Profit-based Exclusive-or Coding Algorithm for Data Retransmission in DVB-H with a Recovery Network

You-Chiun Wang

Abstract—The DVB-H standard is developed by ETSI to broadcast digital videos to handheld devices, but data loss is a critical issue due to the broadcast behavior. On the other hand, DVB-IPDC integrates DVB-H with an IP-based wireless network to provide bidirectional communication. We adopt this wireless network to deal with data retransmission and call it a *recovery network*. The paper argues that network coding can improve retransmission efficiency of the recovery network because DVB-H packet loss often exhibits high correlation. In addition, DVB-H packets may be heterogeneous in the sense that they have different importance. According to these two arguments, the paper considers that DVB-H packets are associated with different *profit* depending on their importance, and proposes an *α-maximum profit network coding problem*. It asks the base station in the recovery network to use no more than α coded packets for handheld devices to retrieve the lost DVB-H packets such that the overall profit is the maximum. An efficient exclusive-or coding scheme, namely the *PEN algorithm*, is proposed to solve this problem. Extensive simulation results also verify the effectiveness of the PEN algorithm.

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

◆

1 INTRODUCTION

To support the mobile TV service, ETSI (European Telecommunications Standards Institute) approved the DVB-H (Digital Video Broadcasting – Handheld) standard in 2004 [1]. Generally speaking, the DVB-H standard is an extension of the successful DVB-T ('T' stands for terrestrial) standard by tailoring the physical and data-link layers to the reception of *handheld devices (HDs)* such as smart phones or PDAs [2]. DVB-H physical layer adopts TPS (transmission parameter signaling) to speed up the service discovery process. Its data-link layer uses a TDM (time division multiplexing) broadcast scheme, namely *time-slicing*, to disseminate multimedia data to HDs. In addition, to protect the data reception against various impairment such as the Doppler influence or impulse noises, the MPE-FEC (multi-protocol encapsulation – forward error correction) scheme is proposed to correct the corrupted data.

However, under poor channel conditions, MPE-FEC may not guarantee to correct all corrupted data [3]. In this case, data retransmission is necessary. Although DVB-H provides a return channel for HDs to feedback some information, Yang et al. [4] point out that it has two major drawbacks to use this return channel for data retransmission. First, the return channel is quite narrow and in consequence it cannot afford to carry a lot of information. Second, the DVB-H server has to schedule both the regular broadcast and the retransmission of lost data, which complicates its design.

DVB-IPDC (IP datacast over DVB-H) [5], on the other hand, features an IP (Internet protocol) interface for easy network integration. It incorporates an optional access to an IP-based wireless network which intends to support interactive applications [6]. In this paper, we call this wireless network a *recovery network* because it provides a bidirectional communication channel for HDs to demand the retransmission of lost data. Fig. 1 presents an example that integrates DVB-H with a recovery network. The DVB-H server periodically broadcasts video data to HDs. When an HD suffers from data loss, this HD can transmit a *recovery request (RREQ)* to its associated *base station (BS)* in the recovery network to ask for retransmission.

DVB-H data loss, however, usually exhibits high correlation, especially in both spatial and temporal domains [7]. Spatial correlation points out that HDs in a small region (for example, a network cell) may lose similar data because of the interference from the same noise(s). Temporal correlation indicates that these HDs could lose a similar sequence of data because the noises often exist for a spell. On the other hand, [8], [9] show that network coding can significantly reduce the redundant (and unnecessary) communication when transmitting correlated or duplicate data. Therefore, this paper suggests applying network coding to facilitate the data retransmission process in the recovery network.

Conventional network coding schemes usually consider that packets are homogeneous. Therefore, they intend to use as fewer coded packets for transmission as possible to save the network bandwidth. However, multimedia data could be "heterogeneous" in the sense that packets have different *importance*. Let us take MPEG-4 (Moving Picture Experts Group) [10], which is one of the popular video compression technique, as an example. MPEG-4 generates multiple data fragments (called *frames*) for a video stream, which can be classified into three categories: I-frames (stand for "intra-coded pictures"), P-frames (stand for "predicted pictures"), and B-frames (stand for "bi-predictive pictures"). I-frames can be reconstructed independently without any reference to other frames. On the other hand, P-frames and B-frames maintain only parts of the image information and thus they depend on I-frames to reconstruct the original image. Therefore, I-frames are more important than P-frames and B-frames.

Suppose that the BS is allowed to use a small number of coded packets to recover the lost frames of HDs in the MPEG-

---

Y.-C. Wang is with the Department of Computer Science and Engineering, National Sun Yat-sen University, Kaohsiung, 80424, Taiwan. E-mail: ycwang@cse.nsysu.edu.tw

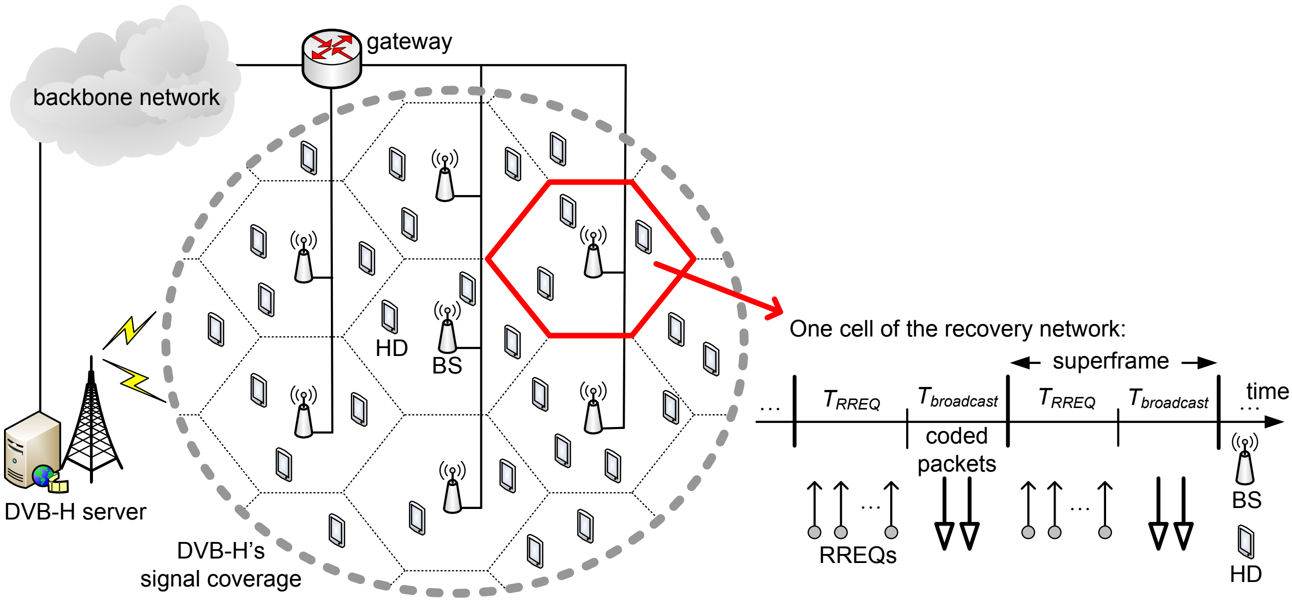


Fig. 1: Integrate DVB-H with a recovery network to support data recovery.

4 example. The conventional network coding schemes could not be directly applied in this case because they treat every lost frame as equal one. Thus, these schemes may generate coded packets to recover the lost P-frames or B-frames from a large number of HDs, leaving important I-frames discarded. In fact, we should prefer those coded packets containing I-frames because most HDs require I-frames to reconstruct the original image information. In other words, recovering I-frames (by coded packets) can obtain more "profit" than recovering P-frames and B-frames.

Motivated by the above argument, this paper proposes the *α-maximum profit network coding problem* (abbreviated to the α-MPNC problem) in a DVB-IPDC system. Specifically, each DVB-H packet is associated with a *profit* value to reflect its importance (depending on the application). We divide the time axis into repeating *superframes* to manage the retransmission process of the recovery network. During each superframe, HDs submit RREQs to indicate their lost DVB-H packets in the previous superframe to the BS. However, owing to the limited period length of a superframe, the BS is allowed to calculate no more than α coded packets to recover the lost DVB-H packets of HDs. Obviously, it is not always possible to recover all of the lost DVB-H packets by using only α coded packets, especially when some HDs lose more DVB-H packets. Therefore, unlike the conventional network coding problems, the objective of our α-MPNC problem is to maximize the overall profit obtained in each superframe.

To solve the α-MPNC problem, we develop a *profit-based exclusive-or network coding algorithm* (abbreviated to the PEN algorithm). The major idea of our PEN algorithm is to construct a *relation graph* to measure the relationship between the coded packets and the lost DVB-H packets. Then, the BS dynamically calculates the total profit which can be gained by using each coded packet and iteratively selects the best one. The contribution of this paper is to propose a new α-MPNC problem which considers the heterogeneity of multimedia data in DVB-H applications. The design of our PEN algorithm is simple but optimal so that the BS can quickly calculate necessary coded packets in every superframe. Extensive simulation results demonstrate that the PEN algorithm can recover the lost DVB-H packets with more importance and therefore verify its effectiveness.

We outline the remainder of this paper as follows: The next section gives a comprehensive survey of related work. Section 3 formulates the α-MPNC problem while Section 4 proposes our PEN algorithm. Section 5 gives the theoretical analysis of the PEN algorithm. Experimental results are presented in Section 6. We conclude this paper in Section 7.

