An Evaluation of the Performance of IEEE 802.11a and 802.11g Wireless Local Area Networks in a Corporate Office Environment

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Abstract—*In recent years there has been considerable interest in the development of standards for Wireless Local Area Networks. In particular, IEEE's 802.11 standard has now been extended to a family of WLAN standards. 802.11a and 802.11g both employ Coded Orthongonal Frequency Division Multiplexing (COFDM) but operate in different frequency bands. In this paper, the performance and relative merits of 802.11a and 802.11g are compared for the scenario of a corporate office wireless LAN application. It is shown that for comparable scenarios 802.11g achieves superior range but that 802.11a achieves higher data rates. Thus the two standards are found to have complimentary strengths and weaknesses.*

I. INTRODUCTION

The IEEE 802 group is responsible for the developments of standards governing Local and Metropolitan Area Networks. In particular, the 802.11 group is responsible for Wireless LAN standards. In recent years, the 802.11 standard for Wireless LANs has been significantly extended.

The original 802.11 standard specifies a common MAC layer and three Physical (PHY) layers [1]. Two of these PHYs facilitate communications in the 2.4GHz Industrial Scientific and Medical (ISM) bands using Direct Sequence (DS) and Frequency Hopped (FH) Spread Spectrum techniques. The third PHY facilitates communication over infra-red links. Data rates of up to 2 Mbits/s are facilitated by each of the PHYs.

The 802.11 standard has subsequently been expanded considerably. Whilst the MAC specification has remained largely unchanged (except for Quality of Service (QoS) enhancements under 802.11e [2]) several new PHY layer specifications have been added. The 802.11a PHY [3] facilitates link adaptive data rates of up to 54Mbits/s, employing COFDM in the 5GHz Unlicensed National Information Infrastructure (UN-II) band. The 802.11b PHY [4] facilitates data rates of up to 11Mbits/s, employing Complementary Code Keying (CCK) and DS Spread Spectrum, also in the 2.4GHz ISM band. Finally, a high rate extension to 802.11b in the 2.4GHz ISM band has been considered by 802.11g [5]. Recently, a solution was selected. This was based upon the link adaptive COFDM modulation scheme of 802.11a with mandatory backward compatibility with 802.11b. Optional modes based on a CCK-COFDM hybrid and a Packet Binary Convolutional Code (PBCC) scheme, were also facilitated. Clearly, there are considerable similarities between the baseband modulation techniques specified in 802.11a and 802.11g with the main distinction between these two standards being the frequency band specified for operation and the additional optional modes of 802.11g.

In this paper a comparison of the 802.11a and 802.11g PHY standards is undertaken on the basis of their capacity/coverage capabilities for an example environment representative of a Corporate office WLAN deployment. In order to undertake a fair comparison, only the common modes of 802.11a and 802.11g are considered. It should be noted that the optional modes of 802.11g and the 802.11b backward compatibility mode are not expected to outperform these common modes in terms of capacity/coverage capabilities (although the commercial benefits of the backward compatibility mode in particular should not be understated).

A state of the art ray-launching propagation model is used to analyse radiowave propagation within the example environment to determine radio channel characteristics (path loss and RMS delay spread) on a point-to-multipoint basis. A throughput performance analysis of the common modes of operation of 802.11a and 802.11g is undertaken to enable the translation of the radio channel characteristics into achievable data rates on a similar point-to-multipoint basis. A capacity/coverage analysis of the two systems then provides a basis for comparison.

The ray-launching propagation model and the example corporate office WLAN environment are described in section II. An analysis of the radio channel characteristics generated by the ray-launching model is also presented. The throughput performance evaluation of the common modes of 802.11a and 802.11g are presented in section III. Section IV presents the capacity and coverage analysis and conclusions are presented in section V.

