# Contents

List of Figures ................................................................................................................................. 3

Abstract ............................................................................................................................................. 5

Chapter 1 Introduction .......................................................................................................................... 7
  1.1 Wireless Reliable Multicast ........................................................................................................ 7
  1.2 Background of Network Coding ............................................................................................. 9
    1.2.1 Traditional Routing and Network Coding ........................................................................ 10
    1.2.2 Network Coding in Wireless Networks .......................................................................... 11
    1.2.3 Previous Work on Network Coding in Wireless Networks ............................................ 12
  1.3 Contributions of This Thesis ..................................................................................................... 15
  1.4 Organization of This Thesis ..................................................................................................... 15

Chapter 2 Network Coding-Based Reliable Wireless Multicast Scheme ..................................... 17
  2.1 Traditional Non-coding Reliable Multicast Scheme .............................................................. 18
  2.2 Network Coding-based Reliable Multicast Scheme ............................................................ 19
  2.3 Coding Algorithm .................................................................................................................... 24
  2.4 Performance Evaluation .......................................................................................................... 26
    2.4.1 Bandwidth Efficiency versus Group Size ....................................................................... 26
    2.4.2 Bandwidth Efficiency versus Number of Receivers ...................................................... 27
    2.4.3 Bandwidth Efficiency versus Packet Loss Rate ............................................................ 29
  2.5 Summary ................................................................................................................................... 31
Chapter 3  Enhanced Reliable Multicast Scheme with New Acknowledgement Mechanism ................................................................. 33

3.1  Coding-based Schemes with New Acknowledgement Mechanisms ........... 34

3.1.1  Group-based Acknowledgment Mechanism ................................... 35

3.1.2  ACK-reduced Group-based Acknowledgment Mechanism ............. 36

3.2  Performance Evaluation ........................................................................ 38

3.2.1  Environments with Only Random Packet Loss .............................. 38

3.2.2  Environments with Both Random and Bursty Packet Loss ............ 40

3.2.3  Comparison between Available Scheme and Proposed Scheme ...... 42

3.3  Summary ................................................................................................ 44

Chapter 4  Conclusion and Future Work ...................................................... 46

4.1  Restatement of The Main Proposals and Contributions ..................... 46

4.2  Future Work .......................................................................................... 47

References ..................................................................................................... 49

Acknowledgements ......................................................................................... 52
List of Figures

1.1 Difference between wired and wireless multicast...........................................7
1.2 An example of available reliable wireless multicast........................................8
1.3 Traditional routing and network coding.........................................................10
1.4 Basic idea of wireless network coding............................................................12
2.1 Packet loss table...............................................................................................20
2.2 Receiving status registered in packet loss table...............................................22
2.3 Combined packets for coding-based retransmission.........................................23
2.4 Combined packets for coding-based retransmission.........................................24
2.5 Heuristic coding algorithm.............................................................................25
2.6 Bandwidth efficiency versus group size.........................................................27
2.7 Bandwidth efficiency versus number of receiver............................................28
2.8 Packet loss table, \( M=2 \) and \( M=8 \).................................................................29
2.9 Bandwidth efficiency packet loss rate............................................................30
2.10 Packet loss table, \( p_i=0.8, p_i=0.6 \) ...............................................................31
3.1 The current and revised ACK packet formats...............................................35
3.2 Correction of pseudo packet loss when using the GB mechanism.....................35
3.3 Example of experiencing a long deep fade.....................................................37
3.4 Bandwidth efficiency packet loss rate............................................................38
3.5 Bandwidth efficiency versus number of receivers...........................................39
3.6 Bandwidth efficiency comparison, with long deep fades...............................40
3.7 Bandwidth efficiency versus packet loss rate..................................................41
3.8 Bandwidth efficiency versus number of receivers

3.9 Comparison between available coding-based scheme and proposed scheme, $p_a=0$

3.10 Comparison between available coding-based scheme and proposed scheme, $p_a=p_i$
Abstract

In the time span of just a few years, wireless networks have emerged from a novelty to popularization. Especially, there has been the high demand for reliable multicast under wireless environments. Reliable multicast provides lossless delivery of bulk data from one sender to a group of receivers. It achieves reliability by using retransmission scheme, in which each lost data packet will be retransmitted again and again until it is received by all of the designated receivers. But in wireless network environments, every link is wireless, which makes data packet lost easily. So, under the premise that reliability is guaranteed, increasing bandwidth efficiency is a major challenge. In this thesis, my main goal is to increase the bandwidth efficiency of reliable multicast in a wireless network by reducing retransmissions.

For the first time, we investigate network coding-based reliable wireless multicast scheme under the condition that the acknowledgments packets (ACKs) suffer from loss. Specifically, in this research, we present the network coding-based scheme for reliable one-hop multicast in wireless networks. In summary, this thesis presents the following contributions to increase the bandwidth efficiency of reliable wireless multicast.

