Proceedings of the 1997 Winter Simulation Conference
ed. S. Andradóttir, K. J. Healy, D. H. Withers, and B. L. Nelson

COLLISION AWARENESS MULTIPLE ACCESS NETWORKS PERFORMANCE OPTIMIZATION

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ABSTRACT

Collision awareness (CA) multiple access networks include the carrier sense multiple access (CSMA), ALOHA, and Ethernet networks. In order to maximize throughput with minimum network delay, these networks employ control parameters such as persistence and backoff. Based upon previous analytic results, the authors derived an asymptotic closed form solution for CA networks. It is demonstrasted that by dynamically changing the persistent value one can ensure that the offered traffic will stay optimal and hence protect the network from over saturation. This technique will greatly enhance the performance of CA networks. Opnet simulation is used to validate the analysis.

1 INTRODUCTION

Carrier sense multiple access (CSMA) protocol and its variations such as CSMA collision detection (CSMA/CD) are well known media access control (MAC) for local area networks. CSMA is also used in radio frequency (RF) voice and data networks. CSMA is known to be superior to other multiple access control techniques such as token ring, polling, and time division multiple access (TDMA) for networks with a large number of stations during lightly loaded periods (i.e., light traffic). One disadvantage of CSMA type networks is that as the total message traffic increases, the amount of message collisions also increases resulting in a degradation of network performance. Once the message traffic demand exceeds a certain limit often referred to as channel capacity, channel throughput diminishes and message delays increase. Overloaded CSMA networks would not recover gracefully and rapidly without some sort of operator intervention. This paper shows that collision awareness (CA) network such as CSMA and Ethernet (i.e., CSMA/CD) can be protected from traffic saturation and that degradation during peak demand can be minimized with a rapid and graceful recovery once the demand returns to normal. The performance of collision awareness networks are examined by the relation between offered traffic and network throughput. A generic closed form solution that is characteristic and asymptotic of the performance of all collision awareness networks is provided. The closed form solution enables the adoption of a dynamic persistent control to maintain optimal offered message traffic at any traffic demand intensity. The concept is validated with Opnet simulation on a radio frequency CSMA subnetwork.

2 COLLISION AWARENSS NETWORKS

A collision awareness (CA) multiple access network may be represented by Figure 1. A finite number of stations are sharing a common media (or channel). The demand from each station i is referred to as offered traffic g_i for the ith station whereas the throughput at station is denoted s_i. The value $c_i = g_i - s_i$ is the rate of collided messages at station i. The total channel throughput is $s = s_1 + s_2 + ... + s_m$ and the total offered message traffic is $g = g_1 + g_2 + ... + g_m$, where m is the number of stations on the network. Collided messages are retransmitted later with some backoff algorithm. A successful transmission is detected by the arrival of an acknowledgment message. The performance of a collision awareness network has been shown to relate closely to the distributions of both idle periods (I_k) and busy periods (B_k) of the media (or shared channel) [Kleinrock, 1976, 1979; Abramson, 1993]. Figure 2 illustrates the interleaving of idle and busy periods in a collision awareness network. In particular, for busy periods when a collision occurs, we have $B = Y + 1$ where Y is the time interval between the beginning of a busy period to the beginning of the last transmitted message in each busy period. Y is typically referred to as the vulnerable period.

To simplify the analysis, we will assume that the message arrivals may be approximated by Poisson distributions and each station operates independently with respect to other stations. In a collision awareness network, messages are typically transmitted under a *p-persisten* transmission protocol. Under such transmission protocol, messages that arrived during an idle period are transmitted with probability p while messages that arrived during a busy period will wait for the next idle period and then are transmitted with probability p. At the beginning of any idle period, a message is restrained from being transmitted with probability 1-p and will try again later with a backoff period b. Collision awareness network performance may be examined by the relationship between channel throughput and the probability of message collisions. Traditionally, the persistence value p is used as a channel control parameter to-prevent a station from attempting to take all available idle periods. The goal is to keep a collision awareness network from operating beyond its channel capacity using a proper backoff strategy. The collision awareness network performance in terms of its channel throughput and message delays is very sensitive to the setting of its persistent value p and its mean backoff delay b. When the network is lightly loaded, one would like to set the persistence value p as high as possible and the backoff delay b as short as possible whereas during saturated periods, one would like to set the persistent value small enough and backoff delay sufficiently large to protect the network from catastrophic performance degradation due to over-saturation. There is a constant dilemma in choosing the proper setting of the two key channel control parameters—the persistence value and backoff delay factor.

