CROSS-LAYER PERFORMANCE ANALYSIS FOR CSMA/CA SYSTEM: IMPACT OF IMPERFECT SENSING

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ABSTRACT

The performance of the carrier sense multiple access / collision avoidance (CSMA/CA) protocol under the presence of carrier sensing errors is analyzed. Two types of carrier sensing errors, false alarm and miss detection, are considered, and their impact on system performance is analyzed using a new CSMA/CA model based on a Markov chain capturing the sensing errors at the physical layer. The throughput as a function of these sensing error probabilities as well as other CSMA/CA parameters is obtained. It is shown that the throughput loss by a poorly chosen sensing threshold is tolerable at intermediate values of the ratio of the packet size to the contention window size, whereas care should be taken in choosing the sensing threshold when the ratio is small or large.

1. INTRODUCTION

With the success of modern wireless industry, various types of local or personal wireless devices are pervasive at our home, office and streets. Many of these technologies use open spectrum that is available to anyone; for example, 802.11 in wireless local area network (WLAN) and ZigBee in wireless personal area network (WPAN) operate in the same ISM band at 2.4 GHz. In addition to this, a new wireless technology, *cognitive radio*, enables primary and secondary users, or peer users to coexist and access the spectrum dynamically in an opportunistic way. In cognitive radio, the system can operate in a centralized scheme with channelization or in a decentralized scheme [1]. In the latter scheme, users sense the channel to determine the availability of channel, and access the channel depending on the sensing outcome. Here, the carrier sensing is dependent on physical-layer parameters such as the signal-to-noise ratio (SNR) of the sensed signal and detector parameters, and is not perfect. Hence, the handling of sensing error is one of the main design issues in such schemes.

The idea of this sensing and opportunistic channel access has already been presented partly in the well-established random access scheme, *carrier sense multiple access/collision avoidance (CSMA/CA) protocol,* that is used in many systems such as WLAN and ZigBee [2],[3]. The performance of CSMA/CA has been analyzed extensively in the past with pioneering works [4],[5] and recent works, especially, for particular systems such as WLAN and ZigBee [6],[7]. In these analyses, however, the carrier sensing model is simplified by assuming the perfect carrier sensing and the physical layer properties are not properly captured. Recently, Krishnamurthy et al. measured the aggregated throughput by varying the carrier sensing threshold in an experiment, and showed that the aggregated throughput changed drastically according to the carrier sensing threshold value [8]. This result shows that it is necessary to analyze the protocol under the sensing errors and to design the overall system by optimizing the physical-layer characteristics and MAC layer parameters jointly to improve the system throughput. Such an attempt was presented by Chen and others [9]. The authors considered the impact of the carrier sensing and joint design under the Markov decision process (MDP) framework, where the transmitter has a control policy of accessing the channel at each slot with a certain probability.

In this paper, we analyze the performance of the CSMA/CA protocol under carrier sensing errors and investigate the impact of the sensing errors on the system performance for the first time to our best knowledge. We consider two types of sensing errors: false alarm and miss detection. We capture the sensing errors by modifying the Markov chain model widely used for the conventional CSMA/CA analysis, and investigate the throughput as a function of these error probabilities for given other CSMA/CA parameters. The normalized saturation throughput of CSMA/CA networks under the presence of sensing error is obtained. With imperfect carrier sensing, the false alarm error has an effect of extending the contention window (CW) size, and the miss detection error results in two additional effects: 1) shrinking the CW size and 2) causing new additional collisions, compared with the perfect carrier sensing CSMA/CA system. We examine the throughput as a function of p_f and p_m. It is seen that the ratio L/W_0 of the packet size L to the CW size W_0 is the critical factor that determines the behavior of throughput as a function of p_m and p_f. It is also seen that p_f is the dominant factor for small L/W_0 whereas p_m is the dominant factor for large L/W_0. The loss by a poorly chosen sensing threshold is tolerable at intermediate values of the ratio L/W_0, whereas care should be taken in choosing the sensing threshold in case that L/W_0. is large or small.

