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AN EXPERIMENTAL EVALUATION OF THREE CANDIDATE MIMO ARRAY DESIGNS FOR PDA DEVICES

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Introduction

It is well known that multiple-input, multiple-output (MIMO) wireless channels, in which multi-element antenna arrays are used at both ends of the link, can in principle offer spectral efficiencies an order of magnitude or more above those available through conventional single antenna systems [1]. However, the performance of a practical MIMO system relies strongly upon the channel characteristics. In this paper, the antenna array is considered as part of the observed channel and an experimental evaluation is reported in which the theoretic information capacity is derived for 3 different antenna element designs for a Personal Digital Assistant (PDA) application.

MIMO Capacity & Impact of the Channel

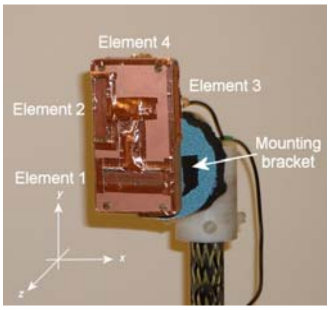
When assessing MIMO capacity it is commonplace to employ either idealised fading channels and antennas (a rich scattering environment seen through omni-directional antenna elements) or measured channel data using a single antenna configuration. In order to maximise channel capacity, either the statistically generated or measured response must offer IID Rayleigh statistics when observed through the antenna ports. For practical environments with rich multipath scattering and wide angular spreads, good channel decorrelation might be expected if element spacing is sufficient and the channel matrix to be full-rank. However, decorrelation at the receiver and the transmit elements does not necessarily imply a full rank MIMO channel offering high capacity in terms of the number of antenna elements employed [2]. An extreme example is the keyhole effect.

As far as the antenna is concerned, the radiation pattern should be overwhelming factor when considering MIMO systems, and perhaps omni-directional in order to fully exploit a multipath rich environment. However, it has been shown that channel capacity is strongly dependent on the received signal-to-noise ratio [3], thus antenna directivity will also have a significant impact, whereas mutual coupling has a much smaller impact [4]. Furthermore, radiation patterns are frequency-dependent and therefore may change considerably over the operating bandwidth of the antenna array, and this too will affect both coverage and polarisation. In addition, measurements based on antenna input bandwidth may indicate that the antenna is absorbing power, however an antenna with a low efficiency (large ‘ohmic’ loss) may appear to be well matched, but in reality only a small percentage of the input power radiated.

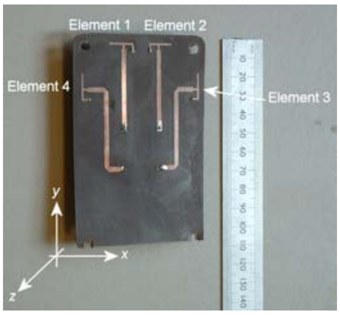
Candidate Antenna Arrays

Three different designs of a four-element antenna array (to mount on the surface of a PDA-type case 63x113x14mm) have been considered. Each design uses the same type of element throughout (Cavity Backed linear slots (Slot), Planar Inverted-F (PIFA) or Dielectric Resonator Antenna (DRA), although element orientations are different in each case. All the elements were designed to operate at 5.2GHz, with a –10dB input bandwidth (reflection coefficient) in excess of 120MHz.

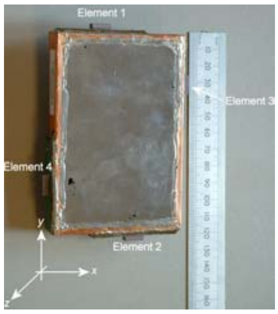
The slot antenna was fabricated using 1.6mm thick Rogers RT/duroid 5880, with an individual element measuring 40x14x3.2mm. Four slots were flush-mounted on a suitable diecast box, see Figure 1(a), with element 1 located on the front of the PDA in the position between where function buttons and the screen. Element 2 was located on the front of the PDA to the left of the screen position. Element 3 was located on the right hand-side at the top of the case, and Element 4 was located centrally on the top edge of the case.



