PERFORMANCE ENHANCEMENT OF OUTDOOR IEEE 802.11 CELLULAR NETWORKS

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ABSTRACT

Most studies about the performance of IEEE 802.11 are limited to a single cell environment. Nevertheless, the idea of designing an outdoor cellular network based on WLAN IEEE 802.11 results very attractive, due to the several advantages that this technology presents: the low cost of the equipment, its operation in unlicensed spectrum and its higher data rates.

If we compare the system performance in a cellular environment with its behavior in a single cell environment, we observe that its performance decreases considerably with the growth of the transmission data rate employed and due to co-channel interference.

In this paper, we propose some enhancement mechanisms, in order to reduce the interference influence on network performance. Moreover, we study the viability of using sectorised antennas at the access points. We present its performance under different load conditions and compare this behavior with the results obtained in an isolated single cell environment, which has no interference.

KEY WORDS

Cellular networks, interference, sectorised antennas, IEEE 802.11, WLAN.

1. Introduction

There have been many developments since 1997, when the Institute of Electrical and Electronics Engineers (IEEE) defined the first standard, IEEE 802.11, for wireless local area networks. IEEE 802.11 worked at 2.4 GHz and at data rates of 1 and 2 Mbps. IEEE 802.11b, which at the same frequency achieved a data rate of 11 Mbps, appeared later. IEEE 802.11a was developed subsequently; it reached 54 Mbps and its working frequency was increased to 5 GHz. This change of frequency, however, decreased its interoperability with older equipment. In answer to this, the IEEE 802.11g was developed, which reaches 54 Mbps but works at 2.4 GHz. In September 2003, a new working group began to develop IEEE 802.11n, which should reach 100 Mbps. The working procedures are practically the same for all these standards; only the modulation, certain fields in the physical layer, the duration of the slot and the interframe space times (DIFS, SIFS and PIFS) change.

Up to now, several papers have been written on various aspects of IEEE 802.11. Reference [1] studies the throughput of the network considering radio coverage aspects and the hidden terminal problem. Reference [2] shows simulation and mathematical results of the throughput of an IEEE 802.11 single cell WLAN, and also proposes dynamic adjustments of the backoff algorithm to improve overall performance. In [3] - [6] we find several analysis of propagation issues in outdoor environments. All these analysis are based on system traffic saturation and calculate the saturation throughput. More recently, several papers have appeared that work without this premise and consider situations of no congestion [7]. We can also find a study of IEEE 802.11 with the presence of errors [12]. Finally, the proposals of the working group IEEE 802.11e, that gives Quality of Service (QoS) possibilities to wireless LANs, have also been studied in [8].

A common aspect of all these studies is that they are limited to a single cell environment. However, the idea of designing an outdoor cellular network based on WLAN IEEE 802.11 results very attractive. IEEE 802.11 presents several advantages in front of 2.5G and 3G wireless networks, due to the low cost of the equipment required and its operation in unlicensed spectrum. Furthermore, IEEE 802.11 offers higher data rates, far exceeding the maximum data rates offered by EDGE (Enhanced Data Rates for GSM Evolution) and WCDMA (Wideband Code Division Multiple Access) networks. In this way, the interoperability between Wi-fi hotspots and the packet cellular networks is being evaluated [9].

Having these considerations in mind, in [13] we have evaluated the IEEE 802.11 network performance in a cellular environment; particularly we have centered our investigations in IEEE 802.11g performance. We have presented its performance under different load conditions and compared these results with the obtained in a single cell environment. In this way, we have determined that for higher data rates the system throughput performance decreases considerably due to co-channel interference. Furthermore, each station performance depends strongly of its relative position to its access point (AP). Thereby, the throughput performance becomes poorer with the distance increase.

In [13] we presented the IEEE 802.11g cellular network performance for different cluster sizes, and we have considered the employment of non-overlapped channels. Actually, at 2.4 GHz it is only allowed to work with three non-overlapped channels. Thereby, the employment of cluster sizes of four and seven cells is not possible taking into account the actual legislation. On the other hand, the legislation at 5 GHz allows the employment of cluster sizes of four and seven cells.

