Collision detection technique for multiple access protocols on radio channels

W F Lo and H T Mouftah outline a protocol that overcomes the difficulty of collision detection in radio channels

The carrier sense multiple access with collision detection protocol (CSMA/CD) has already gained wide commercial acceptance and is used in cable and optical-fibre based local computer networks. However, its use in radio channels is inhibited by the difficulty of sensing remote carriers in the presence of local transmission. A new collision detection technique for radio channels called time-split collision detection is introduced. Collision is detected by a sequence of carrier sense, preamble transmission and carrier sense again at the beginning of a packet transmission. Throughput analysis of a new multiple access protocol using time-split collision detection is also presented. The proposed protocol has throughput performance between those of the CSMA and CSMA/CD.

Keywords: computer networks, radio channels, CSMA/CD, CSMA/TCD

The carrier sense multiple access (CSMA) protocol[1] is a classical multiple access protocol for communication over a common radio channel. In CSMA, a node with a packet to send, or a ready node will listen to the channel first and transmit only if the channel is free. Collision is possible due to the non-zero propagation delay between the nodes. In cable-based CSMA/CD, a ready terminal not only senses the channel before transmission but also monitors the channel during transmission. Due to the small attenuation along the cable, collision can be detected by looking for abnormalities in power level, code violation or discrepancy between transmitted data and actual data on the cable. Improvements in throughput, delay, and stability performance by the inclusion of collision detection have been presented in Refs. 2–4. However, when collision detection is applied directly to radio channels, the signal from the local transmitter will overwhelm the receiver and disable remote carrier sensing.

Department of Electrical Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6

PROTOCOL DESCRIPTION

A new protocol called carrier sense multiple access with time-split collision detection (CSMA/TCD) is created to overcome the collision detection difficulty in radio channels. In CSMA/TCD a ready node will sense the channel, transmit a preamble if the channel is idle and then sense the channel again (see Figure 1). Data will be transmitted only if the channel is still idle in the carrier sensing period. The 'Access algorithm' is as follows:

```
Procedure Access( )
Begin
    If (channel has been idle for the last a units)
      or (the last transmission burst is longer than 2Tp
         and the channel is now free)
      Then Begin
           Transmit preamble of length Tp;
           Sense carrier for a period of Ts;
           If Channel is idle
             Then transmit_data( );
             Else reschedule_transmission( )
      end
      Else   reschedule_transmission( )
end,
```

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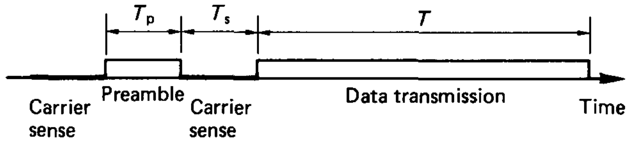

Figure 1. Timing diagram of CSMA/TCD

where a is the end-to-end propagation delay, T_p and T_s are the preamble and carrier sensing period respectively, each of which is longer than or equal to a.

The major assumptions for the analysis of CSMA/TCD protocol are:

A1) All terminals are uniformly distributed on a circular two-dimensional plane Γ of radius R, and area A_0,
A2) The propagation delay between any pair of nodes is proportional to their distance,
A3) The carrier detection time is δ units,
A4) All transmissions and receptions are omni-directional and all nodes are within range of each other,
A5) All packets are of fixed length and take T time units to be transmitted not including the carrier sensing and preamble overhead.
A6) It takes a time units for a transmission burst to clear the channel after the transmission has stopped.
A7) The channel is assumed to be idle throughout at the beginning of a busy period.
A8) The arrival process of the sum of the new and retransmitted traffic is assumed to be Poissonian.

A1 is introduced for the ease of analysis. A2 is different from the usual fixed propagation delay assumption for more detailed modelling. A4 to A7 are the usual CSMA[1] assumptions. A6 and A7 are introduced to simplify the analysis of the unslotted protocol. In the unslotted protocol, the end-to-end propagation delay a is used as the unit time. The unit time of the slotted protocol is taken to be the slot length L.

The way the protocol operates can be explained graphically. Contention from two nodes can be analysed by considering the propagation of the wavefront along a straight line through the two nodes on Γ. Figures 2–4 show the wavefront propagation along the straight line in time. Figure 2 shows the complete withdrawal, in which all the nodes involved in the contention sense the transmission attempt by other nodes and withdraw from the contention. When a node does not detect the transmission attempt from others, an incomplete withdrawal results as shown in Figure 3. Finally when more than one node start transmission very closely together in both space and time an undetected collision results (see Figure 4).

