Cooperative performance bounds of Wireless Local Area Networks

Rasool Sadeghi, João Paulo Barraca, Rui L. Aguiar
Institute of Telecommunications, Aveiro,Portugal
University of Aveiro, Aveiro, Portugal
{rsadeghi, jpbarraca, ruilaa@ua.pt}

Abstract—**In a Wireless Local Area Network (WLAN), capacity gain and delay reduction play a crucial role in system performance. In this paper, we focus on performance improvements when WLANs exploit the concept of cooperation among nodes. We propose a geometrical model to determine the potential location area of relay nodes. The analytical results are validated by simulation. Performance bounds and average of capacity gain and delay ratio are studied for different IEEE 802.11 standards.**

Keywords- cooperation;delay ratio; capacit;relay area.

I. INTRODUCTION

Cooperative communications have been one of the fastest growing areas of research in wireless networks. Cooperation can play a crucial role to save common network resources such as power and spectrum in wireless networking. The concept of cooperation can also be applied to different types of wireless networks, always with the purpose of improving overall system performance by increasing capacity, survivability, range or simply throughput. Improving capacity is one of the most common challenges in cooperative wireless communications, and can be achieved by deploying different techniques at different OSI layers, and with different link layer technologies.

Wireless Local Area Networks (WLANs) have been widely deployed in the last two decades due to the popularity of Internet applications, increased use of portable communication devices such as laptops and smart mobile phones, and the improvement of several physical layer technologies. The IEEE 802.11 [1] family of protocols arose as the dominant industrial standard for WLANs providing simple mechanisms for the establishment of either infrastructure or ad-hoc networks. Also, it can support multiple transmission data rates depending on the instantaneous wireless channel conditions, terminal capabilities, performance requirements, spectrum requirements, or administrative policies. Even though the use of multiple data rates increase the range of wireless communications, this feature leads to the so called performance anomaly problem [2]: if equal transmission opportunity is to be provided to all participant nodes in the same 802.11 network, the result is that nodes using a low data rate will take a lot of time to complete its transmission when they are allowed to transmit, thus degrading the performance of the remaining, higher rate nodes. For example, when using the 802.11g protocol [3], transmitting a packet of fixed size at the minimum data rate (6Mbps) makes the shared communication channel busy for a period of time 9 times longer when compared to a packet transmitted at the highest data rate (54Mbps). Developments of the most recent revisions to the standard, such as 802.11n [4], which boost the maximum data rate up to 300Mbps, further exacerbate the problem. So the ratio of low data rate nodes to all nodes in the same collision domain affects channel efficiency and overall system performance. In other words, the system performance is constrained by those nodes with the lowest data rates. In addition, nodes at the edge of a multirate cell suffer from higher packet loss due to worse channel conditions and higher interference levels.

Two solutions for the performance anomaly problem were proposed with the CoopMAC [5] and rDCF [6] protocols. The main idea behind these proposals is that one low data rate direct transmission link can be replaced by two faster transmission links, using a relay node, yielding higher performance. This mechanism is applied by overhearing other nodes transmissions and by estimating their communication data rates. Then cooperation is enabled by exchanging a set of control packets. These cooperative techniques can improve the network capacity by reducing the transmission delay between the source and destination. However, all scenarios will not provide improved performance, and it is vital to determine if it is worth to create and maintain the relay channels.

In this paper, we aim to provide an analysis of the upper, and lower bounds, as well as the average improvements regarding delay and capacity, under the assumptions of the previous proposals, when using several different variants of the 802.11 set of standards. We also propose a mathematical model to estimate the effective relay area versus the delay improvement achieved by the multi rate modulation methods used in 802.11. Our analysis shows that the multi rate features of 802.11 dominate cooperative behaviors in the network, questioning the applicability of simpler single rate analysis.

The remaining part of this paper is organized as follows: in section II, we present the metric of delay ratio and the mechanism to obtain it in 802.11. Section III considers the mathematical method to calculate the relay area versus the delay ratio. Section IV suggests new parameters to determine the bounds of delay performance and capacity performance improvements. Simulation and results are also presented in section V and section VI concludes the paper and relates the future directions.

