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Range and Throughput Enhancement of Wireless Local Area Networks Using Smart Sectorised Antennas

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***Abstract*—At present, wireless local area networks (WLANs) such as HiperLAN2 and 802.11a are being developed and deployed around the world. In this letter, the use of sectorized antennas is considered as a means to improve the physical layer performance of WLANs. Results demonstrate that throughput and range can be enhanced and/or the transmit power can be reduced. However, these benefits are achieved with a small increase in multiple access protocol overhead. Simulations are performed using measured wideband channels in the 5-GHz band. In cases where the channel exhibits strong Rician characteristics, gains as high as 13 dB are demonstrated. These benefits substantially outweigh the associated medium access control overhead.**

***Index Terms*—HIPERLAN2, IEEE 802.11, orthogonal frequency division multiplexing (OFDM), smart antennas, wireless local area networks (WLANs).**

I. Introduction

WIRELESS local area networks (WLANs) provide wideband wireless connectivity between PCs and other devices as well as access to a core network in corporate, public, and home environments. Smart antennas offer a broad range of ways to improve performance. In general, the use of smart antennas can provide superior coverage, save transmit power, and reduce interference relative to an omni-directional antenna. Since smart antennas are not usually feasible at mobile and portable terminals (due to their physical size), the analysis presented here is confined to the case where the smart antenna is deployed only at the access point.

The use of sectorized antennas is common in many wireless applications because they can provide both link and system advantages. First, an antenna gain is achieved due to the smaller azimuth beamwidth of the sectored antenna. Second, spatial filtering of the channel is achieved; typically resulting in a perceived channel that has a reduced delay spread and increased K-factor if the sector with the strongest signal level is chosen. Third, spatial multiplexing can be employed to increase system capacity.

In this letter, the use of smart sectorized antennas is evaluated by software simulation as a means of improving the performance of WLANs. Performance is evaluated both for the case of measured channels and statistical models (as specified by the standardization bodies [2]). A selective diversity scheme that monitors the signal level on all antennas and selects the strongest at any time is considered. Enhancements in the form of increased range or reduced transmit power are evaluated as are the opportunities to increase link throughput. These benefits are evaluated against a corresponding increase in overheads introduced in the medium access control (MAC) protocol.

The physical layers of the HiperLAN2 [3], [4] and IEEE 802.11a [5] standards are very similar and are based on the use of orthogonal frequency division multiplexing (OFDM). The different modes in HiperLAN2 and 802.11a achieve different data rates according to the combination of sub-band modulation and forward error correction (FEC) coding rate employed (Table I). The availability of these modes with different data rates and C/N requirements enable a link adaptation scheme to adapt the system in an attempt to maximize the achieved data rate for a given link quality [8]. In the case where simple link adaptation is employed, the mode with the highest throughput would be chosen for each instantaneous C/N value. This scenario will be considered here, where it is anticipated that antenna sectorization may improve physical layer throughput by allowing the link adaptation mechanism to use higher modulation modes more frequently [6], [7]. For a discussion of link adaptation strategies that also take into account the latency requirements of real-time applications, the reader is referred to [15].

HiperLAN2 is based on a centrally managed network topology. Thus, a common node, referred to as the access point (AP), manages all communications in the network [4], [8]. The standard also provides support for the use of sectorized antennas at the AP [3], [4]. A sector ID can be used by the mobile terminals (MTs) to identify the sector with the highest power. This is achieved by transmitting separate control information for each sector employed. This facilitates a received signal strength measurement for each sector and for each MT. Subsequently, this information can be fed back to the AP. Although this does not introduce any additional delays (since it is performed in one MAC frame) MAC frame efficiency is reduced by 4.2% for each additional sector.

Since 802.11 is a distributed network, its MAC does not lend itself well to the use of sectorized antennas. A common access point at which to site and manage the sectorized antenna cannot be assumed and it is not practical for every MT to employ a sectorized antenna. Hence, this paper focuses on HiperLAN2.

A fully compliant HiperLAN2 and 802.11a physical layer simulator has been developed and bit-error rate (BER) and protocol data unit error rate (PER) results for the specified channels [2] have been generated [8], [9]. In this letter, simulated physical layer results are compared using wideband measurements for omnidirectional and sectorized antennas. Results demonstrate

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TABLE I
TRANSMISSION MODES

Mode	Modulation	Coding rate R	Bit rate [Mbit/s]
1	BPSK	1/2	6
2	BPSK	3/4	9
3	QPSK	1/2	12
4	QPSK	3/4	18
5	**16QAM (H/2 only)**	**9/16**	**27**
5	**16QAM (IEEE only)**	**1/2**	**24**
6	16QAM	3/4	36
7	64QAM	3/4	54
8	**64QAM (IEEE only)**	**2/3**	**48**

