A Dynamic Queue MAC Protocol for Random Access Channels with Multipacket Reception

Qing Zhao and Lang Tong
School of Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853
{qzhao,ltong}@ee.cornell.edu

Abstract

A dynamic medium access control (MAC) protocol for a finite-user slotted channel with multipacket reception (MPR) capability is proposed. By adaptively changing the size of the contention class (defined as a subset of users who can access the channel at the same time) according to the traffic load and the channel MPR capability, the proposed dynamic queue protocol provides superior channel efficiency at high traffic load and minimum delay at low traffic load. It is shown that considerable throughput gain over purely random access schemes such as slotted Aloha at heavy traffic load and significant delay improvement over scheduled multiaccess strategies such as TDMA at light traffic load are achieved by the proposed protocol.

1. INTRODUCTION

Medium access control (MAC) is a key issue in multiaccess networks where a common channel is shared by a population of users. A MAC protocol is a set of rules that coordinates the transmissions of all users so that the common channel is efficiently utilized.

Based on the assumption that the concurrent transmission of two or more packets results in the destruction of all the transmitted information, numerous multiaccess protocols have been proposed. These multiaccess protocols, according to the amount of contention they allow, can be classified into three groups: contention free schemes, full contention schemes, and limited contention schemes. Contention free protocols, such as TDMA, aim to completely eliminate unsuccessful transmissions caused by packet collision. They provide efficient channel utilization for heavy traffic at the price of large delay at light traffic resulting from the excessive presence of empty slots. In contrast, full contention schemes, such as Aloha [1, 13], tree algorithm [4], first come first serve algorithm [6], aim to avoid unnecessary empty slots by allowing contention among all users. They achieve high channel efficiency at light traffic. However, when the traffic load becomes heavy, frequent collision events lead to severe efficiency loss. Noticing that the design of an efficient MAC protocol at any given traffic load involves avoiding excessive collision events and unnecessary empty slots at the same time, some researchers proposed limited contention schemes. This class of MAC protocols, such as the Urn scheme [12], the dynamic tree protocol [3], the optimal window protocol [10], and the dynamic window protocol [9], determine the number of users who content for a particular slot based on the current traffic load. They change adaptively from full contention schemes at light traffic to contention free schemes at heavy traffic. Efficient channel utilization is achieved at any incoming traffic load.

All the above mentioned MAC protocols are designed exclusively for the conventional collision channel where no packets can be correctly received when more than one is transmitted in one slot. However, with the development of spread spectrum multiple access, space-time coding, and new signal processing techniques, this collision channel model does not hold in many important practical communication systems where one or more packets can be successfully received in the presence of other simultaneous transmissions. For instance, the capture phenomenon is common in local area radio networks. Other examples include networks using CDMA and/or antenna array, multiuser detection techniques, and signal processing based collision resolution algorithms [15].

The new channel model which offers the capability of multipacket reception (MPR) presents a new challenge for the design of MAC protocols. Some researchers have considered the issue of extending existing MAC protocols to channels with MPR capability. In [5, 11], the contention free scheme TDMA is extended to a fully connected half-duplex ad hoc networks with total P conventional collision channels. In [7, 8], the authors analyzed the performance

---

[0] This work was supported in part by the National Science Foundation under Contract CCR-9804019 and the Multidisciplinary University Research Initiative (MURI) under the Office of Naval Research Contract N00014-00-1-0564.

of slotted Aloha for MPR channels with infinite population.

The limited contention scheme named multi-queue service room (MQSR) protocol proposed in [14] is perhaps the first MAC protocol designed explicitly for networks with MPR capability and heterogeneous quality-of-service requirement. By optimally exploiting all available information up to the current slot, this protocol grants access to the channel to an appropriate subset of users so that the expected number of successfully received packets is maximized in each slot, leading to the optimal utilization of the channel MPR capability. The difficulty of this protocol, however, lies in its computational complexity.

In this paper, we propose, for a general MPR channel, a limited contention scheme that provides a performance comparable to that of the MQSR protocol with a much simpler implementation. We dissect the time axis into transmission periods (TP) where the ith TP is dedicated to the transmission of the packets generated in the $(i-1)$th TP. The probability q_i that a user has a packet to transmit in the ith TP depends on the incoming traffic load and the duration of the $(i-1)$th TP. Based on q_i and the channel MPR capability, an optimal size of the contention class (the number of users who gain access to the channel in the same slot) is chosen so that the duration of this TP is minimized. As a consequence, superior delay performance at light traffic load and efficient channel utilization at heavy traffic load are achieved. Furthermore, the interval of q_i on which a possible size (from 1 to the total number of users in the network) of contention class is optimal can be computed off line. When the network starts, the optimal size of contention class for the ith TP is simply obtained from a look-up table, leading to an easy on-line implementation.

