

How to outperform IEEE802.11: Interference Aware (IA) MAC

Daniela Maniezzo^{*‡}, Pierpaolo Bergamo[‡], Matteo Cesana^{*§}, Mario Gerla^{*}

^{*}CS Dept. - University of California Los Angeles - UCLA, California, USA

[‡]Engineering Dept., Ferrara University, Italy

[§]Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy

maniezzo@ucla.edu, pbergamo@ing.unife.it, cesana@elet.polimi.it, gerla@cs.ucla.edu

Abstract—Wireless networks are nowadays very popular. They are mostly based on IEEE802.11 protocol which is known to show low performance in ad hoc networks. Also when infrastructure networks (many access points are placed) are considered, a single transmission could block many radio cells. In this work, we propose Interference Aware (IA) MAC, a modified version of standard IEEE802.11. The main idea is not to set the Network Allocation Vector (NAV) on the reception of each RTS and CTS, but only when it is strictly required, i.e., when a concurrent transmission could actually destroy another transmission. To make it feasible, we propose to insert some information about interference and received power levels into IEEE802.11 control packets. We show the effectiveness of IA MAC by means of an analytical investigation.

I. INTRODUCTION

The recent success of wireless technologies has boosted the development of wireless networking. Both industry and academia have turned their attention to this area, attracted the former by intriguing research issues, the latter by market revenues.

Among the numerous standards for wireless communications, the IEEE802.11b [1] is the one with the highest utilization at the moment. IEEE802.11b defines a MAC (Medium Access Control) layer, MAC management protocols and services, and three physical (PHY) layers respectively based on IR, FHSS at 2.4 GHz and DSSS at 2.4 GHz. The goal of the standard is to deliver services previously found only in wired networks, within mobile users with high throughput, high reliability and continuous network connection. For this reason, IEEE802.11 based networks are often referred to as Wireless LANs.

The wireless environment poses some challenging problems the network design has to cope with. Firstly, the radio channel is prone to errors and temporary failures which are not encountered in the wired world, secondly, the channel is shared and resources are often scarce. In this scenario, the employed access control schemes are key points for achieving effectiveness.

As far as the MAC layer is concerned, two different schemes are standardized: the Point Coordination Function (PCF) and the Distributed Coordination Function (DCF). While PCF consists of a centralized polling based access scheme, the DCF

defines a distributed access algorithm for both infrastructure and ad hoc wireless LANs [1], [2]. As far as unicast data packet transfer is concerned, DCF defines two access methods. The first one is based on a two-way handshake procedure (DATA/ACK), the second one adopts a four-way handshake procedure, where the DATA/ACK phase is preceded by a channel probing/acquiring phase called RTS/CTS (Request To Send/ Clear To Send).

Both of the above methods implement a multiple access scheme based on Carrier Sensing with Collision Avoidance (CSMA/CA). Basically, each node senses the channel before transmitting the first frame of the handshake; if the channel is sensed idle for a certain period of time called DIFS (Distributed InterFrame Space), the node starts transmitting the first frame of the handshake, otherwise the node waits for the channel to be idle for DIFS and draws a random additional backoff time to avoid possible collisions when the channel becomes free (Collision Avoidance). A further channel control mechanism is applied in the four-ways handshake procedure. According to this scheme, each control frame (RTS/CTS) brings information about the duration of the starting communication. Every other node overhearing that frame is prevented from accessing the channel for all the duration of the ongoing communications by setting a proper parameter called NAV (Network Allocation Vector). This procedure is often referred to as Virtual Carrier Sensing.

In this paper we propose a novel MAC layer for Wireless LANs, named Interference Aware MAC (IA-MAC) [3], which extends the capabilities of the basic IEEE802.11 in environments with high interference, both in ad hoc and in infrastructure mode [4], [5]. In Section II we focus on the open problems of wireless networks, in particular the IEEE802.11-based ones, and we give an overview of the proposed approaches of solutions. Section III summarizes the basics of the proposed IA-MAC protocol, while Section IV gives a mathematical model to analyze the performance of the protocol itself and in Section V some results are shown. Finally, Section VI concludes the paper.