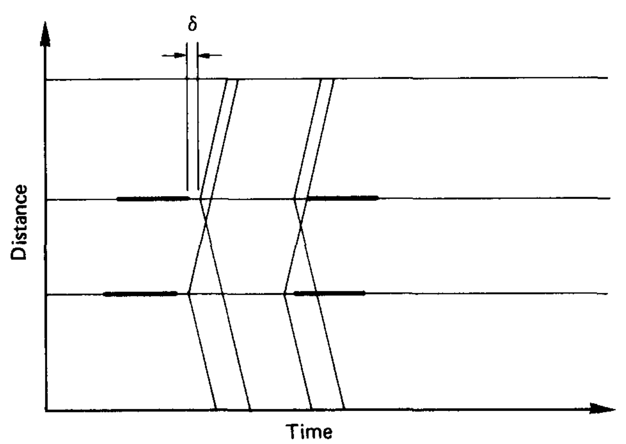

Figure 2. Complete withdrawal. Carrier sense: (———)

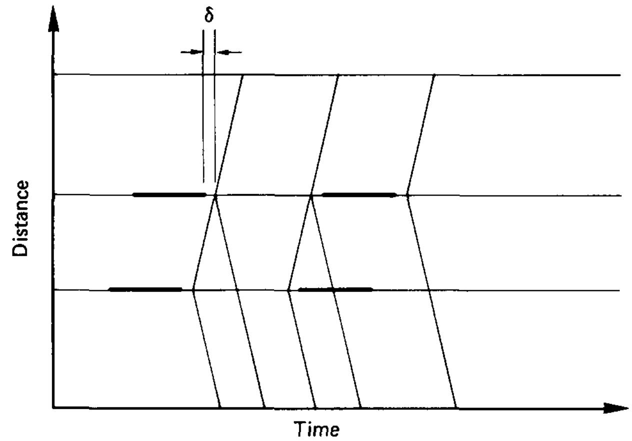

Figure 3. Incomplete withdrawal. Carrier sense: (———)

SLOTTED CSMA/TCD THROUGHPUT ANALYSIS

Similar to CSMA and CSMA/CD, the CSMA/TCD has a slotted and an unslotted version. In the slotted CSMA/TCD, the channel time is divided into fixed size slots of length L. All transmissions are synchronized with the beginning of a time slot. The time slot L is chosen to be the unit time, and $L = T_p = a + \delta$. All time quantities are normalized to L.

From renewal theory[6], the average throughput S is given by:

$$S = \frac{\bar{U}}{\bar{I} + \bar{B}} \tag{1}$$

where $\bar{I}$ is the average idle period and $\bar{B}$ is the average busy period. A cycle is defined as a busy period followed by an idle period (Figure 5). $\bar{U}$ is the average time in a cycle that is carrying useful information.

If the arrival process is Poissonian with g packets per slot; the probability of a busy period resulting in a successful transmission is the probability of exactly one arrival in a slot given that there is at least one arrival in the slot:

$$P_s = \frac{ge^{-g}}{1 - e^{-g}} \tag{2}$$

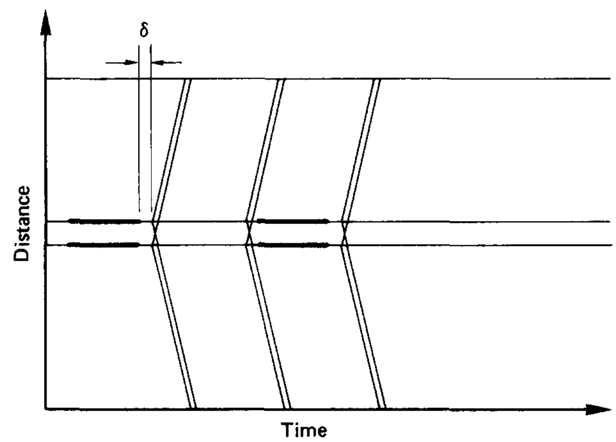

Figure 4. Undetected collision. Carrier sense: (———)

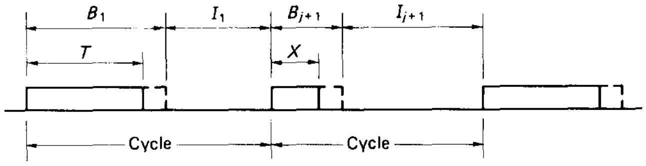

Figure 5. Busy and idle periods of the channel

The average time in a cycle carrying useful information $\overline{U}$ is given by:

$$\overline{U} = P_s T \tag{3}$$

The busy period for a successful transmission is $T + T_s + T_p + 1$, since it takes one slot to clear the channel at the end of a transmission. Similarly, the busy period for an unsuccessful attempt is $1 + x$, where $x = T_p + T_s$ is the collision withdrawal time. The average busy period $\overline{B}$ is given by:

$$\overline{B} = (P_s + P_{uc})(T + T_p + T_s + 1) + (1 - P_s - P_{uc})(x + 1) \tag{4}$$

where P_{uc} is the probability of undetected collision and will be evaluated later in the section. The idle period I is geometrically distributed with mean given by:

$$\overline{I} = \frac{e^{-g}}{1 - e^{-g}} \tag{5}$$

Substituting equations (5), (4) and (3) into equation (1) gives:

$$S = \frac{Tge^{-g}}{1 + ge^{-g}(T + T_p + T_s) + x(1 - e^{-g} - ge^{-g}) + P_{uc}T(1 - e^{-g})} \tag{6}$$