**Network coding based reliable multicast scheme** In chapter 2 we study the application of network coding technique. First, propose a network coding-based reliable multicast scheme to reduce retransmissions caused by packet loss, aiming to address how to apply network coding in reliable wireless multicast to achieve high-level bandwidth efficiency. In the scheme we employ network coding technique to combine several lost packets from different receivers in such a way that multiple receivers are able to recover their lost packets with one retransmission from the source. An efficient coding algorithm is presented for finding the set of lost packets for encoding. Simulation results demonstrate that, our proposed network coding based reliable multicast scheme significantly outperforms the traditional non-coding scheme.

**Enhanced reliable multicast scheme with new acknowledgement mechanism** In the available multicast schemes, once one receiver receives one packet from the source it will
send an ACK to acknowledge the receiving of this packet. We notice that such
acknowledgment mechanism has the following limitation: when an ACK from one receiver
is lost, the source considers the corresponding data packet to be lost at this receiver and
then conducts unnecessary retransmission. Motivated by this basic observation, in chapter
3, we propose a group-based acknowledgment mechanism. In this mechanism, rather than
acknowledging single packet, each ACK acknowledges all previously received packets of
the current group such that the unnecessary retransmissions are greatly reduced.
Simulation results demonstrate that compared to the current acknowledgment mechanism
our proposed enhanced scheme with new acknowledgement mechanism can achieve much
higher bandwidth efficiency.
Chapter 1

Introduction

1.1 Wireless Reliable Multicast

Multicast is a mechanism for distribute identical information from one source to a group of receivers. Instead of sending a separate copy of the data to each individual receiver, the sender just sends a single copy to all the receivers. Multicasting of real-time multimedia information has been receiving a great deal of attention [1], [2], [3] since 1990s. Recently it is widely used in many applications ranging from satellite communications to video meeting. Since most real-time applications can tolerate some data loss but cannot tolerate the delay associated with retransmissions, they either accept some loss of data or use forward error correction for minimizing such loss. The main objective of this kind of multicast protocols for transporting real-time data is to guarantee quality of service by bounding end-to-end delay at the cost of reliability.

In contrast, reliable multicast [4], [5], the lossless delivery of bulk data from one sender to a group of receivers, the objective of this kind of networks is to guarantee complete reliability at the expense of delay. It requires that every designated receiver must receive the correct information sent by the source.

![Wired multicast](image1.png) ![Wireless multicast](image2.png)

**Figure 1.1** Difference between wired and wireless multicast
In the time span of just a few years, wireless networks have emerged from a novelty to popularization. Especially, there has been the high demand for reliable multicast under wireless environments require sequenced and lossless delivery of data. Here we should notice that the wireless multicast is different from wired multicast. In the wireless multicast the network node can only transmit one packet to its neighbors in one time slot; in the wired multicast, however, the network node can transmit different packets to different neighbors in one time slot (refer to Figure 1.1). It is widely used in many important applications such as: in a WLAN (Wireless local area network) a software house distributing the latest release of a software to its clients, a financial institution disseminating market data to its subscribers, a publisher distributing books electronically to bookstores, and a hospital sending patients’ medical image data to physicians in other hospitals. But in wireless network environments, every link is wireless, whose packet lost rate is relatively high. Moreover, different links have different packet loss rates due to some factors (like the distance between the source and the receiver, the building block). So, under the premise that reliability is guaranteed, increasing bandwidth efficiency is a major challenge. One main approach of guaranteeing the reliability in reliable wireless multicast is: retransmission. Using available retransmission approach, the source simply retransmits the lost data if there is at least one receiver not receiving the correct data. In this approach the source assumes to know which packet from which receiver is received through the use of positive acknowledgments (ACKs).

![Diagram](image)

**Figure 1.2** An example of available reliable wireless multicast
Figure 1.2 shows a simple reliable wireless multicast example. Source $S_1$ sends packets to 3 receivers $R_1$, $R_2$, $R_3$. When at the first time it transmits packet $1(P_1)$, $R_1$ successfully receives $P_1$ but $R_2$, $R_3$ cannot. Source retransmits $P_1$ immediately. This time $R_3$ receives $P_1$ but $R_2$ cannot. The source will continue to retransmit $P_1$ again and again until $P_1$ is received by all of the three receivers. Then the source begins to transmit another packet by this way.

The biggest problem of reliable wireless multicast is packets lost easily. Because of the wireless networks, every link is wireless. Such as electromagnetic interference, signal attenuation, there are lots of factors can cause packet loss. But, above we have emphasized that, in reliable multicast, every packet must be received successfully. It means that in some bad wireless environments, it will cost a larger number of retransmissions to guarantee the reliability. This limitation leads to that the bandwidth efficiency of reliable multicast is very low. It will reflect delay and energy consumption on network. So, under the premise that reliability is guaranteed to reduce retransmissions is a major challenge. In my research, I want to use my proposed schemes to reduce retransmissions cause by data packets loss and ACK loss. I will introduce my proposed schemes in detail at chapter 2 and chapter 3.