II. OPEN PROBLEMS AND PROPOSED SOLUTIONS

IEEE802.11 was originally devised explicitly for a single Access Point scenario where all the mobile nodes are within the transmitting range of one another. In this environment, the IEEE802.11 medium access control protocol, which tends to avoid the interference, is able to achieve high efficiency. Problems arise when IEEE802.11 is used both in a pure ad hoc mode, where the basic IEEE802.11 mode is not able to exploit any spatial reuse, and in infrastructured cellular-like scenario where the connectivity is provided by different APs with overlapping transmission ranges, i.e. with non negligible interference [6].

The efficiency of IEEE802.11 based networks can be dramatically impaired by the well known hidden and exposed terminal problems [7]. As a matter of fact, the four-way handshake with the Virtual Carrier Sensing solves only partially the hidden terminal problem, and, to the best of our knowledge, the exposed terminal one is still a pitfall and can deeply affect the performance of multi-hop ad hoc networks based on IEEE802.11 [8].

Different solutions have been proposed in the literature to counteract these shortcomings of the IEEE802.11 standard. In particular, a major effort has been done in the development of an efficient medium access control protocol able to exploit spatial reuse and allow parallel feasible communications [9]. The work on this topic deals primarily with the modification of the numerous timers the IEEE802.11 MAC level [10], [11] with the purpose to achieve a better sharing of the common resource among all the users. Velayutham and Wang [12] proposed a distributed scheduling algorithm for IEEE802.11 networks able to solve the exposed terminal problem and consequently increase the spatial reuse. Recently, some works have appeared aiming at improving the IEEE802.11 MAC layer by exploiting the capture at the physical layer, that is to say the capacity of correctly receiving a transmission even if in presence of interfering communications [13], [14]. Like in the cellular systems, the capture effect is exploited in order to increase the reuse and consequently the bandwidth efficiency of the wireless system [15].

Our work follows this second approach. In details, we propose to enhance the information carried by the CTS packets (and in a more complex approach, also by RTS packets) so that each transmitting/receiving node can have an estimate on the interference it generates on all the other ongoing transmission, and decides to actually transmit/receive if such an interference is “controlled”.

The basic principles of our mechanism are similar to the ones introduced in the Power Controlled Multiple Access (PCMA) proposed by Monks et al. [16]. Both protocols try to exploit the capture effect to increase the spatial reuse, and, like PCMA, IA-MAC is based on a *cooperation principle*, i.e., no station is allowed to transmit/receive if its transmission/reception can destroy ongoing transmissions. On the other hand, our scheme differs from the PCMA in at least two significant aspects: (a) IA-MAC does not implement any

power control, our attention is focused on the access part rather than on the power management, which can be tricky in a distributed environment like the ad hoc one, (b) PCMA uses an additional radio channel in order to transmit a busy tone with information on the interference levels, while in IA-MAC the estimation of the interference is done on the same channel used for data traffic; because of the last reason, IA-MAC seems to be more cost effective and better suited for wireless environments in which the battery consumption is a constraint.

III. IA-MAC BASICS

In the following, IA-MAC is explained by considering that IEEE802.11 DCF is known by the reader, even if a brief description will be given.

In order to reduce the probability of two stations colliding on a receiver because they cannot hear each other (hidden terminal problem), the IEEE802.11 standard use the Request to Send/Clear to Send (RTS/CTS) handshake; a station requiring to transmit a packet first transmits a short control packet called RTS (Request To Send), which includes the source, destination, and the duration of the following frame; the target station replies (if the medium is free) with a control packet called CTS (Clear to Send), which includes the same duration information. All stations receiving either the RTS and/or the CTS, refrain transmission for the given duration.