To evaluate the probability of a busy period resulting in an undetected collision, P_{uc}, consider the circular plane Γ that contains all the nodes. If a node starts transmission at location (x_0, y_0), it is able to detect transmission from nodes outside a radius of $2R\delta/a$ within the same slot, where R is the radius of Γ, δ is the carrier detection time and a is the end-to-end propagation delay. Let (x_i, y_i) be the coordinate of the ith arrival on Γ. A circle of vulnerability V_i can be defined for the ith arrival in a slot as a circle of radius $2R\delta/a$ centred at (x_i, y_i). In a slot with n transmission attempts, undetected collision results if and only if V contains more than one arrival, where $V = V_1 \cap V_2 \cap V_3 \cap \ldots \cap V_n$. Let $P_{uc}(n)$ be the probability of undetected collision given n arrivals in the slot. Assuming $\delta \ll a$, $P_{uc}(2)$ can be expressed as:

$$P_{uc}(2) = A_1/A_0 \tag{7}$$

where $A_1 = \pi(2R\delta/a)^2$ is the area of the circle of vulnerability and A_0 is the area of Γ. For $n > 2$, evaluation of the exact probability $P_{uc}(n)$ is very involved. However, an upper bound $P'_{uc}(n)$ can be derived using a simple argument. Consider the first arrival in a slot arrived at point P_1, for an undetected collision to occur, the second arrival must be located within a radius of $2R\delta/a$ from P_1. The third and subsequent arrivals must fall within a radius of $4R\delta/a$ from P_1, else the intersection of the circles of vulnerability is guaranteed to be empty. Thus, $P'_{uc}(n)$ can be expressed as:

$$P'_{uc}(n) = \frac{A_1}{A_0}\left(\frac{A_2}{A_0}\right)^{n-2} \tag{8}$$

where $A_2 = 4A_1$ is the area of a circle with radius $4R\delta/a$. Equation (8) only gives an upper bound because the condition for undetected collision. Taking the expectation of the $P'_{uc}(n)$ gives an upper bound to the probability of condition for undetected collision. Taking expectation of $P'_{uc}(n)$ gives an upper bound to the probability of undetected collision P'_{uc} as:

$$\begin{aligned} P'_{uc} &= E[P'_{uc}(n)] \\ &= \sum_{n=2}^{\infty} P'_{uc}(n) P_n \\ &= \frac{A_0}{16A_1}\,\frac{e^{-g}}{1 - e^{-g}}\,[e^{gA_2/A_0} - 1 - gA_2/A_0] \\ &= \frac{1}{64(\delta/a)^2}\,\frac{e^{-g}}{1 - e^{-g}}\,[\exp[16g(\delta/a)^2] - 1 - 16g(\delta/a)^2] \end{aligned} \tag{9}$$

where P_n is the probability of n nodes contending for the channel in a busy period and $P_n = g^n e^{-g}/n!\ (1 - e^{-g})$. Substituting equation (9) into equation (6) gives a lower bound for the throughput of slotted CSMA/TCD.

Numerical results of the throughput analysis are shown in Figures 6–8 by varying the value of an individual parameter in the standard parameter set. The standard parameter set used is $T = 20$, $T_s = T_p = 1$ and $\delta = 0.1$. Figure 6 shows the throughput of slotted CSMA/TCD for different packet lengths T. Figure 7 shows the effect of carrier detection time δ on the throughput. The probability of undetected collision for different δ is plotted against offered traffic in Figure 8.

UNSLOTTED CSMA/TCD THROUGHPUT ANALYSIS

The throughput analysis of the unslotted CSMA/TCD is based on the modelling of the wavefront propagation on the two dimensional plane Γ with time. In particular, the usual assumption of fixed maximum propagation delay between any pair of nodes is replaced by assumption A2 for more precise modelling.

Throughput analysis for $\delta = 0$

For simplicity of analysis, consider first the unslotted channel with $\delta = 0$. The throughput of the unslotted