Going a step further, in this paper, we evaluate the suitability of employing cluster sizes higher than three cells at 2.4GHz, taking into account the influence of adjacent-channel interference.

Subsequently, we study the possibility of employing sectorised antennas at the APs, in order to reduce the interference influence on network performance. A well-known technique to increase capacity in the cellular world is sectorization. As the area covered per AP decreases, the number of users per AP is reduced. Reference [15] presents a performance evaluation for IEEE 802.11 hotspots for the supply of an exhibition hall using sectorised antennas. Thereby, in this paper, we evaluate the outdoor cellular network performance using sectorised antennas at the APs

Having these considerations in mind, the organization of the rest of the paper is as follows: section II presents the main topics of the IEEE 802.11 MAC working procedure, section III describes the simulation environment, section IV presents the system behavior employing different cluster schemes, section V exposes its performance using sectorised antennas at the access points, finally section VI concludes with the most relevant points of the article.

2. IEEE 802.11 MAC protocol

IEEE 802.11 has two operating modes: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The most common working mode is DCF, which uses the medium access control (MAC) algorithm called CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). It works as follows: before initiating a transmission, a station senses the channel to determine whether it is busy. If the medium is sensed idle during a period of time called Distributed Interframe Space (DIFS), the station is allowed to transmit. If the medium is sensed busy, the transmission is delayed until the channel becomes idle again. A slotted binary exponential backoff interval is uniformly chosen in [0, CW-1], where CW is the contention window. The backoff timer decreases as long as the channel is sensed idle, stops when a transmission is in progress, and is reactivated when the channel is sensed idle again for longer than the DIFS. When the backoff timer expires, the station attempts transmission. After each data frame is successfully received, the receiver transmits an acknowledgement frame (ACK) after a Short Interframe Space (SIFS) period. The value of CW is set to its minimum value, CW_{min}, in the first transmission attempt, and ascends in integer powers of 2 at each retransmission, up to a pre-determined value (usually 1024).

The IEEE 802.11 MAC protocol supports two kinds of Basic Service Set (BSS): the independent BSS, known as ad-hoc networks, which have no connection to wired networks, and the infrastructure BSS, which contains an AP connected to the wired network. The second BSS assimilates to cellular networks with base stations. In this way, we restrict our investigation to infrastructure networks operating in DCF mode.

3. Simulation environment description

In order to analyze the IEEE 802.11g performance, we use a simulation tool implemented in UPC (Technical University of Catalonia). Our simulation program, written in C++ programming language, follows all the IEEE 802.11 protocol details. It emulates as closely as possible the real operation of each transmitting station. Our simulation tool permits the IEEE 802.11 protocol emulation in a single cell environment and in a cellular network. On the contrary, the well-known NS-2 Simulator allows the performance evaluation of the IEEE 802.11 only in an isolated cell. In this way, we choose the exposed simulation tool in order to study the cellular network performance.

The simulation tool permits the evaluation of different parameters: throughput (user data correctly transmitted by users without considering retransmissions and headers), average transmission delay, average queue delay, probability of collision, packet error ratio (PER), signal to noise and interference ratio (SIR), proportion of erroneous data packets per data packet received, average number of retransmissions per retransmitted data packet and the fraction of time that the packet reception is interfered with a power higher than the noise power. The simulation tool has been verified comparing the results obtained with the information published in [2], under identical simulation conditions.

The values of the parameters used to obtain the numerical results are exposed in Table 1.

The simulation environment consists of 100 hexagonal cells, which form a rectangular area, although only the 36 middle cells are taken to compute the statistics. Each BSS is composed of 1 AP and 10 user stations, which are distributed randomly following a uniform distribution throughout the coverage area. Only user stations transmit data packets with a constant payload size of 1023 bytes. We consider that data are directed from user stations towards the AP, who forwards them to the infrastructure network. Also, other load situations could be considered as in [14], but these will be studied in the future.

As path loss model we employ the propagation model for IEEE 802.11 devices operating at 2.4 GHz in outdoor environments specified in [6]. This model follows the next path loss equation:

$$ploss = 7.6 + 40\log_{10} d - 20\log_{10} h_t h_r, \quad (1)$$

where d is the distance between stations and $ht\ hr$ the antenna heights for transmission and reception.