This mechanism reduces the probability of a collision on the receiver area by a station that is “hidden” from the transmitter (and it does not hear the RTS), since the station hears the CTS and “reserves” the medium as busy until the end of the transmission. The duration information on the RTS also protects the transmitter area from collisions during the ACK (from stations that are out of range of the acknowledging station).

RTS and CTS are used in the IEEE802.11 only if the width of the data packet to be transmitted is greater than a certain threshold. In this paper, we consider to set this threshold to zero, i.e., each transmission requires the RTS/CTS handshake.

IA-MAC behaves exactly as IEEE802.11 apart from the changes in the following. The first subsections explain the basic improvement of IA-MAC to IEEE802.11. In the last subsection, other improvements under investigation are briefly discussed.

A. RTS and CTS

In our proposal, each node uses always the four way handshake, i.e., the RTS (Request To Send) and CTS (Clear To Send) are always sent by the nodes involved in the communication. This is necessary in order to estimate the level of noise and interference.

Moreover, we require a very slight modification of the CTS packet. CTS packet includes the same information of the standard protocol. In addition, we include two new header fields:

- *SINR*: the experienced SINR (Signal to Interference and Noise Ratio) at the time of the reception of the RTS,

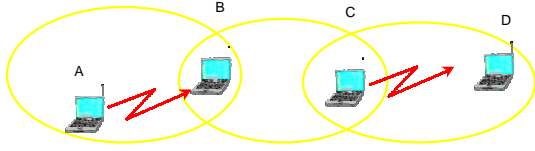


Fig. 1. A is sending a packet to B when C should decide whether to transmit to D.

- P_R : the reception power of the RTS packet.

Since the quantities could be expressed in $dBmW$ (dB milliWatt), the range values can be expressed in 1 byte for each field. These values are used by the node which overhears the CTS to decide whether to set or not the NAV, according to the rules described in the following.

B. Physical and Virtual Channel Sensing

With respect to IEEE802.11, an IA-MAC compliant node does not perform the physical channel sensing phase but always resorts to the Virtual Carrier Sensing. Nevertheless, the protocol belongs to CSMA family, due to the virtual carrier sensing, i.e., the value of the Network Allocation Vector (NAV) determines whether the channel is busy for an oncoming transmission and for the backoff counter. Thus, nodes decrement their backoff counter only when the channel is logically sensed busy and not when a transmission is heard by the node. The backoff counter follows the other rules of the standard protocol (it is decremented after a Distributed InterFrame Space time since the channel was virtually tested free if the last reception has been correct, etc).

C. Network Allocation Vector (NAV)

NAV is always set upon the reception of RTS, as in the standard protocol. Each node which receives the RTS (but the recipient node) sets up its NAV.

NAV is **not** always set on the reception of CTS. If a node receives a CTS from another node, it can compute the impact of a transmission on the other node $SINR$.

For better understanding the protocol, let us consider four nodes (A, B, C, D) in a row (see Figure 1). A is in radio coverage only with B, B with A and C, C with B and D and D only with C. A sent a RTS packet to B and B answered with a CTS. Node C receives a CTS packet from B (in return to a RTS from A), it can estimate how an its own transmission could affect the reception of B.

Let P_B^{RTS} be the power received by B on the RTS sent by A, and let I_B^r be the sum of noise and interference perceived by B. B inserts in its CTS the information of $SINR_B = P_B^{RTS}/I_B^r$ and P_B^{RTS} . C overhears the CTS sent by B. Let P_C^{CTS} be the power C receives on the CTS sent by B. In order to estimate the SINR B would get if C starts transmitting, C considers the channel symmetric, i.e., B would receive a packet from C with the same power P_C^{CTS} . Thus, C estimates that B would perceive a value of SINR equal to:

$$SINR_B^{ext} = \frac{P_B^{RTS}}{I_B^r + P_C^{CTS}} = \frac{P_B^{RTS} SINR_B}{P_B^{RTS} + P_C^{CTS} SINR_B},$$

since $I_B^r = P_B^{RTS}/SINR_B$.

