

Benefits of Beamforming and SDMA in WiFi Access Point for Metropolitan-Area Deployment

Ruby Tweg, Evgeny Levitan, Aviv Aviram, Amit Frieman, and Mati Wax

Abstract— The paper presents the performance gains of a multi-antenna AP for metropolitan-area WiFi deployments, which is gaining traction around the world. The AP has a 6-antenna array and implements single-user maximum ratio combining (MRC) and transmit Beamforming (BF), as well as multi-user four-fold spatial division multiple-access (SDMA). The clients use *standard* WiFi 802.11a/b/g NICs. We present significant performance gain over a conventional WiFi AP, which amounts to doubling the range and quadrupling capacity.

Index Terms— Array Signal Processing, MIMO, Space Division Multiplexing, Wireless LAN

I. INTRODUCTION

Current 802.11a/b/g [1][2] technology is matured, low cost and is now integrated in a large variety of handheld devices. The wide adoption of WiFi clients facilitated the development of public access WiFi networks. What started as limited coverage hot spots turned into wider coverage hot zones, and recently, to a metropolitan-area coverage in hundreds of cities around the world.

Current metropolitan-area WiFi networks suffer from the limited range of existing AP's and their spotty coverage. The limited range leads to dense deployment and consequently to increased cost of deployment and maintenance. Moreover, since the 2.4GHz band contains only 3 non-overlapping channels, the result of dense deployment is a self-interfering network with reduced rate and capacity. Spotty coverage results in dead spots and low rates. The low-rate users consume most of the air-time and consequently their effect on network capacity is detrimental.

As the installed-base of current NICs is large, and it may take many years before shifting to next-generation NICs, the way to improve Metro WiFi networks is to enhance the AP performance.

This paper presents the benefits of using a high-performance 6-antenna AP over a conventional AP that implements a 2-antenna selection diversity reception and single-antenna transmission. The 6-antenna AP uses single-user Maximum Ratio Combining (MRC) reception and Beamforming (BF)

transmission, as well as multi-user four-fold Spatial Division Multiple Access (SDMA) [3][4]. The AP is designed to operate in outdoor channel conditions [5].

The rest of the paper is organized as follows. In section II we present the performance gains of single-user MRC receiver and transmit Beamforming (BF). In section III we present the performance gains of multi-user four-fold SDMA. Then, in section IV the AP interference resilience and its benefits under dense deployment scenario is discussed. A review of the regulatory limitations and its consequences for US and Europe regulatory domains is presented in section V. In section VI we present the performance gain in mobile scenarios and in section VII the effect of the improved AP performance on Mesh deployment. Section VIII presents field-trial results. Finally, our concluding remarks are presented in section IX.

II. SINGLE USER PERFORMANCE GAINS

As the antenna gain, transmit power and noise figure of most WiFi clients are inferior compared to the AP, the limiting factor of the AP's range and coverage is the uplink. Multi-antenna AP can improve the uplink sensitivity using the well known Maximum Ratio Combining (MRC) algorithm. We have implemented the MRC algorithm in the frequency domain for both multi-carrier (OFDM) and single-carrier (CCK and DSSS) modulations. The frequency domain implementation for the single-carrier modulations was selected due to implementation efficiency and re-use considerations. The weights of the MRC are calculated based on channel information, estimated from the preamble of the 802.11 burst. Figure 1 presents the MRC gain of a 6-antenna AP compared to 2-antenna selection diversity reception for 6Mbps, 24Mbps and 54Mbps 802.11 OFDM modulations. The channel model used is based on the 3GPP urban micro spatial channel model [5] for outdoor propagation. The multipath delay spread was drawn from a uniform distribution with maximum delay spread of 600nSec, 400nSec and 200nSec for 6Mbps, 24Mbps and 54Mbps, respectively. Frequency and timing offsets were uniformly generated over +/-25ppm. The antenna array is uniform-circular, of 28cm diameter and with omni-directional antennas of 8dBi. The antenna-pattern used in the simulation is the result of electromagnetic simulation that included antenna-array cross coupling and the effect of the metal base. For selection diversity, we used two antennas at 28cm apart. The simulations were run for 100Bytes data packets. As can be seen, the performance gain for Packet Error Rate (PER) of 1%