TABLE II
CHANNEL SCENARIOS

Name	Characteristic	RMS delay spread (ns)
Channel Model A	Omni	50 (Rayleigh)
Channel Model B	Omni	100 (Rayleigh)
Channel Model C	Omni	150 (Rayleigh)
Channel Model D	Omni	140 (Rician)
R1O	Omni	18 (Rician)
R1S	Sectorised	9 (Rician)
R2O	Omni	29 (Rayleigh)
R2S	Sectorised	24 (Rayleigh)
R3O	Omni	38 (Rayleigh)
R3S	Sectorised	32 (Rayleigh)
R4O	Omni	97(Rayleigh)
R4S	Sectorised	58(Rayleigh)
R5O	Omni	145(Rayleigh)
R5S	Sectorised	117(Rayleigh)
R6O	Omni	134(Rician)
R6S	Sectorised	108 (Rician)

sectorized antenna improvements for most environments; even for those where spatial filtering reduces the degree of frequency selective fading.

II. CHANNEL SCENARIOS

Statistical channel models have been specified by relevant standardization bodies [2] and used to evaluate the performance of both HiperLAN2 and 802.11a in [8]. It should be noted that these are purely temporal models—no spatial characteristics are defined. In order to facilitate the analysis of the benefits of antenna sectorization, wideband spatial-temporal channel measurements were made by Telia Research in both indoor and outdoor environments from a channel sounder incorporating a six element switched-sector antenna [1]. The indoor environment considered was a single floor of Telia Research, Malmo, Sweden, which included both a large entrance hall and several small office areas. The omni-directional transmit antenna was moved at walking pace and complex channel impulse response (CIR) data for each receive sector in turn was measured at intervals of 4 ms. Thus, for each sector, CIRs were measured at a rate of one every 24 ms (within the coherence time of the channel [1]). The outdoor environment was a large public square of dimensions 150 $\times$ 150 m. In this case, both transmitter and receiver were stationary and time variations occurred due to people and cars moving in the surrounding environment.

A total of 2400 20-MHz channel instances from the measurements were used for each measured channel scenario considered

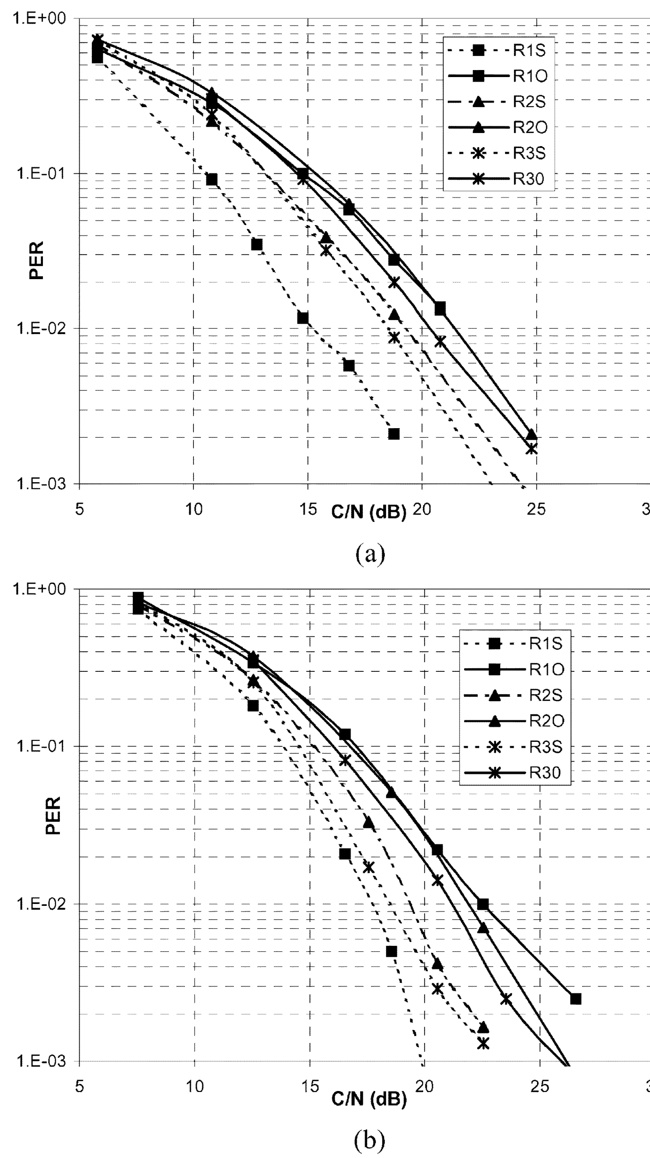

Fig. 1. PER performance for real channel scenarios R1, R2, and R3. (a) Mode 4. (b) Mode 5.

in this letter. For each channel RX ($X = 1 - 6$) in Table II, measurements from two transmitter locations were used (locations with similar rms delay spreads and characteristics were grouped) in order to obtain a total of 2400 channels for the simulations. Table II shows the channel scenarios based on real measurements made in the office environment and the outdoor environment with a 60° switched sectorized antenna at the AP.

