PERFORMACE MODELING OF OVERLAPPING IBSSs IN THE IEEE 802.11 DCF MODE

H. A. Eladly, T. M. Chen
SMU, Dept of EE
PO Box 750338
Dallas, TX, USA

Abstract *- In this paper, we extend a saturation throughput model for the IEEE 802.11 DCF MAC protocol to the case of multiple overlapping IBSSs (Independent Basic Service Sets) sharing the same frequency of operation. This analytical model is a necessary step to the performance modeling of multi-hop ad hoc networks on top of 802.11 platforms.*

I. INTRODUCTION

The IEEE 802.11 standard is gaining a lot of potential in different indoor and outdoor applications. It is being highly considered as the solution for hot spots in next generation wireless networks. Moreover, it is the primer solution for data networks for indoor residential and commercial applications. The introduction of quality of service in 802.11e is giving it even more attention for wireless voice over IP applications. Such potential has made 802.11 a dominant technology in today's WLAN market.

The IEEE 802.11 is considered to be the default platform to implement multi hop mobile ad hoc networks and is already used in almost all of the test beds and simulations for wireless ad hoc network research.

Despite the wide use of 802.11 in multi hop ad hoc networks, various studies have observed degradation in performance when 802.11 is used in multi hop rather than a single hop network [2][3][4][5][6]. Although it can support some kind of ad hoc network architecture, which only means a distributed network as opposed to a centralized one, it is not intended to support the wireless mobile ad hoc network, in which multi hop connectivity is one of its most prominent features. It may work well in small enterprises or homes where a single hop network may exist but not in a large-scale network where multi hopping is a necessity.

In this paper, we are going to model and analyze the performance of the current IEEE 802.11 ad hoc mode in the case of a multi hop network. Such a model is important to understand the observed negative behavior of 802.11. It is also an important first step to lay out a general model for a multi hop ad hoc network using the 802.11 protocol.

The paper is organized as follows, Section II is an overview of the current IEEE 802.11 DCF scheme, the main scheme used to support the ad hoc mode of operation. In section III, we present multi hop modeling and analysis. In section IV we validate our model and carry out a performance analysis. And finally, we conclude our work in section V.

II. THE IEEE 802.11 DCF SCHEME

In the 802.11 protocol, the fundamental mechanism to access the medium is called distributed coordination function (DCF). This is a random access scheme, based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Retransmission of collided packets is managed according to binary exponential backoff rules. The standard also defines an optional point coordination function (PCF), which is a centralized MAC protocol able to support collision free and time bounded services. In this paper, we will focus on the DCF scheme as it is the main scheme used to construct an ad hoc network[1].

DCF describes two techniques to employ for packet transmission. The default scheme is a two-way handshaking technique called the basic access mechanism. This mechanism is characterized by the immediate transmission of a positive acknowledgement (ACK) by the destination station, upon successful reception of a packet transmitted by the sender station. Explicit transmission of an ACK is required since, in the wireless medium, a transmitter cannot determine if a packet is successfully received by listening to its own transmission.

In addition to the basic access, an optional four way handshaking technique, known as request-to-send / clear-to-send (RTS/CTS) mechanism has been standardized. Before transmitting a packet, a station operating in RTS/CTS mode "reserves" the channel by sending a special Request-To-Send short frame. The destination station acknowledges the receipt of an RTS frame by sending back a Clear-To-Send frame, after which normal packet transmission and ACK response occurs. Since collision may occur only on the RTS frame, and it is detected by the lack of a CTS response, the RTS/CTS mechanism allows increasing the system performance by reducing the duration of a collision when long messages are transmitted. As an important side effect, the RTS/CTS scheme designed in the 802.11 protocol is suited to combat the so-called problem of hidden terminals, which occurs when pairs of mobile stations result to be unable to hear each other. In the presence of two overlapping IBSSs, the number of hidden nodes will significantly increase in the system. Consequently, we will perform our investigation in the case of the RTS/CTS mechanism.

There have been various attempts to model and analyze the saturation throughput of the IEEE 802.11 DCF protocol. A model for analyzing the binary exponential backoff mechanism of 802.11 DCF was introduced in [7].