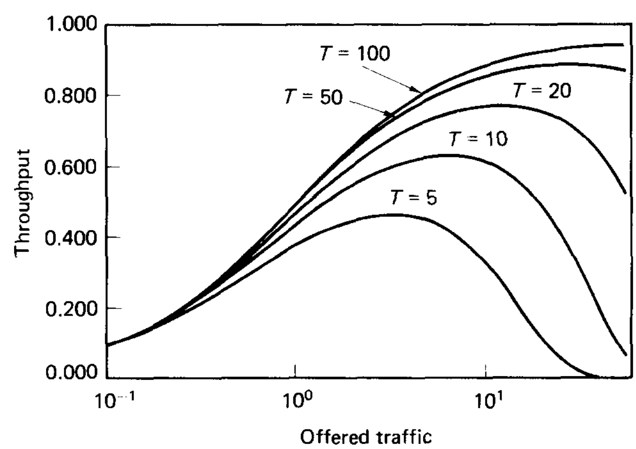

Figure 6. Effect of packet length on throughput for slotted CSMA/TCD

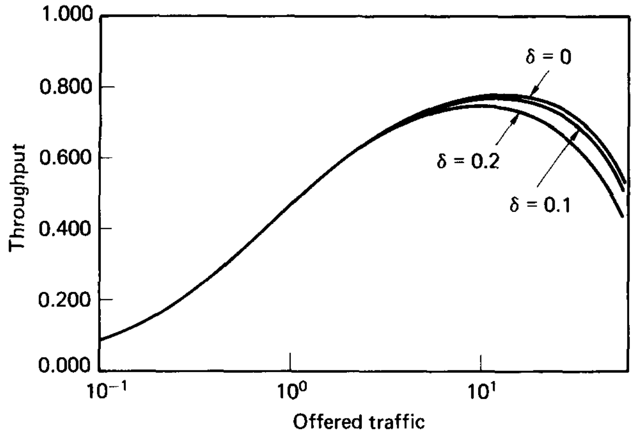

Figure 7. Effect of δ on throughput for slotted CSMA/TCD

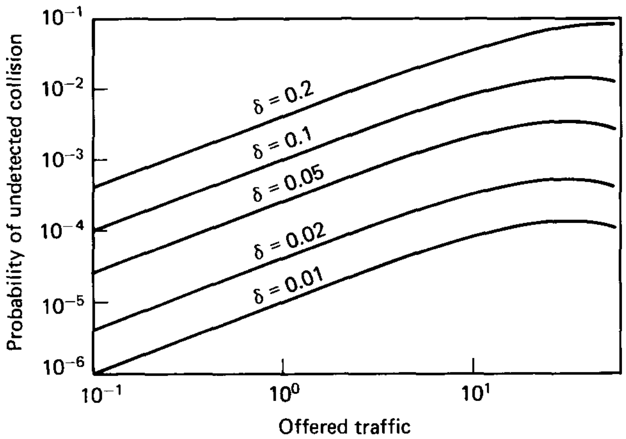

Figure 8. Probability of undetected collision of slotted CSMA/TCD

protocol can also be expressed in the form of equation (1). Here, the mean idle period is simply $\overline{I} = 1/g$, where g is the offered traffic in packets/slot. $\overline{U}$ can be expressed as $\overline{U} = P_s T$, where P_s, the probability of success for a busy period will be evaluated in the sequel. From simple probability arguments, $\overline{B}$ can be expressed as:

$$\overline{B} = (T + 1)P_s + (x + \overline{Y} + 1)(1 - P_s) \tag{10}$$

where x is the collision resolution time, and $\overline{Y}$ is the mean collision non-overlapping time as shown in Figure 9.

To evaluate P_s and $\overline{Y}$, we have to consider the wavefront propagation on Γ with time. Let terminal A, located at polar coordinate (α, ϕ), be the first terminal to attempt a transmission after an idle period. Figure 10 shows how the wavefront of terminal A has separated the three-dimensional space into the complete withdrawal region and the inhibited region. Another terminal, say C, attempting to transmit in the complete withdrawal region of A will result in the complete withdrawal of both terminals A and C after transmitting the preamble. If C attempts to access the channel in the inhibited region, it will sense the carrier from A and will not even transmit the preamble.

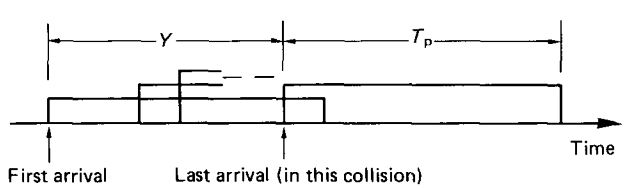

Figure 9. Collision non-overlapping time Y

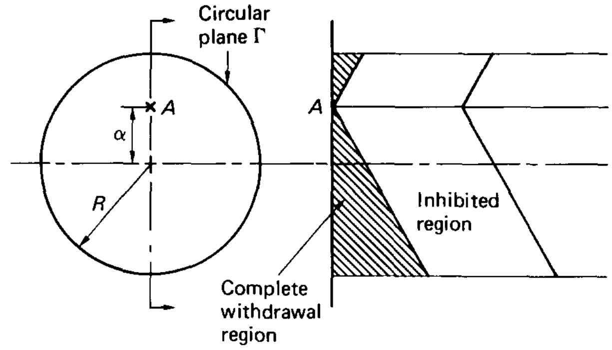

Figure 10. Complete withdrawal and inhibited region for δ = 0

Let the volume of the complete withdrawal region be $V_{cw}(\alpha)$. Defining $\theta(r)$ (see Figure 11) as:

$$\theta(r) = \begin{cases} 2\cos^{-1}\left(\dfrac{r^2 + \alpha^2 - R^2}{2\alpha r}\right), & R - \alpha < r < R + \alpha \\ 2\pi, & r \leqslant R - \alpha \end{cases} \tag{11}$$