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The authors are with Wavion Networks Ltd., Yoqneam, Israel. (R. Tweg phone: +972-52-6097305, e-mail: ruby@wavionnetworks.com)

is 14dB for 54Mbps, 15dB for 24Mbps rates and 8dB for 6Mbps. For $R^{3.5}$ path loss model, these gains translate to a factor of 1.7 in range at low modulations and a factor of 2.7 in range at high modulations.

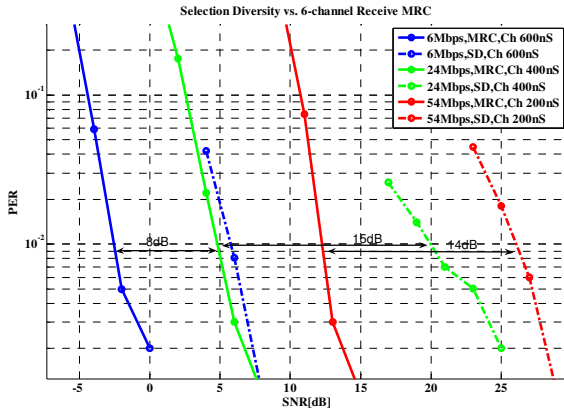


Figure 1: PER/SNR simulation results of 6-antenna MRC reception (solid) compared to 2-antenna selection diversity (SD) reception (dash) for 6Mbps, 24Mbps and 54Mbps 802.11 OFDM modulations

Multi-antenna AP also improves significantly the downlink using Beamforming (BF). BF is performing pre-equalization of the transmitted signal and coherent combining in the air. We have implemented the BF, like the MRC, in the frequency domain for both multi-carrier (OFDM) and single-carrier (CCK and DSSS) modulations. The BF weights are calculated based on the knowledge of the uplink channel, which is acquired by sending a short WLAN MAC control packet to the client and using the response packet for channel estimation. BF also requires that the RF channels hardware response for transmit and receive be identical. This is achieved by an online calibration and compensation process. Figure 2 presents the BF gain for 24Mbps and 54Mbps OFDM modulation for a channel with 400nSec and 200nSec maximum delay spread, respectively, as compared to a conventional single-antenna AP. We present the PER as a function of mean path loss from the AP to the client for our 6-antenna AP and for the single-antenna AP. The transmitted power in both cases is the corresponding FCC power limit. As we point out in section V, for 8dBi antenna gain, the maximum transmitted power for a single-antenna AP is 28dBm, while for our 6-antenna AP the maximum transmitted power is 27dBm. As can be seen in Fig 2, performance gains of 13dB and 11dB are achieved for 24Mbps and 54Mbps, respectively. This gain more than doubles the range of the 54Mbps and 24Mbps modulations at $R^{3.5}$ path loss model compared to conventional AP. Since the AP coverage is limited by the uplink, this significant gain in downlink allows us to reach the limit of the AP coverage area with a rate of 24Mbps and thereby increase overall network capacity.

III. MULTI-USER PERFORMANCE GAINS

SDMA transmission amounts to simultaneous transmission of independent information streams to several clients using a single frequency channel. The transmission algorithm optimizes directed power to each of the clients while minimizing their co-channel interferences [4]. SDMA can be considered as a "network level" multiple-input multiple-out (MIMO) technique in which the "multiple outputs" are located at different clients. As clients are spread in the AP coverage area, full rank of the channel matrix is achieved, resulting-in full performance gain of the MIMO processing.