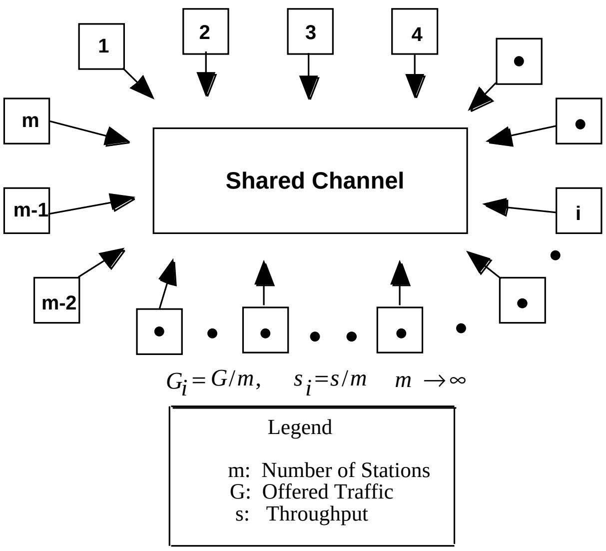

Figure 1: A Shared Medium Network Model

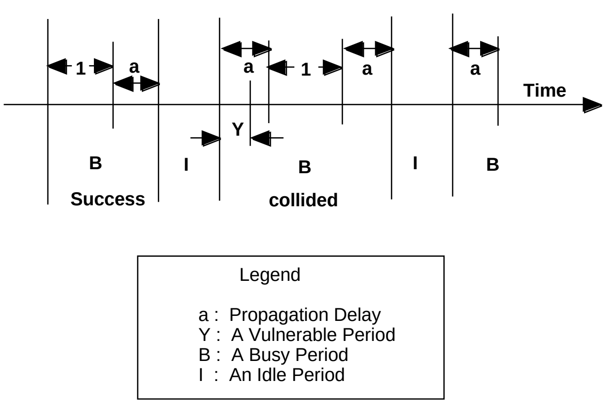

Figure 2: Collision Awareness Busy and Idle Periods

In this paper, the authors present an optimal strategy that will adaptively set both the persistence value and the backoff delay factor so that a collision awareness network will be operating at its maximum possible throughput regardless of the intensity of its total channel demand. With such a strategy, a collision awareness network may be overloaded; nevertheless, its shared medium will not be subjected to an excessive amount of demand beyond its optimal range. The network will be able to sustain indefinitely its maximum possible throughput without suffering the traditional throughput degradation. Moreover, such a collision awareness network will be protected from overload and recover rapidly as peak demands subside. The validation of these new concepts is demonstrated by simulation using a radio frequency CSMA network.

3 A GENERIC EQUATION FOR CA NETWORKS

The analysis of collision awareness network may begin with the network with a finite number of stations depicted in Figure 1. The message flow at station i may be illustrated by Figure 3. A summary describing the notations used in Figure 3 and other parts of the paper is provided here for clarity.

1) Let s_i, c_i, and g_i be the throughput, rate of collided messages, and effective offered message rate to the shared channel respectively at station i with $g_i = s_i - c_i$
2) Let p be the instantaneous persistence value and b be the mean backoff delay. In other words, with probability p the station will transmit a message at the beginning of the next idle period if there is any message awaiting transmission. With probability 1 -

p, the station will put itself in a wait state for an average of b units in time.

3) Let B and I be the length of average busy period and that of an idle period of the shared channel respectivelty.
4) Let G_i be the total offered message rate including the backoff demands $G_i(1 - p)/b$.
5) Let q_i be the probability of a transmission initiated by station I at the beginning of an idle period.
6) Let r_i be the probability of a successful transmission initiated by station i.
7) Let R_i be the number of retransmissions of the last message successfully transmitted at station i. In other words, R_i is the number of collided attempts prior to the arrival of an acknowledgment of the last message sent at station i.

