IEEE 802.11b Distributed Coordination Function with Capture under Near/Far Effect

Zoran Hadzi-Velkov[1], Boris Spasenovski[2]

Abstract - **In this paper, we examined the influence of the capture effect over the IEEE 802.11b DCF. We assumed only the deterministic attenuation of received signals with the distance between the stations and the AP within a single BSS. Using Monte-Carlo simulations, we estimated the frame capture probabilities, and then analytically evaluated network capacity in both Basic and RTS/CTS operating modes.**

Keywords - **IEEE 802.11 DCF, frame capture, near/far effect, capture probability, saturation throughput**

I. Introduction

In classical analysis of random access protocols, it is assumed that all frames involved in collision are destroyed. Although this is reasonable when the frames are received with nearly equal powers, this is somewhat pessimistic assumption in mobile radio environment. Typically the signal received at the base station (access point) from a given station will be subject to attenuation, and possibly multipath fading. Due to the *capture effect*, when frames from different stations collide, it may still be possible to successfully decode the single frame with the strongest received signal strength [2-5].

In this paper, we analytically analyze the impact of the capture effect over the capacity of IEEE 802.11b Wireless LANs [1] in radio channel. The differences in signal strengths yielding to the capture effect occur only due to signal attenuation, which is function of the base-to-station distance (near/far effect).

II. IEEE 802.11b Basic Service Set

The IEEE 802.11 WLANs [1] are designed primarily for indoor communication where stations access a common Access Point (AP), or communicate directly among each other within a limited coverage region called the *Basic Service Set* (BSS). We assume only the first operating mode, where the AP is located in the center of the BSS (Figure 1), and has a coverage area of a normalized unit radius. The mobile stations are uniformly spatially distributed around the AP, so that the PDF of their distances to the AP follow the uniform spatial distribution defined as:

$$h(r) = 2r, \quad 0 < r \le 1 . \qquad (1)$$

[1]Zoran Hadzi-Velkov is with the Faculty of Electrical Engineering, Karpos 2 b.b., 1000 Skopje, Macedonia
[2]Boris Spasenovski is with the Faculty of Electrical Engineering, Karpos 2 b.b., 1000 Skopje, Macedonia

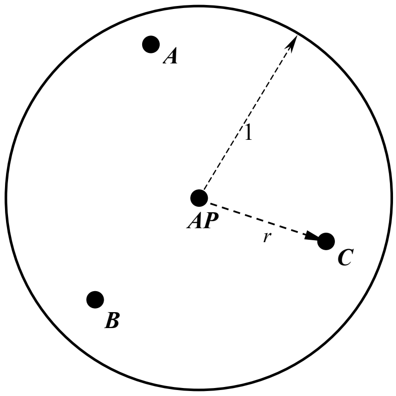


Fig. 1. A single IEEE 802.11 cell with an AP in its center

The asynchronous services in the IEEE 802.11 WLAN are provided by the *Distributed Coordination Function* (DCF). The DCF is based on the CSMA/CA protocol, enhanced by the features of virtual carrier sensing and the announcements of duration of upcoming transmission. *Random backoff mechanism* is initiated in case of collision of multiple simultaneous transmissions. In order to decrease the probability of collision due to possible *hidden station* occurrence, the *Basic access* scheme is extended by the procedure of *RTS/CTS "handshake"*, which is executed prior to the beginning of frame transmission. It is implemented by the exchange of RTS and CTS control frames between the transmitter and receiver. Apart to its known contribution to the robustness of network performance in presence of hidden station effect, we established the RTS/CTS "handshake" has considerable influence with respect to the stability under the capture effect as well.

For the purposes of our analysis, we relied on the results in [7], where the peak (saturation) throughput $S_{\max}$ of the IEEE 802.11 DCF in ideal channel conditions (no capture) is expressed as

$$S_{\max} = \frac{P_{suc} P_{tr} \cdot E[L]}{(1-P_{tr})\sigma + P_{tr} P_{suc} T_s + P_{tr}(1-P_{suc}) T_c} \qquad (2)$$

E[L] is the average frame payload size, although in order to establish upper performance limit, we assumed all generated packets are fixed and maximized so that E[L] = L = 2312 octets. P_{tr} is the probability of at least one transmission in the observed time slot, P_{suc} is the probability of a successful transmission assuming at least one station is transmitting, and σ is duration of an empty slot time. T_s is the average time the channel is sensed busy by each station because of a successful transmission, and T_c is the average time the channel is sensed busy during a collision. The values of T_s and T_c differ depending on the network access mode and additional network operating parameters (Table I).

