A MODIFIED BIT-MAP-ASSISTED DYNAMIC QUEUE PROTOCOL FOR MULTIACCESS WIRELESS NETWORKS WITH HETEROGENEOUS USERS

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ABSTRACT

A modified Bit-Map-assisted Dynamic Queue (BMDQ) protocol is presented for wireless slotted networks with heterogeneous users and multiple packet reception (MPR) capability. As in our recently proposed BMDQ protocol [7], 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. Then given the knowledge of the AUS and the channel MPR matrix, the number of users that can access the channel simultaneously in each packet slot in the DP is chosen to maximize the conditional throughput of every packet slot. In [7], all users are assumed to have the same bit error probability, i.e. they were assumed to be homogeneous. In the proposed modified BMDQ protocol, we allow the users to have unequal bit error probability. In this case, given the AUS, the choice of users to transmit in a given slot to maximize the conditional throughput is no longer just the number of users, but also the specific choice of users. Simulation comparison of the performance of the modified BMDQ protocol with that of the original BMDQ protocol is presented.

1. INTRODUCTION

In recent years, the so-called multi-packet reception (MPR) capability (correct reception of one or more packets in the presence of concurrent transmission)[6] of many wireless systems has drawn much research interest, with a research focus on exploitation of MPR capability in MAC (medium access control) protocol design [1]-[6]. Different form the conventional MAC protocols based on the noiseless collision channel model [1]-[3], recently, several new protocols have been explicitly designed by Tong et al for the MPR channel based on an MPR channel model [4]-[6]. Based on the same MPR channel model, we have proposed a bit-map-assisted dynamic queue (BMDQ) protocol for wireless slotted systems in [7]. In the BMDQ protocol, time is divided into transmission periods (TP's), each TP consisting of a bit-map (BM) slot ("zeroth" slot) in the beginning of the TP, followed by a data transmission period (DP) composed of a variable number of data packet slots. At the start of a given TP, all users having packets to transmit indicate their desire to transmit via the BM slot, which is contention-free following a TDMA scheme: each user is assigned a fixed reservation period in a specific order where it places its signature if it has a packet to transmit. Using the BM slot transmissions, the central controller determines the active user set (AUS) using some signal detection methods. Once the AUS is known and if the AUS is not empty, the DP is constructed following the BM by applying the principles of dynamic queue protocol [4] where the access set consisting of users allowed access to the channel is controlled in every packet slot. Otherwise, no DP exists for the current TP. The DP, therefore the TP, ends when the central controller has determined that all the packets (one per active user) slated for the transmission at the beginning of the TP have been successfully transmitted. The TP flow is illustrated in

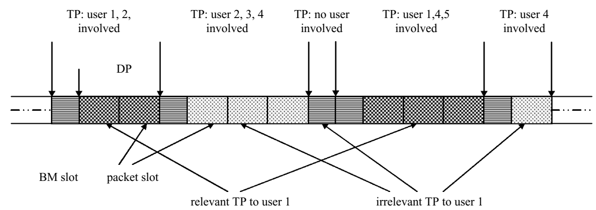

Figure 1. TP flow: each TP includes a BM slot and a DP composed of several packet slots; for a particular user, there are two types of TP's: relevant TP's (the user has data packets in the TP) and irrelevant TP's (the user has no data packets).

Fig. 1.

The MPR channel model used in [7] is inherited from [4]. It is constructed based upon the assumption that all users have identical channel conditions (CSI: channel state information), therefore, identical bit error rates (BER's). Even in AWGN channels, this assumption holds true only under perfect power control, which is hardly fulfilled in practice. In imperfect power control cases (different CSI's, in general), the BMDQ protocol proposed in [7] becomes "invalid." The objective of this paper is to investigate modifications to the original BMDQ protocol to account for the user-dependent BER's. It is shown that the BMDQ protocol is also applicable in this case after appropriate modifications.

2. THE ORIGINAL BMDQ PROTOCOL [7]

Here we briefly review the original BMDQ protocol designed for homogeneous users (users with identical CSI's) and proposed in [7] (to which the reader is referred for further details).

2.1. MPR Channel Model

Following [6], 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 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

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

$(1 \le n \le J,\ 0 \le k \le n)$. The capacity of this MPR channel is defined [6] as the maximum expected number of successfully received packets in one slot

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

Figure 2. Structure of the BM slot

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.

2.2. Structure of the BM slot

The structure of the BM slot is illustrated in Figure 2. A common portion of a short m-sequence [9] (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 [7].