The OFDM has been selected as the modulation scheme for the IEEE 802.11g Extended Rate PHY (ERP-OFDM). It is identical to the modulation scheme employed in the previous IEEE 802.11a PHY, which is very similar to the one chosen in Europe for HIPERLAN/2 PHY. It offers eight PHY modes with different modulation schemes and coding rates; therefore data rates between 6 and 54 Mbps are provided (Table 2).

In this paper we assume that the noise over the wireless medium is white Gaussian noise (AWGN). The bit error probability (P_b) depends on the modulation scheme employed.

The bit error probability [10] for an M-ary QAM modulation with a Gray coding and M = 4, 16, and 64 is calculated by:

$$P_b^{(M)} \approx \frac{1}{\log_2 M} \cdot \left(1 - (1 - P_{\sqrt{M}})^2\right), \quad (2)$$

Table 1

Main parameters used in the simulations

	802.11g (ERP-OFDM)
Transmission data rate (Mbps)	6, 9, 12, 18, 24, 36, 48, 54
MAC header	34 bytes
ACK	14 bytes
PHY Preamble	16 µs
PHY Header	4 µs
Slot Time	9 µs
SIFS	10 µs
DIFS	28 µs
PIFS	19 µs
Minimum backoff window size	16
Maximum backoff window size	1024
OFDM symbol interval	4 µs
Radio cell	200 m
Noise power	-96 dBm

Table 2

Eight PHY modes of IEEE 802.11g ERP-OFDM

Mode	Modulation	Code Rate	Data Rate (Mbps)
1	BPSK	1/2	6
2	BPSK	3/4	9
3	QPSK	1/2	12
4	QPSK	3/4	18
5	16-QAM	1/2	24
6	16-QAM	3/4	36
7	64-QAM	2/3	48
8	64-QAM	3/4	54

where

$$P_{\sqrt{M}} = 2 \cdot \left(1 - \frac{1}{\sqrt{M}}\right) \cdot Q\left(\sqrt{\frac{3}{M-1} \cdot \frac{E_{av}}{N_o}}\right). \quad (3)$$

$P_{\sqrt{M}}$ is the symbol error probability for the $\sqrt{M}$-ary PAM modulation with the average signal-to-noise per symbol $\frac{E_{av}}{N_o}$.

For BPSK modulation, the bit error probability is the same as the symbol error probability:

$$P_b^{(2)} = Q\left(\sqrt{2\frac{E_{av}}{N_o}}\right). \quad (4)$$

In [11], an upper bound was given on the packet error probability, PER, under the assumption of binary convolutional coding and hard-decision Viterbi decoding with independent errors at the channel input. The PER is obtained following (5):

$$PER = 1 - \left(1 - P_u^m\right)^{bits\ per\ interval}. \quad (5)$$

The P_u^m value depends on the PHY mode employed: on its modulation scheme and coding rate. Its detailed calculation is specified in [12].

In order to decide if a packet is received with error at reception time, it is split up in intervals, where the interference power has different values. For each interval the signal to noise and interference ratio is obtained and its correspondent P_u^m computed.

Then, to decide if a packet is erroneous, for each packet interval, a random value between 0 and 1 is calculated. If this value is lower than the PER value, the packet is considered erroneous; otherwise this interval is considered successful and the next one is evaluated in the same way.

4. System behavior employing different cluster schemes

As presented in [13], the throughput performance in a cellular network decreases considerably for higher transmission data rates, due to the influence of interfering packets. Furthermore, data frames generated at stations placed near the limit of the coverage area arrive at its AP with lower power level and obtain an important SIR decrease. In this way, the throughput performance becomes poorer as the stations increase their distance to their AP. Moreover, we have evaluated the cellular network performance for different cluster sizes. It supposes a method to reduce the interference influence on network performance.

Thereby, we propose the employment of clusters of different sizes formed by partially overlapped channels. Without a loss of generality, we employ a transmission data rate of 48 Mbps.