Other models have used simplified backoff rule assumptions such as in [8]. Another model for predicting the saturation throughput of 802.11 DCF in broadcast networks is presented in [9]. The model presented in [7] represents a model with minimal simplifying assumptions and it captures most of the details of the 802.11 ad hoc single hop mode.

In the next section we choose to extend the model in [7] to the case of multiple overlapping IBSSs operating on the same frequency channel.

III. IEEE 802.11 Multi Hop Model

We refer to [7] for the details of the saturation throughput calculation for the IEEE 802.11 single hop DCF scheme. The core contribution of this paper is the calculation of the saturation throughput per IBSS in a network of two overlapping IBSSs. Each IBSS consists of a fixed number $(n+1)$ of contending stations. Both IBSSs share one station that belongs to the overlap region (see Fig. 1 for an example topology). We operate in saturation conditions, i.e., each station always has a packet available for transmission.

Our analysis is performed in two stages. First we obtain the stationary probability τ that the station transmits a packet in a generic slot time. Then we express the throughput normalized with respect to the channel capacity as a function of the computed value of τ.

A. Packet Transmission Probability

Let τ be the probability that a station (except the station in overlap zone) transmits a packet in a generic slot time, τ_o be the probability that the station belonging to the overlap zone transmits a packet in a generic slot time. Then bianchi's solution for the packet transmission probability in [7] can be applied directly to our case:

$$\tau = \frac{2(1-2P)}{(1-2P)(W+1)+(PW)(1-(2P)^m)} \tag{1}$$

$$\tau_o = \frac{2(1-2P_o)}{(1-2P_o)(W+1)+(P_oW)(1-(2P_o)^m)} \tag{2}$$

where P represents the probability that a transmitted packet from any node (except the overlap node) encounters a collision and P_O represents the probability that a transmitted packet from the overlap node encounters a collision. W is the minimum contention Window and m is the backoff stage such that $CWmax = 2^m W$.

Also P and P_o can be expressed as follows :

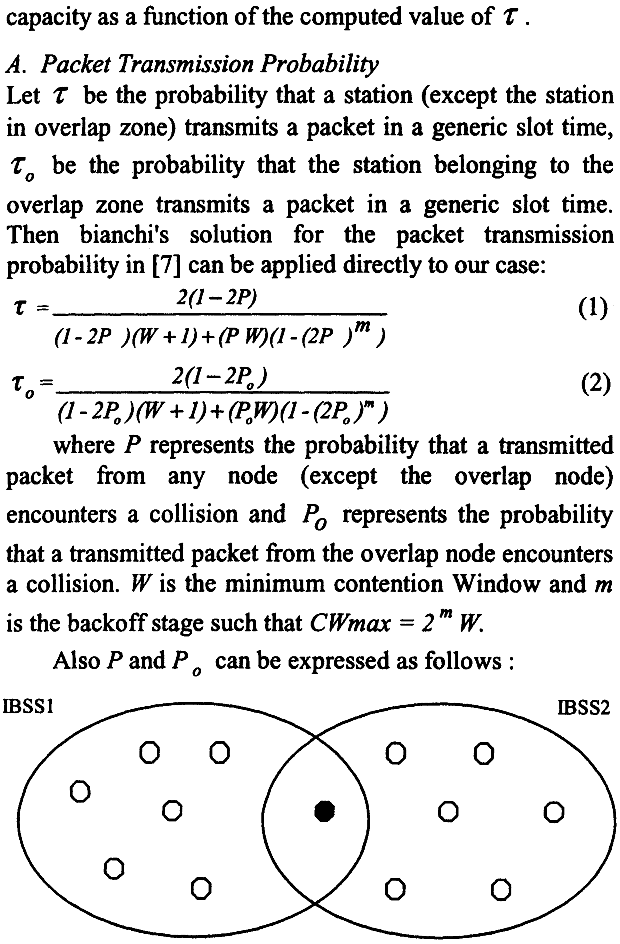

Fig. 1 Overlapping IBSSs in IEEE 802.11

$$P = [1-(1-\tau)^{n-1}(1-\tau_o)]*[1-P(0)] + [1-(1-\tau)^{n-1}(1-\tau)^n(1-\tau_o)]*[P(0)] \tag{3}$$

$$P_o = 1-(1-\tau)^{2n} \tag{4}$$

Where $P[0]$ is the probability that the destination of the packet is the overlap node. If the destinations are sampled from a uniform distribution we can use $P[0] = 1/n$.

