

Performance of Contention Bus Networks with Baseband Captures

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Abstract

Power capture is the characteristic of one signal overpowering the others in contention for a receiver. In a multiple access network which employs contention protocol, occurrence of capture helps a receiver distinguish correctly one signal given that multiple transmissions overlap over the common channel. It has been reported in the literature that performance of radio networks could substantially be higher in the presence of captures than it is without captures. The captures involved in radio networks are primarily FM captures. In this paper, we examine the effect of baseband captures on performance of contention bus networks. In particular, we show that signal attenuations on a cable channel could produce a significant chance of captures and hence greatly lift the throughput.

1. Introduction

For communication networks that use contention protocols, such as ALOHA and various CSMA (carrier sense multiple access)[1], signal collisions occur randomly due to multiple transmissions overlapping in time. Normally, collisions result in a loss of channel capacity since all the signals involved in collisions are destroyed and have to be retransmitted. The capture effect is known as the phenomenon that, in the presence of a collision, a signal is received with acceptable accuracy if this signal has a sufficiently stronger power than its contenders at its receiver. The impact of this effect on random access protocols was first reported by Roberts [2] concerning ALOHA radio networks. With the capture effect, a collision may turn out to be a success, and thus the throughput of a given system should be higher than it is without the effect.

Abramson [3] studied the capture effect in packet radio channels where different distances between the users and the receiver cause different signal levels among contending packets. Kuperus and Arnbak [4] and Namislo [5] analyzed the capture effect on mobile radio networks where varying distances as well as channel fading cause

* The author acknowledges that this paper was based on the outcome of a senior research project supervised by Professor C. C. Lee.

different signal levels at the receiver. Shacham [6] analyzed the capture effect on the throughput-delay performance of a ground-radio star network in which captures are related to geometric locations of transmitters. Results were obtained for various capture capabilities for the receiver. All of these studies concluded that captures can greatly improve throughput of multiple-access networks.

Since the capture effect can improve channel utilization, an interesting question is whether or not it can be “created.” This question was first answered by Metzner [7] who proposed that users can be divided into two groups; one uses high transmitted power and the other low transmitted power. The high-power group then enjoys the benefit of captures when single user of this group collides with user(s) of the low-power group. The same idea was later generalized to more sophisticated networks [8-9] and to the cases where users are divided into more than two power groups [6]. To overcome the disadvantage of assigning fixed priorities to users, a random power selection approach was recently proposed and analyzed by Lee [10]. All these works [6-10] concluded that artificial means of producing captures could further the positive impact of capture effect on the throughput of contention networks.

So far, research work concerning capture effect consider, implicitly or explicitly, network environments for FM captures. In other words, emphasis has been placed upon radio networks. Captures in baseband transmissions caused by signal attenuations in wave-guided transmission media remain to be an unexplored issue. In this paper, we address this issue and study the effect of captures on contention bus networks. We assume that no repeater exists in the network and therefore applications are primarily on local area networks (LAN). In Section 2, we discuss the capture environment of contention bus LAN and present a capture model for baseband transmissions. In particular, practical constraints of LAN (cable attenuation rate and network size, in particular) limit the chance of captures to primarily cases where there are only two concurrent transmissions. However, with two simultaneous transmissions heading for different receivers, it may happen that both transmissions are successful due to “double captures.” In Section 3, we study the probability of capture assuming two simultaneous transmissions. Using the result of Section 3, we obtain in Section 4 the throughput of a contention bus network which complies with IEEE 802 standards for baseband bus networks.

2. The Capture Environment for a Baseband Bus

We shall consider a baseband packet-switched bus network which employs a contention protocol for channel access with no collision detection capability (like the one used in Ethernet). In addition, the channel is assumed to be slotted so that a collision always involves packets in their entirety.