(a) Slot



(b) PIFA



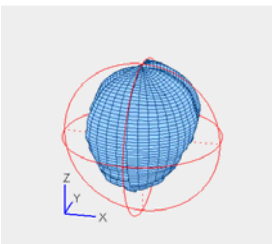
(c) DRA

Figure 1: Photograph of the candidate PDA designs

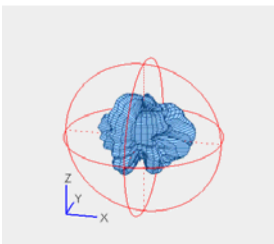
The PIFAs were fabricated on 0.8mm Taconic TLY5 with a dielectric constant of 2.2. The radiating surface covered 13.5x3.5mm beyond the ground plane and 4 such elements were mounted approximately 21mm apart within the PDA and placed towards one end of the device such that when the PDA is held in the hand the antennas are well removed from the normal hand position as shown in Figure 1(b).

The DRA based design employed a ceramic puck measuring 11x4.8x3.2mm mounted on a small pcb assembly of 50x10mm. Four single elements were soldered to a PDA sized copper box to simulate the PDA device. Here the antennas were distributed evenly around the test rig located one on each edge of the box with co-axial cable running inside the box section to SMA connectors on the external surface of the box as shown in Figure 1(c).

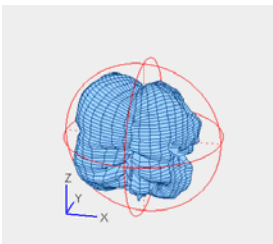
Full 3-D radiation pattern measurements were taken for all antenna element combinations and directivity, radiation efficiency [5], co-polar power and cross polar discrimination (XPD) values were obtained as reported in Table 1 and Figure 2. The latter parameter was obtained as the ratio of maximum cross polar power to maximum co-polar power. It can be seen that the slot offers a highly polarised response, whereas this is not defined for the PIFA as this type of antenna does not offer a good polarised response. The DRA offers a response in between these extremes. In order to establish if these antennas will offer different MIMO capacities when deployed in the same operational environments, a wideband MIMO propagation campaign was conducted. The measurement procedure is described in the following section.



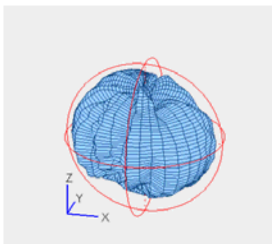
(a) Slot Co-polar



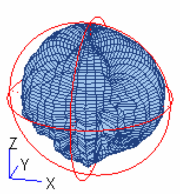
(b) Slot Cross-polar



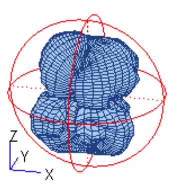
(c) PIFA Co-polar



(d) PIFA Cross-polar



(e) DRA Co-polar



(f) DRA Cross-polar

Note: All 3D polar plot measurements shown here are for relative gain, in dB, with –40dB corresponding to the centre of the sphere. All plots refer to Element 1

Figure 2: Co & Cross Polar Radiation patterns (Element No 1, unused ports terminated)

Antenna Type	Directivity	Efficiency	S_{11} @ <-10dB	Co-Polar Power	XPD
Slot	7.8dBi	81.4%±3.7%	>200MHz	94%	-12.2dB
DRA	4.6dBi	39.0%±2.7%	>300MHz	81%	-4.8dB
PIFA	5.85dBi	40%±5%	>400MHz	58.6%	N/A

Table 1: Antenna Parameters (Element 1) of Candidate PDA Designs

Measurement Procedures

MIMO channel measurements of the candidate PDAs were conducted simultaneously for all devices using a Medav RUSK BRI sounder operating in a *peer-to-peer* communications scenario. At the receiving station the 3 PDAs were placed on a short triangular arm, and the centre of this structure mounted on a rotating arm putting the PDAs at 1.3m above the floor whilst transcribing a circular path of radius 0.5m as shown in Figure 3. The transmitting PDAs were arranged on a horizontal boom also at 1.3m above the floor and approximately 0.75m between devices (see Figure 3). Using this set-up of 3 pairs of PDAs each consisting of 4 antennas, 144 channels were measured repeatedly with the rotating arm taking approximately 10s to complete 360º rotation. During this period 1000 MIMO recordings were taken, using this circular motion in order to avoid static nulls in the data relating to a particular location. The measurements described here were taken in both the Wireless & Network Research Laboratory (WNRL) and a large open plan office. In the WNRL the transmitter was fixed at one location while the receiver was moved to different 21 sites. In the office environment, the receiver was fixed at two different locations while the transmitter was moved to different 13 sites, i.e. 26 measurements were recorded in total. See Figure 4 for the floor plans noting that the arrow refers to the broadside direction of the array.