2.3. The Structure of DP

Let [4]

$$n_0 := \min\{\arg \max_{n=1,\cdots,J} \sum_{k=1}^{n} kC_{n,k}\}. \tag{4}$$

In (4) 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

$$n_i := \min\{\arg \max_{n=1,\cdots,n_{i-1}-1} \sum_{k=1}^{n} kC_{n,k}\}, \quad n_i \geq 1. \tag{5}$$

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 with a randomized order. So initially the number of waiting users $n = K$.
2. Let the size of the access set

$$N_n = \begin{cases} n_0, & n \geq n_0 \\ n_i, & n_{i-1} > n \geq n_i \end{cases} \tag{6}$$

   and let the first N_n users in the waiting list access the channel in the current slot.
3. If the slot is empty (no received signal at the controller), 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 (6). 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 (no received signal at the controller), 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. MODIFIED BMDQ PROTOCOL FOR HETEROGENEOUS USERS

Consider the same network as in Sec. 2.3, with J users transmitting data to a central controller through a common wireless channel, however, with possibly different CSI's for different users. In this case, the MPR matrix (1) is no longer an appropriate description of the network behavior.

3.1. DP Construction

In the DP construction in Sec. 2.3., given n active users, one chooses N_n simultaneous transmissions where N_n is specified by (6). However, when the users' BER's are different, we should follow a different strategy. Let U_i, $1 \leq i \leq J$, denote the total J possible users. Let n active users be given by set $\mathcal{U}_n := \{U_i, i \in \mathcal{I}_n(j)\}$ where $\mathcal{I}_n(j) \subset \{1, 2, \cdots, J\}$ is the index set of the n specifc users in the AUS out of J possible users with $1 \leq j \leq N_{J,n}$, (there are $N_{J,n} := \binom{J}{n}$ distinct $\mathcal{I}_n$'s). Further let $\mathcal{I}_n^{(p)}(j,k) \subset \mathcal{I}_n(j)$ index the p, $(1 \leq p \leq n)$, specific users out of n active users with $1 \leq k \leq N_{n,p}$, (there are $N_{n,p} = \binom{n}{p}$ distinct $\mathcal{I}_n^{(p)}$'s). Define the conditional probability

$$C_{p,l}\left(\mathcal{I}_n^{(p)}(j,k)\right) := P\{l \text{ packets are successfully}$$
$$\text{received} \mid p \text{ users specified by } \mathcal{I}_n^{(p)}(j,k) \text{ are transmitted}\}. \tag{7}$$

Then the expected number of successfully received packets in a slot when p users indexed by $\mathcal{I}_n^{(p)}(j,k)$ are transmitted, is given by

$$\mathcal{C}\left(\mathcal{I}_n^{(p)}(j,k)\right) = \sum_{l=1}^{p} lC_{p,l}\left(\mathcal{I}_n^{(p)}(j,k)\right). \tag{8}$$

Define the optimal user index set

$$\tilde{\mathcal{I}}_n(j) := \arg\left\{ \max_{\mathcal{I}_n^{(p)}(j,k),\ 1\leq p\leq n,\ 1\leq k\leq N_{n,p}} \mathcal{C}\left(\mathcal{I}_n^{(p)}(j,k)\right)\right\}. \tag{9}$$

Following the developments of Sec. 2.3., if we have n active users specified by the index set $\mathcal{I}_n(j)$ at the begining of a packet slot, then the users specified by the index set $\tilde{\mathcal{I}}_n(j)$ in (9) are allowed access to the channel in order to maximize the conditional throughput; this replaces Step 3 in Sec. 2.4.

To make things more concrete, let $n = 3$, $J = 5$ and $\mathcal{I}_3(6) = \{1, 4, 5\}$. Then we have

$N_{3,3} = 1$, $\mathcal{I}_3^{(3)}(6,1) = \{1,4,5\}$,

$N_{3,2} = 3$, $\mathcal{I}_3^{(2)}(6,1) = \{1,4\}$, $\mathcal{I}_3^{(2)}(6,2) = \{1,5\}$, $\mathcal{I}_3^{(2)}(6,3) = \{4,5\}$,

$N_{3,1} = 3$, $\mathcal{I}_3^{(1)}(6,1) = \{1\}$, $\mathcal{I}_3^{(1)}(6,2) = \{4\}$, $\mathcal{I}_3^{(1)}(6,3) = \{5\}$.

Suppose that it so turns out that $\tilde{\mathcal{I}}_3(6) = \mathcal{I}_3^{(2)}(6,3)$, in which case the two users indexed by 4 and 5 (i.e. users U_4 and U_5) are allowed access to the channel. In case the solution is not unique, we break the tie by first picking the smallest size set and then (if needed) pick from among the remaining solutions randomly.