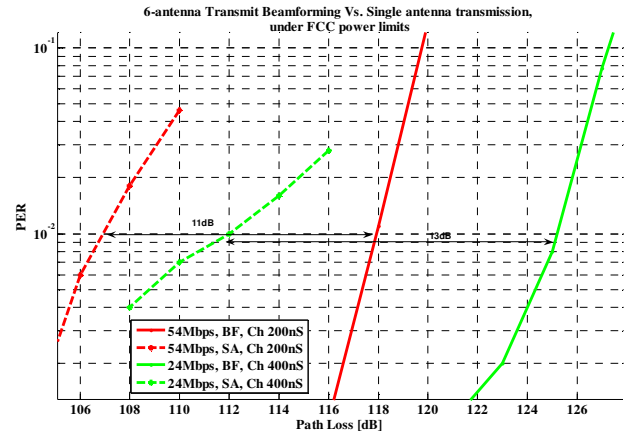


Figure 2: PER vs. Path Loss for Beamforming and conventional AP transmission at 24Mbps and 54Mbps 802.11 OFDM modulations

With 6-antenna AP and simultaneous transmission to 4 clients, up to 216Mbps is achieved at the PHY layer, at 80% of the range of a conventional AP operating at 54Mbps rate, and 96Mbps at the range of a conventional AP operating at 24Mbps rate. The SDMA weights calculation is based on the channel information matrix of the selected 4 clients for SDMA transmission. Before sending a burst of SDMA transmission to a group of 4 clients, the required channel information is acquired by sending a WLAN MAC control packet to each NIC. The response packet is used to calculate its channel information. Figure 3 presents the SDMA transmit PER versus mean path loss to AP antennas, compared with a conventional AP communicating to a single client. The transmitted power in both cases is the corresponding FCC power limit. We should note that the FCC power limits for four-fold SDMA allows four-fold increase in the transmitted power, resulting in a maximum transmitted power of 25dBm for each of the 6 channels.

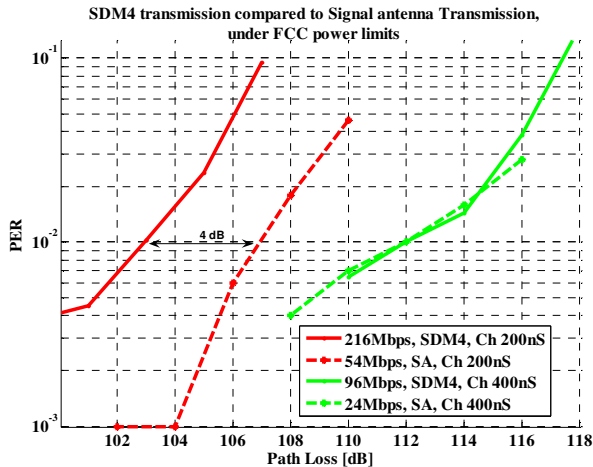


Figure 3: PER vs. Path Loss for Transmit SDMA compared to conventional AP transmission for 24Mbps and 54Mbps 802.11 OFDM modulations

IV. INTERFERENCE RESILIENCE

Due to the success of WiFi equipment deployment at the 2.4GHz band, Metro-WiFi networks need to cope with a large number of co-channel and adjacent-channel interferers.

WiFi MAC CSMA/CA rules defer transmission in cases where "clear-channel-assessment" (CCA) mechanism indicates busy channel. In many cases the interference levels are lower than the CCA threshold, defined in the standard to be -76dBm, but higher than minimum detected signal level which, depending on RF sensitivity, may be about -96dBm. In these cases, a burst can be detected due to the processing gain of its BPSK modulated preamble, but its demodulation would fail due to the interference level.

Our multi-antenna processing provided interference resilience because of the 8dB directivity provided by a 6-antenna array. On receive, the MRC focuses on the client and hence reduces by 8dB, on average, the interference received from other directions. Similarly, on transmit, the BF directs the power to the client, and thereby reduces by 8dB, on average, the level of interference transmitted to other directions.

