Random Access with Controlled Time of Arrival for Distributed Spread-Spectrum Packet Radio Networks

Dong-In Kim and June-Chul Roh

Department of Electronics Engineering, Seoul City University
90 Jeon Nong-Dong, Dong Dae Mun-Ku, Seoul, KOREA 130-743

Abstract

A random-access scheme controlling the time of arrival is proposed for distributed spread-spectrum packet radio networks with small radius. Each terminal can send its packet randomly at anyone of possible N_w time instants, equally spaced over one period of spread-spectrum signals. Such transmissions initiated at different time instants can be resolved because of high time resolution of wideband signals. Theoretical evaluations of throughput demonstrate that the combination of the random-access scheme with C-T protocol results in more significant improvement than the case of R-T protocol, and so the advantages of broadcasting and carrier sense can be utilized with acceptable performance.

1. Introduction

Generally, the operation and performance of packet radio networks using spread-spectrum signals depend on channel access schemes and spreading code protocols [1]. As for the channel access schemes, various forms of random access have been proposed for conventional packet radio networks, which can be mainly divided into two types of ALOHA and carrier sense. Typically, carrier sense assures higher channel efficiency than ALOHA in case of narrowband signaling, but carries somehow different meaning for spread-spectrum systems. In the spread-spectrum system, carrier sense may be used for checking whether the destined terminal is in idle state, because the system basically provides multiple-access capability. Here each idle terminal is trying to lock onto other transmissions and decode the address of a packet, thereafter observing the channel status in the network. Thus, carrier sense causes a lot of burden on each terminal unless every terminal in the system shares a single spreading code.

As for the spreading code protocols, Sousa and Silvester proposed hybrid types of protocols, namely, common-transmitter-based protocol (C-T) and receiver-transmitter-based protocol (R-T) for distributed spread-spectrum packet radio networks [2]. The former scheme is suitable for broadcasting messages to neighboring nodes using the common code. However, it is difficult for the latter scheme to broadcast messages using distinct receiving codes. Also, carrier sense is not allowed for the R-T protocol due to system complexity, while the C-T protocol is capable of monitoring the common channel and gathering informations on the channel activity. Even with the above advantages, the C-T protocol shows poor throughput performance compared to the R-T protocol.

Spread-spectrum signals possess the property of high time resolution after they pass through the correlator/matched-filter receiver [3]. By exploiting this property, we propose a random-access scheme for wireless data communication networks with small radius. The proposed channel access scheme can adjust the transmission time of a packet by randomly choosing anyone of N_w time instants, equally spaced over one period of spread-spectrum signals. As far as the time delay is small, it leads to control the time of arrival such that those packets transmitted at different time instants can be resolved even though they are using the same spreading code. As for the channel access scheme, we here consider the random access with controlled time of arrival (RA/CTOA), and adopt the C-T and R-T protocols for the spreading code protocols.

2. System Model and Spreading Code Protocols

We consider distributed packet radio systems in which the channel has the characteristics of short propagation delay and multipath delay spread and spread-spectrum signals are employed for high time resolution. The system model and spreading code protocols considered herein are similar to [2], that is, a mini-slotted system is assumed so that one minislot is equal to the header length of a packet, and each terminal is operated in half-duplex mode which allows either transmission or reception in a given time. For convenience, we denote the length of a packet by some integer value $L = T_p/T_s$, that is normalized by a slot time T_s.

In the C-T spreading code protocol, a particular i-th terminal uses the common spreading code C^c for encoding the header, while its unique transmitting code C_i^t is employed for encoding the following data packet. For the R-T spreading code protocol, a particular i-th terminal is assigned two distinct spreading codes, one of which is used for receiving the header, that is given by its unique receiving code C_i^r, the other is the transmitting code C_i^t indicating the i-th source terminal, that is used for encoding the data packet. In the

Reprinted from Proc. IEEE International Conference on Communications (ICC'95), Seatle, USA, June 1995.

above protocols, it is required that each terminal has the information about $\{C^c\} \bigcup \{C_i^t\}_{i=1}^K$ and $\{C_i^r, C_i^t\}_{i=1}^K$, and these codes can be generated by using the programmable code generator.

