Physical Carrier Sensing Outage in Single Hop IEEE 802.11 Ad Hoc Networks with Slowly Moving Stations

Jin Sheng and Kenneth S. Vastola
Electrical, Computer and Systems Engineering Department
Rensselaer Polytechnic Institute
Troy, New York

***Abstract*—Physical Carrier Sensing plays a crucial role in the effectiveness of CSMA-based MAC protocols, yet its properties and impact on the system performance under slow fading channel have not been well understood. We demonstrate that carrier sensing can be highly unreliable even within the "carrier sensing range" and the channel is largely stable during a transmission between slowly moving mobile stations. Then we formulate the carrier sensing outage probability between competing mobile stations and propose a model to estimate the frame error rate and normalized throughput of a saturated IEEE 802.11 DCF single-hop ad-hoc network. Our model is validated via extensive simulations using Qualnet. The numerical and simulation results reveal substantial degradation in system performance with a small amount of carrier sensing outage.**

I. Introduction

After Bianchi's seminal work [1] on the saturated performance of IEEE 802.11 WLAN in a perfect channel, the model has been repeatedly amended by considering realistic issues such as finite retry limit [2], unreliable frame delivery due to fading channel [3] [4], hidden terminals [5] and non-saturated MAC queue [6]. It was also linearized and incorporated into a scalable model for Multihop Ad Hoc networks [7], so that the saturated throughput of each individual station in a random topology can be obtained analytically rather than via rounds and rounds of time-consuming simulations. Nonetheless, all above-mentioned work assumes perfect carrier sensing, i.e. within a specific range a transmission is detected with 100% accuracy, and beyond this range, it is not sensed at all.

The perfect effectiveness of physical carrier sensing within the "carrier sensing range" has been assumed in many related topics such as Physical Carrier Sensing (PCS) control. To exploit the *spatial diversity* in a CSMA-based Multihop Ad Hoc network, one may adjust the transmit power of each station and/or their carrier sensing thresholds. An analytical model on the optimal ratio between transmit power and carrier sensing threshold was proposed in [8], which was supplemented by Yang et al. [9] who considered MAC overhead. The aggregate throughput with multiple data rates was studied recently in [10] and [11], and algorithms were proposed to jointly adjust both power and rate [10], or even optimize system performance over carrier sensing threshold, transmit power and data rate all together [11].

Unfortunately, *perfect* carrier sensing rarely exists in reality. First of all, it is usually implemented as an energy detector with minimal overhead, so that even if the received power is above a threshold, we may expect some false negatives in detection. Its impact on performance was analyzed under non-persistent [12], 1-persistent [13] and *p*-persistent CSMA [14]. Even with a perfect detector, there is a more subtle yet more detrimental factor, the slow fading channel, that guarantees an unwanted property of carrier sensing: mobile stations well within the *carrier sensing range* may not detect all carriers, and stations beyond the range may detect them occasionally. In this paper, we generalize several assumptions and formulate the probability of carrier sensing outage under slow Rayleigh fading channel. Moreover, we extend Bianchi's model [1] to analyze the impact of *imperfect* carrier sensing on 802.11 DCF basic access scheme.

The paper is organized as follows. We describe the slow fading channel and justify its connection with physical carrier sensing analytically in Section II. In Section III, we make several key assumptions and formulate the saturated throughput of a homogenous single hop wireless ad hoc network with *imperfect* carrier sensing. The model validation and numerical results are provided in Section IV. Concluding remarks and brief introduction to our on-going work are summarized in Section V.

II. Physical Carrier Sensing Outage under Rayleigh Fading Channel

Any motion of mobile stations or environment causes fluctuations of received signal strength. For slowly moving mobile stations or slowly changing environment, the signal attenuation between two stations is a time varying value summed up (in dB) by three major factors: path-loss, log-normal shadowing and multi-path fading. Let all stations transmit with the same constant power P_t, then over a spatial distance of 20 to 30 wavelengths, there exists a *local mean power* Ω for a particular locality, which is the combined result of a deterministic path-loss factor and a zero-mean Gaussian random variable evaluated in dB caused by large obstructions (shadowing) [15]. Since the effect of shadowing is highly location dependent and exhibits strong spatial correlation over a large distance, to keep our analysis tractable, we omit shadowing and assume Ω is constant over a fixed distance d between two stations.

Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC 2008), Las Vegas, Nevada, March 31 – April 3, 2008.

Specifically, we choose two-ray path-loss model [16] so as to have:

$$\Omega = [\frac{\sqrt{G_l} h_t h_r}{d^2}]^2 P_t, \quad (1)$$

where P_t is the transmit power, G_l is the antenna gain, h_t and h_r are the antenna heights of transmitter and receiver respectively.

A. Single Interferer

When there is no line-of-sight (NLOS) between two mobile stations, the variation of signal envelope received by the idle one can be statistically depicted by Rayleigh fading, i.e. the magnitude of complex envelope z has Rayleigh distribution and its power is exponentially distributed with density [16]:

$$p_{Z^2}(x) = \frac{1}{\Omega} \exp(-\frac{x}{\Omega}) \quad (2)$$

The average duration to fade below a threshold C is [16]:

$$\bar{t}_Z = \frac{e^{\rho^2} - 1}{\rho f_D \sqrt{2\pi}} \quad (3)$$

with $\rho = \sqrt{C/\Omega}$ and f_D is the Doppler frequency, and the fraction of time that the received power is below the same threshold is essentially the CDF of the exponential distribution evaluated at C:

$$\alpha(C, \Omega) = P[z^2 < C] = 1 - e^{-\frac{C}{\Omega}} = 1 - e^{-\rho^2}, \quad (4)$$

which is defined as the *Carrier Sensing Outage Probability* (CSO) in this paper. When $C = \Omega$, i.e. at the edge of *carrier sensing range*, the carrier can only be detected in $1-\alpha(C, C) = e^{-1} \approx 36.8\%$ of time! That is to say that hidden terminals are ubiquitous within a mobile ad hoc network under such channel condition, even with a star topology like a wireless LAN.

Conventionally, if $\bar{t}_Z$ is comparable with the symbol time T_s, the channel is referred to as a *slow fading channel*. However, at pedestrian speed ($1\sim5m/s$), the variation of the 2.4GHz 802.11b channel is so slow that $\bar{t}_Z$ is even comparable with the frame time T_f of a typical DATA frame which takes several to tens of milliseconds to transmit. The slow variation warrants us to assume that *the received power is constant throughout an entire transmission*, so that the probability that a transmission is not sensed by a competing station is equal to α assuming that the moment it starts is uniformly distributed over time. The assumption about constant power level within a frame has been made in various network simulators including Qualnet [17].

To illustrate this property, we set $P_t = 15dBm$, the carrier sensing threshold $C = -93dBm$ and calculate $\bar{t}_Z$ and α at $3m/s$. We also set up a simulation scenario involving two sender and receiver (S-R) pairs that moves at the same speed and in the same direction, and collect the number of detected transmissions that are long enough to rule out ACK frames. The theoretical carrier sensing range is about $420m$ in this case. Both theoretical and simulation results are plotted in Figure 1. We observed that CSO could not

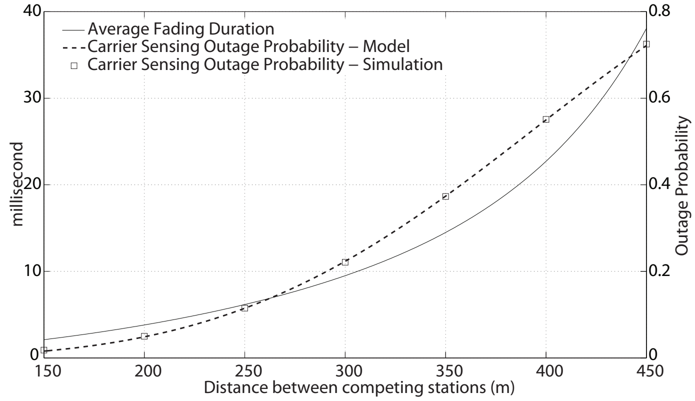

Fig. 1. Average Fading Duration vs. Carrier Sensing Outage Probability

be neglected way before the distance reaches the theoretical *carrier sensing range*, and that the average fading duration grows from several milliseconds to about 30 milliseconds. It is reasonable to assume not only the constant power level within a frame, but also uncorrelated power level between transmissions. Simulations produced the results that perfectly match with our analysis.

The fact that the channel between a slow moving S-R pair remains coherent over multiple consecutive transmissions has been justified by a similar but distinct approach in [18]. However, the previous discovery led to opportunistic scheduling and rate control, while the negative impact on CSMA-based MAC protocols has never been reported.

