Performance Analysis of the Collision Avoidance Procedure of the Advanced Infrared (AIr) CSMA/CA Protocol for Wireless LANs

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***Abstract-* The Infrared Data Association (IrDA) Advanced Infrared (AIr) protocol for indoor optical wireless LANs is examined. AIr Medium Access Control (MAC) layer utilizes a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme to coordinate medium access. To deal with hidden stations, AIr employs a Request To Send / Clear To Send (RTS/CTS) reservation scheme and a long Collision Avoidance Slot (CAS) duration that includes the beginning of receiver's CTS packet. AIr employs linear adjustment of the Contention Window (CW) size to minimize delays emerging from the long CAS duration. This paper develops an analytical model for the Collision Avoidance scheme of the AIr protocol that computes throughput performance assuming error free transmissions and a fixed number of stations. The model is validated by comparing analysis with simulation results. By differentiating the throughput equation, optimum CW size that maximises throughput as a function of the number of the transmitting stations is derived. In the case of AIr protocol where a collision lasts exactly one CAS, different conclusions result for maximum throughput as compared with the corresponding conclusions for the similar IEEE 802.11 protocol. By employing the analytical model, throughput performance for various parameter values is evaluated. The proposed linear CW adjustment is very effective in minimizing delays emerging from empty slots and collisions during the contention period. Linear CW adjustment combined with the long CAS duration provides an effective protection from collisions caused by hidden stations and offers an attractive collision avoidance scheme.**

I. Introduction

The increasing usage of laptop computers leads to a demand for wireless LANs. Infrared Data Association (IrDA) has succeeded in developing standards for indoor infrared connections. IrDA has introduced the IrDA 1.x protocol stack for short range, narrow beam, low cost, high speed, point-to-point links. A large number of devices, including laptops, PDAs, printers, mobile phones and digital cameras, are equipped with an infrared port for their wireless information transfers [1]. IrDA has extended the IrDA 1.x protocol standard by proposing the Advanced Infrared (AIr) protocol stack for wireless LANs. A new physical layer, AIr PHY [2], is proposed that supports wide angle infrared ports. IrLAP, the IrDA 1.x data link layer is replaced by three sub-layers, the AIr Medium Access Control (AIr MAC) [3], the AIr link Manager (AIr LM) [4] and the Air Link Control (AIr LC) [5] sub-layers. IrDA 1.x IrLAP and AIr LC procedures for establishing connections and transferring data are transparent to upper layers.

AIr MAC coordinates access to the infrared medium by employing Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) techniques. A contending station reserves the infrared channel by using a Request To Send / Clear To Send (RTS/CTS) packet exchange, transmits a burst of data packets and terminates the reservation by using an End Of Burst /End Of Burst Confirm (EOB/EOBC) packet exchange.

The Collision Avoidance (CA) procedures of AIr MAC sub-layer define the behavior of a contending for medium access station. The contention period is slotted and a station can transmit an RTS packet only at the beginning of a Collision Avoidance Slot (CAS). AIr MAC defines a long CAS time period that includes the beginning of the CTS packet to avoid collisions from stations hidden from the transmitter that are not able to receive the RTS packet. A contending station first selects a number of CAS to defer transmission in an effort to minimize collisions. This number is randomly selected in the range (0,*CW*-1), where *CW* is the current Contention Window (CW) size. Stations adjust their current *CW* value based on the experienced collisions and successful reservations. AIr LM sub-layer is responsible for selecting *CW* values and passes them down to the MAC layer. AIr LM specification [4] suggests linear *CW* adjustment after a collision and a successful reservation.

