ROBUST WIFI FOR MUSICAL GLOVES (AKA FINGERTIP WIFI)

PROJECT WHITE PAPER

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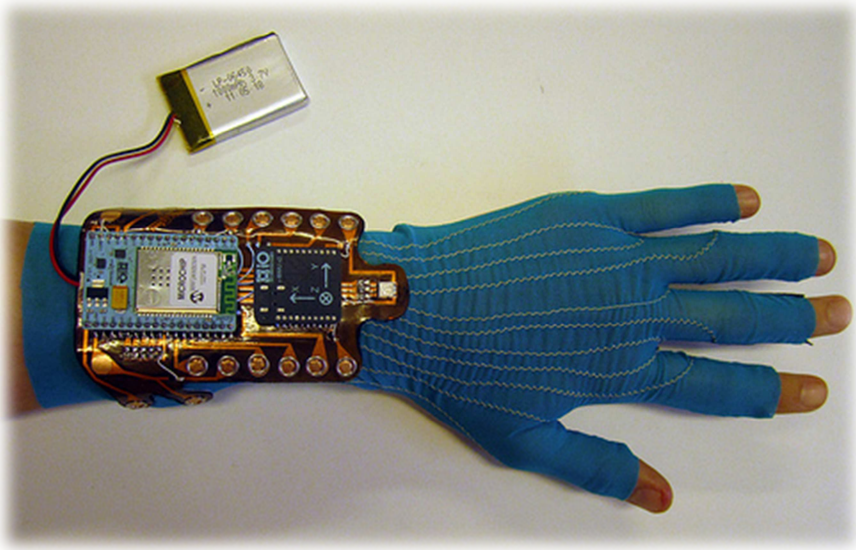

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ABSTRACT

This paper focuses on improving the reliability of an IEEE 802.11 (WiFi) wireless link in professional environments such as theatres and concert halls. Specifically the document focuses on identifying a number of techniques, operating at both the MAC and PHY layer, that help maintain throughout in the presence of uncoordinated WiFi interference.

A Netgear R6300 unit running Broadcom's manufacturer driver was used as the experimental Access Point. Two WiFi clients were evaluated – an X-OSC board and a Broadcom Wiced development board. In the latter case the client also ran a version of Broadcom's manufacturer driver.

The work shows how the impact of WiFi interference can be reduced with appropriate antenna modifications and MAC layer parameter optimizations. The work also shows how the new Quality of Service (QoS) features introduced in 802.11n can be used to enhance operation in a strong interference environment.

The project was motivated by the need to develop a robust on-stage WiFi communications link. This link is used to provide two-way communications to a pair of musical gloves. These gloves are used by musician Imogen Heap as part of her on-stage live performance.

For more background information on this project, including a number of video tutorials, please see the Fingertip WiFi project blog (http://fingertipwifi.wordpress.com).

Table of Contents

List of Acronyms Used

AP -Access Point
CTS - Clear To Send
CW - Contention Window
AIFSN - Arbitration Inter-Frame Spacing
DCF - Distributed Coordination function
DIFS - DCF Inter-Frame Spacing
EDCA - Enhanced Distributed Channel Access
EIRP - Effective Isotropic Radiated Power
HT - High Throughput
IP - Internet Protocol
ISM - Industrial, Scientific and Medical (frequency band)
MCS - Modulation and Coding Scheme
PCB - Printed Circuit Board
QAM - Quadrature Amplitude Modulation
QoS - Quality of Service
RTS - Ready To Send
TXOP - Transmit Opportunity
STA – WiFi Station
VNA - Vector Network Analyser
VOIP - Voice Over IP
VSWR - Voltage Standing Wave Ratio

1 - INTRODUCTION

The University of the West of England (UWE) in collaboration with Bristol-based technology company X-IO and musician Imogen Heap are developing prototypes for a pair of musical gloves (Figure 1.1). These gloves use a variety of sensors, including bend sensors and accelerometers, to measure the user's movements. This information is relayed wirelessly back to a computer via the open source OSC protocol to control a synthesiser program in order to produce music.

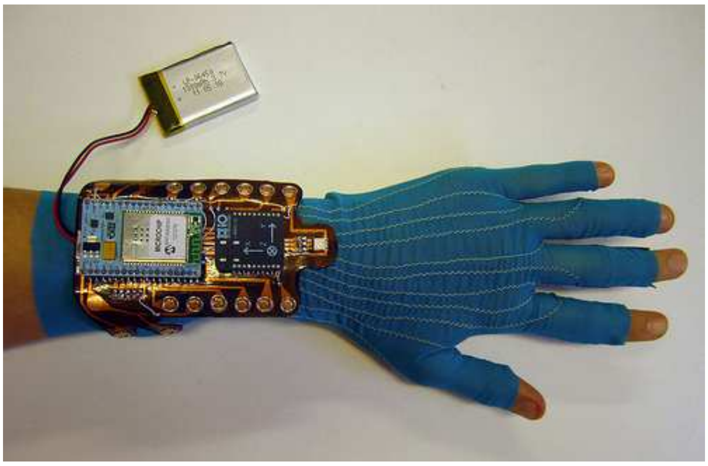


Figure 1.1 - A prototype musical gloves, showing the mounted X-OSC device (left) and accelerometer unit (right

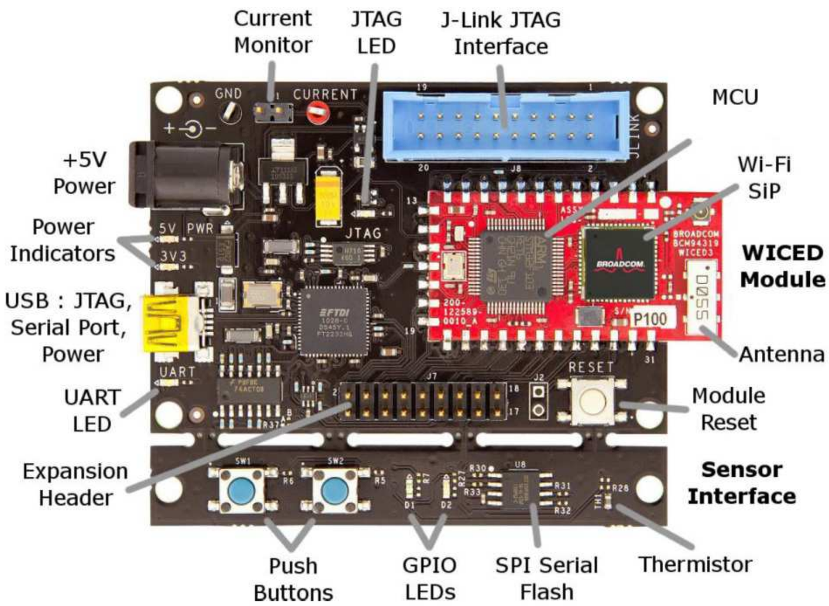


Figure 1.2 – Broadcom's Wiced WiFi Development Board

X-IO are currently exploring how their X-OSC platform (a development board that allows control and input/output data to be sent over an IEEE 802.11g link using the OSC protocol) can be used to allow the public to produce similar gloves and other novel projects.

The University of Bristol (UoB) was approached by X-IO to explore how the reliability of a WiFi link could be improved, with particular emphasis on the performance of 802.11g/n in the kind of interference seen in a professional performance environment.

The increasing prevalence of devices using 802.11 (particularly in the 2.4GHz band where the X-OSC system currently operates) results in the potential for considered interference. This can result in increased communication latency and inconsistent data throughput. In a performance environment there may be many interferers in a relatively small area. The majority of this interference will arise from mobile phones within the audience.

Network semi-conductor solutions company Broadcom kindly sponsored the project. They donated a pair of Netgear R6300 routers and several Wiced (WiFi client) development boards (see Figure 1.2). This hardware came pre-installed with Broadcom's manufacturer firmware, which enables detailed WiFi control and interrogation not possible with commercial products.

2 - EXISTING R6300 ANTENNAS

The Broadcom R6300 unit comes supplied with 6 internal antennas (see Figure 2.1) - 3 for operation in the 2.4 GHz band and 3 for operation in the 5GHz band. As part of the project all of these antennas were characterized in order to establish a baseline for creating alternative antennas better suited to operation in an interference limited performance environment.

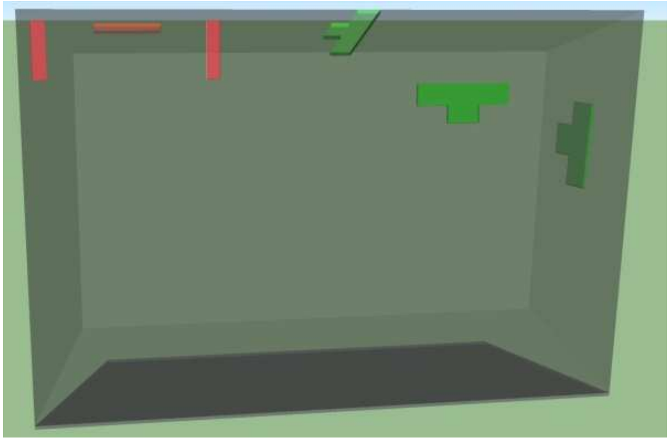


Figure 2.1 - Physical location of R6300 Antennas (red – 5 GHz, green 2.4 GHz)

MEASUREMENT

The R6300 access point (AP) was mounted inside the CSN (Communication Systems & Networks) Group's anechoic chamber and the antenna elements connected to a VNA. The recorded data was fed to a computer and processed using MATLAB. The complex polarimetric field was measured as the unit was rotated through 360 degrees over 19 specific cut planes. Furthermore, measurements were taken using a reference monopole in order to compute the relative power efficiency of the antennas under test.

S-parameter measurements were taken for each antenna using a VNA to determine *i*) the VSWR of the antenna in the center of its operation grange (2.44 GHz in the 2.4 GHz band and 5.25 GHz in the 5 GHz band), *ii*) the frequency at which the antenna was well matched and *iii*) the VWSR at the corresponding match point. All results are given in Appendix A. Figure 2.2 shows an example of one of the measured element patterns at 2.4 GHz.