3. Random Access with Controlled Time of Arrival

Fig. 1 shows the timing diagram for adjusting the transmission time of a packet. We denote the starting time of a slot by 0, and T indicates one period of spread-spectrum signals. Possible N_w time instants are equally spaced over $[0, T)$, namely,

$$t_i = \{t \ : \ iT_w \leq t < iT_w + \delta\}, \quad i = 0, 1, \ldots, N_w - 1 \quad (1)$$

in which δ accounts for the timing drift existing among terminals in distributed networks. Here the timing drift δ should be less than T_w, which is given by $T_w = \frac{T}{N_w}$ and satisfies the condition

$$T_w > \Delta = (\delta + \tau_{max} + T_m) \, . \quad (2)$$

Hence the time window T_w may be established such that the total time delay Δ includes δ, maximum propagation delay τ_{max}, and multipath delay spread T_m. The proposed random access to be able to control the time of arrival is a kind of modified slotted random access in which if each terminal has a packet to send, it chooses one, say t_i, of N_w time instants $\{t_i\}_{i=0}^{N_w-1}$ with equal probability and starts the packet transmission at t_i in a minislot.

The packet signal transmitted at t_i passes through a multipath channel and arrives at the receiver within the time range $[iT_w, iT_w + \Delta]$, which corresponds to the uncertainty time region for synchronization. At the receiver, there are N_w subsystem modules for acquiring sync from the signals locating in N_w time windows $[iT_w, iT_w + \Delta]$, $i = 0, 1, \ldots, N_w - 1$. If the condition $T_w > \Delta$ is satisfied, the received signal existing in a time window does not interfere with signals belonging to the other time windows. So it is possible to acquire sync in the corresponding subsystem module and then decode the address of a packet.

In order to evaluate throughput of the proposed RA/CTOA scheme, we make the modified ALOHA assumption such that *collision may occur when two or more headers using the same spreading code are transmitted at the same time instant in a minislot.* Thus, a packet will be destroyed when its header is collided with other headers, while once the header is correctly received, the following data packet is assumed to be successfully received if the effects of AWGN and the multiple-access noise caused by other transmissions are negligible. For successful packet reception in the RA/CTOA scheme employing the C-T and R-T protocols, it is required to first acquire sync and then decode the address of a packet by properly processing its header. Along with this assumption, we further assume that *if there are one or more collision-free packets at the destined terminal, it receives anyone that is randomly selected out of such packets.*

For a system with small time delay Δ, the period of spread-spectrum signals can be set to $T = T_b$, a bit time, while a M-ary spread-spectrum signal with $T = (\log_2 M)T_b$ may be used for a system with relatively large Δ.

4. Throughput Analysis

In order to emphasize the effect of collision events on throughput, we assume an ideal wireless channel in which the multiple-access noise can be ignored. This assumption will be valid in case of large processing gain available or a set of spreading codes with good correlation properties.

First, the Markov chain model is introduced in evaluating throughput of the RA/CTOA scheme employing hybrid spreading code protocols. In case of a fixed packet length, the number of states is quite large and the analysis is intractable. For this reason, we assume the variable length of packet with geometric distribution, which leads to a Markov chain model with fewer states because of the memoryless property. Then the length L of a packet is distributed as

$$\Pr[L = l] = (1 - q)q^{l-1} \, , \qquad l = 1, 2, \ldots \quad (3)$$

So the average packet length is given by $\bar{L} = \frac{1}{(1-q)}$ and the average length of data packet becomes $\bar{L} - 1$. When a terminal is in idle state or transmitting a last minipacket at the $(t-1)^{\text{th}}$ slot, we assume that it starts the packet transmission with probability p at the beginning of the t^{th} slot.

