation

We now demonstrate the performance of Procrustes and discuss the unique challenges and opportunities presented by a PHY-layer rateless code in a wireless multimedia multicast network.

A. Simulation Setup

Transmitter. The Procrustes transmitter uses a 20MHz bandwidth and is equipped with 8 antennas. It can use any $N_T \in \{1, 2, 4, 8\}$ of them for transmitting a frame. The number of transmitted blocks, $N_B \in \{1, \ldots, 8\}$, sets a lower bound on the bitrate achievable by the transmitter. The video stream can be transmitted using either QPSK, 16QAM or 64QAM modulation rate.

Receiver. Each Procrustes client has $N_R \in \{1, \ldots, 8\}$ antennas and can exploit receive diversity through the use any subset of them for reception, regardless of N_T and N_D.

WiFi model. We compare the multicast performance of Procrustes with that of WiFi MIMO PHY. The WiFi transmitter differs from Procrustes in five ways: (i) $N_D = N_{R,min}$ because the degrees of freedom in a MIMO network is upper bounded by the client with the smallest number of antennas; (ii) $N_T = N_{R,min}$ as this is the typical operating mode of 802.11-based MIMO networks without space-time coding; (iii) each coded block in the coded OFDM frame is simply an unmodified copy of the original uncoded OFDM frame and each bit is repeated N_B times in the transmitted OFDM frame; (iv) $M_B = N_B$ to model the use of 802.11n frame aggregation for transmitting the coded OFDM frame; and (v) a repetition code is used to protect against bit errors — a bit is decoded correctly if and only if more than half of its copies are decoded correctly. Note that we do not use any FEC code with the WiFi model so that we can accurately compare the effects of PHY layer errors in WiFi and Procrustes. FEC codes are orthogonal to Procrustes and can be used together with Procrustes to further reduce bit error rates.

Network. A multicast network consists of a single transmitter and 120 clients. The $N_{R,min}$ of the network refers to the smallest number of antennas that a client can have. The number of antennas in each of these 120 clients are uniformly distributed over $[N_{R,min}, 8]$. We also set $P_{RF_Chain} = 62.5$mW and $P_{Shared} = 50$mW for the client power model [5]. The clients are spatially distributed throughout the network such that the SNR between the client and transmitter is evenly distributed over 5, 10, 15 and 20dB. We use the fading model as given by the `jtcInOffC` model in Matlab.

Metrics — PSNR. We measure the performance of Procrustes and WiFi using the PSNR at the Procrustes clients. [12] shows the relationship between PSNR and the Mean Opinion Score (MOS) of the received video stream.

Multicast ACK. The Procrustes encoder must adjust its coding parameters to ensure that all multicast clients obtain a bitrate and PSNR level that meets the QoS requirements. An ACK mechanism from the multicast clients provides the necessary information for the transmitter to make such adjustments.

The ACK frame is a pseudonoise (PN) sequence, selected from a known set of PN sequences. A candidate set of PN sequences is a set of Zadoff-Chu sequences [4]. Each PN sequence in the set is mapped to a predefined QoS level. The Procrustes transmitter detects ACK frames by correlating the received signals with matched filters and counting the number of corresponding correlation peaks. The matched filter can detect individual PN sequences from multiple overlapping transmissions, thus reducing the ACK delay in large multicast networks.

B. Maximizing PSNR

Figures 2 and 4 show the box plots of the PSNR achieved by Procrustes-PSNR and WiFi-PSNR at different minimum video bitrates. Note that WiFi-PSNR cannot support any of the requested video bitrates when $N_{R,min} = 1$. In that network configuration, it is constrained to use only a single stream and no transmitter configuration can achieve the minimum of 1Mbps bitrate with only stream.