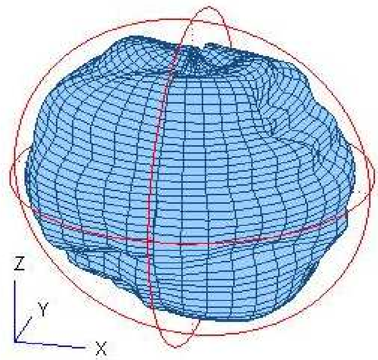


Figure 2.2 - Example Antenna Pattern Measurement (see Appendix A for full results)

SUMMARY OF RESULTS

The antennas at both frequencies displayed broadly similar antenna patterns - all antennas were found to be broadly omni-directional. Typical values for maximum directivity varied between 5.89dBi to 6.75 dBi for the 2.4 GHz antennas and 4.8dBi and 7.18dBi for the 5 GHz antennas.

The efficiency of the 2.4 GHz antennas varied from 43% to 50% compared to the reference monopole. The 5 GHz efficiencies ranged from 53% to 73% compared to the reference monopole.

3 - DEVELOPMENT OF CUSTOM R6300 ANTENNAS

While an omni-directional antenna pattern is ideal for domestic wireless networks - where the user could be positioned at any angle relative to the access point - they are less well suited to a performance environment, where the performer is likely to be positioned on a stage, and as such can be assumed to lie within a limited range of angles relative to the access point. By exploiting this fact we may design an antenna such that the desired signal is maximised while suppressing unwanted interference from the audience, which lies predominately behind the access point.

CALCULATION OF DESIRED ANTENNA CHARACTERISTICS

In order to ascertain the angle over which a high directivity antenna must radiate the dimensions of the Bristol Hippodrome were used as representative large-performance venue. The following model assumes that the antenna array is rigged in the front of house lighting rig (house grid) and that the performer is standing in line with the proscenium arch (the arch surrounding the stage in a tradition theatre layout).

HIPPODROME DIMENSIONS [1]

Proscenium width: 14.36m
Height to grid: 20.12m

Assuming that the antenna is to be mounted centrally on the front of house grid we may approximate the desired angle as follows:

$$\theta = 2 * \tan^{-1}\left(\frac{w}{2h}\right) \tag{1}$$

Where *w* represents the proscenium width and *h* the grid height in meters. Substituting the Hippodrome numbers into equation (1) provides an angle of 0.69 radians or 40°. We therefore assume that the 3dB beam-width of the AP antenna elements should be at least 40° (preferably 10° to 20° wider to allow for variations in the access point positioning and venue layout). Furthermore, to suppress interference the antenna should have a large front-to-back ratio (the ratio of the antennas sensitivity to signals arriving from the front and rear). Such a beam width is wider than could generally be achieved with a parabolic antenna, but is within the range of a Yagi or patch antenna [2].

Patch antennas were chosen in this project since they are physically small, inexpensive and readily available at WiFi frequencies of operation.

ANTENNA DESIGN

The client devices under test in this project (the Microchip MRF24WG0MA and the Broadcom Wiced board) only support the 2.4GHz band. As such the required dimensions for the patch antenna operating in the dominant TM01 mode may be calculated [1] as follows:

$$f_{min} \approx \frac{c}{2\sqrt{\varepsilon_{eff}(f)}}\sqrt{\left(\frac{m}{a_{eff}}\right)^2 + \left(\frac{n}{b_{eff}}\right)^2} \tag{2}$$

Where f represents the resonant frequency, c is the speed of light, ε is the effective relative permeability of the substrate, m and n represent the rectangular modes of the structure, TM_{mn}, a_{eff} and b_{eff} are the effective dimensions of the patch. a_{eff} can be calculated using equation 3.

$$a_{eff} = a + 2\Delta a \quad (3)$$

Where a is the actual dimension of the patch and Δa represents the effects of fringing. b_{eff} may be calculated in a similar manner:

$$b_{eff} = b + 2\Delta b \quad (4)$$

For the design of the antenna the parameters listed in Table 3.1 were used.

Parameter	Value Used	Description	Comment
f_{min}	2.44 GHz	Frequency of resonance	Centre of 2.4GHz WiFi band
c	2.99 * 10^8 ms^{-1}	Speed of light	
ε_{eff}	4.7	Relative permittivity	FR4 permittivity [3]
m	1	TM mode	
n	0	TM mode	
Δa	0.8mm	Fringing	1/2 FR4 Thickness

Table 3.1 - Patch antenna parameters.

Substituting in the values for m and n provides equation 5:

$$a \approx \frac{c}{2f_{min}\sqrt{\varepsilon_{eff}}} - 2\Delta a \quad (5)$$

Substituting in yields a value for a of approximately 0.0267m (2.67cm).

CONSTRUCTION

The prototype antenna consists of three patch antennas mounted on a large sheet of FR4 substrate, which acts as a ground plane. Two of the antennas are vertically polarised, with the third being horizontally polarised in order to take advantage of polarisation diversity.

Each patch is spaced a full wavelength apart (i.e. 12.3cm), to take advantage of space diversity. Each individual antenna connects using an F type connector, which was connected to an F-type to UFL adaptor. Figure 3.1 shows the completed antenna array.

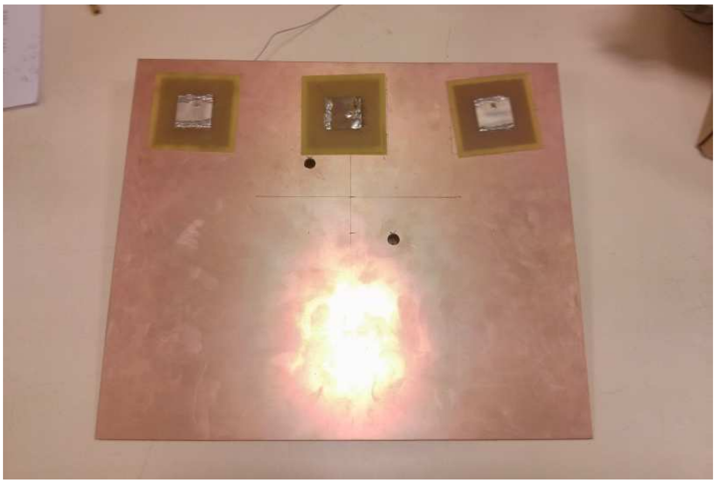


Figure 3.1 - Completed antenna array

MEASUREMENT

After completion, the antenna pattern of each of the three patches mounted on the board was measured using the methods described in Section 2. The resulting antenna patterns are shown in Appendix B. One example pattern is shown in Figure 3.2.

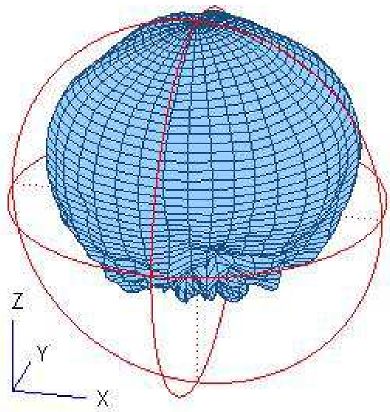


Figure 3.2 – An example of one of the measured patch antennas

The maximum directivity was measured to be in the region of 6.98dBi to 7.77dBi.

Frequently antennas are characterized in terms of a front to back ratio, however this is not an especially helpful metric in this instance. The real metric of interest is the difference in received power level from the stage (desired) and audience (undesired). Such a metric may be derived by taking the ratio between the integration of the Poynting vector around the front 60° of the antenna verses the rear 180° of the antenna. This assumes the audience is positioned behind the Access Point's antenna array. This metric is expressed in equation 6.

$$|E_{av}|^2 = \frac{\oiint_s \left(|E_\theta|^2 + |E_\phi|^2\right) \sin(\theta) d\theta \, d\phi}{\oiint_s \, d\theta \, d\phi} \tag{6}$$

The above metric was computed for each of the three antennas along with the more conventional front to back ratio. The data is given in Table 3.2.

Antenna	1	2	3
"Averaged" front to back (dB)	14.3	13.6	14.1
Front to back ratio (dB)	21.1	21.0	20.8

Table 3.2 - Antenna front to back ratios

4 - SELECTION OF ALTERNATIVE ANTENNAS FOR X-OSC

In addition to replacing the antennas on the R6300 the selection of the single antenna on the X-OSC device was also considered. The X-OSC currently uses a PCB patch antenna on its main board. The device is also available with a UFL connector to enable the attachment of an external antenna.

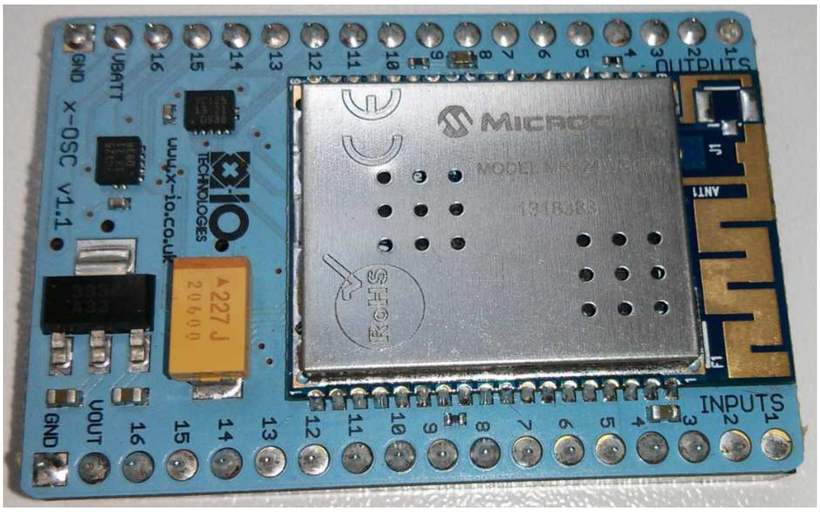


Figure 4.1 - X-OSC with PCB antenna

MEASUREMENT OF EXISTING ANTENNA

The X-OSC antenna was connected directly to a VNA and mounted in an anechoic chamber on a simulated ‘arm’, in order to give an indication of how the antenna would perform when worn by the user in a location next to the glove. The resulting antenna pattern (along with a simulated antenna pattern provided by the board manufacturer) is given in Appendix C.

The measurement of the X-OSC antenna was compared to a measurement of a reference monopole. The X-OSC antenna achieves a power efficiency of 35-40%. This experience yields estimate values that are accurate to within +/- 5%.