Once a terminal happens to transmit a packet, it continues to send the remaining data packet of length $L-1$, regardless of the preceding header being correctly received or not. Likewise, if a terminal receives correctly the header of a packet, it is in the receiving mode during the subsequent $L-1$ minislots. Thus, every terminal in the network remains in anyone of the following four states, namely, (1) successful transmission state, (2) unsuccessful transmission state, (3) receiving state, and (4) idle state. In order to look into the network of finite K users, it is required to know the number n_1 of terminals with successful transmissions and the number n_2 of terminals with unsuccessful ones. If we denote the network state by $z(t) = (n_1, n_2)$, then the state space of $z(t)$ is given by $Z = \{(n_1, n_2) \mid n_1 \geq 0, n_2 \geq 0, \text{and } 0 \leq 2n_1 + n_2 \leq K\}$. So the number of states in the Markov chain model becomes

$$|Z| = (K - \lfloor \frac{K}{2} \rfloor + 1)(\lfloor \frac{K}{2} \rfloor + 1) \, . \quad (4)$$

Here $\lfloor x \rfloor$ denotes the greatest integer not exceeding x. The Markov chain model is irreducible, and hence there exists the stationary distribution $\{\pi(m, n) \mid (m, n) \in Z\}$ [4]. When the transition matrix of Markov chain is denoted by $\mathbf{P}$, the stationary probabilities $\{\pi(m, n)\}$ can be obtained by solving the formula, that is,

$$\pi = \pi\mathbf{P} \, , \qquad \sum_{(m,n) \in Z} \pi(m, n) = 1 \quad (5)$$

where π is a row vector with its element $\pi(m, n)$ for all $(m, n) \in Z$.

A. C-T Spreading Code Protocol

Collision will occur when two or more packets are transmitted at the same time instant in a minislot, because this scheme shares a common spreading code among users for encoding the header. Let us define $p_{kl,mn}$ as the transition probability from (k,l) state to (m,n) state, which is given by

$$\begin{aligned} p_{kl,mn} &= \Pr[\Gamma_{kl,mn}] \\ &= \Pr[z(t)=(m,n) \mid z(t-1)=(k,l)] . \quad (6) \end{aligned}$$

Here $\Gamma_{kl,mn}$ indicates an event of the transition $(k,l) \to (m,n)$ being occurred. To derive the transition probability, we consider an event $C_{i,j}$ that some i of k terminal pairs involved in successful transmission and reception, and some j of l terminals with collided headers are completing their packet transmissions and changing into idle state at the beginning of t^{th} slot. From the geometric distribution of (3), the probability of such event being occurred is given by

$$\Pr[C_{i,j}] = \binom{k}{l}\binom{l}{j}(1-q)^{i+j}q^{k+l-(i+j)} . \qquad (7)$$

Conditioned on this event, the transition probability $p_{kl,mn}$ can be written as

$$p_{kl,mn} = \sum_{i=0}^{k}\sum_{j=0}^{l} \Pr[\Gamma_{kl,mn}|C_{i,j}] \cdot \Pr[C_{i,j}] . \qquad (8)$$

We know that there are $K_I = K-2(k-i)-(l-j)$ idle terminals at the beginning of t^{th} slot. Thus, to have the transition from (k,l) state to (m,n) state, $\mu = m-(k-i)$ terminal pairs of them should change into successful transmission and receiving states, respectively, and also $\nu = n-(l-j)$ terminals of them change into unsuccessful transmission state. In computing the number of ways of doing this, we must consider the states of all terminals in the network and the channel activity at the same time, because the state of a terminal is affected by the states and channel activity of other terminals.