$V_{cw}(\alpha)$ can be expressed as:

$$V_{cw}(\alpha) = \int_0^{R+\alpha} \theta(r)\, r^2/R\, dr \tag{12}$$

The number of nodes arriving in $V_{cw}(\alpha)$ is Poisson distributed with parameter $gV_{cw}(\alpha)/A_0$. Therefore, $P_s(\alpha)$ can be expressed as:

$$P_s(\alpha) = P[\text{a busy period is successful} \mid \text{it starts from radius } \alpha]$$

$$P_s(\alpha) = \exp(-gV_{cw}(\alpha)/A_0) \tag{13}$$

Since terminal A is equally likely to arrive anywhere on Γ, removing the condition on α we have:

$$P_s = \int_0^R P_s(\alpha) \cdot \frac{2\pi\alpha}{A_0} d\alpha \tag{14}$$

To calculate $\overline{Y}$, let us consider Figure 12. The volume of the shaded region $V_Y(y, \alpha)$ is given by:

$$V_Y(y, \alpha) = \int_{2yR}^{R+\alpha} \theta(r, \alpha)\, r\left(\frac{r}{2R} - y\right) dr \tag{15}$$

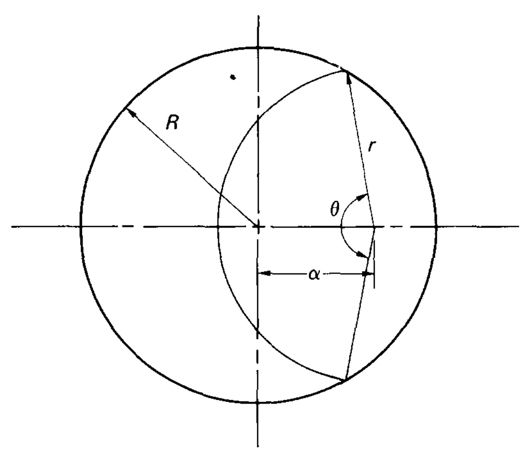

Figure 11. Definition of θ(α, r)

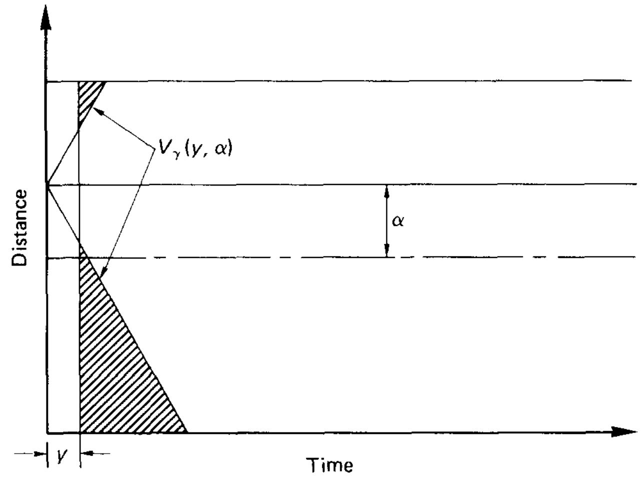

Figure 12. Regions determining collision non-overlapping time Y

From properties of the Poisson arrival process, the distribution function of Y is given by:

$$F_Y(y, \alpha) = P[\text{no arrival in } V_Y(y, \alpha \mid \text{at least one arrival in } V_{cw}(\alpha)]$$

$$= \frac{e^{-(g/A_0) V_Y(y,\alpha)}\left[1 - \exp\left(-\frac{g}{A_0}(V_{cw}(\alpha) - V_Y(y,\alpha))\right)\right]}{1 - e^{-(g/A_0) V_{cw}(\alpha)}} \tag{16}$$

Removing the condition on α we have:

$$F_Y(y) = \int_0^R F_Y(y, \alpha)\frac{2\pi\alpha}{A_0}\,d\alpha \tag{17}$$

$\overline{Y}$ can be expressed as:

$$\overline{Y} = \int_0^1 y\,dF_Y(y) \tag{18}$$

Thus the throughput given by equation (1) is completely specified.

Throughput analysis for δ ≠ 0

For the more general case of non-zero δ, the analysis is complicated by incomplete withdrawals and undetected collisions. In general, a transmission attempt results in one of five outcomes:

- successful transmission,
- complete withdrawal,
- incomplete withdrawal,
- incomplete withdrawal with undetected collision, and
- undetected collision.

The successful transmission outcome refers to the case of a successful transmission due to only one node attempting in the busy period. Incomplete withdrawal refers to only one node failing to detect the transmission attempt of other nodes in the busy period, and a successful transmission result. Incomplete withdrawal with undetected collision refers to more than one node failing to detect the transmission attempt of others in the busy period, and an undetected collision result.

Equation (1) is used again to determine the throughput. $\overline{I}$ is the same as the case of $\delta = 0$ and $\overline{I} = 1/g$. $\overline{U}$ and $\overline{B}$ can be expressed as

$$\overline{U} = (P_{s1} + P_{iw})T \tag{19}$$

$$\begin{aligned}\overline{B} = {} & P_{s1}(T + T_p + T_s + 1) + P_{uc}(T + T_p + T_s + 1 + \delta) \\ & + P_{iwuc}(T + T_p + T_s + 1 + \overline{Y}_{iwuc}) \\ & + P_{iw}(T + T_p + T_s + \overline{Y}_{iw}) + P_{cw}(x + 1 + \overline{Y}_{cw})\end{aligned} \tag{20}$$

where P_{s1} is the probability of success due to only one node transmitting in a busy period. P_{iw} is the probability of incomplete withdrawal. P_{uc} is the probability of undetected collision. P_{iwuc} is the probability of incomplete withdrawal with undetected collision. P_{cw} is the probability of complete withdrawal. $\overline{Y}_{iwuc}$, $\overline{Y}_{iw}$ and $\overline{Y}_{cw}$ is the mean collision non-overlapping time of incomplete withdrawal with undetected collision, incomplete withdrawal and complete withdrawal respectively.