If $SINR_B^{ext}$ is below a certain threshold (γ), C refrains from transmitting by setting its NAV, otherwise it can send its own RTS.

The value of γ should be designed in such a way to take into account that more than one node could increase the experienced interference on the ongoing communications.

D. A Particular Situation

Let us consider the same situation of Figure 1: B transmitted its CTS to A. Suppose C has a packet to be delivered to B. In the standard IEEE802.11, C would refrain the transmission upon reception of the CTS from B. With IA-MAC, C could try to send an RTS to B, unless it has to set the NAV because of the rules described above. In order to avoid such a situation, the nodes should record in their memory the ID of the sender of the CTS they overhear and the transmission duration (which is inserted in the standard CTS packet). In this case, the node could simply set the NAV and reset it when the duration timer expires.

E. Improvements

IA-MAC has better performance with respect to standard IEEE802.11 for two reasons, at least: it permits parallel reliable transmissions which are not allowed by the basic standard, and the backoff timers expire faster, since the physical carrier sensing is disabled. Conversely, IA-MAC uses always RTS/CTS, which is a reasonable assumption if we consider an ad hoc scenario.

In Section IV, an estimation of the performance gain is derived through mathematical analysis.

Future improvements to the protocol we are working on will further increase the spatial reuse and consequently the overall gain. The basic idea is to relax the rule which wants the NAV to be set always upon reception of the RTS. We have found that in some situations the NAV can be unset even if the node has received a RTS. This can be done inserting the information on the interference level in the RTS as well, and exploiting the time diversity among parallel communications, that is to say cases where collision can be avoided because the nodes within the same coverage range are in the same transmitting/receiving state.

IV. AN ANALYTICAL MODEL OF IA-MAC

In order to compare the performance of the standard IEEE802.11 DCF and the proposed IA-MAC, we consider that each transmission of a data packet is preceded by the RTS/CTS exchanging phase.

In this paper, we focus on static ad hoc networks. Note that in most mobility scenarios, nodes do not move for significant distances during a packet transmission time, thus, for capacity analysis, we can assume mobile networks as effectively static.

The status of a wireless link depends on several system and environmental factors that affect sender and receiver ranges. In general, a node transmission range is neither fixed, nor symmetric but it shows time and spatial variability. In this

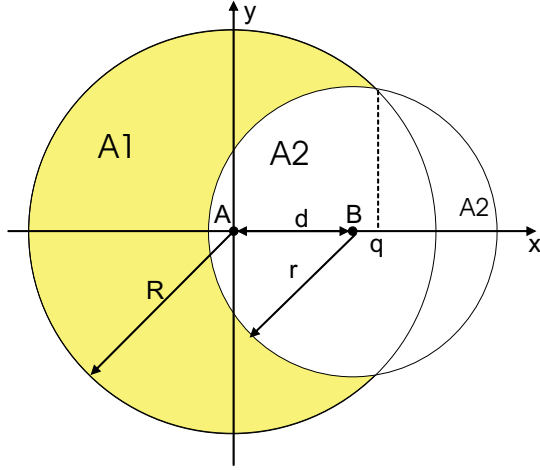


Fig. 2. Coverage and interference areas.

paper, a widely applied optimistic model has been used [17], [18].

Firstly, we introduce the concepts of *coverage range* and *blocking range*, defined respectively as the area where the transmissions of a given node can be correctly detected and the area which is blocked by the transmission of a control packet (RTS/CTS). Secondly, we assume that, given a sample node, both its *coverage range* and *blocking range* can be depicted as a circle of radius R and r respectively, centered in the position of the node itself. The value of R depends on the transmission power level used and on the propagation model adopted, while the value of r depends on the access protocol to be used. It is clear to understand how in the basic IEEE802.11 DCF, the *coverage range* and the *blocking range* are the same, i.e. $R = r$. Finally, we assume uniform transmitted power and uniform propagation law throughout the network, i.e. every node has a *coverage range* with a radius R .