Given a set T_I consisting of K_I idle terminals, only the number $\mu+\nu$ of terminals will start the packet transmission at the t^{th} slot. For derivation of $p_{kl,mn}$, we should properly designate the time instants $\{t_i\}$ at which they start to transmit their packets, and the destinations of their packets. First, the set T_I is partitioned into three sets, *i.e.*, a set T_X of transmitting terminals, a set T_R of receiving terminals, and a set T_o of still idle terminals, whose size are given by $|T_X| = \mu+\nu$, $|T_R| = \mu$, and $|T_o| = K_I - 2\mu - \nu$. The number of ways of doing such partitions is

$$M(K_I,\mu,\nu) = \binom{K_I}{\mu+\nu}\binom{K_I-\mu-\nu}{\mu} . \qquad (9)$$

According to the system assumption, if there are several headers destined to one terminal in T_R, it will be changed into the receiving mode when at least one of them does not collide with other headers. Here other headers also include the headers destined to other terminals in T_R, which must be transmitted at different time instants to avoid collision. We apply the combinatorial theory, specially principle of inclusion and exclusion [5], to derive the number of ways of designating all possible transmission times and destinations of those packets, belonging to T_X, in order to make the event $\Gamma_{kl,mn}$ occur. This number $N_{C-T}(K_I,\mu,\nu)$ can be derived as [6]

$$\begin{aligned} N_{C-T}(K_I,\mu,\nu) &= \sum_{\mathbf{n}\in\Psi} \frac{\mu!}{\prod_e (b_e!)}\binom{N_w}{S_\mu} S_\mu! \\ &\cdot \frac{(\mu+\nu)!}{(\mu+\nu-S_\mu)!\prod_{d=1}^{\mu}(n_d!)} \sum_{g=0}^{f}(-1)^g \binom{f}{g}\binom{N_w-S_\mu}{g} \\ &\cdot g!\,(K_I-\mu-\nu)^g\,[(N_w-S_\mu-g)(K-1)]^{f-g} . \qquad (10) \end{aligned}$$

Here $\mathbf{n} \triangleq (n_1,n_2,\ldots,n_\mu)$, n_d indicating the number of collision-free packets destined to the d^{th} terminal in T_R, $S_\mu = \sum_{d=1}^{\mu} n_d$, $f = |T_X| - S_\mu = \mu+\nu-S_\mu$, and $\Psi = \{(n_1,n_2,\ldots,n_\mu) \mid n_d \le n_{d+1}, 1 \le n_d \le \nu+1, \mu \le S_\mu \le \mu+\nu\}$. The element n_d of $\mathbf{n} \in \Psi$ is listed in an ascending order due to the condition $n_d \le n_{d+1}$, and b_e is equal to the number of the e^{th} largest elements among $\{n_d\}$.

Conditioned on the event $C_{i,j}$, the transition probability from (k,l) state to (m,n) state can be expressed by

$$\begin{aligned} &\Pr[\Gamma_{kl,mn}|C_{i,j}] = p^{\mu+\nu}(1-p)^{K_I-(\mu+\nu)} \\ &\cdot\left(\frac{1}{(K-1)N_w}\right)^{\mu+\nu} M(K_I,\mu,\nu)\, N_{C-T}(K_I,\mu,\nu) . \quad (11) \end{aligned}$$

Therefore, substituting (7) and (9)-(11) upon (8) yields

$$\begin{aligned} p_{kl,mn} &= \sum_{i=0}^{k}\sum_{j=0}^{l}\binom{k}{l}\binom{l}{j}(1-q)^{i+j}q^{k+l-(i+j)} \\ &\cdot p^{\mu+\nu}(1-p)^{K_I-(\mu+\nu)}\left(\frac{1}{(K-1)N_w}\right)^{\mu+\nu}\binom{K_I}{\mu+\nu} \\ &\cdot\binom{K_I-\mu-\nu}{\mu}\sum_{\mathbf{n}\in\Psi}\frac{\mu!}{\prod_e(b_e!)}\binom{N_w}{S_\mu}S_\mu! \\ &\cdot\frac{(\mu+\nu)!}{(\mu+\nu-S_\mu)!\prod_{d=1}^{\mu}(n_d!)}\sum_{g=0}^{f}(-1)^g\binom{f}{g}\binom{N_w-S_\mu}{g} \\ &\cdot g!\,(K_I-\mu-\nu)^g\,[(N_w-S_\mu-g)(K-1)]^{f-g} \qquad (12) \end{aligned}$$

where $\binom{m}{n} = 0$ for $m<0$, $n<0$, or $n>m$.

