Performance Evaluation Of R-ALOHA In Distributed Packet Radio Networks With Hard Real-Time Communications

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Abstract

The performance of reservation ALOHA (R-ALOHA) to support hard real-time communications in a distributed packet radio network is evaluated analytically and by simulation. The network requirements are that each node send an update packet to its communication partner at least every T seconds (called the deadline period) with high reliability. Two scenarios are considered: the worst case and the steady-state case. For the worst-case scenario, two Markovian models are used to investigate how fast the network nodes can recover the communications after a short period of catastrophic failure of the network (i.e., recover reservation). For the steady-state scenario, a Markov chain is formulated to study the trade-off between the key system parameters such as the channel data rate, the packet error probability, the deadline period, and the reliability requirement. One application of this network is for vehicle-to-vehicle communications in intelligent vehicle highway systems where a vehicle periodically sends its updated status (velocity, acceleration, etc.) to the following vehicle to improve safety and the vehicular traffic capacity.

1 Introduction

Packet radio networks (PRN's) have been used for wireless data communications for two decades since the Defense Advanced Research Projects Agency (DARPA) initiated a research effort to develop a packet radio network in 1972 [1]. The goal of most existing PRN's is to provide an efficient and reliable packet transportation system in a typically noisy radio environment. Among the large number of issues involved in the design of PRN's, the efficient sharing of the common radio channel is one of the most important issues. Many channel access protocols have been considered, e.g., ALOHA [3], CSMA [4], etc. The typical performance measures are system throughput and average packet delay.

Recently there has been increased interest in applying advanced control and packet radio technology to highway systems in order to increase highway capacity. Karaasian et al. propose that vehicles in highways cruise in platoons, trains of vehicles with close spacing between consecutive vehicles (see Fig. 1) [2]. In a platoon, a vehicle needs to send its status information (velocity, acceleration, etc.) to its follower periodically so that its follower can keep a safe constant distance from it. Meanwhile, the follower sends an acknowledgment (ACK) back to the vehicle in front of it so that the front one may know that the follower has correctly received the status messages. This type of system requires that the communication between adjacent vehicles not suffer persistent interruption for more than a specified time interval (called the deadline period). For this kind of applications, throughput-delay is not an appropriate performance measure for a channel access protocol. Instead, it is the reliability that determines the performance.

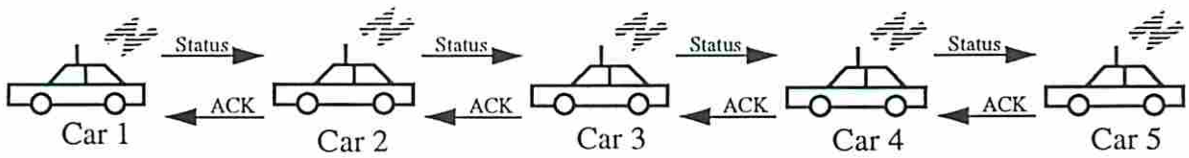

Fig. 1. Real-time vehicle-to-vehicle communications.

In the present study, we evaluate the performance of R-ALOHA [5] in a distributed packet radio network (with hard real-time communications) such as the vehicle-to-vehicle communication system in highways. Deadline failure probability (*DFP*), which will be introduced in the next section, is used as the reliability measure. Two scenarios are considered: the worst case and the steady-state case. Section 3 considers the worst-case scenario. Two Markovian models are proposed to investigate how fast the network nodes (e.g. vehicles) can recover the communications after a short period of catastrophic failure of the network (i.e. recover reservation). The difference between the two models is in the assumption about the capability of distinguishing collision from successful transmission. The steady-state scenario is considered in Section 4. A Markov chain model is proposed to study the trade-off between the key system parameters including the channel data rate, the packet error probability, the deadline period, and the reliability requirement. Numerical results of the models for both of the worst and steady-state cases are presented in Section 5.

2 R-ALOHA and Deadline Failure Probability

In R-ALOHA, channel time is slotted with N consecutive slots constituting a frame. Each user transmits once in a frame. By continuously monitoring the activity of slots, a user randomly chooses an empty slot to transmit its status packet and it checks whether the transmission was successful by the ACK from the receiver. If successful, the sender will become the owner of this slot in the next and subsequent frames. If no ACK is received, however, it assumes a collision and switches to another (empty) slot for the next frame. The ACK's are assumed to be carried on a different channel either by TDM or FDM.

The performance measure of interest is the probability that a user does not receive the status of its partner for more than a specified number of frames. This probability is designated as the deadline failure probability (*DFP*). Most of the time, a user will stick to a certain slot in a frame to transmit its status packets. However, packet errors may occur due to channel fading or collision. Although R-ALOHA is a reservation-based protocol, a collision may still occur when users using the same slot move into the interfering range of one another. When an error is detected, the users involved will switch to other slots that are currently recorded as empty in the next frame. If the number of users that switch simultaneously is small, the probability of an error occurrence is low. The *DFP* is the probability that more than F consecutive packet errors occurs.

3 The Worst Case Scenario

The worst case is when all of the active slots in a frame are corrupted at the same time. All of the users will switch to other slots in the following frames until everyone successfully locks onto a slot. For this case, we study how fast the users in the network can recover reservation.

Assume that there are M users in the system and each is within the interference region of one another so that any simultaneous transmissions will cause mutual collision. In addition, each user must transmit once per N-slot frame ($N > M$). Initially each user randomly chooses one of the N slots. After the first trial, some of the slots are used by exactly one user (success slots), some are left empty (empty slots), and the others are used by more than one user (collision slots). Success slots will be owned in succeeding frames, whereas empty slots are open for contention by users involved in a collision. In reality, a collision slot is usually not distinguishable from a success slot for the users who did not transmit in this slot. For simplicity, the first model assumes that collision slots *are* known to all users and can therefore be used in the next frame. The case where the collision slots are not distinguishable from success slots and hence cannot be used immediately in the next frame is considered in the second model. We define the system stabilization time $SST(M, N)$† to be the number of the frames that elapse until everyone in the system has successfully locked onto a slot (for M users in the system and N slots in a frame). Furthermore, we define the first success time $FST(M, N)$ to be the number of the frames that elapse until a particular user succeeds. By analyzing the underlying combinatorial problem, the distributions and mean values of these two random variables will be derived for both models.