This work focuses on the Collision Avoidance (CA) procedures of the AIr standard and develops an analytical model for the proposed linear CW size adjustment. The model evaluates AIr throughput performance assuming a finite number of stations and an error free infrared channel. The key approximation of this model is the assumption that a reservation attempt collides with a constant probability, which is independent of the number of collisions and successful reservations the station has experienced in the past. An analytical model based on the same assumptions for the exponential backoff adjustment algorithm of the IEEE 802.11 protocol is presented in [6][7]. Our model is validated by comparing simulation with analytical results. The analytical model is proven extremely accurate in evaluating AIr throughput performance for different network sizes. By setting the first derivative of the throughput equation equal to zero, the optimum CW size that maximizes throughput is derived. The analysis is also employed to determine the significance of link layer parameters, such as burst size and minimum CW size value, on throughput performance.

II. Description of AIr-MAC Protocol

The AIr Mac provides reliable and unreliable data transfer and reservation media access. Reserved transfer mode with Sequenced data is presented in fig. 1. Stations with user data first contend for medium access. The contention period is slotted and a station is allowed to transmit only at the beginning of a CAS. A station first selects a backoff number

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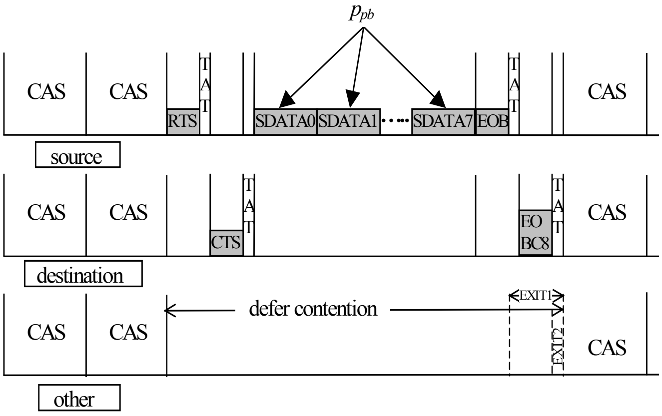


Fig. 1. Reserved Access scheme with Sequenced data (SDATA packets)

of CAS to defer transmission in order to minimise the collision probability with other transmissions. This backoff number is uniformly selected in the range (0,*CW*-1) and the backoff interval is assigned to CAS timer. *CW* is the current CW size and its value depends on the number of successful reservations and collisions experienced so far by the transmitting station. If during the deferral period another transmission is observed, the CAS timer is freezed and restarted when the on-going reservation is finished and the next contention period is started. When the CAS timer reaches zero, the station attempts to reserve the channel and transmits an RTS packet. The reservation time duration is contained in the Reservation Time (RT) field of the RTS packet. While a transmitter is sending a packet, it blinds its own receiver such that it can not receive remote infrared pulses. The receiving station waits a minimum Turn Around Time (TAT) to allow for the transmitter's receive circuitry to recover and responds with a CTS packet. The reservation period is echoed in the RT field of the CTS packet. Thus, stations being able to hear only the RTS or only the CTS packet refrain from transmitting for the entire reservation period, as shown in fig. 1. RTS/CTS packet exchange is employed to address the hidden station problem [9], which occurs when two stations are unable to hear each other.

After a successful RTS/CTS exchange, the transmitter waits a TAT delay, transmits a burst of data packets and requests termination of current reservation by transmitting a End-Of-Burst (EOB) packet. The receiver responds with an End-Of-Burst-Confirm (EOBC) packet confirming reservation termination.

The AIr Link Manager (LM) layer [4] is responsible for adjusting the CW size values. The adjustment algorithm should select 'proper' CW values for the current network size and network load based on whether the station's previous reservation attempts were successful or not. Small CW values will result in a very high collision probability and large CW values will result in a large number of empty CAS. AIr LM specification [4] does not provide rules for CW adjustment but suggests guidelines for increasing and decreasing CW after one or more collisions or successful reservation attempts. AIr MAC defines CAS time duration (σ) as being greater than the transmission time of the RTS packet plus TAT plus the amount of time required to detect the beginning of the returning CTS packet. Such a large σ time ensures that even a contending station hidden from the transmitter but not from the receiver will not cause a collision unless, of course, it had selected the same CAS.