TABLE III
PERFORMANCE AND ANTENNA GAIN

Channel	Performance Gain(dB),mode 4	Performance Gain(dB),mode 5	Antenna Gain (dB), Uplink	Antenna Gain (dB), Downlink
R1	6.7	5	7.25	7.8
R2	2	2.8	4.3	7.8
R3	1.7	2.9	3.5	7.8
R4	N/A	0	7.4	7.8
R5	N/A	-0.7	6.1	7.8
R6	N/A	2	4.9	7.8

These measurements are compared with the models specified by broadband radio access networks (BRAN) [2], [10], also shown in Table II. For each measured channel, two antenna scenarios are considered. The first antenna scenario is the case of a six-sectored receive antenna and is denoted by "S." The second is the case of an omni antenna at the receiver and is denoted by "O." The omni-directional antenna scenario is achieved by averaging and normalizing the six sectors. For both antenna scenarios, the transmitting antenna is omni. It can be seen from Table II that channels R1–R3 are suitable for comparison with the specified channel model A [2] and that channels R4, R5, and R6 are similar to channel models B, C, and D, respectively, due to their similar rms delay spread values and characteristics.

III. PERFORMANCE RESULTS

In [9], PER performances for each of the specified statistical channel models were presented. As the delay spread increases, the performance improves until the delay spread becomes so large that intersymbol interference (ISI) and intercarrier interference (ICI) become limiting factors. This is an OFDM property.

Using the measured channel data, PER results were generated for HiperLAN2 modes for all the channel scenarios. In the case of the sectorized AP, sector selection was based on the strongest received signal. Antenna sector gains are normalized and, therefore, not considered in the following C/N graphs. Results for channel scenarios R1–R3 for modes 4 and 5 are presented in Fig. 1. A comparison of the required C/N values for a target PER of 10^{-2} is summarized in Table III. Performance gains ranging from 1.7 to 6.7 dB were observed for mode 4 for the sectorized antenna compared to the omni-directional case. These results clearly demonstrate that performance in channels R1–R3 is significantly enhanced by sectorization. In channels with a dominant multipath component (R1), the correct choice of sector reduces the multipath activity and improves the Rician statistics, in accordance with [11]. Channel R1 performs better than might be expected for such low root mean square (rms) delay spreads since it exhibits a significant Rician characteristic. It sees great benefit from sectorization for this reason.

Fig. 2 shows the PER performance of all transmission modes for channel scenarios R1O, R3O and R1S, R3S. It can be observed that R3O has better performance than R1O. This is expected and can be attributed to the lower frequency selectivity of R1O relative to R3O. Hence, results with omni-directional antennas confirm that lower rms delay spreads reduce the performance of COFDM systems in Rayleigh fading – in agreement with [8], [9]. Fig. 2 also clearly demonstrates that performance is significantly enhanced by sectorization. It can be seen that mode 7 in channel scenario R1S has better performance than mode 6 in channel scenario R1O.

Although the rms delay spread is reduced when using a sectorized antenna instead of an omni, (see Table II), performance is enhanced due to the selective diversity mechanism and the improvement of the Rician statistics of the channels. It can be observed that channel R1S has better performance than channel R3S. This is because in channels with a dominant multipath component, such as R1, the correct choice of sector reduces the multipath activity and improves the Rician statistics.

Table III summarizes the performance gains achieved by the spatial filtering effect of the sectorized antennas for a PER target of 1%. It can be seen that the benefits in the indoor scenarios range from 1.7 to 6.7 dB depending upon the channel scenario and the mode of transmission.

Fig. 3 presents the simulated performances for the real channel scenarios R4–R6 (mode 5). It can be seen that for the omni-directional case, the simulated PER performances for the measured channels R4-R6 are very similar to those for the corresponding statistical channel models. This indicates that these measured channels are fair equivalents to statistical channel models B, C, and D. Table III also shows the spatial filtering benefits of sectorized antennas for channels R4-R6. It can be seen that in the case of measured channels R4-R6, the performance gain is significantly less than that for channels R1-R3. In these channels, the spatial filtering benefits range from at best 2 dB in channel R6 (which has a significant Rician component) down to -0.7 dB in channel R5 (actually a loss in performance most likely attributed to a lack of any Rician component in that channel and the lower rms delay spread relative to the omni case). The overall reduced effectiveness of sectorized antennas in the outdoor cases is due to the reduced temporal diversity resulting from the use of stationary transmit and receive antennas. This can be observed from Fig. 4, which shows which sector was used more frequently for every channel scenario [probability density function (pdf)].