2 RELATED WORK

This paper aims at adopting network coding to facilitate the data retransmission process to recover the erroneous reception of HDs in a DVB-H system. Below, we first survey existing data recovery algorithms in DVB-H systems, which also adopt another IP-based wireless network for the data retransmission purpose. Then, we discuss the network coding schemes in content distribution and multimedia streaming applications. Finally, we investigate the network coding methods for the error recovery purpose.

2.1 Data Recovery in DVB-H Systems

Several research efforts consider integrating DVB-H with a cellular network, where the latter provides another channel to transmit parity information for data recovery. Gomez-Barquero et al. [11] suggest transmitting parity information through either the DVB-H channel or the cellular network. The BS in the cellular network can choose between the dedicated point-to-point connection or the cell broadcasting manner to send the parity information to HDs. Through extensive simulations, Hechenleitner [12] points out some guidelines for the cellular BS to choose between the point-to-point and point-to-multipoint repair mechanisms under various network conditions. In addition, ETSI develops the *content delivery protocol* [13] to regulate the transmission behaviors in the cellular network. Hummelbrunner et al. [14] combine DVB-H with a UMTS (Universal Mobile Telecommunications System) network, where every three HDs are organized into a group.

The HD with the strongest received signal strength in each group serves as a super peer to take charge of data recovery for its group members.

On the other hand, some studies incorporate DVB-H with a non-cellular network for the data recovery purpose. Akester [15] proposes a multicast protocol to deal with DVB-H data loss through an IEEE 802.11 network. By adopting WiMAX as the recovery network, the work of [7] develops a group acknowledgement scheme to prevent HDs from submitting a large number of duplicate recovery requests to the WiMAX BS, which can alleviate network congestion. Sinkar et al. [16] suggest organizing HDs into a wireless ad hoc network. In this way, HDs can share the lost DVB-H packets with each other through peer-to-peer links. However, none of the aforementioned studies consider applying network coding for data recovery in DVB-H systems.

Yang et al. [17] propose a *prioritized network coding (PNC)* method to deal with error recovery in a DVB-IPDC system, where the BS in a recovery network is allowed to broadcast a fixed number of coded packets in its cell such that the BS can recover the maximum number of lost DVB-H packets while minimize the total number of DVB-H packets discarded due to passing their deadlines. However, the PNC method assumes that all DVB-H packets are homogeneous. On the contrary, our PEN algorithm allows DVB-H packets to have different profit based on their importance, which addresses the diversity of video compression data in DVB-H applications.

2.2 Network Coding in Content Distribution and Multimedia Streaming Applications

Network coding is extensively adopted in content distribution and multimedia streaming applications to improve the communication efficiency. For content distribution applications, Gkantsidis and Rodriguez [18] address how to efficiently deliver large files in a distributed network. Each node in the network adopts a randomization algorithm to generate encoded blocks for the file content and then schedules the time slots to deliver these blocks to its neighbors. The work of [19] develops a peer-to-peer content distribution system based on the sparsely linear network coding scheme, where the system determines the encoding density in order to increase the probability of generating independently encoded blocks. In addition, an encoding interval is adopted to reduce the probability of transmitting linearly dependent packets. Lee et al. [20] consider using network coding for content distribution in a vehicular ad hoc network, and they develop a file swarming protocol to handle the problems of rapid topology change and intermittent connectivity.

For multimedia streaming applications, the study of [21] considers a data-driven overlay network for live multimedia streaming, where every node in the network is associated with a set of partners. Each node periodically exchanges the information of data availability with its partners, retrieves unavailable data from partners, and supplies available data to partners using network coding. Wang and Li [22] propose a randomized push algorithm to exploit random network coding for live peer-to-peer streaming. The objectives are to alleviate buffering delays, resist to peer dynamics, and reduce the bandwidth cost of streaming servers. By adopting random network coding, Liu et al. [23] develop an on-demand video streaming system to minimize the bandwidth cost and buffering delay of each streaming server in a large-scale network. Obviously, all of the above research efforts aim at using network coding to save the bandwidth cost. In contrast to them, our work targets at how to select no more than α coded packets in each superframe such that the overall profit of the satisfied requests (for the lost DVB-H packets) is the maximum.

2.3 Network Coding for Error Recovery

Network coding is also widely adopted to deal with the error recovery issue for data transmission. Larsson [24] extends the multiuser *automatic repeat request (ARQ)* scheme to handle error recovery in multicast applications. Based on the ARQ feedback information from the multicast receivers which indicates their successfully received data, the multicast transmitter can calculate the code weights for the linear combination of all multicast data and thus send coded packets accordingly. In addition, Li et al. [25] consider adopting random network coding to further improve the retransmission mechanism of hybrid ARQ. The work of [26] first partitions HDs into multiple groups, and then adaptively encodes packets according to the data temporarily stored in each HD to reduce the bandwidth cost. Birk and Kol [27] propose an *informed-source coding on demand (ISCOD)* algorithm, whose idea is to translate the network coding problem into the problem of selecting k-partial cliques in a directed graph. The work of [28] proposes a *demand-oriented pairing (DOP)* coding method to reduce the average access time for the receivers to recover their lost packets. However, our PEN algorithm differs from these network coding schemes in two aspects. First, while they assume that the lost packets are homogeneous, our PEN algorithm considers that DVB-H packets are heterogeneous in the sense that they have different profit. Second, these network coding schemes attempt 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 DVB-H packets in the α-MPNC problem, our PEN algorithm tries to maximize the overall profit by using at most α coded packets in every superframe.

3 THE α-MPNC PROBLEM

In accordance with the DVB-IPDC architecture, this paper considers an integrated network shown in Fig. 1, where a DVB-H system and a recovery network are tightly coupled (through a backbone network). HDs roam inside the coverage range of both the DVB-H system and the recovery network. Each HD is equipped with separate transceivers so that it can simultaneously communicate with the DVB-H system and the recovery network without any interference.

In the DVB-H system, the DVB-H server regularly broadcasts video data, which are in the form of *DVB-H packets*, to all HDs. Each DVB-H packet p_j is associated with *profit* $\Phi(p_j)$ to indicate its importance, where $0 < \Phi(p_j) < 1$. On the other hand, the recovery network can be any IP-based wireless network such as LTE, WiMAX, or 3G networks [29]–[31] and it takes charge of retransmitting the lost DVB-H packets to HDs. The recovery network is composed of multiple *cells*, where each cell is coordinated by one BS. Below, we focus the discussion on a single cell of the recovery network.

To manage the data recovery process in the recovery network, we divide the time axis into repetitive superframes. Each superframe is composed of a T_{RREQ} period followed by a $T_{broadcast}$ period. Every HD$_i$ lost DVB-H packets in the previous superframe will submit an RREQ $(\text{HD}_i, p_{j_1}, p_{j_2}, \cdots, p_{j_k})$

TABLE 1: Summary of notations.

notation	definition
p_j	an uncoded DVB-H packet
c_k	a coded packet
$r_{i,j}$	a request indicating that HD$_i$ asks for p_j
α	the number of coded packets that the BS is allowed to broadcast in a superframe
$\Phi(\cdot)$	profit
$\mathcal{R}$	the set of all requests
$\mathcal{C}$	the set of all possible coded packets
$\mathcal{L}$	the set of DVB-H packets lost by HDs
$\mathcal{S}$	the set of DVB-H packets successfully received by HDs
$\mathcal{B}$	the solution set of coded packets
n	the number of operands in the exclusive-or coding scheme
q	the number of packets broadcasted by the DVB-H server in a superframe

to its BS, which requests the BS to retransmit the lost DVB-H packets p_{j_1}, p_{j_2}, $\cdots$, and p_{j_k} in the subsequent $T_{broadcast}$ period. For ease of presentation, we denote by $r_{i,j} = (\text{HD}_i, p_j)$ the *request* that HD$_i$ asks for the lost DVB-H packet p_j. In this way, the aforementioned 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.

Suppose that the BS is allowed to transmit no more than α packets in a $T_{broadcast}$ period due to the limited period length. Given the set of all requests from HDs, denoted by $\mathcal{R}$, the α-MPNC problem determines how the BS broadcasts at most α coded packets in every $T_{broadcast}$ period to retransmit the lost DVB-H packets to its HDs such that the total profit of the *satisfied requests* is the maximum. Table 1 summarizes the notations used in this paper.

We remark that the profit of packets depends on the application requirement and is given as the input of the α-MPNC problem. On possible profit-assignment method is to classify packets into multiple groups based on their types or importance and then give each group of packets a different profit value. Obviously, the profit values can be proportional to the importance degrees. We will present an example using MPEG-4 in Section 6.3. In addition, the profit of packets is defined in the DVB-H server and the BS should query it to get the profit knowledge via the backbone network. In this way, the BS need not take care of profit change when the DVB-H server decides to broadcast a different set of packets.

4 THE PROPOSED PEN ALGORITHM

Since the PEN algorithm relies on the exclusive-or coding technique, the BS should calculate two sets of DVB-H packets based on the set of requests $\mathcal{R}$ in every T_{RREQ} period:

- $\mathcal{L}$: The set of DVB-H packets lost by HDs in the T_{RREQ} period. It can be derived by checking the second index of every request $r_{i,j} \in \mathcal{R}$.
- $\mathcal{S}$: The set of DVB-H packets successfully received by HDs in the T_{RREQ} period. It can be easily derived since the BS knows all packets sent by the DVB-H server in advance.