II. THE PROPAGATION MODEL

The propagation modeling tool is based on a sophisticated ray launching technique. The tool simulates the launch of multiple 'test rays' in 3 dimensions at discrete angles from the transmitter. The interaction of these test rays with the subject environment is simulated until the ray's power falls below a given threshold – at which time the ray is terminated. For a more detailed description of the model, the reader is referred to [6].

A point to point analysis can be employed to generate comprehensive information on the radio channel perceived by

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a transmitter and receiver at distinct points in the environment. On the basis of a predicted power delay profile, signal power, RMS delay spread and K-factor may all be determined. Spatial information also facilitates estimates of RMS azimuth spread.

A point-to-multipoint analysis may also be employed to evaluate all the above information at multiple locations within the subject environment.

For the purposes of this paper, the propagation modeling tool has been employed to provide a point-to-multipoint analysis of the path loss within the example corporate office WLAN environment illustrated in Fig 1. The path loss and RMS delay spread have been evaluated over a two-dimensional grid (with 2m spacing) at a height of 1m above the floor.

Fig. 1 shows the example scenario considered in this paper for the case of a ceiling mounted Access Point (AP) deployed at the center of the environment. The dimensions of this environment are 48m x 48m by 3m. Walls vary in thickness between 50mm (internal partitions) and 150mm (external/load bearing walls). Given its size and number of internal obstructions, this represents a challenging environment for the deployment of wireless LANs. The model assumes a dipole antenna with a gain of 2dBi.

The corresponding path losses that result at a height of 1m (approximate desk height) are shown in Figs. 2 and 3 for the two operating frequencies considered. Similar delay spread calculations were also undertaken. These results are not shown here due to limitations of space, but RMS delay spreads of up to 50ns were evidenced.

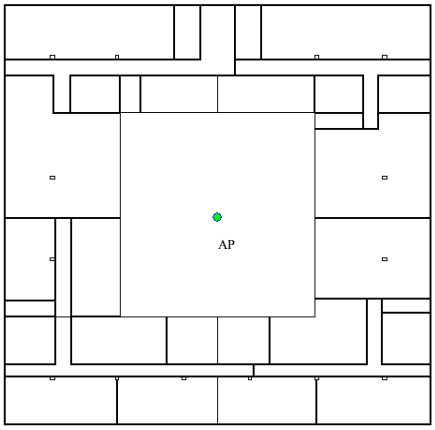

Figure 1. Corporate Office WLAN Deployment

It can be seen from the results that there is a significant difference in the attenuation of the signal for the cases of 2.4GHz and 5.2GHz operating frequencies. This was found to be approximately 11dB on average and up to 38dB in the extreme. This difference in attenuation is due to two phenomena. Firstly, the free space loss of a radio signal is inversely proportional to the wavelength. The smaller wavelength of the 5.2GHz radio signal results in an additional loss of 6.7dB relative to the 2.4GHz signal throughout the environment. Secondly, the behavior of the two different frequency signals when propagating through and reflecting off of the walls in the environment is different. The through wall attenuation suffered by the 5.2GHz signal is greater than that suffered by the 2.4GHz signal. This difference between the losses (as well as the absolute values) is also dependent upon the thickness of the walls.

Since both of these phenomena result in increased loss at 5 GHz relative to 2.4GHz it is not surprising that the path loss at 5.2GHz is consistently higher than at 2.4GHz. This suggests that a poorer range capability can be expected for 802.11a than for 802.11g.

