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Network Coding-based ARQ scheme with Overlapping Selection for Resource Limited Multicast/Broadcast Services

Jung-Hyun Kim, Jihyung Kim, Kwangjae Lim, Dong Seung Kwon

Abstract—Network coding has recently attracted attention as an efficient technique in multicast/broadcast services. The problem of finding the optimal network coding mechanism maximizing the bandwidth efficiency is hard to solve and hard to approximate. Lots of network coding-based schemes have been suggested in the literature to improve the bandwidth efficiency, especially network coding-based automatic repeat request (NCARQ) schemes. However, existing schemes have several limitations which cause the performance degradation in resource limited systems. To improve the performance in resource limited systems, we propose NCARQ with overlapping selection (OS-NCARQ) scheme. The advantages of OS-NCARQ scheme over the traditional ARQ scheme and existing NCARQ schemes are shown through the analysis and simulations.

Keywords—ARQ, Network coding, Multicast/Broadcast services, Packet-based systems.

I. INTRODUCTION

RECENTLY, reliable multicast/broadcast services are becoming more and more popular due to increasing applications such as internet TVs, video news feeds, file downloads, software updates, location based advertisements and queries, etc. For the reliable communication in packet-based multicast/broadcast services, every destination node must be able to correctly receive all data packets sent by the source node in lossy or noisy channel. To surmount the packet loss or error, one of widely used techniques is automatic repeat-request (ARQ) scheme [1]. ARQ scheme had been received little attention in multicast/broadcast services because the source node needs to retransmit a data packet even if the packet is received at all destination nodes except one. However, ARQ scheme for multicast/broadcast services has recently resurfaced as a simple but powerful coding technique named network coding [2], [3], [4] is introduced in ARQ scheme.

Network coding is a promising technique to improve the performance of wireless networks. The basic concept of network coding is to allow the data received from multiple nodes in a network to be encoded at intermediate nodes for the subsequence transmission so that the network throughput is improved. This concept was introduced to ARQ scheme for multicast/broadcast services in order to increase the bandwidth efficiency of ARQ scheme. A retransmission scheme using an XOR operation is first proposed in [5], which is elaborated into lots of network coding-based ARQ schemes [6]-[14].

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The authors in [6] sketch the basic principle about how to perform the inter-flow coding when there are multiple users and extends the idea to multicast services in [7]. In [8], an analytical approach is proposed to determine the improvements in efficiency obtained by network coding, while a lower bound on the transmission overhead is developed in [9], [10]. A specific network coding scheme for two users is further proposed in [9], [10]. In [11], the authors follow up the work in [10] by comparing various packet coding algorithms for the packet-based retransmission. After that, several deterministic schemes are investigated in [12], [13], [14], while the scheme in [11] is a heuristic scheme. These schemes improve the retransmission efficiency more than previous works but they do not take full advantage of network coding in resource limited systems.

For resource limited multicast/broadcast services, we propose a novel network coding-based ARQ with overlapping selection (OS-NCARQ) scheme. We compare the performance of OS-NCARQ with existing schemes, NCARQ in [13] and ARQ in [1]. Simulation results show that the proposed OS-NCARQ scheme outperforms the NCARQ scheme as well as the ARQ scheme.

The rest of this paper is organized as follows: In Section II we give an overview of related works, included the limitation in practical systems. Following them, we propose our scheme, OS-NCARQ, in Section III. We then confirm the performance of proposed scheme with simulation results in Section IV, and finally present the conclusion in Section V.

