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A Study of the Impact of Frequency Selectivity on Link Adaptive Wireless LAN Systems

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Abstract*—Wireless Local Area Networks (WLANs) supporting broadband multimedia communication are being developed and standardized around the world. The HIPERLAN/2, 802.11a and HiSWANa standards provide channel adaptive data rates between 6 and 54 Mbps in the 5GHz radio band. The link adaptation mechanism is not specified in the standards. In this paper the performance of the HIPERLAN/2 system is evaluated in terms of throughput in a range of test channels with different degrees of frequency selectivity. On this basis, the impact of frequency selectivity on system performance is evaluated and the implications for the design of a link adaptation strategy are discussed. The issue of link adaptation for time bounded applications is also considered. The resulting conclusions are generally applicable to all three 5GHz WLAN standards.

***Keywords*—Link Adaptation, Wireless LANs, HIPERLAN/2, 802.11a, HISWANa, OFDM**

I. INTRODUCTION

ETSI, IEEE and ARIB have all recently produced standards for Wireless LANs operating in the 5GHZ band. These standards are HIPERLAN/2, 802.11a and HISWANa respectively. All three exhibit a high degree of commonality, particularly in their Physical (PHY) layer specifications. These PHY layer specifications are based on the use of Coded Orthogonal Frequency Division Multiplexing (COFDM) in combination with dynamic Link Adaptation schemes and all three operate in a 20MHz channel bandwidth. COFDM is employed in order to achieve robust and efficient operation of the modem in a multipath radio environment. COFDM effectively exploits the frequency selectivity of the wideband channel as a source of diversity and provides a unique, low cost strategy for preventing Inter-Symbol Interference (ISI) in the presence of delay spread; this is based on a cyclic repetition of a proportion of the transmitted symbol, known as a Guard Interval (GI). The use of a Link Adaptation scheme in combination with COFDM enables the WLAN to dynamically trade-off link reliability and data rate according to the quality of the available radio link. The modulation scheme and Forward Error Correction (FEC) coding rate may both be varied as part of the link adaptation scheme. Thus, low order modulation and low rate codes may be employed when link quality is poor, maintaining reliability at the cost of reduced data rates. When link quality is high, higher order modulation schemes and high rate FEC coding can maintain reliability whilst maximising data rate.

As with all systems, the link quality can be expected to vary according to the received Carrier to Noise (C/N) or Carrier to Interference (C/I) ratio which are themselves functions of the transmitted signal power, slow fading of the channel and receiver noise power or interference power respectively. Similarly, the frequency selective fading imposed by the channel onto the received signal can also be expected to have an impact on performance. However, the effects of frequency selective fading/delay spread are not obvious. Since wideband fading is a source of diversity which is exploited by COFDM, increased frequency selectivity would indicate increased diversity and hence improved performance. Contrastingly, since the protection against ISI offered by the GI is finite, an increase in frequency selectivity implies a possible increase in excess delay spread which, if it exceeds the GI duration, may lead to ISI which will degrade performance.

In this paper, the impact of frequency selectivity on a link adaptive COFDM WLAN system is investigated. Note that whilst the system actually simulated is one conforming to the HIPERLAN/2 PHY layer specification, given the high degree of commonality between the HIPERLAN/2, 802.11a and HISWANa PHY layers, the majority of conclusions are applicable to all three standards.

II. THE LINK ADAPTATION SCHEME

The HIPERLAN/2 Physical Layer standard specifies various combinations of coding rate (for the FEC convolutional code) and modulation scheme which result in the seven ‘modes’ of a link adaptation scheme as presented in Table 1. Note that support of the seventh mode (using 64-QAM) is optional for HIPERLAN/2. For a more detailed discussion of the standard, the reader is referred to [1,2].