II. RELATED WORK

There have been considerable research efforts devoted to capacity improvement by using cooperation at the physical layer. After the basic idea of cooperative communication introduced by van der Meulen [7,8], El Gamal [9] provided a model for estimation of the lower and upper bounds on the channel capacity for specific relay channel scenarios without fading. Most of the recent research work considered the information-theoretic aspects of relay channel. For example, in [10], the authors studied the coding strategies for wireless channel and the achievable capacity, while the capacity region of a Gaussian relay channel with multiple relay stages was given in [11], and the capacity of relay channels with orthogonal channels has been studied very well in [12]. Different cooperative protocols such as Amplify-and- Forward (AF) and Decode-and-Forward (DF) have been considered in term of outage capacity in [13] and [14]. Gupta and Kumar [15] showed the upper bound of achievable aggregate throughput for multihop transmission. Another scheme that achieves the linear capacity scaling in wireless ad hoc networks when cooperation is used was presented in [16].

Regardless of the theoretical discussion on the channel capacity at physical layer, only a few existing publications on cooperative communication focus in the expected capacity improvement provided by cooperative techniques, as seen at higher layer and at the same time compatible with currently deployed wireless communication technologies, which have inherently multi rate adaptation capabilities.

III. DELAY RATIO AND COOPERATION IN IEEE 802.11

Cooperative WLAN using relay nodes may consider the transmission delay as the main decision factor to initiate the cooperation process. For example, Figure 1 shows an infrastructure WLAN using802.11b with three nodes: Access Point (AP), relay node (R) and node N. Node R can help the AP by relaying packets to node N, with data rates of 11Mbps, while the direct transmission between AP and N is 1Mbps. The ratio between the transmission delay (time a data packet takes to be transmitted over the medium) when using the direct path, and the transmission delay of relay path, which we call *Delay Ratio* (DR), is equal to 0.18. This value indicates that if the processing delay in node *R* and access delay are neglected, we have a 72% of reduction in the transmission delay by using *R* for delivering the packet between *AP* and node *N*. In terms of bandwidth efficiency, the equivalent data rate of this relay channel is given by (1).

$$BW_{Eq.} = \frac{1}{DR} \times 1\ Mbps = \frac{1}{0.18} \times 1\ Mbps \cong 5.5 Mbps \quad (1)$$

The calculation of the delay ratio (which directly related to end-to-end delay and throughput) of a relay channel should be the key issue of every protocol aiming to employ cooperation for improving performance. In the scenario depicted in Figure 1, every node can calculate its own delay ratio by overhearing other nodes communications. For instance, node R, being a potential relay for AP-N communications, can discover the data rates between itself and the AP and node N by overhearing their control frames (RTS and CTS). Node R can estimate potential data rates of AP and node N to itself from the signal to noise ratio of received RTS and CTS frames (because they are broadcasted). Node R can also obtain the actual data rate achieved between AP and node N by overhearing the data frames exchanged between AP and node N. This is possible because the 802.11 MAC header, or in more detail, the PLCP sub-header, contains a field called SIGNAL, which denotes the bit rate of every data packet sent to the network. Similarly, AP and node N can obtain the corresponding data rates to achieve their own delay ratio. Clearly, if the value of the calculated delay ratio is less than 1, the relay channel will possibly provide better transmission characteristics than the direct channel, due to the resulting higher bandwidth and lower transmission delay for end-to-end communication.

In cooperative relay based wireless networks, there are two main questions to be answered: a) which percentage of the access point coverage area can potentially improve performance if a relay node is present, and is used, and b) what are the performance bounds (minimum, maximum and average) of cooperative schemes in the different data rates supported by 802.11 family of standards. In the next sections, we will answer these questions by proposing a mathematical model and some new metrics.