In order to carry out our study, we consider the adjacent-channel interference factors presented in [16], and sum up in Table 3. We take into account the following cluster compositions:

a) cluster of four cells, using channels 1, 4, 8 and 11
b) cluster of four cells, using channels 1, 3, 9 and 11
c) cluster of seven cells, employing channels 1, 3, 5, 7, 9, 11 and 13 (this set-up is only possible in Europe)

Fig. 1 and 2 present the average SIR performance at the AP for packets generated at the most distant stations. As can be observed, employing configuration a) we achieve a better SIR performance than making use of a cluster of three cells and non-overlapped channels. On the other hand, case b) presents a worse configuration; in this way, the channel choice used provokes a higher interference level. Finally, employing configuration c) we obtain a SIR performance similar to the achieved with case a). Moreover, in case c), due to the employment of channels with different channel separation from their neighbours, the station performance depends strongly on the frequency value assigned to its correspondent cell. Cells employing channels 1 and 13 will suffer of a lower interference level, than the cells working under other channel number.

Fig. 3 and 4 present the throughput performance for the most distant stations. The behavior observed agrees with the SIR performance exposed in previous paragraph. Employing configuration a) we achieve a better throughput performance, than using a cluster of three non-overlapped frequencies.

In this way, a better configuration, which can be used in an IEEE 802.11 cellular network operating at 2.4 GHz is configuration a).

Table 3
Channel spacing to overlap factors

Overlap channel spacing	Factor
0	1
1	0.7272
2	0.2714
3	0.0375
4	0.0054
5	0.0008
6	0.0002
7	0

5. System behavior using sectorised antennas at the access points

In order to evaluate the IEEE 802.11g cellular network behavior using sectorised antennas at each AP, we present its performance in presence of different load conditions per station. Furthermore, we compare its performance with the results obtained in a cellular environment employing different cluster sizes, and as well with the behavior observed in an isolated single cell environment, which has no interference and therefore a PER=0. Without a loss of generality, we employ a transmission data rate of 48 Mbps.

Each AP employs three sectorised antennas of 120° with the radiation diagram presented in Fig. 5. In this way, each cell is composed of three sectors, which are working at different frequencies.

First, we evaluate the system performance using sectorised antennas with three sectors and a cluster of one cell. We compare this performance with the obtained employing omnidirectional antennas and clusters of one and three cells, making use of non-overlapped channels. Fig. 6 presents the average SIR performance at stations for the different configurations. Those stations placed in the middle of its respective sector obtain a lower interference level (e.g.: in Fig. 6, the station at 60m is in the middle of the sector). Moreover, employing three different channels and APs with tri-sectorial antennas, we can observe conflictive areas, where stations will receive a high co-channel interference level. These zones are marked in Fig. 7 with a black circle. Consequently, those stations placed in these areas experience higher interference power; and, in this way, a lower SIR performance (e.g.: in Fig. 6, the station placed at 104m).

In order to solve this problem, we propose the use of sectorised antennas with a cluster of three cells. Using this configuration, nine different channels are necessary. Furthermore, we study the system performance employing non-overlapped and also partially overlapped frequencies.

With the employment of nine non-overlapped frequencies, we avoid the problem shown in Fig. 7.

However, with the employment of nine partially overlapped frequencies, we achieve a poorer performance. In order to carry out our study, we consider two situations for the channels employed:

a) a minimum overlap channel spacing of two channels
b) a minimum spacing of three channels

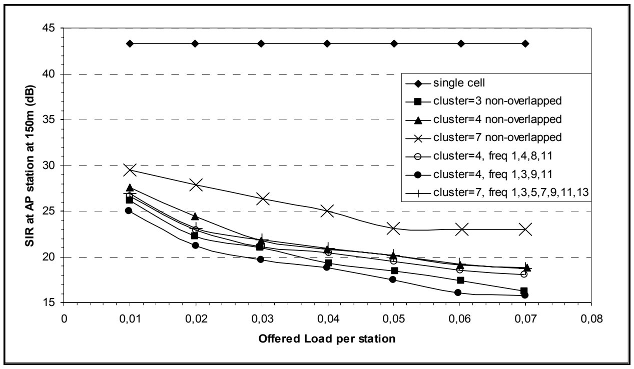

Figure 1. SIR at AP vs. offered load per station, for a station placed at 150m from the AP

