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Closed-loop Antenna Selection for Wireless LANs with Directional & Omni-Directional Elements

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Abstract—Throughput and packet error rate are analysed in a home environment for two different 3x3 wireless LAN solutions. A 3x3 EBF approach (using three radio chains) is compared with a reduced cost 2x2 architecture (using two radio chains). In the 2x2 solution the optimum antenna pair is selected from the same set of three antennas at the AP and client. The impact of directional, as well as omni-directional, antenna elements is considered. The spatial and temporal characteristics of the in-home channels are modelled using 3D ray tracing and combined with appropriately orientated complex polarimetric patterns for each antenna element. Physical layer throughput is calculated for all modulation and coding schemes and (for the 2x2 case) all possible antenna combinations using a novel received bit mutual information rate abstraction technique. Results show that antenna number, pattern and orientation all play a key role in determining the performance of an 802.11n system. As expected, 3x3 EBF outperforms the 2x2 solution; however, with optimum antenna selection the performance of 2x2 EBF is competitive, especially when directional antennas are used at low signal to noise ratios. For distant rooms, 3x3 EBF is only 15% better (in terms of throughput) than 2x2 EBF when directional antennas and dynamic antenna selection are applied. 2x2 EBF with omni antennas results in a 45% reduction in throughput (compared with 3x3 EBF).

Keywords; *MIMO, 802.11n, Eigen-beamforming, directional antennas, antenna switching.*

I. INTRODUCTION

Wireless Local Area Networks (WLANs) are commonly deployed in the home and office. These devices are used as a wireless extension to the Internet. The recent high throughput 802.11n extension supports higher quality video streaming applications. At present, most video-on-demand applications use the transport control protocol with packet errors resolved via end-to-end retransmission. However, multiple service operators are exploring the viability of streaming high-definition content wirelessly from Set Top Boxes (STBs) to low cost receivers (connected to remote televisions) and portable handhelds (phones and tablets) in the home. To support thin client features such as an interactive programme guide and rapid channel switching, near-zero packet error rate (PER) real time protocol services are required. These types of application require a cost-effective and reliable high throughput wireless link.

The 802.11n WLAN standard was ratified in September 2009 and offers high-throughput modes via the use of multi-input multi-output (MIMO) technology [1]. The standard specifies the use of up to four radio chains in both the access point (AP) and client. First generation 802.11n solutions offered two radio chains with peak throughputs of up to 300Mbps at the physical (PHY) layer. Many second generation

solutions offer three radio chains with peak rates of up to 450Mbps. Performance is improved at the expense of increased AP and client cost.

To achieve the headline rates in 802.11n a very high signal to noise ratio is required, and this is only possible in near-ideal conditions. Modulation and Coding Scheme (MCS) adaptation is used to match the data rate to the quality of the link. The antennas used at the AP and client significantly influence the perceived channel quality. The data rate seen at the application layer is reduced by higher layer overheads. For 802.11n the peak application rate is typically around 60% of the PHY rate.

In order to fully exploit the diversity, spatial multiplexing and array gains available to MIMO systems, the antenna configuration and orientation must be carefully considered. Previous measurements [2] have shown that different antenna configurations and orientations have a significant impact on performance. In this paper the performance of a 3x3 Eigen Beam-Forming (EBF) 802.11n system is analysed with directional and omni-directional antennas. Analysis combines the use of detailed polarimetric antenna patterns, state-of-the-art indoor spatial/temporal ray tracing, and advanced PHY layer simulation for all possible MCS modes. For any location and antenna configuration the simulator is capable of determining the best MCS mode (comprising the modulation scheme, the coding rate, and the number of spatial streams), and hence the projected throughput. Rotation of the client is also modelled to determine the impact of antenna orientation. Finally, to reduce cost, optimum antenna selection (based on the same 3x3 array) is applied to create a lower cost 2x2 EBF solution.