Whilst the modes of the link adaptation scheme are defined by the standard, the actual link adaptation algorithm (which selects the most appropriate mode for a given transmission burst) is not. The link adaptation algorithm may be product specific and is likely to be a key technical differentiator between products in a competitive market. The ability of the link adaptation algorithm to consistently employ that mode of transmission which is most appropriate for the current link conditions and application requirements will enable one product to outperform another, despite the fact that they may both have the same nominal limit on achievable data rate. Note that it is not always appropriate to evaluate the performance of a link adaptation algorithm purely in terms of achieved data rate. For applications where latency is a sensitive issue – video being the obvious example – the ability of the link adaptation algorithm to operate within a specified latency constraint (i.e. a maximum PER requirement) will also be crucial. For a more detailed discussion of this issue, the reader is referred to [3].

TABLE I. HIPERLAN/2 TRANSMISSION MODES

Mode	**Modulation**	**Coding Rate**	**Nominal Data Rate, $R_{Nominal}$**
1	BPSK	1/2	6 Mb/s
2	BPSK	3/4	9 Mb/s
3	QPSK	1/2	12 Mb/s
4	QPSK	3/4	18 Mb/s
5	16QAM	9/16	27 Mb/s
6	16QAM	3/4	36 Mb/s
7	64QAM	3/4	54 Mb/s

The performance of both the HIPERLAN/2 and 802.11a Physical Layers has been simulated previously by the authors. These results, in combination with a discussion of the implications and effects of the different HIPERLAN/2 and 802.11 Multiple Access strategies has been published in [1] Similar results have been observed in [4]. In this paper, the PHY layer analysis is extended to cover the range of channel scenarios presented in the following section.

III. CHANNEL SCENARIOS

In order to investigate the impact of frequency selectivity on the performance of HIPERLAN/2, it is necessary to simulate the system in a variety of channel conditions. During the standardisation process, a range of test channel models were defined by ETSI BRAN with the intent of representing the range of likely operating conditions for the system [5]. Five channels (A-E) were defined to represent the range of conditions between a small office and an outdoor picocell. Extensive channel measurement campaigns and propagation modelling tools have been employed by the authors and others to investigate the nature of likely WLAN operating environments, including residential deployments. Whilst channels similar to those defined in the BRAN models have been observed, much evidence also exists of channels tending toward a more narrowband nature – particularly in small scale office and residential environments. For this reason, in this paper, a narrowband channel, 'R', has been added to those defined by ETSI BRAN for the purpose of examining the impact of frequency selectivity on the link adaptive wireless LAN. The resultant set of six test channel models is defined in Table 2.

IV. PER SIMULATIONS

In order to evaluate the performance of HIPERLAN/2 with the defined channel models, the performance of the HIPERLAN/2 PHY layer specification has been simulated to determine the Protocol Data Unit (PDU) Error Rate (PER) as a function of received Carrier to Noise Ratio (C/N) for each channel scenario. The results are shown in Fig. 1-6. Note that each channel has been simulated as quasi-static, with 2000 instances considered in each case and that each path of each channel takes the form of an independent Rayleigh or Rician distributed random variable with a mean value (across the 2000 instances) as defined by the mean channel profile in [5] (or unity in the case of channel R). FEC is implemented in the form of a CSI-enhanced soft decision Viterbi algorithm [6].

TABLE II. TEST CHANNEL SCENARIOS

Name	**RMS delay spread**	**Characteristic**	**Environment**
R	0 ns	Narrowband Rayleigh	Residential NLOS
A	50 ns	Wideband Rayleigh	Small Office NLOS
B	100 ns	Wideband Rayleigh	Medium Office NLOS
C	150 ns	Wideband Rayleigh	Large Office NLOS
D	140 ns	Wideband Rician	Large Office LOS
E	250 ns	Wideband Rayleigh	Outdoor Pico NLOS

From the results it can be seen that performance generally improves as the delay spread increases. This is demonstrated by the progressively lower C/N requirement for a given mode between scenarios R, A, B, C and (for some modes) E. The significant performance gap (7-9dB) between R and A can be attributed to the total lack of frequency diversity in the narrowband case. A less significant difference (~2dB) is evident between scenarios A and B. The difference between scenarios B and C is minimal, implying that the 100ns RMS delay spread is sufficient to decorrelate the sub-band fading and thereby achieve good diversity. The difference in performance between scenario D (Rician) and C (the nearest Rayleigh equivalent) is, perhaps, surprisingly small. This can again be attributed to the ability of COFDM to mitigate frequency selectivity. Finally, the effect of ISI introduced in channel E can be seen to have a severe impact only on modes 6 and 7.