For operation of the modified BMDQ, we need to build a lookup table $\mathbf{I}_{opt}$ off-line, which contains the optimal user index set for all the possible AUS's $\mathcal{I}_n(j)$, $1 \leq n \leq J$, $1 \leq j \leq N_{J,n}$. At the beginning of each slot in DP, the central controller determines the access set $\tilde{\mathcal{I}}_n(j)$ by searching $\mathbf{I}_{opt}$. Note that since $\mathcal{I}_n^{(p)}(j,k) \subset \{\mathcal{I}_p(i)\}$, we can always find a unique $I(n,j,k)$ so that

$$\mathcal{I}_p(I(n,j,k)) = \mathcal{I}_n^{(p)}(j,k) \tag{10}$$

for $k = 1, \cdots, N_{n,p}$. In the construction of the lookup table $\mathbf{I}_{opt}$, if $\tilde{\mathcal{I}}_n(j)$ is known for each $1 \leq j \leq N_{J,n}$, then instead of searching in $\left\{\mathcal{I}_{n+1}^{(p)}(j,k),\ 1 \leq p \leq n+1,\ 1 \leq k \leq N_{n+1,p}\right\}$, we can search for $\tilde{\mathcal{I}}_{n+1}(j)$ in the subset $S_u = \left\{\mathcal{I}_{n+1}(j), \tilde{\mathcal{I}}_n(I(n+1,j,1)), \cdots, \tilde{\mathcal{I}}_n(I(n+1,j,N_{n+1,n}))\right\}$ where $\tilde{\mathcal{I}}_n(I(n+1,j,k))$, $1 \leq k \leq N_{n+1,n})$, is the known optimal set for $\mathcal{I}_{n+1}^{(n)}(j,k)$ (refer to (10)). That is, we have

$$\tilde{\mathcal{I}}_n(j) := \arg\left\{\max_{\mathcal{I}_u \in S_u} \mathcal{C}\left(\mathcal{I}_u\right)\right\}. \tag{11}$$

It is not difficult to show that (11) is equivalent to (9). By using (11) in the construction of $\mathbf{I}_{opt}$, we can save some unnecessary computations.

The procedure for constructing $\mathbf{I}_{opt}$ is summarized as:

1. Let $n = 1$. Determine $\tilde{\mathcal{I}}_1(j)$, $1 \leq j \leq N_{J,1}$ by simply letting $\tilde{\mathcal{I}}_1(j) = \mathcal{I}_1(j)$ from (9).
2. Let $n = n+1$. If $n > J$, the construction ends; otherwise, determine $\tilde{\mathcal{I}}_n(j)$, $1 \leq j \leq N_{J,n}$ from (11), and repeat step 2.

3.2. Procedure of Modified BMDQ Protocol

The following steps are executed in the ith TP.

1. Reserve the zeroth slot for BM. Determine the AUS $\mathcal{I}_n(j)$ using the BM slot transmissions.
2. Let the number of waiting users be n. If $n = 0$, go to step 5, else continue.
3. Determine the access set $\tilde{\mathcal{I}}_n(j)$, which contains m_{opt} users, by searching $\mathbf{I}_{opt}$. Let the m_{opt} users indexed by $\tilde{\mathcal{I}}_n(j)$ access the channel (transmit in the current packet slot).
4. If the current slot is empty, remove all the users in the access set from the AUS, and let $n = n - m_{opt}$. If the slot is not empty and there are k successful packet receptions, remove the specific k successful users from the AUS, 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 concerned with the following steady-state performance measures: throughput, average delay (in the unit of packet slots), and packet loss rate (PLR). 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 PLR β as

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

Consider an AWGN channel, and a network with user population $J = 5$, the packet length of $L_p = 250$ bits, spreading gain $P = 7$, the number of correctable errors $t = 2$ and noise variance $\sigma^2 = 0.2$. Each user has at most $M = 3$ packets in its buffer (buffer size =3 packets). A linear MMSE (minimum mean-square error) multiuser detector as described in [8] is used at the central controller to received the packets from all the users. The power control is imperfect. The recieved amplitude of the jth user is equal to A_j, $j = 1, \cdots, J$. The additive white Gaussian noise at the central controller is zero mean with variance σ^2. In the BM slot, the length of reserved period for each user $N = 15$ chips. It means that the length of BM slot $L_B = JN/(L_pP) = 0.043$ packet slots.