Notice that $\mathcal{L}$ and $\mathcal{S}$ are not complementary to each other (that is, $\overline{\mathcal{L}} \neq \mathcal{S}$). Let $\mathcal{B}$ be the solution set of coded packets and it is null initially. Then, the PEN algorithm contains the followings steps:

- **Step 1:** Calculate all possible coded packets $\mathcal{C}$ from $\mathcal{L}$ and $\mathcal{S}$ using the n-operand exclusive-or coding scheme. Let '$\oplus$' denote the exclusive-or operator. Each coded packet $c_k \in \mathcal{C}$ is then computed by

$$\begin{aligned} & c_k = p_x \oplus p_{y_1} \oplus p_{y_2} \oplus \cdots \oplus p_{y_{n-1}}, \quad (1) \\ & p_x \neq p_{y_i}, i = 1..n-1, \\ & p_{y_1} \neq p_{y_2} \neq \cdots \neq p_{y_{n-1}} \text{ if they are non-zero,} \end{aligned}$$

where $p_x \in \mathcal{L}$ and $p_{y_1}, p_{y_2}, \cdots, p_{y_{n-1}} \in \mathcal{S} \cup \{0\}$. Here, c_k is allowed to include at most one packet in $\mathcal{L}$ (that is, p_x). In this case, an HD losing p_x but already having packets in $\mathcal{S}$ can recover p_x from c_k. Notice that when $p_{y_1} = p_{y_2} = \cdots = p_{y_{n-1}} = 0$, c_k is in fact an *uncoded packet* p_x.
- **Step 2:** To evaluate the relationship between the coded packets and the requests of HDs, the BS constructs a *relation graph* $\mathcal{G}$, which is a bipartite graph:

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

where the vertex set $\mathcal{V}$ includes all possible coded packets $\mathcal{C}$ and all requests $\mathcal{R}$. An edge $(c_k, r_{i,j})$, $c_k \in \mathcal{C}$ and $r_{i,j} \in \mathcal{R}$, belongs to the edge set $\mathcal{E}$ if and only if the coded packet c_k allows HD$_i$ to recover its lost packet p_j. On the graph $\mathcal{G}$, each vertex $r_{i,j} \in \mathcal{R}$ is associated with profit $\Phi(r_{i,j})$, which is equal to the profit of its corresponding packet p_j, that is, $\Phi(r_{i,j}) = \Phi(p_j)$.
- **Step 3:** Compute the profit gained by each coded packet $c_k \in \mathcal{C}$ according to its adjacent vertices in $\mathcal{R}$:

$$\Phi(c_k) = \sum_{r_{i,j} \in \mathcal{R}, (c_k, r_{i,j}) \in \mathcal{E}} \Phi(r_{i,j}). \quad (2)$$

- **Step 4:** Select the coded packet $c_k \in \mathcal{C}$ whose profit $\Phi(c_k)$ is the maximum. In case of tie, the BS arbitrarily selects one coded packet. Then, the solution set $\mathcal{B}$ is updated by $\mathcal{B} \cup \{c_k\}$.
- **Step 5:** Modify the relation graph $\mathcal{G}$ by removing certain vertices and edges. In particular, the BS first removes the vertex c_k since it has been selected in step 4. Then, it removes each vertex $r_{i,j} \in \mathcal{R}$ such that an edge $(c_k, r_{i,j})$ exists in $\mathcal{E}$, because these requests can be satisfied by c_k. Finally, for every such vertex $r_{i,j}$, the BS removes all of its adjacent edges.
- **Step 6:** Repeat steps 3, 4, and 5 until either 1) α vertices from $\mathcal{C}$ have been selected (in other words, $|\mathcal{B}| = \alpha$) or 2) all vertices in $\mathcal{R}$ have been removed by step 5. In either case, the PEN algorithm finishes and the BS broadcasts the coded packets in $\mathcal{B}$ to all HDs during the $T_{broadcast}$ period.

We use an example in Fig. 2 to demonstrate the PEN algorithm, where $\Phi(p_1) = 0.1$, $\Phi(p_2) = 0.3$, $\Phi(p_3) = 0.5$, $\Phi(p_4) = 0.7$, and $\alpha = 2$. Suppose that there are four HDs, HD$_1$, HD$_2$, HD$_3$, and HD$_4$, which submit their RREQs (HD_1, p_1, p_3), (HD_2, p_1, p_2), (HD_3, p_1, p_4), and (HD_4, p_1, p_2) to the BS in the T_{RREQ} period, respectively. Therefore, the BS has the set of requests

$$\mathcal{R} = \{r_{1,1}, r_{1,3}, r_{2,1}, r_{2,2}, r_{3,1}, r_{3,4}, r_{4,1}, r_{4,2}\},$$

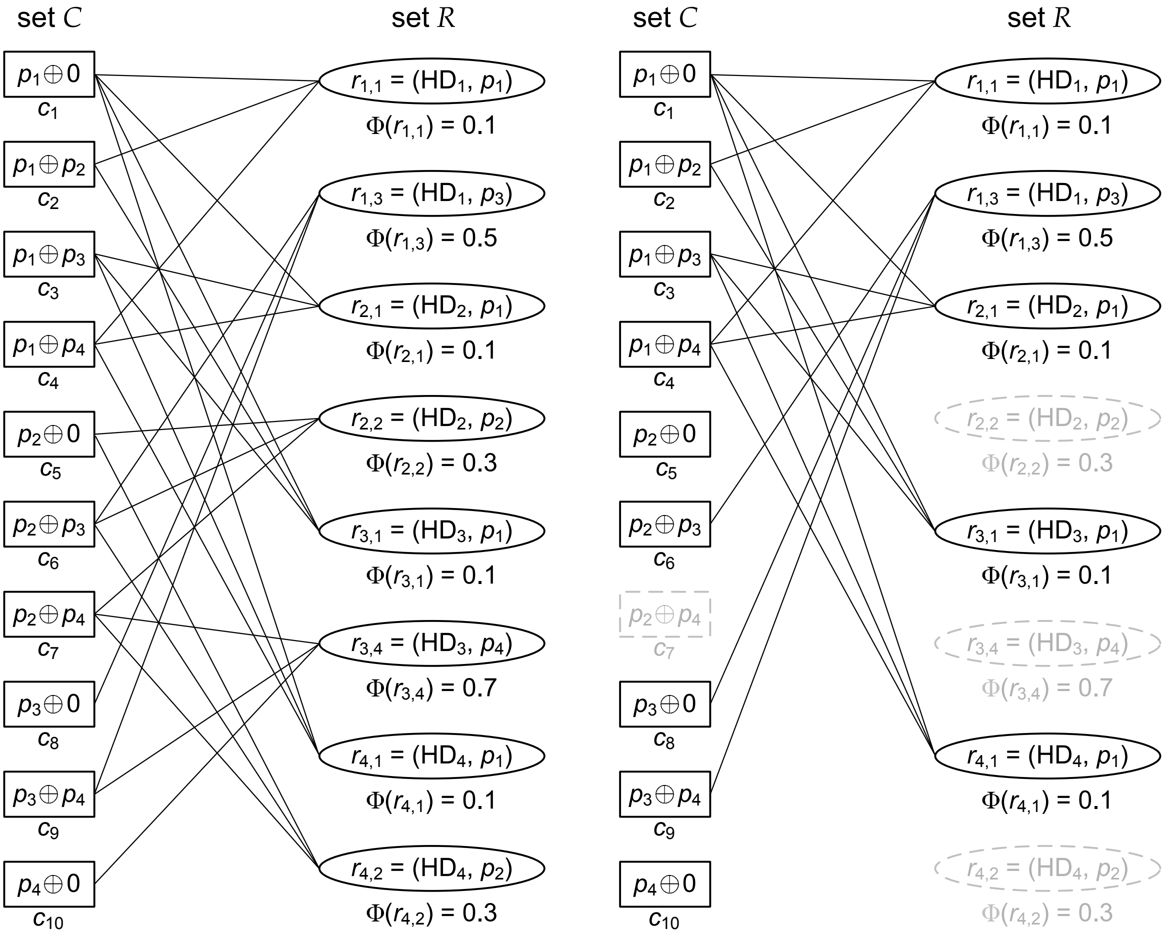
and can calculate both sets

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

Obviously, $\mathcal{L}$ and $\mathcal{S}$ are not complementary to each other. Assuming that $n = 2$ (that is, the two-operand exclusive-or

packet	profit	HD_1	HD_2	HD_3	HD_4
p_1	0.1	×	×	×	×
p_2	0.3		×		×
p_3	0.5	×			
p_4	0.7			×	

(a)



(b) (c)

Fig. 2: An example of the PEN algorithm: (a) the DVB-H packet loss of HDs (denoted by '×'), (b) the initial relation graph $\mathcal{G}$, (c) the modified relation graph by removing vertex c_7 and all of its adjacent vertices.

coding scheme is adopted), the BS can calculate all possible coded packets from $\mathcal{L}$ and $\mathcal{S}$ in step 1:

$$\begin{aligned}\mathcal{C} = \{&c_1 = p_1 \oplus 0, c_2 = p_1 \oplus p_2, c_3 = p_1 \oplus p_3, c_4 = p_1 \oplus p_4,\\ &c_5 = p_2 \oplus 0, c_6 = p_2 \oplus p_3, c_7 = p_2 \oplus p_4, c_8 = p_3 \oplus 0,\\ &c_9 = p_3 \oplus p_4, c_{10} = p_4 \oplus 0\}.\end{aligned}$$