From Fig. 4(a), it can be seen that in channel scenario R1, the dominant sectors are sectors 5 and 6. From Fig. 4(c), it can be seen that sectors 1, 2, 3, and 6 all play an important role in channel scenario R3. This is because in the room that R3 was measured, there was no line of sight (LOS). Hence, the improvement in channel scenario R1 is mainly because of the improvements of the Rician statistics of the channel, while in channel scenario R3, it is mainly due to six-sector selective diversity.

Fig. 4(d)–(f) shows the lack of temporal diversity (evidenced by the same sectors being selected all the time) resulting from

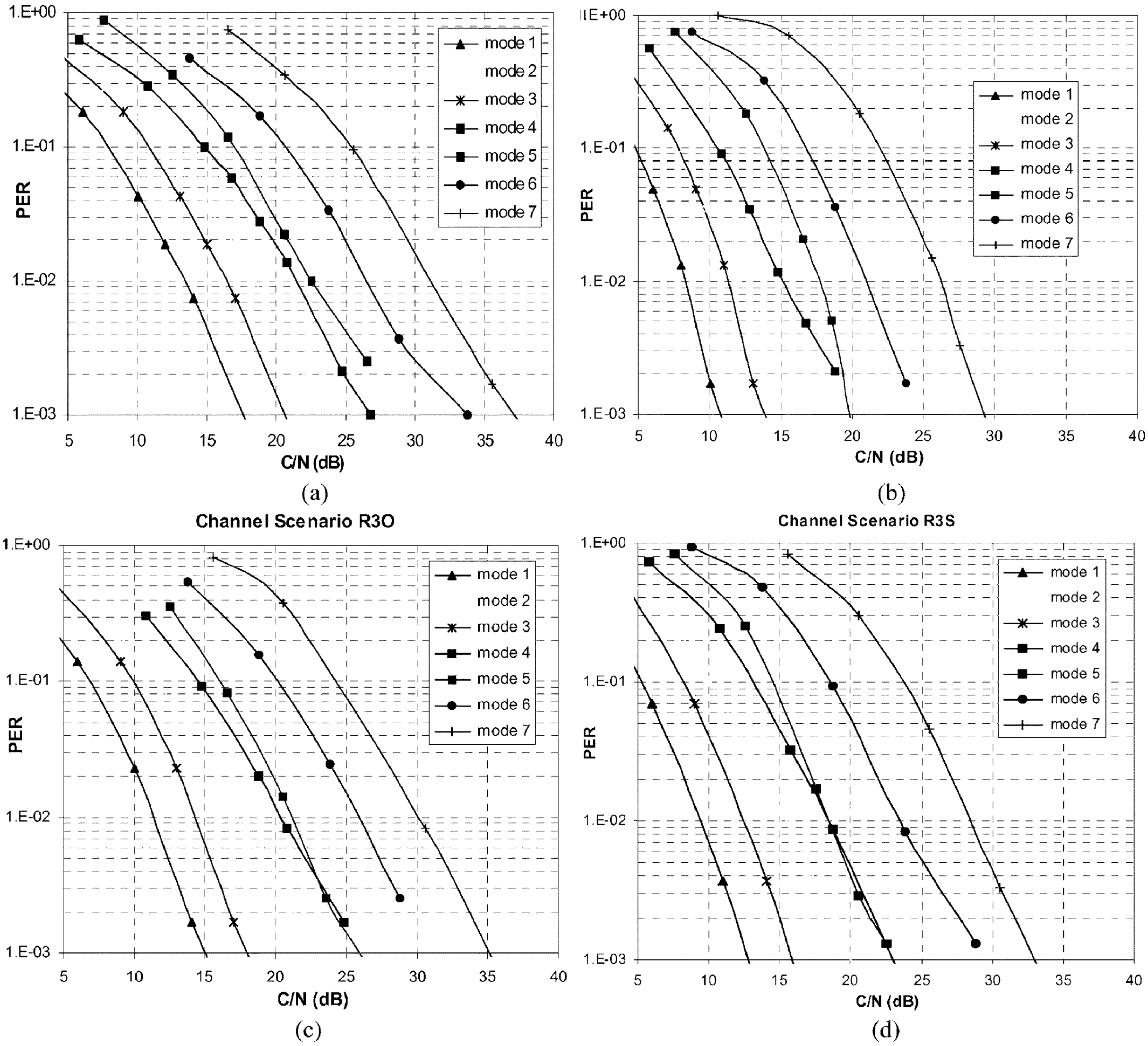

Fig. 2. PER performances for real channel scenarios. a) R1O. b) R1S. c) R3O. d) R3S.

the use of stationary transmit and receive antennas and the concentration of most energy in one sector (resulting also in a high azimuth antenna gain, see Table III), especially for channel scenarios R5 and R6 (recalling that for each channel scenario two different locations were considered, so if the locations are not next to each other, more than one sector will be dominant). However, in the case of channel scenario R6, this is not a problem since the improvements in performance are mainly due to the improvements of the Rician statistics of the channel, similar to channel scenario R1.

