A MODIFIED BIT-MAP-ASSISTED DYNAMIC QUEUE PROTOCOL FOR MULTIACCESS WIRELESS NETWORKS WITH FINITE BUFFERS

Xin Wang *Jitendra K. Tugnait*

Department of Electrical & Computer Engineering
Auburn University, Auburn, Alabama 36849, USA

ABSTRACT

A modified Bit-Map-assisted Dynamic Queue (BMDQ) protocol is presented for wireless slotted systems with multiple packet reception (MPR) capability and finite user-buffers. As in our recently proposed BMDQ protocol [11], in the proposed protocol the traffic in the channel is viewed as a flow of transmission periods (TP). Each TP has a bit-map (BM) slot at the beginning followed by a data transmission period (DP). In the BMDQ protocol the BM slot is reserved for user detection so that accurate knowledge of the active user set (AUS) can be acquired and in any given TP, each active user is allowed to transmit only one data packet. In the proposed modified BMDQ protocol, the active users are allowed to transmit all data packets in their finite buffer. An active user with more than one packet in its buffer is modeled as several different active pseudo-users. In the BM slot, each user transmits information about the number of the data packets its buffer. Then according to the number of the active pseudo-users and the channel MPR capability, the protocol attempts to minimize the expected duration of the DP in the same way as the BMDQ protocol. Simulation comparison of the performance of proposed modified BMDQ protocol with that of the BMDQ protocol is presented.

1. INTRODUCTION

In recent years, as many multi-access techniques and new signal coding and processing techniques have been applied to wireless communications, correct reception of one or more packets in the presence of concurrent transmission has become possible. In fact, this so-called multi-packet reception (MPR) capability [8] is, or will be, one of the characteristics of many existing and future systems. In the conventional noiseless collision channel model, it is assumed that a packet can be successfully received if and only if there are no concurrent transmissions. The conventional MAC protocols, such as ALOHA, the tree algorithm and a class of adaptive schemes [1]-[4], are based on this noiseless collision channel model. Recently, Tong et al [5]-[8] have proposed several new protocols based on an MPR channel model. These protocols are explicitly designed for the MPR channel. Among them, a dynamic queue protocol [5]-[6] was proposed for general MPR channels and can achieve a performance comparable to others [7]-[8] with much simpler implementation. In the dynamic queue protocol, similar to the network-assisted diversity multiple access (NDMA) [9]-[10], the channel traffic is viewed as a flow of transmission periods (TP). When collision occurs, instead of transmitting and retransmitting all colliding packets in all the slots, just an appropriate subset of users is allowed access to the channel in each slot. The size of access set is chosen based on the channel MPR capability and the probability that a user has a packet to transmit in the TP, so that the expected duration of transmission period (TP) is minimized. The protocol of [5]-[6] is limited to one-packet buffers.

In [11], a Bit-Map-assisted Dynamic Queue (BMDQ) protocol is proposed for general MPR channels. Unlike the dynamic queue, in the proposed BMDQ protocol, the AUS can be determined from the bit-map slot; then the principle

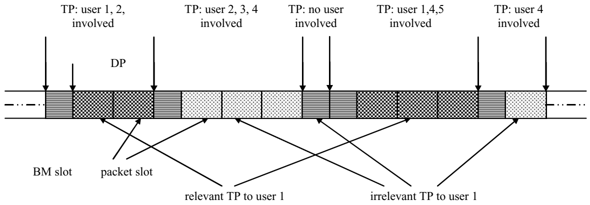

Figure 1. TP flow: each TP includes a BM slot and a DP composed of several packet slots; for a particular user, there are two types of TP's: relevant TP's (the user has data packets in the TP) and irrelevant TP's (the user has no data packets).