B. Multiple Interferers

Intuitively, if there are multiple stations transmitting at the same time, the combined carrier energy would be detected with a higher probability. Let us assume a tagged station is sensing the combined carrier from K stations, and the channel conditions from them to the tagged one are mutually independent. We understand that the sum of K iid exponential random variables is a Erlang-K random variable. But generally, the distribution of the sum of K independent exponential random variables with distinct means is given by [19]:

$$p_{Z^2}(x|\Omega_1, \Omega_2, ..., \Omega_K) = \sum_{i=1}^{K} \frac{\Omega_i^{K-2}}{\prod_{j=1, j\neq i}^{K} (\Omega_i - \Omega_j)} e^{-\frac{x}{\Omega_i}}. \quad (5)$$

The CSO conditioned on K simultaneous transmissions is:

$$\begin{aligned} &\alpha(C, \Omega_1, \Omega_2, ..., \Omega_K) = P[z^2 < C] \\ &= \int_0^C p_{Z^2}(x|\Omega_1, \Omega_2, ..., \Omega_K) dx \quad (6) \\ &= \sum_{i=1}^{K} [\frac{\Omega_i^{K-1}}{\prod_{j=1, j\neq i}^{K} (\Omega_i - \Omega_j)} \int_0^C \frac{1}{\Omega_i} e^{-\frac{x}{\Omega_i}} dx] = \sum_{i=1}^{K} \frac{(1 - e^{-\frac{C}{\Omega_i}})}{\prod_{j=1}^{K} (1 - \gamma_{ij})}, \end{aligned}$$

where

$$\gamma_{ij} = \begin{cases} \frac{\Omega_j}{\Omega_i} & \text{if } i \neq j, \\ 0 & \text{if } i = j. \end{cases} \quad (7)$$

The overall CSO of the tagged station is a weighted average over the conditional versions of all combinations of the competing stations, where the weights are related to not only the topology but also the collision intensity. For simplicity, we only consider pair-wise CSO in the following analysis.

III. System Performance Analysis

The basic access mechanism of IEEE 802.11 Distributed Coordination Function (DCF) is summarized as follows. A station with outbound packets in queue transmits the head-of-line packet if it senses the channel idle for over the amount of time called *Distributed Inter-Frame Space* (DIFS). Otherwise, it maintains a backoff windows size w bounded by a minimum W and a maximum W_{max}, picks a random counter value in range $(0, w-1)$ and decrements the counter by 1 every slot time σ ($20\mu s$ in DSSS) unless the channel is sensed busy. It transmits the head-of-line packet when the counter decrements to zero, and waits for an ACK from the receiver within a short period of time called *Short Inter-Frame Space* (SIFS). If an ACK is not received after a SIFS, the transmission is assumed a failure and the station transits to the next backoff stage, doubles the size of the current backoff windows (Binary Exponential Backoff) and tries again until the retry limit m is reached. The CSMA system with Binary Exponential Backoff (BEB) is obviously much harder to describe mathematically than a p-persistent CSMA, although they serve the same purpose to resolve contentions on a shared channel.

In an ideal channel with perfect carrier sensing (or without hidden terminals in a more conventional manner) and no capture effect, more than one station's backoff counters *MUST* decrement to zero in the same slot time to cause a collision. Besides, when all competing stations are saturated, there are always packets ready to be transmitted in every station's queue. These conditions tremendously reduce the complexity of analysis. Bianchi [1] made a key assumption that "at each transmission attempt, and regardless of the number of retransmissions suffered", each packet collides with constant and independent *conditional collision probability* p. For a homogenous network, it is just necessary to find the relationship between p and the *channel access probability* τ which equals to the probability that the backoff counter of a tagged station decrements to zero, via a bi-dimensional Markov chain that describes the transitions between backoff stages and counter values. The network throughput and latency then can be easily deduced. It is highly recommended to review [1] before diving into the following details.

We are interested in the combined saturated frame error rate and throughput that can be achieved in a homogenous single hop network consisting of n slowly moving contending stations with a quasi-stationary topology, given imperfect carrier sensing due to slow Rayleigh fading and no capture. We focus on a tagged station with the knowledge of CSO measurements $\vec{\alpha} = [\alpha_1, \alpha_2, ..., \alpha_{n-1}]$ between this station and its $n-1$ contenders. We will make several additional definitions and assumptions to Bianchi's work and extend his Markov Chain to understand the dynamics.