V. REGULATORY PERSPECTIVE

In the US, Part 15 of Title 47 of Code of Federal Regulations [6] defines the total transmitted power and antenna gain in the ISM unlicensed bands. In its April 2005 revision, regulation for multiple-antenna processing was set. Due to the directional nature of Beamforming and SDMA transmission, the FCC allows increasing the transmitted power when single-user and multiple-user Beamforming is employed. Conventional APs are limited to 36dBm EIRP, regardless of antenna gain, while single-user Beamforming systems are required to reduce transmit power by 1dB on every 3dB increase in directivity gain over 6dBi. The gain is defined in dB as the sum of the antenna gain and $10 \cdot \log_{10} N$ [dB] where N is the number of array antennas. With 6 antennas, each with a gain of 8dBi, the total transmitted power is limited to 27dBm (each transmitter is limited to 19dBm). The total directed power to the user in

this case is 42.6dBm, as compared with 36dBm of conventional AP. Total directed power is calculated in dB as the sum of the total conducted power, the antenna gain and array gain, given by $10 \cdot \log_{10} N$.

For SDMA, the FCC allows up to 6 SDMA beams to be transmitted simultaneously, each with a power level equal to a single directed beam. That is, up to 6-fold SDMA at 42.6dBm for each SDMA beam is allowed by the regulator.

Current ETSI regulation for the ISM band does not include special regulation for multiple-antenna processing. In its next revision of ISM regulation, due on December 2006, MIMO and other high throughput methods are planned to be regulated [7].

VI. MOBILITY

With conventional AP's, the performance of high velocity clients is limited by the fast channel variations resulting from mobility. Multiple-antenna AP provides significant performance gain in this case. This enhanced performance was investigated in [8][9] where it was shown that MRC robustness to mobility increases as the number of MRC channels increase. Figure 4 presents the achievable performance of a 6-antenna AP at 24Mbps rate with client velocity of 100kmh, for different payload length. Notice that at a velocity of 100kmh, 1500 bytes burst translates to 0.12λ , where λ is the 2.4GHz wavelength. The PER of a static client is presented for reference. The model for the effect of mobility followed [5], with a maximum delay spread of 400nSec. Frequency and timing offset were uniformly distributed in ± 25 ppm range. As can be seen, at payload size of 1500 bytes, a PER lower than 3% is achieved at 15dB SNR, while a conventional AP achieves only a PER of 40% at SNR of 27dB.

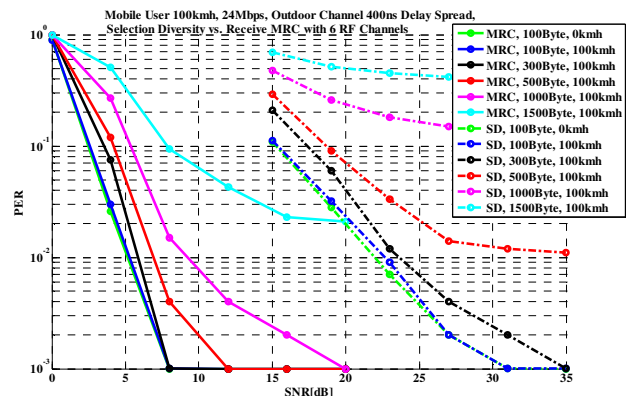


Figure 4: PER/SNR: 6-antenna AP receive-MRC performance (solid) versus selection diversity (SD) (dashed), as a function of burst payload length at 24Mbps rate and 100kmh