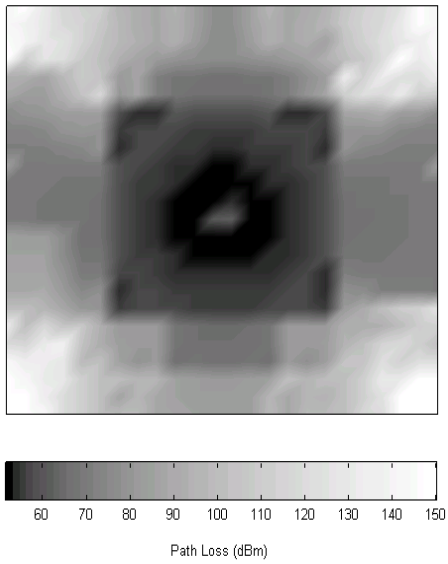

Figure 2. 2.4GHz Path Loss

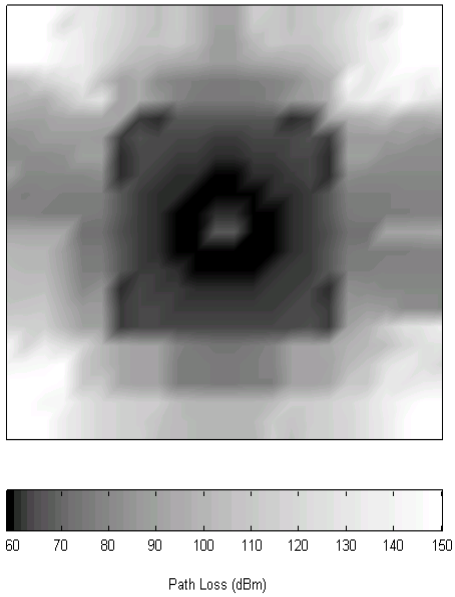

Figure 3. 5.2GHz Path Loss

The area in the direct center of the environment can be seen to exhibit greater signal attenuation than that immediately surrounding it. This can be attributed to the radiation pattern of the dipole antenna, which does not radiate strongly immediately downwards.

III. THROUGHPUT PERFORMANCE ANALYSIS OF 802.11a AND 802.11g

The common modes of operation of 802.11a and 802.11g are all based on the use of COFDM modulation in combination with different sub-band modulation schemes and convolutional coding rates. Eight modes (summarised in Table I) are specified, achieving nominal data rates between 6Mbits/s and 54Mbits/s with differing requirements for the link quality (in terms of Carrier to Noise ratio (C/N) or Carrier to Interference Ratio (C/I), K-factor, RMS delay spread, etc) required to achieve a given packet error rate. These eight modes, with their differing capabilities and requirements facilitate Link Adaptation, whereby the system may adapt to provide a differing data rate according to the quality of the available radio link. For further discussion of this topic, the reader is referred to [7,8].

TABLE I. IEEE 802.11a/g TRANSMISSION MODES

Mode	Modulation	Coding Rate	Nominal Data Rate, $R_{Nominal}$
1	BPSK	1/2	6 Mbits/s
2	BPSK	3/4	9 Mbits/s
3	QPSK	1/2	12 Mbits/s
4	QPSK	3/4	18 Mbits/s
5	16QAM	1/2	24 Mbits/s
6	16QAM	3/4	36 Mbits/s
7	64QAM	2/3	48 Mbits/s
8	64QAM	3/4	54 Mbits/s

Both 802.11a and 802.11g are PHY layer specifications. A system based on either of these PHYs will employ the common 802.11 MAC. This MAC is based on the concept of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Besides the mandatory Distributed Co-ordination Function (DCF) specified by the 802.11 MAC, optional Point Co-ordination Function (PCF) and Request to Send/Clear to Send (RTS/CTS) signaling are also defined in the standard. The PCF facilitates a limited support of time bounded services by allowing terminals to have priority access to the medium at certain times, defined by a Point Co-ordinator device. The RTS/CTS mechanism was provided in order to minimise 'collisions' between terminals in the network due to the hidden node problem [2]. It is interesting to note that in 802.11g, the OFDM modulated signals cannot be demodulated by legacy 802.11b devices – potentially resulting in collisions. The use of the RTS/CTS protocol is a potential solution to this problem as well as to the hidden node problem. For a more detailed discussion of the 802.11 MAC and the overheads it introduces, the reader is referred to [2,7].