Then, step 2 constructs the relation graph $\mathcal{G}$ by both $\mathcal{C}$ and $\mathcal{R}$, as shown in Fig. 2(b). In step 3, the BS computes the profit gained by each coded packet using Eq. (2). For instance, since $r_{1,1}$, $r_{2,1}$, $r_{3,1}$, and $r_{4,1}$ are the adjacent vertices of the coded packet c_1, its profit is

$$\begin{aligned}\Phi(c_1) &= \sum_{r_{i,j}\in\mathcal{R},(c_1,r_{i,j})\in\mathcal{E}} \Phi(r_{i,j})\\ &= \Phi(r_{1,1}) + \Phi(r_{2,1}) + \Phi(r_{3,1}) + \Phi(r_{4,1})\\ &= 0.1 + 0.1 + 0.1 + 0.1 = 0.4.\end{aligned}$$

Similarly, the profit gained by the coded packets c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9, and c_{10} are 0.2, 0.3, 0.3, 0.6, 1.1, 1.3, 0.5, 1.2, and 0.7, respectively. Among all coded packets in $\mathcal{C}$, the BS should select c_7 and add it to the solution set $\mathcal{B}$ because c_7 gains the maximum profit $\Phi(c_7) = 1.3$. Then, according to step 5, the BS removes the following vertices and edges from the graph $\mathcal{G}$:

- vertex c_7
- all vertices adjacent to c_7: $r_{2,2}$, $r_{3,4}$, and $r_{4,2}$
- all corresponding edges: $(c_5, r_{2,2})$, $(c_5, r_{4,2})$, $(c_6, r_{2,2})$, $(c_6, r_{4,2})$, $(c_7, r_{2,2})$, $(c_7, r_{3,4})$, $(c_7, r_{4,2})$, $(c_9, r_{3,4})$, and $(c_{10}, r_{3,4})$

The modified relation graph is thus shown in Fig. 2(c). By executing step 3 again, the BS updates the profit of each remaining coded packet as follows: $\Phi(c_1) = 0.4$, $\Phi(c_2) = 0.2$, $\Phi(c_3) = 0.3$, $\Phi(c_4) = 0.3$, $\Phi(c_5) = 0$, $\Phi(c_6) = 0.5$, $\Phi(c_8) = 0.5$, $\Phi(c_9) = 0.5$, and $\Phi(c_{10}) = 0$. Here, the coded packets c_5 and c_{10} gain no profit because they no longer satisfy any request. Since the coded packets c_6, c_8, and c_9 all gain the maximum profit (that is, 0.5), the BS arbitrarily selects one of them. Then, the PEN algorithm finishes because the BS has selected $\alpha = 2$ coded packets. Therefore, the final solution set will be

$$\mathcal{B} = \{c_7 = p_2 \oplus p_4, c_6 = p_2 \oplus p_3\} \quad \text{or}$$

$$\mathcal{B} = \{c_7 = p_2 \oplus p_4, c_8 = p_3 \oplus 0\} \text{ or}$$
$$\mathcal{B} = \{c_7 = p_2 \oplus p_4, c_9 = p_3 \oplus p_4\}.$$

Actually, the effects of coded packets c_6, c_8, and c_9 are the same because the DVB-H packet p_3 is lost by only HD_1 and HD_1 can recover p_3 according to any of these coded packets.

In the example of Fig. 2, our PEN algorithm can satisfy four requests (HD_2, p_2), (HD_4, p_2), (HD_1, p_3), and (HD_3, p_4) and therefore obtain total profit of 1.8. On the other hand, most of conventional network coding schemes try to use fewer coded packets to satisfy more requests. In this case, one may calculate another solution set

$$\mathcal{B}' = \{c_1 = p_1 \oplus 0, c_6 = p_2 \oplus p_3\}.$$

Obviously, except for the request (HD_3, p_4), all other seven requests can be satisfied by the solution set $\mathcal{B}'$. However, this method obtains total profit of only 1.5, which is smaller than our PEN algorithm. This example points out *it is not always true to obtain larger profit by satisfying more requests* because many HDs could lose some DVB-H packets with small profit.

We then discuss the rationale of our PEN algorithm. Given all possible coded packets $\mathcal{C}$ and all requests $\mathcal{R}$, the BS first constructs a relation graph $\mathcal{G}$ in order to find out the *mapping* between every coded packet $c_k \in \mathcal{C}$ and every request $r_{i,j} \in \mathcal{R}$. In this way, the BS can realize what coded packets can satisfy each request $r_{i,j}$ and, in consequence, calculate the profit gained by every coded packet c_k (by summing up the profit of all its adjacent vertices in the set $\mathcal{R}$). From the relation graph $\mathcal{G}$, the PEN algorithm needs to select at most α vertices in the set $\mathcal{C}$ such that the overall profit gained by these vertices is the maximum. However, the design of the PEN algorithm should be simple because of two reasons. First, the BS has to execute the PEN algorithm in every superframe. Second, the $T_{broadcast}$ period is usually short and it is right after the T_{RREQ} period. Thus, the BS has only a short time to calculate coded packets. Taking the above concern into consideration, the PEN algorithm adopts a greedy strategy by iteratively selecting the coded packet which gains the maximum profit. Notice that the same request may be satisfied by multiple coded packets. Therefore, every time when the BS adds one coded packet to the solution set $\mathcal{B}$, the relation graph $\mathcal{G}$ should be updated by removing all of the requests satisfied by that coded packet. In this way, the profit of each coded packet c_k can always reflect the *additional* profit that the BS can obtain when it selects c_k in an iteration.

5 THEORETICAL ANALYSIS

In this section, we present some analyses for the PEN algorithm. Let m be the number of all possible coded packets in a superframe (in other words, $|\mathcal{C}| = m$) and h be the number of HDs in a cell of the recovery network. Theorem 1 and Corollary 1 analyze the properties of the relation graph $\mathcal{G}$.

Theorem 1. In the relation graph $\mathcal{G}$, each coded packet of the set $\mathcal{C}$ has at most h adjacent edges.

Proof: Without loss of generality, let $c_k = p_1 \oplus p_2 \oplus \cdots \oplus p_n$ be a coded packet of the set $\mathcal{C}$. Suppose that c_k can satisfy the request $r_{i,j}$ = (HD_i, p_j). In this case, HD_i must have successfully received the DVB-H packets $p_1, p_2, \cdots, p_{j-1}, p_{j+1}, \cdots, p_n$. Otherwise, HD_i cannot recover the lost DVB-H packet p_j from the coded packet c_k. Therefore, the set $\mathcal{R}$ must not contain requests (HD_i, p_1), (HD_i, p_2), $\cdots$, (HD_i, p_{j-1}), (HD_i, p_{j+1}), $\cdots$, (HD_i, p_n). In addition, c_k cannot satisfy those requests (HD_i, p_β), where $\beta > n$, because p_β does not appear in any operand of c_k. In other words, it is impossible that a single coded packet c_k can satisfy two or more requests generated from the same HD. However, the coded packet c_k could satisfy multiple requests generated from different HDs. In an extreme case, c_k can satisfy h requests, each generated by one different HD in the cell. □

Corollary 1. The relation graph $\mathcal{G}$ must be incomplete when any HD loses more than one DVB-H packet.

Proof: According to Theorem 1, because each coded packet can satisfy at most one request generated from the same HD, the relation graph $\mathcal{G}$ will not be a complete bipartite graph. □

Notice that the set $\mathcal{C}$ of all possible coded packets can be calculated in advance by the BS in each superframe. It is because the BS knows the set of DVB-H packets broadcasted by the DVB-H server (denoted by $\mathcal{A}$) and both sets $\mathcal{L}$ and $\mathcal{S}$ are actually a subset of $\mathcal{A}$. In this way, the BS does not need to generate the set $\mathcal{C}$ in real time and thus can calculate the solution set $\mathcal{B}$ faster. Theorem 2 shows the worst-case computation complexity of the PEN algorithm.

Theorem 2. Given the set $\mathcal{C}$, the computation complexity of the PEN algorithm is $O(mnh) + O(h \cdot \alpha(m-\alpha))$.

Proof: Based on $\mathcal{C}$ and $\mathcal{R}$, the BS constructs the relation graph $\mathcal{G}$. According to Corollary 1, since the graph $\mathcal{G}$ is not a complete bipartite graph, the BS does not need to check every request for each coded packet in order to construct the edge set $\mathcal{E}$. Instead, for each coded packet $c_k \in \mathcal{C}$, the BS should only check each request $r_{i,j} \in \mathcal{R}$ such that its lost DVB-H packet p_j appears in any operand of c_k (by Eq. (1)). Since each DVB-H packet p_j can be lost by no more than h HDs and the coded packet c_k has at most n non-zero operands in Eq. (1), the check for each coded packet (to determine its adjacent edges) thus requires $O(h \cdot n)$ time. Because there are m coded packets in the set $\mathcal{C}$, the time to construct the edge set $\mathcal{E}$ in step 2 will be $O(m \cdot h \cdot n)$.