Equation (1) is a continuous and monotonically decreasing function of P. Equation (3) yields a continuous and monotonically increasing function of P. Fig. 2 shows the numerical solution of both equations for varying values of W, the minimum contention window. For each value of W, the solution yields a unique value for the packet transmission probability τ which we will utilize to compute the saturation throughput in the next subsection.

B. Throughput calculation

Let S be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. Let P_{tr} be the probability that there is at least one transmission in the considered slot time and P_s be the probability that a transmission occurring in the IBSS is successful. P_s is given by the probability that exactly one station transmits on the IBSS, conditioned on the fact that at least one station transmits. Therefore,

$$P_{tr} = 1-(1-\tau)^n(1-\tau_O) \tag{5}$$

$$P_s = \frac{\gamma_1\tau_O(1-\tau)^n + \tau n(1-\tau)^{n-1}(1-\tau_O)}{P_{tr}} \tag{6}$$

Where γ_1 is the probability that the overlap zone station transmits in $IBSS_1$ and $(1-\gamma_1)$ is the probability that the overlap zone station transmits in $IBSS_2$. We can also express P_l the probability that a transmission occurring in the IBSS is lost as

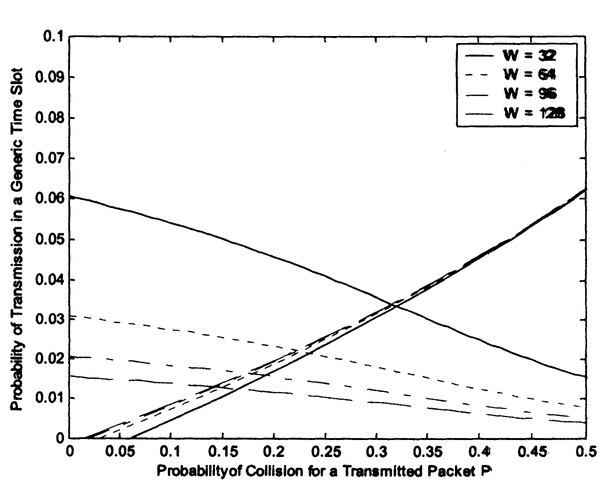

Fig. 2 Numerical solution of p and τ

$$P_l = \frac{\gamma_1 \tau_0 (1-\tau)^n + n\tau(1-\tau)^{n-1}(1-\tau_0)}{P_{tr}} \quad (7)$$

Also P_C the probability that a transmission occurring in the IBSS collides can be expressed as

$$P_C = (1 - P_s - P_l) \quad (8)$$

We can now express S per IBSS as the ratio

$$S = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]}$$

Being $E[P]$ the average packet payload size, the average amount of payload information successfully transmitted in a slot time is $P_{tr} P_s E[P]$, since a successful transmission occurs in a slot time with probability $P_{tr} P_s$. The average length of a slot time is obtained considering that, with probability $1 - P_{tr}$, the slot time is empty; with probability $P_{tr} P_s$ it contains a successful transmission, with probability $P_{tr} P_c$ it contains a collision and with $P_{tr} P_l$ it contains a lost packet due to hidden nodes in the other IBSS. Therefore S per IBSS becomes

$$S = \frac{P_S P_{tr} E[P]}{(1-P_{tr})\sigma + P_{tr} P_S T_S + P_{tr} P_C T_C + P_{tr} P_l T_l} \quad (9)$$

Where,

$$T_s^{RTS} = RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta + ACK + DIFS + \delta$$

$$T_l^{RTS} = T_s^{RTS}$$

$$T_c^{RTS} = RTS + DIFS + \delta$$

T_s^{RTS} is the average time the channel is sensed busy due to a successful transmission; T_l^{RTS} is the average time the channel is sensed busy because of a lost packet; T_c^{RTS} is the average time the channel is sensed busy due to a collision. δ accounts for the propagation delay, RTS for the length of the RTS packet, CTS for the CTS packet, H for the header length.