VII. MESH DEPLOYMENT

Metro WiFi deployments cover large geographical areas. As AP range is limited, dense deployment of AP's is required. To reduce network deployment cost, which is driven by the high cost of wired backhaul, multi-hop mesh technology is proposed. Yet, multi-hop mesh networks suffer from dramatic

decrease in capacity as the number of hops increases. This was analyzed in [10][11] and also demonstrated in [12], where the effect of multi-hop mesh on TCP/IP was measured using WiFi equipment. A multi-antenna AP, when used as mesh-node, can offer high gains in terms of rate, range and interference reduction. Figure 5 presents the link gain of two 6-antenna APs as mesh-nodes, as compared to the link of two conventional APs. We compare the PER as a function of mean path loss to AP antennas, for the FCC power limit. The comparison is done for 24Mbps rate over a channel with 400nSec maximum delay spread. As can be seen, we achieve 21dB gain compared to conventional AP. This gain can be exploited to increase link capacity or to increase the range and thus reduce the number of hops. Note also that the reduction of interference in BF and the interference resilience of MRC reception reduce the interference level in the network and thus allow for more nodes to communicate simultaneously. These significant benefits address the critical pain-points of multi-hop mesh network and improve dramatically the network capacity.

VIII. FIELD TRIALS RESULTS

To demonstrate our system performance gains in typical real life deployment we have conducted a series of field experiments in typical sub-urban environment at 2.4GHz. We have mounted our 6-antenna AP and a conventional AP on top of 3 meters mast on the roof of a 3 story building. As a client we used a laptop that was equipped with a standard WiFi NIC and a GPS receiver for accurate position readings. The client laptop was mounted in a car and was connected to a 2dBi external antenna mounted on the car roof.

Figure 6 and 7 presents the downlink throughput as a function of client position over the AP coverage area for our 6-antenna AP and a conventional AP, respectively. Note that due to WiFi MAC requirement of positive acknowledgement on each downlink packet, downlink throughput is also affected by the uplink performance.

The performance gains in range and throughput are significant. We more than double the range as well as providing significantly more throughput at the AP coverage area.

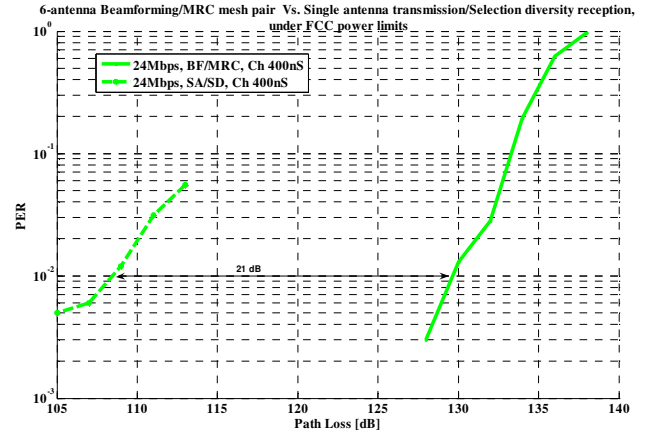


Figure 5: PER vs. Path Loss for two 6-antenna AP (solid) as mesh nodes compare to 2 conventional AP's (dash) for 24Mbps 802.11 OFDM modulation

IX. CONCLUDING REMARKS

This paper presented the benefits of using 6-antenna AP for Metropolitan area WiFi deployment. The AP implements single-user MRC and transmit Beamforming as well as multi-user four-fold SDMA while communicating with *standard* WiFi 802.11a/b/g NICs. The performance gains of the multi-antenna AP over a conventional AP were demonstrated by simulation and field trial experiments. These gains can be summarized as: up to 15dB in uplink, up to 13dB in downlink at the FCC power limit, up to 216Mbps at 80% of conventional AP range of 54Mbps, interference resilience of 8dB on receive and transmit, and significantly better mobility support. These gains enable four-fold reduction in number of AP's for a given deployment and provide significantly better network quality.

Moreover, these gains can also benefit multi-hop mesh networks and solve their major pain points in terms of performance and network capacity.

The regulators in the US have already realized the potential benefits of multi-antenna technology and have revised the regulation to allow the public to gain from it. We hope that the, regulators in Europe will follow soon.