II. TEST ENVIRONMENT AND ANTENNA CONFIGURATION

The MIMO channel matrix 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 [3][4]. This deterministic approach is preferred over the standardized TGN channel model [5] 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 [6] that results from the TGN model differ significantly from real-world measurements. In [7] it was shown that ray tracing can accurately model all aspects of the MIMO matrix channel.

A typical three-floor home is shown in figure 1. The AP is located on the ground floor and ten client locations are distributed around the property. Analysis is performed at 5.2GHz with 12dBm transmit power assumed per radio chain.

Figure 1: Indoor environment with access-point and client locations.

Figure 2: Array configurations; A with omni-directional (left) and B with directional (right) elements. Coordinate systems as shown in figure 1.

Two 3x3 array configurations were investigated, as shown in figure 2. Configuration A uses three ‘idealized’ omni-directional (vertical) elements, while B comprises three ‘idealized’ orthogonally oriented and polarized directional elements that match well to measured patch antennas patterns [2]. The AP and client are assumed to use the same array configuration. The AP location and orientation was fixed, however the client was rotated in azimuth (anti-clockwise about the z-axis) in steps of 10° . This was performed for both antenna configurations.

For the idealized omni-directional elements, the radiation pattern of a vertically polarized (z-directed) electric current source was assumed (figure 3) [8]. All power is contained in the vertical polarization and the maximum directivity is 1.8dBi. The half-power points in elevation are $\pm 45^\circ$ and the radiation efficiency is modelled at 80% (to take cabling losses and mismatch into account). Figure 1 shows the average received power at all ten locations for a single vertical transmit and receive omni-directional element.

For the idealized orthogonally oriented and polarized directional elements of configuration B, two magnetic current sources (z-directed, x-directed and y-directed for element 1, 2 and 3 respectively) were used to form a beam, radiating only into half space (assuming an infinite ground plane). The efficiency of a directional patch antenna can vary significantly according to the substrate [2]. Measured efficiency values, relative to a high-efficiency monopole, are approximately 40% for FR4 and 80% for RT/Duroid substrates. Hence a radiation efficiency of 50% was assumed. Figure 3 shows the 3D horizontal polarization component of the radiation pattern of element 1, while figure 4 shows the vertical and horizontal

polarization components of the patterns of elements 2 and 3. Table I shows the associated pattern statistics.

Figure 3: Vertical polarization component of radiation pattern of omni-directional element of configuration A (left) and horizontal polarization component of radiation pattern of directional element 1 of configuration B (right).

Figure 4: Vertical (left) and horizontal (right) polarization component of radiation patterns of directional element 2 (top) and 3 (bottom) of configuration B.

TABLE I. RADIATION PATTERNS STATISTICS

Element	Power in Polarization (%)		Maximum Directivity (dBi)	
	Vertical	Horizontal	Vertical	Horizontal
Omni-directional	100	0	1.8	-
Directional 1	0	100	-	7.9
Directional 2	84	16	7.9	0.4
Directional 3	57	43	7.9	7.9

In order to compute a statistically valid set of wideband channel matrices suitable for MIMO-OFDM modelling, the procedure reported in [6] was followed. Point-source ray-tracing was 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 was adjusted according to the transmitting/receiving antenna’s relative distance from a zero-phase reference point (see figure 2). The complex gain of each MPC was also adjusted according to the transmitting/receiving antenna E-field pattern response for the corresponding AoD/AoA and polarization. This is described by equation (1).

$$h_{m,n,l} = \begin{bmatrix} E_{Tx,m}^V \\ E_{Tx,m}^H \end{bmatrix}^T \begin{bmatrix} a_l^{VV} e^{j\Phi_l^{VV}} & a_l^{VH} e^{j\Phi_l^{VH}} \\ a_l^{HV} e^{j\Phi_l^{HV}} & a_l^{HH} e^{j\Phi_l^{HH}} \end{bmatrix} \begin{bmatrix} E_{Rx,n}^V \\ E_{Rx,n}^H \end{bmatrix} \quad (1)$$

$h_{m,n,l}$ represents the channel matrix coefficient for the m^{th} transmitting and n^{th} receiving antenna link, and the l^{th} MPC, which is weighted by a complex amplitude $a_l^{XY} e^{j\Phi_l^{XY}}$ (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. Time-binning was applied, with a bin width of 12.5ns. The wideband channel frequency response was computed using a 256-point discrete Fourier transform.