If IA-MAC is used, the *blocking range* of the node sending a CTS is smaller than its *coverage range* ($r < R$) as shown in Figure 2, where two nodes A and B are represented.

Given the nodes A and B in Figure 2, the area of the geometric shape which is the union of the two circumferences centered on the nodes are:

$$\begin{aligned}
 A_{tot}(r, d, R, q) &= A_1(R) + \delta_{A_2}(r, d, R, q) = \\
 &= \pi R^2 + \begin{cases} 0 & d \leq R - r, \\ 2 \int_q^{d+r} \sqrt{r^2 - (x-d)^2} dx + \\ - 2 \int_q^R \sqrt{R^2 - x^2} dx & R - r < d \leq R; \end{cases} \quad (1)
 \end{aligned}$$

where R is the radius of the conference A_1 , $\delta_{A_2}(r, d, R, q)$ is the area included in the circumference A_2 with radius r not included in A_1 , d is the distance between A and B , and q is the abscissa of the intersection points between the two circumferences.

Supposing node A is the RTS sender and node B answers with a CTS, using the standard IEEE802.11 the *blocking ranges* of both nodes are equal, with radius R , and the two corresponding circumferences have their intersection in the

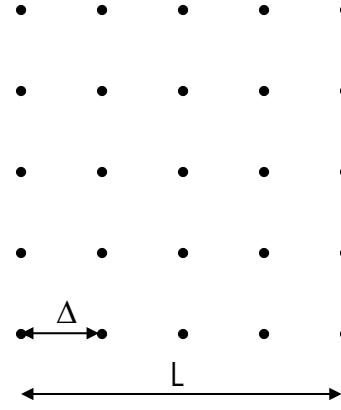


Fig. 3. Grid Network.

abscissa with the same distance from the position of the two nodes ($q = \frac{d}{2}$). Thus, in the standard IEEE802.11 DCF, RTS and CTS block the transmissions of all the nodes within the area given by the union of the two *blocking ranges* centered on the nodes A and B :

$$\begin{aligned}
 A_{std}(d, R) &= A_{tot}(R, d, R, \frac{d}{2}) = \\
 &= \pi R^2 + \frac{d}{2} \sqrt{4R^2 - d^2} + 2R^2 \arctan \left[\frac{d}{\sqrt{4R^2 - d^2}} \right]. \quad (2)
 \end{aligned}$$

On the other hand, if IA-MAC is applied in the same case, the CTS sent by the receiver blocks a smaller number of neighbors than the IEEE802.11 standard one. This is because some nodes that receive only CTS packet do not set NAV according to the rules explained in Section III. The nodes that have to set the NAV, are in the area $A_{IA}(r, d, R) = A_{tot}(r, d, R, q_{IA})$. Inserting the correct value for the intersection point abscissa, $q_{IA} = \frac{d^2 - r^2 + R^2}{2d}$, in Eq. 1 we obtain:

$$\begin{aligned}
 A_{IA}(r, d, R) &= A_{tot}(R, d, R, q_{IA}) = \\
 &= \pi R^2 + \begin{cases} 0 & d \leq R - r, \\ \frac{1}{2} \left[\pi(r^2 - R^2) + a(r, d, R) \right] + \\ + R^2 \arctan \left[\frac{d^2 - r^2 + R^2}{a(r, d, R)} \right] + \\ + r^2 \arctan \left[\frac{d^2 + r^2 - R^2}{a(r, d, R)} \right] & R - r < d \leq R; \end{cases} \quad (3)
 \end{aligned}$$

where $a(r, d, R) = \sqrt{4d^2R^2 - (d^2 - r^2 + R^2)^2}$.