of dynamic queue [5] is applied to construct the TP, however, with the knowledge of AUS. The BMDQ protocol can achieve better network performance than that of the dynamic queue protocol but with simpler implementation due to the acquired knowledge of the AUS [11]. In the BMDQ protocol in any given TP, each active user is allowed to transmit only one data packet. In [11], the application and performance of the BMDQ protocol was investigated for both infinite user buffer and one-packet user buffer cases. The BMDQ protocol is also applicable to the finite user buffer case; however, performance analysis is difficult. In this paper, we propose a modified BMDQ protocol for the finite-user-buffering systems with MPR capability where active users are allowed to transmit more than one data packets in any given TP. With the proposed modified BMDQ protocol, the performance analysis becomes easy; for lack of space we do not present any performance analysis, however. As shown later in simulations, in the finite-user-buffering case, the proposed modified BMDQ protocol outperforms the BMDQ in delay and PLR (packet loss ratio) performance. We apply the proposed modified BMDQ protocol and investigate its performance on a slotted CDMA network with MPR capability provided by spread spectrum.

2. THE BMDQ PROTOCOL

In the BMDQ protocol [11], each TP includes a zeroth slot called bit-map (BM) slot and a data transmission period (DP), which is composed of several packet slots, if needed. In the BM slot, a short period is reserved for each user, in which only the permitted user can transmit. So the AUS can be determined using some signal detection methods. Since there is no multiuser interference in the BM slot, just a short reservation period is required for each user to achieve small detection error probability with simple implementation. Once the AUS is known, if the AUS is not empty, the DP is constructed following the BM by applying the principles of dynamic queue protocol. Otherwise, no DP exists for the current TP. The TP flow is illustrated in Figure 1.

2.1. MPR Channel Model

Following [8], consider a general model for MPR channels described below. We consider a network with J users transmitting data to a central controller through a common wireless channel. The transmission time is slotted and each user generates data in the form of equal-sized packets. The

Figure 2. Structure of the BM slot

slotted channel is characterized by an MPR matrix

$$\mathbf{C} = \begin{bmatrix} C_{1,0} & C_{1,1} & & & \\ C_{2,0} & C_{2,1} & C_{2,2} & & \\ \vdots & \vdots & \vdots & \ddots & \\ C_{J,0} & C_{J,1} & C_{J,2} & \cdots & C_{J,J} \end{bmatrix} \quad (1)$$

where $C_{n,k}$ denotes the probability of having exactly k successes when there are n transmitted packets in a slot

$$C_{n,k} = P\{k \text{ packets successfully received} \mid n \text{ transmitted}\}, \quad (2)$$

$(1 \leq n \leq J,\ 0 \leq k \leq n)$. The capacity of an MPR channel is defined [8] as the maximum expected number of successfully received packets in one slot

$$\eta := \max_{n=1,\cdots,J} \mathcal{C}_n = \max_{n=1,\cdots,J} \sum_{k=1}^{n} kC_{n,k} \quad (3)$$

where $\mathcal{C}_n$ denotes the expected number of successfully received packets when there are n transmitted packets. By definition, η is the maximum throughput the MPR channel can offer, independent of MAC protocols. We assume that the central controller can identify the source of any successfully demodulated packets. The packet generation process, which consists of both new packet origination and packet retransmission, is assumed to follow a Poisson distribution (for analysis purposes).

Slotted CDMA Network Assuming that the MPR capability is provided by spread spectrum, we consider a slotted CDMA network with J users. The user packets have fixed length of L_p bits and each packet is spread by a specific code with processing gain P. In each packet, up to t errors can be corrected due to a block error control coding. The system is operated in a noisy environment where the variance of the additive white Gaussian noise (AWGN) is σ_v^2. Let E_b and E_c denote the bit energy and the chip energy respectively, and define the signal-to-noise ratio (SNR) $\zeta = \frac{E_b}{\sigma_v^2} = \frac{PE_c}{\sigma_v^2}$. Under the Gaussian assumption on the multi-access interference from users with equal power, the bit-error-rate (BER) $p_e(n-1)$ of a packet received in the presence of $n-1$ interfering packets is given by [13](p. 634)