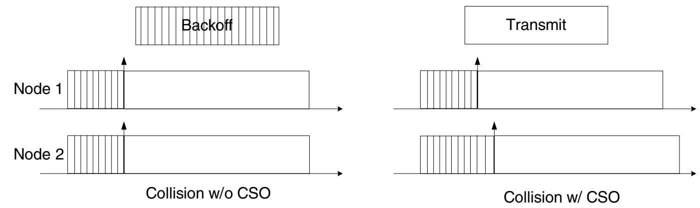

Fig. 2. Illustration of Collision due to Carrier Sensing Outage

A. System Descriptions and Assumptions

There are two different types of collisions in our system from the perspective of a specific station. If there is a concurrent transmission during the first time slot of the transmission of the tagged station, it's a *Type I* collision. Without CSO, all the stations involved in a collision experience a Type I collision, because their backoff counters reaches zero during the same slot time as shown on the left of Figure 2, otherwise the collision shall be avoided. *Type II* is the kind of collision in which no concurrent transmission is going on at the moment the tagged station starts to send a frame. The culprit is another station that fails to detect the first transmission from the tagged station so as to transmit a moment later and partially overlap with the first one. As illustrated in Figure 2, Node 1 starts to transmit when its backoff finishes and its carrier is not detected by Node 2. The backoff counter of Node 2 continues counting down for a while before it reaches zero and causes a collision. The two nodes have different perspectives on this event, though. Node 1 experienced a Type II collision, while Node 2 had a Type I. Here we assume that a normal DATA frame is much longer than a normal backoff window, thus once a carrier is not detected, a collision is inevitable. To summarize, a Type I collision happens during the backoff period of a station while a Type II happens within its transmission period.

In light of the observations, the system can be described alternatively from the perspective of a tagged station as follows. At the beginning of each time slot, the backoff counter decrements 1 with a *correct backoff probability* q or jumps back to zero with probability $1-q$ when it fails to sense a carrier. A frame is transmitted as soon as the counter reaches zero, with a fixed conditional collision probability p. Both p and q are independent to backoff stage and counter value, and will be related with CSO and n later. The condition of successful transmission is that neither Type I nor II collision is experienced by the station. Here the Type I collision includes both the conventional collision and the case in which the tagged station fails to sense a carrier and causes a collision, and it is related with the backoff process only. The Type II collision is solely determined by the channel condition $\vec{\alpha}$.

We keep the assumptions in Bianchi's model as follows:

1) There is no transmission error. A frame is correctly received as long as it is not involved in a collision.
2) The backoff window size is not bounded by a maximum.
3) The probability that an ACK collides with other transmissions is ignored.

We also make several additional assumptions:

1) The duration of a collision is NOT significantly longer than a successful transmission. Any collision is treated as if it happens at the very beginning of the first transmission involved.
2) A transmission is successful if and only if no competing stations transmit at the same time slot and none of them fail to sense the transmission.
3) The duration of a DATA frame is much longer than a normal backoff, so that if a station fails to sense an on-going transmission, its backoff counter would decrement to zero long before the on-going transmission is completed.

B. Modified Markov Chain of Backoff Counter

We expect to formulate a nonlinear system to relate the conditional collision probability p and correct backoff probability q with the channel access probability τ. To achieve that, the backoff process is modeled using a modified version of Bianchi's two-dimensional Markov Chain as shown in Figure 3. Each state is denoted as (i,k) where i is the backoff stage and k is the current value of the backoff counter. The backoff window size at backoff stage i is W_i. The minimum backoff windows size is W and the maximum backoff stage m. The non-null one-step transition probabilities of the modified discrete-time Markov Chain are:

$$\begin{cases} P\{i,k|i,k+1\} = q & k \in (0, W_i-2), i \in (0,m) \\ P\{i,0|i,k+1\} = 1-q & k \in (0, W_i-2), i \in (0,m) \\ P\{0,k|i,0\} = \frac{1-p}{W_0} & k \in (0, W_i-1), i \in (0,m) \\ P\{i,k|i-1,0\} = \frac{p}{W_i} & k \in (0, W_i-1), i \in (1,m) \\ P\{m,k|m,0\} = \frac{p}{W_m} & k \in (0, W_m-1) \end{cases} \quad (8)$$

The first equation accounts for the fact that the backoff counter is decremented in each slot if Physical Carrier Sensing is working properly. The second equation describes our assumption that a failure of carrier detection would mislead backoff counter to count to zero immediately. The last three equations describe the transitions between backoff stages and are kept intact as in Bianchi's model since our modification does not alter them so as to preserve the regularity of the chain.