III. Analytical Model

In this work, we concentrate on saturation throughput for a fixed number of stations n. In saturation conditions, every station always has a burst of packets ready for transmission. This saturation throughput performance figure is defined as the maximum load the system can reach in stable conditions. We also assume ideal channel conditions meaning that a non colliding packet is always received error free to all network stations. All stations always employ the Reserved transfer mode with Sequenced data although the analytical model can be easily altered to evaluate performance of the remaining reserved transfer modes supported by the AIr MAC. After a successful reservation attempt, a station transmits p_{pb} packets per burst of fixed payload size of l bits at a fixed data rate of C bit/s.

Based on AIr LM guidelines, the analytical model considers a CW size increase by 4 after a collision and a CW size decrease by 4 after a successful reservation. AIr LM specification also poses a lower limit of 8 slots (CW_{min}=8) and an upper limit of 256 slots (CW_{max}=256).

The key assumption used in this model is that an RTS transmission always collides with probability p regardless of the CW size used to select the deferral period for the reservation attempt. Our analytical model is divided into two parts. The first part considers the behavior of a single station to compute p and the stationary probability τ that a station transmits in a randomly chosen CAS for a network of n stations. Then, by examining the events that can occur in a randomly chosen CAS, throughput performance is expressed as a function of probability τ.

A. RTS Transmission Probability

Let $b(t)$ be the stochastic process that represents the backoff time counter for a specific station. Process $b(t)$ does not represent the remaining time before a transmission attempt but follows an integer time scale that represents the number of the remaining CAS before transmission. Time scale is also slotted; t and t+1 represent the beginning of two consecutive slot times. Every station increments t at the beginning of every CAS. This discrete time scale is not directly related to system time as a successful reservation may occur between two consecutive CAS. As explained earlier, when an incoming RTS packet is received, the CAS timer is freezed and restated again at the beginning of the CAS that follows the successful reservation. Thus, the time between two increments in the t scale may involve a successful reservation.

The backoff counter for every station depends on the collisions and on the successful reservation attempts experienced by the station in the past. As a result, process $b(t)$ is non markovian. We define for convenience W=CW_{min}. Let m be the 'maximum backoff stage' defined as CW_{max}=W+4m and we adopt the notation

$$W_i = W + 4i, \quad i \in (0, m) \tag{1}$$

where i is defined as the 'backoff stage'. As CW_{min}=8 and CW_{max}=256, W=8 and m=62. Let $s(t)$ be the stochastic process representing the backoff stage (0,...,m) of the station at time t.

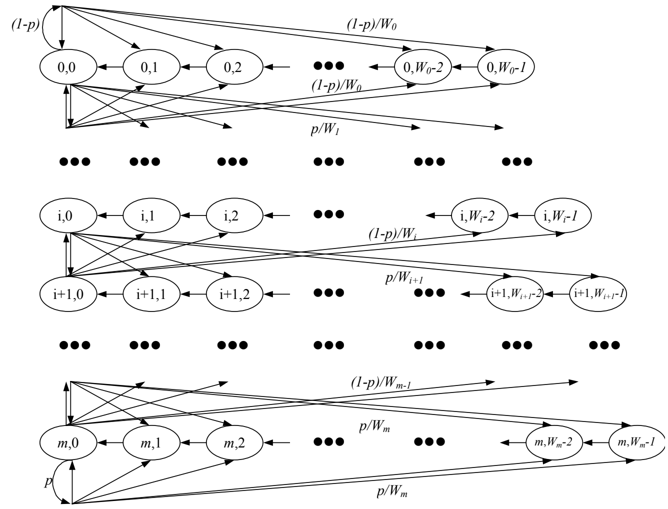


Fig. 2. Markov Chain model for backoff CW

The key approximation of this model is that a packet transmission collides with the same probability p regardless of the CW size used for this transmission. Based on this assumption and as p is assumed to be constant, the bidimensional process *{s(t),b(t)}* can be modeled by the discrete-time Markov chain presented in fig. 2. Adopting the short notation

$$P\{i_1, k_1 \mid i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1 \mid s(t) = i_0, b(t) = k_0\}$$

the only non null one-step transition probabilities are:

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 & k \in (0, W_i - 2) \quad i \in (0,m) \\ P\{i,k \mid i+1,0\} = (1-p)/W_i & k \in (0, W_i - 1) \quad i \in (0, m-1) \\ P\{i+1,k \mid i,0\} = p/W_{i+1} & k \in (0, W_{i+1} - 1) \quad i \in (0, m-1) \\ P\{0,k \mid 0,0\} = (1-p)/W_0 & k \in (0, W_0 - 1) \\ P\{m,k \mid m,0\} = p/W_m & k \in (0, W_m - 1) \end{cases} \tag{2}$$

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}, i \in (0,m), k \in (0, W_i - 1)$ be the stationary distribution of the chain. Owing to chain regularities,

$$b_{i0} = \left(p/(1-p)\right)^i b_{00}, \ i \in (0,m) \tag{3}$$

$$b_{ik} = \frac{W_i - k}{W_i} b_{i0}, \ i \in (0,m), k \in (0, W_i - 1) \tag{4}$$

Equations (3) and (4) express all $b_{i,k}$ values as a function of b_{00} and of probability p. To find b_{00} the normalisation condition can be applied

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{ik} \sum_{i=0}^{m} b_{i0} \frac{W_i + 1}{2} = \frac{b_{00}}{2} \sum_{i=0}^{m} \left(\frac{p}{1-p}\right)^i (W_i + 1) \tag{5}$$

and by substituting W_i from (1), after some algebra

$$1 = \frac{b_{00}}{2}\left[(W+1)\frac{(1-p)^{m+1} - p^{m+1}}{(1-2p)(1-p)^m} + \right.$$

$$\left. + \frac{4p(1-p)}{(1-2p)^2}\left(1 - \frac{p^m(1+m) - p^{m+1}(2m+1)}{(1-p)^{m+1}}\right)\right] \tag{6}$$

Equation (6) expresses b_{00} as a function of the conditional collision probability p, the smallest implemented contention window size W and the number of employed backoff stages m. Using the above analysis, the probability τ that a station transmits in a randomly chosen slot time can be evaluated. As a station transmits when the backoff timer reaches the value of zero,

$$\tau = \sum_{i=0}^{m} b_{i0} = b_{00} \sum_{i=0}^{m} \frac{p^i}{(1-p)^i} = b_{00} \frac{(1-p)^{m+1} - p^{m+1}}{(1-2p)(1-p)^m} \tag{7}$$

Substituting the value of b_{00} from (6) into (7), τ becomes

$$\tau(p): \tau = \frac{2}{W + 1 + \dfrac{4p\left((1-p)^{m+1} + (2m+1)p^{m+1} - (m+1)p^m\right)}{\left((1-p)^{m+1} - p^{m+1}\right)(1-2p)}} \tag{8}$$

Probability τ depends on collision probability p which is derived next. The probability p that a reservation attempt collides equals to the probability that at least one of the remaining n-1 stations transmit in the same slot time. Assuming that all stations "see" discrete-time Markov chain presented in fig. 2 in the steady state and transmit with probability τ in a randomly chosen slot time,

$$p = 1 - (1-\tau)^{n-1} \tag{9}$$

Equations (8) and (9) form a non linear system in the unknowns τ and p. The system can be solved by employing numerical methods evaluating τ and p for a certain W and m combination. The simultaneous non linear equations have a unique solution.