Finally, by solving the formula (5) with (12), we derive the stationary probabilities $\{\pi(m,n)\}$, and then system throughput can be evaluated as

$$\beta = \sum_{(m,n)\in Z} m\pi(m,n) \quad \text{minipackets / slot} . \qquad (13)$$

B. R-T Spreading Code Protocol

The possibility of collision in the R-T protocol will be lower than that in the C-T protocol, since collision may occur when two or more packets are transmitted at the same time instant t_i in a minislot and also destined to the same terminal. Similar to the case of C-T protocol, conditioned on the event $C_{i,j}$, we first evaluate the number of ways of designating all possible transmission times of those packets belonging to T_X, and their destinations for the event $\Gamma_{kl,mn}$. This number $N_{R-T}(K_I,\mu,\nu)$ can be derived as [6]

$$N_{R-T}(K_I,\mu,\nu) = \sum_{\mathbf{n}\in\Psi} \frac{\mu!}{\prod_e(b_e!)} \frac{(\mu+\nu)!}{(\mu+\nu-S_\mu)!\prod_{d=1}^{\mu}(n_d!)}$$
$$\cdot \prod_{d=1}^{\mu} N(n_d) \sum_{g=0}^{f}(-1)^g \binom{f}{g} \binom{(K_I-2\mu-\nu)N_w}{g}$$
$$\cdot\, g!\,[(K_I-\mu-1)N_w-g]^{f-g} \tag{14}$$

where all parameters has the same meaning as in (10), but the element n_d of $\mathbf{n}$ indicates the number of packets destined to the d^{th} terminal in T_X regardless of collision, and

$$N(n_d) = \sum_{v=1}^{\min(N_w,n_d)} (-1)^{v-1} \binom{N_w}{v} \binom{n_d}{v} v!\,(N_w-v)^{n_d-v}. \tag{15}$$

Conditioned on the event $C_{i,j}$, the transition probability $\Pr[\Gamma_{kl,mn}|C_{i,j}]$ from (k,l) state to (m,n) state has the expression in (11) with $N_{C-T}(K_I,\mu,\nu)$ replaced by $N_{R-T}(K_I,\mu,\nu)$. Now, combining this with (8) yields the transition probability $p_{kl,mn}$

$$p_{kl,mn} = \sum_{i=0}^{k}\sum_{j=0}^{l} \binom{k}{l}\binom{l}{j}(1-q)^{i+j}q^{k+l-(i+j)}$$
$$\cdot\, p^{\mu+\nu}(1-p)^{K_I-(\mu+\nu)} \left(\frac{1}{(K-1)N_w}\right)^{\mu+\nu} \binom{K_I}{\mu+\nu}$$
$$\cdot \binom{K_I-\mu-\nu}{\mu} \sum_{\mathbf{n}\in\Psi} \frac{\mu!}{\prod_e(b_e!)} \frac{(\mu+\nu)!}{(\mu+\nu-S_\mu)!\prod_{d=1}^{\mu}(n_d!)}$$
$$\cdot \prod_{d=1}^{\mu} N(n_d) \sum_{g=0}^{f}(-1)^g \binom{f}{g} \binom{(K_I-2\mu-\nu)N_w}{g}$$
$$\cdot\, g!\,[(K_I-\mu-1)N_w-g]^{f-g}. \tag{16}$$

Hence system throughput can be evaluated in (13) after obtaining the stationary probabilities $\{\pi(m,n)\}$ through the formulas (5) and (16).

5. Results

First, throughput β of the C-T protocol is plotted in Figs. 2 and 3 for several values of N_w when $K = 12$ and $\bar{L} = 5, 20, 50$. We see that β increases in proportion to N_w because of lower possibility of collision. It is also observed that for fixed N_w, throughput is enhanced with increased $\bar{L}$, while as $\bar{L}$ increases, the performance gain resulting from increased N_w is relatively reduced. This is because throughput is mainly dependent on the collision events for small $\bar{L}$ and N_w, but for large $\bar{L}$ and N_w, it depends on the number of potential transmitter-receiver pairs. In case of $N_w = 1$, we can check our numerical results to exactly coincide with them in [2], and simulation results for $\bar{L} = 20$ are well in accord with theoretical results.

