Mellios, E., Kong, D., Halls, D., Hilton, G. S., & Nix, A. R. (2011). Evaluating the antenna performance of 802.11n wireless routers in an indoor environment. In *IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS), 2011* (pp. 1 - 5). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/COMCAS.2011.6105870>

Link to published version (if available):
[10.1109/COMCAS.2011.6105870](https://doi.org/10.1109/COMCAS.2011.6105870)

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Evaluating the Antenna Performance of 802.11n Wireless Routers in an Indoor Environment

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Abstract — The antenna performance of three 2x2 802.11n wireless routers is assessed at 2.4GHz using a laptop as a reference client. The analysis combines in-situ measured 3D radiation patterns with state-of-the-art 3D ray-tracing for a number of different client locations and access-point/client orientations in a typical three-floor home. A router employing two PIFAs achieves the highest average signal level on the top floors (3-10dB better); a router with two external dipoles on the same floor level (1-5dB better); and a router with two patches is in-between and results in the largest signal variations (5-15dB larger dynamic range).

Index Terms — 802.11n, MIMO, antennas, PIFA, patch, dipole, ray-tracing.

I. INTRODUCTION

Wireless Local Area Networks (WLANs) are commonly deployed in the home and office. The IEEE 802.11n WLAN standard was ratified in September 2009 and employs multiple antennas at both ends of the link to provide data rates up to 600Mbps [1][2]. These rates make indoor wireless networks attractive for high-throughput demanding applications such as video-streaming [3]. In order to fully exploit the diversity, spatial multiplexing and array gains available to multi-input multi-output (MIMO) systems, a high signal-to-noise ratio (SNR) is required. The antennas used at the access point (AP) and client influence the perceived channel quality and must be carefully considered. Previous measurements [4] and simulations [5][6] have shown that different antenna configurations and orientations have a significant impact on performance.

In this paper the antenna performance of three 2x2 802.11n wireless routers are compared at 2.4GHz (Figure 1). Router 1 is 18cm high by 17cm wide by 2.5cm thick and uses two Planar-Inverted-F-Antennas (PIFAs); Router 2 (used in [4]) is 24cm high by 10cm wide by 12cm thick and uses two orthogonally polarized directional patches on RT/Duroid 5880 substrate; while Router 3 is 4.5cm high by 12cm wide by 16cm thick with two vertical omni-directional external dipoles of the type widely used in MIMO WLANs. A laptop with two orthogonally oriented PIFAs is used as a reference client (Figure 2). A SISO link between two theoretic vertical Hertzian dipoles [7] is also modelled for benchmarking purposes. Antenna performance results are presented as cumulative distribution functions of the received signal strength at the client for a large number of AP and client orientations, showing comparative antenna performances for the three routers. Results demonstrate the importance of measuring 3D radiation patterns of all the individual elements

of a MIMO system in-situ and not just a single element in isolation.

Figure 1: Antenna configurations of wireless routers.

Figure 2: Laptop client antenna configuration.

II. ANTENNA RADIATION PATTERNS

The radiation patterns of all the antennas were measured at 2440MHz in an anechoic chamber such that the interaction of the antennas with the local environment (i.e. the box/laptop casing, the Printed-Circuit-Boards (PCBs) and a wooden surface) is taken into account. All the patterns are 3D and contain full polarization and phase information. Figure 3 shows the far-field total power radiation patterns of the antennas of the three wireless routers, the laptop client, and the ideal vertical Hertzian dipole. Table I summarises the pattern statistics. The 3D patterns allow a full insight into the behaviour of the antenna system that is simply not possible to deduce from single planes (e.g. x-y, x-z, y-z). It is clear that the placement of the antennas inside a box, and the mounting of the box on a table, significantly affect the radiation characteristics. For example, the main beam of patch 2 is split into two, leading to a beam null in the azimuth plane and a 3.6dB increase in the maximum measured directivity compared to patch 1.

It should be noted that all the antennas in this study are assumed to be 100% efficient. Future work should include accurate antenna efficiency measurements, as it will have impact on performance.

Figure 3: Total power antenna radiation patterns (measured at 2440MHz).

TABLE I
ANTENNA PATTERNS STATISTICS

Antenna	Power in Polarization (%)		Maximum Directivity (dBi)	
	Vertical	Horizontal	Vertical	Horizontal
Hertzian Dipole	100	0	1.8	-
PIFA 1	49	51	5.0	3.9
PIFA 2	23	77	4.5	6.4
Patch 1	95	5	7.6	-3.6
Patch 2	14	76	3.4	11.2
Dipole 1	94	6	4.9	-3.1
Dipole 2	90	10	5.0	-1.4
Laptop Antenna 1	51	49	4.8	5.0
Laptop Antenna 2	65	35	5.8	3.4

III. PROPAGATION ENVIRONMENT

The MIMO channel between the AP and each client is modelled as the spatial convolution of the detailed polarimetric element patterns with the spatial and temporal multipath components from a 3D indoor ray-tracer [8][9]. This deterministic approach is preferred over the standardized TGN channel model [10] since the latter makes several simplifying assumptions. For example, the TGN model *i*) uses simplified angle spread distributions, *ii*) restricts propagation to the azimuth plane (elevation is ignored), *iii*) uses highly simplified

polarization models, and *iv*) has no mechanism to model specific element patterns. It was shown in [11] that results from the TGN model differ significantly from real-world measurements. In [12] it was shown that ray-tracing can accurately model all aspects of the MIMO channel.

