Demo: Bringing Hybrid Analog-Digital Beamforming to Commercial MU-MIMO WiFi Networks

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ABSTRACT

Commercial off-the-shelf (COTS) IEEE 802.11ac WiFi systems only use a low number of antennas. This limits the multi-user MIMO (MU-MIMO) performance and, hence, the throughput of such systems, especially in dense environments. We present a unique solution based on hybrid digital-analog (HDA) beamforming to overcome the limitation of COTS WiFi hardware and effectively increase the MU-MIMO gain and to unlock the potential of MU-MIMO in WiFi. We use COTS WiFi hardware in combination with a self-developed beamforming module and novel algorithms for the HDA approach, leveraging the MU-MIMO precoding of the WiFi system. The implemented control and signal processing software is fully transparent to the WiFi part, i.e., no protocol changes are needed. We demonstrate the increase in MU-MIMO gain using unmodified COTS end-user terminals.

CCS CONCEPTS

• **Hardware → Wireless devices**; **Beamforming**; Hardware test;
• **Networks → Wireless local area networks**.

KEYWORDS

MU-MIMO, WiFi, hybrid digital analog beamforming, COTS

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1 HYBRID BEAMFORMING FOR WIFI

In 2013, the IEEE 802.11ac standard extended WiFi to enable multi-user MIMO (MU-MIMO) operation. It supports up to eight spatial streams [1]. The adoption of the full MU-MIMO capability was very slow. Due to the limited number of antennas, which is often equal to the number of spatial streams, the achievable MU-MIMO gain is limited, i.e. it is limited by the rank of the channel matrix. The channel matrix is likely to be not full rank as the channels of the users are not independent to each other [5]. Hence, the maximum MU-MIMO gain is lower than the number of hardware streams. In the 5G mobile communication standard, this limitation is overcome by the concept of massive MIMO using a larger number of antennas [3]. Unfortunately, the cost of this concept might be to high for COTS WiFi products since every antenna needs an additional TX/RX chain. However, in the context of millimeter-wave systems research proposed hybrid digital-analog (HDA) beamforming as a solution to cost and complexity issues [4].

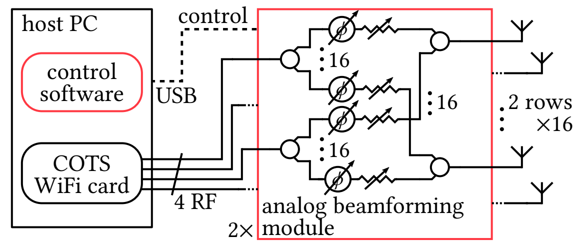

Figure 1: Architecture of the HDA MU-MIMO system with the HDA extension marked in red.

We propose to use HDA beamforming to achieve full MU-MIMO capabilities of the IEEE 802.11 standard. HDA systems use both analog beamforming and digital precoding to implement MU-MIMO processing. The analog part uses hardware to connect a larger number of antenna elements to a lower number of digital streams (see Figure 1). The concept can be seen, as if the analog hardware is forming an effective channel for the digital system, which is more diagonally dominant and, thus, increasing the MU-MIMO gain. Such a system can be realized to be fully transparent to the digital processing, i.e., no changes to the WiFi protocol are needed. Hence, COTS WiFi hardware can be used for the digital part of the system – which also supports angle of arrival (AoA) estimation [9]. In general, such systems will be most useful in larger rooms like auditoriums due to the high number of users and the additional space for larger antennas.

2 HDA-WIFI PROTOTYPE

Our implementation of the HDA MU-MIMO system consists of hardware, both COTS and self developed, and software components. Figure 1 shows an overview of the system. The main components are the antenna array, the analog beamforming module, the COTS WiFi hardware, and the control and signal processing software running on a host PC.

The analog beamforming module connects the antennas to the RF ports of the WiFi card. In an initial state, also called beam alignment (BA), the control software estimates the AoA of the signals from the users. It is using different beamforming patterns during this process. We use the received signal strength indicator (RSSI) reported by

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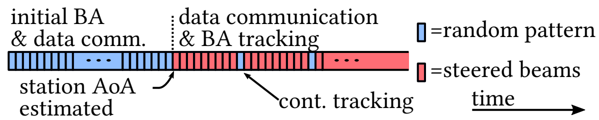

Figure 2: Time sequence of the HDA control protocol.

the WiFi driver[1] of the normal uplink traffic for the estimation. This process is transparent to the WiFi system: it sees a fluctuating channel as if the users would be moving. Once the AoA is estimated, the software steers a beam created using a standard phased array / Fourier-matrix based algorithm towards the client station. Hence, increasing its signal-to-noise ratio and decreasing the interference to other users. Thus, it is forming the effective channel seen by the WiFi MU-MIMO processing. To track moving users or find new users, the BA is periodically re-executed. The time flow is depicted in Figure 2.