3.1 Model 1

Let $p[k \mid m, n]$ be the probability of k success slots given that each of the m users randomly selects one of the n slots, and $b[m, i, x]$ be the binomial probability that i out of m users randomly with probability x choose a particular slot. $b[m, i, x]$ is given by

$$b[m, i, x] = \binom{m}{i} x^i (1-x)^{m-i}, \text{ where } \binom{m}{i} = \frac{m!}{i!\,(m-i)!}.$$

By conditioning on the number of transmissions in the first of the n available slots, $p[k \mid m, n]$ is given by the recursive formula as follows.

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† Mathar and Mann have studied $SST(M, N)$ -- they found the mean but not the distribution [6].

$$p[k|m,n] = b[m,0,1/n]\,p[k|m,n-1] + b[m,1,1/n]\,p[k-1|m-1,n-1] + \sum_{i=2}^{m} b[m,i,1/n]\,p[k|m-i,n-1], \tag{1}$$

where $n \geq 1, m \geq 0, m \geq k \geq 0$.

The boundary conditions of (1) are

$$p[k|m,n] = \begin{cases} 1, & \text{if } n=1, m=0, k=0 \\ 0, & \text{if } n=1, m=1, k=0 \\ 1, & \text{if } n=1, m=1, k=1 \\ 1, & \text{if } n=1, m\geq 2, k=0 \\ 0, & \text{if } n=1, m\geq 2, k>0 \\ 1, & \text{if } n\geq 2, m=0, k=0 \\ 0, & \text{if } n\geq 2, m=1, k=0 \\ 1, & \text{if } n\geq 2, m=1, k=1. \end{cases}$$

Define X_f to be the number of the success slots after the fth frame, $f = 1, 2, 3, ...$ We have the probability of k success after the first frame's contention given by

$$Pr\{X_1 = k\} = p[k|M,N], \qquad 0 \leq k \leq M.$$

With the distribution of X_1, we can compute the distribution of X_f ($f \geq 2$) iteratively. That is,

$$Pr\{X_f = k | X_{f-1} = j\} = p[k-j|M-j, N-j], \qquad 0 \leq j \leq k \leq M.$$

By unconditioning on X_{f-1}, we get the probability of k successes after the fth frame's contention by

$$Pr\{X_f = k\} = \sum_{j=0}^{k} Pr\{X_{f-1} = j\}\, p[k-j|M-j, N-j], \qquad 0 \leq k \leq M.$$

With the distribution of X_f, we can compute the cumulative distribution functions of *SST* and *FST* in the sequel.

$$Pr\{SST \le f\} = Pr\{X_f = M\}, \qquad f \ge 1.$$

$$Pr\{FST \le f\} = \sum_{j=1}^{M} Pr\{X_f = j\}\frac{j}{M} = \frac{1}{M}E\{X_f\}, \qquad f \ge 1.$$

With the distribution of *SST* and *FST*, the mean values of *SST* an *FST* can be computed numerically. Nevertheless, the following recursive relations provide a faster way to get the mean values of *SST* and *FST*. The mean of *SST*, $E\{SST|M, N\}$, can be obtained by computing $E\{SST|0, N-M\}$, $E\{SST|1, N-M+1\}$, $E\{SST|2, N-M+2\}$, and so on, iteratively. The recursive formula to compute the above is

$$E\{SST|m, n\} = \sum_{k=0}^{m} p[k|m, n]\,(1 + E\{SST|m-k, n-k\}), \qquad 0 \le m \le n,$$

with the boundary conditions given by $E\{SST \mid 0, n\} = 0$ for $n \ge 0$. Similarly, the mean of *FST*, $E\{FST|M, N\}$, can be obtained by using the recursive form

$$E\{FST|m, n\} = \sum_{k=0}^{m} p[k|m, n]\,\left(\frac{k}{m} + \frac{m-k}{m}(1 + E\{FST|m-k, n-k\})\right), \quad 0 \le m \le n,$$

with the boundary condition as $E\{FST \mid 0, n\} = 0$ for $n \ge 0$. The worst-case *DFP* given by model 1 can be computed by

$$Pr[FST \ \ge \ \text{Deadline Period}], \tag{2}$$

where the value of the deadline period is provided by the communications requirements of the system.

3.2 Model 2

In this model, collision slots cannot be used in the next frame but will become available one frame later. Let $p[k, j \mid m, n]$ be the probability of k successful slots and j empty slots given that each of the m users randomly selects one of the n slots, and $b[m, i, x]$ be the same as defined before. By looking at what happens in the first of the n available slots, we can get $p[k, j \mid m, n]$ by the recursive formula as follows.

$$p[k,j|m,n] = b[m,0,1/n]\,p[k,j-1|m,n-1] + b[m,1,1/n]\,p[k-1,j|m-1,n-1] + \sum_{i=2}^{m} b[m,i,1/n]\,p[k,j|m-i,n-1], \tag{3}$$

for $n \geq 1, m \geq 0, m \geq k \geq 0, n - \delta(m) \geq j \geq max(n-m, 0)$,

where $\delta(m) = \begin{cases} 0, & \text{for } m = 0, \\ 1, & \text{for } m > 0, \end{cases}$ and $max(a,b) = \begin{cases} a, & \text{if } a \geq b, \\ b, & \text{otherwise.} \end{cases}$

The boundary conditions of (3) are

$$p[k,j|m,n] = \begin{cases} 1, & \text{if } n = 1, m = 0, k = 0, j = 1 \\ 0, & \text{if } n = 1, m = 1, k = 0, j = 0 \\ 1, & \text{if } n = 1, m = 1, k = 1, j = 0 \\ 1, & \text{if } n = 1, m \geq 2, k = 0, j = 0 \\ 0, & \text{if } n = 1, m \geq 2, k > 0, j = 0 \\ 1, & \text{if } n \geq 2, m = 0, k = 0, j = n \\ 0, & \text{if } n \geq 2, m = 1, k = 0, j = n-1 \\ 1, & \text{if } n \geq 2, m = 1, k = 1, j = n-1. \end{cases}$$