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Throughput [Mbps] - Conventional AP - 22-Nov-2005

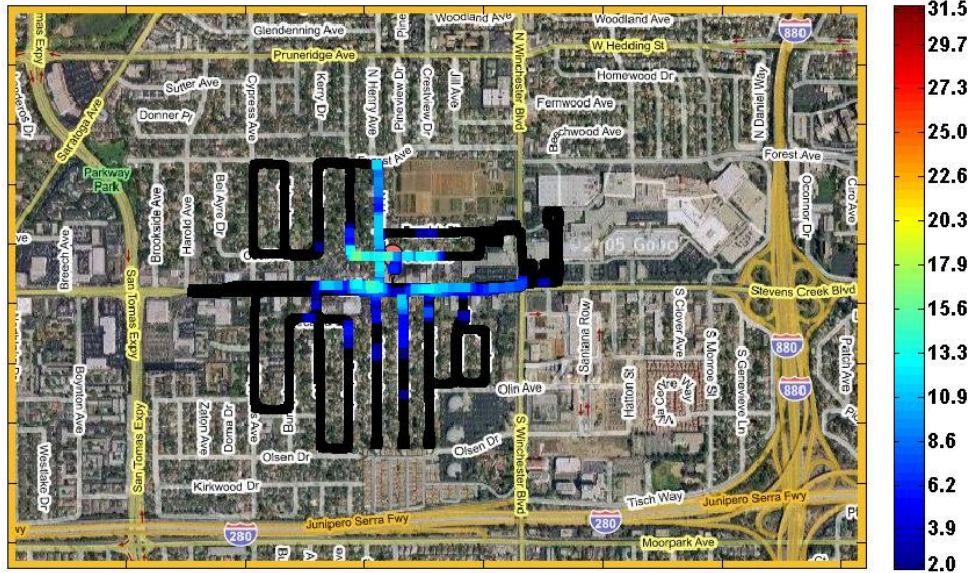


Figure 6: Field trial mapping of throughput vs. client location: Conventional AP

Throughput [Mbps] - 6-antenna AP - 20-Nov-2005

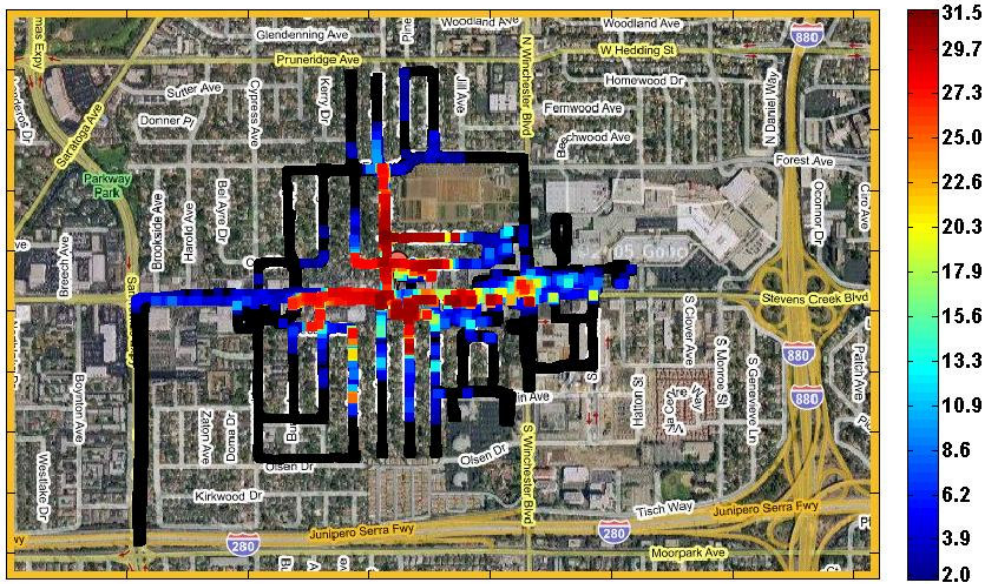


Figure 7: Field trial mapping of throughput vs. client location: our 6-antenna AP