II. BACKGROUND AND PRELIMINARIES

In this section, we present ARQ scheme and NCARQ scheme in packet-based multicast/broadcast services. Consider a network in Figure 1(a), a source node S wants to deliver seven data packets, $d1 \sim d7$, to five destination nodes, $n1 \sim n5$, in one *window* duration. Here, *window* is defined as a period of continuous transmissions by the source node. Since the communication channel is usually not ideal, a data packet may be corrupted or lost during the transmission. In our scenario, node $n1$ loses data packets, $d1 \sim d5$, node $n2$ loses data packets, $d1$ and $d3 \sim d5$, node $n3$ loses data packets, $d2, d5$, and $d6$, node $n4$ loses data packets, $d4$ and $d6$, and node $n5$ loses a data packet, $d7$, as illustrated in Figure 1(b). Since destination nodes don't receive all data packets, they

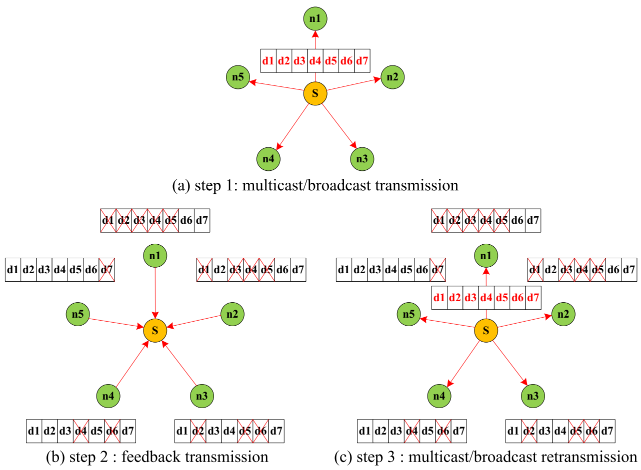

Fig. 1. An example of the traditional ARQ scheme.

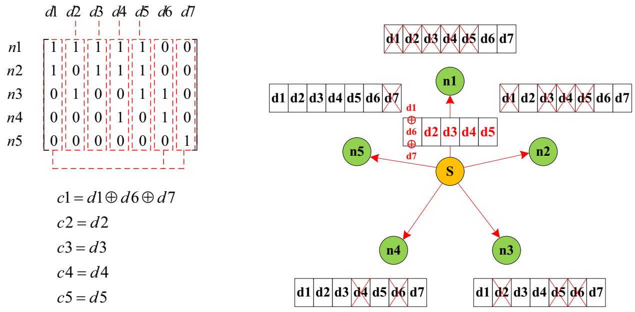

Fig. 2. An illustration of NCARQ retransmission.

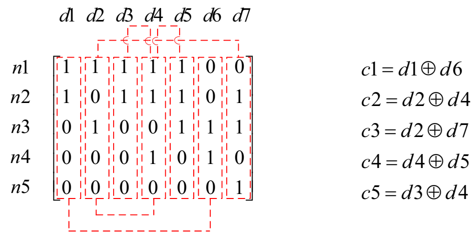

Fig. 3. An example of packet selection for retransmission [14].

send a feedback message for requesting retransmission to the source node. When the source node gets feedback messages, it retransmits all requested data packets. So, the source node retransmits seven data packets, $d1 \sim d7$, in Figure 1(c).

A. Network Coding for ARQ

In NCARQ schemes, a source node encodes original data packets by performing an XOR operation (denoted by $\oplus$) and then retransmits the encoded data packet. At the beginning of each *window*, the source node check whether it had gotten any feedback messages from destination nodes. If it had gotten the messages, the source node selects original data packets (not encoded) requested for the retransmission and then encodes the selected packets by performing an XOR operation on them. After generating encoded data packets, the source node broadcasts encoded data packets and new original data packets (if it has extra resource) to all the destination nodes.

In order to describe how to select data packets for retransmission, we define a feedback matrix F as follows:

$$F = \begin{bmatrix} F(n_1,d_1) & \cdots & F(n_1,d_j) & \cdots & F(n_1,d_J) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ F(n_i,d_1) & \cdots & F(n_i,d_j) & \cdots & F(n_i,d_J) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ F(n_I,d_1) & \cdots & F(n_I,d_j) & \cdots & F(n_I,d_J) \end{bmatrix}. \quad (1)$$

A source node set up the feedback matrix using feedback messages from destination nodes. If node n_i fails to receive the packet d_j successfully, $F(n_i, d_j) = 1$. Otherwise, $F(n_i, d_j) = 0$. The source node generates retransmission packets by using the feedback matrix. At this time, each encoded packet should be decoded by as many destination nodes as possible.