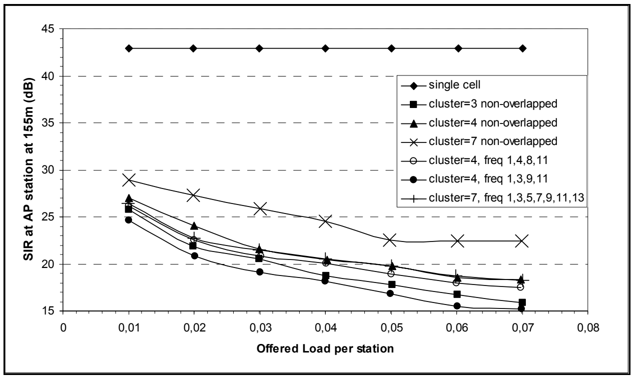

Figure 2. SIR at AP vs. offered load per station, for a station placed at 155m from the AP

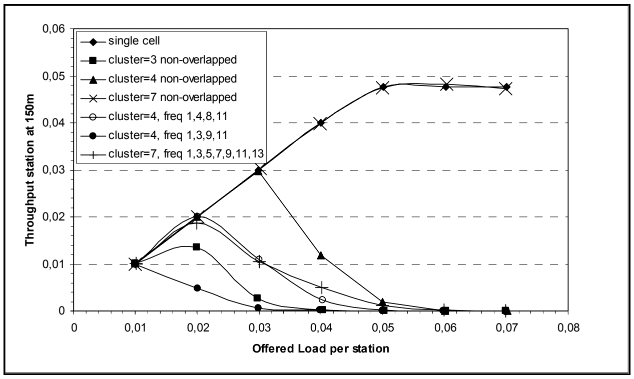

Figure 3. Throughput vs. offered load per station, for a station placed at 150m from the AP

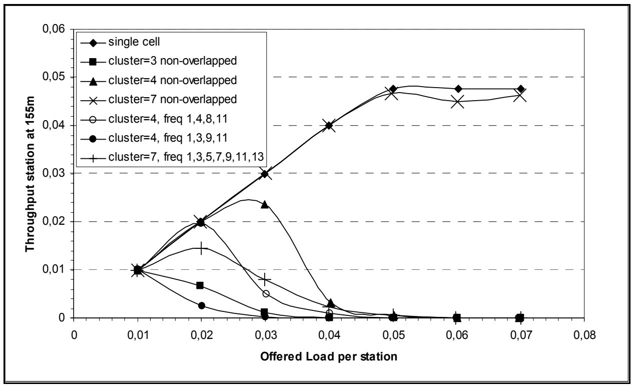

Figure 4. Throughput vs. offered load per station, for a station placed at 155m from the AP

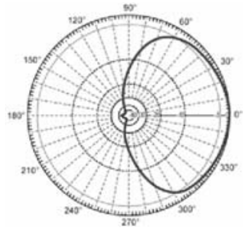

Figure 5. Antenna Gain Pattern

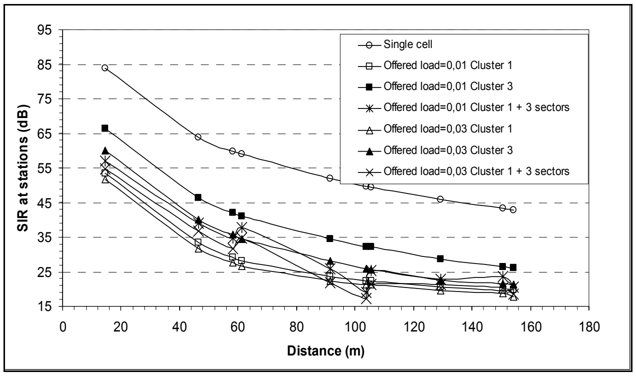

Figure 6. SIR at stations vs. station distance to its AP, for different load conditions per station

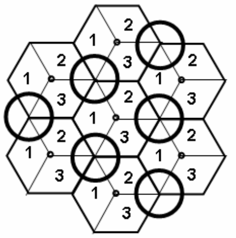

Figure 7. Cellular network with APs using tri-sectorial antennas

Fig. 8 presents the average SIR performance at stations. As explained previously, the interference level at the stations depends strongly on their position inside their corresponding sector. Those stations placed in the middle of its respective sector obtain a lower interference level (e.g.: in Fig 8, the station at 60m is in the middle of the sector). Consequently, those stations near the sector edges experience higher interference power; and, in this way, a lower SIR performance (e.g.: in Fig. 8, the station at 104m is in the border of the sector). This fact explains the small fluctuations of the sectorised system graphs.