If we consider a mesh (or grid) network with distance Δ between two contiguous nodes (see Figure 3), in the IEEE802.11 standard case the number of simultaneous transmissions in the network is given by:

$$N_{std}(d, R) = \frac{L^2 / \Delta^2}{A_{std}(d, R) / \Delta^2} = \frac{L^2}{A_{std}(d, R)}; \quad (4)$$

where L is the side of the squared network area. Note that the result is not related to Δ , which means it is not related to the number of nodes in the network. This is because the blocked area does not depend on the number of the nodes or on its density. Obviously, the result depends on L because it is a function of the total available area L^2 .

Using IA-MAC in the same network configuration of Figure 3, the number of possible simultaneous transmissions are:

$$N_{IA}(r, d, R) = \frac{L^2/\Delta^2}{A_{IA}(r, d, R)/\Delta^2} = \frac{L^2}{A_{IA}(d, R)}. \quad (5)$$

We define the capacity gain G of the IA-MAC for the network topology considered as the ratio between $N_{IA}(r, d, R)$ and $N_{std}(d, R)$:

$$\begin{aligned} G(r, d, R) &= \frac{N_{IA}(r, d, R)}{N_{std}(d, R)} = \\ &= \begin{cases} \frac{\pi R^2 + b(d, R, R)}{\pi R^2} & d \leq R - r, \\ \frac{\pi R^2 + b(d, R, R)}{\pi R^2 + b(d, R, r)} & R - r < d \leq R; \end{cases} \quad (6) \end{aligned}$$

where: $b(r, d, R) = \frac{1}{2} [\pi(r^2 - R^2) + a(r, d, R)] + R^2 \arctan \left[\frac{d^2 - r^2 + R^2}{a(r, d, R)} \right] + r^2 \arctan \left[\frac{d^2 + r^2 - R^2}{a(r, d, R)} \right]$ (basically: $b(r, d, R) = A_{IA}(r, d, R) - \pi R^2$ when $R - r < d \leq R$).

Note that G is neither function of Δ nor of L . The derived result is generic for a mesh network.

V. PERFORMANCE RESULTS

In this Section some analytical results are shown in order to verify the improvement of the proposed scheme with respect to the basic access scheme.

The performances have been evaluated by considering different value of r (radius from the receiver in which nodes set their NAV upon the reception of a CTS packet). Basically, in the real environment, r is a function of the threshold γ discussed in Section III. For a single fixed r value, we evaluate the capacity gain $G(r, d, R)$ of the network with respect to the distance d between the sender and the receiver nodes.

Figure 4 shows the capacity gain G as a function of d , for different values of r . Since $d \leq R$ (otherwise the receiver does not hear the RTS) and $r \leq R$ (the maximum transmit radius is equal to R), the variables of the function G are normalized to R . Thus, the plots show $G(\frac{r}{R}, \frac{d}{R}, 1)$.

When $\frac{d}{R} \rightarrow 0$, the two circles are overlapping and the gain is very low. When $\frac{d}{R} \rightarrow 1$, IEEE802.11 blocks the largest area, while IA-MAC can show its effectiveness. The smaller r , the greater G , because the blocked area is reduced very much. For a given value of $\frac{r}{R}$ the gain G changes its increasing trend when $\frac{d}{R} = 1 - \frac{r}{R}$, because of the conditions in Eq. 6.

In the best situation, the network capacity obtained with IA-MAC is about 40% greater than IEEE802.11. Greater gains could be achieved if smaller values of $\frac{r}{R}$ are considered. Actually, if values of $\frac{r}{R} < \frac{1}{2}$ are considered, it means that being some nodes closer to the receiver than to the transmitter, they are not blocked and this does not make sense.