4.1. User Detection in the BM slot

The performance of the user detection is determined by the length of reserved period N for each user in the BM slot and the corresponding threshold T for the user detector [7]. We consider *nonfading channel with imperfect power control* such that the amplitude of each user's signal, A_j, $(j = 1, 2, \cdots, J)$, is a constant whereas its phase is random and uniformly distributed in $[0, 2\pi)$. By [10], [7], the detection probability $P_D^{(j)}$ and the false alarm probability $P_F^{(j)}$ for optimal detection of the jth user are given by

$$P_D^{(j)} = Q\left(\frac{A_j}{\sigma/\sqrt{N}}, \frac{T}{\sigma/\sqrt{N}}\right), \quad P_F^{(j)} = \exp\left(-\frac{T^2}{2\sigma^2/N}\right) \tag{12}$$

where $Q(\alpha,\beta) := \int_\beta^\infty z\, e^{-\frac{z^2+\alpha^2}{2}} I_0(\alpha z)\, dz$ is the Marcum's Q-function and $I_0(\cdot)$ is a modified Bessel function of the first kind. The threshold T of the optimal detector is chosen to satisfy a predetermined false alarm probability P_F (for all users). Since the power control is imperfect, the amplitude A_j may be different for different users, therefore $P_D^{(j)}$ may be different too.

4.2. Lookup Table $\mathbf{I}_{opt}$ Construction

We assume that the $J \times J$ cross-correlation matrix of the users' spreading codes is given by

$$\mathbf{R} = \begin{bmatrix} 1 & -1/P & \cdots & -1/P \\ -1/P & 1 & \cdots & -1/P \\ \vdots & \vdots & \ddots & \vdots \\ -1/P & -1/P & \cdots & 1 \end{bmatrix}. \tag{13}$$

For this cross correlation matrix, each user needs to be assigned a different m sequence, or the same m sequence [9] with different phase offsets, of length P. Clearly, the bit error probability for various users under different AUS's is different. Consider an example for illustration. Suppose the current AUS is $\mathcal{I}_4(1) = \{1,2,3,4\}$. Then by [8], the bit error probability for the jth $(j = 1,2,3,4)$ user can be approximated as $(\bar{\sigma}^2 := \sigma^2/P)$

$$p_e^{(j)}\left(\mathcal{I}_4(1)\right) = Q\left(\left[\frac{\bar{\sigma}^2(\tilde{\mathbf{M}}\tilde{\mathbf{R}}\tilde{\mathbf{M}})_{k,k}}{A_j^2(\tilde{\mathbf{M}}\tilde{\mathbf{R}})_{k,k}} + \sum_{j=1,\ j\neq k}^{4} \beta_k^2\right]^{-1}\right) \tag{14}$$

where $\tilde{\mathbf{R}} = \mathbf{R}_{(1:4,1:4)}$ is the upper left 4×4 submatrix of $\mathbf{R}$, $\tilde{\mathbf{M}} := (\tilde{\mathbf{R}} + \bar{\sigma}^2 \tilde{\mathbf{A}}^{-2})^{-1}$, $\tilde{\mathbf{A}} := \mathrm{diag}\{A_1, A_2, A_3, A_4\}$, $\beta_k := \frac{A_k (\tilde{\mathbf{M}}\tilde{\mathbf{R}})_{j,k}}{A_j (\tilde{\mathbf{M}}\tilde{\mathbf{R}})_{j,j}}$. Given the number of correctable errors t, the probability of successfully receiving a packet from jth user under the current AUS is given by

$$p_s^{(j)}\left(\mathcal{I}_4(1)\right) = \sum_{i=0}^{t} B\left(i, L_p, p_e^{(j)}\left(\mathcal{I}_4(1)\right)\right) \tag{15}$$

where $B(u, U, s)$ denotes the probability mass at the value u of a Binomial random variable with total U trials and a success probability s, i.e. $B(u, U, s) = \binom{U}{u} s^u (1-s)^{U-u}$. Given $p_s^{(j)}\left(\mathcal{I}_4(1)\right)$, we can obtain $C_{4,l}\left(\mathcal{I}_4(1)\right)$, $l = 1, 2, 3, 4$, defined in (7). For instance, let

$$\mathbf{P} = \left[p_s^{(1)}\left(\mathcal{I}_4(1)\right), p_s^{(2)}\left(\mathcal{I}_4(1)\right), p_s^{(3)}\left(\mathcal{I}_4(1)\right), p_s^{(4)}\left(\mathcal{I}_4(1)\right)\right]. \tag{16}$$