B. *Throughput Analysis*

Based on the station transmission probability τ and on the RTS collision probability p evaluated in the previous section, throughput efficiency can be evaluated. P_{tr} is defined as probability that at least one reservation attempt occurs in a given slot time. For a network of n stations, each transmitting with probability τ , P_{tr} is given by

$$P_{tr} = 1 - (1-\tau)^n \tag{10}$$

The probability P_s that an occurring RTS transmission is successful is given by the probability that one station transmits and the remaining n-1 stations remain silent provided that at least one transmission occurs in the channel:

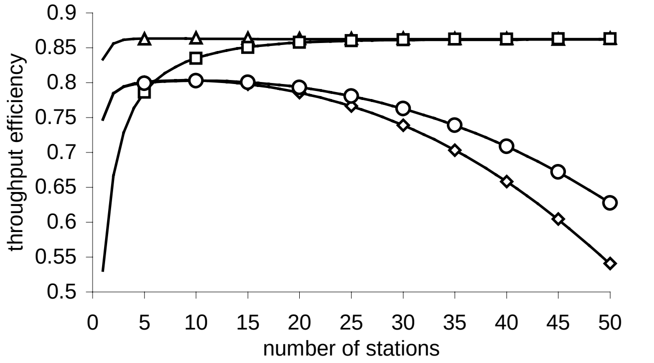
$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1 - (1-\tau)^n} \tag{11}$$

A successful transmission in a randomly selected slot occurs with probability $P_{tr}P_s$ and the time utilized in transmitting payload information is given by $P_sP_{tr}\ l\ p_{pb}/C$. The average slot duration can be evaluated by considering that with probability 1-P_{tr} the slot is empty; with probability $P_{tr}P_s$ the slot contains a successful transmission and with probability P_{tr}(1-P_s) the slot contains a collision. Thus, throughput efficiency S can be evaluated by dividing the time transmitting payload information in a slot time with the average slot duration

$$S = \frac{P_{tr} P_s l\, p_{pb} / C}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s)\sigma} \tag{12}$$

where T_s is the slot duration when a successful transmission occurs and σ is the CAS time duration. Equation (12) can be easily reduced to

$$S = \frac{P_{tr} P_s l\, p_{pb} / C}{P_{tr} P_s T_s + \sigma - P_{tr} P_s \sigma} \tag{13}$$



△ W=8, m=62, p_{pb}=8 □ W=64, m=62, p_{pb}=8
◇ W=8, m=4, p_{pb}=4 ○ W=8, m=5, p_{pb}=4

Fig. 3. Throughput efficiency: analysis versus simulation, l=16 Kbits, C=4 Mbit/s

When the Reserved transfer mode with Sequenced data is implemented

$$T_S = D + p_{pb}\left(F_S + l/C\right) \tag{14}$$

where D is the reservation overhead that includes the transmission time of the RTS, CTS, EOB and EOBC packets and the TAT delays that follow these packets and F_S is the transmission time of the SDATA packet overhead. According to AIr MAC specification, D=1.74 msec, F_S=0.25 msec and σ=0.8 msec.

III. Model Validation

The analytical model presented in the previous section is validated by comparing its results with that obtained using the AIr simulator developed in [10]. The simulator is written in C/C++ programming language and emulates station behavior as closely as possible. Fig. 3 shows that the analytical model is very accurate for AIr performance. Analytical results (lines) match with simulation results (symbols) for different W, m and p_{pb} values, even for networks having only a few stations. The analytical model calculates accurate results even for large initial CAS window size (W) values and for small backoff stage (m) numbers. Simulation results are obtained with a 95% confidence interval lower that 0.002.

IV. Optimum CW Size

Optimum CW size (W_{opt}) can be found by employing the analytical model for m=0 (no backoff stages). The key assumption of the analytical model that a reservation attempt collides with a constant probability always holds true when no backoff stages are considered. Throughput equation (13) can be rewritten as

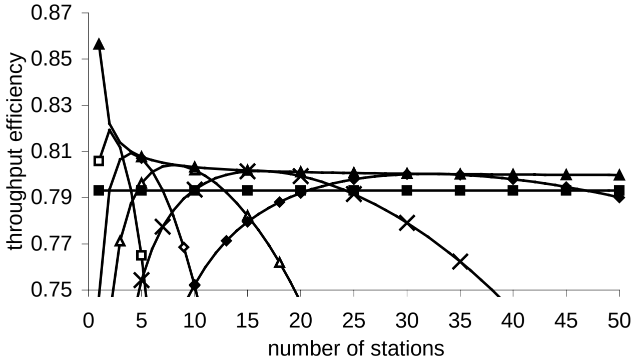
$$S = \frac{l\, p_{pb} / C}{T_s - \sigma + \sigma/(P_{tr} P_s)} \tag{15}$$