Let D (meters) be the length of the bus and N the number of stations which are equally spaced on the bus. We label the stations such that the transmission distance between station i and station j is:

$$D(i,j) = |i-j| D/(N-1) \quad (1)$$

Let α (dB/meter) be the attenuation constant of the bus channel. All the stations use the same power level P (dBm) for packet transmissions. Then in the absence of collisions, the minimum received signal power is given by

$$P_{\min} = P - \alpha D \text{ (dBm)} \quad (2)$$

which is the case for communications between Station 1 and station N . Therefore, P_{\min} should be sufficient for a receiver to decode a packet. Baseband networks typically employ Manchester or differential Manchester signaling [1] for which the pulse amplitude determines signal power. Let $A_{\min} = K(10^{P/20})$ be the corresponding amplitude level for P_{\min} , where K is some constant depending on the dimension of amplitude used. When two colliding packets are present at the receiver of one of them with different amplitude levels, say A_1 and A_2 with $A_1 > A_2$, then the packet having A_2 is certainly destroyed, though the other may survive depending on the magnitude of $(A_1 - A_2)$. Specifically, if the interfering packet is the weaker one (i.e. the one having amplitude A_2), then it will reduce the strength of the packet of interest such that the latter has only $(A_1 - A_2)$ available for decoding. If

$$(A_1 - A_2) \geq A_{\min}, \quad (3)$$

then apparently the packet will be successfully received. We shall use (3) as the condition for capture, even though it is somewhat conservative.

For baseband bus LAN the network parameters are such that collisions involving more than two packets could not result in captures. Therefore, we will focus on the case where collisions result from two stations transmitting in the same slot. Let one of the transmissions be from station i to station j and the other be from station k to station q , where stations j and q need not be distinct. Then station j will be able to decode station i 's packet if

$$A(i, j) - A(k, j) \geq A_{\min} \quad (4)$$

where

$$A(m, n) = 10^{[P - D(m,n)\alpha]/20} \quad (4a)$$

is signal amplitude of the packet from station m when it arrives at station n . Likewise, station q will be able to decode station k 's packet if

$$A(k, q) - A(i, q) \geq A_{\min} \quad (5)$$

It is interesting to note that (4) and (5) may hold at the same time and thus two captures occur concurrently. This would be the case if the two communication pairs involved are sufficiently far apart. Nevertheless, the probability that only one of (4) and (5) holds is higher as will be seen in the next section.

3. The Probability of Captures

In this section, we evaluate the probability of captures when there are exactly two concurrent transmissions. Specifically, we shall obtain, for some practical network parameters, the probability p_1 that exactly one of the two transmissions is successful and the probability P_2 that both transmissions capture their intended receivers. We assume that every station in the bus network has an equal probability to transmit and that a transmission is equally likely to be addressed to any of the other stations on the bus. The analysis will begin with enumerating all the possible pairs of transmitter-receiver pairs $[(i,j), (k,q)]$. It is then followed by calculating the number of such pairs that would result in captures.

For convenience, we will use a quad-tuple (i,j,k,q) to represent concurrent transmissions from station i to station j and from station k to station q ; where $1 \leq i, j, k, q \leq N$. Apparently, the number of possible couplets (m,n) with $1 \leq m, n \leq N$ and $m \neq n$ (a station does not transmit to itself) is

$$m-N(N-1) \quad (6)$$

Therefore, with the constraint that $i \neq k$ (a station does not transmit two packets concurrently), the total number of possible quad-tuples is given by

$$M=m[m-(N-1)]/2 = N(N-1)^3/2 \quad (7)$$

Let Q be the set that contains all these quad-tuples with $|Q|=M$. In terms of capture effect, the set Q can be partitioned into three subsets:

$$Q = Q_0 \cup Q_1 \cup Q_2 \quad (8)$$

where Q_0 contains all the quad-tuples that produce no captures (i.e. both transmissions fail); Q_1 contains all the quad-tuples that produce exactly one capture (i.e. one packet is

successfully received, the other destroyed); and Q_2 contains all the quad-tuples that feature double captures (i. e. both transmissions are successful). Then we have

$$p_1 = |Q_1|/|Q| = 2|Q_1|/N(N-1)^3 \quad (9a)$$

and

$$p_2 = |Q_2|/|Q| = 2|Q_2|/N(N-1)^3 \quad (9b)$$

Unfortunately, explicit analytical expressions for $|Q_1|$ and $|Q_2|$ were found to be unattainable. In the Appendix, we present an algorithm that evaluates $|Q_1|$ and $|Q_2|$ and then computes p_1 and P_2 using (9a) and (9b) respectively. Basically, the algorithm inspects each element of Q and classifies it to Q_0 , Q_1 , or Q_2 according to (4) and (5). Listed in Table 1 and Table 2 are some numerical results for p_1 and p_2 . The network parameters used are as follows:

Table 1:

N= 50 stations
D= 500 meters (row 1) and 1000 meters (row 2)
 α = 0.0228 db/meter (standard 50-ohm, .4-in. diameter coaxial cable, e.g.,
RG-213/U, operated at 10MHz)

Table 2:

N= 50 stations
D= 200 meters (row 1) and 500 meters (row 2)
 α = 0.0456 db/meter (standard 50-ohm, .2-in. diameter coaxial cable, e.g.,
RG-58/U, operated at 10MHz)

It is seen that the probability of capture is very significant. This implies that a substantial number of collision events result in successful packet transmissions. Therefore, the channel throughput for the contention bus network should rise. In the next section, we study such throughput improvement on a slotted ALOHA baseband bus network.

4. Throughput of ALOHA Bus with Captures

The probability of captures obtained in Section 3 implies that a significant gain in channel throughput can be expected for contention bus networks. In this section, we examine this gain for networks that comply with IEEE 805 standard, 10base5 or 10base2 [11], for baseband bus LAN and employ slotted ALOHA for medium access. For 10base5

and 10base2 baseband bus systems, the channel rate is 10 MHz, the cable segment lengths are $D=500$ meters and $D=200$ meters, respectively, and the cable specifications are such that Tables 1 and 2 are applicable. In particular, we shall study $N=50$ stations case and use Tables 1 and 2 for throughput analysis of the contention bus networks under consideration.

Throughput analysis for slotted ALOHA is typically based on a Poisson packet arrival rate assumption [1]. Let G be the Poisson rate for packet arrivals, including new and retransmitted packets. Then, the probability of k transmissions within a slot is given by:

$$p(k)=G^k e^{-G}/k! \quad (10)$$

Without captures, $k \geq 2$ represents unsuccessful transmissions and thus, the channel throughput is given by:

$$S=p(1)= Ge^{-G} \quad (11)$$

which reaches a maximum of 0.368 at $G=1$ [1]. With potential captures, the throughput becomes:

$$S_c = p(1) + \sum_{k=2}^{\infty} p(k)q(k) \quad (12)$$

where

$$q(k) = \sum_{j=1}^k P_j \text{ captures } |k \text{ concurrent transmissions)} \quad (13)$$

With the bus network parameters assumed, it is readily shown that

$$q(k)=0 \text{ for } k \geq 3 \quad (14)$$

Therefore, we have for the baseband bus network under consideration:

$$S_c=p(1) + p(2)q(2) = p(1) + p(2)[p_1 + 2p_2] = Ge^{-G} + (p_1+2p_2)G^2 e^{-G}/2 \quad (15)$$

where p_1 and P_2 have been defined in Section 3 and can be computed by the algorithm in the Appendix. Recall that p_2 is the probability that both packet transmissions are successful given that there are exactly two concurrent transmissions. As far as channel throughput is concerned, two captures for two concurrent transmissions are double success, and hence the factor $2p_2$ in (15).

The maximum throughput (also known as network capacity) can be obtained by differentiating S_c with respect to G and solving for the zeros of this equation. This results in the value of G , namely G_m , where S_c is at its peak:

$$G_m = 1 - (1/p) + \sqrt{1 + (1/p^2)} \quad \text{where } p = p_1 + 2p_2 \quad (16)$$

which is then used to compute $S_{c(\max)}$ of the system. Listed in Table 3 are the values of p obtained in the previous section along with the corresponding G_m and $S_{c(\max)}$, where $p=0.0$ corresponds to no capture. We can see how captures impact the maximum throughput.

Figure 1 and Figure 2 show S (throughput without captures) and S_c (throughput with captures) versus traffic rate G for the 10base5 ALOHA bus and 10base2 ALOHA bus, respectively. It is seen that S_c (the middle curve) is significantly larger than S (the lower curve) except for small G 's where collision probability is insignificant. Also included in Figure 1 is the throughput S_c (upper curve) for $D=1000$ meters and in Figure 2 the same for $D=500$ meters. It is observed that throughput gain increases sharply with cable length. In fact, constraints on bus length are primarily due to attenuation considerations. Nevertheless, we have just shown that longer cable length could provide higher throughput for contention bus networks due to capture effect. Therefore, as long as P_{\min} (defined in Sec. 2) is acceptable for packet decoding, network designers and standardization organizations should seriously consider extending segment length for contention bus.