Let $b_{i,k}$ be the stationary probability of the state (i,k). Because all states $(i, k>0)$ with non-zero backoff counter value would eventually transit to $(i,0)$, we have the simple equations to describe the relationship between $b_{i,0}$'s:

$$\begin{cases} b_{i-1,0}\cdot p = b_{i,0} \rightarrow b_{i,0} = p^i b_{0,0} & 0<i<m \\ b_{m-1,0}\cdot p = (1-p)b_{m,0} \rightarrow b_{m,0} = \frac{p^m}{1-p} b_{0,0} \end{cases} \quad (9)$$

The stationary probability of states for the non-zero backoff counter is:

$$b_{i,k} = \frac{1-q^{W_i-k}}{(1-q)W_i} b_{i,0} \quad i \in (0,m), k \in (1, W_i-1) \quad (10)$$

Note that the stationary probability of the states in the last backoff stage is parameterized by $\frac{1}{1-p}$. Moreover, it is consistent to Bianchi's model since as $q \rightarrow 1$, i.e. with perfect CS, $b_{i,k} \rightarrow \frac{W_i-k}{W_i} b_{i,0}$. With the fact $\sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p}$, we have the probabilities of all states expressed as a function of $b_{0,0}$:

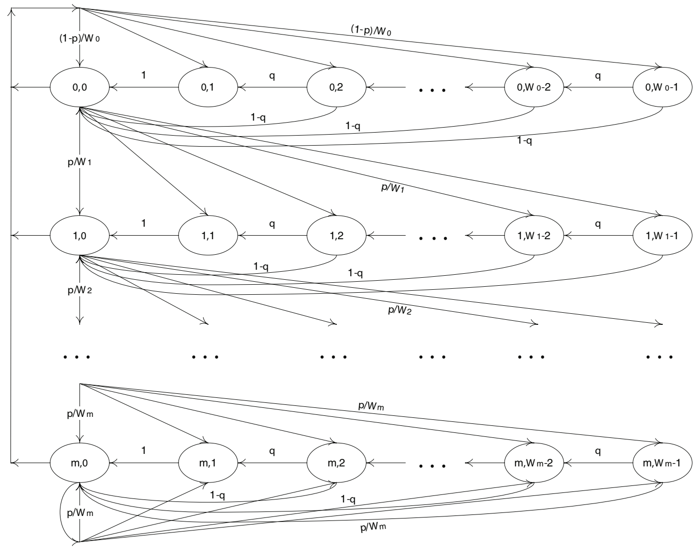

Fig. 3. Modified Markov Chain

$$\begin{cases} b_{i,k} = p^i \frac{1-q^{W_i-k}}{(1-q)W_i} b_{0,0} & i \in (0, m-1), k \in (1, W_i-1) \\ b_{m,k} = \frac{p^m}{1-p}\frac{1-q^{W_m-k}}{(1-q)W_m} b_{0,0} & k \in (1, W_i-1) \end{cases} \quad (11)$$

Now we apply the normalization condition of the Markov chain, i.e. all the stationary probabilities shall add up to one, to find a closed form of $b_{0,0}$:

$$\begin{aligned} 1 &= \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} + \sum_{i=0}^{m}\sum_{k=1}^{W_i-1} b_{i,k} \quad (12) \\ &= b_{0,0}\left[\frac{1}{1-p} + \frac{1}{(1-p)(1-q)} - \frac{A-B}{W(1-q)^2(1-p)}\right], \end{aligned}$$

where

$$A = \frac{1-p+(p/2)^{m+1}}{1-p/2}, \quad (13)$$

$$B = (1-p)\sum_{i=0}^{m-1}(\frac{p}{2})^i q^{2^i W} + (\frac{p}{2})^m q^{2^m W}. \quad (14)$$