Then, the BS iteratively executes steps 3, 4, and 5 until α coded packets have been selected from the set $\mathcal{C}$. We then analyze the time spent in each of these α iterations. Specifically, in the first iteration, the BS has to calculate the overall profit gained by each coded packet. According to Theorem 1, since each coded packet has no more than h adjacent edges, the total time spent to calculate the profit gained by all coded packets will be $O(m \cdot h)$. Then, the BS selects the coded packet which gains the maximum profit. This selection, in fact, can be merged in the above profit calculation and thus takes no extra time. For the second iteration, since one coded packet has been removed from the set $\mathcal{C}$ (according to step 5), it takes $O((m-1) \cdot h)$ time to update the profit gained by each coded packet and also to select the one with the maximum profit. Following the similar calculation, the time spent in the ith iteration will be $O((m-(i-1)) \cdot h)$. Therefore, the total time to iteratively execute steps 3, 4, and 5 will be

$$\begin{aligned} &O\left(\sum_{i=1}^{\alpha}(m-(i-1)) \cdot h\right) \\ &= O\left(h \cdot \left(\alpha m - \frac{\alpha(\alpha-1)}{2}\right)\right) \\ &= O(h \cdot \alpha(m-\alpha)). \end{aligned}$$

By summing up the above results, the overall computation complexity of the PEN algorithm will be $O(mnh) + O(h \cdot \alpha(m - \alpha))$. □

Suppose that the DVB-H server broadcasts q packets (that is, $|\mathcal{A}| = q$). Then, we have

$$m = C(q, n) = \frac{q!}{(q-n)! \cdot n!},$$

where $C(\cdot, \cdot)$ denotes the combination function. Obviously, m grows fast as q becomes larger. To deal with this problem, we divide the time axis into multiple superframes and thus q is the number of packets sent by the DVB-H server in a superframe. By limiting the length of the superframe, the computation of our PEN algorithm is more efficient because m becomes smaller as q is reduced. In addition, we can use a simpler exclusive-or coding scheme (that is, n is smaller) to improve the computation complexity. For example, we can have $m = O(q^2)$ when the two-operand exclusive-or coding scheme is adopted. We will also evaluate the effect of q and n on the performance of the PEN algorithm in Section 6.4.

Notice that one may use a dynamic programming scheme to find the optimal solution (of coded packets) from the set $\mathcal{C}$. However, such a scheme will encounter higher computation complexity. Although our PEN algorithm adopts a greedy strategy, it in fact can find the optimal solution with less computation complexity. This is proved in Theorem 3.

Theorem 3. The PEN algorithm can find the optimal solution to the α-MPNC problem.

Proof: Because our PEN algorithm adopts a greedy strategy, we show that the α-MPNC problem can be solved by a greedy algorithm. To do so, we need to prove that the α-MPNC problem has the *optimal substructure* and *greedy choice* properties.

For the optimal substructure property, we let $\mathcal{B}$ be the optimal solution to the α-MPNC problem and the coded packet c_k be an element in $\mathcal{B}$. Then, we consider the $(\alpha - 1)$-MPNC problem without selecting c_k and show that $\mathcal{B} - \{c_k\}$ must be the optimal solution to the $(\alpha - 1)$-MPNC problem. This is done by contradiction. In particular, we assume that $\mathcal{B} - \{c_k\}$ is not the optimal solution to the $(\alpha - 1)$-MPNC problem. In this case, the $(\alpha - 1)$-MPNC problem must have the optimal solution, say, $\mathcal{B}' - \{c_k\}$ where $\mathcal{B}' \neq \mathcal{B}$. Let $\Phi(\mathcal{B})$ denote the total profit gained by the solution $\mathcal{B}$. Then, we have

$$\begin{aligned} & \Phi(\mathcal{B}' - \{c_k\}) > \Phi(\mathcal{B} - \{c_k\}) \\ \Rightarrow\ & \Phi((\mathcal{B}' - \{c_k\}) \cup \{c_k\}) > \Phi((\mathcal{B} - \{c_k\}) \cup \{c_k\}) \\ \Rightarrow\ & \Phi(\mathcal{B}') > \Phi(\mathcal{B}). \end{aligned}$$

This implies that $\mathcal{B}'$ is a better solution to the α-MPNC problem, which results in a contradiction. Thus, the α-MPNC problem has the optimal substructure property.

For the greedy choice property, we assume that $\mathcal{B} = \{c_1, c_2, c_3, \cdots, c_\alpha\}$ is the optimal solution to the α-MPNC problem, where $\Phi(c_1) > \Phi(c_2) > \Phi(c_3) > \cdots > \Phi(c_\alpha)$. Suppose that the coded packet c_k has the maximum profit. If $c_k = c_1$, we prove that the α-MPNC problem has the greedy choice property. Otherwise, we can derive another solution $\mathcal{B}' = \{c_k, c_2, c_3, \cdots, c_\alpha\}$. Since $\Phi(c_k) > \Phi(c_1)$, we have $\Phi(\mathcal{B}') > \Phi(\mathcal{B})$. This implies that $\mathcal{B}'$ is a better solution, which causes a contradiction. Thus, the α-MPNC problem has the greedy choice property.

Since the α-MPNC problem has both the optimal substructure and greedy choice properties, our PEN algorithm can find the optimal solution to it. □

6 EXPERIMENTAL RESULTS

We develop a simulator in C++ to evaluate the performance of the proposed PEN algorithm. In our simulations, we aim at investigating the behaviors in one single cell of the recovery network, where the BS is responsible for serving ten HDs. The time axis is divided into 2000 superframes[1]. During each superframe, the DVB-H server broadcasts 30 DVB-H packets to all HDs. To assign profit to each DVB-H packet, we group every five DVB-H packets, say, p_1, p_2, p_3, p_4, and p_5 into a cluster and consider two profit-assignment scenarios as follows:

- **Low variation of profit (LVP) scenario:** $\Phi(p_1) = 0.1$, $\Phi(p_2) = 0.2$, $\Phi(p_3) = 0.3$, $\Phi(p_4) = 0.4$, $\Phi(p_5) = 0.5$.
- **High variation of profit (HVP) scenario:** $\Phi(p_1) = 0.1$, $\Phi(p_2) = 0.3$, $\Phi(p_3) = 0.5$, $\Phi(p_4) = 0.7$, $\Phi(p_5) = 0.9$.

In addition, a probability P_{loss} is adopted to simulate the DVB-H packet loss, where the erroneous reception of DVB-H packets by each HD follows the uniform distribution. In the simulations, the loss probability P_{loss} is ranged from 0.1 to 0.4. We compare our PEN algorithm with the PNC method [17] mentioned in Section 2.1, where the PNC method attempts to recover the maximum number of lost DVB-H packets in each superframe. Because we focus on studying the performances of different network coding schemes, it is assumed that the communication in the recovery network is *reliable*. In other words, both RREQs and coded packets will not be lost in our simulations. We adopt the two-operand exclusive-or coding scheme to calculate the set $\mathcal{C}$ for both the PEN and PNC schemes.

Below, we first investigate the effect of different loss probabilities P_{loss} on the profit gained by each network coding scheme. Then, we measure how different network coding schemes behave when the α value changes. Taking the MPEG-4 application as an example, we then evaluate the performances of different network coding schemes. Finally, we observe the effect of q and n on the performance of our PEN algorithm.

6.1 Effect of Different Loss Probabilities P_{loss}

In this experiment, we let $\alpha = 5$ so that the BS can broadcast at most five coded packets in every $T_{broadcast}$ period. Tables 2 and 3 present the total profit of recovered DVB-H packets and the total number of satisfied requests in a superframe under different loss probabilities P_{loss}, respectively. Obviously, when the loss probability P_{loss} grows, both the total profit and the number of satisfied requests also increase. Since the number of lost DVB-H packets increases as P_{loss} grows, there is a good possibility that the BS can calculate a coded packet to satisfy more requests.

From Table 2, we observe that both PEN and PNC schemes obtain larger (total) profit in the HVP scenario because DVB-H packets are assigned with larger profit. In addition, our PEN algorithm outperforms the PNC method as it can obtain larger

---

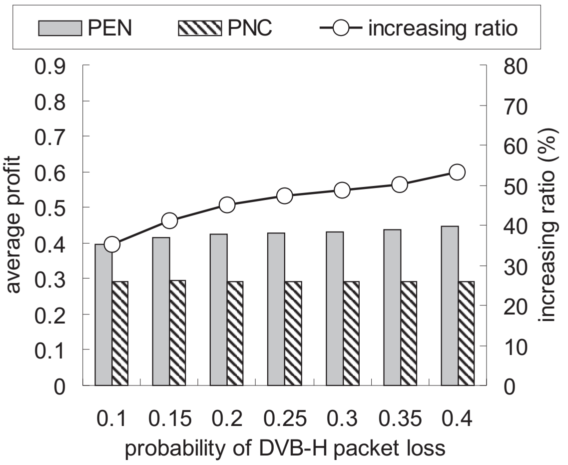
[1] Thus, each experiment is repeated 2000 times and we take the average as the simulation result.

TABLE 2: The total profit of recovered DVB-H packets in a superframe under different loss probabilities P_{loss}.