TABLE I
RELEVANT NETWORK PARAMETERS

Parameter	Default
Channel Rate	1 Mbps
PHY Preamble	144 symbols
PHY Header	48 symbols
MAC header	34 octets
ACK	14 octets + $PHY_{pre/hdr}$
RTS	20 octets + $PHY_{pre/hdr}$
CTS	14 octets + $PHY_{pre/hdr}$
SIFS	20 μs
DIFS	50 μs
Slot_Time σ	20 μs
Retry limit *m*	5
Initial contention window *W*	8
T_s^{basic}	19334 bits
T_c^{basic}	19010 bits
$T_s^{rts/cts}$	20030 bits
$T_c^{rts/cts}$	402 bits

When network is saturated with traffic, probability τ depends on number of contending stations *N*, initial contention window *W*, and maximal number of retransmissions *m* before a frame is discarded from transmit queue during the binary exponential backoff procedure. Given $W = 8$ and $m = 5$, we estimated probability τ in function of collision size *N* with our own C simulator, as depicted in Figure 2.

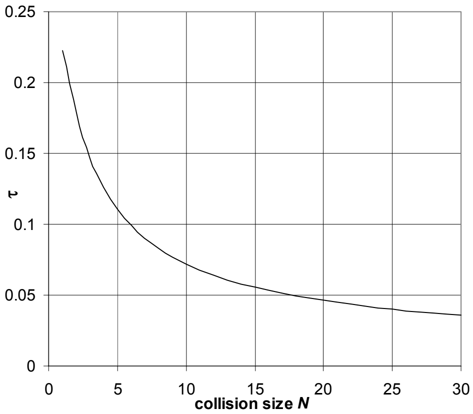


Fig. 2. Transmission probability τ of each station in a random slot time estimated by simulation

III. CAPTURE MODEL AND NETWORK CAPACITY

Our capture model only takes the deterministic power loss of signals into account. The path-loss exponent for indoor channels in the BSS picocell is typically taken equal to 4. Thus, the normalized received signal power P_i between station *i* and the AP at mutual distance r_i is:

$$P_i = \frac{1}{r_i^4}, \quad 0 < r_i \le 1, \tag{3}$$

Since r_i is random variable distributed according to (1), one can derive the PDF of each of the normalized received signal power P_i as follows:

$$f_{P_i}(p_i) = \frac{1}{2} p_i^{-3/2}, \quad p_i \ge 1 \tag{4}$$

During simultaneous transmission of multiple stations beginning in a same time slot σ, the AP captures a frame if the power of detected frame P_u sufficiently exceeds the joint power (incoherent addition) of *n* interfering contenders $P_{int} = \sum_{k=1}^{n} P_k$ by a certain threshold factor for the duration of a certain time period (over which instantaneous power is assumed to remain approximately constant). Thus, the capture probability is the probability of signal-to-interference ratio $\gamma = P_u / P_{int}$ exceeding the product $z_0 \cdot g(S_f)$, where z_0 is known as the capture ratio, and $g(S_f)$ is the processing gain of the correlation receiver. Actually, the processing gain introduces a reduction of interference power by factor $g(S_f)$, which is inversely proportional to the spreading factor S_f. We assume that a receiver determines weather a possible successful capture has occurred during the transmission of the preamble/header part of the frame ($PHY_{pre/hdr}$), which is transmitted using the DSSS modulation of a fixed 11-chip Barker spreading sequence (i.e. $S_f = 11$). Given rectangular-shaped chips, $g(S_f)$ can be expressed as in [6]:

$$g(S_f) = \frac{2}{3 \cdot S_f} \; . \tag{5}$$

Assuming *n* interfering frames, the capture probability can be expressed as in [4]:

$$P_{cap}(zo \cdot g(S_f) \mid n) = \Pr ob(\gamma > zo \cdot g(S_f) \mid n)$$
$$= \int_0^\infty dp_1 f_{P_1}(p_1) \cdots \int_0^\infty dp_n f_{P_n}(p_n) \int_{z_0 \cdot g(S_f) \cdot (p_1 + \cdots + p_n)}^\infty f_{P_u}(p_u) dp_u \,, \tag{6}$$

where $f_{Pu}, f_{P1}, \ldots, f_{Pn}$ are the power PDFs of the useful signal and of each of the *n* interferers, respectively, under assumption of their mutual statistical independence.

