XOR Coding Scheme for Data Retransmissions with Different Benefits in DVB-IPDC Networks

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***Abstract*—DVB-H is developed to broadcast digital videos to handheld devices, but data loss is a concern due to the broadcast behavior. On the other hand, DVB-IPDC combines a wireless network with DVB-H to provide bidirectional communications. Such a wireless network can be used to handle data retransmissions and we call it a *recovery network*. The paper argues that network coding can improve retransmission efficiency of the recovery network since packet loss often exhibits high correlation. Besides, packets are heterogeneous in the sense of priority or importance. Thus, recovering different packets can obtain different benefits. Based on these two arguments, the paper proposes a *maximum benefit problem*, which asks the base station in the recovery network to use a limited number of coded packets for handheld devices to retrieve their lost packets such that the overall benefit is maximum. An efficient XOR coding scheme is developed to solve this problem. The paper contributes in addressing a new coding issue in DVB-IPDC.**

***Index Terms*—broadcast, DVB-IPDC, network coding, packet retransmission, wireless network.**

I. INTRODUCTION

Recently, ETSI adopts the DVB-H (Digital Video Broadcasting – Handheld) standard to disseminate videos to *handheld devices (HDs)* by using the broadcast service [1]. DVB-H is considered as one of the popular mobile TV formats. However, owing to the broadcast behavior, HDs could be vulnerable to data loss [2], [3]. Although DVB-H provides a return channel for HDs to feedback some information, it is inefficient to use such a channel to handle data retransmissions due to two reasons [4]. First, the return channel is usually narrow and cannot carry much information. Second, the DVB-H server has to schedule both the regular broadcasts and the retransmissions of lost data, which complicates its design.

DVB-IPDC (IP datacast over DVB-H) [5] integrates DVB-H with an IP-based wireless network, which allows HDs to interact with the system. In this paper, we call this wireless network a *recovery network* because it can support a bidirectional communication channel for HDs to demand the retransmission of lost data. Fig. 1 gives an example, where DVB-H and a recovery network coexists. The DVB-H server periodically broadcasts video data to HDs. When any HD encounters data loss, it can send *recovery requests (RREQs)* to the associated *base station (BS)* in the recovery network to ask for retransmission.

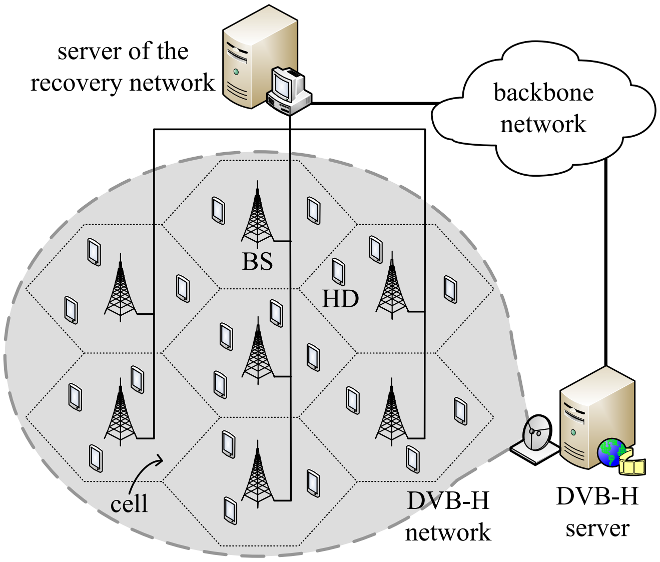


Fig. 1: Integration of DVB-H with a recovery network.

DVB-H data loss, however, usually has correlation. Yang et al. [6] point out that HDs may lose different pieces of a video stream, but such loss could exhibit spatial and temporal correlation. Spatial correlation means that HDs in a cell may lose similar data due to the same noise. Temporal correlation indicates that these HDs may lose a similar sequence of data since the noise could exist for a while. Thus, to improve the retransmission efficiency of the recovery network, it is suggested to adopt the *network coding* technique in this paper to well utilize the above correlation.