Even in those cases where the spatial filtering of the sectored antenna does not achieve a high performance gain, the sectored antenna still offers an azimuth gain relative to an omni-directional antenna. In the case where the sectored antenna is used to receive (uplink), it can be seen from Table III that this azimuth gain is less than the theoretical 7.8 dB that would be expected for a 60° aperture antenna. This is due to the loss of the received energy that falls outside of the strongest sector (this energy could be "recovered" if maximal ratio combining was employed). In the case where the sectored antenna is used to transmit (downlink) the full azimuth gain of the antenna can be achieved, but will be most likely exploited as a power saving due to the effective isotropic radiated power (EIRP) limits imposed by the regulatory framework.

The same applies for the mobile terminal at the uplink. Instead of increasing the uplink range, this gain could be translated into a battery power saving at the MT. Given the poor power efficiency of linear power amplifiers, the use of sector gain at the AP is an alternative method of maintaining uplink range whilst lowering the transmit power required at the MT. This will enable the use of lower power modules (possibly integrated on chip) and thereby result in far less power loss and greater battery life.

IV. Power Saving or Range/Throughput Enhancements in the Uplink

The physical layer modes are selected by a link adaptation scheme. As demonstrated in the previous section, antenna sectorization may improve throughput by allowing the link adaptation mechanism to make use of the higher data rate modes at lower C/N thresholds.

Based on the PER performances of each mode, Fig. 5 shows the physical layer throughput in measured channels R1 and R3 for both the omni-directional and sectorized scenarios. It

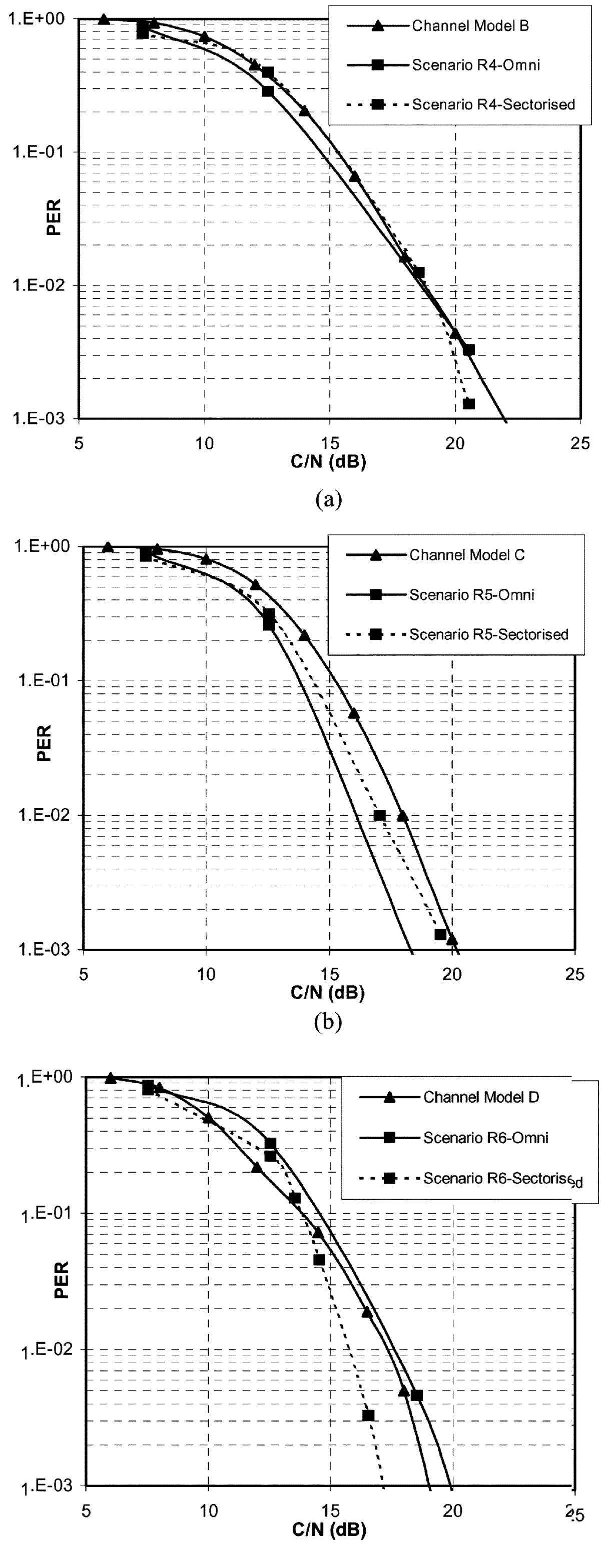

Fig. 3. PER performances for real channel scenarios. (a) R4. (b) R5. (c) R6.

can be seen that antenna sectorization improves physical layer throughput either by allowing the link adaptation mechanism to make use of higher rate modes or by reducing the PER for a given C/N if the same mode is used. An increase in physical layer throughput of up to 9 Mb/s (and 20% on average) can be seen for R1 and up to 4 Mb/s (and 11% on average) for R3. Note that these physical layer throughput enhancements are only due to spatial filtering and diversity. The antenna gains (shown in Table III) will provide substantial further improvements.