The overheads introduced by the 802.11 MAC are mode dependent and also differ between 802.11a and 802.11g. Overheads are primarily due to the requirement to implement Distributed Inter-Frame Spaces (DIFS) and Short Inter-frame Spaces (SIFS) between data packet transmissions as well as ARQ signaling. The variation of overhead with mode is due to the fact that the DIFS and SIFS are of fixed duration whilst, for a given packet size, the packet duration is shorter for higher rate modes. The difference in overhead between 802.11a and 802.11g is due to the fact that different lengths are specified for the DIFS and SIFS in 802.11a and 802.11g. In order to inter-operate effectively with legacy 802.11b devices, 802.11g devices will be required to implement the DIFS, SIFS and ARQ in a manner common with 802.11b. If the backward compatibility with 802.11b devices were to be neglected, 802.11g devices could operate with the same MAC overhead as 802.11a devices. MAC efficiencies were calculated based on the ratio of the time used to transmit actual data relative to the total time occupied by the data and the various associated signaling overheads. Table II summarises these MAC efficiencies for the eight modes of 802.11a and 802.11g using both the mandatory OFDM modulation and optional CCK-OFDM. The efficiency values are given for the case of the DCF both with and without RTS/CTS signaling and assume a packet size of 1500bytes. Note that if CCK-OFDM modulation is employed, the RTS/CTS signaling is not needed to prevent collisions between 802.11g and legacy 802.11b devices since the 802.11b devices are capable of demodulating the CCK modulated 802.11g packet headers. However, the RTS/CTS signaling may still be required in order to deal with the hidden node problem. Given that the MAC efficiency is higher for the mandatory OFDM mode of transmission with RTS/CTS than for CCK-OFDM without RTS/CTS, the value of the optional CCK-OFDM mode is dubious.

TABLE II. MAC EFFICIENCY

Mode	Mac Efficiency, η_{MAC}					
	802.11a		*802.11g OFDM*		*802.11g CCK-OFDM*	
	With	*Without*	*With*	*Without*	*With*	*Without*
1	85%	90%	78%	81%	73%	76%
2	82%	87%	71%	74%	66%	68%
3	78%	84%	66%	69%	59%	62%
4	72%	79%	57%	61%	50%	52%
5	66%	74%	51%	54%	43%	45%
6	58%	66%	41%	44%	34%	36%
7	51%	60%	35%	37%	28%	29%
8	49%	57%	32%	35%	26%	27%

A detailed PHY layer software simulation of 802.11a has been developed previously by the authors. This has been used to evaluate the Packet Error Rate (PER) as a function of C/N for example test channels [7]. For the purposes of this paper, the software simulation has been employed to evaluate performance in terms of PER for the radio channel conditions indicated by the results of the propagation simulation described in section II. The net throughput of each mode at the top of the MAC layer may be calculated according to:

$$Throughput = R_{Nominal}(1 - PER)\eta_{MAC}$$

where $R_{Nominal}$ and η_{MAC} can be found from Tables I and II respectively, and the PER performances have been simulated with the PHY layer software simulation tool developed by the authors. Two example link adaptation curves for the case of a wideband Rayleigh fading channel with 50ns RMS delay spread (as defined in [9]) are shown in Figs. 4 and 5. Fig. 4 shows the variation of the data rate achieved by 802.11a at the top of the MAC layer (thus taking into account the MAC

efficiency values given in table II) as a function of C/N, for the case of a 1500byte packet. Fig. 5 shows a similar variation of data rate with C/N for the case of 802.11g. For both cases, it is assumed that RTS/CTS is employed and that no collisions occur in the wireless medium. This facilitates a fair comparison of both systems without interference from hidden nodes or legacy 802.11b devices. Note that the throughput at the PHY layer (and hence at the MAC layer as well) also varies as a function of other radio link parameters – the delay spread for example – and that these factors have also been considered in the analysis.