V. THROUGHPUT PERFORMANCE

In order to calculate the mean throughput of the WLAN in a given channel, the throughput is calculated from the nominal data rate for a given mode and the PER according to:

$$R_{\text{Actual}} = (1 - PER)R_{\text{Nominal}}$$

The results are shown in Fig. 7-12. It can be seen that the link adaptation curves for the different test channels do not differ significantly except in the cases of the two extreme channels. Channel R offers relatively poor performance due to the lack of frequency diversity in the narrowband channel. In channel E the high excess delay spread has a severe impact on mode 7. This is due to the effects of ISI. The lower rate modes are not significantly affected by the ISI.

Given the substantial differences in performance observed in the PER results, a similar difference in throughput performance might be anticipated. However, it can be seen that the differences in this case are much smaller. This can be attributed to the fact that throughput is proportional to 1-PER and not to the PER itself. The only significant exception is the case of mode 7 for scenario E where the PER is so severe that that mode is never useful.

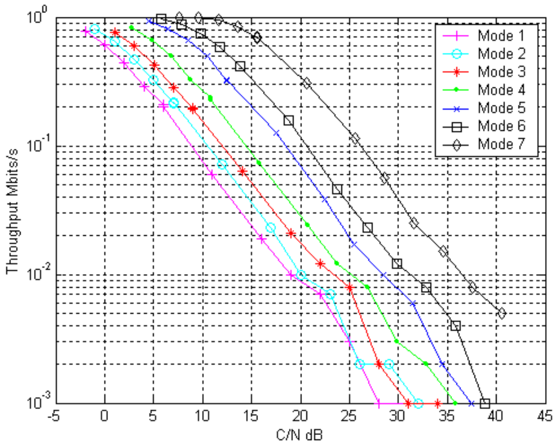

Figure 1. PER Performance in Channel R

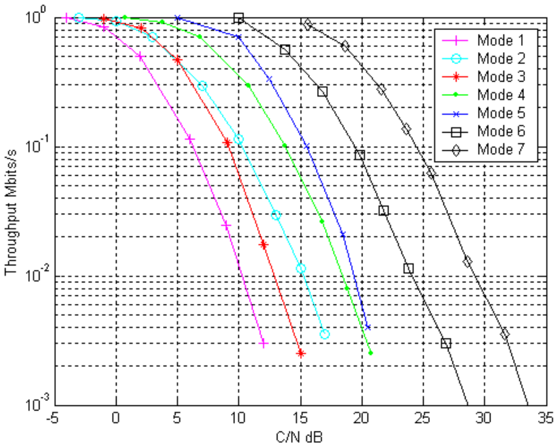

Figure 2. PER Performance in Channel A

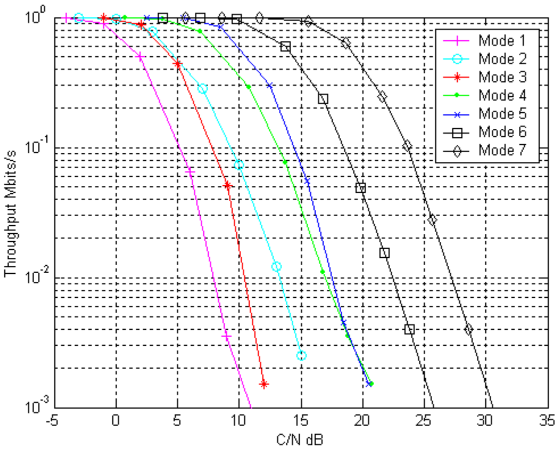

Figure 3. PER Performance in Channel B

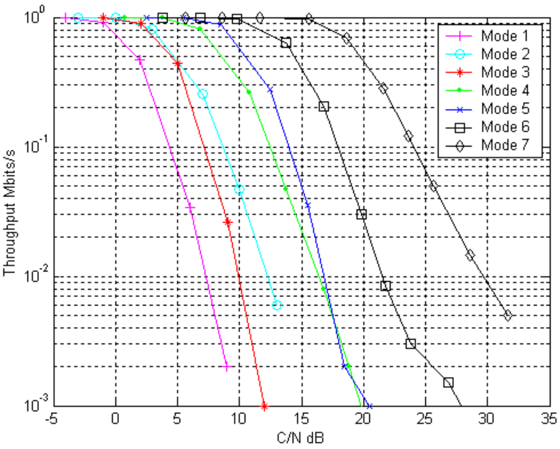

Figure 4. PER Performance in Channel C

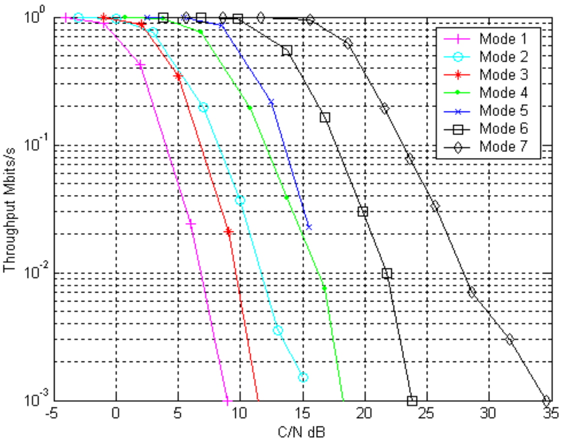

Figure 5. PER Performance in Channel D

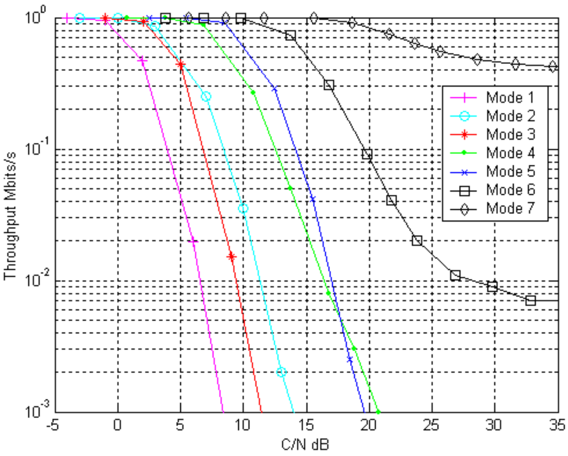

Figure 6. PER Performance in Channel E

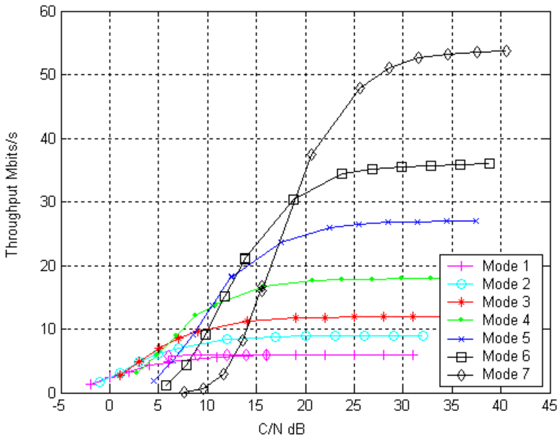

Figure 7. Throughput in Channel R

