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Abstract—A three element patch antenna array is designed for a 2x3 802.11n wireless home media server application for high-definition video streaming at 2.4GHz. An efficiency comparison shows that the use of the RT/Duroid substrate results in a 3dB improvement in performance over the cheaper FR4 substrate. The RT/Duroid patches are characterised in terms of input responses, full (3D) radiation patterns and directivities, including mounting on the terminal and local environment. The performance of the MIMO system is evaluated in an office environment in terms of received power, data throughput, datagram error rate, coverage area, and delay jitter. Results are compared with commercial omnidirectional antennas. Although high performance is possible (data rate at least 40Mbps), it depends heavily on the orientation of the box due to the directional radiation of the patches. An antenna selection scheme may therefore prove beneficial in future designs.

I. INTRODUCTION

With the imminent switch-off of analogue television in most countries, digital television is set to dominate. A digital signal can be received in several ways (roof or portable antenna, digital cable, satellite, IPTV, etc.). For distribution around the home, removal of the inconvenient cables is desirable via the use of wireless technologies. The recently developed IEEE 802.11n standard for Wireless Local Area Networks (WLANs) employs multiple antennas and promises data rates up to 600Mbps, making indoor wireless networks even more attractive for high-definition video streaming applications [1], [2].

A new market is emerging for wireless home media servers; these are devices that connect to a Set-Top-Box and enable the wireless delivery of the digital video signal to televisions, laptops, fixed PCs, and mobile phones around the home. Furthermore, antennas are preferred to be placed inside the Set-Top-Box and to be ‘invisible’ to the user, mainly for aesthetic reasons.

The research objectives of this paper can be summarised as follows:

- Design and compare the efficiency of two directional microstrip patch antennas on substrates of different costs for a 2x3 802.11n wireless home media server application. The system is to be used for high-definition video streaming in the 2.4GHz frequency band.
- Characterisation of the antennas in terms of input responses, full (3D) radiation patterns and directivities (including the effect of the Set-Top-Box and the box mounting on a wooden table).
- System performance evaluation in a real indoor office environment in terms of received power, data throughput, datagram error rate, coverage area, and delay jitter.
- Comparison with commercial omnidirectional antennas of the type widely used in MIMO WLANs.

II. SUBSTRATE CHOICE AND EFFICIENCY

The Set-Top-Box application requires the elements to be placed inside the box, hence low profile microstrip patches were chosen as the most suitable antenna type [3]. The different types of substrates give the ability to design patches of various costs (a crucial factor for commercial applications) and efficiencies (this essentially affects the maximum data rate and coverage). Normally, there is a trade-off between cost and efficiency. Therefore, two probe feed square patch antennas were designed for comparison: one on the low cost FR4 substrate ($\varepsilon_r$ approximately 4.5, patch dimension 28.7mm square) and one on the higher cost, and with a significantly lower loss tangent, RT/Duroid 5880 ($\varepsilon_r=2.2$, patch dimension 40.3mm square). Both used 1.6mm thick substrates.

The efficiency of the two patches was measured with respect to a monopole antenna with the same resonant frequency using the technique described in [4]. The results were relative efficiencies of approximately 40% using FR4 and 90% using RT/Duroid. This 3dB improvement in performance was the main reason for the selection of the RT/Duroid substrate, since high-definition video streaming places high demands in terms of throughput and packet error rate.

III. ANTENNA INPUT RESPONSES AND RADIATION PATTERNS

As the elements are to be placed inside a Set-Top-Box, the input responses and the radiation patterns must include not only the box but also a table mounting. This therefore accounts for the local interactions and gives a much more realistic interpretation of how the antennas would operate in the ‘real world’. In order to simulate the Set-Top-Box, three RT/Duroid patches were placed in a polycarbonate box (24x12x10cm) using nylon screws for fixing. The three antenna elements were orthogonally polarised and their main beams were directed to the three different axes (see Fig. 1). In
this way, 3D coverage is achieved and correlation between the antennas is minimised (this can be shown by comparison of patterns in Fig. 3).