The benefits of sectorization for physical layer throughput must be offset against the additional MAC overhead. In [12], MAC overheads were calculated. The MAC efficiency depends on the number of sectors and drops from 78% for the omni case to 60% when six sectors are employed [12]. Although there is an additional overhead, throughput can be traded off for additional range or power saving.

The path loss between AP and MT can be calculated with the propagation model shown in the following [10], [13]:

$$L_P = 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 + \alpha d. \tag{1}$$

Where d is the distance between the AP and MT, λ is the wavelength and α is the attenuation (in decibels per meter) added to the line of sight path loss to model loss due to walls in a linear function (decibels) of distance [10]. Equation (1) gives a reasonable model for estimating mean path loss over distance. For more accurate results, a propagation modeling tool can be used [14]. The maximum output power for indoor-only applications is 200 mW $= 23$ dBm in the lower 200 MHz of the European radio local area network (RLAN) spectrum designation [9]. In the upper band (5470–5725 MHz), 1-W EIRP and outdoor usage is allowed. If a receiver threshold of -85 dB/m is assumed [13], the max path loss (MPL) for reception in lower band is given by MPL $= 23 - (-85) = 108$ dB. MPL $= 115$ dB in the upper band. Although it was observed that channel scenarios R1S and R3S enhance link throughput over distance, (achieving a range extension of 4–12 m beyond the original 30 or 50 m range depending on the throughput, scenario, and shadowing loss) MAC overheads should also be considered.

Combining the results from Fig. 5 and Table III (antenna gain) the system throughput including MAC overheads over range can be seen in Fig. 6(a) and (b) for $a = 1$ and $a = 0.5$, respectively. It can be seen that the use of sectorized antennas increases the operating range. Note that the amount of range enhancement depends on the attenuation value a considered and, more generally, the propagation model employed and that scenarios R1 and R3 demonstrate the best and worst cases of range enhancement in the indoor environment. As expected, the throughput is lower for the first few meters due to the additional MAC overhead. This is due to the fact that mode 7 (54 Mb/s) can be used at this range even with omni antennas. Note that as described in Section IV, instead of increasing the uplink range, the antenna gain could be translated into a battery power saving at the MT.

V. Power Saving or Range/Throughput Enhancements in the Downlink

In the case where the sectored antenna is used to transmit (downlink) the full azimuth gain (7.8 dB) of the antenna can be achieved, but is more likely to be exploited as a power saving at the AP due to the EIRP limits imposed by the regulatory framework. EIRP limitations mean that it is not possible to fully utilize range extensions for a high transmit power device although lower packet error rates can be achieved via the use of sectored antennas. However, for the case of low transmit power