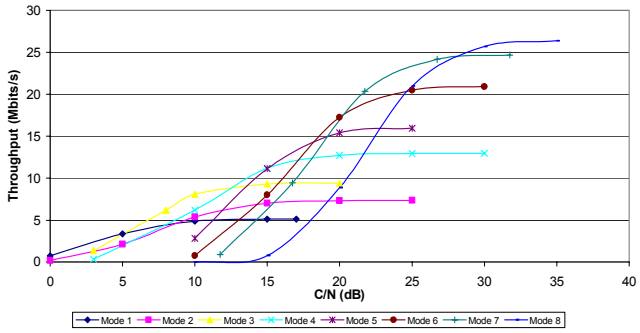

Figure 4. MAC Throughput of 802.11a using DCF and RTS/CTS with 1500byte packets in a wideband Rayleigh channel - 50ns RMS delay spread

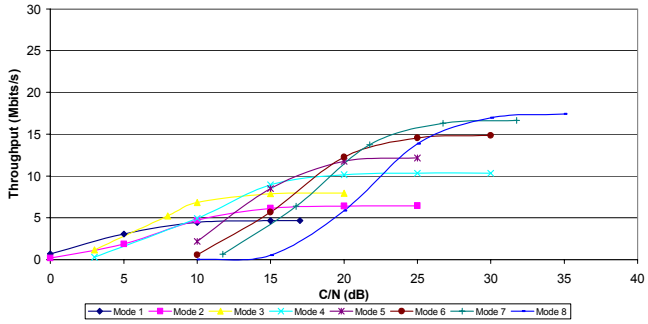

Figure 5. MAC Throughput of 802.11g using DCF and RTS/CTS with 1500byte packets in a wideband Rayleigh channel - 50ns RMS delay spread

From Figs. 4 and 5 the effects of the different MAC overheads on the link throughput performances of 802.11a and 802.11g can be seen. The MAC efficiency decreases as the PHY data rate increases. This has the effect of compressing the link adaptation curves downwards such that the benefits of the nominal PHY rate are somewhat compromised. This is accentuated in the 802.11g link throughput graph due to its even higher MAC overheads. In this case, it can be seen that the graph is almost linear and that the highest rate mode offers only marginal advantage over the second highest and so on. MAC overheads limit the maximum data rates of 802.11a and 802.11g with RTS/CTS and 1500byte packets to approximately 26Mbits/s and 17Mbits/s respectively.

IV. Capacity and Coverage Analysis

Based on the point-to-multipoint propagation analysis, the nominal PHY layer performance of the different common modes of operation of 802.11a and 802.11g and the corresponding MAC overheads, it is possible to evaluate the data rates achieved by each of the two standards throughout the example environment for each of the example scenarios.

Fig. 6 shows the data rate achieved throughout the environment by 802.11g for the case of the centrally mounted access point, assuming a transmit power of 15dBm and using DCF, RTS/CTS and 1500byte packets. Figure 7 shows the data rate achieved by 802.11a for the same conditions.

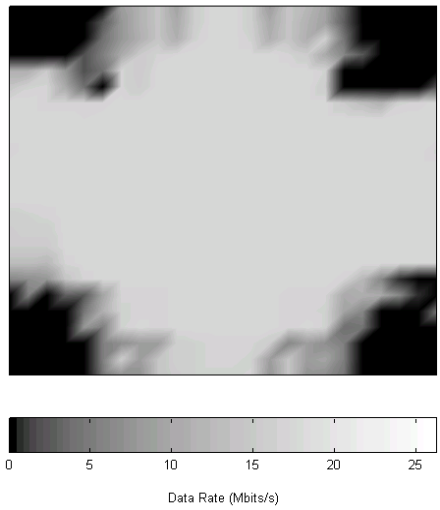

Figure 6. Data Rate Achieved by 802.11g with 15dBm transmit power

Figure 7. Data Rate Achieved by 802.11a with 15dBm transmit power

Fig. 8 shows the rate-coverage comparison for 802.11a and 802.11g for the cases of 15dBm, 23dBm and 30dBm transmit power. As expected, it can be seen that 802.11a achieves a higher maximum data rate than 802.11g. This can be attributed to its more efficient MAC parameters. It can be seen that 802.11g achieves superior coverage by around 10% at lower data rates (<15Mbits/s) for the cases of 15dBm and 23dBm transmit power. However, this coverage advantage is not evident for the case of 30dBm transmit power for which it

can be seen that the coverage of 802.11g up to 15Mbits/s is not significantly better than that of 802.11a. The poorer MAC efficiency of 802.11g prevents it from achieving data rates greater than 17Mbits/s, thus it has consistently poorer coverage than 802.11a at these data rates.