Figure 5: Instantaneous frequency power profile example of a 3x3 MIMO channel (configuration B; location 6; box rotation 210°).

An example of an instantaneous frequency power profile can be seen in figure 5 for each of the 3x3 links. We take 128 (40MHz) or 64 (20MHz) contiguous frequency samples to represent the instantaneous channel. To calculate the average channel performance for a given location, we repeat this procedure for 1000 channel realisations, applying a uniformly distributed $[0, 2\pi]$ random phase to each MPC.

III. LINK-LEVEL ABSTRACTION AND VALIDATION

Performing link-level analysis for large numbers of locations, MCS modes, antenna configurations and orientations is computationally prohibitive when bit-accurate PHY simulation is applied. To predict these links in an efficient and scaleable manner, a PHY abstraction technique is required.

In OFDM systems, where coded blocks are used in the frequency domain, the frequency selective channel introduces large SNR variations across the subcarriers. Using a technique known as Effective SNR Mapping (ESM), this SNR vector can be compressed into a single *effective* SNR (ESNR) [9]. The calculated ESNR can then be used with non-faded bit-accurate performance curves (produced using a bit accurate 802.11n link level simulator) to provide an accurate prediction of the instantaneous PER for a given channel realization. The post-processing SNR values across the coded frequency block at the input to the decoder (including any MIMO processing) are used as the input to the abstraction model. The ESM PHY

abstraction method is fully described in [9] and used extensively in [10] and [11].

To verify the accuracy of the Received Bit Mutual Information Rate (RBIR) abstraction engine, figure 6 shows the BER vs SNR performance for two different 2x2 MIMO modes (single and dual stream) using $\frac{1}{2}$ rate 16QAM. Channel data was based on 1000 frequency domain channel matrix snapshots for location 5. The markers show results from our bit accurate link layer simulator, while the continuous lines were generated from the abstraction model. Excellent agreement can be observed.

Figure 6: Validation for wideband channel 2x2 EBF (1 and 2 streams).

5 hours of computing time is required to compute just one of the bit accurate graphs shown above (based on a standard dual-core PC). The RBIR abstraction graph can be generated in approximately 20 seconds. This vast speed-up allows us to consider thousands of channels, antenna types, orientations, geometries and polarizations.

IV. SIMULATION PARAMETERS

For each of the ten different client locations a set of 1000 channel snap-shots were generated. Based on the AP and client orientation and antenna type, the optimum MCS mode is chosen. For 3x3 EBF all eight MCS modes are analysed together with 1, 2 and 3 stream EBF (24 combinations). For 2x2 EBF there are nine different ways to select two antennas from three at both the AP and client. For each of the nine antenna combinations the algorithm considers 1 and 2 spatial streams and all 8 MCS modes (i.e. $16 \times 9 = 144$ combinations). This data is then used to compute the PER and throughput for 3x3 EBF and each of the nine possible 2x2 EBF schemes. The simulation is based on a 5GHz carrier and a channel bonded 40MHz transmission using 128 sub-carriers (108 active sub-carriers). Peak throughputs of 450, 300 and 150Mbps are achieved for 3, 2 and 1 spatial streams respectively. A noise floor of -93dBm is assumed in the receivers.

V. RESULTS

The optimum MCS is chosen using the RBIR abstraction technique. The mode that maximizes throughput for a PER of 10% or less is chosen. The same RBIR algorithm is used to select the optimum subset of 2x2 antennas. Table II shows the received SNR and the optimum throughput (TP) for 3x3 EBF and all nine of the 2x2 EBF combinations for location 5 (see

figure 1). The client was randomly oriented to an azimuth angle of 150° . The directional antennas generally result in higher SNR (compared to the omni-directional elements). The directional antennas are shown to outperform the omni devices for all 3x3 and 2x2 combinations in terms of throughput. At location 5, using directional antennas, the best 2x2 EBF solution achieved 80% of the 3x3 throughput. Interestingly, the optimum 2x2 scheme achieved its peak rate of 300 Mbps. Using the omni antennas, the best 2x2 combination achieved 58% of the 3x3 throughput.