As l, p_{pb}, C, T_S and σ are constants, throughput is maximized when the expression

$$u = P_{tr} P_s \tag{16}$$

is maximized. By substituting P_{tr} and P_S from (10) and (11), (16) becomes

$$u = n\tau(1-\tau)^{n-1} \tag{17}$$



□ CW (slots)=4 ◇ CW (slots)=8 △ CW (slots)=16
x CW (slots)=32 ◆ CW (slots)=64
▲ maximum S_{max} ■ maximum S_{appr}

Fig. 4. Throughput efficiency versus n for fixed CW size, l=16 Kbits, p_{pb}=4, C=4 Mbit/s.

and by setting its first derivative versus τ equal to zero, after some algebra

$$\tau_{opt} = 1/n \tag{18}$$

When m=0, (8) reduces to

$$\tau = 2/(W+1) \tag{19}$$

Combining (18) and (19)

$$W_{opt} = 2n - 1 \tag{20}$$

Maximum throughput efficiency can be evaluated from (15) if we substitute P_{tr} and P_s from (10) and (11) for τ_{opt} given from (18)

$$S_{\max} = \frac{l\, p_{pb} / C}{T_s - \sigma + \sigma\left(n/(n-1)\right)^{n-1}} \tag{21}$$

Equation (21) shows that maximum throughput efficiency depends on the number of stations. However, for large n maximum throughput reaches a steady value. This conclusion is different to the expressed conclusion in [7][8] that maximum throughput is independent of n for the exponential backoff adjustment scheme of the IEEE 802.11 protocol. This is so although linear and exponential backoff schemes coincide when no adjustment (m=0) is allowed. Different conclusions arise from the approximations necessary for calculating maximum throughput in [7][8] because a collision lasts several CAS time periods in the 802.11 protocol. Fig. 4 plots throughput efficiency versus number of stations for fixed CW values and focuses on the maximum achievable throughput efficiency (note the different y-axis scale). It also plots S_{max} given from (21) and the approximated maximum throughput efficiency S_{appr} calculated by performing the approximations presented in [7][8] for AIr's physical and link layer parameter values. Figure shows that when collisions last exactly one CAS duration, as in the AIr protocol, the approximations result in a lower calculated throughput, especially for very small LANs.

V. Performance Evaluation

The effectiveness of the proposed CW size adjustment algorithm combined with the long CAS period is shown in fig. 5, which compares AIr with maximum throughput for