Next, Figs. 4 and 5 shows β of the R-T protocol as a function of N_w for $K = 12$ and $\bar{L} = 5, 20, 50$. It is obvious that throughput is slightly improved with increased N_w. Throughput is affected by two factors, namely, the collision events and the number of potential transmitter-receiver pairs. But the proposed RA/CTOA scheme reduces only the possibility of collision, and hence the performance improvement is relatively small in case of the R-T protocol with lower possibility of collision. Similarly, we can compare numerical results of $N_w = 1$ with them in [2], and simulation results for $\bar{L} = 20$ with theoretical results.

6. Conclusion

We have proposed a novel channel access scheme for distributed spread-spectrum packet radio networks with limited transmission range. It was demonstrated that the C-T protocol combined with the proposed RA/CTOA has superiority over the previous C-T protocol without RA/CTOA [2], and also exhibits a comparable performance to the R-T protocol with RA/CTOA. This implies that the C-T protocol can be preferably adopted instead of the R-T protocol when the RA/CTOA scheme is considered, since the former provides the advantages of broadcasting or carrier sense to be able to further enhance the channel efficiency. We observed that the performance improvement becomes saturated as $\bar{L}$ and N_w increase, and with small $N_w = 2-5$, most of this can be achieved when $K = 12$ and $\bar{L} > 10$. So the RA/CTOA scheme may be applied to distributed spread-spectrum networks without causing any large system complexity and also extra overhead for synchronization among terminals by allowing more timing offset δ.

Acknowledgement

This work was supported in part by Korea Telecommunication Research Center and Korea Research Foundation.

References

[1] M. B. Pursley, "The role of spread spectrum in packet radio networks," *Proc. IEEE*, vol. 75, pp. 116-134, Jan. 1987.

[2] E. S. Sousa and J. A. Silvester, "Spreading code protocols for distributed spread-spectrum packet radio networks," *IEEE Trans. Commun.*, vol. COM-36, pp. 272-281, March 1988.

[3] M. K. Simon, J. K. Omura, R. A. Scholtz, and B. K. Levitt, *Spread Spectrum Communications*, 3 vols., Rockville, Maryland: Computer Science, 1984.

[4] L. Kleinrock, *Queueing Systems*, vol. I, New York, NY: Wiley, 1975.

[5] M. Hall, Jr., *Combinatorial Theory*, 2nd Ed., New York, NY: John Wiley & Sons, 1986.

[6] D. I. Kim and J. C. Roh, "Random access with controlled time of arrival for distributed spread-spectrum packet radio networks," submitted to the *IEEE/ACM Trans. Networking*

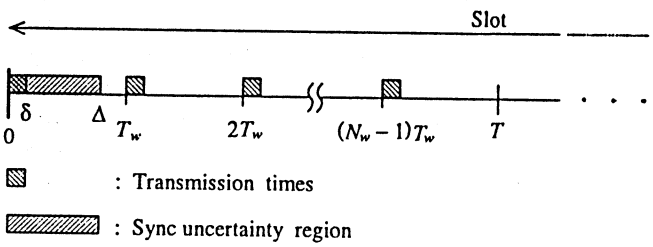

Fig. 1. Timing diagram for adjusting the transmission times in RA/CTOA.