Generally speaking, data packets often have different priorities or importance based on their precedence or timing constraint. For instance, real-time packets should be differentiated from non-real-time packets by giving a higher priority [7], [8]. In addition, the video compression technique usually generates multiple packets with different priorities or importance for a video stream. Take MPEG-4 [9] as an example. It defines three types of packets: I-frame (intra-coded picture), P-frame (predicted picture), and B-frame (bi-predictive picture). I-frames can be reconstructed without any reference to other frames. However, P-frames and B-frames hold only parts of the image information and they rely on I-frames to reconstruct the original image. Obviously, I-frames have higher importance than P-frames and B-frames. Thus, when HDs lose different types of frames, the BS can obtain more “benefit” when it retransmits I-frames to HDs.

Motivated by the above arguments, this paper proposes a *maximum benefit coding (MBC) problem* in a DVB-IPDC network. Each DVB-H packet is assigned with a *benefit* based on its priority or importance (depending on the application). The time axis is divided into *superframes*. In each superframe, the BS collects RREQs from HDs and calculates a set of coded packets used to recover their lost packets. Assume that the BS can broadcast no more than τ coded packets in every superframe. The MBC problem asks how to select the set of coded packets such that the overall benefit is maximum. To solve the problem, we develop an MBC algorithm using XOR coding, whose idea is to construct a bipartite graph to give the relationship between coded packets and lost packets. The BS then dynamically measures the total benefit obtained by each coded packet and iteratively selects the best one. Simulation results show the effectiveness of our MBC algorithm.

In the literature, several studies follow DVB-IPDC by combining DVB-H with another wireless network. Akester [10] proposes a multicast protocol to deal with DVB-H data loss through an IEEE 802.11 network. The work of [11] integrates DVB-H with a cellular network to transmit parity data to HDs to repair their erroneous packets. By using WiMAX as the recovery network, [6] develops a group acknowledgement scheme to prevent HDs from submitting a large number of duplicate RREQs to the WiMAX BS, which alleviates network congestion. Sinkar et al. [12] suggest organizing HDs into an ad hoc network to share the lost DVB-H packets through peer-to-peer links. However, none of them apply network coding to facilitate the retransmission process of the recovery network. The work of [13] proposes a *prioritized network coding (PNC) problem* in DVB-IPDC, where the BS is allowed to broadcast a fixed number of coded packets in its cell such that the BS can recover the maximum number of lost packets while minimize the total number of packets discarded due to passing their deadlines. However, the PNC problem does not consider that packets have different benefits.

Some studies use network coding to handle error recovery in data transmissions. In [14], the sender adopts *automatic repeat request (ARQ)* to identify the data lost by the receivers, and then generates the coded packets accordingly. By dividing HDs into different groups, [15] adaptively encodes packets based on the data temporarily stored in each HD to reduce the bandwidth cost. Birk and Kol [16] propose an *informed-source coding on demand (ISCOD)* method, whose idea is to translate the coding problem to the problem of selecting k-partial cliques in a directed graph. The work of [17] develops a *demand-oriented pairing (DOP)* coding scheme to reduce the average access time for the receivers to recover their packets. However, our MBC algorithm differs from these coding schemes in two aspects. First, while they assume that the lost packets are homogeneous, our MBC algorithm considers that packets are heterogeneous in the sense that these packets have different benefits. Second, these coding schemes try to use the minimum number of coded packets to recover *all* of the lost packets. By contrast with them, since it is not always possible to recover all lost packets in the MBC problem, our algorithm tries to maximize the overall benefit by using a limited number of coded packets.

TABLE I: Summary of notations.

notation	definition
$\mathcal{R}$	the set of all requests (collected from RREQs)
$\mathcal{L}$	the set of the packets lost by any HD
$\mathcal{S}$	the set of the packets successfully received by any HD
$\mathcal{C}$	the set of all possible coded packets
$r_{i,j}$	a request indicating that HD_i demands a lost packet p_j
$b(\cdot)$	benefit function, where $b(p_j)$ and $b(r_{i,j})$ are the benefits of a lost packet p_j and a request $r_{i,j}$, respectively

We organize the remainder of this paper as follows: Section II formally defines the MBC problem and Section III proposes our MBC algorithm. Simulation results are presented in Section IV. Section V concludes our work.