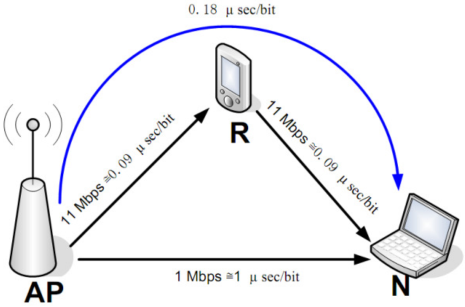


Figure 1. Cooperative scenario using relay node in infrastructure WLAN

IV. RELAY AREA IN COOPERATIVE IEEE 802.11

Different data rates in 802.11 can result in different delay ratios perceived by relay nodes. A relay can change its location within an area called *relay area* while its delay ratio does not change. To obtain the relay area versus delay ratio, we consider the geometric model of cooperation. As depicted in Figure 2, if node N, located at the transmission range of R_1, supports 1Mbps data rate to AP, the intersection area of A_{ijk} denotes the potential area for a relay node to support data rates of i Mbps and j Mbps to AP and N respectively, and the associated delay ratio can be expressed as (2).

$$DR_{ijk} = \frac{i^{-1} + j^{-1}}{k^{-1}} \quad (2)$$

where, the numerator is the end-to-end delay of transmitting data using relay, and the denominator is the direct transmission delay from AP to N with data rate of k Mbps. Table 1 summarizes all values of delay ratio less than 1 and their relay area for a direct transmission data rate of 1Mbps. To obtain the value of A_{ijk} we consider the area overlapping two circles with radii of r_1 and r_2 and distance of l between their centers. The overlap area, denoted by S_{r1r2} can be formalized as (3).

$$S_{r1r2} = {r_1}^2 \sin^{-1}(h/r_1) + {r_2}^2 \sin^{-1}(h/r_2) - hl \quad (3)$$

where, $h = \frac{\sqrt{2{r_1}^2{r_2}^2 + 2({r_1}^2 + {r_2}^2)l^2 - ({r_1}^4 + {r_2}^4) + l^4}}{2l}$.

The relation between this overlap area of two circles and relay area of *Aij´*s in Figure 2 can be calculated as (4).

$$(4)\begin{cases} A_{11-11} = S_{R_{11}-R_{11}} \\ A_{11-5.5} = A_{5.5-11} = S_{R_{11}-R_{5.5}} - S_{R_{11}-R_{11}} \\ A_{11-2} = A_{2-11} = S_{R_{11}-R_{2}} - S_{R_{11}-R_{5.5}} \\ A_{5.5-5.5} = \left(S_{R_{5.5}-R_{5.5}} - S_{R_{11}-R_{5.5}} - A_{11-5.5}\right)/2 \\ A_{5.5-2} = A_{2-5.5} = \left(S_{R_{5.5}-R_{2}} - S_{R_{5.5}-R_{5.5}} - A_{2-11}\right)/2 \end{cases}$$

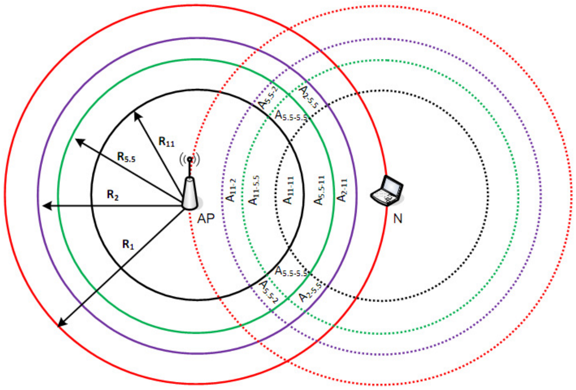


Figure 2. Relay area for direct transmission of 1Mbps

TABLE I. DIFFERENT VALUES OF DELAY RATIOWHEN CONSIDERING A DIRECT TRANSMISSION CHANNEL OF 1MBPS

Relay Area	**$A_{11-11-1}$**	**$A_{11-5.5-1}$, $A_{5.5-11-1}$**	**$A_{5.5-5.5-1}$**	**A_{11-2-1}, A_{2-11-1}**	**$A_{5.5-2-1}$, $A_{2-5.5-1}$**
Delay ratio	0.18	0.27	0.36	0.59	0.68

By applying the recursive calculations in (4), we obtain the relay area for every direct transmission data rates supported by 802.11 standards. In order to evaluate the delay performance and capacity gain of cooperative 802.11 based on the relay area, we define two parameters in the next section.