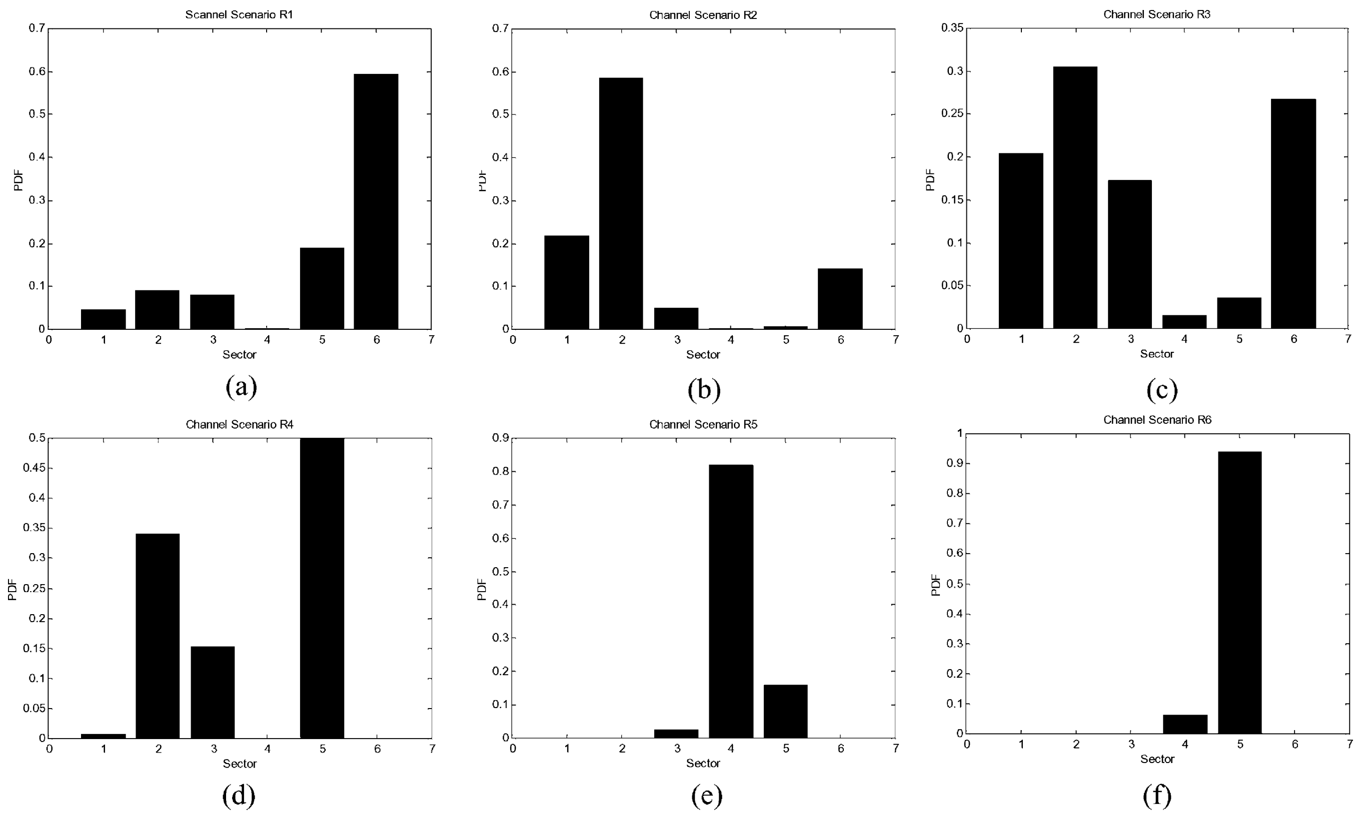

Fig. 4. PDF for sectors 1–6 for channel scenario. (a) R1. (b) R2. (c) R3. (d) R4. (e) R5. (f) R6. (Note: Not the same scale is used in each pdf).

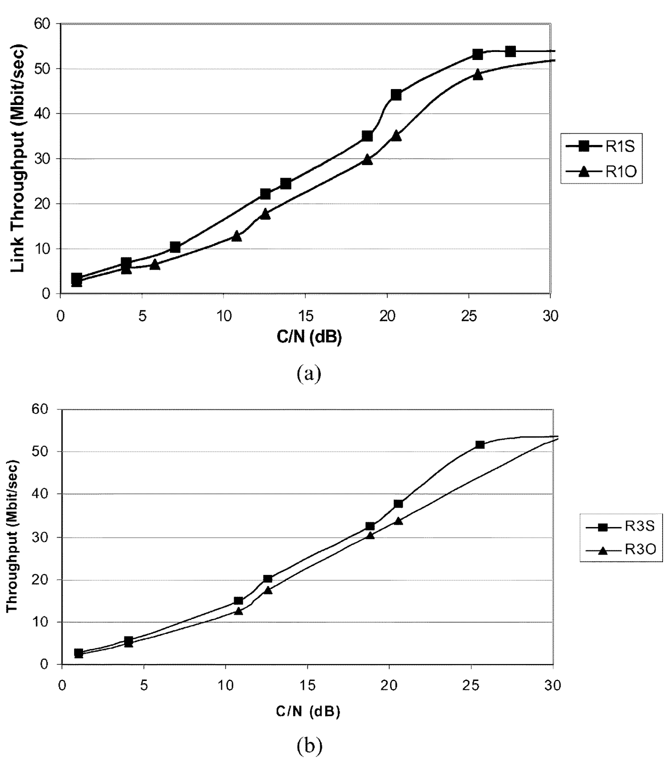

Fig. 5. Comparison of link throughput with sectorized and omni antennas for (a) channel R1 and (b) channel R3.

units (which would not normally transmit at the EIRP limit for an omni-directional antenna), range extensions can be achieved similar to the uplink case. Fig. 6(c) shows the range that can be achieved with a low transmit power unit (assuming that it transmits 7.8 dB less power) and the range that can be achieved from the low transmit power unit incorporating a sectorized antenna for the case of channel R1.

Even if the system already operates at maximum power, the link throughput improvements presented in Fig. 5 still apply for the downlink case. However, since it may not be possible to exploit the azimuth gain of the antenna for range extension, the benefits will often be less than for the uplink case. Fig. 6(c) also shows the throughput of an omni-directional antenna, already operating at maximum power. For this case, the sectorized antenna will provide the same throughput after the distance of 25 m but with a power saving of 7.8 dB. For both cases, the throughput is lower for the first few meters due to the additional MAC overhead.