II. PROBLEM FORMULATION

Following DVB-IPDC, let us consider an integrated network in Fig. 1, where a DVB-H network and a recovery network coexist. The DVB-H network periodically broadcasts multimedia data to HDs (in the form of DVB-H packets). Each packet p_j is associated with a *benefit* $b(p_j)$, where $0 < b(p_j) \leq 1$. On the other hand, the recovery network can be any broadband wireless network such as 3G, WiMAX, or LTE networks and it is responsible for retransmitting the lost packets to HDs. The recovery network is composed of multiple cells, each being coordinated by one BS. Each HD has separate interfaces to receive packets from the DVB-H server and a BS without interfering with each other. We then focus our discussion on a *single cell* of the recovery network.

To manage the retransmissions of the lost packets, we divide the time axis into repeating *superframes*. Each superframe is composed of a T_{req} period and a T_{send} period. In the T_{req} period, each HD_i encountering packet loss will submit an RREQ $(\text{HD}_i, p_{j_1}, p_{j_2}, \cdots, p_{j_k})$ to its BS, which asks to retransmit the lost packets p_{j_1}, p_{j_2}, $\cdots$, and p_{j_k}. For ease of presentation, let us denote by $r_{i,j} = (\text{HD}_i, p_j)$ the *request* that HD_i demands the retransmission of packet p_j. Thus, the above RREQ can be interpreted as a set of requests $\{r_{i,j_1}, r_{i,j_2}, \cdots, r_{i,j_k}\}$ by the BS. Each request $r_{i,j}$ also has a benefit $b(r_{i,j}) = b(p_j)$. In addition, let us define $\mathcal{R}$ as the the set of all requests (collected from RREQs) in the T_{req} period. Then, according to $\mathcal{R}$, the BS has to calculate no more than τ coded packets to be broadcasted to all HDs in the following T_{send} period.

Given $\mathcal{R}$, the MBC problem determines how to use at most τ coded packets in every T_{send} period to recover the lost packets of HDs such that the overall benefit is maximum. Table I summarizes the notations used in this paper.

III. MBC ALGORITHM

In this section, we propose an MBC algorithm which adopts the XOR coding technique. Before detailing how the MBC algorithm works, we first discuss how to generate the set $\mathcal{C}$ of *all possible coded packets* from $\mathcal{R}$. In particular, let $\mathcal{L}$ be the set of the packets lost by any HD. Unlike $\mathcal{R}$, $\mathcal{L}$ does not care which packet lost by which HD. However, $\mathcal{L}$ can be easily derived from $\mathcal{R}$ by checking the second index (that is, the index j) of each request $r_{i,j}$. On the other hand, let $\mathcal{S}$ be the set of the packets successfully received by any HD. Because the BS knows the packets broadcasted by the DVB-H server in advance, it can also easily calculate $\mathcal{S}$ from $\mathcal{R}$. Notice that $\mathcal{L}$ and $\mathcal{S}$ are not complementary to each other. Let us use the example in Fig. 2(a) to explain how to calculate $\mathcal{L}$ and $\mathcal{S}$ from $\mathcal{R}$. Suppose that there are four HDs, HD_1, HD_2, HD_3, and HD_4, which submit RREQs (HD_1, p_2), (HD_2, p_1, p_4), (HD_3, p_1), and (HD_4, p_1, p_2) to the BS, respectively. Then, the BS can calculate that

$$\mathcal{R} = \{r_{1,2}, r_{2,1}, r_{2,4}, r_{3,1}, r_{4,1}, r_{4,2}\}. \quad (1)$$

In addition, from $\mathcal{R}$, the BS can derive that

$$\mathcal{L} = \{p_1, p_2, p_4\} \text{ and } \mathcal{S} = \{p_1, p_2, p_3, p_4\}.$$