Define X_f and E_f to be the number of successful slots and the number of empty slots after the fth frame, respectively. We have

$$Pr\{X_1 = k, E_1 = j\} = p[k,j|M,N], \qquad 0 \leq k \leq M, 0 \leq j \leq N.$$

Then the joint density of X_f and E_f can be computed by conditioning on $X_{f\text{-}1}$ and $E_{f\text{-}1}$ as follows.

$$Pr\{X_f = k, E_f = j\} = \sum_{u=0}^{k} \sum_{v=N-u-j}^{N-u} Pr\{X_{f-1} = u, E_{f-1} = v\} \cdot p[k-u, j-(N-u-v) \mid M-u, v], \qquad f \geq 2, 0 \leq k \leq M, 0 \leq j \leq N,$$

Note that $(N\text{-}u\text{-}v)$ is the number of collision slots in frame $(f-1)$, which will become empty in frame f. Then the marginal distribution of X_f is given by

$$Pr\{X_f = k\} = \sum_{j=0}^{N} Pr\{X_f = k, E_f = j\}, \qquad 0 \le k \le M.$$

With the distribution of X_f, the cumulative distribution functions of SST and FST are given by

$$Pr\{SST \le f\} = Pr\{X_f = M\}, \qquad f \ge 1.$$

$$Pr\{FST \le f\} = \sum_{j=1}^{M} Pr\{X_f = j\}\frac{j}{M} = \frac{1}{M}E\{X_f\}, \qquad f \ge 1.$$

With the distribution of SST and FST, the mean values can be computed numerically. Alternatively, the following recursive formulae provide another way to get the mean values. For the mean of SST, $E\{SST|M, N\}$ can be found by solving a linear equations system of size MN as follows.

$$E\{SST| m, n\} = \sum_{k=0}^{m} \sum_{j=n-m}^{n} p[k, j| m, n]\ (1 + E\{SST| m-k, j+N-n-M+m\}), \tag{4}$$

where $0 \le m \le n, 0 \le m \le M, 0 \le n \le N$.

The boundary condition of (4) is $E\{SST| 0, n\} = 0$ for $n \ge 0$. For the mean of FST, $E\{FST|M,N\}$ can be obtained by solving a similar linear equations system shown below.

$$E\{FST| m, n\} = \sum_{k=0}^{m} \sum_{j=n-m}^{n} p[k, j| m, n]$$

$$\cdot\left(\frac{k}{m} + \frac{m-k}{m}(1 + E\{FST| m-k, j+N-n-M+m\})\right), \tag{5}$$

where $0 \le m \le n, 0 \le m \le M, 0 \le n \le N$. The boundary condition of (5) is $E\{FST| 0, n\} = 0$ for

$n \geq 0$. As by model 1, the *DFP* of the worst case given by model 2 can be computed by (2).

4 The Steady-state Scenario

In the worst-case analysis just presented, it is assumed that a packet error occurs only if two or more users simultaneously switch to the same slot. Once a user makes a successful transmission in a slot, the following transmissions in that slot will always be successful. In this section, we assume that an error occurs in a reserved slot with probability P_e which accounts for the impact of channel fading and collision (due to user mobility) on the packet transmission. We define the recovery time (*RT*) to be the number of frames it takes for a user to lock onto a slot, once the user has a packet error. Suppose we know the distribution of *RT*, the *DFP* is

$$P_e \cdot Pr[RT \geq \text{Deadline Period}]. \tag{6}$$

In the following, we formulate a Markov chain to find the mean of *RT*. Then the distribution of *RT* is obtained by assuming that *RT* is geometrically distributed.

4.1 The Markov Chain Analysis

Similar to the worst-case analysis, it is assumed that there are M users in the system, each one is within the interference region of each other, and every user transmits once per frame of N slots ($N > M$). Nevertheless, errors will occur in a reserved slot with probability P_e. In the steady state, a user will be in one of the two states: the good state and the bad state. A user is in the good state if it gets a reserved slot and a packet error does not occur. If a packet error does occur due to fading or collision, the user will switch to an empty slot in the next frame. The switch will be successful if there is no other users who switch to the same slot simultaneously, i.e., we neglect the possibility of getting an error due to channel fading while a user is switching.

Let X_f be the number of users who need to switch at the end of frame f, and Y_f be the number of empty slots in frame f. There are $(M - X_f)$ users in the good state and $[N - (M - X_f) - Y_f]$ collision slots in frame f. The collision slots in frame f cannot be used in frame $(f + 1)$ because they are indistinguishable from success slots. But they will become available in frame $(f + 2)$.

In frame $(f + 1)$, the X_f users will compete for the Y_f empty slots. In addition, for the $(M - X_f)$ users in good state, each one have a packet error in frame $(f + 1)$ with probability P_e. Let A be the number of successful slots, B be the number of empty slots after the competition, and C be the number of users who have a packet error in frame $(f + 1)$. Thus X_{f+1} and Y_{f+1} can be expressed as $(X_f - A) + C$ and $B + [N - (M - X_f) - Y_f]$, respectively. The random variables A and B have the joint conditional probability distribution

$$Pr[A = k, B = j | X_f = m, Y_f = n] = p[k, j \mid m, n],$$

and the random variable C has the conditional distribution

$$Pr[C = i | (M - X_f) = m] = \binom{m}{i} P_e^i (1 - P_e)^{m-i}.$$

Although the transition probabilities of the two dimensional chain (X, Y) can be computed and the equilibrium state probabilities can be solved accordingly, we do not try to solve the above 2-dimensional Markov chain. Instead, we propose an approximate one-dimensional Markov chain with state variable X_f being the number of users who need to switch in frame $(f + 1)$. For the one-dimensional Markov chain, we assume that there are $\lfloor X_f/2 \rfloor$ collision slots in frame f. Therefore, Y_f can be approximated by $Y_f' = N - (M - X_f) - \lfloor X_f/2 \rfloor$, where $\lfloor \ \rfloor$ is the floor function which returns the largest integer that is smaller than or equal to the argument. Then we have $X_{f+1} = X_f$ -