Figure 13 shows the incomplete withdrawal and undetected collision regions. P_{s1} is the probability of no other arrival in the region R_{uc}, R_{iw} and R_{cw}. P_{s1} can be evaluated with a procedure similar to the evaluation of P_s in the case of $\delta = 0$. For the evaluation of P_{iwuc}, the R_{iw} of node A (see Figure 13) is 'thin' and may be approximated by a two dimensional plane. An approximation for P_{iwuc} can be evaluated by following a procedure similar to that used in the evaluation of P'_{uc} in the unslotted case.

Undetected collision occurs when there is one or more arrivals in A's undetected collision region and there is no arrival in the no-arrival zone (see Figure 13) to cause a complete withdrawal. The upper bound to the probability of undetected collision P'_{uc} is given by:

$$P'_{uc}(\alpha) = \left[1 - \exp\left(-\frac{g}{A_0}V_{uc}\right)\right]\exp\left[-\frac{g}{A_0}V_{na}(\alpha)\right] \tag{21}$$

$$P'_{uc} = \int_0^R P'_{uc}(\alpha)\frac{2\pi\alpha}{A_0}\,d\alpha \tag{22}$$

where V_{uc} is the volume of the undetected collision region and $V_{na}(\alpha)$ is the volume of the shaded region in Figure 14.

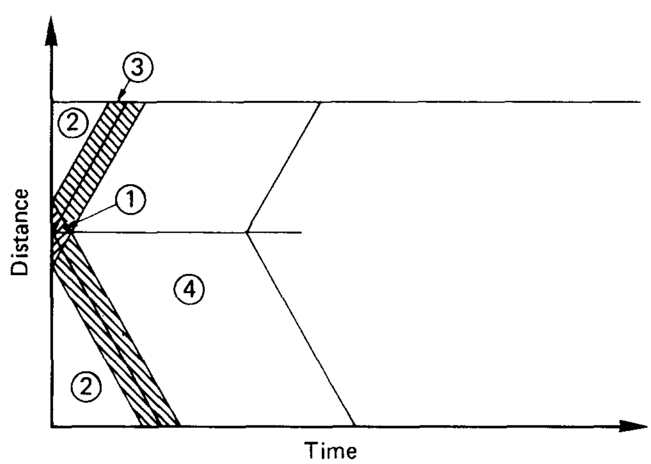

Figure 13. Different regions of a transmission attempt for δ > 0. ①: Undetected collision; ②: complete withdrawal; ③: incomplete withdrawal; ④: inhibited

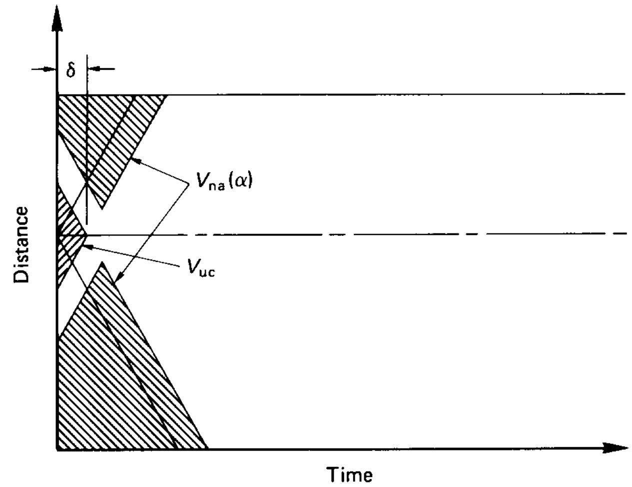

Figure 14. No-arrival region for undetected collisions

The exact probability of incomplete withdrawal is difficult to evaluate. A simple lower bound to P_{iw} is the probability of no arrival in R_{cw} and one arrival only in R_{iw}.

$$P''_{iw}(\alpha) = e^{-(g/A_0)V_{cw}(\alpha)} \frac{g}{A_0} V_{iw}\, e^{-(g/A_0)V_{iw}} \quad (23)$$

$$P''_{iw} = \int_0^R P''_{iw}(\alpha) \frac{2\pi\alpha}{A_0} \mathrm{d}\alpha \quad (24)$$

where P''_{iw} is a lower bound to P_{iw}. The lower bound given above is not very tight and could be improved by substituting $V_{cw}(\alpha)$ with a smaller volume as in Ref. 7.