Consider the network model in Figure 1 again. Using a traditional retransmission mechanism, the source node retransmits seven lost data packets, $d1 \sim d7$, separately. Using a network coding mechanism illustrated in Figure 2, the source node encodes requested data packets $d1$, $d6$, and $d7$ into $c1$ by performing an XOR operation on the three original data packets, that is $c1 = d1 \oplus d6 \oplus d7$, and then broadcasts $c1$. Since node $n1$ and node $n2$ already received both data packets $d6$ and $d7$ correctly, they can obtain $d1$, by decoding the correctly received $c1$ using already received data packets, $d6$ and $d7$, that is $d1 = c1 \oplus (d6 \oplus d7)$. Similarly, node $n3$ and node $n4$ can obtain $d6$ using already received $d1$ and $d7$. Similarly, node $n5$ can obtain $d7$ using already received $d1$ and $d6$. The other lost data packets, $d2 \sim d5$, can be instantly decoded for each destination node. As a result, only five retransmission data packets are needed for the seven requested data packets, two packets less than the number of packets needed when using a traditional retransmission mechanism. Since network coding saves the transmission resource in the network, it can improve the retransmission efficiency and the network throughput in resource limited networks.

B. Limitations and Guidelines in Resource Limited Systems

Despite the high retransmission efficiency compared with the traditional ARQ scheme, existing NCARQ schemes proposed in [12], [13], [14] which is the most closely related work still suffer from the following limitations in resource limited systems.

First, we observe that the NCARQ scheme in [14] does not realize the full potential of network coding. In the NCARQ scheme, a source node selects original data packets having a small hamming weight for a packet encoding. However, it should select original data packets when their corresponding nodes have no intersection. If some packets requested by a common node are selected for the packet encoding, the node can not recover any original data packets with only the encoded packet. In Figure 3, we consider an example using the scheme in [14]. The retransmission packet $c2$ is encoded by original data packets, $d2$ and $d4$. The set of nodes that requests the packet $d2$ is $\{n1, n3\}$ and the set of nodes that requests the packet $d4$ is $\{n1, n2, n4\}$. In this scenario, node $n1$ can not recover any original packets with only $c2$

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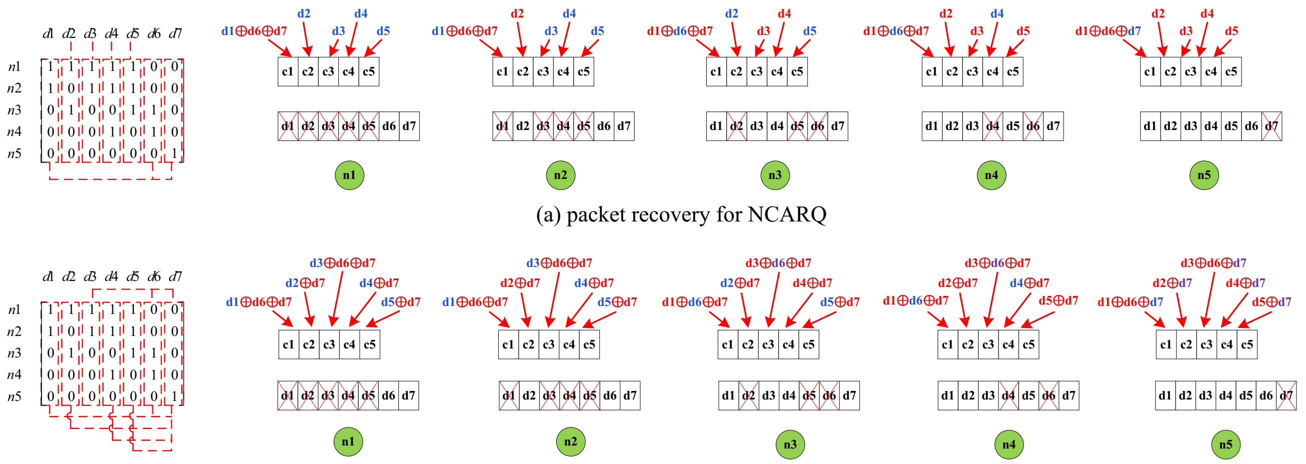