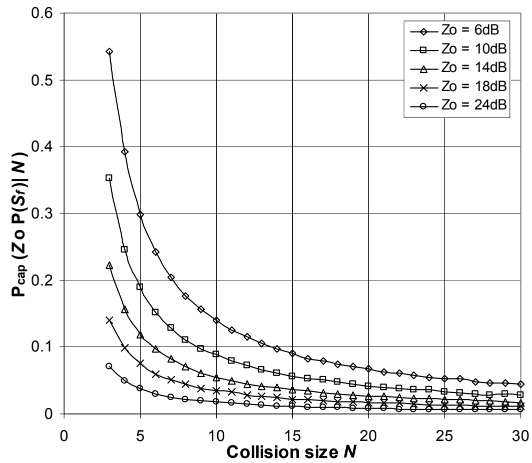


Fig. 3. Conditional capture probability for different capture ratios

It is difficult to obtain a closed-form expression of (6) for arbitrary large n. Therefore, we use a Monte-Carlo simulations to obtain the values of (6) for each separate n. Fig. 3 depicts the conditional capture probability P_{cap} ($z_0 \cdot g(S_f)| n$) in function of total number of contending stations N (the single useful plus the n interfering frames, $N = 1 + n$), parameterized over several values of the capture ration z_0 that are of practical interest.

Given total of N stations contending for the channel in a same time slot, the probabilities P_{tr} and P_{suc} can be expressed through the probability τ of station transmitting in a randomly chosen slot time, i.e.

$$P_{tr} = 1 - (1-\tau)^N , \tag{7}$$

and

$$P_{suc} = \frac{N\tau(1-\tau)^{N-1} + P_{cap}}{P_{tr}} . \tag{8}$$

Equation (8) indicates that, given at least one station is transmitting, probability of successful transmission P_{suc} is formed by adding the capture probability P_{cap} to the probability of transmission of exactly one station $N\tau(1-\tau)^{N-1}$.

Probability τ also impacts the overall probability of frame capture P_{cap} as the following:

$$P_{cap} = \sum_{i=1}^{N-1} R_i \cdot P_{cap}(z_o \cdot g(S_f) | i) , \tag{9}$$

where R_i is the probability of i interfering frames being generated in the observed time slot,

$$R_i = \binom{N}{i+1} \tau^{i+1} (1-\tau)^{N-i-1} . \tag{10}$$

In Figure 4, the capture probability P_{cap} is estimated according to (9) in function of N by using probabilities τ from Fig. 2. It is evident that the capture probability P_{cap} rises with the decrease of the capture ratio z_0 and the increase of the number of contending stations N.

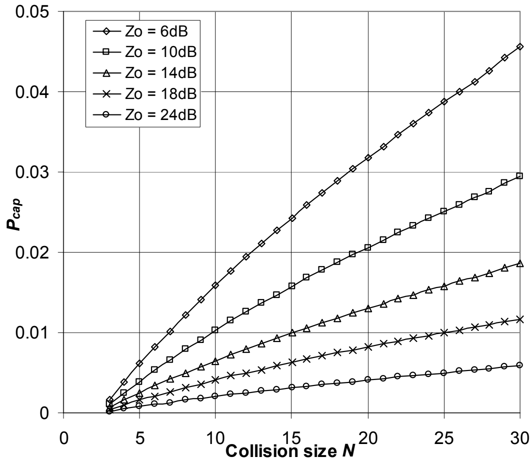
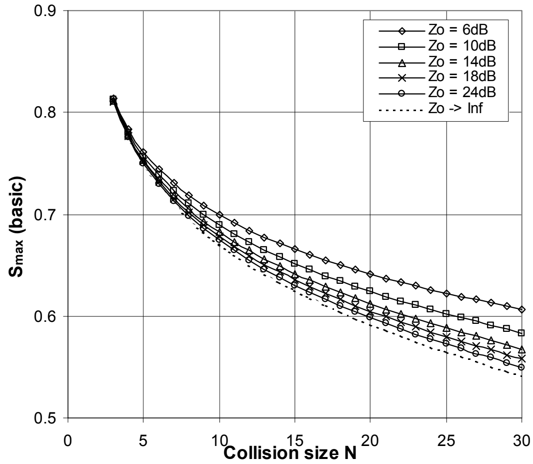
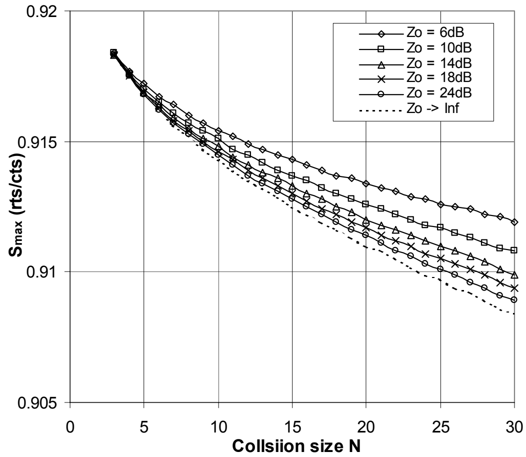


