Throughput and Delay Analysis for a New Efficient CSMA/CD Based Protocol

Hamid Barghi, IEEE Student Member, Jon G. Bredeson, IEEE Fellow
and William Cronenwett, IEEE Senior Member

The University of Oklahoma
Norman, Oklahoma

ABSTRACT
As the communication load on a local area network such as ETHERNET increases, the network moves very quickly toward instability. It is possible to increase the network throughput by the use of advance reservation. A Two-channel Reservation Network with Priority Access (TCRN/PA) is described which uses both two channels and advance reservation to increase network throughput with shorter delay than CSMA–CD. A contention channel (C-channel) carries the reservation broadcasts while a data channel (D-channel) delivers the transmitted data. Each D-channel transmission is restricted to a limited number of data packets so that no one station dominates the channel. Each station limits the number of unsuccessful attempts to transmit each C-channel request packet to 20. Data packets sent to each station for transmission are ranked according to their arrival time with older data sent at higher priority. The performance of TCRN/PA is compared with CSMA–CD based networks such as SRMA and ring and polling networks for identical system bandwidths and is found to give greater throughput as well as shorter delay, particularly at high throughputs.

NETWORK DEFINITION

Two channels and a first-in first-out memory (FIFO) form the Two Channel Reservation Network with Priority Access (TCRN/PA). A contention channel (C-channel) carries the reservation broadcasts, a data channel (D-channel) delivers the actual data, and a reservation table (R-table) records the priorities of message transmissions on the D-channel.

TCRN/PA operates as follows: A station with data to transmit broadcasts a small request packet which contains the station address, the length of the data packet, and a trailing group of CRC error check bits. The use of multiple reservation copies in the request packet reduces the probability of error in the C-channel and, therefore, in the R-table. When the request packet is successfully received by all stations, each station updates its R-table. The transmitting station then waits for the proper time slot according to the R-table and transmits the data packet on the D-channel.

The C-channel in TCRN/PA is based on the non-persistent CSMA–CD. The D-channel carries the actual messages. Only one station is permitted to transmit on the D-channel at any time. Thus, there is no contention between users to gain access to the D-channel and never any collision on the channel. A copy of the R-table is transmitted with every data packet. The R-table specifies which users have one or more reserved slots on the D-channel. The R-table works as a FIFO with each entry corresponding to one station. The length of the FIFO sets the maximum number of stations allowed to queue for the D-channel. If the R-table is full, no station is allowed to transmit any request on the C-channel until at least one entry becomes available. In this case packets generated are lost. Each user has a copy of the R-table in its memory and updates it if one of the conditions below occurs:

1. After a data packet is transmitted on the D-channel and the line is sensed idle, the current entry of the R-table is removed and all other entries move up one step.
2. After a request packet is successfully received by all stations, the first available entry is given to the user which transmitted the request.
3. If a user detects an error in its R-table, or if a user has just entered the network, the R-table is replaced with the information in the data packets on the D-channel.

Figure 1 shows the TCRN/PA in operation with the R-table at several different times. Note that the data packets can be of different sizes, but the request packets are all the same size.

Packets arriving at each station are ranked according to their arrival time. Thus packets which were created first have the highest priority. This ensures that transmitted packets have priority over newly arrived packets. Each transmission is limited to a fixed number of data packets so that no one station dominates the channel to the exclusion of other stations.

Figure 1. TCRN/PA in Operation.
To establish synchronization of control information at the proper time, and to maintain the correct count of packets in the queue in case of synchronization error, each station must report in its data packet information concerning the condition of its queue. This information can also be used by stations newly joining the queue. We assume here that all stations are synchronized on the time axis. Discussion of how time synchronization of the stations can be achieved is beyond the scope of this paper, but has been addressed at length in [1]. The channels are also assumed to be slotted with slot size equal to the maximum propagation delay of the channels. This assumption simplifies analysis of the network; in real situations, however, the channels may or may not be slotted. The following assumptions are needed in order to analyze TCRN/PA:
1. All reservation request packets have the same size, but data packets may have variable sizes.
2. There is no error due to channel noise.
3. Messages generated form a Poisson distribution.
4. Each station can only transmit or receive at any one time.
5. Each station can receive all other stations (no capture effect).
6. Collisions are destructive.
7. Random delay after collision is large compared to request packet time.
8. Only one data packet is generated at one time, and there is packet queuing at individual stations.
9. The state of the channel is sensed instantaneously.
10. Propagation delay of the channel is less than the request packet time.
11. The output of the C-channel is Poisson.