2. SYSTEM MODEL

We consider a network consisting of N transmitter-receiver pairs operating under the CSMA/CA protocol, as shown in Fig. 1. To facilitate the analysis, we consider a slotted CSMA/CA system with time synchronization among users. We assume that transmitters in the network have only one backoff stage, a packet consists of L slots, and the CW size at the backoff stage is W_0 slots. We also assume that CSMA/CA nodes are in the saturated mode. That is, the buffer of each transmitter is full and each transmitter always has packets to transmit.

2.1. Receiver operating characteristics (ROC) of carrier sensor

At the beginning of each slot, each transmitter senses the channel and the sensing outcome is used to determine the availability of the

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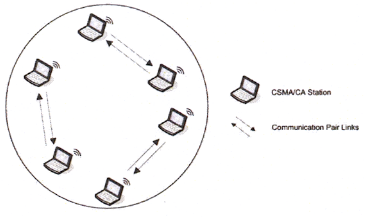

Fig. 1. Multi-pair CSMA/CA network

channel. If the level of the sensor's input signal is larger than a predetermined threshold, the transmitter determines that the channel is busy. Otherwise, it regards the channel as idle. However, the channel sensing is not perfect and there can be sensing errors because of noise or channel distortion during the sensing operation. There are two types of sensing errors: false alarm and miss detection. *False alarm errors* are defined as errors which occur when the sensor determines that the channel is busy when the channel is actually idle. On the other hand, *miss detection errors* are defined as errors which happen when the sensor determines that the channel is idle provided that the channel is actually busy. The false alarm probability p_f and the miss detection probability p_m are typically dependent on the input signal-to-noise ratio (SNR), the sensor type and the sensing threshold value. The operation of channel sensors is typically characterized by the *receiver operating characteristics (ROC)* which describes the miss probability as a function of the false alarm probability, as shown in Fig. 2. The different curves in Fig. 2 correspond to different input SNR values or sensor types. In case of known signals, the matched filter detector can be used whereas the energy detector is typically used when the signal is unknown to the sensor. In both cases, the miss detection probability decreases monotonically as the false alarm probability increases. For a given SNR and sensor type, changing the sensing threshold value moves the operating point (p_f, p_m) along the curve in the figure. Note that either of p_m or p_f can be almost zero at the very high SNR regime in Fig. 2, while both p_m and p_f are away from zero except two end points in the normal operating mode. Separate analysis is provided for high SNR cases in later sections.

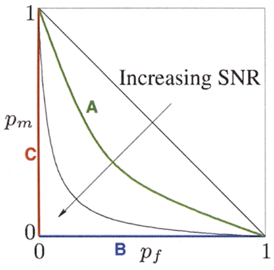

Fig. 2. Typical receiver operating characteristics curve - A: normal operating mode, and B and C: high SNR operating modes (B: false alarm error only, C: miss detection error only)