Fig. 2 shows the reflection coefficients measured with a patch placed at different distances from the inside surface of the box. A comparison with an isolated element is also provided (single element mounted on a large ground plane). The resonant frequency is shifted towards the lower end of the 2400-2483.5MHz band of interest as the antenna-box distance is decreased. This will alter the performance of the communication system by introducing higher mismatch losses, and hence in future designs this will be compensated for by reducing the size of the elements.

Fig. 3 shows the full (3D) far field radiation patterns (vertical and horizontal components) of the three antennas. Table I shows the pattern statistics. The 3D patterns allow significantly greater insight into the behaviour of the antenna system that is simply not possible to deduce from single planes (eg. x-y, x-z, y-z). It is clear that the placement of the antennas inside the box, and the mounting of the box on a table, significantly affect the radiation characteristics (for example the main beam of element B is split into two, leading to a beam null and a 3.2dB increase in the maximum measured directivity compared to an isolated element).

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.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>RADIATION PATTERN STATISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Element</strong></td>
<td><strong>Power in Polarisation (%)</strong></td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>A</td>
<td>95</td>
</tr>
<tr>
<td>B</td>
<td>14</td>
</tr>
<tr>
<td>C</td>
<td>46</td>
</tr>
<tr>
<td>Isolated</td>
<td>98</td>
</tr>
</tbody>
</table>

IV. SYSTEM PERFORMANCE EVALUATION IN A REAL INDOOR OFFICE ENVIRONMENT

The performance of the antenna system described and measured in Section III is now investigated in a real indoor office environment. The location represented a total area of about 330m² (Fig. 4). Measurements include received power, data throughput, datagram error rate, coverage area, and delay jitter.

The set-up of the experiment incorporated two polycarbonate boxes as terminals, one for the server and one for the client. The server and the client were connected with 100Mbps Ethernet to a PC and a laptop respectively. At both ends of the system, the antennas were connected to a wireless radio card, which implemented a 2x3 802.11n MIMO system. The position of the server was fixed during all measurements.
and two of the three elements were chosen for the transmitter unit. In this paper results for elements B and C, which radiated their main beams towards the direction of the -y and +z axis respectively, are presented. At the client, all three patch antenna elements were used. Since the Set-Top-Box placement by the end-user cannot be predicted, the measurements were conducted for several different box orientations in every location. The configurations of the radio card were as follows: Spatial Multiplexing mode [5]; Output power: 12dBm; Frequency band: 2.4-2.4835GHz; Channel bandwidth: 20MHz; Guard interval: 800nsec.

**B. Throughput**

Using the network testing tool ‘Iperf’ [9], measurements in terms of datagram error rate were conducted for five different MAC layer throughputs (10, 20, 40, 60 and 80Mbps) in every location and for every client box orientation. UDP data streams were used, with each datagram consisting of 1470 bytes. The UDP protocol was preferred to TCP since its connectionless nature avoids MAC layer retransmissions and thus the communication is faster and more efficient. UDP is preferred for real-time video applications where lost datagrams are preferable to delayed datagrams [10].

Table II shows the throughput attained in each location for 8 different box orientations for a datagram error rate lower than 10%. It can be seen that the system is able to achieve high levels of throughput in all the test locations (at least 40Mbps). That level of throughput is normally enough for high-definition video streaming applications, which usually need a MAC layer data rate of 10-20Mbps [11]. Therefore, coverage is achieved in the whole area of the office (~330m² with three walls as the worst case scenario).

However, it should be noted that due to the directional radiation nature of the patches, performance depends heavily on the orientation of the box, which is controlled by the end-user and is unpredictable. Throughput measurements for a number of different box orientations in each location demonstrated throughput differences of up to 40Mbps, as it can be seen in Table II.