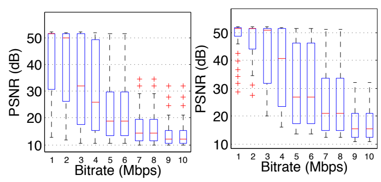
With $N_{R,min} = 1$, Procrustes-PSNR clients achieve a median video MOS of Excellent at bitrates of 1 and 2Mbps. MOS decreases to Good at 3Mbps, Fair at 4Mbps and Poor thereafter. This trend improves as $N_{R,min}$ increases due to the availability of additional degrees of freedom within the network. With $N_{R,min} = 8$, the median MOS remains at Excellent as video bitrates increase up to 3Mbps. In contrast, WiFi-PSNR clients do not achieve median video MOS better than Fair at all bitrates. Furthermore, note that with only two available streams at $N_{R,min} = 2$, WiFi-PSNR transmit at bitrates greater than 8Mbps.

Figures 3 and 5 shed some light on this performance gap by showing the transmission parameters used by Procrustes-PSNR and WiFi-PSNR for each OFDM frame. Each bar chart plots the parameter values for all bitrates. For each bitrate, the parameter values for $N_{R,min} = 1, 2, 4, 8$ are shown in that order. Note that the parameters for WiFi-PSNR in Figure 5 show only 3 bar plots for each bitrate because WiFi-PSNR cannot support the minimum bitrate at $N_{R,min} = 1$.

Procrustes-PSNR uses all 8 transmit antennas in almost all situations to exploit transmit diversity to maximize the PSNR at the receivers. Furthermore, Procrustes-PSNR uses more data dimensions than the minimum number of receive antennas in all cases. This increases the overall transmission rate, especially for clients with larger numbers of antennas. Clients with fewer antennas than N_D collect additional coded blocks to obtain sufficient linear equations for (2). This is evident from the fact that Procrustes-PSNR transmits more coded blocks than WiFi-PSNR in many cases.

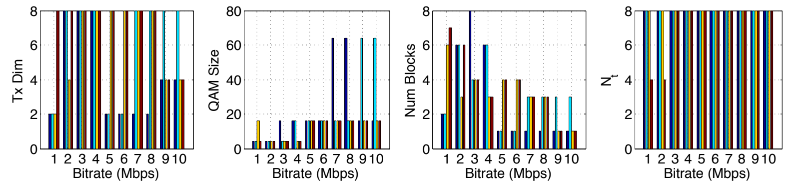
WiFi-PSNR, on the other hand, is limited to selecting the number of streams and associated modulation rates. We emphasize the WiFi-PSNR has to conservatively select parameters that are feasible for the client with the smallest number of antenna and worst channel state. Note that the addition of transmit diversity will not improve the throughput of WiFi-PSNR multicast because diversity codes (e.g. Alamouti codes) are fixed rate codes, which again have to be conservatively selected to support the "weakest" client. Furthermore, transmit diversity may help clients with low SNR channels, but are of limited use to clients with high SNR channels.

Intuitively, Procrustes-PSNR selects N_T and N_D to meet the demands of clients with larger antennas and better channels, while allowing other clients to reduce decoding error by collecting more coded blocks. The ability to trade-off between



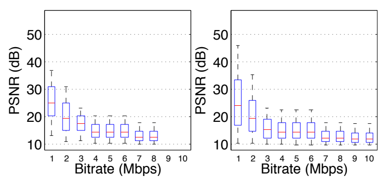
(a) $N_{R,min} = 1$ **(b)** $N_{R,min} = 8$

Fig. 2: PSNR achieved by Procrustes-PSNR in two multicast networks.



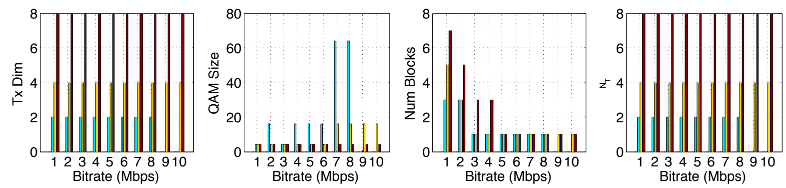
(a) Data dims, N_D **(b)** Modulation rate **(c)** # blocks, N_B **(d)** TX antennas, N_T

Fig. 3: Transmit parameters of Procrustes-PSNR. Each bar chart plots the parameter values for all bitrates. For each bitrate, the parameter values for $N_{R,min} = 1, 2, 4, 8$ are shown in that order.