(b) packet recovery for OS-NCARQ

Fig. 4. A simple example of how OS-NCARQ increases the reliability.

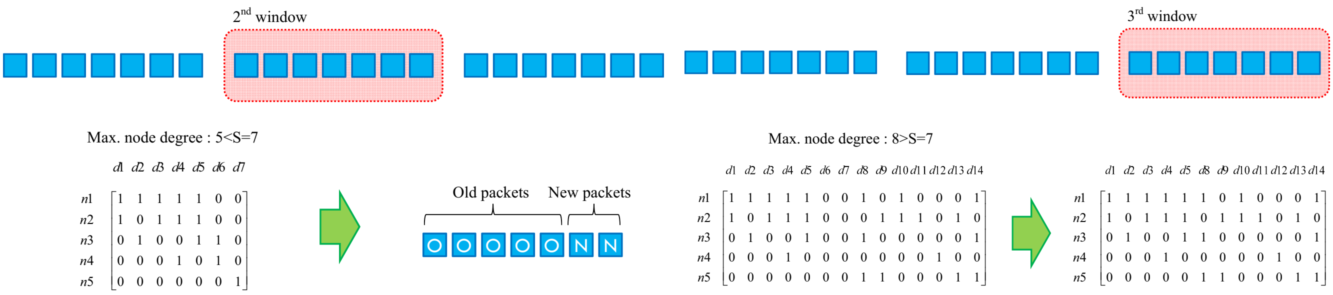

Fig. 5. An illustration of how retransmission packets are generated in the second window.

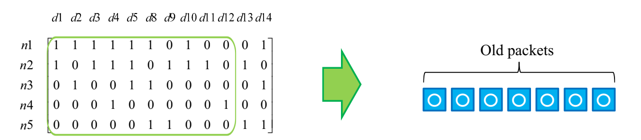

Fig. 6. An illustration of how retransmission packets are generated in the third window.

since the node requests both $d2$ and $d4$. In other words, the node should linearly operate several received retransmission packets to recover a original packet after receiving another retransmission packets including only one of $d2$ and $d4$. In this case, there is the serious performance degradation since the node should successively receive all the encoded packets for the linear operation. Thus, encoding of original data packets requested by destination nodes is only possible when the sets of request nodes have no intersection each other so that each retransmission packet is used for recovering one original data packet for each destination node.

Second, existing NCARQ schemes in [12], [13], [14] do not allow overlapping selection. In other words, a source node selects original packets only one time per encoding. This non-overlapping selection leads to destination nodes receiving meaningless retransmission packets. Figure 4 shows the impact of the second limitation. For example, in Figure 4(a), the encoded packets $c2 \sim c5$ are meaningless for node $n5$ since the node already receives original data packets $d2 \sim d5$. But in Figure 4(b), node $n5$ can use $c2 \sim c5$ as well as $c1$ for recovering the requested data packet $d7$. In other words, node $n5$ with overlapping selection acquires the recovering chance four more times compared to non-overlapping selection.