$A' + C$, where A' is the number of success slots given X_f users competing for Y_f' slots. The transition probabilities is given by

$$Pr[X_{f+1} = j | X_f = i] = Pr[(A' - C) = (i - j) | X_f = i]$$

$$= \sum_{k=0}^{i} Pr[A' = k | X_f = i] \cdot Pr[C = k - i + j | A' = k, X_f = i]$$

$$= \sum_{k=0}^{i} p[k| i, Y'_f] \cdot b[M - i, k - i + j, P_e],$$

where $Y_f' = [N - (M - i) - \lfloor i/2 \rfloor]$.

Now we can solve the equilibrium state probabilities, $Pr[X = k]$, $k = 0, 1, \ldots, M$, and compute the mean of X, denoted by $E\{X\}$. By Little's formula, the expected time in the bad state, $E\{RT\}$, is given by

$$E\{RT\} = E\{X\} / S,$$

where S is the expected number of users leaving the bad state per frame. Define S_k to be the expected number of users leaving the bad state given $X = k$. We have

$$S = \sum_{k=0}^{M} S_k Pr[X = k],$$

and

$$S_k = \sum_{j=0}^{k} j \cdot p[j| k, N - (M - k) - \lfloor k/2 \rfloor].$$

By assuming that RT has a geometric distribution with the mean equal to $1/\mu$, the distribution of RT is given by $Pr[RT = k] = \mu(1-\mu)^{k-1}$, $k = 1, 2, \ldots, \infty$. Suppose the communications requirement specifies that deadline period is F frames. Then the DFP can be computed by

$$DFP = P_e \cdot Pr[RT \geq \text{Deadline Period}]$$

$$= P_e \cdot (1 - \mu)^{F-1}.$$

This gives the relations among the key system parameters such as channel data rate (proportional to N), the packet error probability (P_e), the deadline period (F frames), and the reliability requirement (DFP).

5 Numerical Results and Discussions

In this section, two networks are considered: network A and network B. Network A shown in Fig. 2 consists of 9 cars ($M = 9$) where every car is within the interfering range of any other, i.e., any two or more simultaneous transmissions in a slot will result in a collision.

Fig. 2. Network A: Each and every of the 9 cars interferes and is interfered by all other cars.

Network B shown in Fig. 3 consists of a hundred cars in a linear highway where only the closest eight cars can interfere with a particular car. For example, cars 11-14 and 16-19 are the potential interfering sources of car 15; cars 41-44 and 46-49 are the potential interfering sources of car 45.

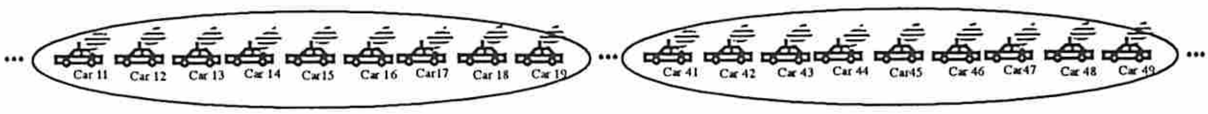

Fig 3. Network B: The interference range of a particular car covers the closest 4 cars in front and the closest 4 cars behind it. For example, the interference range of car15 is between car 11 and car19; the interference range for car16 is between car12 and car 20, etc.

Network A and network B are similar in that every car can only detect the existence of 8 interfering users. We use computer simulation to check if the performance of network A is a good approximation of that of network B. Note that both networks use R-ALOHA with N-slot frames.

Figs. 4-7 concern the worst-case scenario; Figs. 8-10 consider the steady-state scenario. Fig. 4 shows the probability distribution of the system stabilization time (*SST*) for network A in the worst case. It can be seen that the distribution of *SST* for model 1 is very close to that for model 2. Simulation results also verify this observation. It implies that when N (= 16 in this case) is large compared with M (= 9), the assumption that collision slots can be used immediately in the next frame does not significantly affect the accuracy of model 1, but the computation is greatly simplified. Fig. 5 shows the mean values of *SST* of model 1 as a function of M and N. As expected, the mean of *SST* decreases as N increases or as M decreases.

Fig. 6 shows the probability distribution of the first success time (*FST*) for network B in the worst case. The good match between analytical and simulation results confirms that network A is a good approximation of network B as far as *FST* is concerned. Fig. 7 shows the mean of *FST* of model 1 as a function of M and N. Similar to the mean of *SST*, the mean of *FST* decreases as N increases or as M decreases.

For the steady-state scenario, the probability distribution of the recovery time (*RT*) is shown in Fig. 8. The almost perfect match between the simulation results for networks A and B implies that network A is indeed a good approximation of network B. Good agreement between the analytical and simulation results is also observed. Fig. 9 shows the mean of *RT* as a function of N, which is proportional to the channel data rate given that the packet size (in bits) is fixed. As expected, mean *RT* decreases as N increases.

Fig. 10 shows the deadline failure probability (*DFP*) as a function of N and P_e. It can be seen that *DFP* decreases as N increases or as P_e decreases. One interesting trade-off arises by increasing the channel data rate, we can either have larger N by fixing the packet size or achieve smaller P_e by using more powerful error correction codes. Which way is more beneficial is subject to more study.

6 Conclusion

A new performance measure, deadline failure probability (*DFP*), is constructed to evaluated the performance of R-ALOHA as applied to packet radio networks to support hard real-time communications. Both the worst and the steady-state cases are considered. In the worst-case analysis, two Markovian models are used to investigate how fast the network nodes can recover the communications after a short period of catastrophic failure of the network. Whereas model 1 of the worst case is simpler, model 2 is more realistic. In the steady-state analysis, a Markov chain is formulated to study the time spent to regain reservation once a packet error occurs. The proposed models can be applied as tools to trade off the system reliability with the important system parameters such as the channel data rate and the packet error probability.