5. Conclusion

We have studied the effect of baseband captures on contention bus networks. We showed that signal attenuation on cable bus indeed cause significant probability of captures. Consequently, the channel throughput is substantially lifted by the events of capture. Although numerical results reported in this paper are restricted to baseband buses complying with IEEE 802 standards, the analysis is readily extendable to baseband buses with various parameters. It is expected that the probability of captures and hence the improvement on channel throughput would increase with cable length, provided that the same type of cable is employed and that P_{\min} is acceptable for packet decoding.

The problem considered in this paper is limited to natural captures. Like radio networks it may be possible to develop random-signal-level access methods [10] for contention bus networks so that the positive impact of capture effect can be furthered. In this direction, power constraint for the transmission medium will be a major factor, however. Another area of possible extension of this work is concerning the throughput analysis of baseband buses which employ more sophisticated contention protocols, such as 1-persistent, p -persistent, and non-persistent CSMA [1].

Fig. 1. Throughput vs Offered Load with and without captures

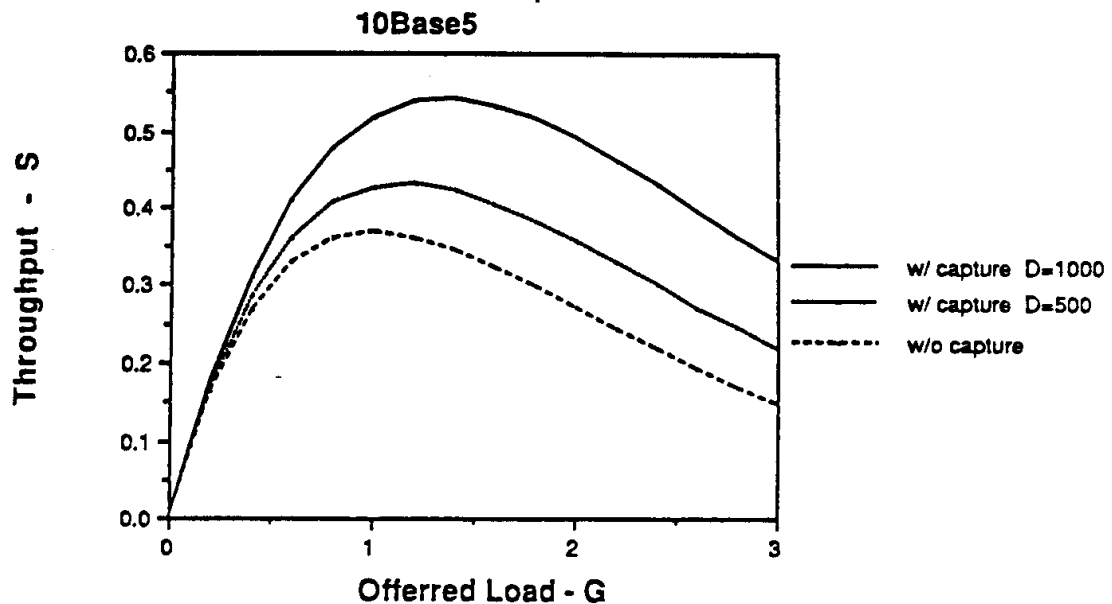
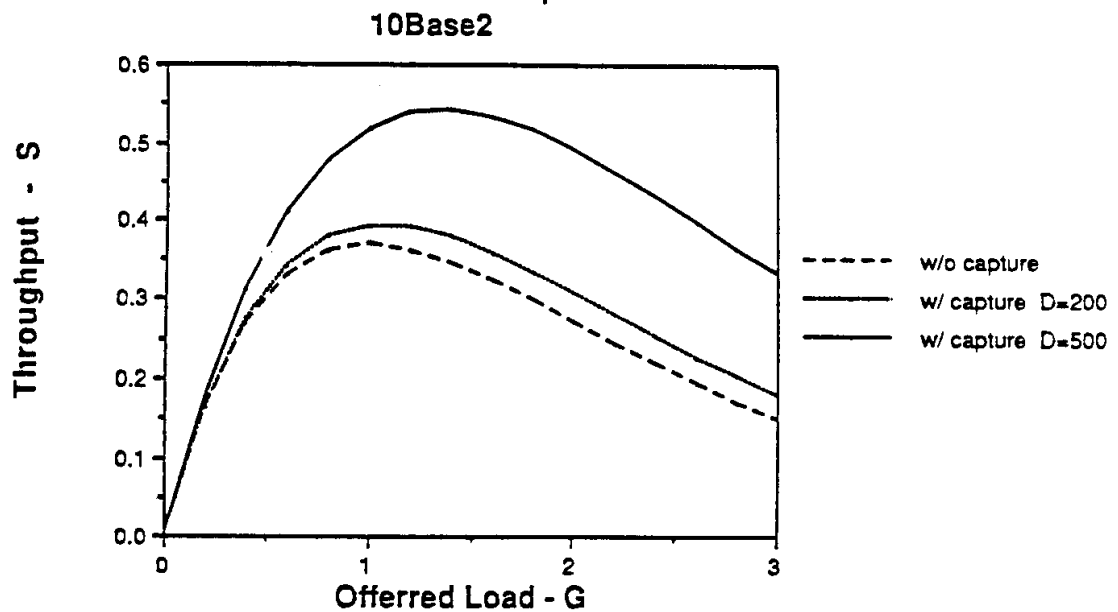