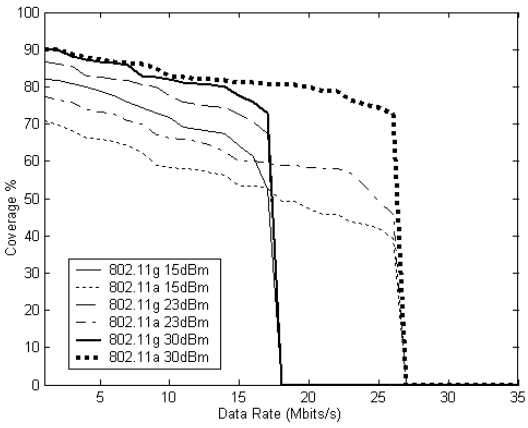

Figure 8. Coverage Comparison

V. CONCLUSIONS

In this paper, the differing conditions of radiowave propagation between the 2.4GHz operating frequency employed by 802.11g and the 5GHz operating frequency employed by 802.11a have been investigated. It has been shown that signal attenuation at 5GHz is significantly higher due to the increased losses associated with free space propagation and through wall attenuation. Additionally, the MAC efficiencies of the common PHY layer transmission modes of 802.11a and 802.11g have been calculated. It has been shown that the lower MAC efficiency of 802.11g (when maintaining backward compatibility with 802.11b) results in significantly reduced throughput relative to 802.11a. This poor MAC efficiency is common to all the high rate extensions to the original 802.11 standard and results from the combination of increasingly fast PHY layers with a single legacy MAC.

By combining the results of the propagation analysis, PHY layer simulation results and MAC overhead calculations, it has been shown that a single 802.11g network achieves superior coverage but lower data rates relative to 802.11a for the example environment considered.

The different operating frequencies employed have other implications than just the propagation characteristics of the radio channel. The 2.4GHz ISM band is 83MHz wide. Allowing for guard bands, this enables the operation of 3 802.11g networks on non-overlapping frequencies. The 2.4GHz ISM band is also likely to exhibit significant interference from other communications systems such as Bluetooth as well as other devices such as Microwave Ovens. In contrast, the operating frequencies available to 802.11a in the 5GHz band make it possible to operate 12 networks on non-overlapping frequencies without the presence of significant interference. However, the transmit power limits in some parts of this band are lower than in the 2.4GHz ISM band. All these factors should be considered in combination with the different radio propagation characteristics when evaluating the relative merits of the two bands.

Clearly the nature of the environment in which the network is to be employed will have a significant impact on coverage. For smaller (e.g. residential) environments with less signal attenuation, 802.11a is likely to achieve similar coverage to 802.11g but with higher data throughput. In larger environments, particularly with more internal partitions, the superior coverage of 802.11g will be more evident. However, the larger range of operating frequencies available for 802.11a will enable multiple networks to be deployed to improve coverage whilst also enjoying the benefits of higher maximum data rates.

The value of the backward compatibility of 802.11g with 802.11b should not be understated. 802.11b looks set to dominate the near term WLAN market under the 'WiFi' brand [10]. The backwards compatibility of 802.11g makes it the obvious choice for evolution of this market by facilitating a smooth transition between standards. Interestingly, the development of baseband OFDM chipsets for 802.11g may in turn accelerate the development of 802.11a devices which will differ from 802.11g only in terms of their RF components. A dual band 802.11g/a device would appear a realistic and desirable option for the future.

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