Assuming a uniform distribution of the distances between source and destination d in the interval $[0, R]$, the stochastic average of the capacity gain function $G(r, d, R)$ is given by:

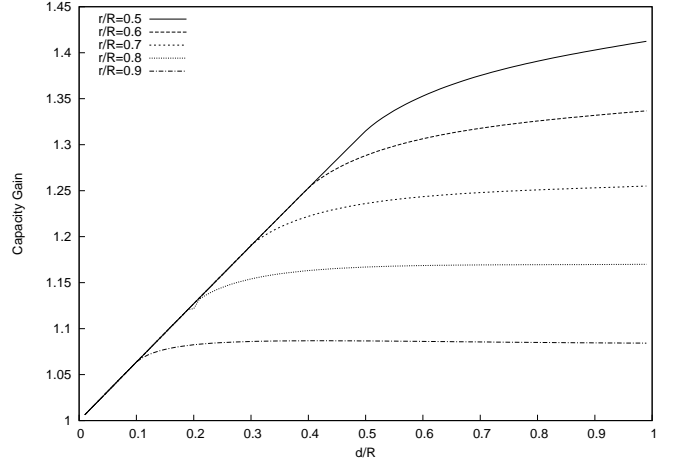


Fig. 4. Capacity Gain vs. sender-receiver distance.

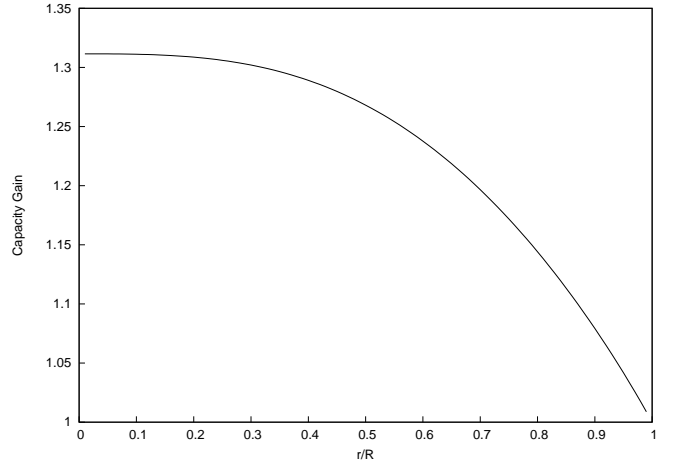


Fig. 5. Stochastic Average Capacity Gain vs. Receiver Transmission Radius.

$$\begin{aligned} \Gamma(r, R) &= \frac{1}{R} \int_0^{R-r} \frac{\pi R^2 + b(d, R, R)}{\pi R^2} dd + \\ &+ \frac{1}{R} \int_{R-r}^R \frac{\pi R^2 + b(d, R, R)}{\pi R^2 + b(d, R, r)} dd. \quad (7) \end{aligned}$$

Figure 5 shows the results of the numerical computation of the integral $\Gamma(\frac{r}{R}, 1)$. The variables are normalized as above.

The performance increases with the normalized blocking radius $\frac{r}{R} = \frac{1}{2}$ (the capture effect is considered perfect) is about 26%. With a more realistic value of $\frac{r}{R} (\frac{r}{R} = \frac{7}{10})$, the increase is about 20%, which definitely shows the effectiveness of the proposal.

VI. CONCLUSION AND RESEARCH IN PROGRESS

In this paper we have presented an effective improvement to IEEE802.11 MAC protocol. The proposed scheme, Interference Aware IA-MAC, achieves a higher spatial reuse in the network by allowing feasible parallel transmissions. To

reach this goal we propose to include some information on the Signal To Interference and Noise Ratio (SINR) and received power levels into CTS header and to slightly modify the actual IEEE802.11 DCF.

Furthermore, we tested the effectiveness of the the proposed protocol by developing an analytical model which is able to give some performance indices in terms of generalized network capacity. Under the discussed assumptions, the increase of performance with respect to the basic IEEE802.11 reaches a maximum gain of 30%.