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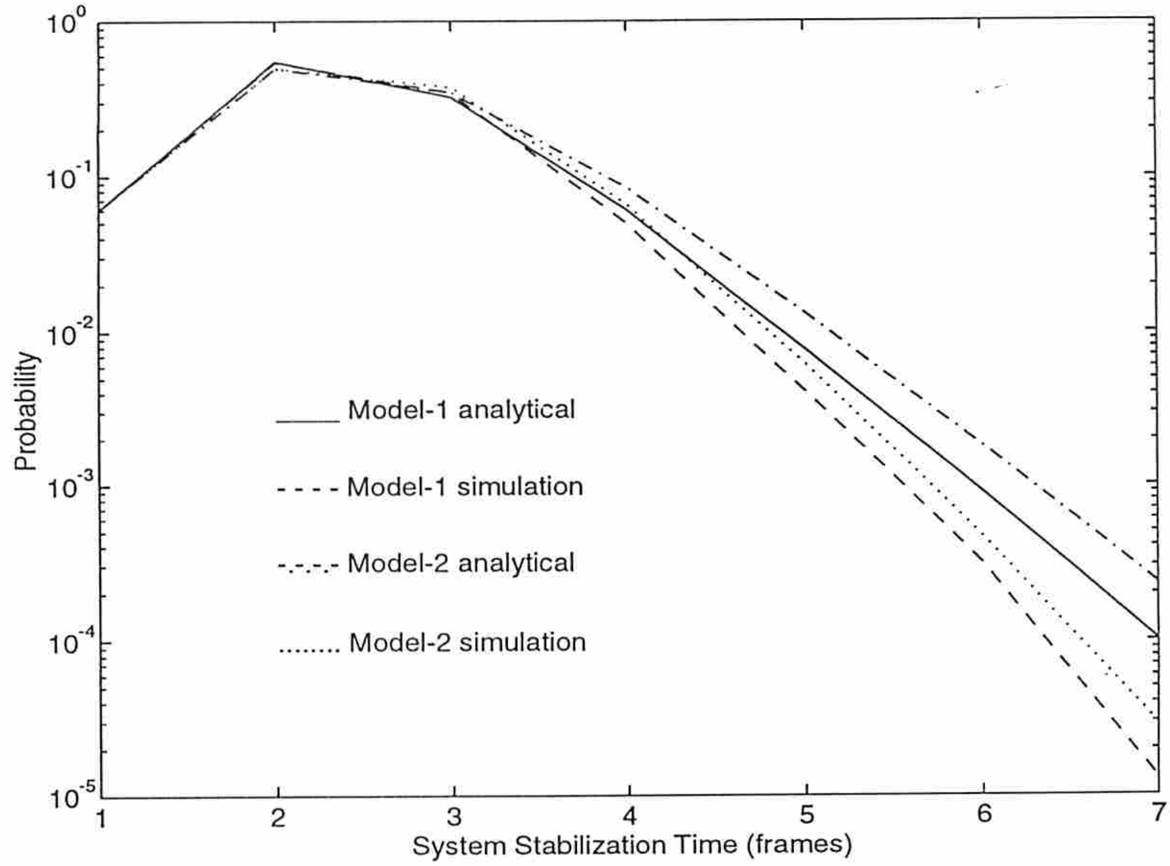

Fig. 4. The probability distribution of the system stabilization time for network A in the worst case. The number of users in the system is 9; the number of slots in a frame is 16.