Figure 4: Indoor environment with access-point and client locations.

A typical three-floor home is shown in Figure 4. The AP is located on the ground floor and ten client locations are distributed around the property. Analysis is performed at 2.4GHz with 12dBm transmit power assumed per radio chain. The AP and the client are rotated over 360° in azimuth (about the z-axis in steps of 10°). It is also assumed that the laptop client is tilted in elevation (about the x-axis) between 0° and 40° in order for the user to see the screen. Point-source ray-tracing is performed from the AP to each client location. This provides information on the amplitude, phase, time delay, angle-of-departure (AoD) and angle-of-arrival (AoA) of each multipath component (MPC). The phase of each MPC is adjusted according to the transmitting/receiving antenna's relative distance from a zero-phase reference point. The complex gain of each MPC is also adjusted according to the transmitting/receiving antenna E-field pattern response for the corresponding AoD/AoA and polarization. The received signal strength at the client is computed by equation (1).

$$P_{mn} = \sum_{l=1}^L \left[\begin{matrix} E_{Tx,m}^V \\ E_{Tx,m}^H \end{matrix} \right]^T \begin{bmatrix} a_l^{VV} e^{j\Phi_l^{VV}} & a_l^{VH} e^{j\Phi_l^{VH}} \\ a_l^{HV} e^{j\Phi_l^{HV}} & a_l^{HH} e^{j\Phi_l^{HH}} \end{bmatrix} \begin{bmatrix} E_{Rx,n}^V \\ E_{Rx,n}^H \end{bmatrix} \right]^2 \quad (1)$$

P_{mn} represents the total received power for the m^{th} transmitting and n^{th} receiving antenna link. L is the total number of MPCs, each of which is weighted by a complex amplitude $a_l^{XY} e^{j\Phi_l^{XY}}$ (a 2x2 matrix for all four possible polarization combinations). $E_{Tx,m}^{V/H} / E_{Rx,n}^{V/H}$ represents the vertical/horizontal polarization component of the m^{th} transmitting and n^{th} receiving antenna E-field radiation pattern value that corresponds to the appropriate AoD/AoA.

TABLE II
RECEIVED SIGNAL STRENGTH FOR EACH ANTENNA-TO-ANTENNA LINK AVERAGED OVER ALL AP AND CLIENT ORIENTATIONS AT EACH LOCATION
(CLIENT ANTENNA 1 / CLIENT ANTENNA 2; BLUE/RED: STRONGEST/WEAKEST LINK)

	Hertzian Dipoles (Benchmark)	PIFA 1 (Router 1)	PIFA 2 (Router 1)	Patch 1 (Router 2)	Patch 2 (Router 2)	Dipole 1 (Router 3)	Dipole 2 (Router 3)
Location 1	-32	-38 / -38	-39 / -43	-37 / -34	-40 / -44	-39 / -36	-39 / -36
Location 2	-38	-45 / -44	-45 / -50	-43 / -41	-47 / -52	-44 / -42	-45 / -42
Location 3	-52	-58 / -57	-56 / -59	-57 / -54	-56 / -58	-58 / -55	-58 / -56
Location 4	-77	-86 / -83	-90 / -91	-82 / -79	-92 / -95	-83 / -80	-84 / -81
Location 5	-55	-44 / -49	-45 / -48	-56 / -55	-45 / -49	-55 / -55	-54 / -53
Location 6	-72	-67 / -68	-66 / -69	-75 / -72	-67 / -72	-76 / -73	-71 / -68
Location 7	-71	-76 / -73	-77 / -77	-78 / -72	-77 / -79	-80 / -74	-76 / -70
Location 8	-78	-59 / -62	-56 / -59	-69 / -70	-59 / -63	-67 / -69	-69 / -71
Location 9	-62	-60 / -61	-63 / -63	-67 / -65	-62 / -63	-69 / -67	-62 / -61
Location 10	-88	-80 / -83	-80 / -83	-90 / -89	-79 / -84	-91 / -91	-85 / -85

IV. RESULTS

Using the process described in Section III, the received signal strength at the client is computed at each location for each antenna-to-antenna link, AP rotation, and client tilt and rotation. Table II presents the received signal strength at the client for each antenna-to-antenna link, averaged over all access point and client orientations at each location. The strongest link at each location is colour-coded with blue and the weakest with red. Figures 5 and 6 show the cdf of the received signal strength at the client at the example locations 2 and 5, using all the different router antennas. The benchmarking SISO link of the two Hertzian dipoles is also included.

Figure 5: Cdf of received signal strength at the client at location 2.