Suppose that a two-operand XOR coding scheme is adopted. Then, each coded packet $c_k \in \mathcal{C}$ can be calculated by

$$c_k = p_x \oplus p_y, \quad p_x \neq p_y, \quad (2)$$

where $p_x \in \mathcal{L}$, $p_y \in \mathcal{S} \cup \{0\}$, and $\oplus$ denotes the XOR operator. Here, a coded packet c_k can be a requested packet p_x when $c_k = p_x \oplus 0$. Continuing the example in Fig. 2(a), we can calculate the set of all possible coded packets

$$\begin{aligned} \mathcal{C} = \{ & c_1 = p_1 \oplus 0, c_2 = p_1 \oplus p_2, c_3 = p_1 \oplus p_3, \\ & c_4 = p_1 \oplus p_4, c_5 = p_2 \oplus 0, c_6 = p_2 \oplus p_3, \\ & c_7 = p_2 \oplus p_4, c_8 = p_4 \oplus 0, c_9 = p_4 \oplus p_3\}, \end{aligned} \quad (3)$$

from both $\mathcal{L}$ and $\mathcal{S}$.

Given both $\mathcal{R}$ and $\mathcal{C}$, our MBC algorithm involves the following five steps:

- **Step 1:** Let $\mathcal{B}$ be the solution set. Initially, we have $\mathcal{B} = \emptyset$. Then, we construct a bipartite graph

  $$\mathcal{G} = (\mathcal{V}, \mathcal{E}) = (\mathcal{C} \cup \mathcal{R}, \mathcal{C} \times \mathcal{R}),$$

  where the vertex set $\mathcal{V}$ contains all possible coded packets (that is, $\mathcal{C}$) and all requests (that is, $\mathcal{R}$). An edge $(c_k, r_{i,j}) \in \mathcal{E}$, where $c_k \in \mathcal{C}$ and $r_{i,j} \in \mathcal{R}$, exists if and only if the coded packet c_k allows HD_i to successfully recover its lost packet p_j. On graph $\mathcal{G}$, each vertex $r_{i,j}$ in $\mathcal{R}$ is associated with a benefit $b(r_{i,j})$.
- **Step 2:** For each vertex c_k in $\mathcal{C}$, we calculate its *current benefit* by summing up the benefits of all its adjacent vertices in $\mathcal{R}$.
- **Step 3:** Select the vertex c_k from $\mathcal{C}$ such that its current benefit is maximum. If there is a tie, we can arbitrarily select one such vertex. Then, we add c_k to $\mathcal{B}$.
- **Step 4:** Remove vertex c_k and all of its adjacent vertices in $\mathcal{R}$. The corresponding edges will be also removed from $\mathcal{G}$ accordingly.
- **Step 5:** Repeat steps 2, 3, and 4 until either we have selected τ vertices from $\mathcal{C}$ or all vertices in $\mathcal{R}$ are removed in step 4. Finally, the BS can broadcast the coded packets in $\mathcal{B}$ to all HDs in the T_{send} period.

Let us use the example in Fig. 2 to explain how the MBC algorithm works. Suppose that $\tau = 2$. Given $\mathcal{R}$ and $\mathcal{C}$ in Eq. (1) and Eq. (3), respectively, we can construct a bipartite graph $\mathcal{G}$ shown in Fig. 2(b). Then, we calculate the current benefit of each vertex in $\mathcal{C}$. For example, for vertex c_1, since its adjacent vertices in $\mathcal{R}$ include $r_{2,1}$, $r_{3,1}$, and $r_{4,1}$, its current benefit will be