1.2 Background of Network Coding

Network coding is a new approach to increase the transmission capacity of a network [6]. In a traditional store-and-forward network, packets are forwarded hop-by-hop along the intermediate nodes from a source to a destination. An intermediate node forwards the packets as it receives through a predefined path. It works like a router in a computer network. All it does is route messages. Each message on an output link is just a copy of a message on an input link. On the other hand, network coding techniques allow an intermediate node to perform some lightweight computation, so that each message on an output link can be a function of the messages on the input links. This is called network encoding. So we can have some processing, or coding, in the network, instead of just at the endpoints. For many problems such as multicast and broadcast, using appropriate encoding schemes at each intermediate node (typically linear combination of input data) can achieve the network capacity. Recently network coding technique also be broadly applied to
1.2.1 Traditional Routing and Network Coding

In today’s practical communication networks such as the Internet, data information delivery is performed by routing. Each network node functions as a switch or a router, which either relays information from an input link to an output link, or replicates information received from an input link and sends it to a certain set of output links, (i.e. by having intermediate nodes store and forward packets). However, theoretically, a network node can not only perform as a switch, but also function as an encoder which encodes (or mixes) the incoming data (packets) from the input links and then sends the encoded (mixed) data to the output links.

The conception of network coding combining the functions of coding and routing, plays an important role in field of communications in 21st century. Due to the extra encoding function, compared with tradition routing function, each network node achieves both the routing and coding function rather than only switching (routing).

![Figure 1.3: Traditional routing and network coding](image)

Figure 1.3 shows a simple multicast example that explains the principle of network coding in the view of network system. Assume that all links are error-free and have a capacity of one bit per unit time. Nodes (sink nodes) $A$ and $B$ will transmit 1 bit data.
separately to the nodes E and F at the rate of 1 bit capacity per unit time.

Figure 1.3 (a) shows a traditional routing way, in which node C can only transmit 1 bit during one unit time to node D, and also node D can only transmit 1 bit data to both E and F. Thus, if we want to transmit 2 bits \( b_1 \) and \( b_2 \) from C to D, we will use the link twice (two units time). At the same time, E and F totally receive 3 bits, and the average rate is 1.5 bit/unit time; Figure 1.3 (b) shows the network coding methods. Node C encodes the incoming data by using XOR method, namely \( b_1 \) \( b_2 \), and transmits the encoded data to D. Afterwards, the encoded data will be transmitted from D to node E and F. At this time, node E will be able to decode \( b_2 \) from the received data \( b_1 \) and \( b_1 \) \( b_2 \), and so does the node F. The average transmit rate is 2 bit/unit time.

Since the proposal of network coding, this topic has been undergoing an active development in the research community. Various studies in the past years have resulted in a significant advance in our understanding of network coding. So far, it has been shown that this generality of network coding over routing can provide many potential advantages in both wired and wireless networks, such as throughput improvement, resource efficiency, computational efficiency, and robustness to network dynamics, etc.

1.2.2 Network Coding in Wireless Networks

Above we have discussed the basic conception of network coding and compared the average transmit rate with traditional routing. Network coding can be also applied to wireless networks, where each network-node takes advantage of wireless medium (like the broadcast communication channel) and conducts data processing in order to increase the capacity or the throughput of the network.

The basic idea of wireless network coding can be illustrated using the scenario in the Figure 1.4, where node A wants to send packet \( P_1 \) to node B and node B wants to send packet \( P_2 \) to node A with the help of intermediate node R. Assume node R has received \( P_1 \) and \( P_2 \). In traditional transmission way, node R transmits \( P_1 \) and \( P_2 \) separately. However, node R can XOR \( P_1 \) and \( P_2 \) together and broadcast \( P_1 \) \( P_2 \). Upon receiving \( P_1 \) \( P_2 \), node A can decode \( P_2 \) by \( P_2 = P_1 \) \( P_1 \) \( P_2 \). Similarly, node B can decode \( P_1 \) by \( P_1 = P_2 \) \( P_1 \) \( P_2 \).
Therefore, with the network coding function, node $R$ can forward two packets in one single packet transmission and its transmission efficiency is improved by 100% when $P_1$ and $P_2$ have the same size. In this example, by applying network coding, every link has been just used once, and this coding method successfully reduces both the number of transmission and network delay as well as increases the throughput of network.

![Figure 1.4 Basic idea of wireless network coding](image)

### 1.2.3 Previous Work on Network Coding in Wireless Networks

Network coding has gained much popularity in wireless networks. So far, considerable efforts have been devoted to demonstrate the benefits of applying network coding for different communication paradigms in wireless networks. At the first stage of network coding research areas, many researchers have been mainly focusing on how to improve the throughput of networks by designing coding algorithm and analyzing the benefit of coding over routing. Afterwards, network coding has been acknowledged as a promising technology, the research interests have been mainly involved in wireless multicast capacity and linear network coding algorithm. During this period, most proposed methods have been around theory analysis, centralized, and many research works dealt with network coding in cross-layer design for the physical layer, MAC layer and link layer resource. Below, we review the application of network coding.