CONSIDERATION OF ALTERNATIVE ANTENNAS

The requirements for the external antenna were that it should be as omni-directional as possible (i.e. minimize the peaks and nulls in the horizontal plane) and should be small enough to fit within the glove assembly. The antenna should also be reasonably efficient (however it is worth noting that the output power level is not critical in this application - see Section 5 for details on the link budget.

Three candidate antennas was selected for testing in the chamber - two small patch antennas similar to those used in the WiFi access point and one cloth (wearable) antenna currently being developed in the University of Bristol’s Communication Systems & Networks group.

ALTERNATIVE ANTENNA CANDIDATES

Each antenna in turn was tested in our anechoic chamber and its efficiency compared to a reference monopole. Figure 4.2 shows the wearable antenna under test in our anechoic chamber. Radiation patterns for the candidate antennas are given in Appendix D. The results of the efficiency tests are shown in Table 4.1.

Candidate	Antenna Name	Efficiency relative to reference monopole
1	Centurion Multi-band	40%
2	WINizEN W5EW10	30%
3	Prototype ‘wearable’ Antenna	27%

Table 4.1 - Candidate Antenna Efficiencies

Figure 4.2 - Cloth antenna under test in the chamber

Based on the above results (and analysis of the antenna patterns) it is recommended that candidate antenna 1 should be used. This antenna provides similar, if not better, efficiency levels to the existing antenna but crucially has a more even radiation pattern and can readily be positioned for more favorable reception. While candidate 2 provides a good radiation pattern it is not as efficient as antenna 1 (although since power efficiency is not the prime driver this antenna is still perfectly usable). Candidate 3 is not considered suitable for this project since its antenna pattern is too directional, resulting in reduced directivity around the back of the antenna. Since the access point could be behind the antenna this is not desirable. Furthermore, candidate 3 was the least efficient of the antennas under test.

Further Work in the area of Wearable Antennas

Although not suitable in the form available for testing in this project, the use of a cloth antenna has considerable potential for integration into textile products such as the glove. Further research into creating a less directional antenna suitable for this application is recommended.

Use of an external antenna provides an opportunity to mount the antenna remotely from the gloves. As the wearer will partially block signals from the antenna further research should be conducted into the best on-body position for an external antenna.

5 - LINK BUDGETS

In this section a link budget is developed to better understand the AP to glove radio channel. A range of parameters are required to complete the budget, many of which were acquired experimentally. This section describes the methods used to develop the link budget for this project.

THE ATTENUATION CONSTANT

The starting point for the link budget is equation 7 below. This allows the average received power to be determined as function of antenna gains, carrier frequency, separation distance and attenuation constant [4]:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^n \tag{7}$$

Where:

- P_r is the average received power
- P_t is the transmit power to the antenna port
- G_t is the transmitter antenna gain (relative to an isotropic source)
- G_r is the receiver antenna gain (relative to an isotropic source)
- λ is the wavelength of the transmitted signal
- R is the separation distance between transmitter and receiver (in meters)
- n is the attenuation constant (also known as the path loss exponent).

Other than the attenuation constant in a professional environment for the artist and audience, all the other parameters are known. The antenna gains were measured and reported in Sections 3 and 4. The attenuation constant is empirically derived and typically takes a value between 2 and 4. A value of 2 represents an ideal channel with direct line-of-sight between the AP and client. Values greater than 2 are used to model the antenna attenuation (for directional antennas) and shadowing caused by blocking objects in the link (walls, furniture, people etc.).

MEASUREMENT OF THE ATTENUATION CONSTANT

In order to measure the path loss exponent for a typical performance space an experiment was performed based on the study reported by Erceg [5].

In order to perform the experiment an R6300 AP was set up in a lecture theatre (a space chosen for its similarity to a typical performance space) and measurements of received signal strength were taken at discrete intervals away from the access point. Given knowledge of the average received power, a best fit value for the attenuation constant was derived.

Full results from this experiment are given in Appendix E. The attenuation constant was found to lie in the range from 2.62 and 2.69.

CALCULATION OF LINK BUDGET

By knowing the sensitivity of the receiver (i.e. the minimum average received power required to achieve an acceptable link) equation 8 may be used to calculate a maximum separation between the AP and STA for reliable operation. Additional margins may be employed to take account of small scale fading (the constructive and destructive summation of multipath components).

The maximum separation distance is calculated using the link budget via equation 8 [11]:

$$\log(d) = \frac{PL - 2\log\left(\frac{4\pi}{\lambda}\right)}{10n} \tag{8}$$

Where *d* is the separation distance and PL represents the maximum tolerable path loss. All other symbols have their usual meanings. The maximum tolerable path loss PL in dB can be calculated from equation 9:

$$PL = P_t + G_t + G_r - SNR_{AWGN} - \gamma_{FM}, \tag{9}$$

where

- P_t is the transmitter power in dBW;
- G_t is the transmitter antenna gain in dBi;
- G_{r+} is the receiver antenna gain in dBi;
- SNR_{AWGN} is the receiver sensitivity in dBW;
- γ_{FM} is the small scale fade margin in dB.

The completed link budget for this project is given in Appendix F. The results show that with the directional antenna the maximum separation exceeds 500m. Similarly, devices operating up to 200m behind the antenna can still connect and interfere with the system. Given these large operating distances there is a strong argument for deliberately attenuating the received signal at the AP. For example, the use of a 20dB attenuator would still provide 100m range for the artist, however audience interference would then reduce to just 30m behind the AP.

A further enhancement to consider in the future is to apply the attenuator only to the receive path of the AP. This would allow the transmit signals from the AP to remain at full power. One possible solution is to fix the transmit/receive switch at the AP to transmit. This is likely to introduce 20dB or more attenuation into the receive path, hence desensitizing the AP to audience interference.

6 - Investigation Into MRF24WG0MA Firmware

For its WiFi communication the X-OSC board employs a Microchip MRF24WG0MA 802.11g module, controlled by a microprocessor. As part of the project the firmware for the WG0MA unit was reviewed to establish whether improvements could be made in the future.

Methods for improving the performance were based on suggestions in 802.11 Wireless Networks [6].Client parameters that can be altered include:

Fragmentation Threshold

This threshold determines the maximum transmitted frame size - any frames larger than this size must be fragmented. In a high interference environment increasing this parameter results in the need to re-transmit fewer frames, and therefore increase the effective throughput.

Retry Limit

Each 802.11 station has a long and short retry limit. A station will attempt to transmit a frame up to the retry limit, before declaring it as lost to the layer above. Increasing these limits means that it takes longer for the MAC layer to declare a segment as lost to the layer above (for example TCP).

Listen Interval

A station's listen interval adjusts the period of time during which a station will sleep between receiving frames. The benefit of doing this is primarily to reduce power consumption. However increasing the listen interval can also decrease latency.

However the API provided for use with the WG0MA does not provide access to MAC layer settings. As all of the above parameters operate on the MAC layer they cannot be adjusted from the manufacturers default in the current glove solution.

7 - WICED BOARD MEASUREMENT

In addition to a pair of R6300 platforms, Broadcom also supplied two of their Wiced development boards. These are small stand-alone WiFi clients that add internet connectivity to "Things", thus creating the "Internet of Things".

As part of this project the maximum throughput of these boards was measured when connected to the R6300 AP. Measurements were performed inside our anechoic chamber (effectively an interference free environment) and in lab conditions (i.e. considerable levels of 2.4 GHz interference).

The Wiced boards conform to the 802.11b/g/n standards [5], but are only capable of operation in the 2.4 GHz band at the present time. Plans exist to produce 5 GHz enabled units in the near future.

TEST MEASUREMENT SETUP

The test setup consists of a laptop running *Iperf*, a freely available software tool for measuring network performance between any two nodes[1], connected to a R6300 router over a gigabit Ethernet connection (this effectively ensures that the cabled connection will not be the bottleneck in the test). The Wiced board is connected to the R6300 and bi-direction tests are performed for jitter, latency and throughput. The setup is summarised in Figure 7.1.

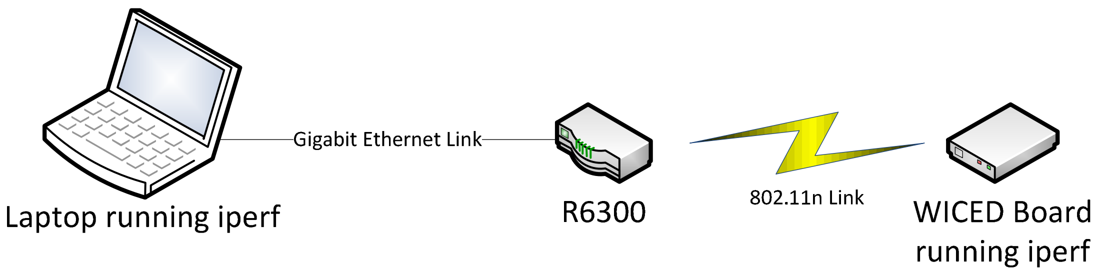


Figure 7.1 - WICED Board Measurement Setup

EXPERIMENTAL RESULTS

A summary of the results are provided in Tables 7.1 to 7.4. A full set of results are given in Appendix G.

Load	Throughput (Mbit/s)	Jitter (ms)
100kB	32.50	0.64
1MB	31.03	0.57
10MB	33.33	0.72
100MB	33.43	0.90
Mean	32.58	0.71

Table 7.1 - Send Averages Measured Within the Anechoic Chamber.

[1] More information about *Iperf* and its source code may be found at https://code.google.com/p/iperf/

Load	Throughput (Mbit/s)	Jitter (ms)
100kB	**38.23**	**0.24**
1MB	42.77	0.12
10MB	**41.13**	**0.23**
100MB	41.27	0.23
Mean	**40.85**	**0.20**

Table 7.2 - Receive Averages Measured Within the Anechoic Chamber.

Load	Throughput (Mbit/s)	Jitter (ms)
100kB	2.95	1.07
1MB	12.07	1.15
10MB	18.30	0.89
100MB	19.83	0.87
Mean	10.63	0.80

Table 7.3 - Send averages measured in an interference environment.

Load	Throughput (Mbit/s)	Jitter (ms)
100kB	**3.77**	**0.59**
1MB	10.47	0.37
10MB	**14.57**	**0.29**
100MB	15.20	0.22
Mean	**8.80**	**0.29**

Table 1.4 - Receive averages measured in an interference environment.

The average round trip latency was found to be 4.6ms.