Figure 3: Rotating Spinning Arm (Left) and Transmitter Assembly (Right)

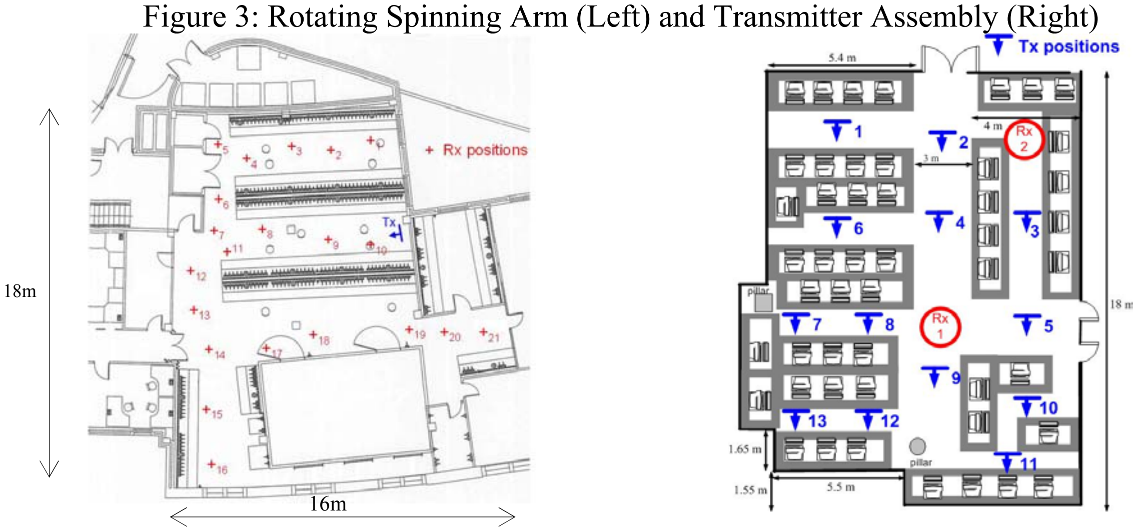


Figure 4: Floor plans of measurement environment WNRL (left) & Open Plan Office (right)

Data Analysis and Results

The channel data gathered from the measurements described above was used to compare the different PDA configurations in terms of offered capacity (C). From Shannon [6] the maximum information theoretic capacity applies to noisy but band-limited channels, thus by integrating this narrowband expression over the measurement bandwidth (W), the wideband capacities for this experimental configuration can be calculated [7].

$$\left(C/W\right)_{MIMO} = 1/N \cdot \sum_{i=1}^{N} \log_2\left[\det\left(\mathrm{I_n} + \rho/n_T \cdot \mathrm{H_i^H H_i}\right)\right] \qquad bits/s/Hz \qquad \textbf{Equation 1}$$

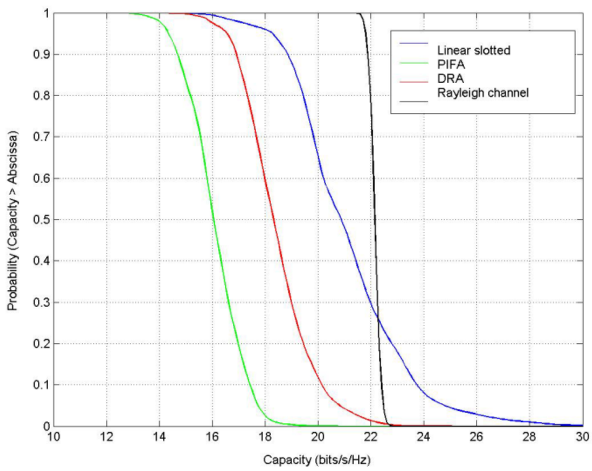
Where n_R and n_T equals the number of receiving and transmitting antennas respectively, $\boldsymbol{H_i}$ the instantaneous normalised channel gains formed (n_R by n_T matrix), $\boldsymbol{I_n}$ denotes the $N*N$ identity matrix with $N = min(n_T, n_R)$ and ρ is the signal to noise ratio (SNR).