TABLE II. DIRECTIONAL/OMNI PERFORMANCE OF 3X3 AND 2X2 AT LOCATION 5, ROTATION 150° . RESULTS AVERAGED OVER 1000 INDEPENDENT REALISATIONS, EACH WITH OPTIMAL MCS AND SPATIAL STREAM NUMBER.

Average SNR 3x3 (dB)		41.6/24.0									
Average TP 3x3 (Mbps)		375.4/289.5									
Best SNR 2x2 (dB)		44.3/23.9									
BestTP 2x2 (Mbps)		299.9/169.0									
SNR 2x2 (dB)	33.0/20.3	40.0/20.4	39.3/20.3	33.2/20.3	40.8/20.3	40.2/23.9	25.9/20.4	37.7/20.4	47.7/20.5		
TP 2x2 (Mbps)	296.1/163.0	298.1/165.2	279.9/164.5	295.7/150.0	299.9/150.0	279.2/162.5	283.4/165.5	292.8/165.0	260.7/169		

Figure 7: Throughput performance of 2x2 and 3x3 through 360° rotation at location 9.

Figure 7 shows the throughput of the 3x3 and optimum 2x2 EBF combinations for the omni and directional elements at location 9 as the client rotates through 360° . Previous work has shown that MIMO capacity is influenced by the orientation of the AP and client [12]. For most orientations the best results are achieved by the directional 3x3 EBF solution (with peak rates in excess of 250Mbps for several orientations). At some orientations (for example, from 280° through to 10°) the directional antennas reduce throughput. This occurs in a small number of cases since the directional antennas sometimes result in lower signal levels (if misaligned to the significant multipath clusters). The omni result for 3x3 EBF provides a consistent throughput at all orientations; however the reduced SNR lowers the throughput compared to the directional antennas. With directional antennas the optimum 2x2 configuration achieves a peak rate of 230Mbps. With omni antennas the 2x2 system offers just 55-80Mbps depending on orientation. For some orientations (from 50° to

240°) the optimum directional 2x2 solution is even better than the full cost 3x3 solution with omni elements.

Using directional antennas the 2x2 EBF solution is much closer (compared to the omni elements) to the full 3x3 EBF throughput. The 2x2 directional elements achieve 70-99% of the 3x3 throughput, while with omni antennas it reduces to 45-62%. With directional elements there tends to be a greater variance in the SNR per antenna link. Selecting the best set of 2x2 links from the larger set of 3x3 links exploits the greater diversity present with directional antennas. The weaker links are discarded, leaving only the stronger links where the directional antennas are well aligned to the multipath scatter. For omni antennas the mean power per link is similar, and hence there is little gain selecting the optimum 2x2 subset. Results show that at some orientations the 2x2 EBF solution offers very nearly the same performance as 3x3 EBF. Given the cost reduction of a 2x2 solution, antenna selection from a larger 3x3 set of directional antennas is particularly attractive.

Figure 8: Throughput vs SNR performance for selected 2x2 and 3x3 solutions at locations 3 and 5. Location 3, rotation 100° , chosen due to reduced Eigen value spread.

Figure 8 shows the throughput performance of the 3x3 solution alongside the optimum 2x2 combination for both types of antenna. The data was generated for locations 5 and 3. Tables III to VI show the Eigen structure of the 3x3 and optimum 2x2 matrix channel for both locations. It should be noted that the SNR is based on the 3x3 channel. The 3x3 EBF performance depends on the Eigen structure of the channel, while 2x2 EBF performance depends on the signal level of the optimum combinations and resulting Eigen structure. At location 5 the Eigen structure for the omni-directional antennas is better than the directional antennas, and hence the overall throughput performance for the omni-directional antenna (as a function of SNR) is better. However, for location 3, the Eigen structure with the directional antennas is better than the omni devices, and hence the directional antennas outperform the omni elements (in terms of throughput vs SNR). Directional antennas generally increase the SNR at a given location, hence although omni elements may have better throughput vs SNR (such as location 5) in practice the

throughput with directional antennas normally exceeds that of omni antennas due to the increased SNR (see Table II).