(a) $N_{R,min} = 2$ **(b)** $N_{R,min} = 8$

Fig. 4: PSNR achieved by WiFi-PSNR.



(a) Data dims, N_D **(b)** Modulation rate **(c)** # blocks, N_B **(d)** TX antennas, N_T

Fig. 5: Transmit parameters of WiFi-PSNR.

the continuum spatial and temporal parameters in a multicast environment is the key to the good performance of Procrustes-PSNR. We emphasize that such a capability is not available in fixed rate STBC or MIMO codes.

V. Conclusion

This paper introduces Procrustes, a PHY-layer rateless code that overcomes channel and antenna heterogeneity in wireless multimedia multicast networks. The Procrustes transmitter can generate an endless stream of PHY-layer coded blocks without full knowledge of the hardware and channel characteristics at the Procrustes clients. Each client then recovers the original transmission after sufficient linearly coded blocks have been collected. We also demonstrated the performance of Procrustes through detailed simulations. This new approach to wireless communications is necessary in light of the upsurge of streaming video over wireless networks with heterogeneous client devices.

References

[1] S. Aditya and S. Katti. FlexCast: graceful wireless video streaming. *Mobicom*, 2011.

[2] E. Aryafar, N. Anand, T. Salonidis, and E. W. Knightly. Design and Experimental Evaluation of Multi-User Beamforming in Wireless LANs. *Mobicom*, pages 197–208, 2010.

[3] E. Aryafar, M. A. Khojastepour, K. Sundaresan, S. Rangarajan, and E. Knightly. ADAM: An Adaptive Beamforming System for Multicasting in Wireless LANs. *INFOCOM*, 2012.

[4] E. Chai, K. Shin, J. Lee, S.-J. Lee, and R. Etkin. Building Efficient Spectrum-Agile Devices for Dummies. *Mobicom*, 2012.

[5] S. Cui and A. Goldsmith. Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks. *JSAC*, 22(6):1089–1098, 2004.

[6] D. Gesbert, M. Kountouris, R. W. Heath, Jr, C.-b. Chae, and T. Sälzer. Shifting the MIMO paradigm. *Signal Processing*, (September):36–46, 2007.

[7] S. Gollakota, S. Perli, and D. Katabi. Interference alignment and cancellation. *SIGCOMM*, 2009.

[8] A. Gudipati and S. Katti. Strider: Automatic rate adaptation and collision handling. *SIGCOMM*, pages 158–169, 2011.

[9] H. Jafarkhani. A quasi-orthogonal space-time block code. *Communications, IEEE Transactions on*, 49(1):1–4, 2001.

[10] K. Lin, W.-l. Shen, and C. Hsu. Quality-Differentiated Video Multicast in Multi-Rate Wireless Networks. *Trans. on Mobile Computing*, pages 1–14, 2011.

[11] J. Perry, H. Balakrishnan, and D. Shah. Rateless spinal codes. *Hotnets*, pages 1–6, 2011.

[12] S. Sen, S. Gilani, S. Srinath, and S. Schmitt. Design and implementation of an approximate communication system for wireless media applications. *Proceedings of the ACM SIGCOMM 2010 conference*, pages 15–26, 2010.

[13] M. Shanechi and U. Erez. Rateless Codes for MIMO Channels. *GLOBECOM*, (1):1–5, 2008.

[14] A. Shokrollahi. Raptor codes. *Information Theory, IEEE Transactions on*, 52(6):2551–2567, 2006.

[15] V. Tarokh and H. Jafarkhani. Space-time block codes from orthogonal designs. *Information Theory, IEEE*, 45(5):1456–1467, July 1999.