$$b(r_{2,1}) + b(r_{3,1}) + b(r_{4,1}) = 0.1 + 0.1 + 0.1 = 0.3.$$

Calculating in a similar way, we can obtain the current benefits of vertices c_2, c_3, c_4, c_5, c_6, c_7, c_8, and c_9 as 0.4, 0.3, 0.2, 0.4, 0.4, 0.8, 0.4, and 0.4, respectively. Among all vertices in $\mathcal{C}$, we select vertex c_7 because it has the maximum current benefit. Then, by step 4, we remove vertex c_7 and all of its adjacent vertices in $\mathcal{R}$ (that is, vertices $r_{1,2}$, $r_{2,4}$, and $r_{4,2}$). By removing the corresponding edges, the resulting graph is shown in Fig. 2(c). We then recalculate the current benefits of vertices c_1, c_2, c_3, c_4 as 0.3, 0.2, 0.3, 0.2, respectively. (The current benefits of other vertices in $\mathcal{C}$ are zeros since they do not have adjacent vertices in $\mathcal{R}$.) Because both vertices c_1 and c_3 have the maximum current benefit (that is, a tie), we can select either of them. Then, the MBC algorithm finishes since we have selected $\tau = 2$ coded packets. Therefore, we can obtain the solution set

$$\begin{aligned} \mathcal{B} &= \{c_1 = p_1 \oplus 0, c_7 = p_2 \oplus p_4\}, \quad \text{or} \\ \mathcal{B} &= \{c_3 = p_1 \oplus p_3, c_7 = p_2 \oplus p_4\}. \end{aligned}$$

In fact, because all HDs have successfully received packet p_3, the effects of coded packets c_1 and c_3 will be the same. In this example, the coded packets in $\mathcal{B}$ can allow each HD to recover all of its lost packets.

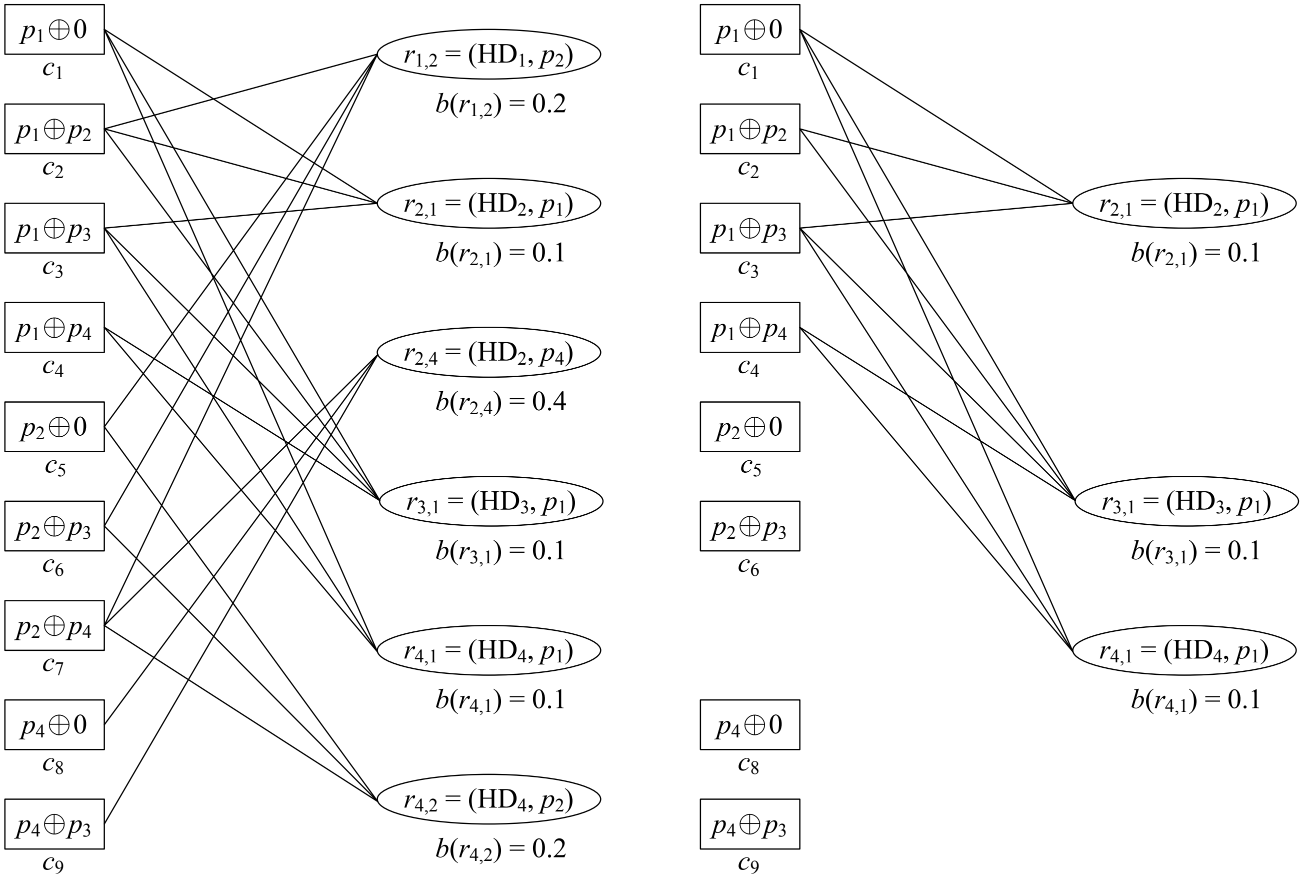
We then discuss the rationale of our MBC algorithm. Given all possible coded packets $\mathcal{C}$, what we have to do is to first find out the *mapping* between every coded packet $c_k \in \mathcal{C}$ and every request $r_{i,j} \in \mathcal{R}$. In other words, we have to calculate what coded packets can satisfy each request $r_{i,j}$. To do so, we thus construct a bipartite graph $\mathcal{G}$, which is widely used to show the relationship between two sets, to list the aforementioned mapping. Then, the MBC algorithm calculates the current benefit of each coded packet c_k, which is the overall benefit (of requests) that the BS can obtain if it chooses to broadcast c_k. By adopting a greedy strategy, our MBC algorithm iteratively selects the coded packet which can obtain the maximum (overall) benefit. Notice that the same request may be satisfied by multiple coded packets. Therefore, every time when we select one coded packet c_k, we have to remove all of its adjacent vertices in $\mathcal{R}$ (that is, the requests satisfied by c_k) from $\mathcal{G}$. In this way, the current benefit of each coded packet c_k can always reflect the "additional" benefit that the BS can obtain when it chooses c_k in every iteration.