Third, for retransmission resource limited systems, it is a hard problem, which area of feedback matrix is selected to generate retransmission packets. If we ignore this point, we should consider all requested packets from first *window* to last *window* whenever we generate retransmission packets and it derives us to very high complexity operation. This point is not considered in [12], [13], [14]. For example, in Figure 5, a source node generates a feedback matrix for encoding retransmission packets in the second *window*. Here, the node degree is the row weight of the feedback matrix and S is the size of *window*. The maximum node degree is 5 which is smaller than S. In this case, the source node generates retransmission packets using the initial feedback matrix without an additional selection process and then retransmits the encoded packets. Another example is in Figure 6. A source node generates a feedback matrix for encoding retransmission packets in the third *window*. The maximum node degree is 8 which is bigger than S. In this case, the source node needs an additional selecting process. The source node selects an area from $d1$ to one less than the minimum value among indices of $(S+1)th$ lost packet of destination nodes. The selected area

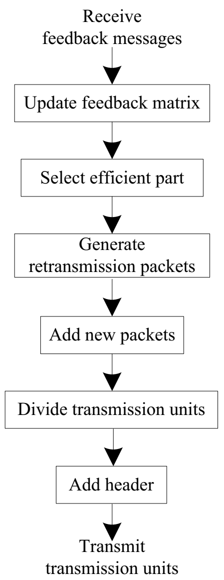

Fig. 7. Flow chart for OS-NCARQ implementation.

by source node is $d1 \sim d12$. With this rule, we can perform the packet encoding process with low complexity.

III. OS-NCARQ : Network Coding-based ARQ scheme with Overlapping Selection

To overcome the limitations mentioned above, we propose OS-NCARQ for resource limited multicast/broadcast services. In this section, we provide a process of OS-NCARQ implementation and a simple structured packet encoding algorithm for OS-NCARQ.

A. Procedure of OS-NCARQ

Figure 7 abstracts the architecture of OS-NCARQ. At the first step, a source node received feedback messages from destination nodes and updates a feedback matrix. At the second step, the source node selects the effective part of the feedback matrix. At this time, the source node leaves out packets transmitted more than maximum transmission number and packets received successfully by all destination nodes. After that, if maximum node degree is bigger than S, the source node selects the area from minimum index among indices of first lost packet of destination nodes to the previous index of minimum index among indices of $(S+1)th$ requested packet of destination nodes. At the third step, the source node generates retransmission packets from the selected part. At the fourth step, if the number of encoded packets is smaller than S then the source node adds new original packets as many as possible, whereas if the number of encoded packets is bigger than or equal to S then the source node chooses only S packets for the retransmission. At the fifth step, the source node divides total packets into the transmission units. Here, the transmission unit is defined as the amount of packets for one continuous transmission and the total packets for each *window* can be only one transmission unit or also be a few transmission units according to the amount of resource allocation. At the sixth step, a header is attached in front of data packets per the transmission unit. The header includes the information of packets such as the number of packets and packet indices. The structure of the transmission unit is illustrated in Figure 8. The packet number denotes the number of packets in the transmission unit, the packet degree is the number of original packets composing each retransmission packet, and the packet index represents each original packet index. Finally, the source node transmits the transmission units.

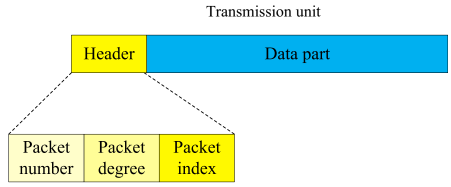

Fig. 8. The structure of transmission unit.

Algorithm 1 NCARQ with Overlapping Selection (OS-NCARQ)

1: initialize $F(n_i, d_j)$ where $n_i \in N,\ d_j \in D,\ \hat{D} = \phi,\ k = 0$
2: for $d_j \in D,\ d_j \notin \hat{D}$
3: set $k = k + 1,\ c_k = d_j,\ d_j \in \hat{D}_{c_k}$
4: for $d_{j'} \in D,\ d_{j'} \neq d_j$
5: if $F(n_i, d_{j''}) = 0$ for all $n_i,\ d_{j''}$, where $d_{j''} \in \hat{D}_{c_k},\ d_{j''} \neq d_j,\ n_i \in N(d_{j'})$
6: set $c_k = c_k \oplus d_{j'},\ d_{j'} \in \hat{D}_{c_k}$
7: end if
8: end for
9: end for