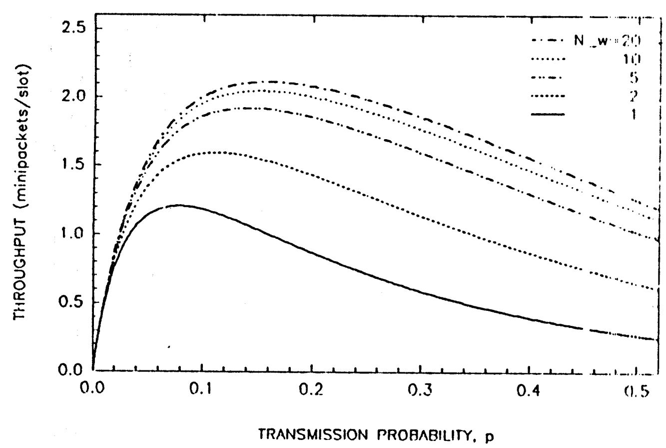

Fig. 2. Throughput β of the RA/CTOA using C-T protocol when $K = 12$, $\bar{L} = 5$.

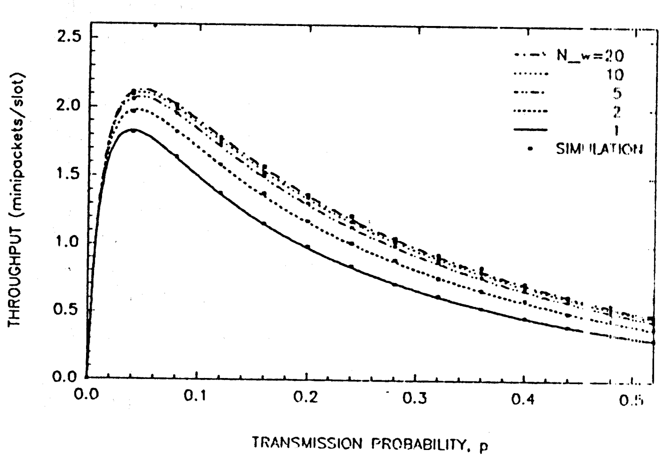

Fig. 3. Throughput β of the RA/CTOA using C-T protocol when $K = 12$, $\bar{L} = 20$.

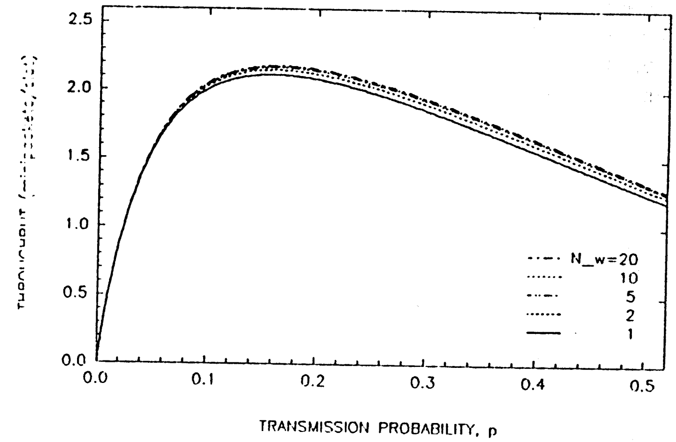

Fig. 4. Throughput β of the RA/CTOA using R-T protocol when $K = 12$, $\bar{L} = 5$.

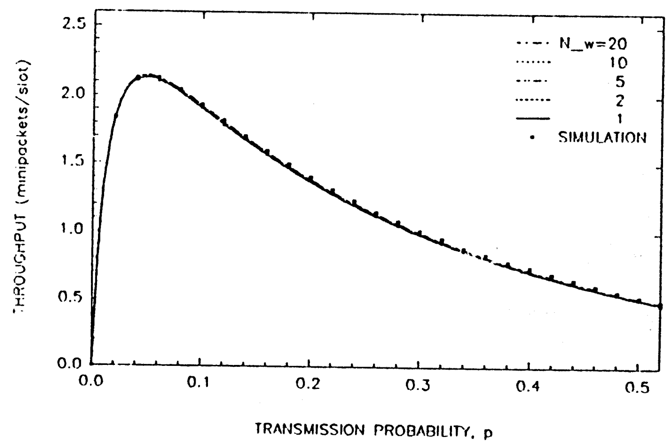

Fig. 5. Throughput β of the RA/CTOA using R-T protocol when $K = 12$, $\bar{L} = 20$.