With the employment of nine channels, we avoid the appearance of conflictive areas. However, the use of partially overlapped channels increases the interference level considerably and, in this way, those stations placed near sector edges decrease more their throughput performance, in comparison with others placed in the center of the sector (in Fig. 9, the stations at 104m, 130m, 150m and 155m are placed in the border of the sector).

In those areas, with a high density of users per AP, sectorizing is a good technique to increase capacity, because the number of users per AP is reduced. In this way, if sectorizing is necessary, the best choice is employing nine non-overlapped channels. Actually, at 2.4

GHz it is only allowed to work with three non-overlapped channels. On the other hand, the legislation at 5 GHz allows the employment of such a number of frequencies.

6. Conclusions

Due to the several advantages presented by IEEE 802.11 networks, the idea of designing a cellular network becomes very attractive. However, as we have presented in a previous study [13], the system performance in a cellular environment decreases in relation to its behavior in a single cell environment, due to the presence of interfering packets.

Thereby, in this paper we present several enhancement proposals. First, we evaluate the suitability of employing cluster sizes higher than three cells at 2.4 GHz, taking into account the influence of adjacent-channel interference. Results reveal that employing four partially overlapped channels it is possible to achieve a better performance than making use of a cluster of three cells and non-overlapped channels. However, a higher reduction in the interference level is necessary, in order to assimilate the system performance to the obtained in a single cell environment. This fact encourages us to implement new techniques. Adding a power control algorithm could bring a higher decrease in the interference level.

Finally, we present the cellular network performance using sectorised antennas at the APs. Results obtained show that if sectorizing is necessary, the best choice is employing nine non-overlapped channels. However, this selection will only be possible working at 5 GHz.

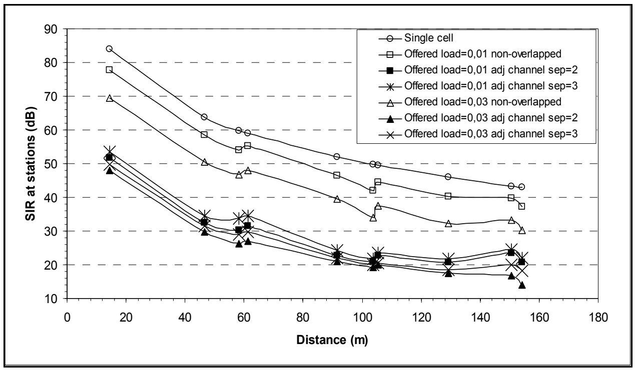

Figure 8. SIR at stations vs. station distance to its AP, for different load conditions per station and 9 frequencies

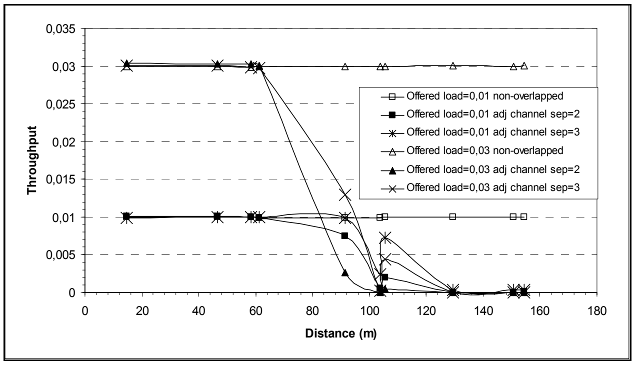

Figure 9. Throughput per station versus station distance to its AP, for different load conditions per station and 9 frequencies

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References:

[1] H. S. Chaya, S. Gupta, Performance modeling of asynchronous data transfer methods of IEEE 802.11 MAC protocol, *Wireless Networks*, Kluwer Academic Publishers, Vol. 3, No. 3, 1997, pp. 217 - 234.