The computed values of τ and τ_0 in the previous subsection can now be used to calculate S. Fig. 3 shows the effect of varying the number of stations on the case of overlapping IBSSs as well as a single IBSS on the saturation throughput value. We notice that the saturation throughput value in the case of overlapping IBSSs is significantly lower than that in the case of a single IBSS when the number of stations is low. The difference in the throughput value decreases as the number of stations increase. This is attributed to the fact that as the number of stations increase $P[0]$ gets very small and therefore the term responsible for the lost packets due to overlapping has a negligible effect on the degradation of throughput value.

IV. Model Validation And Performance Evaluation

In order to validate our model, we have a developed a java-based simulator that follows most of the details of the IEEE 802.11 DCF protocol. We carried out an experiment in which we observe the saturation throughput with respect to varying, number of stations per IBSS. Simulation results have validated our analytical model as shown in Fig. 3. The values of the parameters used to calculate the simulation and analytical numerical results are summarized in Table I.

The value of the packet transmission probability is sensitive to the number of stations per IBSS. This is shown in Fig. 4 and Fig.5 in which the value of τ decreases as we increase the number of stations per IBSS. This is an expected result because when the number of stations increases, there is more contention per IBSS and the probability that a station transmits a packet in a generic time slot should decrease.

In the case of having only one IBSS with $(n+1)$ stations i.e. no overlap with any other IBSS, let P' be the probability that a transmitted packet from a node encounters a collision in this single IBSS. Therefore,

$$P' = 1 - (1-\tau)^n \quad (10)$$

From (3),(4) & (10)

$$\frac{P_o}{P'} = 1 + (1-\tau)^n \quad (11)$$

Also,

$$\frac{P}{P'} = \frac{1}{(1-(1-\tau)^n)}[1-(1-\tau)^{2n} * (\frac{n-1+(1-\tau)^n}{n(1-\tau)^{n+1}}) * (\frac{W + W(1-(1-\tau)^{2n}\sum_{i=0}^{m-1}(2(1-(1-\tau)^{2n}))^i - 1)}{W + W(1-(1-\tau)^{2n}\sum_{i=0}^{m-1}(2(1-(1-\tau)^{2n}))^i + 1})] \quad (12)$$

$\frac{P_o}{P'}$ and $\frac{P}{P'}$ can be used to evaluate the effect of overlap of IBSSs operating on the same frequency channel on the probability of collision.

TABLE I
ANALYTICAL AND SIMULATION PARAMETERS

Parameter	Value
Packet Payload	2400 bits
ACK	112 bits
RTS	160 bits
CTS	112 bits
Channel bit rate	1Mbps
SIFS	28 micro seconds
DIFS	128 micro seconds
ACK-Timeout	300 micro seconds
CTS-Timeout	300 micro seconds

Fig. 6 shows that the probability of collision in the case of overlapping IBSSs is always greater than the case of a single IBSS which simply means that overlapping of IBSSs raises the probability of a packet encountering a collision than the single IBSS case.