$$p_e(n-1) = Q\left(\sqrt{\frac{3P\zeta}{(n-1)\zeta + 3P}}\right) \quad (4)$$

where $Q(.)$ is the Marcum's Q-function [12]. If errors occur independently in a packet, the probability of receiving a packet successfully is given by

$$p_s(n-1) = \sum_{i=0}^{t} B(i, L_p, p_e(n-1)). \quad (5)$$

By the definition of $C_{n,k}$, we have

$$C_{n,k} = B(k, n, p_s(n-1)). \quad (6)$$

Therefore, we can construct the MPR matrix $\mathbf{C}$ for such a network using (1) and (6).

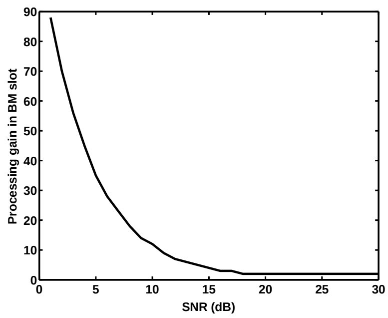

Figure 3. Required processing gain P_m in ths BM slot

2.2. User Detection in the BM slot

The structure of the BM slot is illustrated in Figure 2. A common portion of a short m-sequence [12] (Sec. 13.2.5) is used for every user to transmit in its reserved period. Therefore the same matched filter can be used as the detector for all users. For further details, see [11].

2.3. The Structure of DP

Let [5]

$$n_0 := \min\{\arg \max_{n=1,\cdots,J} \sum_{k=1}^{n} kC_{n,k}\}. \quad (7)$$

In (7) there may be more than one value of n leading to the maximum; we pick the smallest such n. Clearly, under a heavy traffic load, n_0 packets should be transmitted simultaneously to achieve the channel capacity, η. Similarly, we can define

$$n_i := \min\{\arg \max_{n=1,\cdots,n_{i-1}-1} \sum_{k=1}^{n} kC_{n,k}\}, \quad n_i \geq 1. \quad (8)$$

So with the knowledge of n_0, we can find n_1, and this process can be iterated to find n_{i+1} from n_i. The iteration stops when n_i becomes 1 and we obtain a look-up vector $\mathbf{N}_{opt} = [n_0, n_1, \cdots, 1]$.

We determine the access set and construct the DP according to $\mathbf{N}_{opt}$ as follows:

1. Let the waiting list be composed of the users in the AUS. So initially the number of waiting users $n = K$.
2. Let the size of the access set

$$N_n = \begin{cases} n_0, & n \geq n_0 \\ n_i, & n_{i-1} > n \geq n_i \end{cases} \quad (9)$$

   and let the first N_n users in the waiting list access the channel in the current slot.
3. If the slot is empty, remove all the users in the access set from the waiting list, and let $n = n - N_n$. If the slot is not empty and k packets are successfully received, remove these k users from the waiting list, and let $n = n - k$.
4. Repeat steps 2 and 3 until $n = 0$.

2.4. The Procedure of the BMDQ Protocol

We now summarize the basic procedure of the BMDQ protocol. The following steps are executed in the ith TP.

1. Reserve the zeroth slot (which has a length different from that of the packet slot) for BM. Determine the AUS using the BM slot transmissions.
2. Form a waiting list with all the users in the AUS in a randomized order. Let the number of waiting users $n = K$ if there are K users in the AUS. If $n = 0$, go to step 5, else continue.

3. Determine the access set size N_n via (9). Let the first N_n users in the waiting list access the channel, namely, transmit their packets in the current packet slot, one packet per user.
4. If the slot is empty, remove all the users in the access set from the waiting list, and let $n = n - N_n$. If the slot is not empty and k packets are successfully received, remove these k users from the waiting list, and let $n = n - k$.
5. Repeat steps 3 and 4 until $n = 0$. This ends the DP of the ith TP and starts the $(i+1)$th TP.