Since the five outcomes of a transmission attempt listed at the beginning of the subsection includes all the possible outcome, P_{cw} can be expressed as:

$$P_{cw} = 1 - P_{s1} - P_{uc} - P_{iwuc} - P_{iw} \quad (25)$$

The only unspecified terms left in equation (20) are the collision non-overlapping times $\overline{Y}_{iwuc}$, $\overline{Y}_{iw}$ and $\overline{Y}_{cw}$. Since $\overline{Y}_{iwuc}$ is weighted with P_{iwuc} in equation (20), and P_{iwuc} is much less than unity, approximating $\overline{Y}_{iwuc}$ with its maximum value of unity does not introduce much error. $\overline{Y}_{iw}$ can be evaluated by following with an argument similar to $\overline{Y}$ for the case of $\delta = 0$. $\overline{Y}_{cw}$ can be evaluated indirectly by first evaluating $\overline{Y}_{w}$ the collision non-overlapping time for both complete and incomplete withdrawal, and obtaining $\overline{Y}_{cw}$ from the following relationship:

$$P_w(\alpha)\overline{Y}_w(\alpha) = P_{iw}(\alpha)\overline{Y}_{iw}(\alpha) + P_{cw}(\alpha)\overline{Y}_{iw}(\alpha) \quad (26)$$

where $P_w(\alpha) = P_{iw}(\alpha) + P_{cw}(\alpha)$.

The throughput for different packet lengths is shown in Figure 15. Figure 16 shows the effect of δ on throughput of the unslotted CSMA/TCD. From figure 16, the curve of highest throughput corresponds to δ = 0.1 rather than δ = 0. This is mainly caused by the presence of incomplete withdrawal for non-zero δ conditions, which contributes to successful transmission. The upper bound for the probability of undetected collision P'_{uc} is plotted against offered traffic for different values of δ in Figure 17.

SIMULATION RESULTS

Extensive simulation has been performed to validate the analytical results derived in the previous sections. The simulation program, or simulator, is written in FORTRAN 77 based on event driven simulation technique. The operation of the protocol is modelled at the level of wavefront propagation on Γ with time. A common simulator is used to simulate both the slotted and the unslotted protocol. An additional constraint is applied to the slotted protocol for aligning the start of each transmission to a slot boundary. For the slotted protocol, assumptions A6 and A7 are always true and the simulation and analytical models are equivalent. For the unslotted protocol, assumptions A6 and A7 are not assumed in the simulation. Because of the relaxation of these simplifying assumptions, the simulation results are more realistic than their analytical counterparts. The simulation throughput is

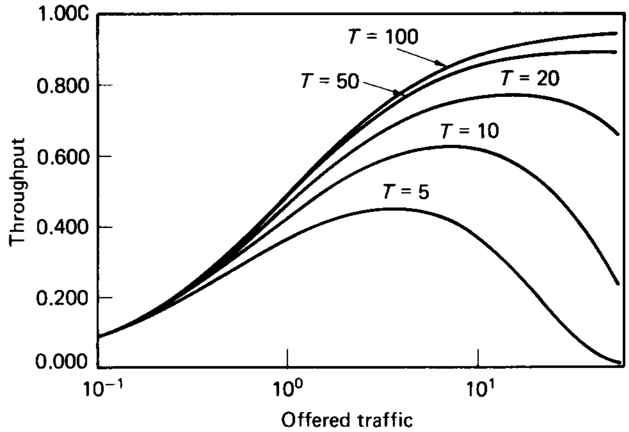

Figure 15. Effect of packet length on throughput for unslotted CSMA/TCD

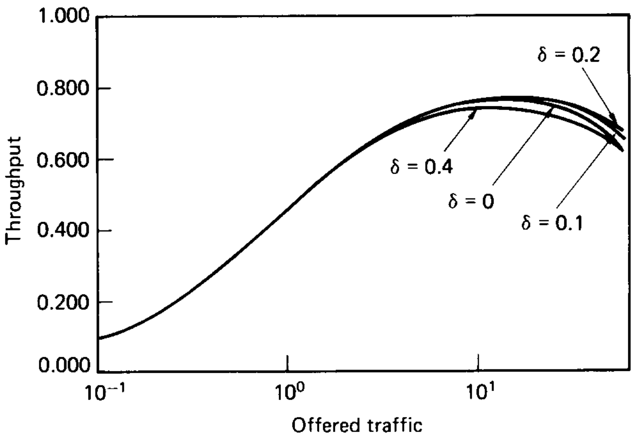

Figure 16. Effect of δ on throughput for unslotted CSMA/TCD

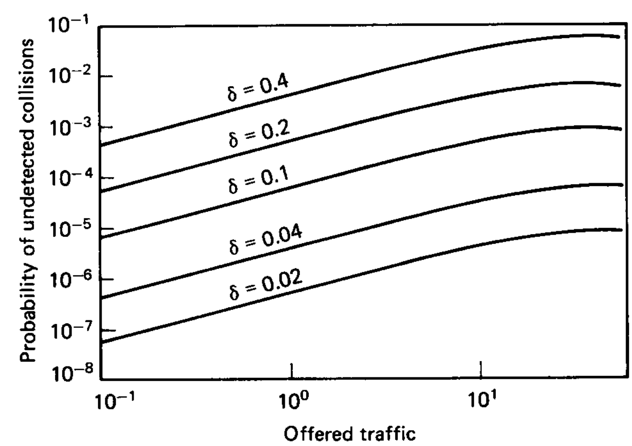

Figure 17. Probability of undetected collision of unslotted CSMA/TCD

compared with the analytical throughput together with the 95% confidence interval for the slotted and unslotted protocol in Figures 18 and 19 respectively. Throughput of the *p*-persistent CSMA/TCD is also studied with simulation. The effect of *p*-persistence on unslotted CSMA/TCD is shown in Figure 20.