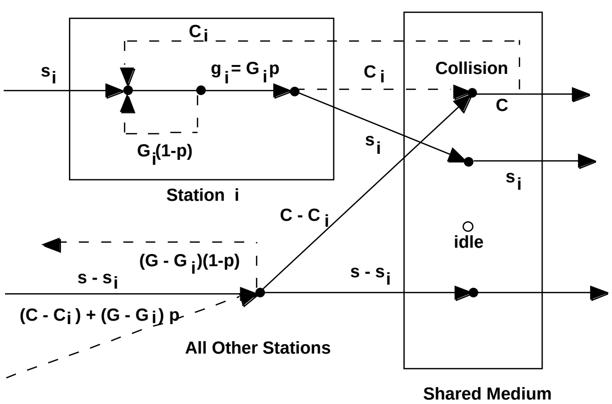

Figure 3: Messages Flow In A Collision Awareness Network

We now have the following equations relating G_i, p, g_i, s_i, c_i, R_i, q_i, r_i, and b.

$$G_i = s_i + C_i + G_i(1 - p)/b \tag{1}$$

$$g_i = pG_i \tag{2}$$

$$g_i / s_i = R_i + 1 \tag{3}$$

$$q_i = (1 - e^{-BG_i})p \tag{4}$$

$$r_i = q_i * s_i/g_i = q_i \prod_{j\neq i}^{m}(1 - q_j) \tag{5}$$

In particular, for uniformly distributed demands, we may assume that gi = g/m, Gi = G/m, si = s/m, qi = q, and rewrite equation (5) as

$$\begin{aligned} s &= g(1-q)^{m-1} = g[1-(1-e^{-BG/m})p]^{m-1} \\ &= g[1-pBG/m+O(1/m^2)]^{m-1} \end{aligned} \tag{6}$$

As m approaches ∞, equation (6) becomes an asymptotic equation relating s, g, B, G, and p, which applies to all collision awareness networks including ALOHA, CSMA, and CSMA/CD slotted or nonslotted. Asymptotically, we get:

$$s_a = \lim_{m\to\infty} s = ge^{-pBG} = ge^{-Bg} = pGe^{-pBG} \tag{7}$$

[Note that we use: $\lim_{m\to\infty} (1-x/m)^{m-1} = e^{-x}$.]

Equation (7) is an explicit equation of throughput s, busy period B, offered traffic G, effective traffic $g = pG$, and persistence p for collision awareness networks. It also allows us to determine optimal throughput s^* and the optimal persistence control parameter p^*. Optimal throughput will occur *when* $ds_a/dg = g(1-Bg)e^{-Bg} = 0$, which gives optimal throughput s^* where

$$s^* = g^*/e; \qquad g^* = p^*G = 1/B \tag{8}$$

Equation (8) is a generic expression for the optimal throughput of any collision awareness networks. In other words, any collision awareness network is optimal whenever the ratio of throughput to the effective offered traffic is equal to or less than $1/e$. This result is totally independent of the distribution of busy period B. One can verify its correctness by comparing it with the classic results for the slotted or nonslotted ALOHA networks or the slotted or nonslotted CSMA networks with or without collision detection (CD). In particular, average busy period of ALOHA networks is 2 with $s^* = 1/2e$ while the average busy period for the slotted ALOHA is 1 with $s^* = 1/e$. (Note that in all cases the average transmission time is normalized to 1.)

Based upon information derived from equations (1) to (8), we conclude that a strategy to achieve optimal g for all possible G may be stated as follows. From equation (8), optimal p for all possible G must achieve $g = pG = g^* = s^*e = se$, resulting in $p = es/G$. Clearly, p must be set inversely proportional to $R = G/s$ (³ g/s). The value g/s at station i is simply $g_i/s_i = R_i + 1$ in equation (3). Consequently, p may be inversely proportional to R_i while the backoff delay b should be set proportional to R_i. The two simplest functions that are inversely proportional to R_i are $p_1(R_i) = a/(c\,R_i + d)^k$ and $p_2(R_i) = af^{(cR_i + d)}$ with $f < 1$ and $1 \le c$.

In this study, we use Opnet simulation to determine the suitability of p_1 and p_2. On a very high frequency (VHF) CSMA network with 200 stations competing for a single channel of 31.5 kbps data rate, both functions do improve the total channel throughput. However, $p_1(R_i)$ did not reduce g fast enough and the network throughput slowly decreases as g increases steadily. Using $p_2(R_i)$with $a = e$, $f = 0.4$, $c = d = 1$, and $b = R_i$ reduces g within the optimal g^* and the network sustains the maximum possible throughput at $s^* = 0.4$ withoutn oticeable degradation in channel throughput long after the channel has reached its saturation point. In other words, the network is protected from the typical catastrophic degradation during a long and over saturation period and the maximum possible channel throughput is sustained regardless of the intensity of external arrivals and internal retransmissions of collided attempts. The value f in p_2 can be used as the key control parameter to ensure that maximum possible channel throughput g^* is maintained beyond the network saturation point.