2.2. Operation of CSMA/CA with sensing errors: A Markov chain model

The operation of CSMA/CA nodes is widely modelled using Markov chains with states being the values of the backoff counter. We propose a new Markov chain model for the CSMA/CA under the presence of carrier sensing errors at the physical layer. To capture the sensing errors, transitions capturing the events of sensing errors are introduced and corresponding transition probabilities are assigned from the physical layer parameters. Fig. 3 shows the proposed model for the operation of each CSMA/CA node capturing the false alarm and miss detection errors at the sensing stage, where the state transition occurs every slot. The chain is divided into the right and left sides with state S_0 being the center. The right side corresponds to the states of decreasing the value of the backoff counter. Here, state S_i represents that the CSMA/CA node has the backoff counter value of i, and the node does not transmit a packet in these states $(1 \le i \le W_0 - 1)$. On the other hand, the left side corresponds to the states of transmitting a packet $(-(L-1) \le i \le 0)$, and state S_i in the left side represents that the CSMA/CA node is transmitting $(-i+1)^{th}$ slot of a packet with the backoff counter value of 0. In the states of the right side of the chain, there are two conditions under which the node decreases its backoff counter value; the node decreases its current backoff counter value by one 1) when the carrier sensor of the node determines that the channel is idle (with probability $1-p_f$) when it is actually idle (with probability $1-\alpha$, where α is the channel activity factor), or 2) when the carrier sensor of the node declares that the channel is idle (with probability p_m) when it is actually busy (with probability α). Hence, the transition probability from State S_i to State S_{i-1} is given by $\alpha p_m + (1-\alpha)(1-p_f)$ in the right side of the chain. In addition, looping from State S_i to State S_i is also possible when the carrier sensor declares the presence of a signal in the channel and the transition probability for this is given by $(1-\alpha)p_f + \alpha(1-p_m)$. In the left side of the chain, on the other hand, the CSMA/CA node is in the process of transmitting a packet with length of L slots. When the backoff counter value of the node reaches zero (State S_0), the node starts to transmit a packet. Whether the transmission of each slot of the packet is successful or not, the node continues transmitting the packet and the state of the node moves to the left until it finishes the transmission of the packet. If the transmission is not collided by the transmission of other nodes during the whole packet duration, the packet is successfully transmitted. If at least one of the L slots of the packet is collided, on the other hand, we consider that the packet is collided and the transmission is not successful. Whether the transmission is successful or collided, the node selects a new value for the backoff counter randomly from $[0, W_0 - 1]$ after the transmission. Thus, the state transition probabilities for the chain are given by

$$\begin{aligned}
&P\{S_{i-1}|S_i\}{=}\alpha p_m + (1-\alpha)(1-p_f), && i \in [1, W_0{-}1],\\
&P\{S_i|S_i\}{=}\alpha(1-p_m) + (1-\alpha)p_f, && i \in [1, W_0{-}1],\\
&P\{S_{(i-1)}|S_i\}{=}1, && i \in [{-}(L{-}2), 0],\\
&P\{S_i|S_{-(L-1)}\}{=}1/W_0, && i \in [0, W_0{-}1].
\end{aligned}$$

The stationary probability distribution is unique since the proposed Markov chain in Fig. 3 is ergodic. We denote the stationary probability for State S_i as b_i. From the above transition probabilities, we obtain the relation between the stationary probability probabilities as

$$\begin{aligned}
&b_i{=}b_0, && i \in [-(L{-}1), -1],\\
&b_i{=}\frac{b_0}{\alpha p_m + (1-\alpha)(1-p_f)}\,\frac{W_0 - i}{W_0}, && i \in [1, W_0{-}1],
\end{aligned} \tag{1}$$

and the normalization condition for the stationary distribution is given by

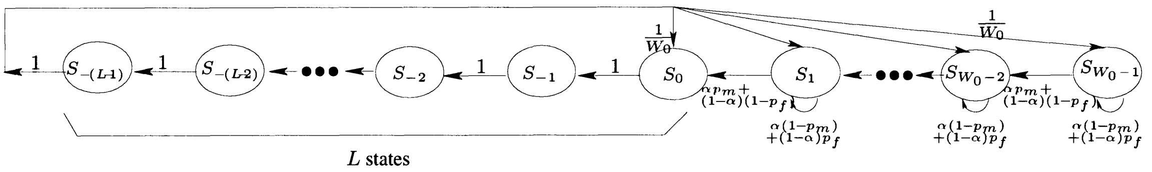

Fig. 3. Markov chain model for a CSMA/CA node with sensing errors ($0 \le p_f, p_m \le 1$)

$$1 = \sum_{i=-(L-1)}^{W_0-1} b_i = b_0\{L + \frac{1}{\alpha p_m + (1-\alpha)(1-p_f)} \frac{W_0-1}{2}\}. \tag{2}$$

From the above relations, we obtain the stationary probability b_0 for State S_0 as a function of p_f, p_m, W_0 and L, given by

$$b_0(p_f, p_m, W_0, L) = \frac{2\{\alpha p_m + (1-\alpha)(1-p_f)\}}{2L\{\alpha p_m + (1-\alpha)(1-p_f)\} + (W_0-1)}. \tag{3}$$

The stationary probabilities for other states are obtained using (1) and b_0.