The variables used in the calculations are now defined: 
- \(T\) is the length of a slot in seconds.
- \(\lambda\) is the probability of a new packet arrival per second.
- \(\mu\) is the probability of a successful transmission during a slot in the contention period.
- \(T_c\) is the amount of time required for a request packet to be transmitted in slots, and \(T_d\) is the random variable for the time required for a data packet to be transmitted in slots with \(T_d\) average.
- \(g\) is the ratio of \(T_d/T_c\).
- \(s\) is defined as the average number of packets successfully received (without collision) on the C-channel per request packet time, \(S_c\) as the average number of packets successfully received on the C-channel per data packet time, and \(S\) as the average number of packets transmitted on the D-channel per data packet time. \(g\) is the average number of packets (new and retransmitted) on the C-channel per slot, \(G_c\) is the average number of packets on the C-channel per request packet time, and \(G_d\) is the average number of packets on the C-channel per average data packet time.
- \(D\) is the average number of request packet times required to transmit a request packet successfully, and \(D\) is the average number of data packet times between the time a data packet is generated and the time it is received by the receiving station.

### NETWORK THROUGHPUT

The C-channel is based on non-persistent Carrier Sense Multiple Access with Collision Detection. The analysis of CSMA–CD has been fully discussed in [2, 3]. A cycle is defined as a transmission period (either successful or unsuccessful) plus an idle period as shown in Figure 2. It takes one slot of time for the request packet to reach all the other stations. The collision detection is assumed to be instantaneous (with the first bit). At this time if no collision has occurred, the transmission will continue for \(T_c - 1\) more slots. One additional slot is required for all stations to sense the channel idle. If at the beginning of the first slot any other station senses the channel, it will find the channel available, thus a collision of packets will happen. In this case at the end of the first slot the transmitting stations will discover the collision and stop transmission. One additional slot will cause all other stations to sense the C-channel idle. Assuming an infinite model, all cycles are statistically identical.

![Figure 2. C-channel cycle.](image)

\[P_s = g e^{-\theta}/(1 - e^{-\theta})\]

The average idle period, \(\bar{T}\), is:
\[\bar{T} = e^{-\theta}/(1 - e^{-\theta})\]

The average transmission period, \(\bar{T_P}\), (either successful or unsuccessful) is:
\[\bar{T_P} = P_s T_c + (1 - P_s) 2 + 1\]
\[\bar{T_P} = [1/(1 - e^{-\theta})][g T_c e^{-\theta} - 2 g e^{-\theta} - 3 e^{-\theta} + 3]\]

C-channel throughput normalized to request packet time is then defined as:
\[s = P_s T_c / (\bar{T_P} + \bar{T})\]
\[s = (T_s g e^{-\theta})/(T_s g e^{-\theta} - 2 g e^{-\theta} - 2 e^{-\theta} + 3)\]

and C-channel throughput normalized to data packet time can be found from:
\[S_c = (T_s g e^{-\theta})/(T_d T_c g e^{-\theta} - 2 g e^{-\theta} - 2 e^{-\theta} + 3)\]

where:
\[g = G_c / T_c = G_d / T_d\]
The network throughput is defined as the average number of data packets received correctly during one data packet time. If on the average more than one reservation request packet goes through the C-channel during each data packet time, the D-channel will always have a packet to transmit in steady-state situations. Therefore, the throughput of the network will be equal to one, which is also the capacity of the network. If less than one request packet per data packet time arrives, the network throughput will be the same as the C-channel throughput normalized to the request packet time.

\[ S = \frac{(T_e/T_c)S_e}{qS_e} = s \quad S_e < T_e/T_d \]

If one request packet goes through the C-channel on average during a data packet time, the D-channel is always busy transmitting data packets. If on average more than one request packet arrives during each data packet time, the R-table will eventually overflow and the system will become unstable even though the network is operating at its maximum capacity. The network throughput normalized to the data packet time is given as:

\[ S = \frac{(T_2g - s^3)(T_2ge - 2ge - 2e^-s + 3)}{(T_2ge - 2ge - 2e^-s + 3)} \]

**NETWORK DELAY**

The network delay is broken into four parts: the average delay due to the individual station queuing \( D_x \), the delay of the request packet on the C-channel \( D_y \), the delay of the queue according to the R-table \( D_2 \), and the data packet transmission time on D-channel \( T_d \). Queuing at each individual station is modelled as an M/M/1/K system, where \( K \) is the number of packets allowed to queue at each station. From [10] we have:

\[ D_x = \frac{L}{\lambda_a} \]

where \( L \) is the expected number of packets in the queuing system in the steady state. Assuming the average service rate to be equal to the arrival rate, we find:

\[ L = \frac{K}{2} \]

and

\[ D_x = \frac{K}{2\lambda_a} \]