4 AN OPNET SIMULATION

The concepts of using dynamic persistence and backoff control to limit the effective offered traffic demand at the maximum allowable level has been tested and validated with Opnet simulation on a VHF CSMA network for the next generation air/ground data communications design. Figure 4 illustrates such a network with one ground station and 80 aircraft. The ground station or an aircraft in Figure 4 is referred to as a node. Each node is simulated as a station shown in Figure 5. Messages are generated at the source according to a set of arrival and size distributions. A scaling factor is used to control the rate of message arrivals. The data link service (DLS) layer handles time out and the scheduling of retransmission. The MAC layer implements the *p-persistent* CSMA with backoff depicted in Figure 6. Collision and signal-in-space interference are handled by Opnet. The channel bandwidth is set such that the data rate is 31.5 kbps in simplex mode. The transceiver has a power level of 15 watts. The total demand on the shared channel for 200 aircraft is set to 60 kbps far exceeding the channel capacity. The VHF CSMA Opnet model was run for different *p-persistent* values and average message sizes (or the a value defined as the ratio of propagation delay to average transmission time).

Figure 7 illustrates the typical CSMA curve of throughput vs. offered traffic from the result of a sample run. The throughput (s) vs. offered traffic (G) curve of Figure 7 generated using a p value of 0.2 compares favorably with that predicted by a classic analytic equation [see Abramson,1993]. Since the network is clearly overloaded, a catastrophic performance degradation will occur shortly after some initial warm-up period. Figure 8 illustrates the diminishing of channel throughput s as a function of the simulation time. With the same network and message traffic demand, a different picture of channel throughput was observed as shown in Figure 9 when the dynamic persistence value of $p = e(0.2)^{R_i}$ with $b = R_i$ is used.