2. THE MODEL

We consider a communication network with M users who transmit data to a central controller through a common channel. Each user generates data in the form of equal-sized packets. Transmission time is slotted and each packet requires one time slot to transmit. With probability p, a user independently generates a packet within each slot.

The slotted channel is such that the probability of having k successes in a slot where there are n transmissions depends only on the number of transmitted packets

$$C_{n,k} = \mathsf{P}[k \text{ packets are correctly received} \mid n \text{ are transmitted}]\ (1 \le n \le M, 0 \le k \le n).$$

The multipacket reception matrix of the channel is then defined as

$$\mathbf{C} = \begin{pmatrix} C_{1,0} & C_{1,1} & & & \\ C_{2,0} & C_{2,1} & C_{2,2} & & \\ \vdots & \vdots & \vdots & & \\ C_{M,0} & C_{M,1} & C_{M,2} & \cdots & C_{M,M} \end{pmatrix}. \qquad (1)$$

For such an MPR channel, we define the channel capacity as

$$\eta \triangleq \max_{n=1,\cdots,M} \mathcal{C}_n, \qquad (2)$$

where

$$\mathcal{C}_n \triangleq \sum_{k=1}^{n} k C_{n,k} \qquad (3)$$

is the expected number of packets correctly received when n packets are transmitted. Let

$$n_0 \triangleq \min\{\arg \max_{n=1,\cdots,M} \mathcal{C}_n\}. \qquad (4)$$

We can see that at heavy traffic load, n_0 packets should be transmitted simultaneously to achieve the channel capacity η. Noticing that the number of simultaneously transmitted packets for achieving η may not be unique, we define n_0 as the minimum to save transmission power. For MPR channels with n_0 greater than 1, contention should be preferred at any traffic load in order to fully exploit the channel MPR capability.

This general model for MPR channels, also considered in [7, 8, 2], applies to the conventional collision channel and channels with capture as special examples. The reception matrix of the conventional collision channel and channels with capture are given by

$$\begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 1 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & 0 & 0 & \cdots & 0 \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 1-p_2 & p_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 1-p_M & p_M & 0 & \cdots & 0 \end{pmatrix}, \qquad (5)$$

where p_i is the probability of capture given i simultaneous transmissions.

We assume that the central controller can distinguish without error between empty and nonempty slots. Furthermore, if some packets are successfully demodulated at the end of a slot, the central controller can identify the source of these packets. However, if at least one packet is successfully demodulated at the end of a slot, the central controller does not assume the knowledge whether there are other packets transmitted in this slot but not successfully received.

Our goal here is to design, for a multiaccess network specified above, a MAC protocol that adaptively controls the size of the contention class according to the channel MPR capability and the current traffic load.

3. THE DYNAMIC QUEUE PROTOCOL

3.1. The Structure of Transmission Period

As illustrated in Figure 1, we assume that the network starts at time 0 and one slot lasts one time unit. At the beginning of the first slot, each user with probability q_1 has a packet to transmit. This specifies the network initial condition and is known to the central controller. The time axis is dissected into transmission periods (TP). The first TP starts with the first slot, and only those packets generated before time 0 can be transmitted. The first TP ends and the second TP starts when the central controller can assert that all packets generated before time 0 have been successfully transmitted. In the second TP, packets generated in the first TP are transmitted. We assume that besides the packet waiting for transmission in the current TP, each user can hold at most one packet. Thus, at the beginning of a TP, each user has at most one packet. Suppose that at the beginning of the ith ($i > 1$) TP, each user with probability q_i has a packet. We have

$$q_i = 1 - (1-p)^{L_{i-1}}, \tag{6}$$

where L_{i-1} denotes the length of the $(i-1)$th TP defined as the number of slots it contains.

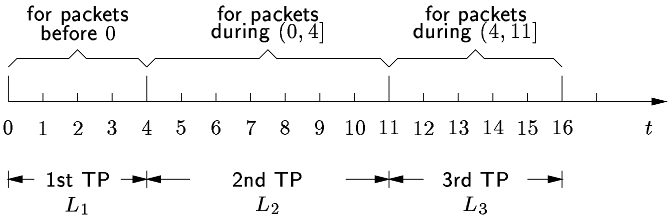

Figure 1: The Structure of Transmission Period.