Some preliminary ideas are given on how to further improve IA-MAC by including information even in RTS packets and by taking into account the transmission durations of the packets.

To test the effectiveness of the protocol and the consistency of our analytical work, IA-MAC will be implemented in QualNet Simulator [19].

VII. ACKNOWLEDGEMENTS

This work has been partially funded by the UC Core program Core01-10091 under the sponsorship of ST Microelectronics. Corresponding Author: D. Maniezzo UCLA Department of Computer Science, BH 3731, 420 Westwood Plaza, Los Angeles, CA 90024, USA, dmaniezzo@ieee.org.

REFERENCES

- [1] <http://grouper.ieee.org/groups/802/11/>
- [2] IEEE Standard 802.11, *Wireless LAN media access control (MAC) and physical layer (PHY) specifications*, 1999.
- [3] D. Maniezzo, M. Cesana, M. Gerla, *IA-MAC: Interference Aware MAC for WLANs*, UCLA Computer Science Department Technical Report 020037.
- [4] K.K. Leung, B. McNair, L.J. Cimini, J.H. Winters, *Outdoor IEEE 802.11 cellular networks: MAC protocol design and performance*, ICC 2002, New York, NY, USA, April 2002.
- [5] P. Gupta, P.R. Kumar, *The capacity of wireless networks*, IEEE Transactions on Information Theory, Volume 46 Issue 2, March 2000.
- [6] Haitao Wu, Shiduan Cheng, Yong Peng, Keping Long, Jian Ma, *Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?*, IEEE Communication Magazine, Volume 39, Issue 6, June 2001.
- [7] Haitao Wu, Shiduan Cheng, Yong Peng, Keping Long, Jian Ma, *IEEE802.11 distributed coordination function (DCF): analysis and enhancement*, ICC 2002, New York, USA, April 2002.
- [8] C.C. Chow, V.C.M. Leung, *Performance of IEEE 802.11 medium access control protocol over a wireless local area network with distributed radio bridges*, WCNC 1999, New Orleans, LA, USA, September 1999.
- [9] J. Deng and Z. Haas, *Dual busy tone multiple access (DBTMA)- a multiple access control scheme for ad hoc networks*, IEEE Transactions on Communications, Volume 50, Issue 6, June 2002.
- [10] V. Bharghavan, *MACAW: a Media Access Protocol for Wireless LAN's*, SIGCOMM 1994, London, UK, September, 1994.
- [11] F. Talucci, M. Gerla, L. Fratta, *MACA-BI (MACA By Invitation)-a receiver oriented access protocol for wireless multihop networks*, PIMRC 1997, Oulu, Finland, September 1997.
- [12] A. Velayutham, H. Wang, *Solution to the Exposed Node Problem of 802.11 in Wireless Ad-Hoc Networks*, <http://www.cs.iastate.edu/vel/research/E-MAC.pdf>.
- [13] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin and J.-P. Sheu, *A Multi-Channel MAC Protocol with Power Control for Multi-Hop Mobile Ad Hoc Networks*, The Computer Journal, vol. 45, 2002.
- [14] J. So, N. Vaidya, *A Multi-channel MAC Protocol for Ad Hoc Wireless Networks*, Dept. of Electrical and Computer Engineering, University of Illinois, USA, Technical Report, January 2003.
- [15] T. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall, New Jersey, 1996.
- [16] J.P. Monks, V. Bharghavan, W.-M.W. Hwu, *A power controlled multiple access protocol for wireless packet networks*, INFOCOM 2001, Anchorage, Alaska, April 2001.
- [17] D. Hong and S. Rappaport, *Traffic models and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures*, IEEE Transactions on Vehicular Technology, Vol. 35, no. 3, August 1986.
- [18] A. B. McDonald and T. F. Znati, *A Path Availability Model for Wireless Ad-Hoc Networks*, WCNC 1999, New Orleans, LA, USA, September 1999.
- [19] <http://www.qualnet.com/>