By now, a great deal of existing work has shown that network coding exhibits unique advantages over conventional routing for different communication paradigms, such as the unicast, multicast, and broadcast.
For the unicast scenario, Wu et al. [7] has demonstrated that the network coding and physical-layer broadcast can both be performed in wireless networks to achieve high communication efficiency. Li et al. [9] has applied network coding in wired networks in multiple unicast sessions. Later, Katti et al. [10] has proposed a practical network coding called COPE, which can take advantage of overheard packets and can essentially improve the network throughput of multi-hop wireless networks. Based on the COPE-type coding scheme, the coding-aware routing was proposed in [11], [12]. Recently, some researchers have proposed the analog network coding to utilize wireless interference for network coding [13], [14].

Concerning the broadcast case, distributed probabilistic broadcast algorithms and deterministic broadcast algorithms have been proposed by Fragouli et al. [15] and Li et al. [16], respectively, resulting in a significant energy saving.

As for multicast case, Wu et al. [8] has showed adopting network coding for minimum-cost multicast can be formulated as a linear optimization problem and solved in polynomial time in the case of mobile ad hoc network. Lun and Medard [17] have proposed a non-centralized computation and decentralized algorithms based on network coding to establish the minimum-cost multicast tree, the corresponding theoretical throughput analysis of multicast with network coding has also been conducted in [18] for unreliable Ad hoc networks.

About the packet-loss-permitted multicast (bound delay at the expense of reliability), like video/audio conferencing. Chachulski et al. [19] presents MORE, a MAC-independent opportunistic routing protocol and implemented MORE in the Click modular router running on off-the-shelf PCs equipped with 802.11 (WiFi) wireless interfaces. Park et al. [20] present CodeCast, a network coding based ad hoc multicast protocol. CodeCast is well-suited especially for multimedia applications with low loss, low latency constraints such as audio/video streaming. In[21], J. Barros et al redefine the encoding rules in order to break the chains of linear combinations that cannot be decoded after one of the packets is lost. To circumvent unduly computational complexities, [22] design a heuristic scheme which can achieve significant performance gain when compared to an existing method.
These practical network coding-based multicast schemes have been presented to effectively achieve high reliability (less than 100% packet delivery ratio).

Some work also has been done on the application of network coding to both single-hop and end-to-end reliable wireless multicast. For single-hop reliable wireless multicast, Keller et al. [23] presented several schemes with the simple XOR coding operation to achieve high transmission efficiency and small decoding delay, whereas Nguyen et al. [24] proposed the optimal XOR-based coding schemes in terms of transmission efficiency, without the consideration of decoding delay. In [25], for the two-receiver single-hop multicast, Tran et al. proposed a joint network-channel coding technique to achieve higher bandwidth efficiency than the traditional hybrid ARQ. In [26], for three-receiver single-hop reliable multicast, Sundararajan et al. proposed a new coding algorithm to minimize the decoding relay while maintaining the optimal throughput. Different from the above block-by-block schemes, [27] presented the drop-when-seen algorithm which performs network coding over high order finite field and can significantly reduce the sender’s queue size. As for the coding-based end-to-end reliable wireless multicast, [28], [29] studied the design of effective feedback mechanisms by using some techniques like the ACK superposition. For the direct extension of network-coding-based one-hop reliable multicast scheme, Ghaderi et al. [30] theoretically analyzed the achieved gain compared to end-to-end ARQ, end-to-end FEC (using rate less coding), link-by-link ARQ, and showed that network coding-based scheme can significantly reduce the number of transmissions compared to other three schemes. Similarly, Fujimura et al. also showed that conducting network coding at each intermediate node can achieve higher transmission efficiency than adopting the end-to-end rate less coding (like Raptor codes) [31]. However, there work does not explicitly consider the specific design of coding scheme. They all based on the assumption that each receiver can send ACKs timely and successfully to the source node. Different from the available work, for the first time, we investigate network coding-based reliable wireless multicast scheme under the condition that the acknowledgments packets (ACKs) suffer from loss.
1.3 Contributions of This Thesis

Until now all of the schemes on reliable multicast over wireless networks based on the assumption that each receiver can send ACK timely and successfully to the source node. Different from these schemes, for the first time, we investigate network coding-based reliable wireless multicast scheme under the considering that the acknowledgments packets (ACKs) should be lost. Base on this thought, in this research, we focus on the network coding-based link-by-link recovery scheme for reliable one-hop multicast in wireless networks. The thesis contributions are summarized below.

- Application of network coding technique

  We apply network coding technique to wireless reliable multicast. Design a network coding-based reliable multicast scheme to reduce retransmissions caused by packet loss, aim to address how to apply network coding in reliable wireless multicast to achieve high-level bandwidth efficiency. And obtain a better performance bandwidth efficiency compared with traditional non-coding scheme.

- Enhanced reliable multicast scheme with new acknowledgement mechanism

  Further considering the problems of dealing with the ACK- loss problem in practice, we purposed an enhanced reliable multicast scheme with revised acknowledge mechanism. Effectively solve the problem that unnecessary retransmissions caused by ACK loss.