Fig. 4. P_{cap} increases with number of contending stations N

The theoretical saturation throughput under capture in Basic and RTS/CTS "handshake" access modes is calculated according to (2), and displayed in Fig. 5. The graphs refer to an IEEE 802.11 network at 1 Mbps, while corresponding system parameters must be used according to IEEE 802.11b standard to obtain curves for 2, 5.5, and 11 Mbps. This is also the case for all subsequent results.



(a) Basic access



(b) RTS/CTS access

Fig. 5. DCF theoretical saturation throughput exposed to the capture effect

If Basic access scheme is utilized (Fig. 5a), it is obvious that presence of capture effect generates certain throughput improvement as z_0 decreases. For example, given z_0 = 6 dB and 10 stations within a single BSA, the peak theoretical throughput is estimated to 70%, as opposed to 67 % in the absence of capture ($z_o \rightarrow \infty$). Conversely, the use of the RTS/CTS "handshake" access scheme (Fig. 5b) contributes significantly to the robustness of the IEEE 802.11 network under capture. Conversely, the influence of our capture model over the saturation throughput in RTS/CTS "handshake" operating mode can be disregarded. The value of the capture ratio z_0 to apply in order to determine the actual throughput increase depends on the receiver design. In addition, the impact of the capture effect is negligible if the network is not congested.

IV. Conclusions

In this paper, we provided an analytical analysis of the influence of capture effect over the capacity of IEEE 802.11b Distributed Coordination Function. We assumed only the deterministic attenuation of the received signals with the distance between the uniformly spatially distributed stations and the AP located in the center of the BSS (i.e. near-far effect). Using Monte-Carlo simulations, we estimated the frame capture probabilities in function of the number of contending stations. Then, we used these results to produce the expressions for the saturation throughput within a single cell of the IEEE 802.11 WLAN exposed to the capture effect.

Finally, it is important to point out that multipath fading (i.e. Rayleigh and/or Rician faded channels) in not considered. Its influence is expected to produce additional influence over the capacity of IEEE 802.11 WLANs. Refer to [8] and [9] for details. This issue will be further addressed elsewhere.

References

[1] IEEE Standard for Wireless LAN Medium Access Control and Physical Layer Specifications, IEEE 802.11b, Nov. 1999.

[2] C. Arnbak and W. van Blitterswijk, Capacity of Slotted Aloha in Rayleigh-fading channels, IEEE J. Select. Areas Commun., Vol. SAC-5, pp. 261-269, Feb. 1987.

[3] C.T.Lau and C.Leung, Capture Models for Mobile Packet Radio Networks, IEEE Trans. on Commun., Vol. COM-40, pp. 917-925, May 1992.

[4] M. Zorzi and R.R. Rao, Capture and Retransmission Control in Mobile Radio, IEEE J. Select Areas Commun., Vol. 12, No. 8, pp.1289 – 1298, Oct. 1994.

[5] A. Zahedi and K. Pahlavan, Natural Hidden Terminal and the Performance of the Wireless LANs, Proc. IEEE 6th Int. Conf. on Univ. Pers. Comm, pp. 929-933, 1997.

[6] J. Perez-Romero, L.G. Alonso and R. Agusti, Average Block Error Probability in reverse Link of a Packet DS/CDMA System under Rayleigh Fading Channel Conditions, IEEE Comm. Letters, Vol. 4, No. 4, pp. 116-118, April 2000.

[7] J. Bianchi, Performance Analysis of IEEE 802.11 Distributed Coordination Function, IEEE J. Select. Areas Commun., Vol. 18, No. 3, pp. 535–547, March 2000.

[8] Z. Hadzi-Velkov and B. Spasenovski, Capture Effect in IEEE 802.11 Wireless LANs, Proc. IEEE ICWLHN 2001, pp. 164-173, Singapore, December 5-7, 2001.

[9] Z. Hadzi-Velkov and B. Spasenovski, IEEE 802.11 DCF with Capture over Rician-Fading channel, Proc. Third IEEE Workshop on WLANs, Boston, USA, September 27-28, 2001