[2] G. Bianchi, Performance analysis of the IEEE 802.11 Distributed Coordination Function, *IEEE Journal on selected areas in communications*, Vol. 18, No. 3, March 2000, pp. 535 - 547.

[3] M. V. Clark, K. K. Leung, B. McNair, Z. Kostic, Outdoor IEEE 802.11 cellular networks: radio link performance, *IEEE International Conference on Communications 2002 (ICC 2002),* Vol. 1, April 2002, pp. 512 - 516.

[4] K. K. Leung, B. McNair, L. J. Cimini, J. H. Winters, Outdoor IEEE 802.11 cellular networks: MAC protocol design and performance, *IEEE International Conference on Communications 2002 (ICC 2002),* Vol. 1, April 2002, pp. 595 - 599.

[5] C. Steger, P. Radosavljevic, J. P. Frantz, Performance of IEEE 802.11b wireless LAN in an emulated mobile channel, *Vehicular Technology Conference 2003. (VTC 2003-Spring)*, Vol. 2, April 2003, pp. 1479 - 1483.

[6] D. B. Green, A. S. Obaidat, An accurate line of sight propagation performance model for ad-hoc 802.11 wireless LAN (WLAN) devices, *International Conference on Communications 2002 (ICC 2002),* Vol. 5, April 2002, pp. 3424 - 3428.

[7] E. Ziouva, T. Antonakopoulos, The IEEE 802.11 Distributed Coordination Function in small-scale ad-hoc wireless LANs, *International journal of wireless information networks*, Kluwer Academic Publishers, Vol. 10, No. 1, January 2003, pp. 1 - 15.

[8] S. Choi, J. del Prado, S. Shankar N, S. Mangold, IEEE 802.11e contention-based channel access (EDCF) performance evaluation, *IEEE International Conference on Communications 2003 (ICC 2003),* Vol. 2, May 2003, pp. 1151 – 1156

[9] D. A. Joseph, B. S. Manoj, C.S. Ram Murthy, The interoperability of Wi-fi hotspots and packet cellular networks and the impact of user behaviour, *The 15th International Symposium on Personal, Indoor and Mobile Radio Communications 2004 (PIMRC 2004)*, Vol. 1, September 2004, pp. 88-92.

[10] J. G. Proakis, *Digital Communications, 4th ed.,* McGraw Hill, New York, 2001.

[11] M. B. Pursley, D. J. Taipale, Error probabilities for spread-spectrum packet radio with convolutional codes and Viterbi decoding, *IEEE Transactions on communications*, Vol. COM-35, No. 1, Jan 1987, pp. 1-12.

[12] D. Qiao, S. Choi, K. G. Shin, Goodput analysis and link adaptation for IEEE 802.11a wireless LANs, *IEEE Transactions on mobile computing*, Vol. 1, No. 4, October - December 2002, pp. 278 - 292.

[13] E. Lopez-Aguilera, J. Casademont, J. Cotrina, Outdoor IEEE 802.11g cellular network performance, *IEEE Global Telecommunications Conference (GLOBECOM 2004),* Vol. 5, November – December 2004, pp. 2992-2996..

[14] E. Lopez-Aguilera, J. Casademont, J. Cotrina, Study of Asymmetric Traffic Influence on IEEE 802.11 WLAN Family, Enhancement Proposals, *13th IEEE Workshop on Local and Metropolitan Area Networks (LANMAN 2004)*, April 2004, pp. 45-50.

[15] A. Otyakmaz, U. Fornefeld, J. Mirkovic, D.C. Shutz, E. Weiss, Performance evaluation for IEEE 802.11g hotspot coverage using sectorised antennas, *The 15th International Symposium on Personal, Indoor and Mobile Radio Communications 2004 (PIMRC 2004)*, Vol. 2, September 2004, pp. 1460-1465.

[16] M. Burton, Channel Overlap Calculations for 802.11b Networks, *White Paper, Cirond Networks Inc.*, February 2002.