WICED BOARD CONCLUSIONS

These results demonstrate the impact of running a WiFi system in an interference heavy environment. Both the maximum send and receive streams are heavily impacted in the interference environment, although interestingly the increase in jitter is minimal, suggesting that the majority of the jitter is caused either by the generation of data in *iperf* or in other parts of the test network (network adaptors, routers etc.).

The maximum data rate observed was 42.77Mbits^{-1}. This compares favorably with the maximum theoretical data rate, which may be computed as shown in equation 10 [8]

$$C = BR_cMS\left(1 - \frac{t_g}{t_t}\right), \tag{10}$$

where

- C is the capacity of the link;
- R_c is the coding rate;
- B is the available bandwidth;
- M is the number of bits per symbol;
- t_g is the period of the guard interval;
- t_t is the total time taken to transmit a frame including the guard interval;
- S is the number of spatial streams.

For 802.11n in MCS mode 7 (the highest MCS mode achievable using a single spatial stream Wiced board) assuming a 20MHz channel and a 400ns guard interval, the peak physical layer data rate is 72.2Mbit/s. Applying a 10% IP header overhead and a 30% MAC layer overhead, the peak application rate drops to 45.4Mbps (which aligns well with the anechoic chamber measurements).

8 - 802.11N IN THE PRESENCE OF 802.11G

This section explores whether legacy devices (specifically devices using 802.11g) have on a negative impact on 802.11n operation in the 2.4 GHz band.

802.11 MIXED MODE

The 802.11g standard was ratified in 2003 and was intended to allow backwards compatibility with 802.11b devices operating in the 2.4 GHz band while offering comparable data rates to the 5 GHz and shorter-range 802.11a standard. The 802.11g standard is constrained to operate only within the 2.4 GHz band [9].

In order to maintain compatibility with legacy versions of the 802.11 standard newer editions of the standard implement "protection modes" in order to avoid interfering with legacy standards. In the case of 802.11g, operating in the presence of 802.11b, this can result in a performance reduction of up to 50% [6].

When 802.11n is operating in the presence of legacy devices there are several adaptations that must be performed to ensure compatibility [10]. 802.11n devices have the option of transmitting using a 20MHz or 40MHz bandwidth - however 20MHz must be used in the presence of legacy 802.11 devices. In practice 40MHz bandwidths are rarely used in the 2.4 GHz band due to the limited amount of spectrum and the high levels of observed interference.

In order to operate in mixed mode an 802.11n AP must first transmit a legacy pre-ample and then a HT pre-amble - this increases the overheads in each transmission. RTS and CTS, or CTS to self-frames, must be sent at sufficiently slow speeds (for example around 6Mbit/s for 802.11b) for all devices to be able to receive them. Although these messages are short, they still take significantly longer to send in legacy mode. Overall, when 802.11n runs in a legacy mode its throughput can be seriously degraded.

EXPERIMENTAL RESULTS

An experiment was conducted to establish the impact the presence of 802.11g devices have on the 802.11n link between the Broadcom Wiced boards and the R6300 access point.

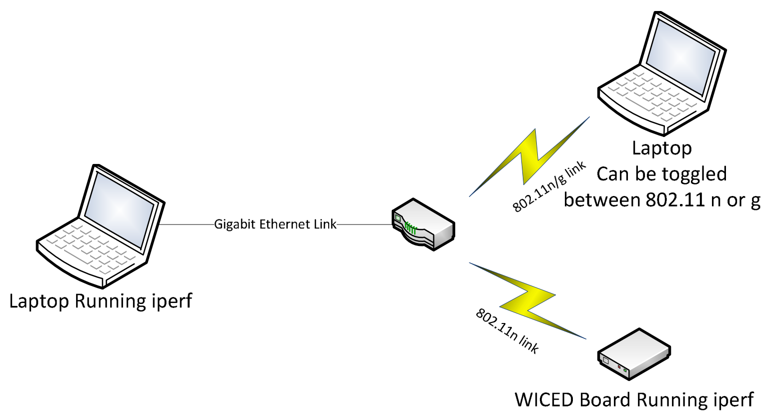


Figure 8.1- Mixed Mode Testing Setup

The test setup shown in Figure 8.1 consisted of a laptop running *iperf* connected via a gigabit Ethernet link to a R6300 AP. A Wiced board also running *iperf* connects wirelessly to the access point, as does a second laptop. The second laptop can be switched between 802.11n and 802.11g. Data rate tests are not performed from this laptop.

The results of the experiment are given in Appendix H. A summary of the results are provided in Tables 8.1 and 8.2.

Load	Throughput (Mbit/s)	Jitter (ms)
N and N	**13.97**	**9.53**
N and G	14.63	9.82
Mean	**14.30**	**9.68**

Table 8.1- Send averages for mixed mode operation

Load	Throughput (Mbit/s)	Jitter (ms)
100kB	**8.77**	**12.77**
1MB	7.88	13.80
0.00	**8.32**	**13.28**

Table 8.2- Receive averages for mixed mode operation

MIXED MODE CONCLUSIONS

While there is plenty of evidence to suggest that mixed mode operation constrains the throughput of 802.11n links this was not observed in our measurements. This might be because the protocol stack on the Wiced board is the main bottleneck rather than delays in the 802.11 mixed mode protocol.

9 - TXOP AND QOS SETTING ADJUSTMENT

The IEEE 802.11e standard introduced the idea of quality of service to WiFi systems. 802.11e allows traffic to be categorised into 4 different access classes [11]:

- Voice (VO);
- Video (VI);
- Best effort (BE);
- Background application (BK).

These capabilities are intended to allow delay sensitive traffic (such as voice over IP packets) to receive a higher priority when being transmitted over the network - for example it is less important for a packet containing email data to reach its destination than a packet containing the data being transferred as part of a telephone call.

Different EDCA parameters may be set for each access class. The EDCA parameters include:

- TXOP length;
- CWmin;
- CWmax;
- AIFSN.

CONTENTION IN THE 802.11 MAC

When an 802.11 station wishes to send a frame it must first sense the channel for the DIFS time to ensure that no other station is attempting to transmit. If the channel is clear it may then transmit data for the duration of its transmit opportunity (TXOP).

If the transmission is not successful (i.e. the channel was sensed to be active by another user) then the AP must back off for a random period (adjusted using CWmin and CWmax) before attempting to transmit again [8].

By adjusting the AIFSN used for the link we may ensure that traffic is more likely to be transmitted when it is ready to be sent. By adjusting TXOP we can ensure that once the channel has been acquired a large amount of data may be sent before the station needs to compete again for access to the medium. By adjusting CWmin and CWmax we can control the time required for a station to wait once the medium has been sensed to be busy. This has a strong impact on fairness, since stations that attempt to retransmit after a short duration are far more likely to secure the channel.

A combination of the above settings can produce an AP that is very aggressive (unfair). Generally this is not desirable, however in a performance environment where a particular link is be used by the artist as part of their performance, this type of aggressive behavior is beneficial. Specifically, the performer's link needs to take priority over general WiFi signalling coming from the audience.

EXPERIMENTAL RESULTS

To test the benefits of more aggressive QoS parameters an experiment was devised based on an access point communicating to a wanted node (the performer) and an unwanted node (the audience).

A laptop running *iperf* was connected to an R6300 AP via a gigabit Ethernet link. A second laptop, also running *iperf*, was connected via a gigabit Ethernet link to a second R6300 configured as a station (STA). End to end throughput tests were then performed along this link.

In order to simulate interference a second laptop (again running *iperf*) was connected to a third R6300 unit, also configured as an AP, but not associated with the other two R6300s. Connected wirelessly to this AP was a Wiced board, running *iperf*, which acted as a load. The arrangement is shown in Figure 9.1.

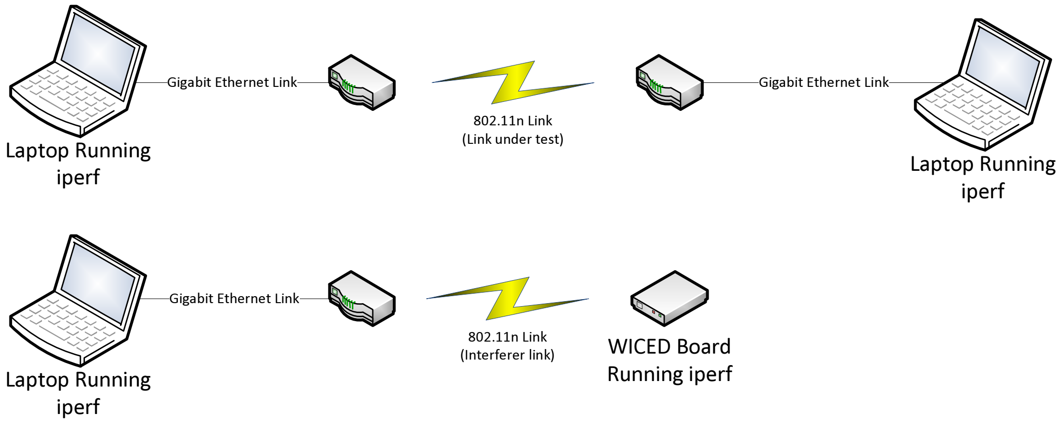


Figure 9.1- Experimental Setup for QoS Parameter Testing

In order to generate sufficient data to saturate the channel (in time) each of the APs was constrained to operate in MCS mode 1 (6Mbps). Both APs were manually configured to operate on the same 2.4GHz radio channel. This scenario represents the worst case scenario, when a WiFi station in the audience is trying to transmit packets all the time on the same channel as the performer.