1.4 Organization of This Thesis

Chapter 2 in this thesis studies the application of network coding in wireless reliable multicast. Chapter 3 proposes a group-based acknowledgment mechanism. Chapter 4 demonstrates our conclusion and outlines some future work in this area. In more detail, the thesis is organized as follows.

Chapter 2 in this thesis studies the application of network coding in wireless reliable multicast. We propose a network coding-based scheme of reliable wireless multicast. In the
scheme we employ network coding technique to combine several lost packets from different receivers in such a way that multiple receivers are able to recover their lost packets with one retransmission by the source. An efficient coding algorithm is presented for finding the set of lost packets and encoding. The advantages of the proposed schemes over the traditional reliable wireless multicast are shown through simulations results and analysis.

Chapter 3 in this thesis studies motivated by reduces unnecessary retransmissions cause by ACK loss. First propose a group-based acknowledgment mechanism, where each ACK can acknowledge all previously received data packets of the current group rather than one single data packet, such that the unnecessary retransmissions are greatly reduced. Then we further propose another group-based acknowledgment mechanism, where receivers will not send ACK for each data packet reception, but start to send acknowledgment from the last two packets in the transmission phase, such that the amount of feedback is greatly reduced. Both theoretical analysis and simulation are conducted to demonstrate that, compared to the current acknowledgment mechanism in network coding-based reliable multicast schemes, these two proposed mechanisms can achieve much higher bandwidth efficiency. In particular, the former one can achieve better performance over the latter one in the wireless networks with long deep fades, while the second one can outperform the first one in the wireless networks without intermittent long deep fades.

In Chapter 4, we give a final perspective on our work and outline some future work in this area.
Chapter 2

Network Coding-Based Reliable Wireless Multicast Scheme

The reliable multicast generally does not allow data loss, but can tolerate delay due to retransmissions. In our research, we focus on the network coding-based link-by-link recovery scheme for reliable multicast [4], which aims to achieve high bandwidth efficiency by reducing retransmissions.

Traditionally, to ensure the reliable link-layer multicast the source simply retransmits the lost packets one by one. Nguyen et al. [32] has proposed two network coding based schemes (a static one and a dynamic one) for the reliable link-layer multicast in wireless networks. The main idea of these coding-based reliable multicast schemes is to first store (buffer) the lost packets for some time, then, rather than transmit these lost packets one by one, the source XORs an optimal set of lost packets with distinct designated receivers together into one packet and transmits this XOR-ed packet in one retransmission. By intelligently XOR-ing multiple lost packets together, the current coding-based multicast schemes can result in a significant improvement on the transmission efficiency of reliable link-layer multicast. But, it has been proved that finding the optimal set of lost packets for XOR-ing belongs to the complex NP-complete problems [33]. That is to say, these two schemes are not scalable to a large number of multicast receivers. And all of available schemes are designed based on the assumption that each receiver can send ACKs timely and successfully to the source node. Thus these schemes are clearly insufficient to describe real-world scenarios. In our research, we design practical coding algorithm and conduct simulations all under the considering that ACKs may be lost due to different reasons.

Before discussing traditional non-coding scheme and our purposed network coding-based scheme, we make the following assumptions for all the two multicast schemes:
1) There is one source and $M > 1$ receivers.
2) Assume that date is sent in total $Q$ packets, and each packet is sent in a time slot of fixed duration.
3) Assume that the source knows which packets each receiver already received through the use of positive acknowledgments (ACKs). (ACK may be lost due to different reasons)
4) Packet loss at a receiver $R_i$ follows the Bernoulli distribution with parameter $p_i$. In addition, the packet losses at different receivers are independent.

### 2.1 Traditional Non-coding Reliable Multicast Scheme

In this section, we briefly review the available non-coding scheme for the reliable link-layer multicast and its limitations.

In traditional non-coding scheme, a receiver sends an ACK immediately whenever there is a packet receipt in the current time slot, or it has received this packet correctly in some previous time slots. To achieve the reliable link-layer multicast, traditionally the source simply retransmits the lost packets one by one.

The transmission of packets is done the following way:

The multicast source:

1. Transmit one packet $P$.
2. If the source does not receive ACK from one or more receivers, retransmit packet $P$.
3. Step 2 is repeated until the source receives ACK from each receiver.
4. Repeat Steps 1, 2 and 3 until all data packets are transmitted.

The receiver:

1. If received a data packet that is not received before, sends an ACK packet to the
source immediately as a feedback.

This scheme is clearly suboptimal in terms of bandwidth utilization as it implies that the source has to resend a packet until all the receivers receive this packet correctly. Below we use an example to show how the traditional non-coding reliable multicast scheme works.