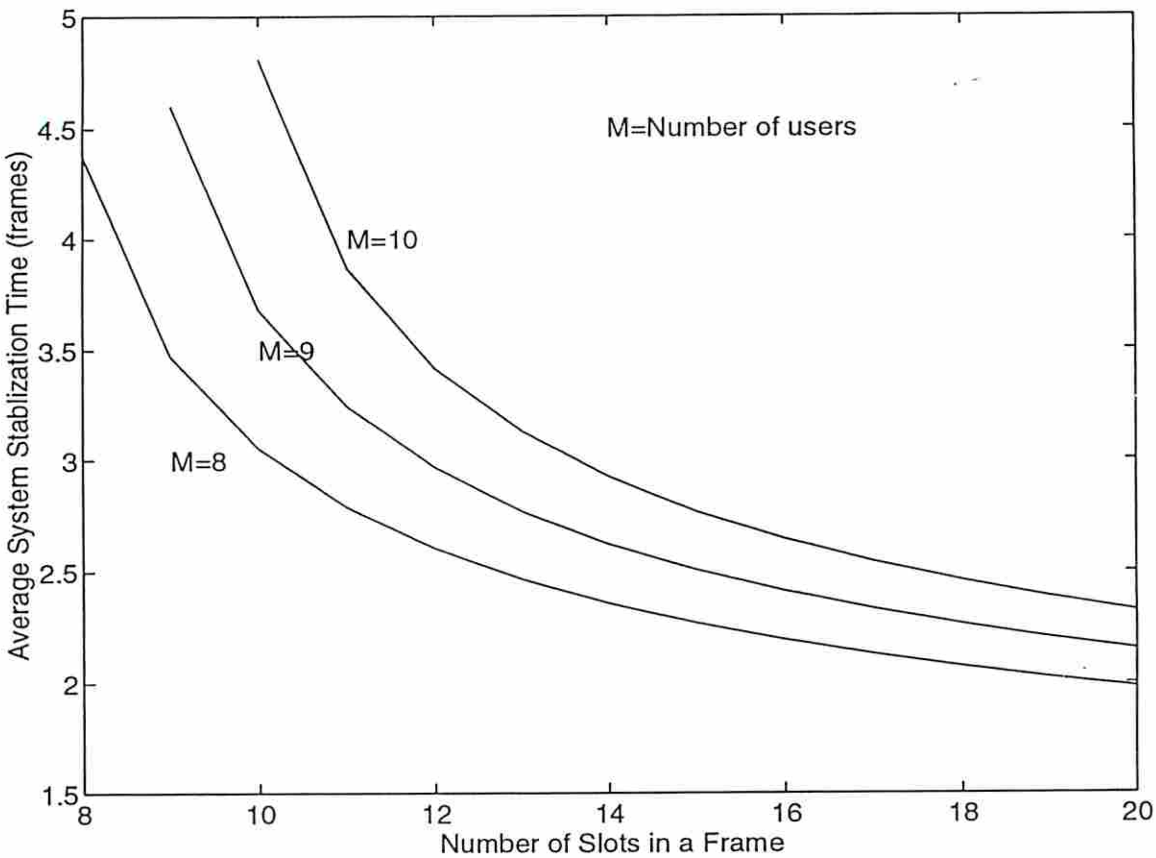

Fig. 5. The average system stabilization time as a function of M (number of users) and N (number of slots in a frame) for network A in the worst case.

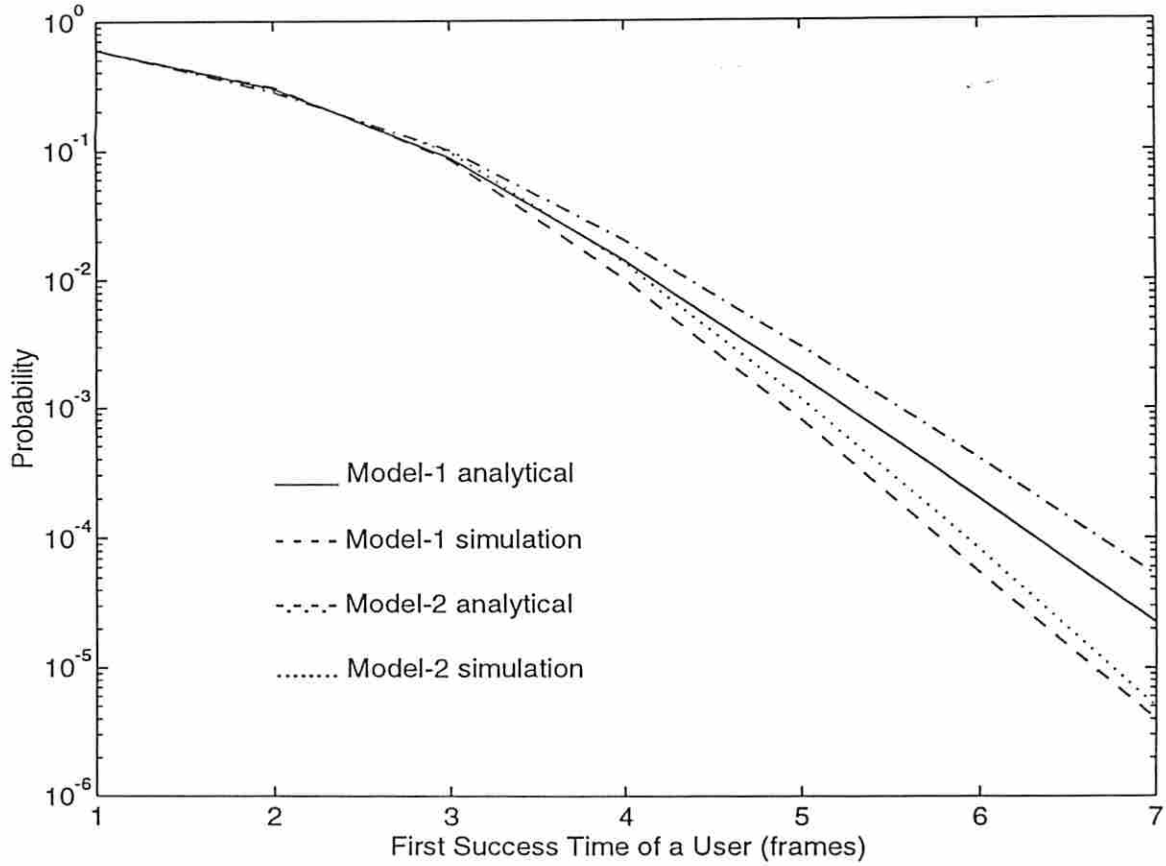

Fig. 6. The probability distribution of the first success time for network B in the worst case. The number of users in the interference range is 9; the number of slots in a frame is 16.