At location 5 the Eigen value spread of the channel is large when directional antennas are used, and hence it is more difficult to achieve the maximum throughput (450Mbps using 3 spatial streams). This occurs since the second and third spatial channels are weak, thus requiring a strong overall SNR to enable their use. However, for the same directional antennas it can be seen that the optimum 2x2 combination has a good Eigen structure (the power of the two eigen channels are close, and hence dual stream 300Mbps operation is possible at lower values of SNR). In location 3, since the eigenvalue spread of the 3x3 channel using directional antennas is better, three stream operation is possible 3dB earlier than location 5. However, since the eigenvalue spread for the omni antennas is worse at location 3, it is much harder to achieve three spatial streams, even at SNR values approaching 40dB.

Figure 8 shows that the performance of the optimum 2x2 combination is very close to that of the more expensive 3x3 solution when directional antennas are used, especially at lower SNR values. Hence, little difference in throughput was seen between the 3x3 and the optimum 2x2 EBF operation for distant (low SNR) locations in the home.

TABLE III. EIGENVALUES AND SELECTED ANTENNAS

		SNR (dB)	Link (CL/AP)	Eigenvalues	Eigenvalues of 3x3
Loc. 5	Directional	18,21	12, 13	3.38, 2.94	7.75, 0.62, 0.61
		others	13, 13	4.49, 3.03	
	Omni	0-21	13, 12	2.35, 1.60	6.24, 1.63, 1.11
		24-36	23, 23	2.40, 1.73	
		39	12, 13	2.37, 1.63	
Loc. 3	Directional	0-12	23, 23	2.33, 2.25	4.71, 2.21, 2.07
		15-39	13, 13	2.91, 2.84	
	Omni	27	12, 13	2.51, 1.49	8.67, 0.28, 0.05
		others	13, 13	2.52, 1.49	

Figure 9: Throughput vs SNR performance of all nine 2x2 combinations at location 5 (left: Directional, right: Omni).

Figure 9 shows the throughput performance at location 5 for all nine 2x2 combinations using both types of antenna. The results show that the different 2x2 combinations are similar when omni-directional elements are used. However, with directional antennas there is significantly more variation between the antenna combinations. The SNR values in Figure 9 are quoted for the 3x3 channel. The difference in performance between the nine combinations results from the

different signal levels and Eigen structures. Figure 9 shows that the performance difference between the best and worst 2x2 combination exceeds 10dB for the directional antennas, but is only a couple of dB for the omni devices.

VI. CONCLUSIONS

Results show that EBF with dynamic 2x2 antenna selection (taken from a larger set of 3x3 antennas) achieved high throughput for almost all locations and orientations, especially when directional antennas were employed. In more distant rooms (for example location 9 in our multi-storey house), dynamic 2x2 EBF using directional antennas provided 70-99% (depending on client orientation) of the throughput achieved by the more expensive 3x3 system. For omni antennas the relative throughput dropped to 45-62%. Results were seen to vary significantly according to the chosen antenna pair when directional antennas were applied. With omni antennas performance was largely independent of antenna choice. For directional antennas, dynamic antenna selection ensured good Eigen structure in the 2x2 channel matrix for most client orientations, reducing the sensitivity to orientation observed with a fixed 2x2 directional system. Overall, the performance of optimum 2x2 EBF was particularly strong at low SNR values (assuming directional antennas). Throughputs similar to the more expensive 3x3 approach were observed. We conclude that EBF with optimum 2x2 antenna selection (taken from a larger set of 3x3 directional antennas) is an attractive and cost effective solution for wireless applications in the home.

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