3.2. The Structure of the Dynamic Queue Protocol

We consider all M users are waiting in a queue for the transmission of their packets at the beginning of the ith TP. Based on q_i given by (6) and the channel MPR capability, the central controller determines the size N_i of the contention class for this TP. Then, the first N_i users in the queue are enabled to access the channel in the first slot of the ith TP. At the end of this slot, the central controller detects whether this slot is empty or not. If it is empty, all these N_i users are processed and the next N_i users in the queue are enabled in the next slot. On the other hand, if this slot is not empty and k ($k \geq 0$) packets are successfully received, the sources of these k packets are processed; the rest $N_i - k$ users along with the next k users in the queue are enabled to access the channel in the next slot. This procedure continues until all M users are processed.

With this structure, the only parameter to be designed is N_i, the size of the contention class for the ith ($i \geq 1$) TP, which we discuss in Section 3.3.

3.3. The Optimal Size of the Contention Class

The optimal size N_i of the contention class for the ith TP is chosen so that the expected length of this TP is minimized, *i.e.*, the expected number of slots for processing all M users each of whom with probability q_i has a packet is minimized. Specifically, N_i is determined by

$$N_i = \arg \min_{N=1,\cdots,M} E[L_i \mid N], \tag{7}$$

where $E[L_i \mid N]$ is the expected length of the ith TP when the size of the contention class is chosen to be N.

In order to determine N_i, we calculate $E[L_i \mid N]$ as the absorbing time of a finite state discrete time Markov chain. It can be shown that the number of unprocessed users at the beginning of a slot along with the number of packets that will be transmitted in this slot forms a Markov chain. Specifically, at the beginning of a slot in the ith TP, the network is in state (j,k) if there are j ($j = 0, \cdots, M$) unprocessed users and k ($k = 0, \cdots, \min\{N,j\}$) packets will be transmitted in this slot. The transition probability from state (j,k) to state (l,m) is given by

$$p_{(j,k),(l,m)} = \left\{ \begin{array}{l} B(m, \min\{N,l\}, q_i) \\ (\text{if } k=0, l=\max\{j-N,0\}, m=0,\cdots,\min\{N,l\}) \\ C_{k,j-l} B(m-k+j-l, \min\{j-l, \max\{j-N,0\}\}, q_i) \\ (\text{if } k=1,\cdots,\min\{N,j\}, l=j-k,\cdots,j, \\ m=k-(j-l),\cdots,k) \\ 0 \quad (\text{otherwise}) \end{array} \right. , \tag{8}$$

where $B(u,U,s)$ denote the probability mass at the value u of a Binomial random variable with total U trials and a success probability s, *i.e.*,

$$B(u,U,s) \triangleq \binom{U}{u} s^u (1-s)^{U-u}. \tag{9}$$

The initial condition of this Markov chain is given by

$$P[X_0 = (M,k)] = B(k,N,q_i), \quad k = 0,\cdots,N, \tag{10}$$

where X_0 denote the initial state of the Markov chain. With state (0,0) defined as the absorbing state, $E[L_i \mid N]$ becomes the absorbing time of this Markov chain, which is defined as the expected number of transitions until the first hit of state (0,0). Define $e_{(j,k)}$ as the expected remaining time until absorption given that the current state is (j,k). Let

$$\mathbf{e} \triangleq [e_{(M,0)}, \cdots, e_{(M,N)}, e_{(M-1,0)}, \cdots, e_{(1,0)}, e_{(1,1)}, e_{(0,0)}]^t. \tag{11}$$

We then have

$$(\mathbf{I} - \mathbf{P})\mathbf{e} = \mathbf{1}, \tag{12}$$

where $\mathbf{P}$ is the transition probability matrix with entries specified by (8), $\mathbf{I}$ and $\mathbf{1}$ denote, respectively, an identity matrix and a vector with all entries equal to 1.

From (12), we can solve for $e_{(M,k)}$ for $k = 0, \cdots, N$. Thus, considering the initial condition of the Markov chain given by (10), we can calculate $E[L_i \mid N]$ as

$$E[L_i \mid N] = \sum_{k=0}^{N} B(k, N, q_i) e_{(M,k)}. \qquad (13)$$

With $E[L_i \mid N]$ computed for all possible N, the optimal size N_i of the contention class for the ith TP can be easily obtained from (7).

It can be shown that $E[L_i \mid N] = \infty$ if $\mathcal{C}_N = 0$. Hence,

$$N_i \in \{N : \; 1 \leq N \leq M, \; \mathcal{C}_N > 0\}. \qquad (14)$$

This justifies in certain sense that the proposed protocol enables the same set of users after a collision (no packets are successfully received).