As the aim of this initial analysis was to obtain a relative comparison of the 3 antenna types, care had to be taken when normalising the channel gains (H). It was noted that the mean received power levels at a given location for the 3 PDA antenna configurations differed significantly. Thus, if the 3 PDA antennas were individually normalised, this difference in received power would be removed and thus was undesirable. In addition, if all channels were considered, the channel coefficients from the antenna with highest gain would have a mean value above unity, and the respective MIMO capacities for a fixed SNR will be exaggerated.

In order to circumvent this problem, the channel coefficients are processed without normalisation, however mean path loss compensation is applied. Here, the mean path loss was calculated for each measurement location from the 16x3 Single-Input Single-Output (SISO) sub-channels linking the identical PDAs together. The mean path loss (P) was obtained from the mean total received power (R_P) from the corresponding SISO channels as:

$$P = (Tx_P - R_P)\ dB \qquad \textbf{Equation 2}$$

With Tx_p (transmit power) = 27dBm. Thus for a fixed SNR of 20dB, the parameter ρ in Equation 1 with the non-normalised channel gains [G] will become ρ = (P + 20) dB. The maximum achievable capacity in the form of complementary cumulative distribution functions (CCDF) for these measurements is shown in Figure 5 as well as for the theoretical Rayleigh case. This was calculated through standard normalised channel coefficients and a fixed SNR of 20dB.



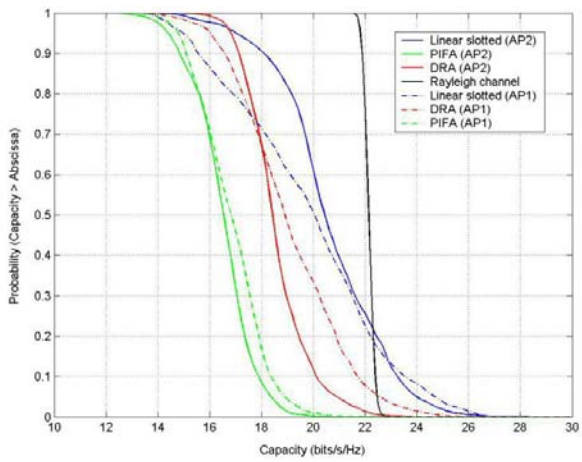


Figure 5: Offered Capacity CCDFs for WNRL (left) and Open Plan Office (right)

Conclusions

From the samples tested the results indicate that the linear slot antenna provided the highest overall capacities, although in the open plan office measurements, the DRA could match or exceed this performance at higher levels of outage. Both of these antennas show a high degree of variability in their cumulative capacity distributions as against the PIFA. With the PIFA, the achievable capacities are consistently lower as well as the variability in the capacity distributions. In a normal fixed SNR CCDF computation, this variability (or the gradient of the curve) is a related to the level of channel correlation (the fully un-corrrelated Rayleigh channel capacity CCDF gives the steepest slope). However, with the mean path loss approach adopted in this paper, it is felt that the variations in received signal power as the antennas are rotated 360˚ gives rise to this variability. The radiation patterns of the 3 antennas reveals that the linear slot antenna has the highest directivity and radiation efficiency as well as greatest cross-polar discrimination. The DRA also offers modest cross-polar discrimination, but has a lower radiation efficiency. The PIFA has a slightly better efficiency, when the total radiated power is considered rather than the polarised response. Hence, the linear slot antenna and DRA show fluctuations in received signal power and MIMO capacity as a user moves, whereas the PIFA offers nearly constant results, albeit at a comparatively lower capacity.

An interested reader in the topics described here is also directed towards [8] as well as a companion paper [9] on pattern correlation of the candidate arrays employed here.

Acknowledgements

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