V. DELAY PERFORMANCE AND CAPACITY GAIN IN COOPERATIVE IEEE 802.11

For each data rate supported by 802.11 we have a different value of delay ratio with different relay area (Table I). In order to have a criterion for delay performance improvement, for every direct transmission of *k* Mbps, we can define Average Weighted Delay Ratio (AWDR) as (5).

$$AWDR_k = \frac{\sum_i \sum_j A_{ijk} * \overline{DR}_{ijk}}{\sum_i \sum_j A_{ijk}} \quad (5)$$

where,

$$\overline{DR} = \{DR | DR_{ijk} < 1\} \quad (6)$$

In order to find the bounds of delay performance, the minimum and maximum of $\overline{DR}$ set are given by (7) and (8).

$$LowerBoundofDelayRatio(LBDR) = \min\{\overline{DR}\} \quad (7)$$

$$UpperBoundofDelayRatio(UBDR) = \max\{\overline{DR}\} \quad (8)$$

In the next section, we present the results of AWDR, LBDR and UBDR for every direct data rate transmission of 802.11. To consider the capacity improvement of cooperative scenario, we also define Cooperative Capacity (CC) as (9):

$$CC_{ijk} = \left({}^{1}/_{DR_{ijk}}\right) * k \quad (9)$$

where, DR_{ijk} is obtained by (2) and *k* is the direct data rate transmission. Average Weighted Cooperative Capacity (AWCC) is the next metric to determine the average capacity of cooperative communication in comparison to non-cooperative one.

$$AWCC_k = \frac{\sum_i \sum_j A_{ijk} * \overline{CC}_{ijk}}{\sum_i \sum_j A_{ijk}} \quad (10)$$

where,

$$\overline{CC} = \left\{ CC \middle| CC_{ijk} = \frac{1}{DR_{ijk}} and DR_{ijk} < 1 \right\} \quad (11)$$

We define two more parameters as the minimum and maximum of $\overline{CC}$ set in (12) and (13), in order to obtain an evaluation of the expected capacity improvement:

$$LowerBoundofCooperativeCapacity(LBCC) \\ = \min\{\overline{CC}\} \quad (12)$$

$$UpperBoundofCooperativeCapacity(UBCC) \\ = \max\{\overline{CC}\} \quad (13)$$

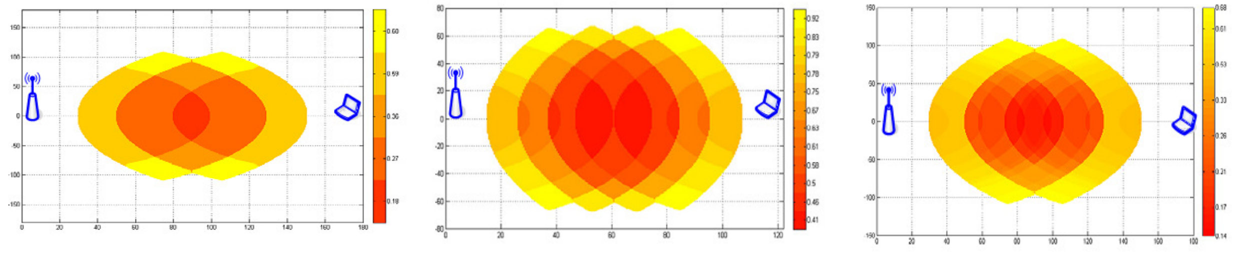
In the next section, we present the relay area based on delay ratio for different revisions of 802.11. We also consider the AWCC, LBCC and UBCC for every direct transmission data rate.