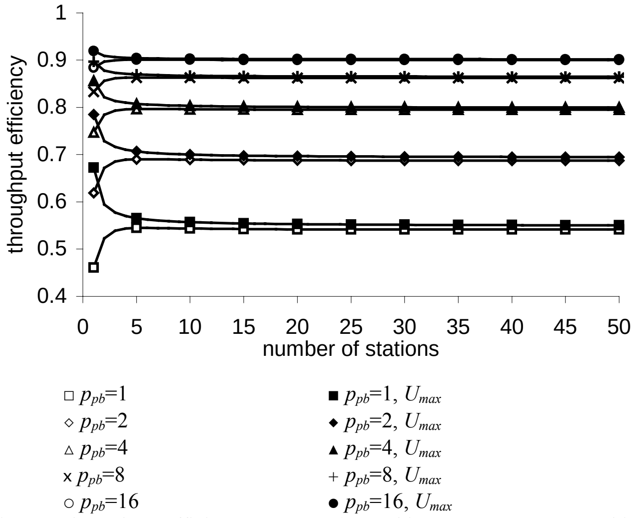


Fig. 5. Throughput efficiency versus n, l=16 Kbits, W=8, m=62, C=4 Mbit/s

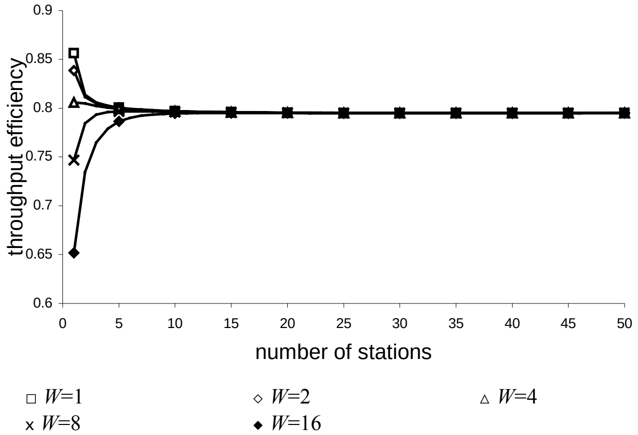


Fig. 6. Throughput efficiency versus n, m=62, l=16 Kbits, p_{pb}=4, C=4 Mbit/s.

different p_{pb} values. It reveals that AIr achieves throughput efficiency very close to the maximum for large networks. However, for LANs with a few transmitting stations, a significantly lower throughput is observed. Fig. 6 plots throughput efficiency versus network size for different CW_{min} (W) values. Figure shows that throughput is independent of W for large networks. It also shows that as W increases, throughput decreases for small networks. Significant throughput increase is observed by reducing W to one if only one or two stations contend for medium access, a usual case in real life wireless LANs. The situation is explained by considering that, for such small LANs, the proposed W value of 8 is significantly greater than the optimum W_{opt} value calculated by (20). Thus, throughput decreases due to the increased number of empty CAS. As a conclusion, for the considered network scenarios, W should be safely reduced to one in order to significantly increase throughput for small networks. Fig. 7 compares maximum throughput with throughput achievable when W is reduced to one. It shows that the achieved throughput is very close to the maximum. Direct comparison with fig. 5 shows that throughput efficiency is greatly improved for small networks due to the implementation of the lower W value.

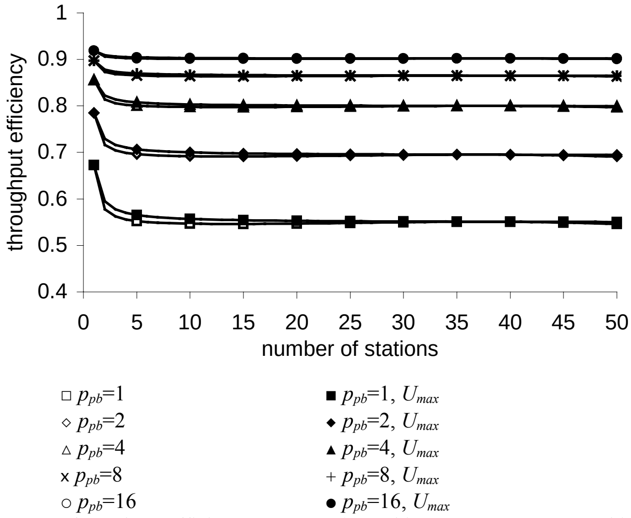


Fig. 7. Throughput efficiency versus n, l=16Kbits, W=1, m=20, C=4 Mbit/s

VI. CONCLUSIONS

This paper presents an analytical model to calculate AIr throughput performance assuming finite number of stations and error free transmissions. Comparison with simulation results confirms that the model predicts AIr throughput performance accurately. The model is employed to evaluate throughput efficiency for various network scenarios. Reducing the minimum Contention Window size increases throughput in LANs with a few transmitting stations. Results indicate that the proposed long Collision Avoidance Slot duration combined with the linear Contention Window adjustment are quite effective in achieving excellent throughput performance. Considering that this scheme also deals with collisions caused by hidden stations, it provides an efficient choice for Collision Avoidance procedures.

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