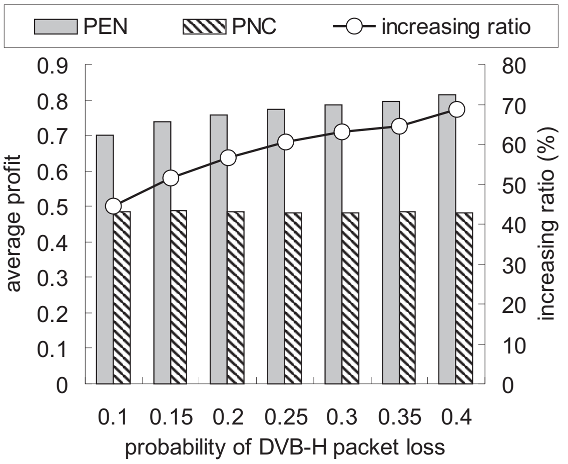
probability P_{loss}		0.10	0.15	0.20	0.25	0.30	0.35	0.40
LVP scenario	PEN	4.42	5.91	7.25	8.58	9.82	11.03	12.23
	PNC	3.62	4.76	5.71	6.63	7.47	8.33	9.08
HVP scenario	PEN	7.74	10.42	12.81	15.19	17.41	19.59	21.75
	PNC	5.99	7.90	9.47	10.99	12.38	13.80	15.05

TABLE 3: The total number of satisfied requests in a superframe under different loss probabilities P_{loss}.

probability P_{loss}		0.10	0.15	0.20	0.25	0.30	0.35	0.40
LVP scenario	PEN	11.17	14.25	17.13	20.02	22.71	25.14	27.43
	PNC	12.37	16.19	19.57	22.80	25.71	28.53	31.22
HVP scenario	PEN	11.06	14.09	16.89	19.61	22.17	24.63	26.75
	PNC	12.37	16.19	19.57	22.80	25.71	28.53	31.22



(a) LVP scenario



(b) HVP scenario

Fig. 3: Comparison on the average profit of recovered DVB-H packets in each superframe under different loss probabilities P_{loss}.

profit in every superframe. On the other hand, from Table 3, we observe that the number of satisfied requests by the PEN algorithm in the HVP scenario is slightly smaller than that in the LVP scenario (when the loss probability P_{loss} is the same). The reason is that in the HVP scenario, some lost DVB-H packets have quite large profit (for example, $\Phi(p_j) = 0.9$) so that our PEN algorithm will try to calculate coded packets to recover these lost DVB-H packets. In this case, the BS has to give up recovering some lost DVB-H packets with very small profit (for example, $\Phi(p_j) = 0.1$), which causes a decrease in the number of satisfied requests. Interestingly, the PNC method satisfies the equal number of requests in both the LVP and HVP scenarios. It is because the PNC method does not take the profit into consideration and the set of lost DVB-H packets is actually the same in the LVP and HVP scenarios. Thus, the PNC method will generate the same set of coded packets in both scenarios.

Fig. 3 presents the average profit of recovered DVB-H packets in each superframe under different loss probabilities P_{loss}, which is calculated by dividing the total profit from Table 2 by the corresponding number of satisfied requests from Table 3. The *increasing ratio* is defined by

$$\frac{\text{average profit}_{\text{PEN}} - \text{average profit}_{\text{PNC}}}{\text{average profit}_{\text{PNC}}} \times 100\%.$$

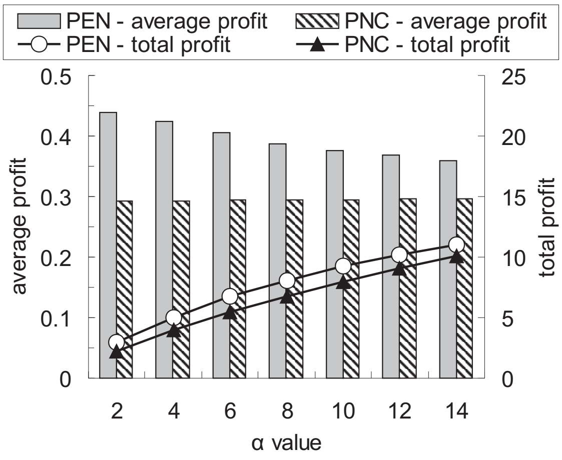
From Fig. 3, we observe that the average profit gained by our PEN algorithm increases when the loss probability P_{loss} grows. Such a trend is more significant in the HVP scenario. The reason is that the PEN algorithm has a preference for the lost DVB-H packets with larger profit. When more DVB-H packets are lost and their profit has a larger variation, the PEN algorithm can gain larger average profit. On the contrary, without taking profit into account, the average profit gained by the PNC method appears constant. The average profit gained by the PNC method is 0.29 and 0.48 in the LVP and HVP scenarios, respectively, which is close to the average packet profit (that is, 0.3 in the LVP scenario and 0.5 in the HVP scenario), because DVB-H packet loss is assumed to follow the uniform distribution in our simulations. According to Fig. 3, the increasing ratio grows from 35.2% to 53.3% and from 44.5% to 68.7% in the LVP and HVP scenarios, respectively, when the loss probability P_{loss} increases from 0.1 to 0.4. This result demonstrates the effectiveness of our PEN algorithm (compared with the PNC method), especially in the HVP scenario.

6.2 Effect of Different α Values

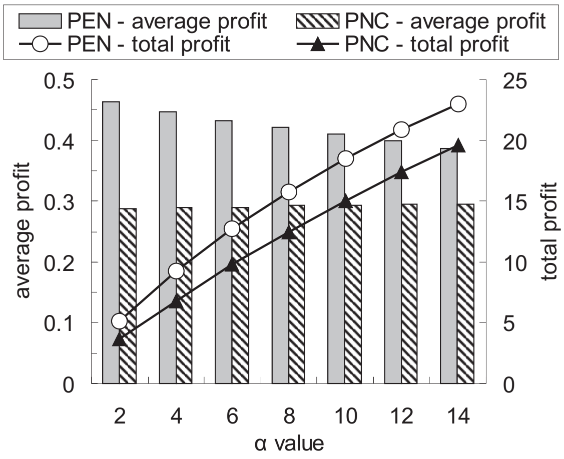
We then investigate the effect of different α values on the profit gained by each network coding scheme in every superframe. In this experiment, the α value is set to 2, 4, 6, 8, 10, 12, and 14. In addition, we set the loss probability P_{loss} to 0.15 and 0.35.

Figs. 4 and 5 present the average and total profit of recovered DVB-H packets in each superframe under different α values in the LVP and HVP scenarios, respectively. By comparing these figures, we have the following five observations:

1) With a larger loss probability P_{loss}, both the PEN and PNC schemes can gain larger *total* profit.
2) With a larger loss probability P_{loss}, the *average* profit gained by the PEN algorithm increases but that by the PNC method remains (almost) constant.



(a) $P_{\text{loss}} = 0.15$

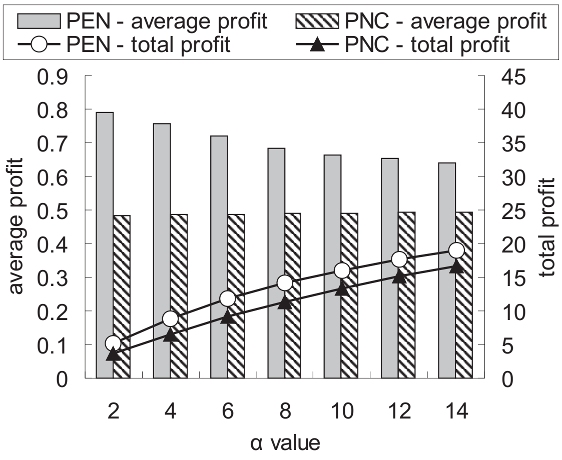


(b) $P_{\text{loss}} = 0.35$

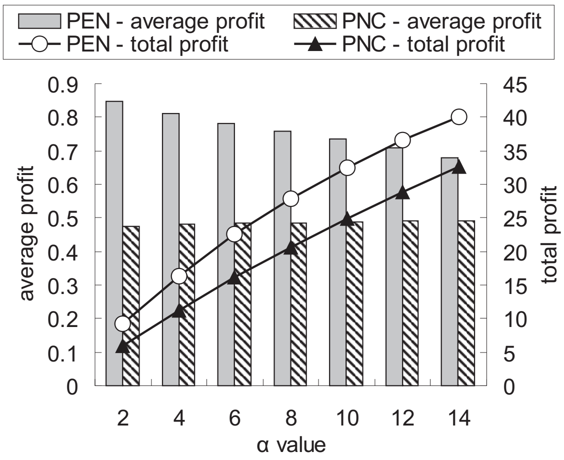
Fig. 4: Comparison on the average and total profit of recovered DVB-H packets in each superframe under different α values in the LVP scenario.

3) Both the PEN and PNC schemes perform better in terms of profit gained in the HVP scenario.
4) When the α value grows, both the PEN and PNC schemes can gain larger *total* profit.
5) When the α value grows, the *average* profit gained by the PEN algorithm decreases but that by the PNC method remains (almost) constant.

Observations 1), 2), and 3) are identical to the observations in the experiment of Section 6.1. Because the BS is allowed to broadcast more coded packets when the α value grows, more lost DVB-H packets can be recovered, which results in observation 4). The reason of observation 5) is explained as follows: When the α value grows, there is a good possibility that our PEN algorithm can select the lost DVB-H packets with smaller profit, especially when they are requested by more HDs. In this case, the average profit gained by the PEN algorithm would decrease. On the other hand, because the PNC method attempts to recover the maximum number of requests without considering their profit, the average profit gained by it will be approximate to the average packet profit. This phenomenon also appears in the experiment of Section 6.1. In short, our PEN algorithm can always improve the overall profit gained by the BS compared with the PNC method, no matter how the α value changes.



(a) $P_{\text{loss}} = 0.15$



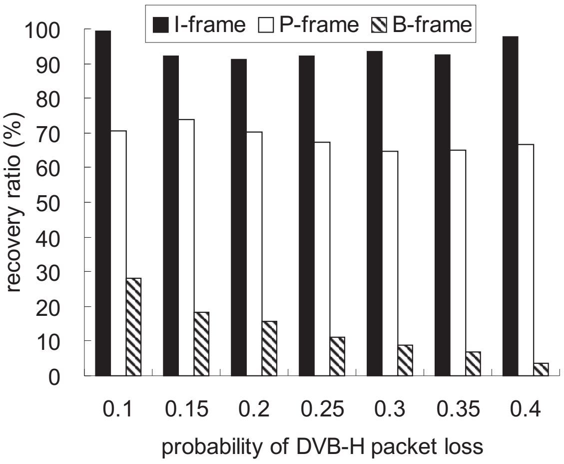
(b) $P_{\text{loss}} = 0.35$

Fig. 5: Comparison on the average and total profit of recovered DVB-H packets in each superframe under different α values in the HVP scenario.