3. THE MODIFIED BMDQ PROTOCOL FOR SLOTTED CDMA NETWORKS WITH FINITE BUFFERS

For an M-packet user-buffer case, each user can hold from 0 to M packets in its buffer. In the proposed modified BMDQ protocol, all the data packets generated in the last TP and held in the user's buffer would be transmitted in the current TP. Clearly, if a user generates more than M data packets in the last TP, only the first M packets are kept in the buffer and will be transmitted while others are discarded. In the BM slot, for each user, a short period is reserved in which only the permitted user can transmit. However, instead of transmitting nothing but the same m-sequence segment in its reserved period (as in the BMDQ protocol), the user transmits information about the number of packets held in its buffer. If a user has packets for transmission, it is called an active user. If an active user holds more than one packet for transmission, we view these packets as one packet each from several different pseudo-users so that each pseudo-user holds one packet. Then we apply the scheme used in the BMDQ protocol for packet transmission.

3.1. MPR Channel Model for Slotted CDMA Networks

We have the same set-up as in Sec. 2.1 except that in the proposed modified BMDQ protocol, if a user has a M-packet-buffer, it is modeled as M different pseudo-users. Therefore the slotted CDMA network with J users becomes a system with MJ pseudo-users. The expressions for the BER $p_e(n-1)$ and the packet success probability $p_s(n-1)$ are as in (4) and (5), respectively. With $C_{n,k}$ as in Sec. 2.1, for this slotted CDMA network with MJ pseudo-users, the channel is characterized by an MPR matrix

$$\mathbf{C} = \begin{bmatrix} C_{1,0} & C_{1,1} & & & \\ C_{2,0} & C_{2,1} & C_{2,2} & & \\ \vdots & \vdots & \vdots & \ddots & \\ C_{MJ,0} & C_{MJ,1} & C_{MJ,2} & \cdots & C_{MJ,MJ} \end{bmatrix}. \quad (10)$$

The capacity of this MPR channel is given by (see Sec. 2)

$$\eta := \max_{n=1,\cdots,MJ} C_n = \max_{n=1,\cdots,MJ} \sum_{k=1}^{n} kC_{n,k}. \quad (11)$$

3.2. The Structure of the BM slot

In the BM slot, each user transmits a short message in its reserved period indicating the number of packets m, $(0 \le m \le M)$, held in its buffer. Therefore at least $L_m = \lceil \log_2 M \rceil + 1$ bits are required for this short message. If the message is spread with processing gain P_m (different from P), then in the BM slot the SNR is given by $\zeta_m = \frac{P_m E_c}{\sigma_v^2} = \frac{P_m}{P}\zeta$. Note that this short message is transmitted in the absence of any multiuser interference. Therefore, from (4), its BER p_{se} is given by

$$p_{se} = Q\left(\sqrt{\frac{3P_m \cdot \zeta_m}{3P_m}}\right) = Q\left(\sqrt{\frac{P_m}{P}\zeta}\right). \quad (12)$$

Clearly, by increasing P_m (therefore the length of the BM slot since the chip rate is constant), we can make p_{se} as small as possible. If $p_{se} \le 0.0001$, we assume that the BER of the short message is negligible. Let the (chip) $SNR = E_c/\sigma_v^2$. For achieving $p_{se} \le 0.0001$, the plot of required P_m versus SNR is shown in Figure 3.

3.3. The Structure of DP

Similar to [11], define

$$n_0 := \min\{\max_{n=1,\cdots,MJ} \sum_{k=1}^{n} kC_{n,k}\}, \quad (13)$$

$$n_i := \min\{\max_{n=1,\cdots,n_{i-1}-1} \sum_{k=1}^{n} kC_{n,k}\}, \quad n_i \ge 1. \quad (14)$$

In the proposed modified BMDQ protocol, an active user with more than one packet is modeled as several different active pseudo-users with different spreading codes. Suppose that at the end of the BM slot, it is estimated that there are K $(1 \le K \le MJ)$ active pseudo-users. Then the DP is constructed exactly as in Sec. 2.3, with the pseudo-users playing the role of real users.