Fig. 2. Throughput vs Offered Load with and without capture



D	p_1	p_2
500m	0.229	0.0425
1000m	0.501	0.1552

Table 1

D	p_1	p_2
200m	0.1067	0.0130
500m	0.501	0.1552

Table 2

$p_1 = 2p_2$	G_m	$S_{c(max)}$
0.0	1.0	0.368
0.133	1.066	0.393
0.314	1.1535	0.430
0.812	1.355	0.542

Table 3

Appendix: Algorithm Compute Capture Probabilities

```

Var
    i,j,k,q:integer                    (indices for the quad-tuples)
    A(i,j):Array(1..100,1..100);      (array to hold the station distances)
    dum:Integer;                       (flag for categorizing into Q1 or Q2)
    Amin,                               (minimum amplitude receiver decodes)
    p1, p2:Real;                         (Probability of capture)
    Q,                                  (total number of quad-tuples)
    Q1,                                  (number quad-tuples with one capture)
    Q2:integer;                           (number quad-tuples with two captures)

Const
    N=50;                               (number of stations)
    D=500;                               (length of bus in meters)
    α=.0228;                             (rate of decay in db/m)

(create a function which calculates the distance between all the stations)
    Function D(i,j:integer):real
    Begin
        D=abs(I-j)“α”D/(N-1)
    End

Begin
    For i=1 to N do                      (create an array which holds the
        For j=1 to N do                  amplitude of a signal attar it
            A(ij)=10(P- D(i,j)α)/20        propagates from station i to station j)
        Amin=10(P-αD)/20;                (compute Amin)
        For i=1 to N do                  (count up all the quad-tuples)
            For j=1 to N do
                For k.=i+1 to N do
                    For q-1 to N do
                        if i≠j and k≠q then    (station can't transmit to itself)
                            begin
                                Q=Q+1;        (count quad-tuple)
                            end
                        (set flag then make the comparisons)
                        Dum=0;
                        if (A(i,j)-A(k,j) ≥ Amin then dum=dum+1;
                        if (A(k,q)-A(i,q)) ≥ Amin then dum=dum+1;
                        (Add one to Q1 if one of the comparisons were met)
                        if dum=1 then Q1=Q1 +1;
                        (Add one to Q2 if both comparisons were met)
                        if dum=2 then Q2=Q2+1;
                    end(f)
                end(for)
            end(for)
        end(for)
    end(for)
    p1=Q1/Q
    p2=Q2/Q

end.

```

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Biography

Dale Ward was born in Tacoma, Washington on August 18, 1965. He graduated from Henry Foss High School, in Tacoma, earning an International Baccalaureate diploma in 1984. He is currently a senior at Northwestern University and plans to graduate, with honors, in June 1988 with a Bachelor of Science degree in electrical engineering. The following September he will be pursuing graduate studies in electrical engineering at the University of California, Santa Barbara where he has been granted the state funded MICRO Fellowship. After completing the PhD program, he is interested in pursuing a research career in telecommunications. Mr. Ward is a member of Eta Kappa Nu, Air Force ROTC, and the Fraternity of Phi Gamma Delta.