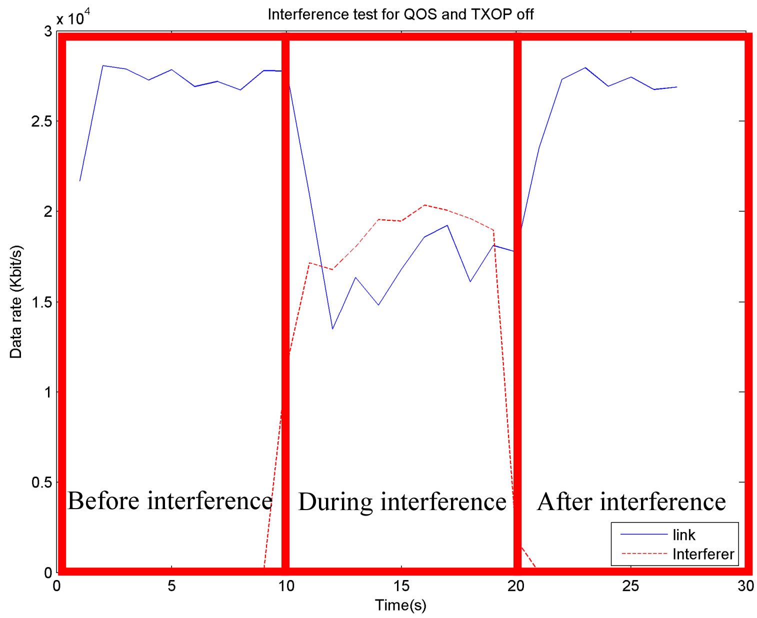


Figure 9.1- Sample test data with all QoS settings disabled

Tests were performed with the QoS parameters turned off at the AP, with TXOP alone enabled, with aggressive CW settings alone enabled and with a combination of TXOP and aggressive CW settings enabled. Each test began by running the test link in isolation for ten seconds. The interferer link was then switched on for 10 seconds, before being disabled for a further 10 seconds. The aim was to explore how well we could protect the performer's link during the middle 10 second interference period. Figure 9.1 clearly the results obtained with the QoS settings disabled.

The specific parameters for the QoS used in the experiment are given in Table 9.1.

Parameter	Original Value	Altered Value
CW min	4	2
CW max	**10**	**3**
AIFSN	7	1
TXOP	**0**	**65504**

Table 9.1- Quality of Service Parameters Used

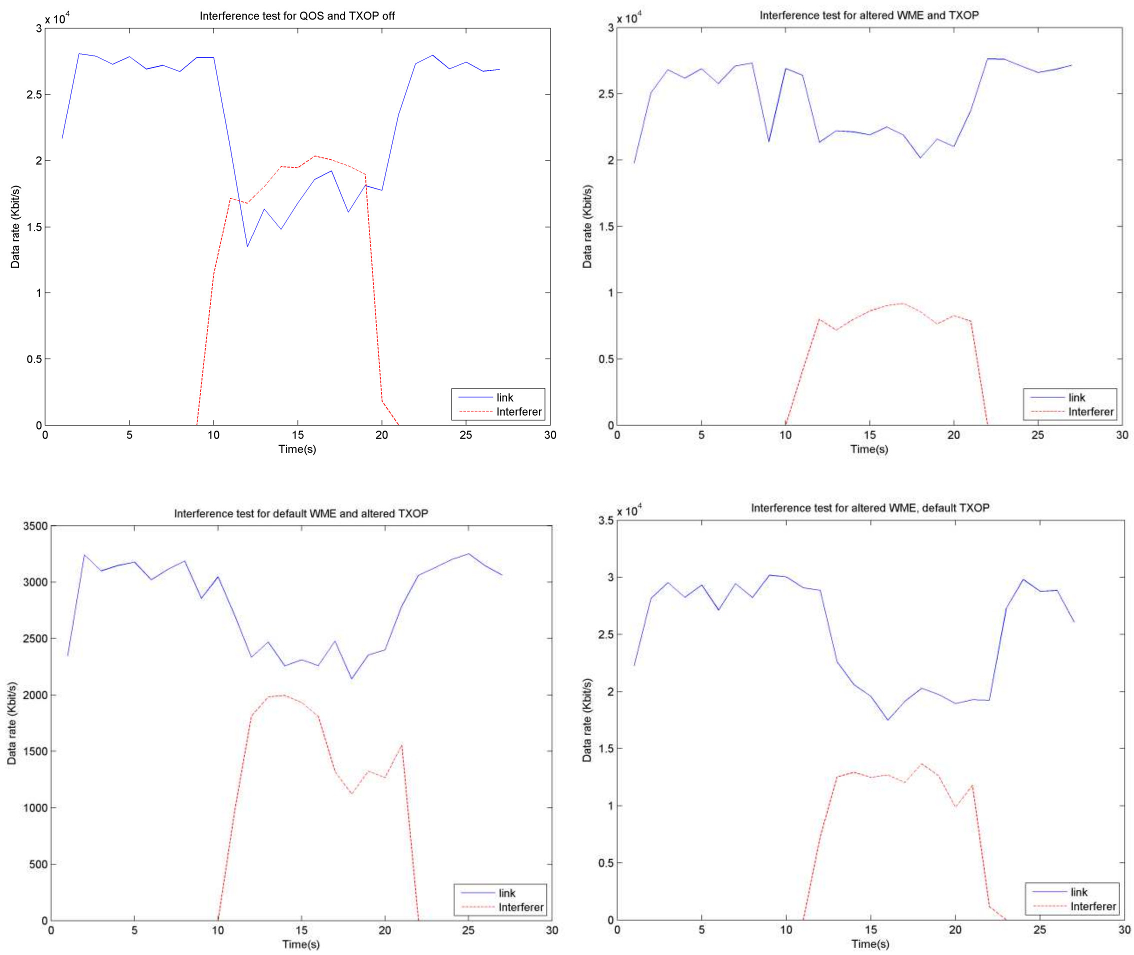


Figure 9.2 - Results of TXOP and QOS parameter testing for various permutations

In general the results showed that by adjusting both the TXOP and the contention window parameters the AP-to-performer link could be given an unfair advantage in acquiring and retaining the channel.

Figure 9.2 shows that the performer link is now largely unaffected as the persistent interferer turns on after 10 seconds where the altered router parameters are used. In the original experiment (Figure 9.1) the performer link dropped to 50% of its throughput when the interference was present.

This drop in connectivity is likely to adversely affect the show. However, Figure 9.2 shows that with appropriate 802.11e/n QoS parameters the audience will have little impact on the wanted wireless link.

It should be noted that the Microchip MRF24WG0MA does not support 802.11e and hence the benefits of TXOP and modified CW settings cannot be applied to the current-OSC product. We recommend moving to the Broadcom/Murata unit (http://www.murata-ws.com/sn8200.htm). These combine the Broadcom BCM 43362 Chipset and a ST Microelectronics ARM Cortex (see Figure 9.3). In the future these modules are expected to support 5GHz operation where there are many more available channels and hence significantly less interference.

Figure 9.3 - The Broadcom/Murata 802.11n 2.4GHz unit.

It should be noted that this experiment explored the downlink from the AP to the client. Similar MAC parameter adjustments are required in the client to provide the same benefits on the uplink from the client to the AP. Such changes are possible using the Broadcom device but not with the Microchip module. This means the benefits of interference suppression cannot be achieved on the glove to AP link using the current X-OSC design.

10 – Final Demonstration

The final demonstration was intended to repeat the analysis of the amended QoS parameter settings and determine the degree of interference suppression that could be achieved using directional antennas at the AP. The venue selected for this demonstration was the University of Bristol's Pugsley lecture theatre. The theatre provides a large, open, high ceilinged space with raked seating similar to that found in many medium and large performance venues. The Pugsley lecture theatre is capable of seating around 220 people.

The experiment was based on the setup described in Section 9 of this report. The only difference between the two configurations was that the test link was made up of a connection between a Wiced board/XOSC board and an R6300, whereas the interferer link now comprised two R6300 units. This modification was made to make the setup as close as possible to the gloves use case.

In addition, this allowed the R6300 on the test link to use an external and directional antenna array. Similarly, the XOSC was also able to make use of the recommended external antenna.

Results

In general the system performed well during the demonstration, with the alteration of QoS parameters being particularly effective at protecting the performer's link, a set of typical test results is shown in Figure 10.1.

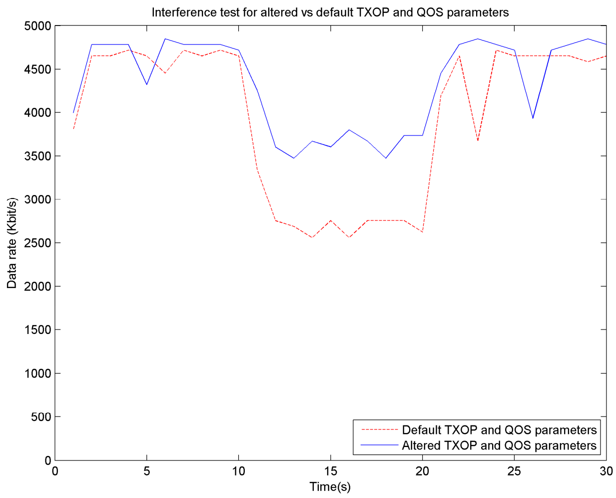
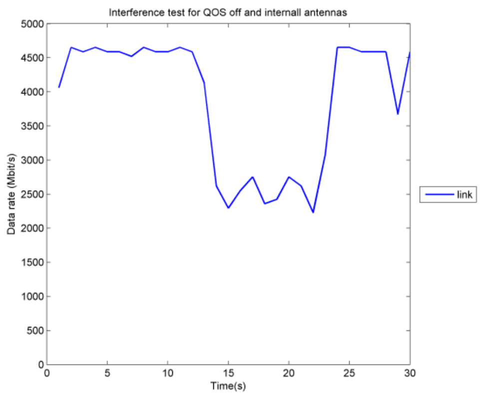


Figure 10.1 - QoS and TXOP testing parameters

However, at the start of the demonstrations the wanted data rates were seen to fluctuate more rapidly than in the chamber. This may well be a result of the university WiFi active in the room.



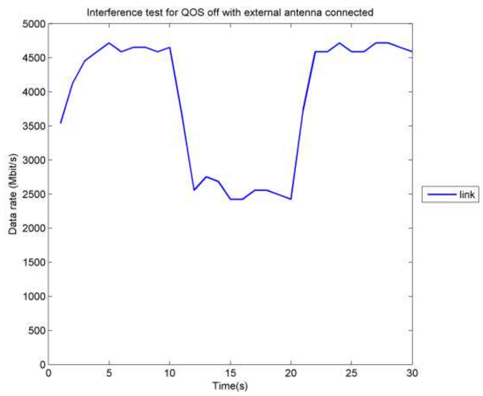


Figure 10.2 – (left) No QoS and omni-directional antennas, (right) No QoS and directional antennas

However, when the external antennas were connected to the AP the data rates became smoother and the sudden peaks and troughs were suppressed.