3. PERFORMANCE ANALYSIS OF CSMA/CA PROTOCOL UNDER THE PRESENCE OF SENSING ERRORS

In this section, we analyze the system performance of the CSMA/CA network under the presence of carrier sensing errors. We first consider the normal sensor operating mode A of the ROC in Fig. 2, and then investigate the two high SNR operating modes B and C in Fig. 2 to gain insights into the different impacts of the false alarm error and miss detection error on the MAC performance.

3.1. Collision probability p_c, channel activity α, and normalized throughput S when the carrier sensor is in the normal operating mode

Our approach to calculate the overall system throughput is based on the symmetry among the CSMA/CA nodes. That is, one particular node is not favored over other nodes. Hence, we first calculate the per-node throughput of an arbitrary node considering the operation of all the other nodes, and the overall system throughput is given by the product of the number of nodes and the per-node throughput. To simplify the problem and gain insights into the impact of sensing error, we focus on the two pair case. Fig. 4 shows the operation of a CSMA/CA network with two pairs of nodes under the presence of carrier sensing errors. The transmission of data from one transmitter to its corresponding receiver is successful if no other transmission occurs during the transmission (period 1 and 3). If two transmitters start transmitting their data packets simultaneously, a collision occurs (period 2). This happens even in CSMA/CA networks with perfect carrier sensing as well as in imperfect carrier sensing cases. However, the transmission attempt by one transmitter in the middle of the transmission of the other transmitter occurs only in the imperfect sensing case (period 4 and 5). Hence, these additional collisions need to be incorporated in modelling the operation of the CSMA/CA model under the presence of carrier sensing errors.

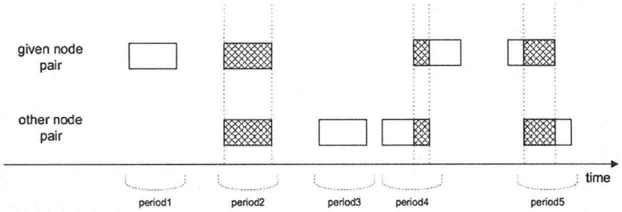

Fig. 4. Data transmission flow time diagram of two pairs of nodes in a CSMA/CA network with sensing errors

We denote the l^{th} slot collision probability by p_{c_l} and we assume that p_{c_l} is the same irrespective of the value of l, ($2 \le l \le L$) except the case of $l = 1$. (The case of $l = 1$ corresponds to Period 2 in Fig.4.) We denote it as $p_c (= p_{c_2} = p_{c_3} = \cdots = p_{c_L})$. The transmission of the node of interest is collided in the middle of its transmission when the other transmitter is in State S_1 and miss-detects the channel. (See period 5 in Fig. 4.) Thus, p_c can be expressed as

$$p_c = \frac{b_1}{\sum_{i=1}^{W_0-1} b_i} \times p_m = \frac{2p_m}{W_0}. \tag{4}$$

assuming the stationary distribution of all nodes in the network is the same in steady state. Note that the on-going transmission of the node of interest confines the conditional probability space of the other node to $\{i : 1, 2, \cdots, W_0 - 1\}$. Since α is the probability of channel's being busy from the perspective of the node of interest, α can be expressed as the sum of the stationary probabilities of the states in the left side of the Markov chain of the other node, and is given by

$$\alpha = \sum_{i=-(L-1)}^{0} b_i. \tag{5}$$

under the steady-state assumption.