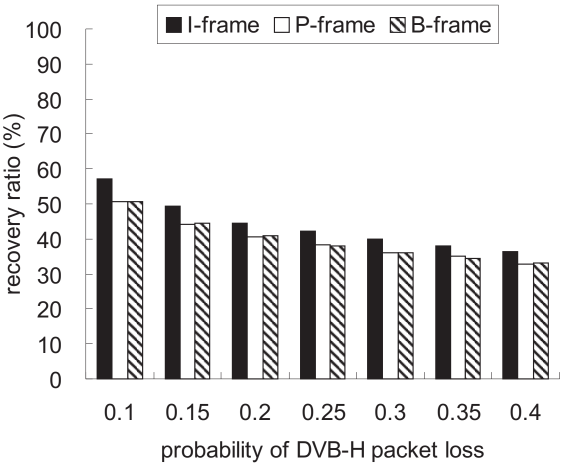
6.3 MPEG-4 Example

In the experiment, we take the MPEG-4 application as an example to demonstrate the effectiveness of our PEN algorithm. Recall that MPEG-4 generates three types of compressed frames for a video chip: I-frame, P-frame, and B-frame. An I-frame can be decompressed independently. A P-frame should refer to its previous frame for decompression. A B-frame have to refer to both its previous and next frames for decompression. Thus, their importance will be I-frame $>$ P-frame $>$ B-frame, and in consequence, we set $\Phi(\text{I-frame}) = 0.9$, $\Phi(\text{P-frame}) = 0.6$, and $\Phi(\text{B-frame}) = 0.3$. In addition, the DVB-H server broadcasts 36 MPEG-4 frames to all HDs in each superframe. Following the *GOP (group of pictures) structure* defined in the MPEG-4 standard [10], these 36 frames follow the sequence of {I, B, B, P, B, B, P, B, B, I, B, B, P, B, B, P, B, B, I, B, B, P, B, B, P, B, B, I, B, B, P, B, B, P, B, B}. We set $\alpha = 8$ so that the BS can use at most eight coded packets to recover the lost frames of HDs.

Fig. 6 presents the recovery ratios of I-frames, P-frames, and B-frames under different loss probabilities P_{loss}. For our PEN algorithm, the recovery ratio of I-frames is significantly larger than the recovery ratios of other frames. P-frames can also have a much larger recovery ratio than B-frames. When the loss probabilities P_{loss} increases, the recovery ratio of I-frames still keeps above 90% while the recovery ratio of P-frames slightly decreases. On the other hand, the recovery ratio



(a) PEN algorithm



(b) PNC method

Fig. 6: Comparison on the recovery ratios of I-frames, P-frames, and B-frames under different loss probabilities P_{loss}.

of B-frames drops fast because the PEN algorithm treats them as trifling frames (since Φ(B-frame) is only 0.3). When there are more requests, the PEN algorithm first gives up the requests asking for B-frames. On the average, the recovery ratios of I-frames, P-frames, and B-frames in the PEN algorithm are 94.15%, 68.37%, and 13.23%, respectively. This result shows that the PEN algorithm can recover most of the important I-frames and thus improve the video quality of HDs.

For the PNC method, the recovery ratio of I-frames is slightly larger than the recovery ratios of other frames. In addition, the recovery ratios of P-frames and B-frames are close to each other. When the loss probability P_{loss} grows, the recovery ratios of all frames decrease. It is because the PNC method attempts to maximize the total number of satisfied requests but does not consider the profit of each frame. When lost I-frames and B-frames compete to be recovered, the PNC method may let the BS select the unimportant B-frames for retransmission. On the average, the recovery ratios of I-frames, P-frames, and B-frames in the PNC method are 43.96%, 39.60%, and 39.69%, respectively. Since no more than half I-frames are recovered by the PNC method, the video quality of HDs would be degraded.

This experiment gives a conclusion that when the BS has limited resource (for example, the number of allowed coded packets), it is not always true that the system performance can be increased by satisfying the maximum number of requests. Instead, the BS needs to take packet profit into account and tries to first recover the lost packets with higher profit. This is the design rationale of our PEN algorithm.

6.4 Effect of q and n on The PEN Algorithm

Recall that q is the number of packets broadcasted by the DVB-H server in each superframe and n is the number of operands in the exclusive-or coding scheme. In this experiment, we evaluate the effect of q and n on the performance of our PEN algorithm.

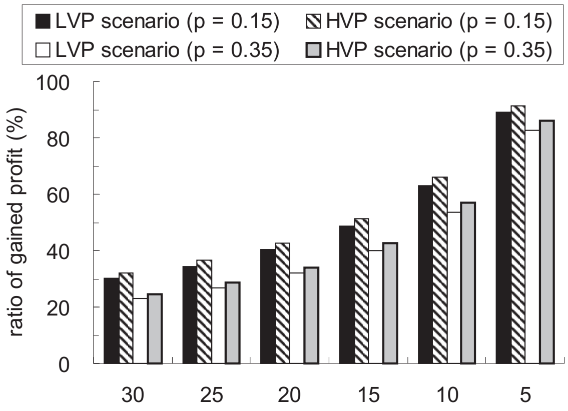
To observe the effect of q, we set $\alpha = 3$ and let q decrease from 30 to 5. Fig. 7(a) shows the ratio of profit gained by the PEN algorithm to the total profit of all lost packets, while Fig. 7(b) presents the ratio of requests satisfied by the PEN algorithm to the total number of requests from HDs. Obviously, both ratios increases as q decreases, which means that the PEN algorithm performs better under a smaller q value (when α is fixed). When the DVB-H server broadcasts fewer packets (that is, q becomes smaller), HDs will also lose fewer packets (in other words, $\mathcal{L}$ becomes smaller). In this case, there is a high possibility that the BS can use a fixed α number of coded packets to recover more lost packets, which helps it gain more profit. In addition, decreasing q can reduce the computation complexity of the PEN algorithm. That is why we divide the time axis into multiple small superframes. From Fig. 7, we can observe that a higher loss probability p decreases both ratios, because HDs lose more packets and thus the size of $\mathcal{L}$ increases. The BS gains more profit but satisfies fewer requests in the HVP scenario than that in the LVP scenario. Since packets have larger variation of profit in the HVP scenario, the PEN algorithm usually prefers recovering those packets with larger profit first. In this case, some packets with smaller profit but lost by slightly more HDs may not be selected, which thus decreases the number of satisfied requests.

To observe the effect of n, we set $\alpha = 5$ and $q = 30$. In addition, we let n increase from 1 to 5. Fig. 8(a) shows the total profit gained by the PEN algorithm in a superframe, while Fig. 8(b) presents the total number of requests satisfied by the PEN algorithm in a superframe. Notice that when $n = 1$, every packet in $\mathcal{C}$ is in fact an uncoded packet. From Fig. 8, we can observe that the performance of our PEN algorithm increases as n becomes larger, especially when n grows from one to two. This verifies the effectiveness of the exclusive-or coding scheme, since each coded packet could satisfy multiple requests. However, such increase becomes unobvious when $n \geq 3$, which indicates that using two- or three-operand exclusive-or coding scheme is sufficient for the PEN algorithm to obtain a good performance.

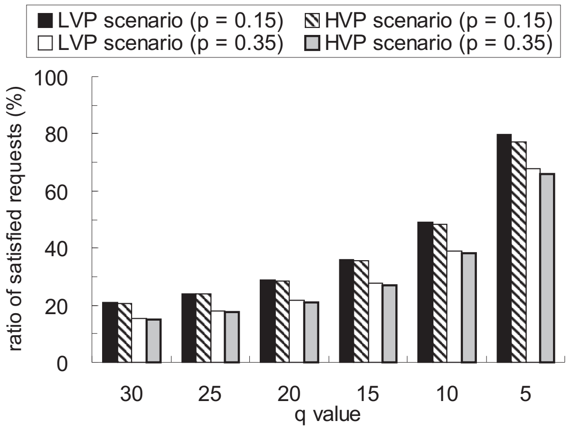
To sum up, when α is fixed, a smaller q value can increase the performance of the PEN algorithm. In addition, a smaller n value ($n > 1$) would not slash the performance but help improve the computation complexity. Notice that one could refer to Fig. 7 to determine the length of a superframe. For example, supposing that $\alpha = 3$, if we want the ratio of profit gained in each superframe larger than 50%, then we can allow the DVB-H server to broadcast around ten packets in a superframe.