In the classical analysis of CSMA[1], the slotted CSMA is shown to support a higher throughput than the unslotted CSMA. However, the analytical results of the CSMA/TCD

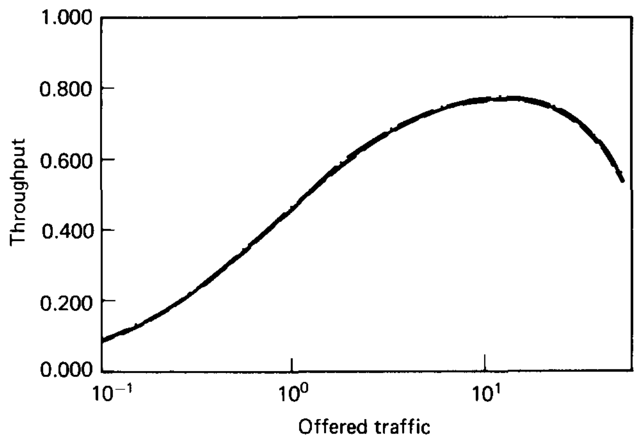

Figure 18. Comparison between analytical and simulation throughput for slotted CSMA/TCD (T = 20, δ = 0.1). Simulation: (———); 95% confidence interval: (- - -); analytical: (- · - · - ·)

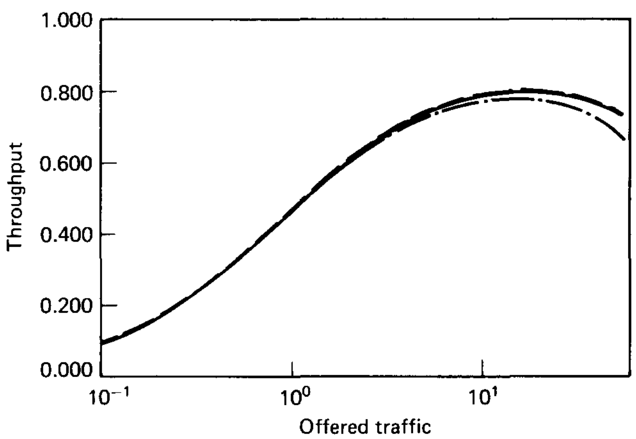

Figure 19. Comparison between analytical and simulation throughput for unslotted CSMA/TCD (T = 20, δ = 0.1). Simulation: (———); 95% confidence interval: (- - -); analytical: (- · - · - ·)

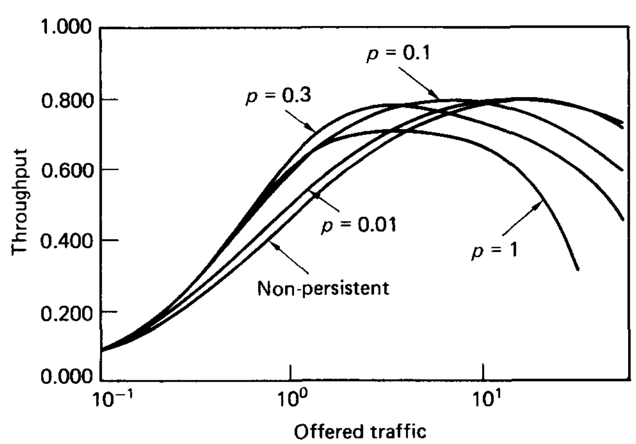

Figure 20. Effect of p-persistence on unslotted CSMA/TCD throughput

show that the unslotted protocol outperforms the slotted protocol at least in the higher offered traffic region. The discrepancy is due to the different assumptions in propagation delay. In Ref. 1 the propagation delay between any pair of nodes is assumed to be equal to the maximum end-to-end propagation delay. The distance-proportional propagation delay assumption (A2) used in the unslotted CSMA/TCD analysis in the previous section allows more accurate modelling of the protocol operation. Despite the distance-proportional propagation delay, assumptions A6 and A7 are still underestimating the throughput of the unslotted protocol. Simulation results show that the unslotted protocol actually provides a higher throughput than the slotted protocol at all levels of offered traffic.

CONCLUSIONS

The CSMA/TCD supports a higher throughput than the classical radio channel CSMA protocol. The new protocol requires no extra hardware over CSMA. The improvement in performance is obtained through more efficient use of the existing resources. For long packets, the overhead of T_p and T_s is small and the throughput of the CSMA/TCD approaches that of the CSMA/CD. For extremely short packets, the preamble and carrier sense overhead become excessive, and the throughput may fall below that of CSMA. Besides offering a higher throughput than CSMA, the protocol also has a much more gentle roll-off of throughput at high offered traffic. Combined with random delay retransmission, the gentle roll-off improves channel stability.

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