Assume that there 5 packets $P_1, P_2, P_3, P_4, P_5$ and 3 receivers $R_1, R_2, R_3$. Source $S$ send packets to this receiver one by one. $P_1$ was received by all the 3 receivers. After receiving $P_1$ each receiver send an ACK packet to the source. ACK from $R_2$ and $R_3$ were successfully received, But the ACK packet from $R_1$ was lost. So the source has to retransmit $P_1$ immediately, until it receives the ACK packet from $R_1$. Then the source continues to send $P_2$. $P_2$ was only lost at $R_3$, the source will retransmit $P_2$ again and again until it is indicated by ACK from $R_3$ that $P_2$ is received. As same as $P_2$, $P_3$ was lost at $R_2$, $P_5$ was lost at $R_1$. The source also have to retransmit each of them immediately, until they are correctly received by all of the receivers. In the 5 packets Only $P_4$ was received by the entire receivers at the first transmission, and all of ACK packets are successfully received in time.

In this scenarios, even if each of the lost packet was successfully received in one retransmission. It also has to cost 4 retransmissions. This scheme is clearly suboptimal in terms of bandwidth utilization as it implies that the source has to resend a packet immediately until all the receivers receive this packet correctly.

2.2 Network Coding-based Reliable Multicast Scheme

Network coding techniques allow an intermediate node to combine data from different input links before sending the combined data on its output links. This is called network encoding. For many problems such as multicast and broadcast, using appropriate encoding schemes at each intermediate nodes (typically linear combination of input data) can achieve the network capacity. Network coding technique can also be applied to wireless networks [7], [8].

In our research, we design practical coding algorithm and conduct simulations all
under the considering that ACKs may be lost due to different reasons. We consider an application of network coding to increase the bandwidth efficiency of reliable multicast in a wireless network. In particular, we employ network coding to reduce the number of retransmissions as a result of packet losses.

In this coding-based scheme, data packets are separated into groups with the same size. The transmission of each group of packets consists of the transmission phase and in this scheme, each receiver is similar to that of the receiver in non-coding scheme in which it sends the ACK immediately if it receives a packet correctly.

![Packet loss table](image)

**Figure 2.1** Packet loss table

In transmission, data packets are transmitted group by group [4]. Source does not retransmit the lost packet immediately when it do not receive an ACK. Instead, the source maintains a table of lost packets and the corresponding receivers for which their packets are lost.

According the packet loss table as **Figure 2.1** shows during the retransmission phase our proposed scheme can combines different (use especial coding algorithm) lost packets from different receivers in such a way that multiple receivers are able to recover their lost packets with single transmission by the source.

Formally, our purposed network coding based scheme (for the transmission of one group of packets) is illustrated as follows:
In transmission phase:

1. The source maintains a packet table, whose entry $e_{i,j}$ is set to 0 if receiver $R_i$ has $P_j$; otherwise, set to 1.

2. Let $j=1$.

3. Source $S$ multicasts packet $P_j$ to $M$ receivers

4. If receiver $R_i$ receives the packet, sends an ACK packet to the source immediately as a feedback.

5. If the source receive an ACK packet from $R_i$, write 0 on the pack loss table at corresponding position $e_{i,j}$. Else, write 1.

6. $j=j+1$. Repeat 3-5, until accomplish to send $N$ packets.

7. End

In Retransmission phase:

1. According as the packet loss table, source forms a new packet by XORing a set of the lost packets obtained by our heuristic coding algorithm.

2. Source sends the combined packets to designated receivers (DR).

3. If designated receiver $R_i$ receives the packet, sends an ACK packet to the source immediately as a feedback.

4. If the source receives one ACK, write 0 on the pack loss table at corresponding position.

5. Repeat 1-4 until each entry $e_{i,j}$ is 0.

Then let me use a case to show how the scheme works. Assume that data is sent in total 5 data packets. There are 3 receivers ($R_1, R_2, R_3$).
In transmission phase first the source separate packets into groups and every group has 5 packets. Before transmits data packets, the source built a packet loss table for memorizing the lost packets and the corresponding receivers for which their packets are lost. Then the source begin to sent packets in Group $G_1 (P_1,P_2, P_3, P_4, P_5)$. Source does not retransmit the lost packet immediately when it does not receive an ACK. Instead, continue to send $P_1, P_2, P_3, P_4, P_5$ one by one .And in this procedure, if the source receive an ACK from a receiver, write 0 on the pack loss table at corresponding position, else write 1.Use the same case in 2.1. If $P_1$ was received by all of the 3 receivers. After receive $P_1$ each receiver send an ACK packet to the source. ACK from $R_2$, $R_3$ were successfully received, But the ACK packet from $R_1$ was lost. $P_2$ was only lost at $R_3$, $P_3$ was lost at $R_2$, $P_5$ was lost at $R_1$. In the 5 packets Only $P_4$ was received by the entire receivers at the first transmission, and all of ACK packets are successfully received in time. The packet loss table was shown on Figure 2.2.