3.1.1. Normalized throughput

We define P_{bo} as the probability that a node has a positive backoff counter value, and define τ as the probability that a node transmits a packet conditioned that it has a positive backoff counter value. Then, P_{bo} and τ are given by

$$P_{bo} = \sum_{i=1}^{W_0-1} b_i, \text{ and } \tau = \frac{b_1}{P_{bo}}(1 - p_f). \tag{6}$$

The probabilities of successful transmission, collision, and idle channel, denoted by P_s, P_c, and P_i, respectively, are obtained using the stationary distribution and given, as functions of P_{bo}, τ, p_c, and L, by

$$\begin{aligned} P_s &= 2{P_{bo}}^2\tau(1-\tau)(1-p_c)^{L-1} \times L, \\ P_i &= {P_{bo}}^2(1-\tau)^2, \\ P_c &= 1 - P_s - P_i. \end{aligned} \tag{7}$$

where ${P_{bo}}^2$ represents the probability that all the nodes (here, 2 nodes) have positive backoff counter values. Here, the factor of two in P_s represents the number of pairs in the network, and we have the factor of L because we assume that the length of successful transmission is equal to the packet length and we apply the *slot-by-slot* approach where the state transition occurs every slot and the derivation of P_s, P_c, and P_i is based on this slot-by-slot transition probability. (Once the event corresponding to ${P_{bo}}^2\tau(1-\tau)(1-p_c)^{L-1}$

occurs, L consecutive slots are consumed for a successful transmission.) Finally, the normalized throughput S is given by

$$S = \frac{P_s}{P_i + P_s + P_c} \frac{\mathbb{E}\{P\}}{\mathbb{E}\{L\}}, \tag{8}$$

where $\mathbb{E}\{P\}$ and $\mathbb{E}\{L\}$ are the average payload length and the average packet length, respectively. In our analysis, we assume that $\mathbb{E}\{P\}$ and $\mathbb{E}\{L\}$ are equal to L. Hence, S is simply given by

$$S = 2{P_{bo}}^2 \tau (1-\tau)(1-p_c)^{L-1} \times L. \tag{9}$$

Note that S is a function of L, P_{bo}, τ, and p_c, and P_{bo}, τ, and p_c are functions of L, N, p_m, p_f, and W_0 as seen in (4) and (6). S as a function of L, p_m, p_f, and W_0 is investigated through this relationship.

3.2. Carrier sensing at high input SNR

In this section, we consider two ROC regions at very high SNR to investigate the effect of each of the false alarm and the miss detection on the operation of the CSMA/CA by setting the one type of sensing error probability to zero. The overall effect by both of p_f and p_m in the normal operating region of ROC can be explained by the joint effect.

3.2.1. False alarm only case ($0 \leq p_f \leq 1$, $p_m = 0$)

When the input SNR is high and the sensing threshold of the sensor is low, the sensor operates in the mode B in Fig. 2. The sensor rarely determines that a channel is idle when it is actually busy ($p_m \approx 0$). In this case, however, sensor can determine that the channel is busy even if it is actually idle, and the false alarm probability takes a value in the entire range of $[0,\ 1]$. Since the value of p_m is equal to zero, b_0 for State S_0 is obtained as a function of p_f, W_0, and L and given by

$$b_0(p_f, W_0, L) = \frac{2(1-\alpha)(1-p_f)}{2L(1-\alpha)(1-p_f) + (W_0 - 1)}. \tag{10}$$

The l^{th} slot collision probability p_c $(2 \leq l \leq W_0)$ except $l = 1$ is equal to zero from (4) since p_m is zero. The stationary distribution b_i and the normalized throughput S in this case are obtained accordingly using (7), (8) and (10).

The effect of the false alarm error on the CSMA/CA is equivalent to extending the CW size W_0 of the CSMA/CA. This can be explained as follows. The stationary probability for S_i is obtained from (1) and given by

$$b_i = \frac{b_0}{(1-\alpha)(1-p_f)} \left(1 - \frac{i}{W_0}\right),\ 1 \leq i \leq W_0 - 1.$$

The stationary probability b_i of State S_i increases as p_f increases. The increase can be similarly obtained by extending the CW size W_0 with fixing p_f. Hence, the increased false alarm probability has a similar effect of extending the contention window size, and the node stays for a longer time in the contention period due to the false alarm.