3.4. The Procedure of the Modified BMDQ Protocol

We now summarize the basic procedure of the modified BMDQ protocol. The following steps are executed in the ith TP.

1. Reserve the zeroth slot for BM, and determine the number of the pseudo-users K at the end of the BM.
2. Form a waiting list with all the active pseudo-users in a randomized order. So initially the number of waiting users $n = K$. If $n = 0$, go to step 5, else continue.
3. Determine the access set size N_n via (9) but using (13) and (14). Let the first N_n pseudo-users in the waiting list access the channel.
4. If the slot is empty, remove all the users in the access set from the waiting list, and let $n = n - N_n$. If the slot is not empty and there are k successful packet receptions, remove these k pseudo-users from the waiting list, and let $n = n - k$.
5. Repeat steps 3 and 4 until $n = 0$. This ends the DP of the ith TP and starts the $(i+1)$th TP.

4. SIMULATION EXAMPLE

Here we are mainly concerned with the long-term (steady-state) behavior, namely, the steady-state performance measures such as throughput, traffic load and average delay. Simulations are conducted based on the assumption that all users' packets follow a Poisson distribution with rate λ (packets per packet duration). We define the system's throughput R as the expected number of successfully transmitted packets per packet slot duration

$$R := \frac{\text{expected no. of successfully transmitted packets / TP}}{\text{expected length of TP}}$$

and define the traffic load G as the expected number of transmissions (including retransmissions) per packet slot duration

$$G = \frac{\text{expected number of transmissions / TP}}{\text{expected length of TP}}.$$

As in [11], we define the Packet-Loss-Rate (PLR) β as

$$\beta = \frac{\text{expected number of discarded packets / TP}}{\text{expected number of generated packets / TP}}.$$

From Sec. 3.2., we know that by increasing the length of the BM slot, the number of packets for transmission for each user can be estimated with as small BER as desired. In simulations we assumed that the number of pseudo-users is accurately known at the end of the BM slot.

Consider a network with user population $J = 10$, the packet length of $L_p = 250$ bits, spreading gain $P = 8$, the number of correctable errors $t = 5$, and SNR $\zeta = 10dB$. From Fig. 3, when SNR $\zeta = 10dB$, for achieving $p_{se} \leq 0.0001$, the required processing gain in the BM slot $P_m = 12$. Assume that each user has at most $M = 4$ packets in its buffer. Then the length of the BM slot is $L_B = \frac{JP_m \cdot \log_2 M}{L_p P} = 0.12$ packets. From (11), the MPR capacity of this channel is $\eta = 2.8990$, which is achieved by simultaneously transmitting $n_0 = 4$ packets per slot.

We tested the proposed modified BMDQ , the (original) BMDQ [11] and the dynamic queue [5] protocols on such a simulated slotted system. In the simulations, each user's buffer was fed with a Poisson source with intensity λ. For a fixed value of λ the system was run for a time period equivalent to 10000 TPs. The approach of [5] had the knowledge of λ to compute the probability of packet generation in a TP whereas BMDQ protocols do not need this information for implementation. Note that the dynamic queue protocol of [5] is limited to user buffers of size one packet. The comparisons among these three protocols are in Figs. 4-6. In these figures, each point of the curves is obtained as the average of the simulation results. As seen in the figures, achieving the same throughput, the proposed modified BMDQ protocol has smaller average delay and PLR than the BMDQ protocol. Note that PLR is large for the dynamic queue protocol [5] as it has a buffer size of only one packet.

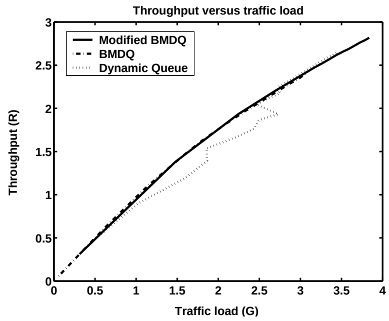

Figure 4. Comparison of the three protocols: throughput versus traffic load.