VI. SIMULATION AND RESULTS

To compute the relay area based on the calculation of (3) and (4), we need the transmission ranges supported at different data rates. So we set a simple scenario with two nodes that communicate using 802.11bg, and then we change their location in order to obtain different data rates. This way we can evaluate all possible data rates supported by 802.11b and 802.11g. Table II indicates the data rates of different transmission ranges for BER<10^{-5} achieved in a simulation by OMNET++: as expected, when distance changes, data rates will be adapted.

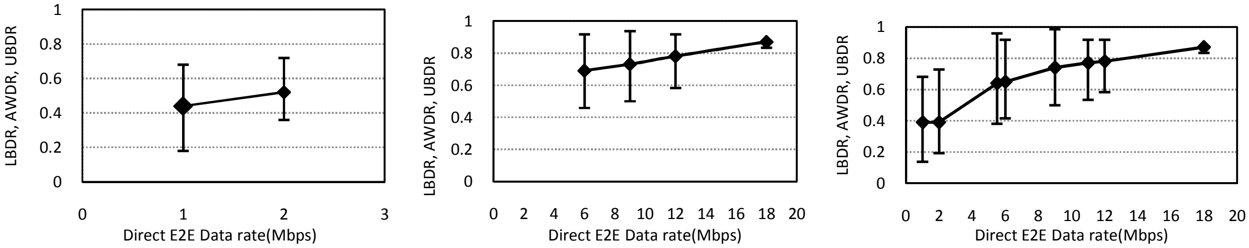
TABLE II. DATA RATES AND TRANSMISS ION RANGES OF 802.11BG

802.11bg	**802.11g**	**Data rate (Mbps)**	6	9	12	18	24	36	48	54
		Range (meter)	122	107	96	85	75	61	42	31
	802.11b	**Data rate (Mbps)**	1	2	5.5	11				
		Range (meter)	180	150	130	100				



(a) (b) (c)

Figure 3. Relay area versus delay ratio for direct transmission data rate of a) 1Mbps-802.11b, b) 6Mbps-802.11g and c) 1Mbps -802.11bg



(a) (b) (c)

Figure 4. AWDR, LBDR and UBDR for a) 802.11b, b) 802.11g and c) 802.11bg

Since every revision of 802.11 supports different data rates, we select just the minimum data rate supported by each standard to show the relay area versus delay ratio, in geometrical representation and percentage of coverage area. Figure 3 depicts a visual spectrum representation of the relay area in 802.11b, g, and bg revisions, when the data rate of direct path is 1Mbps, 6Mbps and 1Mbps respectively. As the color of spectrum bar changes from red to yellow, the delay ratio increases, and the performance benefit of cooperation by a relay channel decreases. Figure 5 presents the percentage of relay area versus delay ratio. As depicted, 802.11b presents a delay ratio between 0.18 and 0.68, whereas 802.11g present values from 0.45 to 0.91.When using 802.11bg the interval of values varies between 0.14 and 0.68. Figure 4 presents the AWDR, LBDR and UBDR for all direct data rates supported by 802.11b, g and bg, as discussed in equations (5) to (7). Figure 4.a shows that in 802.11b, both for 5.5Mbps and 11 Mbps, using a relay channel will never lead to improved transmission delay. In 802.11g improvements can be achieved for direct path data rates of 6, 9, 12 and 18Mbps (Figure 4.b), while in 802.11bg cooperation can be useful when the direct path is capable of 1, 2, 5.5, 6, 9, 12 or 18Mbps. It is worth mentioning that AWDR of some data rates in 802.11bg is less than the same data rates in 802.11b and 802.11bg. For instance, AWDR at 1Mbps changes from 0.44 in 802.11b to 0.4 in 802.11bg, and AWDR at 6Mbps changes from 0.7 in 802.11g to 0.65 in 802.11bg. Thus, due to more cooperation possibilities, 802.11bg could achieve higher performance than 802.11b and 802.11g in term of delay reduction, especially for the similar end-to-end direct data rates. An analysis of the results in Figures 4.b and 4.c indicates that LBDR and UBDR for 18Mbps is very close to its AWDR, because of low overlapping area of transmission ranges for a direct path at 18Mbps.