3.2.2. Miss detection only case ($p_f = 0$, $0 \leq p_m \leq 1$)

When the input SNR at the carrier sensor is high and the sensing threshold is set to a large value, the sensor rarely makes a false alarm error ($p_f \approx 0$) whereas the miss probability can range over $[0, 1]$. The Markov chain model for the normal operating mode in Fig. 3 can be simplified in this case since the value of p_f is equal to zero. The stationary probability b_0 for State S_0 is obtained as a function of p_m and W_0, and given by

Table 1. CSMA/CA related parameter values

Parameter	Value	Description
L	1, 2, 3, 4, 5 slots	Length of Packet
W_0	4, 8, 32, 64	Contention Window Size

$$b_0(p_m, W_0, L) = \frac{2\{\alpha p_m + (1-\alpha)\}}{2L\{\alpha p_m + (1-\alpha)\} + (W_0 - 1)}. \tag{11}$$

Note that P_S in the miss detection only case depends on the l^{th} collision probability p_c $(l \geq 2)$ whereas it is not dependent on p_c in case of false alarm only. Hence, the miss detection affects both the right and left sides of the Markov chain in Fig. 3. On the right side of the chain, the stationary probability b_i for State S_i decreases as p_m increases. This has a similar impact of decreasing the CW size. On the left side of the chain, on the other hand, p_m increases the l^{th} slot collision probability p_c as shown in (4) and results in more collisions.

4. NUMERICAL RESULTS

In this section, we first verify our analysis in Section 3 using simulations, and investigate the throughput performance as a function of the physical layer sensing parameters p_f and p_m as well as other CSMA/CA parameters based on the analytic results. The CSMA/CA parameter setting in our analysis and simulation is shown in Table 1.

Fig. 5 shows the normalized throughput for the false alarm error only scenario. The solid lines represent the analytic results while the simulation results are shown with marks. It is seen that the simulation well matches our analysis based on the new Markov chain model. The throughput decreases as the false alarm probability increases since CSMA/CA transmitters become more conservative in channel use and lose the chances of successful transmissions.

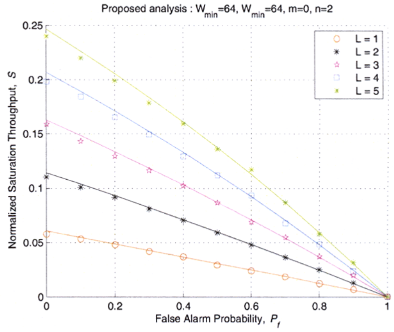

Fig. 5. Normalized throughput S in the false alarm only case ($0 \leq p_f \leq 1, p_m = 0$) - solid line: analysis, dot: simulation

Fig. 6 shows the normalized throughput for the miss detection only scenario. The simulation and analysis do not perfectly match in some cases, but the analysis well predicts the actual trend. The behavior of the throughput as a function of p_m depends on $\frac{L}{W_0}$. When $\frac{L}{W_0}$ is small, the throughput increases as p_m increases. This is because the increase in p_m results in the effect of shrinking the CW size by decreasing the backoff counter value although the channel is busy by another user. Since L is small compared with W_0 in this case, collisions during the packet transmission do not occur frequently. In other words, the utilization of channel is improved by being more aggressive in channel access. When L is large, on the other hand, the throughput is a decreasing function of p_m since collision in the middle of transmission happens frequently because of the large packet size compared with W_0.

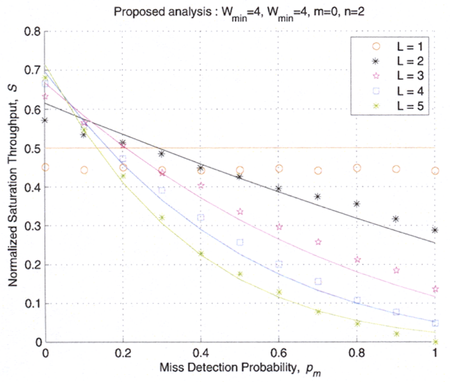

Fig. 6. Normalized Throughput S of a CSMA/CA network for miss detection only scenario ($p_f = 0, 0 \leq p_m \leq 1$) - solid line: analysis, dot: simulation