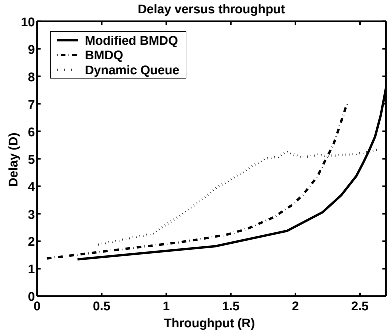

Figure 5. Comparison of the three protocols: delay versus throughput.

REFERENCES

[1] S. Tanenbaum, *Computer Network, 3rd ed.*. Upper Saddle River, NJ: Prentice-Hall, 1996.

[2] J I. Capetanakis, "Generalized TDMA: The multi-accessing tree protocol," *IEEE Trans. Comm.*, vol. 27, pp. 1476-1484, Oct. 1979.

[3] N. Abramson, "Fundamentals of packet multiple access for satellite networks," *IEEE Journal on Selected Areas in Commun.*, vol. 10, pp. 309-316, Feb. 1992.

[4] T. Shinomiya, and H. Suzuki, "Slotted ALOHA mobile packet communication systems with multiuser detection in a base station," *IEEE Trans. Vehicular Tech.*, vol.49, pp. 948-955, May 2000.

[5] Q. Zhao, and L. Tong, "A dynamic queue protocol for multiaccess wireless networks with multipacket reception," *IEEE/ACM Trans. Networking*, in review. [Conf. version in *Proc. 34th Asilomar Conf.*, Pacific Grove, CA, Nov. 2001.]

[6] Q. Zhao and L. Tong, "The dynamic queue protocol for spread spectrum random access networks," in *Proc. 2001 MILCOM*, Washington, DC, Oct. 2001.

[7] Q. Zhao and L. Tong, "An adaptive multi-queue service room MAC protocol for wireless networks with multipacket reception," in *Proc. 2000 Allerton Con. Comm., Control, Computing*, Urbana, IL, Oct. 2000.

[8] L. Tong, Q. Zhao, and G. Mergen, "Multipacket reception in random access wireless networks: From signal processing to optimal medium access control," *IEEE Commun. Mag.*, vol. 39, pp. 108-113, Nov. 2001.

[9] R. Zhang, N.D. Sidiropoulos and M.K. Tsatsanis, "Collision resolution in packet radio networks using rotational invariance techniques," *IEEE Trans. Comm.*, vol. 50, pp. 146-155, Jan. 2002.

[10] M. K. Tsatsanis, R. Zhang and S. Banerjee, "Network assisted diversity for random access wireless systems," *IEEE Trans. Signal Proc.*, vol. 48, pp. 702-711, March 2000.

[11] Xin Wang and J.K. Tugnait, "A bit-map-assisted dynamic queue protocol for multi-access wireless networks with multiple packet reception," in *Proc. Joint Intern. Conf. Wireless LANS & Home Networks (ICWLHN 2002) and Networking (ICN 2002)*, pp. 549-560, Atlanta, Aug. 2002.

[12] J.G. Proakis, *Digital Communications, 4th ed.* NY: McGraw-Hill, 2001.

[13] T.S. Rappaport, *Wireless Communications: Principles and Pratice, 2nd ed.* Prentice-Hall, 2002.

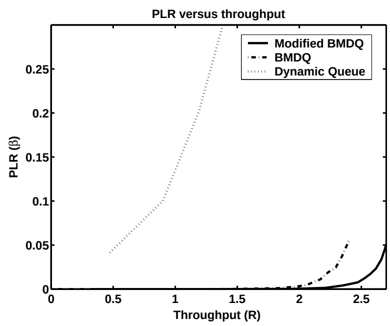

Figure 6. Comparison of the three protocols: PLR (packet loss ratio) versus throughput.