Figure 6 depicts AWCC, LBCC and UBCC of 802.11b, g and bg as discussed in equations (10), (12) and (13). It can be seen a higher capacity improvement of 802.11bg over 802.11b and 802.11g, when using similar data rates. For example, AWCC improves 18% from 802.11bg to 802.11g for a direct path data rate of 1Mbps, while for 2Mbps in 802.11bg, AWCC is 40% higher in 802.11bg than in 802.11b. Also, in the case of 6Mbps, we can observe 7% improvement of AWCC from 802.11bg to 802.11g.

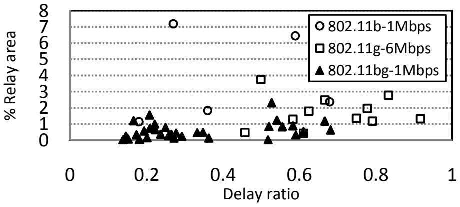
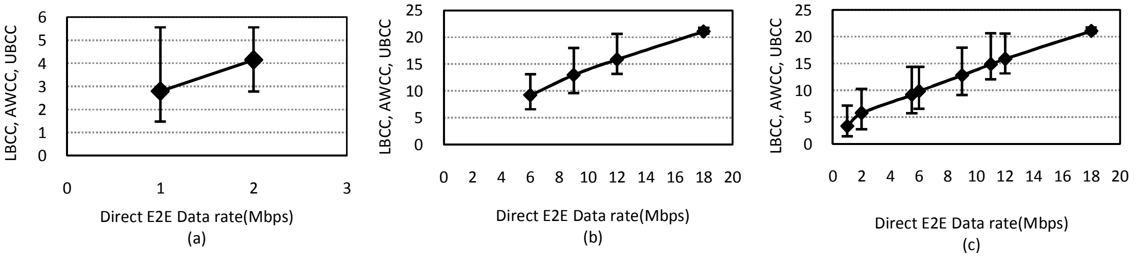


Figure 5. Percentage of relay area versus delay ratio

In order to evaluate the results of the theoretical analysis, we setup a simulation scenario as shown in Figure 3.a. The simulator used was OMNET++, version 4.0 [12] in a Ubuntu environment. Simulations scenarios were configured for an 802.11b based indoor network, and had duration of 20 seconds, transmitted power of 100mW, packet size of 1024 bytes, and CBR flows of 24Mbps. The results presented are the average of 50 simulation runs, and the direct end-to-end data rate is 1Mbps.

Figure 7.a compares the theoretical analysis and the simulation results. As delay ratio increases, the gap between theoretical analysis and simulation throughputs are going down. This effect reflects the higher negative impact of forwarding delay and access medium delay on the performance of relay with low delay ratio. This effect also is shown in Figure 7.b, where we present the capacity gain of theoretical and simulation results. For example in delay ratio of 0.18, we can see a capacity gain of 300% in simulation while in our simplified theoretical model, it can be 550% and AWCC of 1Mbps in 802.11b is about 280%. To decrease the gap between the real scenario and



(a) (b) (c)

Figure 6. AWCC, LBCC and UBCC for a) 802.11b, b) 802.11g and c) 802.11bg

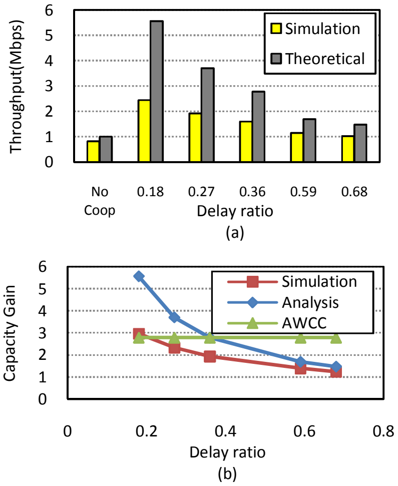
achieved bound of capacity improvement, we should design the cooperative MAC protocols to decrease the forwarding delay and medium access delay. Our simulations were performed with “vanilla-like” versions of 802.11, where no such optimizations were in place. In order to apply the cooperation benefits achieved at lower layer to cross layer design issues, we can create a table to estimate the potential throughput and capacity gain versus delay ratio. For example, by applying curve fitting for results of Figure 7.b, capacity gain as a function of delay ratio can be obtained as (14).

$$CG(dr) = 3.6\, e^{-7.8\, dr} + 2.5\, e^{-dr} \quad (14)$$

This estimation can be more useful when we have different traffic service requirements at higher layer and network interface card which support different data rates with various ranges at lower layers.