Then ($\mathbf{P}_i$ denotes the ith component of $\mathbf{P}$)

$$\begin{aligned} C_{4,2}\left(\mathcal{I}_4(1)\right) &= \mathbf{P}_1\mathbf{P}_2(1-\mathbf{P}_3)(1-\mathbf{P}_4) + \mathbf{P}_1(1-\mathbf{P}_2)\mathbf{P}_3(1-\mathbf{P}_4) \\ &+ \mathbf{P}_1(1-\mathbf{P}_2)(1-\mathbf{P}_3)\mathbf{P}_4 + (1-\mathbf{P}_1)\mathbf{P}_2\mathbf{P}_3(1-\mathbf{P}_4) \\ &+ (1-\mathbf{P}_1)\mathbf{P}_2(1-\mathbf{P}_3)\mathbf{P}_4 + (1-\mathbf{P}_1)(1-\mathbf{P}_2)\mathbf{P}_3\mathbf{P}_4. \end{aligned}$$

With all the $C_{p,l}\left(\mathcal{I}_n(j)\right)$'s, we can then build the lookup table $\mathbf{I}_{opt}$ for the operation of the modified BMDQ.

4.3. Simulation Results

We picked $\bar{\sigma}^2 = 0.2 = P^{-1}\sigma^2 = \sigma^2/7$, $P_F = 0.005$ and $\mathbf{A} = [A_1, A_2, A_3, A_4, A_5] = [0.8, 0.9, 1, 1.1, 1.2]$ leading to a bit SNR of 5 (7dB) for user 3 (chip SNR of -1.46dB). We tested the modified BMDQ procedure and the original BMDQ procedure on such a simulated slotted system. In order to execute the original BMDQ protocol, the central controller assumed perfect power control resulting in the assumed values $A_i = 1$, $i = 1, \cdots, 5$. Under this assumption, the necessary optimal lookup vector N_{opt} defined in Sec. 2.3. is obtained through (4) and (5) as $N_{opt} = [2, 1]$. This means that if the size of AUS is greater or equal to 2, the central controller randomly picks 2 users from the AUS to transmit; otherwise, it lets the only user in the AUS transmit. In the simulations, each user's buffer was fed with a Poisson source with intensity λ (packets per packet slot). For a fixed value of λ, the system was run for a time period equivalent to 10,000 TP's. The comparisons between the two protocols are depicted in Figs. 3-5. As seen in these figures, the modified BMDQ protocol outperforms the original BMDQ protocol for most λ's since it is explicitly designed for heterogeneous users.

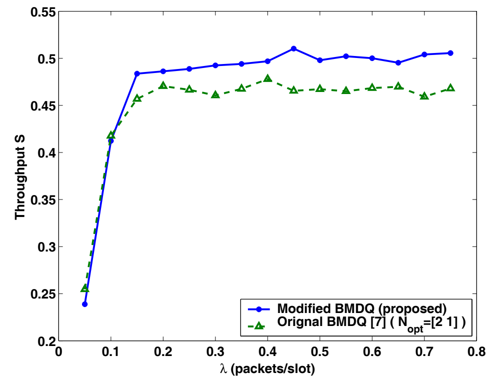

Figure 3. Comparison of throughput.

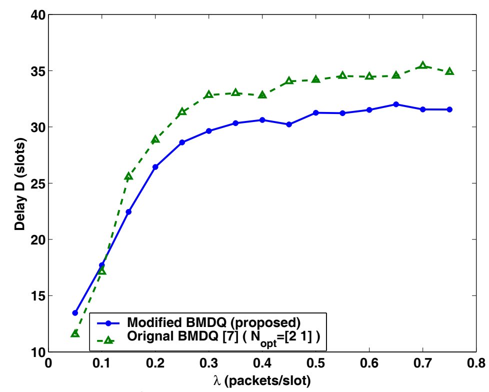

Figure 4. Comparison of delay.

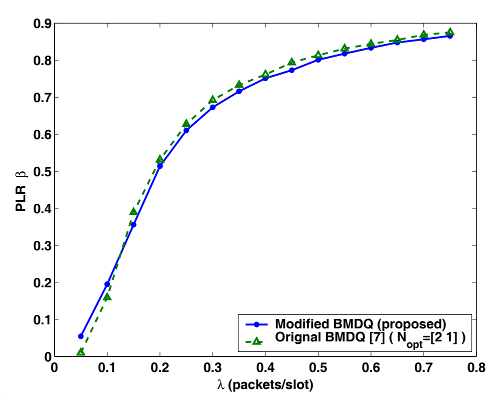

Figure 5. Comparison of PLR (packet loss ratio) versus throughput.

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