We point out that the optimal size of the contention class can be computed off line. By varying q_i from 0 to 1, we can construct a table that specifies the interval of q_i on which a size N ($N = 1, \cdots, M$) of the contention class is optimal (a typical look-up table is illustrated in Figure 2). Thus, when the network starts, the optimal size of the contention class for each TP can be obtained by looking up this table; little on-line computation is required to implement the dynamic queue protocol.

3.4. Protocol Statement

The basic procedure of the dynamic queue protocol can be stated as follows.

In the ith ($i > 1$) TP,

1. Let W denote the number of unprocessed users. Set $W = M$.
2. Compute q_i as given by (6).
3. Choose N_i based on q_i from the look-up table.
4. The first N_i users form the access set which is defined as the set of users who gain access to the channel.
5. Users in the access set access the channel in the current slot.
6. At the end of this slot,
   - if the slot is empty, update W as $W = W - A$, where A is the size of the access set. Remove all users from the access set. The next $\min\{N_i, W\}$ users in the queue form the access set;
   - if the slot is not empty and k packets are successfully received, remove the source of these k packets from the access set. Update W as $W = W - k$. The next $\min\{k, W\}$ users in the queue join the access set.
7. Repeat Step 5 and Step 6 until $W = 0$. This starts the $(i + 1)$th TP.

4. SIMULATION EXAMPLES

Presented in this section are simulation studies on the throughput and delay performance of the proposed dynamic queue protocol in a CDMA network with $M = 10$ users. The MPR capability of this network is provided by 3 orthogonal codes. A packet is transmitted with a code randomly picked from these 3 codes. A packet is successfully received if and only if no other packet transmitted in this slot uses the same code. It can be shown that the capacity of this MPR channel is $4/3$ and $n_0 = 2$ (see (4)) packets should be transmitted simultaneously in each slot to achieve this capacity.

We first construct the look-up table that specifies the q_i intervals on which a possible size (from 1 to 10) of contention class is optimal. The result is shown in Figure 2. This result demonstrates clearly the trend that the heavier the traffic is (larger q_i), the smaller the contention class should be, as intuition suggests. Note that the optimal size of contention class equals to $n_0 > 1$ at the heaviest traffic load ($q_i = 1$). This shows that contention may be preferable at any traffic load for an MPR channel.

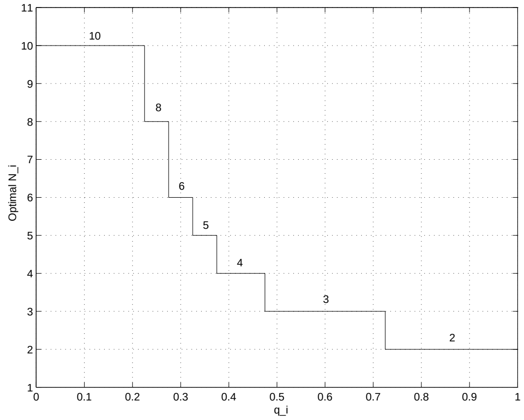

Figure 2: The Optimal Size of Contention Class

The expected length of a TP provided by the proposed dynamic queue protocol is plotted in Figure 3 as a function of q, the probability that a user has a packet to transmit in this TP. Compared to schemes with fixed size of contention class, the advantage of dynamically changing the size of contention class according to the traffic load q is obvious.

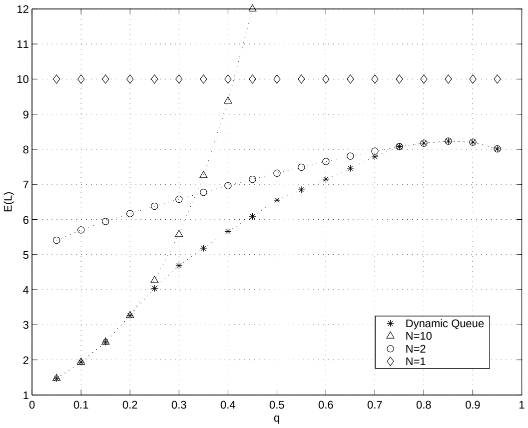

Figure 3: The Expected Length of A TP

The throughput performance of the dynamic queue protocol at different incoming traffic load p is compared to that of the multi-queue service room (MQSR) protocol [14] and the slotted Aloha with optimal retransmission probability. As demonstrated by Figure 4, a significant improvement in throughput is achieved by the proposed protocol over slotted Aloha with optimal retransmission probability. Compared to the MQSR protocol which aims to determine the access set for each slot by optimally exploiting all available information, comparable performance is achieved by the dynamic queue protocol with a much simpler implementation.