The retransmission phase starts at a fixed interval of time in terms of number of time slots $T$, e.g. $T = 80$.During the retransmission phase, the source use coding algorithm encode a set of the lost packets from different receivers by XORing. Then retransmit this encoded packet to all of the receivers. The encoded packets may be lost during the retransmission. The scheme is have the source dynamically changes the encoded packets based on what the receivers have received. The source keeps sending out the encoded packets until no more lost packets on the table, it then resumes the transmission of the next group of packet. Even though a receiver successfully receives the encoded packets, it must
be able to recover the lost packets, and it does so by XORing this encoded packets with appropriate set of previously successful packets. In this case Fig 2.3 shows a pattern of lost packets (denoted by the connected circle) for 3 receivers $R_1$, $R_2$ and $R_3$. The combined packets are $P_1$, $P_2$, $P_3$, $P_5$.

<table>
<thead>
<tr>
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Lost: 1  Received: 0

**Figure 2.3** Combined packets for coding-based retransmission: $P_1$, $P_2$, $P_3$, $P_5$.

Receiver $R_1$ recovers $P_1$ as $P_1 = P_2 \oplus P_3$ ($P_1$, $P_2$, $P_3$). Similarly, receiver $R_2$ recovers packet $P_3$ as $P_3 = P_1 \oplus P_2$ ($P_1$, $P_2$, $P_3$). Note that if two packets have the same designated receiver, they cannot be combined together like $P_1$ and $P_3$ (The detail will be introduced in the next section).

Assuming that all the retransmissions are correctly received by all the receivers at the first attempt, then clearly the number of retransmissions for this scheme is only 2 while it is 4 for non-coding scheme.

Now, suppose the packet $P_1 \oplus P_2 \oplus P_3$ is lost at receiver $R_2$, but is received correctly at receiver $R_1$ and $R_3$. In this case, the scheme is have the source dynamically changes the combined packets based on what the receivers have received. For example, **Fig. 2.4** shows a same pattern of lost packets as in the previous scenario, the source can transmit packet $P_3 \oplus P_5$. The combined packets are $P_1 \oplus P_2 \oplus P_3$, $P_3 \oplus P_5$. 

23
The scheme can efficiently improve the bandwidth efficiency by reducing retransmissions which caused by data packets loss. The advantage of the proposed scheme over the traditional wireless multicast is shown through simulations. Specifically, we present an efficient heuristic algorithm for finding an approximately optimal solution of this finding the maximum set of lost packets. The algorithm will be introduced in the next section.

2.3 Coding Algorithm

In the above, we introduced our network coding-based reliable wireless multicast scheme. In this scheme, the “coding algorithm” is the core. How to effectively combine a set of the lost packets together? Then in this section, I introduce our proposed efficient heuristic algorithm for choosing the lost packet.

For a lost packet $P_i$, call the lost packets having one or more common designated receivers with it as its neighbor packets. Let $d_i$ be the number of $P_i$’s neighbor packets. Let $w_i$ be the number of $P_i$’s designated receivers. Our heuristic algorithm is to find lost packets with distinct designated receivers as many as possible. Its main idea is to select coding packets from the set of candidate packets one by one so as to achieve the low complexity. Notice that once a packet $P_i$ is selected for coding (i.e. XOR-ing), any one of its $d_i$ neighbor packets cannot be selected for coding. Thus, at each selection step, our algorithm selects out the lost packet $P_i$ which has the maximum value of $w_i / d_i$ and removes $P_i$’s $d_i$ neighbor packet.
packets from the set of candidate packets. The reason for this is that selecting the packet with the maximum value of \( w_i/d_i \) can effectively increase the total number of designated receivers (since \( w_i \) is the increment of the number of intended receivers when including \( P_i \) for XOR-ing) and also leave as many lost packets as possible in the set of lost packets for further selection. Such a selection rule can guarantee that after each packet selection, maximal candidate packets are left for further selection.

Specifically, the heuristic algorithm is as follows.

Let \( S_t = \{P_i, \ldots, P_L\} \) be the set of lost packets in. The coding algorithm selects a packet \( P_i \) with the maximum value of \( w_i/d_i \), then removes from \( S_t \) both the \( P_i \) and its \( d_i \) neighbor packets, and iterates this process on the remaining \( S_t \) until \( S_t \) is empty. The set of selected packets is the output of this algorithm. Formally, it is illustrated as follows.

---

**Figure 2.5** Heuristic coding algorithm

Now, we analyze the computational complexity of the above heuristic algorithm. To obtain the set \( C \) of lost packets for XOR-ing, the source first takes time \( O(N^2) \) to initialize \( S_t \), \( C \) and \( c_{i,j} \). Step 2 takes time \( O(MN^2) \) to calculate \( d_i \) and \( c_{i,j} \). Steps 4, 5 and 6 take time \( O(N) \),
and Step 7 takes time $O(MN)$. The iteration of Steps 4, 5, 6 and 7 will be conducted $O(N)$ times. Thus, the overall computational complexity is $O(MN^2)$.

With the coding schemes, we can not only achieve the low computational complexity, but also take full advantage of network coding to improve the bandwidth efficiency, as shown in the next section.

### 2.4 Performance Evaluation

In this section, through extensive simulation we investigate bandwidth efficiency for different reliable multicast schemes. We define the transmission bandwidth efficiency as the ratio of the number of successfully transmitted data bytes to that of the actual transmitted bytes. Let $M$ denotes the number of receivers, $N$ denotes the group size of lost-packet buffer. And $p_i$ denotes the packet loss probability of receiver $R_i$. For each scenario of parameter setting, our simulation conducts the multicast transmission of $N \times 10^5$ packets.