Router 3 (dipoles) has the best antenna performance at location 2, which is on the same floor level. This is because the dipoles radiate most of the power omni-directionally in the azimuth plane. Dipole 1 transmits the strongest signal to the client for 70% of the time. Dipole 2 is worse by only about 1dB, as the cdf curve is essentially shifted to the left by 1dB. Therefore, the two antennas are expected to work well together as a MIMO system, as they both result in similar signal levels. The cdf curves of both the dipoles have a dynamic range (i.e. difference between maximum and

minimum value) of about 15dB due to the AP rotation, and the client tilt and rotation. The performance of the two PIFAs of router 1 is always worse than both the dipoles. The cdf curves of PIFA 1 and PIFA 2 are shifted to the left by about 3dB and 6dB respectively, with respect to dipole 1. This is because the PIFAs drive most of the radiated power high in elevation rather than in the horizontal plane. The dynamic range of the cdf curves is about 18dB and 21dB for PIFA 1 and PIFA 2 respectively. The patch antennas of router 2 have significantly different signal levels to each other, as the cdf curve of patch 2 is shifted to the left by about 8dB with respect to patch 1. Due to the more directional beam of the patches, their performance is more sensitive to the AP/client orientation compared to the dipoles or the PIFAs, as the dynamic range of their cdf curves is about 27dB. Patch 1 achieves the best antenna performance for 30% of the time, and is also able to result in the strongest signal level at location 2 (about -33dBm). This is a result of the main beam of the pattern being in the azimuth plane. On the other hand, the performance of patch 2 is always the worst as a result of the pattern null in the horizontal plane, as shown in Section II.

Figure 6: Cdf of received signal strength at the client at location 5.

The results at location 5 can be analysed in a similar way. It can be noticed in Figure 6 that router 1 with the two PIFAs

has now the best antenna performance. PIFA 2 transmits the strongest signal to the client for about 95% of the time, with PIFA 1 being only 0-2dB worse. This is because the PIFAs point their main beam high in elevation and location 5 is on top of the router. The performance of patch 2 is quite high and comparable to the PIFAs, as the main beam of its pattern is split into two and is pointing high in elevation, as shown in Section II. However, its directional radiation makes it more sensitive to orientation and thus results in a higher dynamic range. On the other hand, patch 1 has very poor performance as its main beam lies in the azimuth plane, making it impossible to achieve good 3D coverage. The signal level from the two dipoles of router 3 is also very weak due to the null in their radiation patterns in the direction of the z-axis.

Figure 7: Received signal strength averaged over all antenna links and access point/client orientations at each location.

Figure 8: Dynamic range of received signal strength at each location.

Figure 7 summarises the received signal strength at the client, averaged over all antenna links and AP/client orientations for each router at each location. At locations 1-4, which are on the same floor level, router 3 (dipoles) results in the highest average signal level, whereas router 1 (PIFAs) in the lowest (1dB to 5dB difference). On the other hand, router 1 transmits the highest signal in average to almost all the top floors client locations, where router 3 has the worst average

performance (3dB to 10dB difference). The only exception is location 7, where dipoles perform better. The average performance of router 2 (patches) is in almost all cases in-between the other two.

Figure 8 shows the dynamic range (i.e. difference between maximum and minimum value) of the received signal strength at the client at each location using the three routers. It can be noticed that routers 1 and 3 result in dynamic range values between 17dB and 32dB. This shows that even with routers that employ omni-directional antennas, the performance is very sensitive to the AP/client orientation. The dynamic range values observed with router 2 are 5dB to 15dB higher than the other two. As explained above, router 2 is much more sensitive to orientation and results in the highest signal variations due to the directional radiation of the patches.

V. CONCLUSIONS

This paper assessed the antenna performance of three 2x2 802.11n wireless routers at 2.4GHz using a laptop as a reference client. A router with two PIFAs achieved the highest average signal level on the top floors (3-10dB better); a router with two external dipoles on the same floor level (1-5dB better); and a router with two patches was in-between and resulted in the largest signal variations (5-15dB larger dynamic range than the other two routers).

Results demonstrated the importance of measuring 3D radiation patterns of all the individual elements of a MIMO system in-situ. Antennas must be designed for a communication system accounting for the effect that the application will have on their performance. It is important not just to measure the performance of a single element in isolation.

Results presented in this paper are at the RF-level and predict the signal strength for all the antenna-to-antenna links of a MIMO system. However, in order to predict the system-level performance of our devices, which is the performance that the end-user is going to experience, these results have to be combined with a system-level simulator. Hence, the impact of the various modulation and coding schemes (MCS) of the 802.11n standard and the different MIMO transmission techniques (e.g. eigen-beamforming or spatial-multiplexing) will be taken into account. This is part of our future work and some initial results can be found in [5][6].

ACKNOWLEDGEMENTS

The antenna pattern measurements used the extensive laboratory facilities and the anechoic chamber at the Centre for Communications Research, University of Bristol, UK. Evangelos Mellios would like to thank the University of Bristol Centenary scheme for his postgraduate scholarship.

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