Figure 10.2 shows results with internal (left) and external (right) antennas. In both cases modified QoS settings were not used. It can be seen that the external and directive antennas on their own are not sufficient to suppress the unwanted interference.

Figure 10.3 shows the result of using combined QOS and TXOP with the external antennas vs. an un-altered system.

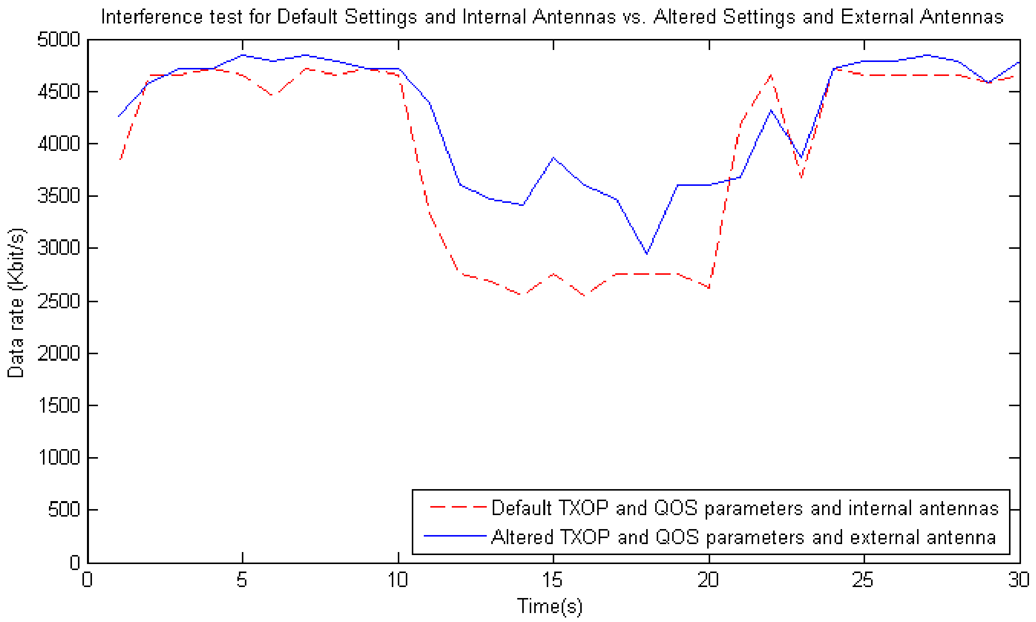


Figure 10.3 - External antennas vs. an Un-altered system.

Figure 10.4 shows WiFi activity in the room at the time of the experiment. Two overlapping APs were active on the same channel as our AP, and several AP were active on both adjacent channels.

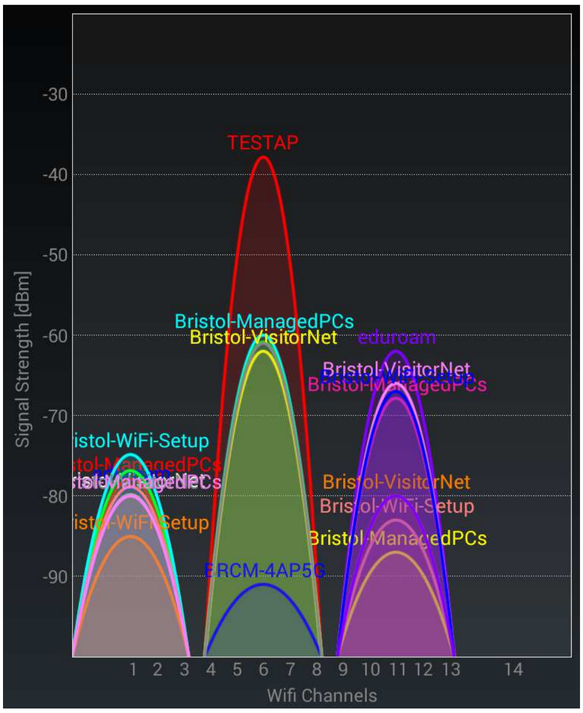


Figure 10.4 - Capture of Wireless APs detectable during the demonstration

In Figure 10.3 there is still a noticeable drop in performance during the interference period. In this experiment the wanted link was running at almost 100% utilization of the channel rate. If time had allowed a further experiment would have been performed using a lower rate (say 1Mbps) on the wanted connection. It is likely that in this case the impact of interference would have been minimal.

11 – Conclusion and Recommendations

Conclusion

802.11 is increasingly becoming the de-facto standard for wireless computer networking. Its ability to allow computer equipment to be portable and compact - to the extent where it is easy to mount discreetly on the body - makes it ideal for use in the performance environment where mobility and aesthetics are key.

However, if 802.11 is to be used in such environments care must be taken to ensure that it is able to withstand the unique operating challenges that a performance environment presents. The presence of a potentially vast pool of interferers coupled with a requirement for high reliability makes this a very challenging environment when attempting to operate in the 2.4GHz ISM band.

This project has suggested and trialed various methods to help ensure that 802.11 devices operate well in these environments. A working system has been demonstrated that was shown to reduce the effect of interferers on the link. Furthermore this project has investigated the potential of Broadcom's Wiced module for use in a future respin of the X-OSC hardware that powers the gloves.

Report Recommendations

With reference to the Imogen Heap glove project the following recommendations are made:

- The internal antenna fitted to the MRF24WG0MA should be replaced by a Centurion Multi-band or similar omni-direction antenna. For best effect the antenna should ideally be mounted high and slightly away from the body (as the body is a good RF absorber).
- A multi-antenna access point should be employed for use in performances - although the XOSC is only fitted with one antenna the space diversity offered by 3 antennas at the AP is still beneficial.
- The AP should be fitted with a directional antenna similar to that described in Section 3 of this report in order to improve the wanted signal and reduce the effects of audience interference.
- Particularly for smaller venues the AP should be fitted with attenuators of 10-20dB to reduce the signal levels detected behind the AP while still maintaining sufficient forward looking reception.
- The AP should be operated with modified 802.11e QoS parameters as described in Section 9. Ideally Broadcom's manufacturer driver should be use to enable non-standard CW and TXOP settings to be applied.
- Further investigation should be conducted into the possibility of moving to an alternate platform where access to the MAC parameters of the device is enabled. We recommend the Broadcom/Murata SN8200 units.
- Serious consideration should be given to use of the 5GHz spectrum when hardware allows. 802.11b/g devices do not operate at 5GHz and the greater number of available channels further reduces interference.

SUGGESTIONS FOR FURTHER INVESTIGATION

- Once the Broadcom Wiced device is able to support 5GHz further experiments should be performed to investigate the benefits of this band.
- Towards the end of the project it was suggested that attenuating the RX of the Broadcom board may prevent it from hearing competing stations and therefore cause it to compete unfairly by deliberately creating a hidden terminal problem. This approach was trialed, but invariably led to reduced data (probably due to an increase of collisions on the channel). This theory should be investigated further.
- This report suggests a value for the attenuation constant that is representative of a typical performance space. However, this value is based on measurements in just one space. Further measurements in alternative venues are recommended.

12 – ACKNOWLEDGEMENTS

The authors are extremely grateful to Broadcom. This project would not have been possible without their financial support and hardware donations. In particular, we would like to thank Broadcom's Gordon Lindsey and David Armour for their tireless support and advice. Without this expert help it would not have been possible to configure and control the WiFi hardware.

The authors are grateful to Dr Geoff Hilton for explaining how to perform the required antenna measurements. We are also grateful to the CSN Group for providing free access to their Anechoic Chamber. Finally, we would like to thank Seb Madgwick for inspiring the project and providing technical assistance with the X-OSC boards and protocols.

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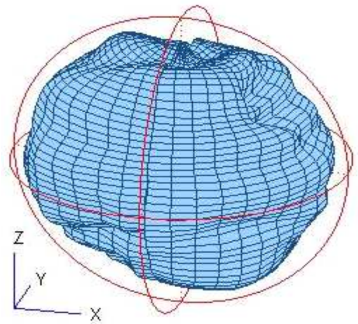
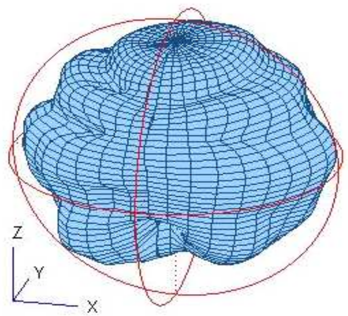
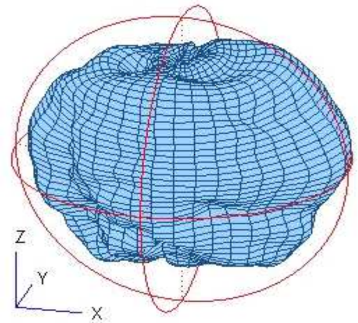
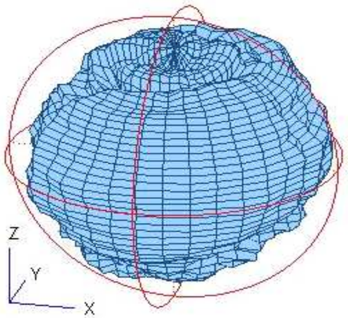
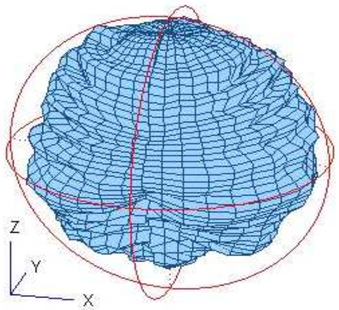
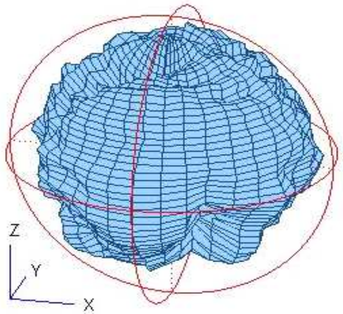
Appendices

Appendix A - R6300 Antenna Patterns

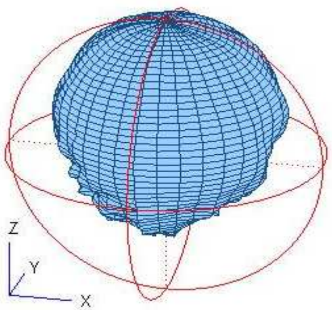
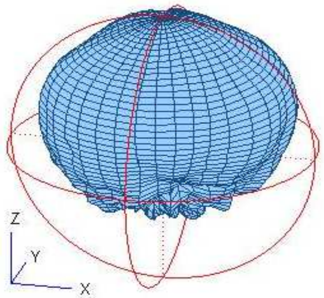
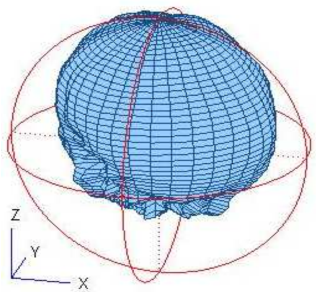
R6300 Black 2.4GHz	R6300 Blue 2.4GHz	R6300 Gray 2.4GHz
		
Efficiency: 43.48 %	**Efficiency:** 43.83 %	**Efficiency:** 49.81 %
Match at: 2598 MHz	**Match at:** 2354 MHz	**Match at:** 2525 MHz
Maximum Directivity: 5.89 dBi	**Maximum Directivity:** 6.75 dBi	**Maximum Directivity:** 6.75 dBi
Average radiation intensity 0.43 w/sr	**Average radiation intensity** 0.26 w/sr	**Average radiation intensity** 0.21 w/sr

Antenna colours refer to the colour of the wire connecting the antenna to the main board.
For a description of the location of each antenna please refer to Figure 2.1.