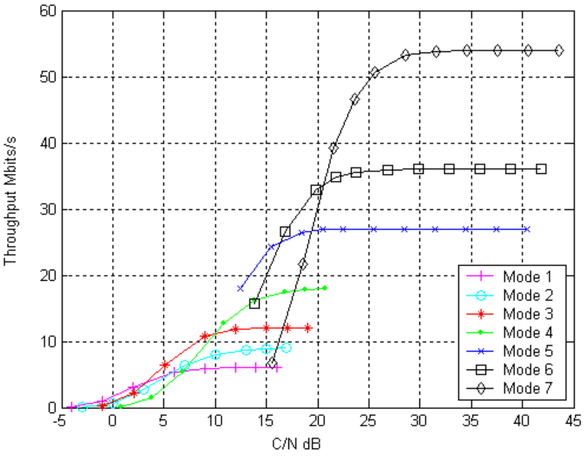

Figure 8. Throughput in Channel A

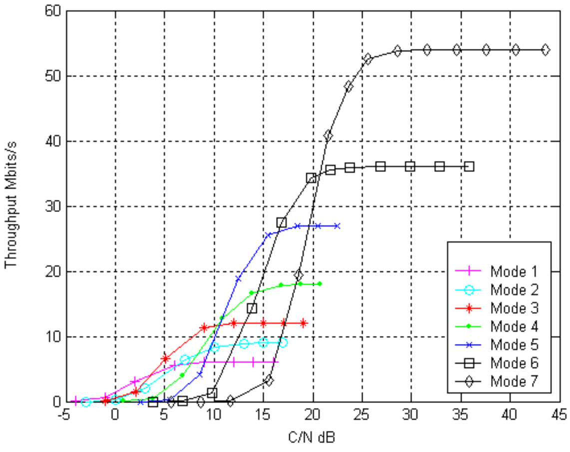

Figure 9. Throughput in Channel B

Figure 13 shows the link throughput curve for channel scenario A with an additional requirement to constrain the PER to be less than 1%. It can be seen that the PER requirement shifts the link throughput graph substantially relative to the case where only data rate is considered (Figure 8).

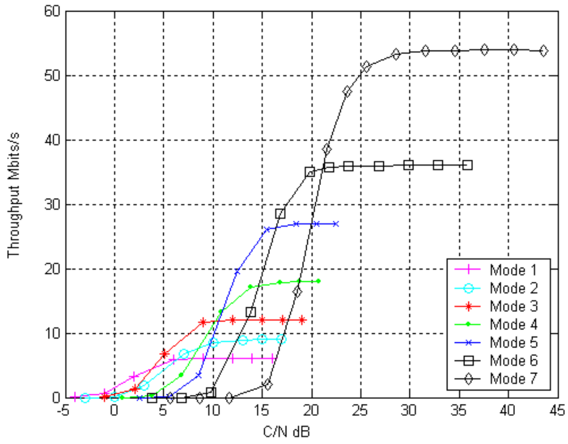

Figure 10. Throughput in Channel C

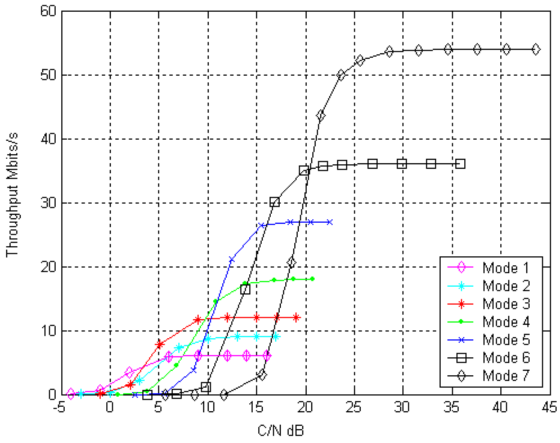

Figure 11. Throughput in Channel D

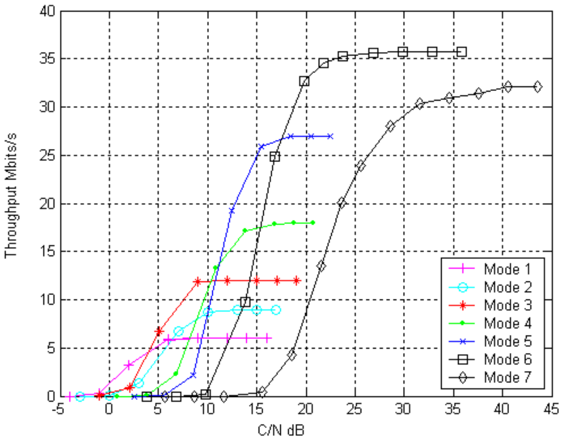

Figure 12. Throughput in Channel E

In order to investigate the implications of these graphs for the link adaptation algorithm, Table 3 summarises the range of C/N values (to the nearest dB) for which each mode offers maximal throughput for a given scenario.