The probability τ that a station transmits in a randomly chosen slot is simply the sum of the stationary probability of the states with zero-value backoff counter, so for the given MAC parameters, τ is a function of (p,q) pair:

$$\begin{aligned} \tau &= F(p,q) = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} \\ &= \frac{(1-q)^2}{(1-q)^2 + (1-q) - \frac{A-B}{W}} \quad (15) \end{aligned}$$

According to our approximate system description, a transmission from a tagged station is successful if and only if none of the other $n-1$ stations fails to sense it after it commences and none of them happens to backoff to zero at the same slot (including the case in which the tagged station fails to sense ongoing transmission from the competing stations). The modified Markov chain only considered the cases in which the tagged station fails to sense transmission from other stations, so that in the other system equation, we include the probability that other stations fails to sense the transmission from the tagged station. Given the independence assumption and the value of τ, we have:

$$p = G(\tau) = 1 - (1-\tau)^{(n-1)} \prod_{i=1}^{n-1} (1-\alpha_i) \qquad (16)$$

Now we quantify the unknown parameter q. The backoff counter of a tagged station jumps to zero if and only if at least one transmission from other competing stations and a CSO occurs in the same slot. Since any competing station has the same chance to access the channel, there is an average CSO probability $\bar{\alpha} = \frac{\sum \alpha_i}{n-1}$ for the tagged station, thus:

$$q = H(\tau) = 1 - \bar{\alpha}[1 - (1-\tau)^{(n-1)}] \qquad (17)$$

Equations (15), (16) and (17) forms a nonlinear system which can be easily solved numerically. Both $G(\cdot)$ and $H(\cdot)$ are obviously monotonic and continuous for $\tau \in (0,1)$, and so is $F(\cdot)$ for $p, q \in (0,1)$. The uniqueness of the solution was not contradicted in our extensive numerical experiments.

C. Saturated Throughput

The analysis based on the bi-dimensional Markov chain produces the channel access probability τ of each competing station. It has been assumed that each station transmit randomly and independently, so that p_{tr} the probability that there is at least one transmission in a randomly picked slot and p_{succ} the probability that a transmission occurring on the channel is successful are

$$p_{tr} = 1 - (1-\tau)^n, \qquad (18)$$

$$p_{succ} = \frac{p_{no\_coll}}{p_{tr}} = \frac{n\tau(1-\tau)^{(n-1)} \prod_{i=1}^{n-1} (1-\alpha_i)}{1-(1-\tau)^n}. \qquad (19)$$

The normalized system throughput is the fraction of time the channel is used to successfully transmit payload bits. If all DATA frames are of the same length, say L bits, we can make use the result in [1]:

$$S = \frac{P_{succ} P_{tr} L}{(1-P_{tr})\sigma + P_{succ} P_{tr} T_s + (1-P_{succ}) P_{tr} T_c}, \qquad (20)$$

where

$$H = PHY_{hdr} + MAC_{hdr},$$
$$T_s = H + L + SIFS + ACK + DIFS,$$
$$T_c = H + L + DIFS,$$

as we assumed that a collision is not significantly longer than a success.

TABLE I
PARAMETERS IN QUALNET SIMULATIONS

802.11 PHY	802.11b	Data Rate	1Mbps
TX Power	15dBm	CS Threshold	-93dBm
Retry Limit m	6	Min Backoff Window W	32
RTS Threshold	2300	Slot Time σ	20μs
SIFS	10μs	DIFS	50μs
PHY Header	192bits	MAC Header	224bits

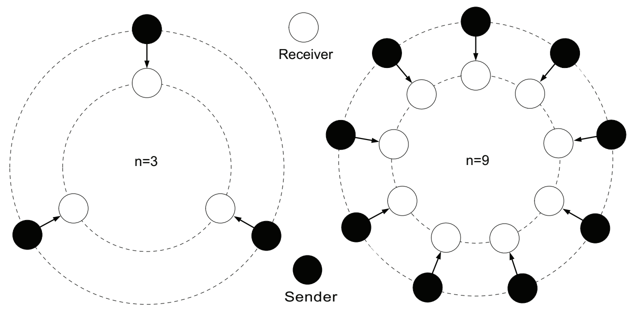

Fig. 4. Homogenous Topology

IV. SIMULATION VALIDATION

Our model was validated using Qualnet [17] simulator. The source code was altered to disable capture effect. Sample topologies consisting of 3 and 9 contending stations are shown in Figure 4. There are two concentric circles. All competing senders are placed uniformly on the outer circle, and all receivers on the inner one. Each S-R pair is on the same radius, where a saturated CBR flow is set up between them. The distance between each S-R pair, i.e. the difference of the concentric circle's radius, is so close that even with slow Rayleigh fading, the transmission would be 100% reliable without interference. The routes are set manually to prevent routing oscillation and short routing packets. All nodes move at 1m/s towards the same direction and maintain the relative distances. We then vary the radius of the network to obtain various values of $\bar{\alpha}$. Each round of simulations runs over 100 seconds. All shared parameters are presented in Table I.