R6300 Black 5GHz	R6300 White 5GHz	R6300 Gray 5GHz
		
Efficiency: 52.50 % **Match at:** 5630 MHz **Maximum Directivity:** 5.52 dBi **Average radiation intensity** 0.26 w/sr	**Efficiency:** 72.77 % **Match at:** 5720 MHz **Maximum Directivity:** 7.18 dBi **Average radiation intensity** 0.2 w/sr	**Efficiency:** 67.64 % **Match at:** 5720 MHz **Maximum Directivity:** 4.8 dBi **Average radiation intensity** 0.21 w/sr

Antenna colours refer to the colour of the wire connecting the antenna to the main board.
For a description of the location of each antenna please refer to Figure 2.1

APPENDIX B - CUSTOM ANTENNA ARRAY PATTERNS

R6300 Patch 1 2.4GHz	R6300 Patch 2 2.4GHz	R6300 Patch 3 2.4GHz
		
Efficiency: 41 % **Maximum Directivity:** 7.76 dBi **Average front to back ratio** 10.8 dBi	**Efficiency:** 39.1 % **Maximum Directivity:** 6.98 dBi **Average front to back ratio** 11.2 dBi	**Efficiency:** 41 % **Maximum Directivity:** 7.77 dBi **Average front to back ratio** 11.2 dBi

Patches are numbered left to right when looking at the front of the antenna array.

APPENDIX C - X-OSC ANTENNA PATTERNS

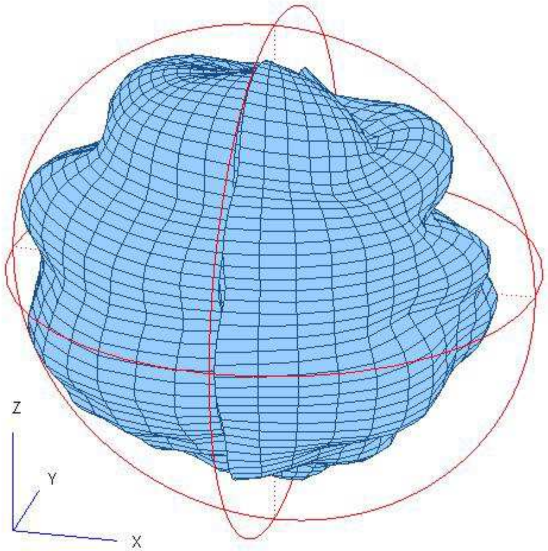


Figure C1 - Measured antenna pattern

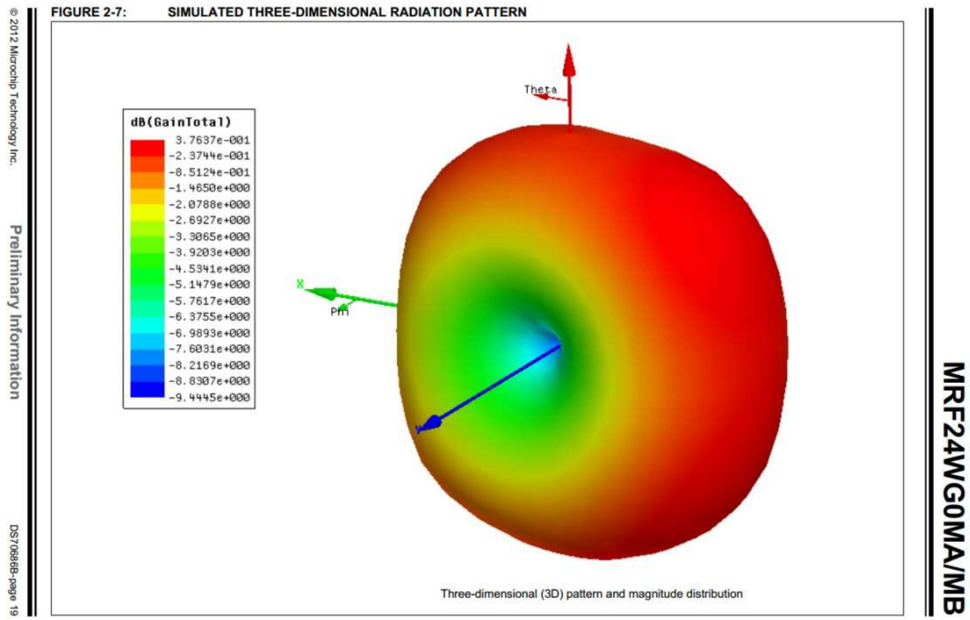


Figure C2 - Microchip Simulated Antenna Pattern

APPENDIX D - CANDIDATE ANTENNA PATTERNS

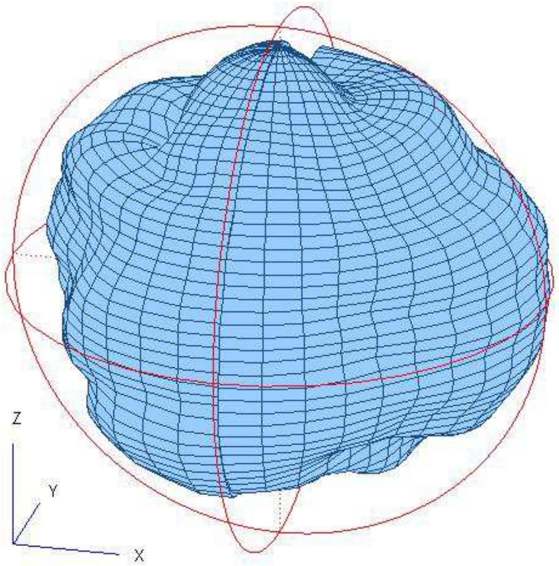


Figure D1 - Candidate 1 Antenna Pattern

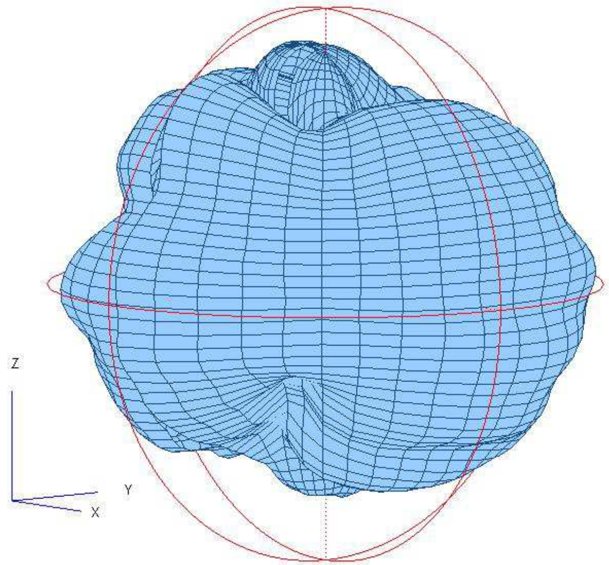


Figure D2 - Candidate 2 Antenna Pattern

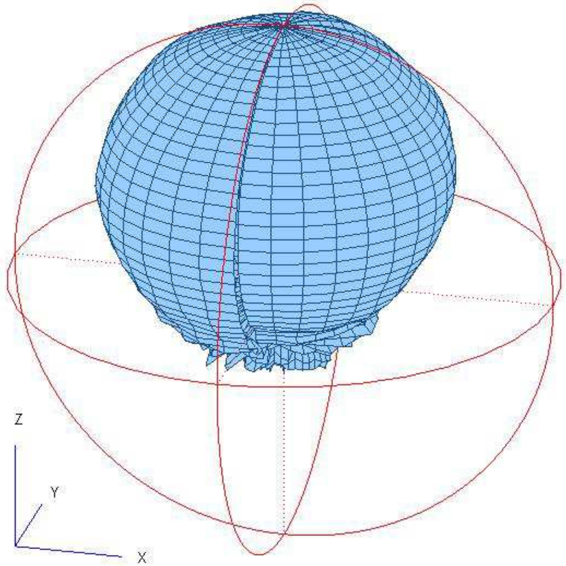


Figure D2 - Candidate 3 Antenna Pattern

Appendix E - Results of Attenuation Constant Experiment

Calculation of Free Space Path Loss from experimental data

Measurements using AP antennas from the front							
Distance from a.p (m)	Received Signal Power dBm						
	Sample 1	Sample 2	Sample 3	Mean	EIRP dBm	Pt/Pr dB	Path Loss Exponent
1	-34	-36.00	-35.00	-35.00	23.61	58.61	2.92
2	-39	-43.00	-42.00	-41.33	23.61	64.94	2.81
3	-39	-42.00	-47.00	-42.67	23.61	66.28	2.67
4	-44	-45.00	-46.00	-45.00	23.61	68.61	2.63
5	-46	-48.00	-46.00	-46.67	23.61	70.28	2.59
6	-49	-46.00	-50.00	-48.33	23.61	71.94	2.58
7	-49	-55.00	-53.00	-52.33	23.61	75.94	2.66
					Mean	68.09	2.69