With the verification of our analysis, we examine the behavior of the throughput as a function of p_f and p_m for various sets of CSMA/CA parameters (L and W_0). Fig. 7 shows the throughput for the normal operating mode of carrier sensor. It is observed that the ratio $\frac{L}{W_0}$ of the packet length to the CW size is the critical parameter to determine the behavior of the throughput as a function of p_f and p_m. When the ratio is small, the throughput is insensitive to p_m whereas it is sensitive to p_f, as shown in Fig. 7 (a). When the ratio is large, on the other hand, the throughput is insensitive to p_f while it is sensitive to p_m, as shown in Fig. 7 (d). This is explained as follows. For a small value of L/W_0, the additional sojourning time in the backoff counter's decreasing states due to the extension effect caused by p_f is relatively large compared with small L, and the throughput is much dependent on p_f value. Since L is small, the chance of collision is already small and the effect of p_m is negligible. The opposite behavior for a large value of the ratio L/W_0 in Fig.7 (d) is explained similarly. Thus, p_f is the dominant factor for small L/W_0, whereas p_m is the dominant factor for large L/W_0.

At the intermediate values of the ratio L/W_0, the throughput is quite flat in both directions of increasing p_f and p_m near $(0, 0)$, and thus is insensitive both to p_f and p_m. These results suggest that the throughput loss by a poorly chosen sensing threshold, which determines p_f and p_m, is tolerable at the intermediate value of the ratio L/W_0. On the other hand, care should be taken in the design of the sensing threshold when L/W_0 is too large or too small.

5. CONCLUSION

We have analyzed the performance of the CSMA/CA protocol under carrier sensing errors. We have obtained the normalized throughput using a modified Markov chain model that captures two types of sensing errors: false alarm and miss detection. We have investigated the throughput as a function of the false alarm and miss detection probabilities. The behavior of the throughput as a function of the false alarm and miss detection probabilities depends on other CSMA/CA parameters such as the CW size W_0 and packet length L. It is shown that the ratio L/W_0 of the packet size to the CW size is the critical factor that determines the behavior of throughput as a function of p_m and p_f. The throughput loss by a poorly chosen sensing threshold is tolerable at intermediate values of the ratio L/W_0, whereas care should be taken in choosing the sensing threshold for too small or too large values of L/W_0. Simulation validates our analysis and the analysis model can be used to jointly optimize the sensing parameters and conventional CSMA/CA parameters to maximize the system throughput. Future works include the extension to N pair case, sensitivity analysis, etc.

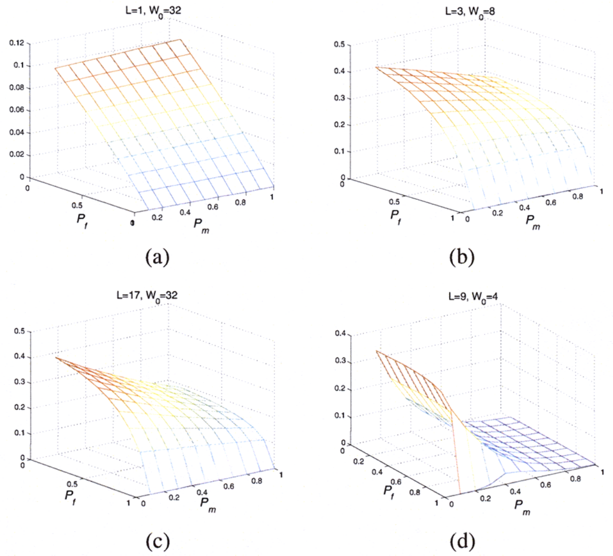

Fig. 7. Normalized throughput S of a CSMA/CA network in the sensor's normal operating mode: (a) $L = 1, W_0 = 32$ and $L/W_0 = 0.0313$ (b) $L = 3, W_0 = 8$ and $L/W_0 = 0.3750$ (c) $L = 17, W_0 = 32$ and $L/W_0 = 0.5313$ (d) $L = 9, W_0 = 4$ and $L/W_0 = 2.2500$

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