The average C-channel delay \( D_c \) can be found using non-persistent CSMA–CD definitions, and here the analysis is parallel to [2, 3]. The complete analysis is given in [4, 5, 6]. For slot size equal to maximum propagation delay \( T = 1 \) and in steady-state \( (S_e = \lambda T_c) \), we have \( D_c \) in terms of slots given by:

\[ D_e = T_e + 1.5 + 1/\mu - (1 - e^{-S_e/T_c})(2T_c/S_e + \mu - 3)/(2(\mu e^{-S_e/T_c} + 1/T_c + e^{-S_e/T_c} - 1) + S_e((T_e + 1)^2 + 2(T_c + 1)/\mu + (\mu^2 - 2\mu + 2)/2)[T_e - S_e(1/\mu + T_e + 1)] \]

The channel delay is not affected by \( \mu \) for channel throughput of less than 0.1, but when channel throughput increases, the channel delay increases for smaller \( \mu \). By using assumption 11, the D-channel delay has been formulated. The D-channel is modeled as a M/G/1 queue. Based on Pollock Khinchin analysis in [7], the average delay of the D-channel, \( D_d \), due to the combined delay of \( D_x \) and \( T_d \) is found to be:

\[ D_d = D_y + T_d = T_2[(1 + C^2)/(2 - 2S)] \]

where \( C \) is the coefficient of variation of the data packet length. For constant packet length we have \( C = 0 \), and so the delay is given by:

\[ D_d = T_2[(2 - S)/(2 - 2S)] \]

and for exponential packet length with mean of \( T_d \), \( C = 1 \).

\[ D_d = T_2[1/(1 - S)] \]

The total network delay \( D \) for constant packet length is,

\[ D = T_2[(2 - S)/(2 - 2S)] + D_x + D_e \]

**BANDWIDTH CONSIDERATIONS**

The C-channel does not require the same bandwidth as the D-channel. If it is necessary to divide the bandwidth, \( W_c \), of an existing channel (either cable or radio channel), the upper limitation of the bandwidth division can be expressed as follows,

\[ W_d = W/T_d(T_d + T_c) \]

\[ W_c = W/T_c(T_d + T_c) \]

where \( W_d \) and \( W_c \) are the bandwidth assignments for D-channel and C-channel respectively. However, since the C-channel has to operate at 100% (not possible), the bandwidth of C-channel should be increased to operate in the linear portion of the throughput versus traffic curve. Notice that if parallel channels are used, the large bandwidth of the C-channel will prevent the C-channel traffic from reaching the unstable point although the network is in saturation and operating at the maximum capacity of 1.

**NUMERICAL RESULTS**

Simulation studies prove the analytical model of TCRN/PA. Figure 3 shows the throughput of the C-channel against the offered traffic. There are no points provided.
by the C–channel simulation beyond channel traffic of 20 packets per packet time. The reason is that the C–channel becomes unstable when the increase in the traffic intensity causes the throughput to fall. The simulator can not operate in the unstable region because of the increasing number of collisions and the required computer time. Figure 4 shows the delay versus throughput for the C–channel.

![Figure 4. Delay versus throughput with simulation results.](image)

The network throughput has been plotted against the C–channel traffic in Figure 5. The delay versus throughput of the network is shown in Figure 6.

![Figure 5. Network throughput versus contention channel traffic.](image)

![Figure 6. Network delay versus throughput.](image)

As all these plots show, the numerical results of simulation are very close to the analytical model of TCRN/PA.

**PERFORMANCE COMPARISON**

A performance comparison of TCRN/PA with random access protocols is presented in Figures 7 and 8. A look at the graphs shows that TCRN/PA performs better than CSMA–CD when the throughput is above 50%. TCRN/PA performs better than slotted ALOHA for all throughputs.
Reservation networks are compared in Figures 9-11. Roberts' reservation ALOHA [9] has worked well in satellite use but its performance is not as satisfactory in local area networks. SRMA [8,9] with non-persistent CSMA shows the best performance in local area networks. TCRN/PA performs better than SRMA over all channel capacities. Also, TCRN/PA performs better than SRUC [11] regardless of the number of stations.
Figures 12 and 13 show comparisons of TCRN/PA with ring and polling networks for different values of M, where M is the number of stations. Here again TCRN/PA performs considerably better.

Figure 12. Performance comparison of TCRN/PA with register insertion ring networks for $M = 25$ and $M = 50$.

Figure 13. Performance comparison of TCRN/PA with polling networks for $M = 15$ and $M = 100$.

REFERENCES