### Table II

<table>
<thead>
<tr>
<th>Different Box Orientations</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8</td>
<td></td>
</tr>
<tr>
<td>1 80 80 80 80 80 40 60</td>
<td>Location 1</td>
</tr>
<tr>
<td>2 60 80 60 40 80 80 60</td>
<td>Location 2</td>
</tr>
<tr>
<td>3 40 40 40 60 60 40 60</td>
<td>Location 3</td>
</tr>
<tr>
<td>4 20 20 40 20 20 40 20</td>
<td>Location 4</td>
</tr>
<tr>
<td>5 20 20 40 40 40 40 40</td>
<td>Location 5</td>
</tr>
</tbody>
</table>

**C. Delay Jitter**

In real-time video streaming applications, the actual end-to-end delay is normally not a major problem. What has great impact on the video quality is delay jitter, which is essentially the variation around the mean value of the delay [11].

![Fig. 6 Delay jitter](image-url)
Fig. 6 shows the delay jitter that was measured in the five locations for the different data rates. It can be seen that the higher the throughput, the smaller the delay jitter. This is due to the fact that since the packet size is fixed (1470 bytes), it needs less time to be transmitted at higher bit rates than at lower bit rates. The measured delay jitter values are all rather small (maximum value of about 1.6msec at 10Mbps).

V. COMPARISON WITH OMNIDIRECTIONAL ANTENNAS

The performance of the communication system with the patch antenna elements was also compared with commercial omnidirectional antennas that are widely used in WLANs. Following the same system set-up, two omnidirectional antennas were used at the server and three at the client. The received power and the MAC layer throughput for a datagram error rate lower than 10% were measured and the results are presented in Table III. The directional patch antennas achieve a larger coverage area on the same floor (where the main beams are pointing) but cannot achieve full 3D coverage (poorer results on top and lower floors).

TABLE III

<table>
<thead>
<tr>
<th>Locations</th>
<th>Omnidirectional</th>
<th>Patches</th>
<th>Omnidirectional</th>
<th>Patches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received Power (dBm)</td>
<td>-29</td>
<td>-39</td>
<td>-60</td>
<td>-60</td>
</tr>
<tr>
<td>Maximum Throughput (Mbps)</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

An RT/Duroid microstrip patch antenna was designed for a 2x3 802.11n wireless home media server application for high-definition video streaming at 2.4GHz. Comparison of the efficiency of this with one on an FR4 substrate demonstrated that the expensive RT/Duroid construction resulted in a 3dB improvement in performance with respect to the cheaper FR4 (relative efficiencies of about 90% and 40% respectively).

The RT/Duroid patches were then characterised in terms of input responses, full (3D) radiation patterns and directivities, including the effect of the Set-Top-Box and the box mounting on a table. The effect of the box mounting detuned the antennas by about 20MHz and therefore this needs to be accounted for in future designs. Furthermore, full pattern data show how ‘identical’ elements actually produce significantly different patterns and directivities (7.1–11.2dBi) due to orientation and box mounting.

The MIMO system performance was evaluated in an office environment in terms of received power, throughput, datagram error rate, coverage area, and delay jitter. It was shown that satisfying coverage was possible in the whole area of the office (at least 40Mbps). However, the performance proved to depend significantly on the orientation of the box, which is controlled by the end-user and is unpredictable. Throughput differences of up to 40Mbps were observed for a large number of different box orientations in every location.

Finally, the performance of the system with the patch elements was compared with commercial omnidirectional antennas that are widely used in MIMO WLANs. Results demonstrated that the patches performed better on the same floor level, where their main beams were orientated, but resulted in worse performance on the top and lower floors.

In order to overcome the problems of unpredictable Set-Top-Box orientation and the lack of full 3D coverage, and to fully exploit the benefits of the directional radiation of the patches, an ideal solution for Set-Top Boxes would be the employment of an antenna selection scheme at the server. This would incorporate directional patch antennas pointing their main beams to all possible directions in 3D space and would select the ‘best’ antenna combination.

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