Measurements using AP antennas from the rear							
Distance from a.p (m)	Received Signal Power dBm						
	Sample 1	Sample 2	Sample 3	Mean	EIRP dBm	Pt/Pr dB	Path Loss Exponent
1	-37	-37.00	-36.00	-36.67	22.99	59.66	2.97
2	-39	-40.00	-40.00	-39.67	23.61	63.28	2.74
3	-38	-43.00	-45.00	-42.00	23.61	65.61	2.64
4	-41	-44.00	-45.00	-43.33	23.61	66.94	2.56
5	-47	-47.00	-49.00	-47.67	23.61	71.28	2.63
6	-49	-49.00	-50.00	-49.33	23.61	72.94	2.62
7	-47	-51.00	-51.00	-49.67	23.61	73.28	2.57
					Mean	67.57	2.67

Measurements using Patch antennas from the front							
Distance from a.p (m)	Received Signal Power dBm						
	Sample 1	Sample 2	Sample 3	Mean	EIRP dBm	Pt/Pr dB	Path Loss Exponent
1	-34	-33.00	-35.00	-34.00	22.99	56.99	2.84
2	-40	-38.00	-40.00	-39.33	22.99	62.32	2.70
3	-40	-40.00	-43.00	-41.00	22.99	63.99	2.57
4	-44	-46.00	-46.00	-45.33	22.99	68.32	2.62
5	-46	-47.00	-47.00	-46.67	22.99	69.66	2.57
6	-47	-50.00	-50.00	-49.00	22.99	71.99	2.58
7	-48	-46.00	-49.00	-47.67	22.99	70.66	2.48
					Mean	66.28	2.62

APPENDIX F - COMPLETED SYSTEM LINK BUDGETS

Internal R6300 and Microchip Antennas (omnidirectional)

Transmitter Calculations				
Power Transmitted (Pt)	0.25 W	-6.02 dBW	23.98 dBm	Set in R6300 Firmware
Transmitter Gain (Gt)	-0.37 dBi	0.92 linear		Measured in anechoic chamber
EIRP	0.23 W	-6.39 dBW		

Reciever Calculations				
Reciever Gain(Gr)	-0.35 dBi	0.92 linear		Measured in anechoic chamber
Sensitivity(AWGN)	-104.21 dBm	-134.21 dBW		Measured experimentally
Fade margin	15.00 dB			Reccomended fade margin for Wifi
Sensitivity (Fading)	-89.21 dBm	-119.21 dBW		
Other margins	dB			Accounts for the effects of walls, furnishings etc
Sensitivity (all margins)	-89.21 dBm	-119.21 dBW		

Maximum free space path loss	112.47 dBW	Result

Calculation of Maximum distance to signal drop				
Frequency of operation	2.44 GHz	2.44E+09 Hz		Centre of Wifi spectrum
Wavelength	0.12 m			c = fλ
Path loss	112.4654 dBW			Taken from calculations above
n	2.69			Measured experimentally

Maximum seperation distance	482.13 m	Result

External R6300 and Microchip Antennas - Standing in front

Transmitter Calculations				
Power Transmitted (Pt)	0.05 W	-13.01 dBW	16.99 dBm	Set in R6300 Firmware
Transmitter Gain (Gt)	6.00 dBi	3.98 linear		Measured in anechoic chamber
EIRP	0.20 W	-7.01 dBW		

Reciever Calculations				
Reciever Gain(Gr)	-0.35 dBi	0.92 linear		Measured in anechoic chamber
Sensitivity(AWGN)	-104.21 dBm	-134.21 dBW		Measured experimentally
Fade margin	15.00 dB			Reccomended fade margin for Wifi
Sensitivity (Fading)	-89.21 dBm	-119.21 dBW		
Other margins	dB			Accounts for the effects of walls, furnishings etc
Sensitivity (all margins)	-89.21 dBm	-119.21 dBW		

Maximum free space path loss	111.8457 dBW	Result

Calculation of Maximum distance to signal drop				
Frequency of operation	2.44 GHz	2.44E+09 Hz		Centre of Wifi spectrum
Wavelength	0.12 m			c = fλ
Path loss	111.8457 dBW			Taken from calculations above
n	2.62			Measured experimentally

Maximum seperation distance	540.89 m	Result

External R6300 and Microchip Antennas - Standing in behind

Transmitter Calculations				
Power Transmitted (Pt)	0.05 W	-13.01 dBW	16.99 dBm	Set in R6300 Firmware
Transmitter Gain (Gt)	-4.00 dBi	0.40 linear		Measured in anechoic chamber
EIRP	0.02 W	-17.01 dBW		

Reciever Calculations				
Reciever Gain(Gr)	-0.35 dBi	0.92 linear		Measured in anechoic chamber
Sensitivity(AWGN)	-104.21 dBm	-134.21 dBW		Measured experimentally
Fade margin	15.00 dB			Reccomended fade margin for Wifi
Sensitivity (Fading)	-89.21 dBm	-119.21 dBW		
Other margins	dB			Accounts for the effects of walls, furnishings etc
Sensitivity (all margins)	-89.21 dBm	-119.21 dBW		

Maximum free space path loss	101.8457 dBW	Result

Calculation of Maximum distance to signal drop				
Frequency of operation	2.44 GHz	2.44E+09 Hz		Centre of Wifi spectrum
Wavelength	0.12 m			$c = f\lambda$
Path loss	101.8457 dBW			Taken from calculations above
n	2.66			Measured experimentally

Maximum seperation distance	207.92 m	Result

Appendix G - WICED Board Measurements

WICED Board Averages in Anechoic Chamber					
Sending			Receiving		
Load	**Throughput (Mbits/s)**	**Jitter (ms)**	**Load**	**Throughput (Mbits/s)**	**Jitter (ms)**
100kB	32.50	0.64	100kB	38.23	0.24
1MB	31.03	0.57	1MB	42.77	0.12
10MB	33.33	0.72	10MB	41.13	0.23
100MB	33.43	0.90	100MB	41.27	0.23
Mean	32.58	0.71	**Mean**	40.85	0.20
Average round-trip latency (ms):		4.60			

Result set 1 - 100kB					
Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	31.70	0.60	1.00	35.80	0.43
2.00	32.90	0.81	2.00	37.70	0.09
3.00	32.90	0.52	3.00	41.20	0.19
Mean	32.50	0.64	**Mean**	38.23	0.24

Result set 2 - 1MB					
Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	30.60	0.54	1.00	42.60	0.15
2.00	30.70	0.60	2.00	43.00	0.07
3.00	31.80	0.57	3.00	42.70	0.12
Mean	31.03	0.57	**Mean**	42.77	0.12

Result set 2 - 10MB					
Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	33.40	0.80	1.00	42.60	0.14
2.00	33.30	0.79	2.00	38.60	0.38
3.00	33.30	0.56	3.00	42.20	0.18
Mean	33.33	0.72	**Mean**	41.13	0.23

Result set 2 - 100MB					
Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	33.40	0.90	1.00	42.10	0.23
2.00	33.50	1.13	2.00	39.30	
3.00	33.40	0.67	3.00	42.40	
Mean	33.43	0.90	**Mean**	41.27	0.23

Latency Measurement	
Repeat number	**Latency (ms)**
1	4.00
2	8.00
3	3.00
4	3.00
5	3.00
6	3.00
7	8.00
8	5.00
9	4.00
10	5.00
Mean	4.60

WICED Board Averages in Noisy Enviroment

Sending			Receiving		
Load	**Throughput**	**Jitter**	**Load**	**Throughput**	**Jitter**
100kB	2.95	1.07	100kB	3.77	0.59
1MB	12.07	1.15	1MB	10.47	0.37
10MB	18.30	0.89	10MB	14.57	0.29
100MB	19.83	0.87	100MB	15.20	0.22
Mean	10.63	0.80	**Mean**	8.80	0.29

Result set 1 - 100kB

Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	2.78	1.10	1.00	3.16	0.79
2.00	3.03	1.04	2.00	3.56	0.24
3.00	3.05	1.07	3.00	4.60	0.73
Mean	2.95	1.07	**Mean**	3.77	0.59

Result set 2 - 1MB

Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	11.30	1.04	1.00	8.81	0.45
2.00	11.80	1.54	2.00	10.80	0.40
3.00	13.10	0.87	3.00	11.80	0.26
Mean	12.07	1.15	**Mean**	10.47	0.37

Result set 2 - 10MB

Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	18.60	0.87	1.00	14.40	0.13
2.00	17.80	0.68	2.00	14.40	0.40
3.00	18.50	1.13	3.00	14.90	0.33
Mean	18.30	0.89	**Mean**	14.57	0.29

Result set 2 - 100MB

Sending			Receiving		
Repeat number	**Throughput (Mbits/s)**	**Jitter (ms)**	**Repeat number**	**Throughput (Mbytes/s)**	**Jitter (ms)**
1.00	20.20	0.87	1.00	15.20	0.22
2.00	19.80		2.00	15.30	
3.00	19.50		3.00	15.10	
Mean	19.83	0.87	**Mean**	15.20	0.22

APPENDIX H - 802.11N/G MIXED MODE TESTING

Sending			Receiving		
Load	**Throughput**	**Jitter**	**Load**	**Throughput**	**Jitter**
N and N	13.97	9.53	100kB	8.77	12.77
N and G	14.63	9.82	1MB	7.88	13.80
Mean	14.30	9.68	**Mean**	8.32	13.28

Result set 1 - N WICED and N Laptop					
Sending			Receiving		
Repeat number	**Throughput WICED (Mbits/s)**	**Throughput Laptop (ms)**	**Repeat number**	**Throughput WICED (Mbits/s)**	**Throughput Laptop (ms)**
1.00	14.00	9.97	1.00	8.83	13.90
2.00	13.20	7.92	2.00	8.69	12.00
3.00	14.70	10.70	3.00	8.78	12.40
Mean	13.97	9.53	**Mean**	8.77	12.77

Result set 2 - N WICED and G Laptop					
Sending			Receiving		
Repeat number	**Throughput WICED (Mbits/s)**	**Throughput Laptop (ms)**	**Repeat number**	**Throughput WICED (Mbits/s)**	**Throughput Laptop (ms)**
1.00	14.30	9.60	1.00	7.99	13.60
2.00	14.60	9.77	2.00	7.62	13.60
3.00	15.00	10.10	3.00	8.02	14.20
Mean	14.63	9.82	**Mean**	7.88	13.80