The frame error rate p collected from simulation matches our model as shown in Figure 5. The theoretical FER curves for 3 and 9-nodes network are plotted. The FER data for CBR flows with 500-byte and 1500-byte payload were collected and compared with the lines produced by our model. Despite our rough approximations and assumptions, the model still captures the major factors of the system with impressive accuracy against simulations.

It is perfectly clear that CSO is disastrous to the network performance if capture effect is not taken into account. Several percent of undetected on-going transmission can double the FER. However, stations spend less time in backoff due to CSO, so that one may be curious whether the throughput can benefit from it. The answer is NO, at least with the standard 802.11 MAC parameters. The numerical and simulation results for CBR flows with 1024-byte payload are shown in Figure

Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC 2008), Las Vegas, Nevada, March 31 – April 3, 2008.

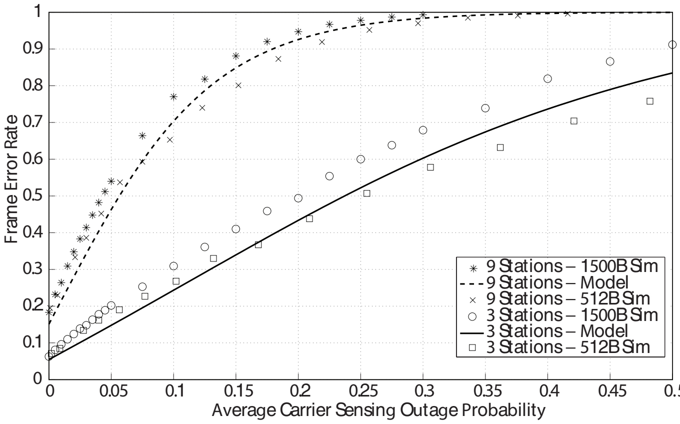

Fig. 5. Frame Error Rate: Model vs. Simulations

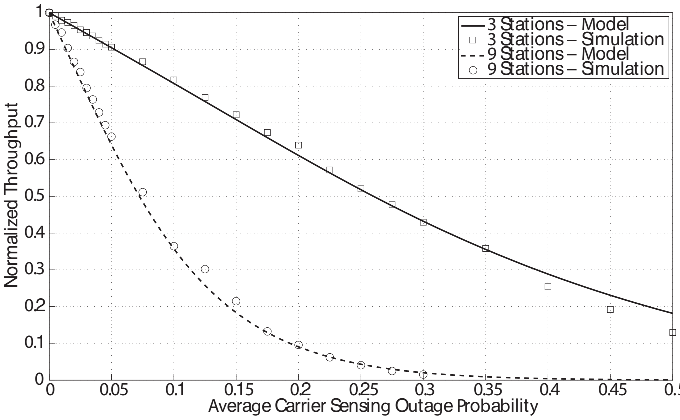

Fig. 6. Normalized Saturated Throughput: Model vs. Simulations

6. The normalized throughput is again normalized to the ideal normalized throughput without CSO to emphasize the performance degradation. More competing stations lead to more throughput degradation with the same $\bar{\alpha}$.

In reality, the system throughput would not drop to zero as the network diameter increases. Sooner or later, the capture effect shall turn the tide depending on the distance between the sender and receiver. However, the savior hardly visits before the performance has greatly suffered throughout our simulations with various settings, unless the carrier sensing threshold is ridiculously low and spatial reuse is essentially disabled. Further theoretical investigation on the combinational effect of physical capture and CSO, or even real life experiments on a wireless test-bed are highly desired.

V. Conclusion

We discovered the existence of Physical Carrier Sensing Outage in mobile ad hoc networks consisting of slowly moving stations and quantified its intensity. Its impact on the saturated throughput of a homogenous single-hop network was studied by an extended Bianchi model, assuming no capture and no transmission error. The performance degradation is so grave that we suggest CSO to be considered seriously in related topics.