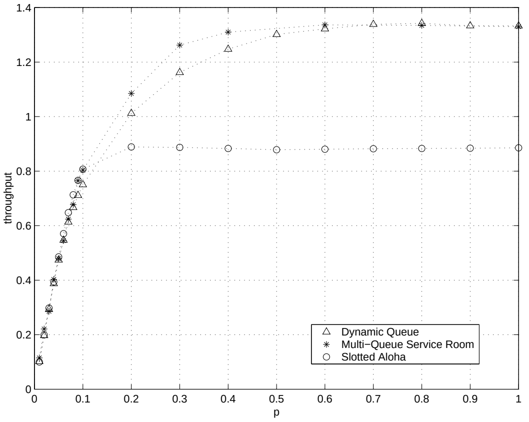

Figure 4: Throughput Comparison

5. CONCLUSION

In this paper, we propose the dynamic queue protocol for multiaccess networks with MPR capability. According to the traffic load and the channel MPR capability, this protocol optimally controls the number of users who gain access to the channel in the same slot. As a consequence, unnecessary empty slots at light traffic and excessive collision events at heavy traffic are avoided simultaneously, leading to efficient channel utilization at any incoming traffic load. Furthermore, the proposed protocol is particularly attractive in its simple implementation.

6. REFERENCES

[1] N. Abramson. "The Aloha System - Another Alternative for Computer Communications". In *Proc. Fall Joint Comput. Conf., AFIPS Conf.*, page 37, 1970.

[2] J. Q. Bao and L. Tong. "Performance Analysis of Slotted Aloha Ad Hoc Networks with Multiple Packet Reception". *Submitted to IEEE Trans. Communications.*

[3] J.I. Capetanakis. "Generalized TDMA: The Multi-Accessing Tree Protocol". *IEEE Trans. Communications*, 27(10):1476–1484, Oct. 1979.

[4] J.I. Capetanakis. "Tree Algorithms for Packet Broadcast Channels.". *IEEE Trans. Information Theory*, 25(5):505–515, Sept. 1979.

[5] I. Chlamtac and A. Farago. "An Optimal Channel Access Protocol with Multiple Reception Capacity". *IEEE Trans. Computers*, 43(4):480–484, April 1994.

[6] R. Gallager. "Conflict Resolution in Random Access Broadcast Networks". In *Proc. of AFOSR Workshop on Comm. Theory and Appl.*, pages 74–76, Sept. 1978.

[7] S. Ghez, S. Verdú, and S.C. Schwartz. "Stability Properties of Slotted Aloha with Multipacket Reception Capability" . *IEEE Trans. Automat. Contr.*, 33(7):640–649, July 1988.

[8] S. Ghez, S. Verdú, and S.C. Schwartz. "Optimal Decentralized Control in the Random Access Multipacket Channel". *IEEE Trans. Automat. Contr.*, 34(11):1153–1163, Nov. 1989.

[9] M.G. Hluchyj. "Multiple Access Window Protocol: Analysis for Large Finite Populations". In *Proc. IEEE Conf. on Decision and Control*, pages 589–595, New York, NY, 1982.

[10] M.G. Hluchyj and R.G. Gallager. "Multiaccess of A Slotted Channel by Finitely Many Users". In *Proc. Nat. Telecomm. Conf.*, pages D4.2.1–D4.2.7, New Orleans, LA., Aug. 1981.

[11] S. Kim and J. Yeo. "Optimal Scheduling in CDMA Pakcet Radio Networks". *Computers and Operations Research*, 25:219–227, March 1998.

[12] L. Kleinrock and Y. Yemini. "An Optimal Adaptive Scheme for Multiple Access Broadcast Communication". In *Proc. International Conference on Communications*, pages 7.2.1–7.2.5, June 1978.

[13] L.G. Roberts. "Aloha Packet System with and without Slots and Capture". In *(ASS Note 8). Stanford, CA: Stanford Research Institute, Advanced Research Projects Agency, Network Information Center.*, 1972.

[14] Q. Zhao and L. Tong. "An Adaptive Multi-Queue Service Room Protocol for Wireless Networks with Multipacket Reception". In *Proc. 2000 Allerton Conference on Communications, Control, and Computing*, Urbana, IL, Oct. 2000.

[15] Q. Zhao and L. Tong. "Semi-Blind Collision Resolution in Random Access Wireless Ad Hoc Networks". *IEEE Trans. Signal Processing*, 48(10):2910–2920, Oct. 2000.