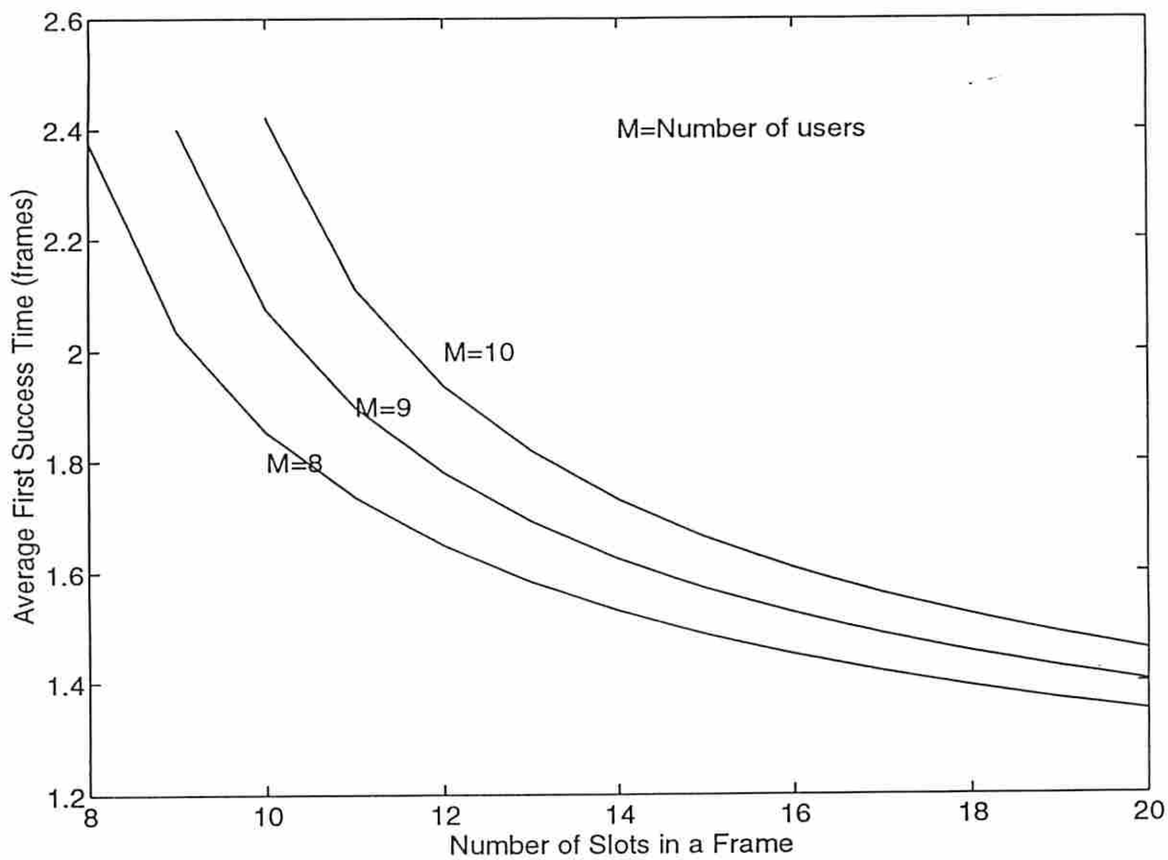

Fig. 7. The average first success time for various values of M (number of users within an interference range) and N (number of slots in a frame) for network B in the worst case.

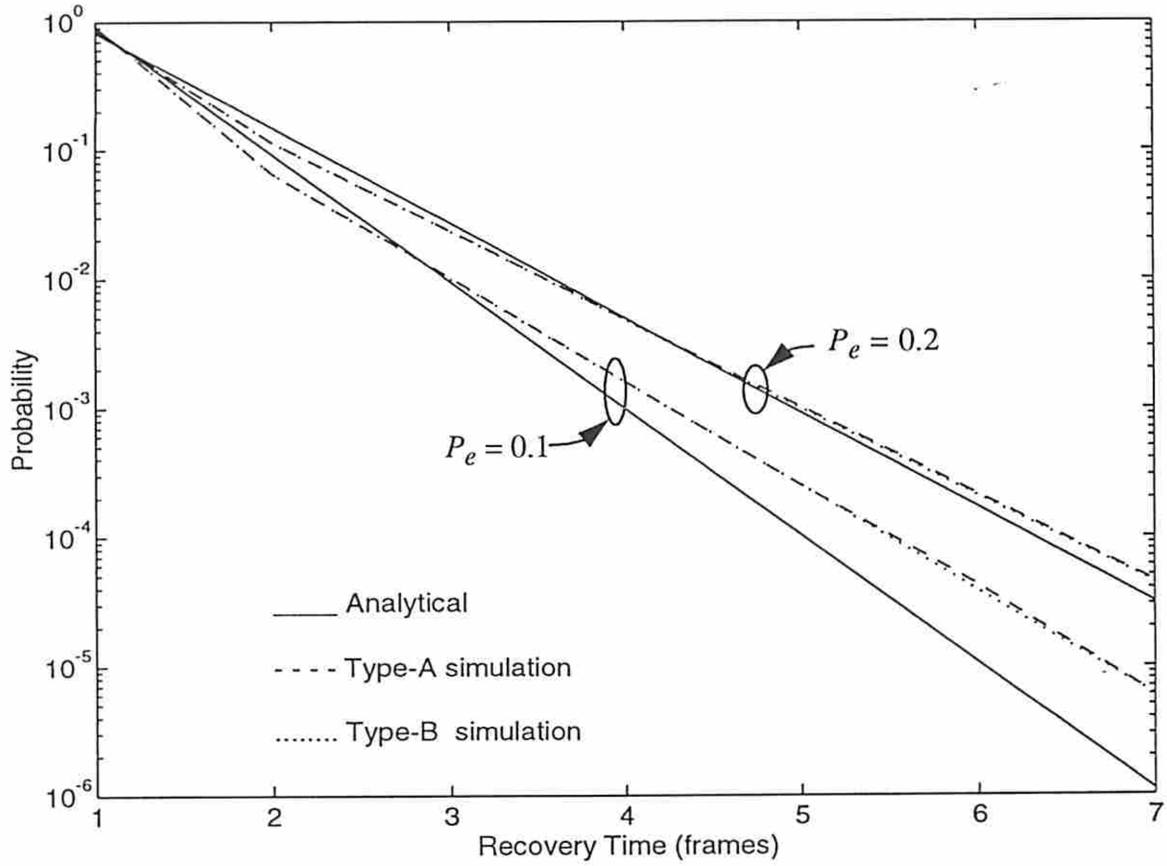

Fig. 8. The probability distribution of the recovery time with the packet error probability $P_e = 0.1$ and 0.2 for networks A and B in the steady state.