We are currently working on further enhancement of our model to incorporate the capture effect and extend our results to multihop networks with arbitrary topology. We are also interested in studying the approaches to subdue CSO by utilizing PHY and MAC layer information and potential benefit from multi-antenna.

Acknowledgment

The authors would like to thank anonymous reviewers for valuable corrections and constructive suggestions.

References

[1] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, 2000.

[2] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "IEEE 802.11 packet delay-a finite retry limit analysis," in *Proceedings of IEEE GLOBECOM '03*, vol. 2, 2003, pp. 950–954 Vol.2.

[3] Z. Hadzi-Velkov and B. Spasenovski, "Saturation throughput - delay analysis of IEEE 802.11 DCF in fading channel," in *Proceedings of IEEE ICC '03*, vol. 1, 2003, pp. 121–126 vol.1.

[4] V. Pourahmadi, S. H. Jamali, and R. Safavi-Naieeni, "Saturated throughput analysis of the IEEE 802.11b DCF mode in a slow rayleigh fading channel," in *IEEE International Conference on Networks*, vol. 1, 2005.

[5] T.-C. Hou, L.-F. Tsao, and H.-C. Liu, "Analyzing the throughput of IEEE 802.11 DCF scheme with hidden nodes," in *Proceedings of IEEE VTC '03*, vol. 5, 2003, pp. 2870–2874 Vol.5.

[6] D. Malone, K. Duffy, and D. Leith, "Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions," *IEEE/ACM Trans. Netw.*, vol. 15, no. 1, pp. 159–172, 2007.

[7] M. C. Marcelo and J. J. Garcia-Luna-Aceves, "A scalable model for channel access protocols in multihop ad hoc networks," in *Proceedings of MobiCom '04*. Philadelphia, PA, USA: ACM Press, 2004.

[8] J. Zhu, X. Guo, L. L. Yang, W. S. Conner, S. Roy, and M. M. Hazra, "Adapting physical carrier sensing to maximize spatial reuse in 802.11 mesh networks: Research articles," *Wirel. Commun. Mob. Comput.*, vol. 4, no. 8, pp. 933–946, 2004.

[9] X. Yang and N. Vaidya, "On physical carrier sensing in wireless ad hoc networks," in *Proceedings of IEEE INFOCOM '05*, vol. 4, 2005, pp. 2525–2535 vol. 4.

[10] T.-S. Kim, J. C. Hou, and H. Lim, "Improving spatial reuse through tuning transmit power, carrier sense threshold, and data rate in multihop wireless networks," in *Proceedings of MobiCom '06*. New York, NY, USA: ACM Press, 2006, pp. 366–377.

[11] T. Y. Lin and J. C. Hou, "Interplay of spatial reuse and SINR-determined data rates in CSMA/CA-based, multi-hop, multi-rate wireless networks," in *Proceedings of IEEE INFOCOM '07*, 2007, pp. 803–811.

[12] S. G. Glisic, R. Rao, and L. B. Milstein, "The effect of imperfect carrier sensing on nonpersistent carrier sense multiple access," in *Proceedings of IEEE ICC '90*, 1990, pp. 1266–1269 vol.3.

[13] S. G. Glisic, "1-persistent carrier sense multiple access in radio channels with imperfect carrier sensing," *IEEE Transactions on Communications*, vol. 39, no. 3, pp. 458–464, 1991.

[14] I. Ramachandran and S. Roy, "Analysis of throughput and energy efficiency of p-persistent CSMA with imperfect carrier sensing," in *Proceedings of IEEE GLOBECOM '05*, vol. 6, 2005.

[15] G. L. Stüber, *Principles of mobile communication (2nd ed.)*. Norwell, MA, USA: Kluwer Academic Publishers, 2001.

[16] A. Goldsmith and A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.

[17] S. N. Technologies, "Qualnet." [Online]. Available: http://www.scalable-networks.com/

[18] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "OAR: an opportunistic auto-rate media access protocol for ad hoc networks," *Wirel. Netw.*, vol. 11, no. 1-2, pp. 39–53, 2005.

[19] Y. D. Yao and A. U. H. Sheikh, "Outage probability analysis for microcell mobile radio systems with cochannel interferers in rician/rayleigh fading environment," *Electronics Letters*, vol. 26, no. 13, pp. 864–866, 1990.