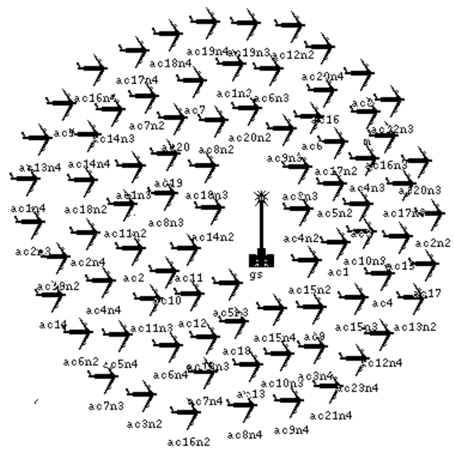

Figure 4 : A VHF CSMA Network

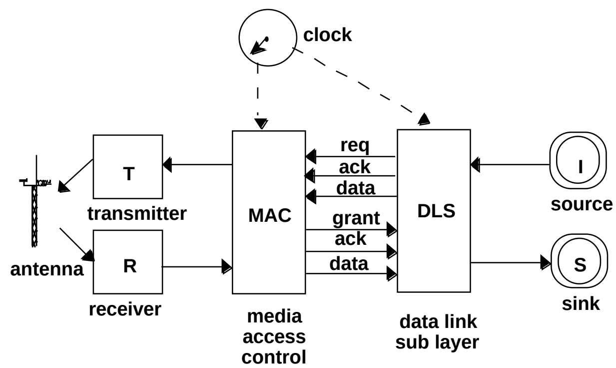

Figure 5: A VHF CSMA Network Node Model in Opnet

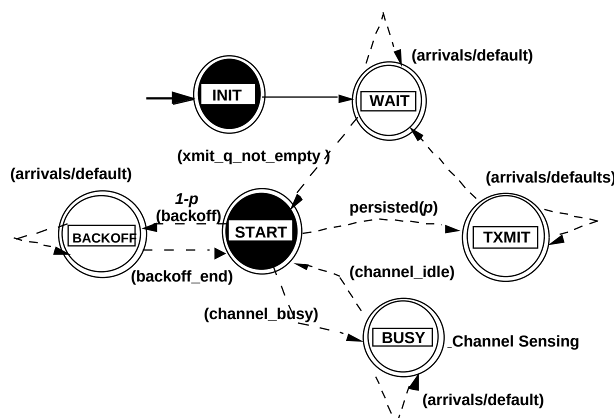

Figure 6: A VHF CSMA Network MAC Simulation In Opnet

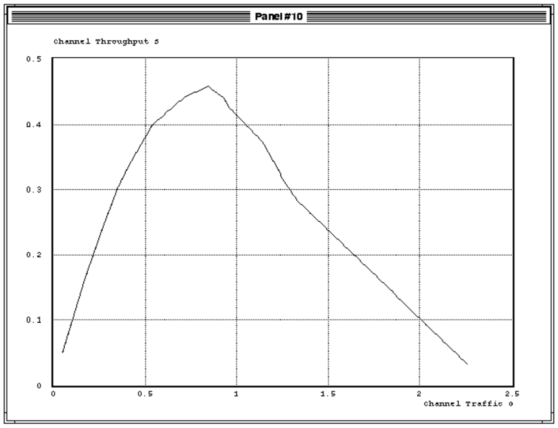

Figure 7:
A VHF CSMA Network With p = 0.2 and a = 0.084

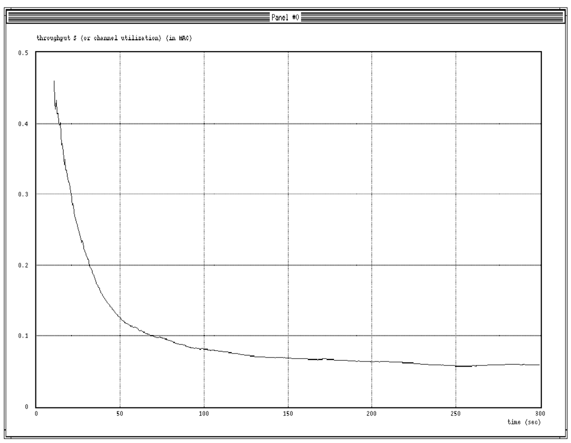

Figure 8:
Fixed Persistence Value Beyond Network Saturation

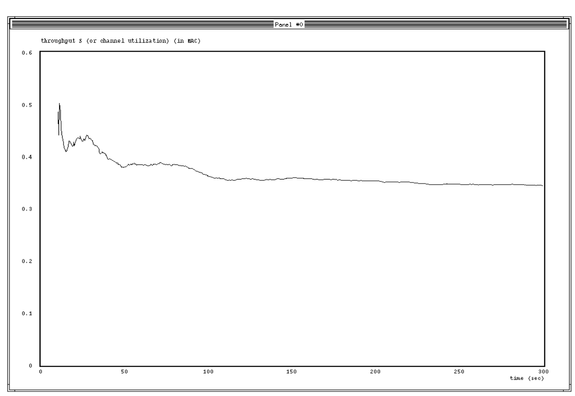

Figure 9:
Dynamic Persistence Control Beyond Network Saturation

Figure 10 illustrated the advantage of using the adaptive persistence value to protect the channel from being overloaded. Since the analysis provided in Section 3 is applicable to any CA network, one would also expect similar improvement in throughput over other CA networks such as CSMA/CD or ALOHA networks. As the channel throughput improves the average message delay must also be improved (i.e, decreased) accordingly.

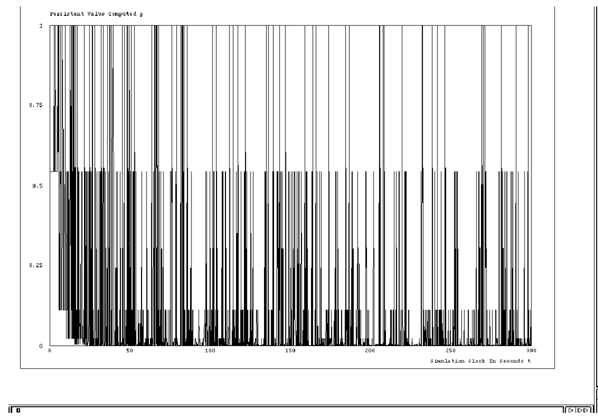

Figure 10:
Dynamic Persistence Control During Network Saturation

5 CONCLUSIONS

Using both analytic equations and simulations, the authors have demonstrated that dynamic persistence control can significantly improve the performance of collision awareness networks. In particular, near optimal channel throughput may be sustained indefinitely regardless of the intensity of the offered traffic. Consequently, the typical catastrophic performance degradation of collision awareness networks such as Ethernet, CSMA, ALOHA, and others can be avoided. A closed form solution that characterizes the channel performance of collision awareness networks is established and a procedure to protect a CA network from over saturation is provided and simulation of an overloaded VHF CSMA network is illustrated. The simplicity of this procedure offers small changes with significant benefits to the existing MAC protocols of collision awareness networks. Moreover, the procedure will also enhance the performance of a given CA network at low utilization prior to network saturation. Further fine tuning of the suggested adaptive persistence channel control parameters should be examined. \parindent=15pt Note: The contents of this material reflect the views of the authors. Neither the Federal Aviation Administration nor the Department of Transportation makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

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