7 CONCLUSIONS AND FUTURE WORK

DVB-H is developed to disseminate digital videos to HDs but it could encounter serious data loss under poor channel

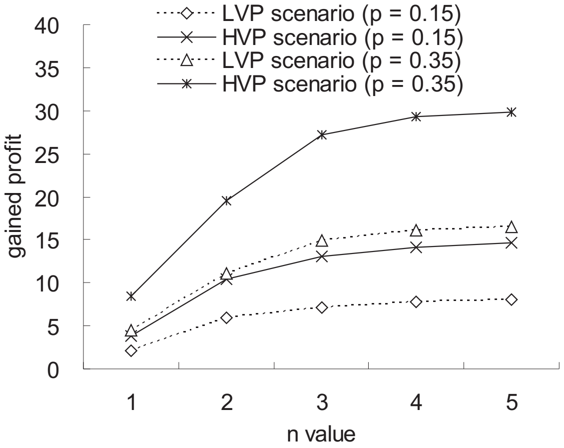


(a) ratio of gained profit

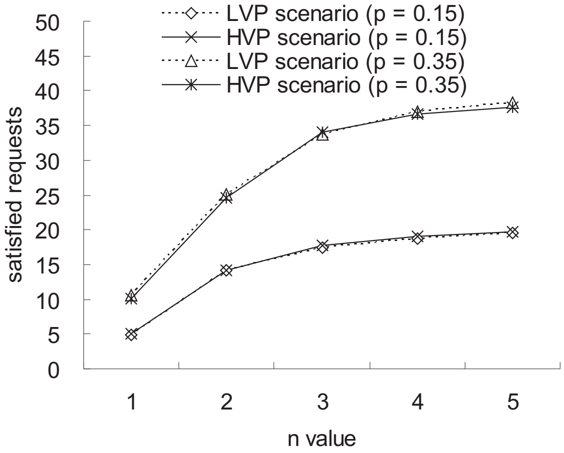


(b) ratio of satisfied requests

Fig. 7: Effect of q on the PEN algorithm.



(a) gained profit in a superframe



(b) satisfied requests in a superframe

Fig. 8: Effect of n on the PEN algorithm.

conditions. Fortunately, DVB-IPDC provides an architecture to support the retransmission of lost DVB-H packets through another wireless network, which we call the recovery network. This paper argues that network coding can substantially improve the retransmission efficiency of the recovery network and DVB-H packets are heterogeneous in the sense that they have different importance. Thus, the α-MPNC problem is proposed by considering that each DVB-H has different profit. By constructing a relation graph to evaluate the relationship between coded packets and lost DVB-H packets, this paper develops a PEN algorithm to efficiently solve the α-MPNC problem. Simulation results demonstrate that our PEN algorithm can help the BS gain more profit compared with the PNC method.

Recently, ETSI develops a new profile, DVB T2-Lite [32], for DVB-T to provide *service-specific robustness*. Specifically, various levels of data robustness are given to different services. This can be achieved by *physical layer pipes (PLPs)*, which are logical channels to carry one or multiple services. PLPs can have different data rates and error protection parameters (for example, code rates and modulations). Therefore, it deserves further investigation to support differential data recovery for heterogeneous services using this feature of DVB T2-Lite.

REFERENCES

[1] European Telecommunications Standards Institute, “Digital video broadcasting (DVB); Transmission system for handheld terminals (DVB-H),” ETSI EN 302 304 v1.1.1, Nov. 2004.

[2] G. Faria, J.A. Henriksson, E. Stare, and P. Talmola, “DVB-H: digital broadcast services to handheld devices,” *Proc. of the IEEE*, vol. 94, no. 1, pp. 194–209, 2006.

[3] O. Eerenberg, A. Koppelaar, A.M. Stuivenwold, and P.H.N. de With, “P-recovery in the DVB-H link layer for TV on mobile,” *IEEE Trans. Consumer Electronics*, vol. 57, no. 2, pp. 339–347, 2011.

[4] W.H. Yang, Y.C. Wang, Y.C. Tseng, and B.S.P. Lin, “Spatial and temporal packet recovery schemes for DVB-H systems through IP-relay wireless networks,” *Proc. IEEE Int’l Conf. Comm.*, 2009.

[5] European Telecommunications Standards Institute, “Digital video broadcasting (DVB); IP datacast over DVB-H: architecture,” ETSI TS 102 469 v1.1.1, May 2006.

[6] M. Kornfeld and G. May, “DVB-H and IP datacast–broadcast to handheld devices,” *IEEE Trans. Broadcasting*, vol. 53, no. 1, pp. 161–170, 2007.

[7] W.H. Yang, Y.C. Wang, Y.C. Tseng, and B.S.P. Lin, “A request control scheme for data recovery in DVB-IPDC systems with spatial and temporal packet loss,” *Wireless Comm. and Mobile Computing*, vol. 13, no. 10, pp. 935–950, 2013.

[8] S.Y.R. Li and R.W. Yeung, and Y.N. Cai, “Linear network coding,” *IEEE Trans. Information Theory*, vol. 49, no. 2, pp. 371–381, 2003.

[9] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “XORs in the air: practical wireless network coding,” *IEEE/ACM Trans. Networking*, vol. 16, no. 3, pp. 497–510, 2008.

[10] F.C. Pereira and T. Ebrahimi, *The MPEG-4 Book*. Prentice Hall PTR, 2002.

[11] D. Gomez-Barquero, N. Cardona, A. Bria, and J. Zander, “Affordable mobile TV services in hybrid cellular and DVB-H systems,” *IEEE Network*, vol. 21, no. 2, pp. 34–40, 2007.

[12] B. Hechenleitner, “Repair costs of the IPDC/DVB-H file repair mechanism,” *Proc. IEEE Wireless Telecomm. Symp.*, pp. 137–144, 2008.

[13] European Telecommunications Standards Institute, “Digital video broadcasting (DVB); IP datacast over DVB-H: content delivery protocols,” ETSI TS 102 472 v1.3.1, Jun. 2009.

[14] P. Hummelbrunner, S. Buchinger, W. Robitza, D. Selig, M. Nezveda, and H. Hlavacs, "Peer to peer mobile TV recovery system," *Proc. ACM Int'l Interactive Conf. Interactive TV&Video*, pp. 263–272, 2010.

[15] R. Akester, "Reducing multicast collision loss for digital TV over 802.11 wireless networks," *WSEAS Trans. Information Science and Applications*, vol. 3, no. 1, pp. 903–907, 2004.

[16] K. Sinkar, A. Jagirdar, T. Korakis, H. Liu, S. Mathur, and S. Panwar, "Cooperative recovery in heterogeneous mobile networks," *Proc. IEEE Int'l Conf. Sensor, Mesh and Ad Hoc Communications and Networks*, pp. 395–403, 2008.

[17] W.H. Yang, Y.C. Wang, and Y.C. Tseng, "Efficient packet recovery using prioritized network coding in DVB-IPDC systems," *IEEE Comm. Letters*, vol. 16, no. 3, pp. 382–385, 2012.

[18] C. Gkantsidis and P.R. Rodriguez, "Network coding for large scale content distribution," *Proc. IEEE INFOCOM*, pp. 2235–2245, 2005.

[19] G. Ma, Y. Xu, M. Lin, and Y. Xuan, "A content distribution system based on sparse linear network coding," *Proc. Workshop on Network Coding*, 2007.

[20] U. Lee, J.S. Park, J. Yeh, G. Pau, and M. Gerla, "CodeTorrent: content distribution using network coding in VANET," *Proc. ACM Int'l Workshop on Decentralized Resource Sharing in Mobile Computing and Networking*, 2006.

[21] X. Zhang, J. Liu, B. Li, and T.P. Yum, "CoolStreaming/DONet: a data-driven overlay network for peer-to-peer live media streaming," *Proc. IEEE INFOCOM*, pp. 2102–2111, 2005.

[22] M. Wang and B. Li, "R2: random push with random network coding in live peer-to-peer streaming," *IEEE J. Selected Areas in Comm.*, vol. 25, no. 9, pp. 1655–1666, 2007.

[23] Z. Liu, C. Wu, B. Li, and S. Zhao, "UUSee: large-scale operational on-demand streaming with random network coding," *Proc. IEEE INFOCOM*, 2010.

[24] P. Larsson, "Multicast multiuser ARQ," *Proc. IEEE Wireless Comm. and Networking Conf.*, pp. 1985–1990, 2008.

[25] Z. Li, Q. Luo, and W. Featherstone, "N-in-1 retransmission with network coding," *IEEE Trans. Wireless Comm.*, vol. 9, no. 9, pp. 2689–2694, 2010.

[26] D.N. Yang and M.S. Chen, "Data broadcast with adaptive network coding in heterogeneous wireless networks," *IEEE Trans. Mobile Computing*, vol. 8, no. 1, pp. 109–125, 2009.

[27] Y. Birk and T. Kol, "Coding on demand by an informed source (ISCOD) for efficient broadcast of different supplemental data to caching clients," *IEEE Trans. Information Theory*, vol. 52, no. 6, pp. 2825–2830, 2006.

[28] C.H. Chu, D.N. Yang, and M.S. Chen, "Using network coding for dependent data broadcasting in a mobile environment," *Proc. IEEE Global Telecomm. Conf.*, pp. 5346–5350, 2007.

[29] W.H. Yang, Y.C. Wang, Y.C. Tseng, and B.S.P. Lin, "Energy-efficient network selection with mobility pattern awareness in an integrated WiMAX and WiFi network," *Int'l J. Comm. Systems*, vol. 23, no. 2, pp. 213–230, 2010.

[30] F. Zarai, K.B. Ali, M.S. Obaidat, and L.Kamoun, "Adaptive call admission control in 3GPP LTE networks," *Int'l J. Comm. Systems*, 2012.

[31] Y. Xu, R. Yin, T. Han, and G. Yu, "Dynamic resource allocation for device-to-device communication underlaying cellular networks," *Int'l J. Comm. Systems*, 2012.

[32] European Telecommunications Standards Institute, "Digital video broadcasting (DVB); Next generation broadcasting system to handheld, physical layer specification (DVB-NGH)," ETSI EN 302 755 v1.3.1, Nov. 2012.