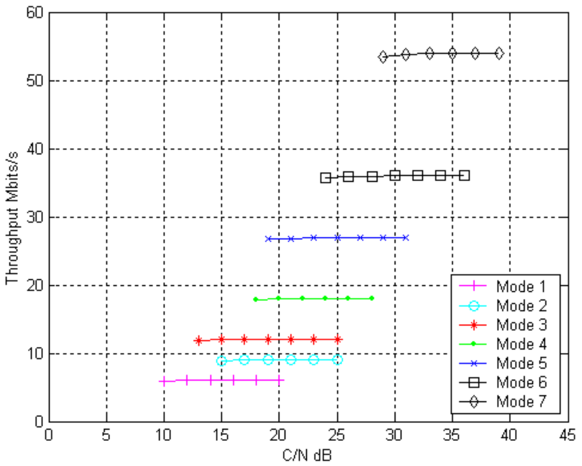

Figure 13. Throughput in Channel A with 1% Maximum PER Criterion

TABLE III. MODE SELECTION RANGES

	Mode						
Scenario	***1***	***2***	***3***	***4***	***5***	***6***	***7***
Without Maximum PER Specification							
R	-	0-3	3-6	6-10	10-13	13-18	18+
A	0-3	-	3-10	10-12	12-16	16-21	21+
B,C,D	0-3	-	3-10	10-11	11-16	16-21	21+
E	0-4	-	4-10	10-11	11-17	17+	-
With Maximum PER Specification of 1%							
A	10-13	-	13-17	17-19	19-24	24-29	29+

It can be seen that mode 2 is very rarely useful, offering only a trivial advantage in the narrowband extreme.

In the case where mode selection is made purely on the basis of maximising data rate, mode selection in scenarios B, C and D are near identical and also very similar to scenario A. Mode selection for scenario E is also very similar to B, C and D with the exception that mode 7 is never used (and would in fact introduce a severe drop in throughput if selected).

Comparing results for scenario A for the cases of link adaptation with and without a maximum PER specification (i.e. for non-time bounded and time bounded applications) shows that there are substantial differences due to the fact that the 1% PER requirement places a greater demand on each mode than the requirement to maximise data rate. The PER requirement imposes a minimum C/N requirement of 10dB and significant increases (7-10dB) can be observed in the minimum C/N for the selection of a given mode.

VI. CONCLUSIONS

The negligible difference in throughput performance between scenarios B, C and D (and minimal differences with A) suggests that frequency selectivity does not have as significant an impact on throughput as might be expected. A received Signal Strength Indication (RSSI) measurement is mandated by the standards and could be readily translated to a C/N estimate by the link adaptation algorithm. This could then be a simple one-dimensional look-up table based on the most appropriate mode selection for scenarios B, C and D (or including a small bias towards scenario A). Such an algorithm would achieve maximal data rate in many deployments. It would only be in the more extreme channel scenarios that performance would degrade. It is not possible to include the extreme scenarios into a one-dimensional look-up table without skewing the throughput downwards for the entire range of C/N (when including scenario R) or skewing the throughput drastically downwards for higher C/N (when including channel E).

Channel E is only realistic for outdoor deployments such as can be expected when WLANs are employed as ‘hot spot’ overlays for cellular networks [7]. Channel R is only realistic for very small indoor (e.g. residential) deployments. Given these facts, a link adaptation algorithm which neglects to consider frequency selectivity (other than an indication of environment type [e.g. residential, office or outdoor] supplied during deployment) should be capable of achieving near maximal data rates for the environment for which it is configured.

Clearly, a system capable of estimating the frequency selectivity of the channel would be capable of adapting more dynamically to its environment. No estimate of frequency selectivity is mandated by the standards. However, the provision of a training sequence supporting frequency domain channel estimation would suggest that an estimate of frequency selectivity could be implemented without a particularly large difficulty or cost to the manufacturer.

All of the above analysis neglects the issue of latency. The analysis of the impact of a 1% maximum PER requirement for the case of channel A indicates a substantial impact on the link adaptation algorithm. Thus (for channel scenario A at least) a 2-dimensional link adaptation process is required in order to maximise data rate within a given PER constraint. In order to verify that this is the case for other scenarios and to determine whether frequency selectivity has a more significant effect on link adaptation for time-bounded applications, further investigation is required.

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