VI. Conclusion

The application of sectorized antennas to the HiperLAN2 standard affects performance in two ways. First, the sectored antenna offers an azimuth power gain relative to a dipole antenna and second, combined spatial filtering of the radio channel and diversity are achieved. The measured channels considered in this letter have been shown to be good equivalents to statistical models already defined. In most cases, performance is affected (usually improved) by spatial filtering/diversity. In channels with a dominant multipath component, the correct choice of sector will reduce the multipath activity and improve the Rician statistics. As shown in Table III, gains of up to 6.7 dB occur. In channels with high angular spread and no dominant component, improvement will occur from six-sector antenna diversity. The value of spatial filtering is very much dependent on the environment and has been shown to vary between 0 and 6.7 dB for

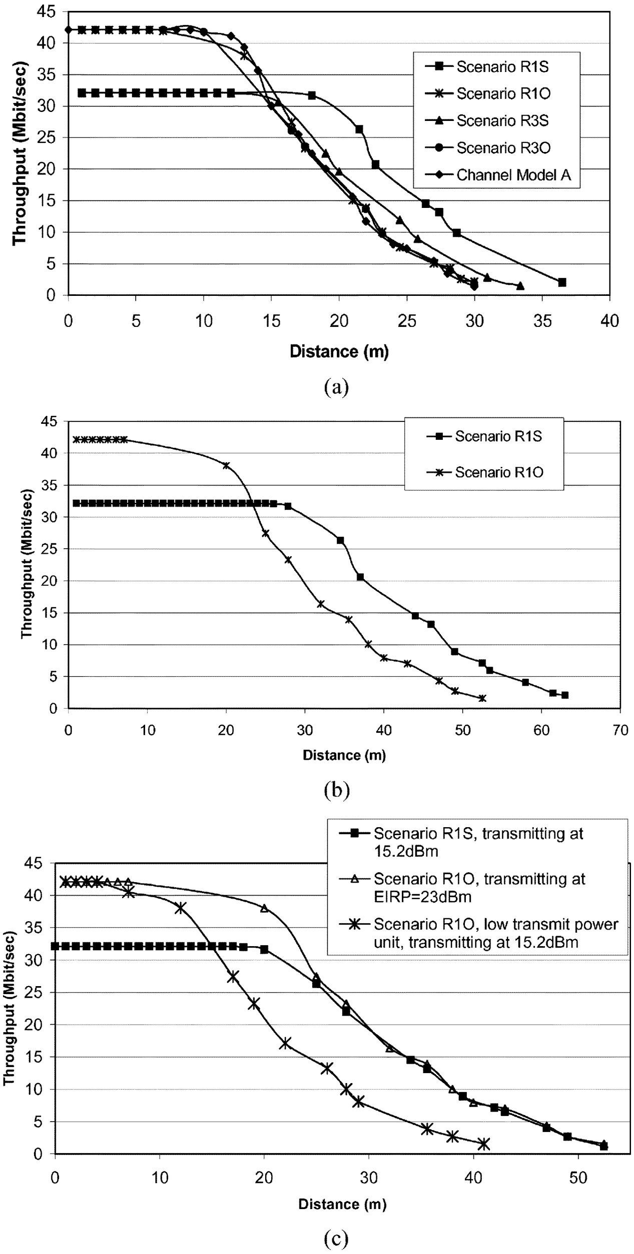

Fig. 6. Uplink throughput of HIPERLAN2 over distance from AP. (a) $a = 1$. (b) $a = 0.5$. (c) Downlink throughput of HIPERLAN2 over distance ($a = 0.5$).

the cases considered here. The spatial filtering/diversity gain results in a reduced C/N requirement for a given data rate to be achieved. Thus, it may be exploited to improve data rate for a given range and transmit power, improve range for a given data rate and transmit power or reduce transmit power for a given data rate and range. Note that the PER performance improvement will also result in lower transmission delays (since less packets will need retransmission) something that is very important for multimedia applications. A significant gain (3.5–7.25 dB in the uplink and 7.8 dB in the downlink) is also achieved in all scenarios via the mechanism of antenna gain. In the case of downlink transmissions, this benefit can mainly be exploited as power saving at the access point for a given range and data rate. EIRP limitations mean that it is not possible to fully utilize range extensions although higher data rates may be possible. In the case of the uplink, the azimuth gain may be exploited in the same way as that due to spatial filtering (power saving, range extension or higher transmission mode). AP sectorization offers a means of improving the performance of a HiperLAN2 link. In cases where the channel exhibits strong Rician characteristics, the gain can be extremely high. For example, it has been shown in this paper that gains of 13 dB on the uplink and 6.7 dB on the downlink (with a further 7.8 dB power saving) are possible for a typical mode of operation. Throughput results over distance for one AP have also shown that range and/or throughput can be increased with the use of sectorized antennas at the AP. The advantages with smart sector antennas could result in deployment of public WLAN systems where range and throughput are especially important. Sectorized antennas will also reduce interference. Additionally, because the use of sectorized antennas results in a perceived channel that has a reduced delay spread and increased K-factor, the enhancement of a WLAN by means of smart sectored antennas will increase the maximum delay spread conditions under which it could be expected to function effectively.

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