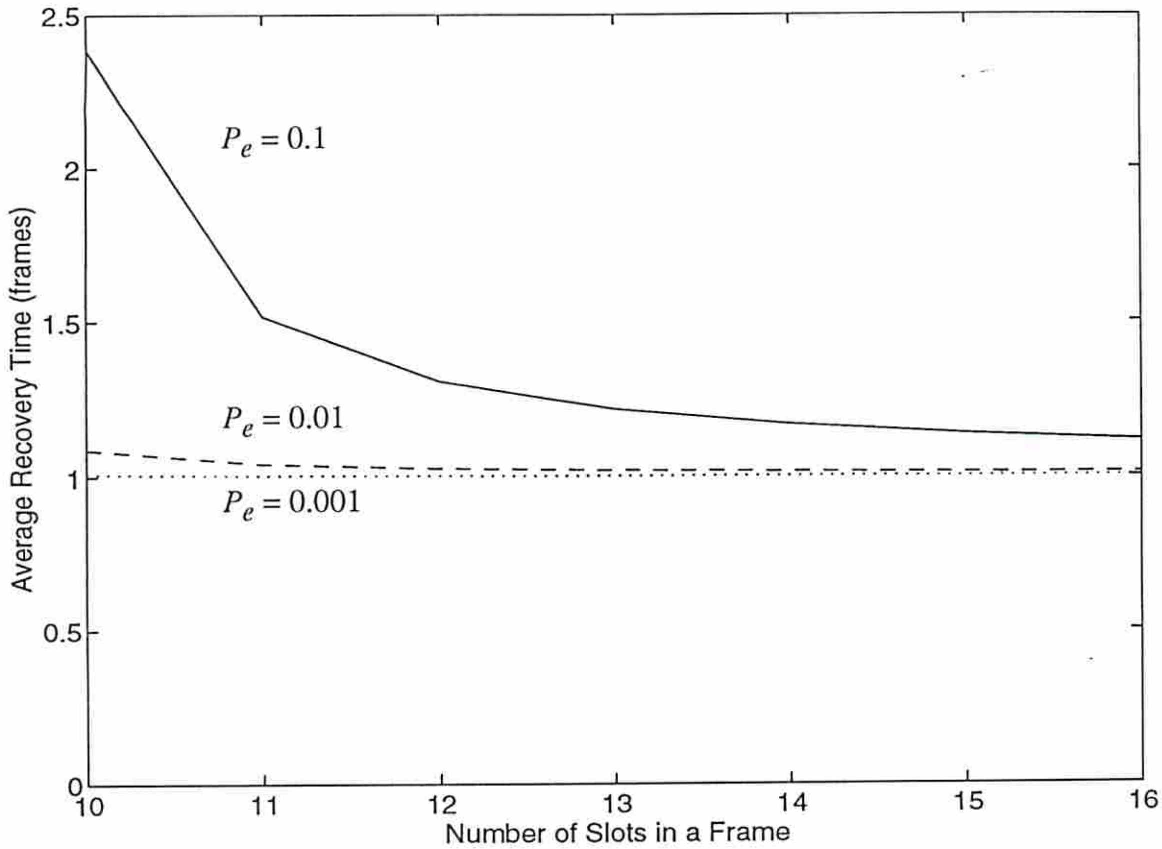

Fig. 9 Average recovery time as a function of the number of slots in a frame and the packet error probability (P_e) for network B in the steady state.

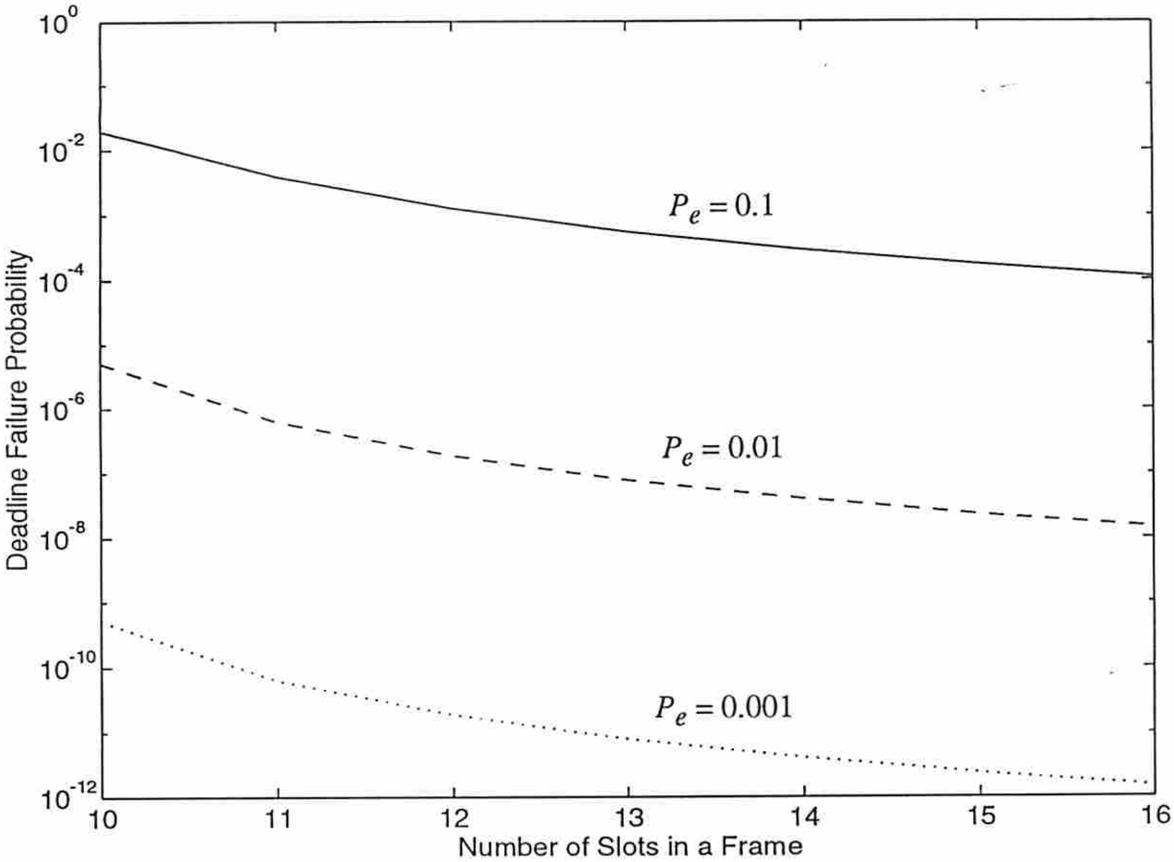

Fig. 10. The deadline failure probability as a function of the number of slots in a frame and the packet error probability (P_e) for network B in the steady state. The deadline period is assumed to be 4 frames.