VII. CONCLUSIONS

In this paper, we evaluate cooperation in 802.11 standards in terms of capacity gain and delay reduction based on a very simple theoretical and geometrical model. Delay ratio and relay area as potential locations of relay nodes are calculated for different data rates. Upper bound, lower bound and average values of delay performance and capacity gain are presented. Simulation results demonstrate that 802.11bg present better performance for similar data rates supported by 802.11b and 802.11g. Even though in our simplified method the forwarding delay and access delay are not taken into account. In order to decrease the gap between theoretical and real scenario results, we should consider these aspects to optimize cooperative MAC protocols. Cooperative protocols can be also considered as a cross layer design issue to fulfill the upper layer requirements based on lower layer specifications.



(a)

(b)

Figure 7. a) Theoretical and simulation results of data rate versus delay ratio, b) Capacity gain.

REFERENCES

[1] IEEE, Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications, IEEE Std 802.-11-99,August 1999.

[2] Heusse, M., Rousseau, F., Berger-Sabbatel, G., Duda, A.: Performance anomaly of802.11b. In: Proceedings of IEEE INFOCOM, vol. 2, pp. 836– 843 (2003)

[3] IEEE Std. 802.11g, Supplement to Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Further High-Speed Physical Layer Extension in the 2.4GHz Band.

[4] IEEE Std. 802.11n, Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput

[5] Liu, P., Tao, Z., Narayanan, S., Korakis, T., & Panwar, S. S. (2007). CoopMAC: A cooperative MAC for wireless LANs.IEEE Journal on Selected Areas in Communications, 25(2),340–354.

[6] Zhu, H., & Cao, G. (2006). rDCF: A relay-enabled mediumaccess control protocol for wireless Ad Hoc networks. IEEETransactions on Mobile Computing, 5(9), 1201–1214.

[7] E. C. van der Meulen. Three-terminal communication channels. Advances in Applied Probability, 3:120–154, 1971.

[8] E. C. van der Meulen. A survey of multi-way channels in information theory: 1961–1976.IEEE Transactions on Information Theory, 23(1):1–37, January 1977.

[9] T. Cover and A. E. Gamal. Capacity theorems for the relay channel. IEEE Transactions onInformation Theory, 25(5):572–584, September 1979.

[10] G. Kramer, M. Gastpar, and P. Gupta. Cooperative strategies and capacity theorems for relaynetworks. IEEE Transactions on Information Theory, 51(9):3037–306, September 2005.

[11] A. Reznik, S. R. Kulkarni, and S. Verdu. Degraded Gaussian multirelay channel: capacityand optimal power allocation. IEEE Transactions on Information Theory, 50(12):3037–3046,December 2004.

[12] A.A. El Gamal and S. Zahedi. Capacity of a class of relay channels with orthogonalcomponents. IEEE Transactions on Information Theory, 51(5):1815–1817, May 2005.

[13] J.N. Laneman and G.W. Wornell. Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks. IEEE Transactions Information Theory,49(10):2415–2425, October 2003.

[14] J.N. Laneman, D.N. C. Tse, and G. W. Wornell. Cooperative diversity in wireless networks: efficient protocols and outage behavior. IEEE Transactions on Information Theory,50(12):3062–3080, December 2004.

[15] P. Gupta and P. R. Kumar. The capacity of wireless networks. IEEE Transactions onInformation Theory, pp. 388–404, March 2000.

[16] A. Ozgur, O. Leveque, and D.N. C. Tse. Hierarchical cooperation achieves optimal capacityscaling in ad hoc networks. IEEE Transactions on Information Theory, 53(10):3549–3572,October 2007.