IV. SIMULATION RESULTS

To measure the performance of our MBC algorithm, we develop a simulator by using the C++ language. In the simulator, we focus on investigating the behaviors in one cell

packet	benefit	HD$_1$	HD$_2$	HD$_3$	HD$_4$
p_1	0.1		×	×	×
p_2	0.2	×			×
p_3	0.3				
p_4	0.4		×		

(a)



(b) (c)

Fig. 2: An example of the MBC algorithm: (a) the packet loss of HDs (denoted by '×'), (b) the initial graph $\mathcal{G}$, (c) the modified graph by removing vertex c_7 (and its adjacent vertices $r_{1,2}$, $r_{2,4}$, and $r_{4,2}$) from $\mathcal{G}$.

of the recovery network, where a BS is responsible for serving ten HDs. The time axis is divided into superframes. During each superframe, the DVB-H server will broadcast 20 packets to all HDs. For every five packets, say, p_1, p_2, p_3, p_4, and p_5 of these 20 packets, we assign their benefits as follows: $b(p_1) = 0.1$, $b(p_2) = 0.3$, $b(p_3) = 0.5$, $b(p_4) = 0.7$, and $b(p_5) = 0.9$. In addition, we consider a probability P_{loss} of packet loss, which is ranged from 0.1 to 0.4. There are totally 1000 superframes in our simulation. We compare our MBC algorithm with the PNC algorithm [13] discussed in Section I, where it tries to recover the maximum number of lost packets in each superframe.

TABLE II: Total benefits obtained in a superframe by using different coding algorithms.

P_{loss}	0.10	0.15	0.20	0.25	0.30	0.35	0.40
MBC	6.63	9.01	11.30	13.49	15.58	17.62	19.68
PNC	5.36	7.07	8.70	10.15	11.50	12.80	14.10

TABLE III: The number of lost packets recovered in a superframe by using different coding algorithms.