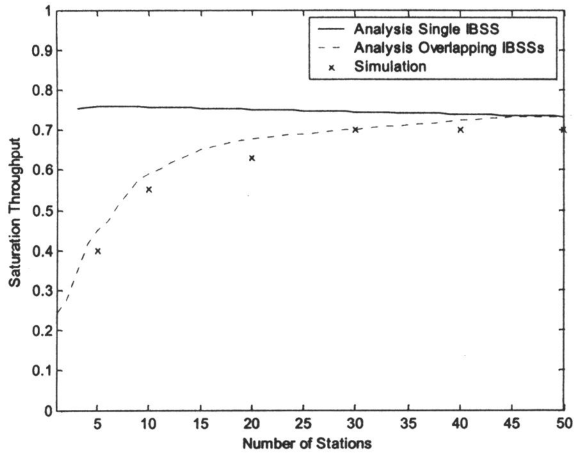

Fig. 3 Validation of Analytical model

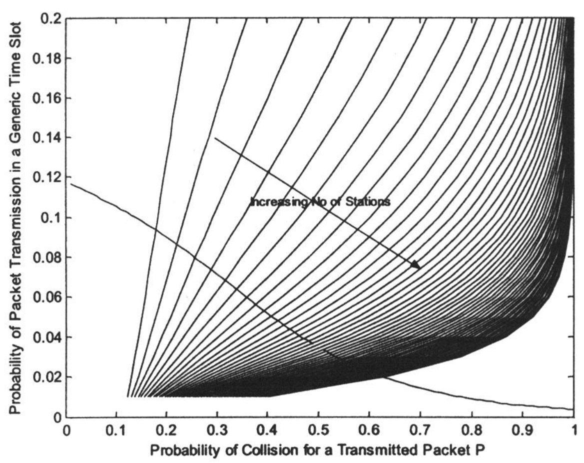

Fig. 4 Solving for τ as the number of stations increase

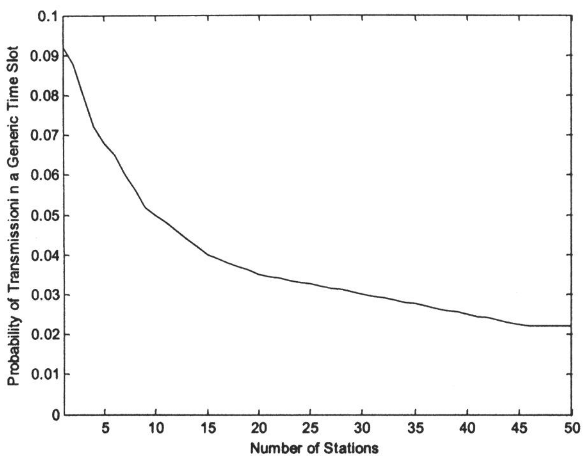

Fig. 5 τ versus the number of stations per IBSS

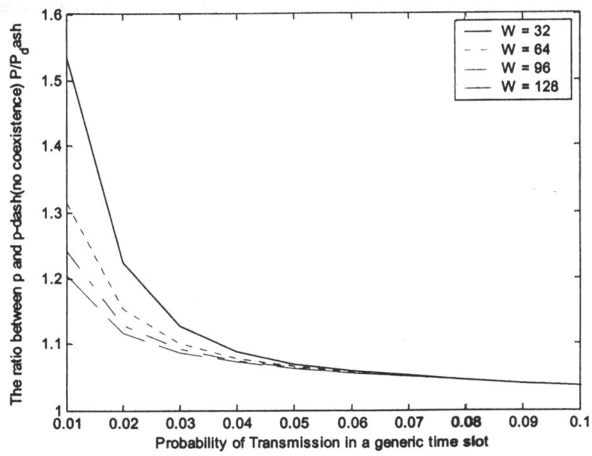

Fig. 6 The effect of overlap on the collision probability

V. Conclusion

In this paper, we have presented an analytical model to compute the saturation throughput performance of the IEEE 802.11 DCF in the case of a multi hop network. Simulation results have validated our model in which a noticeable degradation in performance is observed in the multi hop case. As the number of nodes in the overlap zone increase with respect to the number of nodes per IBSS, the performance is worse. Such degradation in performance is due to the undisciplined interaction with nodes in overlap zones.

VI. References

[1] IEEE Std. 802.11,"Wireless LAN Media Access Control (MAC) and Physical Layer (PHY) Specifications," 1999.

[2] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC Protocol Work Well In Multihop Wireless Ad hoc Networks?," *IEEE Communications Magazine*, June 2001.

[3] M. Gerla, K. Tang, and R. Bagrodia, "TCP Performance In Wireless Multihop Networks," *IEEE WMCSA '99*, New Orleans, LA, Feb. 1999.

[4] K. Tang and M. Gerla, "Fair Sharing Of MAC Under TCP In Wireless Ad hoc Networks," *Proc. IEEE MMT '99*, Venice, Italy, Oct. 1999.

[5] B. Bensaou, Y. Wang, and C. C. Ko, "Fair Media Access In 802.11 Based Wireless Ad hoc Networks," *Proc. Mobihoc 2000*, Boston, MA, Aug. 2000.

[6] N. H. Vaidya, P. Bahl, and S. Gupta, "Distributed Fair Scheduling In A Wireless LAN," *Proc. Mobcom 2000*, Boston, MA, Aug. 2000.

[7] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function", IEEE JSAC, Vol.18, No.3,Mar 2000, pp 535-47.

[8] H. S. Chhaya and S. Gupta, "Performance modeling of asynchronous data transfer methods of IEEE 802.11 MAC protocol," *Wireless Net-works*, vol. 3, pp. 217–234, 1997.

[9] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit", IEEE/ACM Trans on Networking, Vol.8, No.6, Dec 2000, pp 785-799.