For generating encoded packets, rather than using a heuristic algorithm to find the optimal set of requested packets, here we propose a simple structured algorithm. The pseudocode of the proposed algorithm for encoding retransmission packets is given in Algorithm 1. In the algorithm, N is the set of destination nodes, D is the set of original packets, $N(d_j)$ is the set of nodes that request the packet d_j, c_k is the kth encoded packet. $\hat{D}_{c_k}$ is the set of original packets used for encoding c_k, that is $\hat{D}_{c_k} = \{d_1, \cdots, d_m, \cdots, d_M\}$, where $c_k = d_1 \oplus \cdots \oplus d_m \oplus \cdots \oplus d_M$. $\hat{D}$ is the union of sets $\hat{D}_{c_k}$.

IV. Simulation Results

In this section, we evaluate the performance of OS-NCARQ and compare it against two baselines: 1) NCARQ scheme in [13] and 2) ARQ scheme in [1]. Simulation metrics are the reception success ratio, the transmission efficiency, and the impact of number of nodes. We define parameters, R, S, T, and P_{loss}, for describing simulation scenarios. R is a number of receiver nodes, S is a number of packets for a window, T is maximum number of transmission for a packet, and P_{loss} is the packet loss ratio. We consider three scenarios : case 1) R=5, S=7, T=4, case 2) R=8, S=10, T=2, case 3) P_{loss}=0.1, S=10, T=2. For each case, the simulation is repeated 10,000 times independently.