P_{loss}	0.10	0.15	0.20	0.25	0.30	0.35	0.40
MBC	9.71	12.95	15.68	18.22	20.74	23.09	25.40
PNC	11.08	14.61	17.98	21.03	23.93	26.66	29.35

Given $\tau = 5$ (that is, the BS can broadcast at most five coded packets in a T_{send} period), Table II presents the total benefits obtained by using the MBC and PNC algorithms. On the other hand, Table III presents the number of lost packets recovered in a superframe by using the MBC and PNC algorithms. (Notice that since two or more HDs could lose the same packets, the number of lost packets may exceed

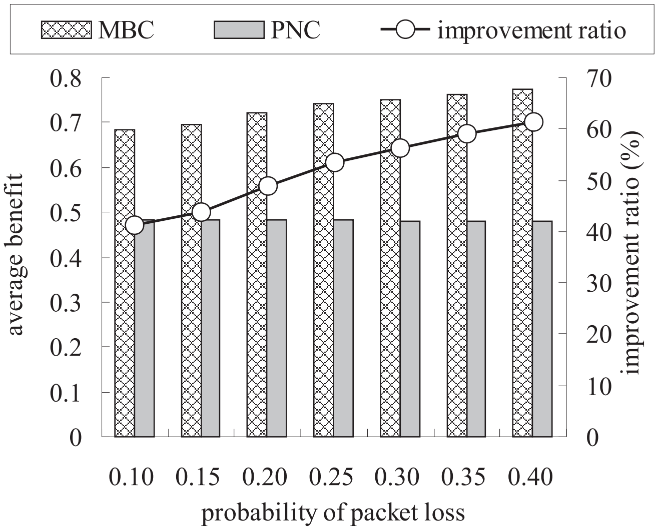


Fig. 3: Comparison on the average benefits obtained in a superframe by using different coding algorithms.

20. In our simulation, the maximum number of lost packets in a superframe will be $10 \times 20 = 200$ since we have 10 HDs.) Obviously, when the probability P_{loss} becomes larger, both algorithms can obtain more benefits and recover more lost packets, because the number of lost packets increases. However, although the PNC algorithm can recover more lost packets, it obtains a smaller (total) benefit compared with our MBC algorithm. The reason is that the PNC algorithm does not care about the priority or importance of each lost packet. Therefore, the PNC algorithm may calculate coded packets to deal with those packets which are lost by more HDs but have less importance. On the contrary, our MBC algorithm takes the importance of each lost packet into account, so it can generate coded packets which obtain a larger (total) benefit.

Fig. 3 summarizes the results from both Tables II and III, where the *improvement ratio* is defined by

$$\frac{\text{benefit}_{\text{MBC}} - \text{benefit}_{\text{PNC}}}{\text{benefit}_{\text{PNC}}} \times 100\%.$$

From Fig. 3, we can observe that the average benefit obtained by the PNC algorithm is almost the same (approximately 0.48), no matter how the probability P_{loss} changes. On the contrary, the average benefit obtained by our MBC algorithm increases from 0.68 to 0.77 when the probability P_{loss} increases from 0.1 to 0.4. Therefore, the improvement ratio also increases from 41.1% to 61.3% accordingly. This simulation result verifies the effectiveness of our MBC algorithm in terms of benefit obtained, which demonstrates that our MBC algorithm can perform well when the lost packets have different priorities or importance.

V. CONCLUSIONS

DVB-IPDC provides an architecture to deal with the packet retransmission issue in DVB-H. It can substantially improve the retransmission efficiency of DVB-IPDC by applying network coding. Observing that multimedia packets may have different priorities or importance, this paper formulates a new MBC problem where the BS can obtain different benefits by recovering different packets. By using a bipartite graph to compute the relationship between coded packets and lost packets, our MBC algorithm allows the BS to broadcast at most τ coded packets in each superframe to increase the overall benefit of the recovered packets. The effectiveness of the MBC algorithm is also verified by the simulations.

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