2.1 Hardware Details

Our custom antenna array consists of microstrip patches with a tunable center frequency between 2.2 GHz and 2.5 GHz. The array has a size of 2 rows and 16 columns with a spacing of $\lambda/2$ (at a frequency of 2.4 GHz). The analog part is realized using our self-developed analog beamforming module [2]. One module is a network of controllable phase shifters and amplitude modulators with a resolution of 8 bit. It is reciprocal and can be used for TX and RX. The network has a size of 2×16, meaning that two RF chains can be connected to 16 antenna elements (i.e., one row). We use two analog modules in parallel to connect the four RF ports of the WiFi hardware to the two rows of the antenna (see Figure 1). This HDA structure is called one-stream-per-subarray (OSPS) [7]. The insertion loss of the module is 13 dB.[2] The maximum beamforming gain of our antenna for one stream is 12 dB.

For the digital precoding and WiFi processing, we use a QNAP® QWA-AC2600 card operating on channel 1 of the 2.4 GHz band. This card is based on a Qualcomm QCA9984 chip, which supports IEEE 802.11ac with MU-MIMO. Unfortunately, we found out that in our configuration even under perfect channel conditions (i.e., stations connected with RF cables) this chip only supports three concurrent single stream users in MU-MIMO mode. This limitation might be a design choice by Qualcomm [5]. The card is plugged into a standard Intel processor-based PC.

2.2 Software and Signal Processing Details

The software runs on the host PC with Linux kernel in version 5.4. The COTS WiFi card uses the default ath10k driver and firmware. The user data path is fully decoupled from the control software of the HDA system. We run hostapd[3] to enable access point functionality towards client stations.

The control software is written in Python. A detailed description of the BA procedure is given in [6]. In summary, it estimates the AoA using a power measurement, e.g., the RSSI value, and, hence, is robust against phase variations of the WiFi chip [8] and the channel. In contrast to [6], we use beam patterns with amplitudes of one and random phases per element. Using such patterns results on average (over different patterns) in 0 dB antenna gain in every direction. This guarantees that users do not suffer from long connection losses.

[1] The ath10k WiFi driver reports the received power in dB.
[2] The insertion loss is due to hardware impairments excluding the loss from the power distribution in the beamforming network. The module is a research platform and not optimized in terms of loss.
[3] http://w1.fi/hostapd/

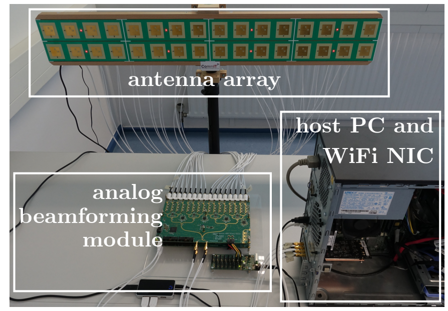

Figure 3: Prototype used during the demonstration.

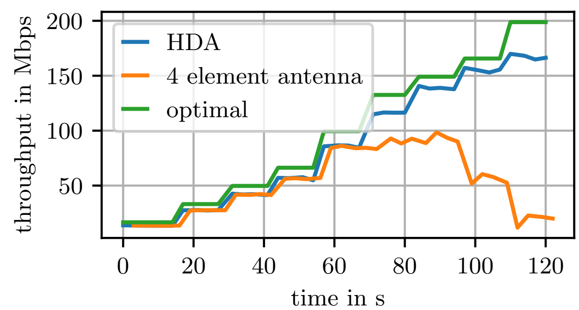

Figure 4: iperf3 throughput of the HDA system and the 4 element antenna system during a MCS sweep.

3 DEMONSTRATION

We demonstrate our novel HDA concept using a COTS WiFi system combined with our new hardware and signal processing extensions. We show the performance gain over a standard four element antenna configuration – supporting four unmodified COTS user stations. Figure 3 shows the demo setup.

We measure the throughput performance using the iperf3 tool. We show the MU-MIMO gain with and without the HDA system (we can also fix the used modulation and coding schemes (MCSs) in our graphical user interface). During the demonstration, the four user stations are placed in a large room which is served by the HDA access point prototype. We sweep through all possible MCS values (MCS0 to MCS8) and measure the throughput for both systems. The optimal throughput is the rate which can be achieved with the given MCS without the protocol overhead. The HDA system constantly reaches a maximum MU-MIMO gain close to three even with high MCS values. In contrast, the MU-MIMO gain of the four element antenna system has a higher variation and drops to lower values for the higher MCS values (see Figure 4).

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