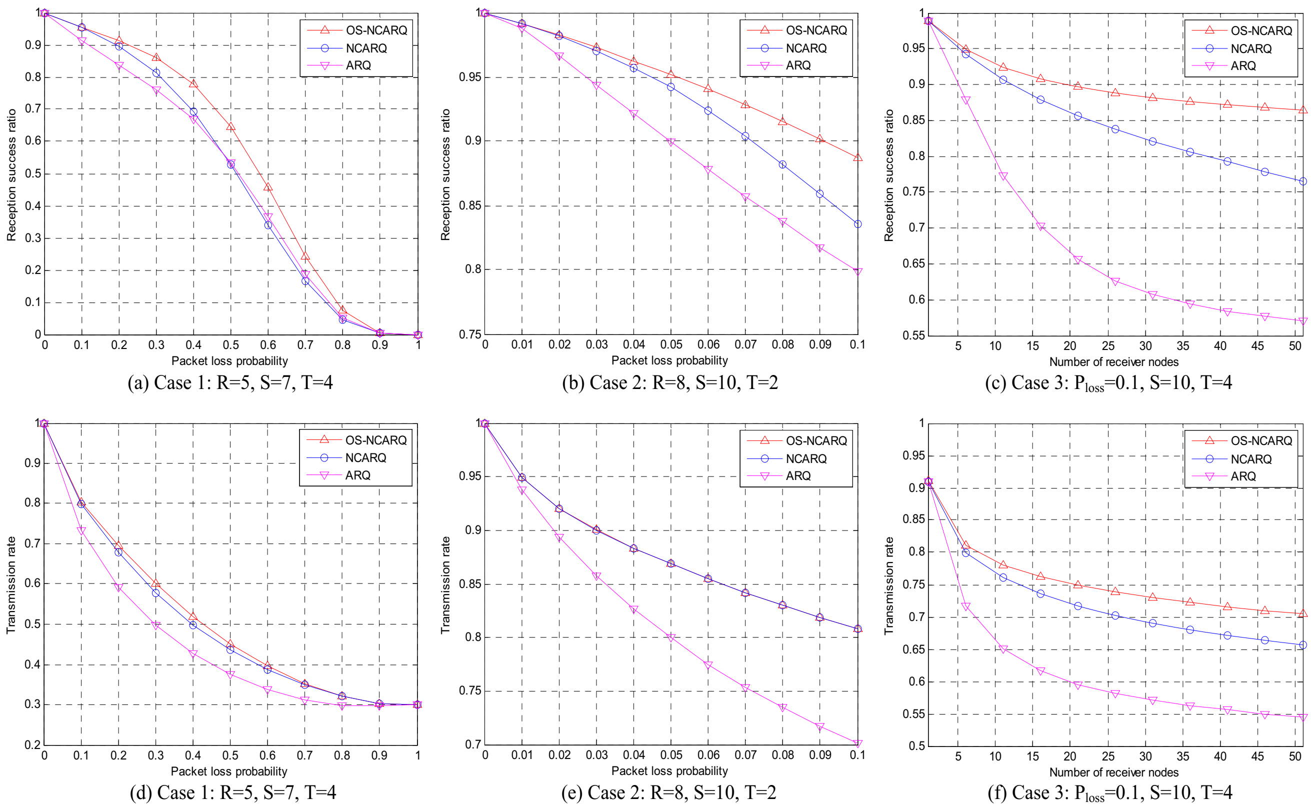

Fig. 9. Performance comparison; (a) Reception success ratio versus packet loss probability (R=5, S=7, T=4), (b) Reception success ratio versus packet loss probability (R=8, S=10, T=2), (c) Reception success ratio versus number of destination nodes (P_{loss}=0.1, S=10, T=2), (d) Transmission rate versus packet loss probability (R=5, S=7, T=4), (e) Transmission rate versus packet loss probability (R=8, S=10, T=2), (f) Transmission rate versus number of destination nodes (P_{loss}=0.1, S=10, T=2).

A. Reception success ratio

The reception success ratio is defined as the ratio of packets received by all destination nodes to original packets transmitted by a source node. Figure 9(a) and Figure 9(b) show the reception success ratio versus the packet loss probability for case 1 and case 2 respectively. In Figure 9(a), OS-NCARQ outperforms both NCARQ and ARQ for the overall packet loss probability range whereas NCARQ outperforms ARQ for the only low packet loss probability range. Through the comparison of Figure 9(a) and Figure 9(b), we can expect that the gap between OS-NCARQ, NCARQ and traditional ARQ increases with increasing the number of receiver nodes, R. Moreover, OS-NCARQ significantly outperforms ARQ with only $T = 2$ while the degradation trend of the relative performance of NCARQ compared with OS-NCARQ in Figure 9(b) appears earlier than the trend in Figure 9(a) with increasing the packet loss probability.

B. Transmission efficiency

We further investigate the transmission rate versus the packet loss probability under different parameters as plotted in Figure 9(d) and Figure 9(e). Here, the transmission rate is defined as the ratio of new original packets to overall transmitted packets. In both of figures, OS-NCARQ has the best performance and NCARQ has slightly lower performance than OS-NCARQ.

C. Impact of number of nodes

Now, we turn our attention to the effect of increasing the number of destination nodes. Figure 9(c) shows the reception success ratio versus the number of destination nodes. As mentioned above, we can see that the gap between OS-NCARQ, NCARQ and traditional ARQ increases with increasing the number of destination nodes. Figure 9(f) shows the transmission rate versus the number of destination nodes. Similarly with previous results, OS-NCARQ has best performance among three schemes.

V. Conclusion

In this paper, we propose a novel network coding-based ARQ scheme with overlapping selection (OS-NCARQ) to increase the bandwidth efficiency in resource limited multicast/broadcast services. Packet encoding algorithm in OS-NCARQ acquires more chance to recover requested data packets so that it guarantees more efficient and effective retransmission. The advantages of OS-NCARQ schemes over the traditional ARQ scheme and existing NCARQ schemes are shown through the analysis and simulations.

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