#### 2.4.1 Bandwidth Efficiency versus Group Size

For network coding-based scheme, the transmission bandwidth efficiency greatly depends on the packets group size, so we first investigate the transmission bandwidth of different schemes under different group sizes. **Figure 2.6** shows the transmission bandwidth efficiency of traditional non-coding scheme and our proposed coding-based scheme. In this case there are 8 receivers, and the average data packet loss probability $p_i$ is 0.2. The group size of varies as shown on the x-axis.

**Figure 2.6** From this figure, first we can clearly observe that in general the bandwidth efficiency of our proposed network coding-based scheme higher and higher as the group size increases. When the group size $N$ equal to 0, the packet loss table there are only one column. There is no coding chance. Our proposed coding-based scheme works as same as traditional non-coding scheme. But from **Figure 2.6** we can see that when the group size is not very small, the coding-based multicast scheme can substantially outperform the
traditional non-coding scheme.

For example, in the environment of Figure 2.6, using group size \( N = 16 \), compared to the traditional non-coding reliable wireless multicast scheme the bandwidth efficiency can be improved by over 52.9% when using our proposed network coding based scheme.

Remarks: Note that if the packet loss probability is not very high, a larger group size \( N \) results in better bandwidth efficiency. (I will discuss the bandwidth efficiency as the packet loss probability increase in 2.4.3) When \( N = 1 \), the network coding-based scheme reduces to the non-coding scheme.

### 2.4.2 Bandwidth Efficiency versus Number of Receivers

Figure 2.7 shows the transmission bandwidth efficiency of traditional non-coding scheme and our proposed coding-based scheme. In this case and group size is 16 (In coding-based scheme, every group includes 16 data packets), and the average data packet loss rate \( p_i \) is 0.4. The number of receivers varies as shown on the x-axis.
From this figure, first we can observe that in general the bandwidth efficiency of both schemes decreases as the number of receiver increases. The reason is that as the number of receiver increases, the possibility of packet loss at different receivers will higher and higher. In Figure 2.8 we use an extreme example compare $M=2$ with $M=4$ to explain the reason. Each receive has a independently packet loss rate $p_i=0.25$

In (a), there are only 2 revisers. Even there are no 2 packets are lost at the same receiver. There are only 8 lost packets ($P_1, P_2, P_3, P_4, P_5, P_6, P_7$ and $P_8$) at all of the 16 packets. On the other hand, in (B), there are 8 receivers. Even there some packets are lost at same receiver. Every packet are lost packet (every column in the table at least include one “1”). It means that every data packet must be retransmitted at least one time. And there is another reason. As the receiver increase the feedback overhead cause by ACK packets will be higher.
2.4.3 Bandwidth Efficiency versus Packet Loss Rate

Figure 2.8 Packet loss table, $M=2$ and $M=8$

In Fig.2.7 we also can observe that the improvement of bandwidth efficiency becomes significant as the number of receiver increases. That is because as the number of receiver increases the coding chance will be higher and higher. More receivers can recover the lost packet by one encoded packet sent from the source.

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(a) Packet loss table, $M=2$.

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(b) Packet loss table, $M=8$
From **Figure 2.9**, we also can clearly observe that in general the bandwidth efficiency of our proposed network coding-based scheme has higher bandwidth efficiency than traditional non-coding scheme. And it is easy to understand that in general the bandwidth efficiency of each scheme decreases as the data packet loss rate increases. If \( p_i = 0 \), every packet is successfully received in one transmission. There is no retransmission. So the two schemes have the same value of bandwidth efficiency.

![Bandwidth efficiency versus packet loss rate](image)

**Figure 2.9** Bandwidth efficiency versus packet loss rate

In this figure we also observe that for the low-packet-loss environment compare with non-coding scheme the improvement of our proposed scheme becomes significant as the pack loss rate increase. For example, in the environment of **Figure 2.9**, using packet loss rate \( p_i = 0.2 \), compared to the traditional non-coding reliable wireless multicast scheme the bandwidth efficiency can be improved by over 53.4% when using our proposed network coding based scheme.

In **Figure 2.10(a)** \( p_i = 0.2 \), the receivers can recover their lost by decode the combined packet \( P_1 \oplus P_2 \oplus P_4 \).
In the other hand, for the high-packet-loss environment, as the packet loss rate increase, the coding chance will lower and lower. At the point $p_i = 0.6$, our coding-based scheme almost have the same bandwidth efficiency to non-coding scheme. Above I have introduced that, for a lost packet $P_i$, call the lost packets having one or more common designated receivers with it as its neighbor packets. Neighbor packets cannot be combined together. In Figure 2.10, under the condition that $p_i = 0.6$. We can observe that $P_1$ have 4 neighbor packets, it cannot be combined with any other packet. As the same as $P_1$, $P_2$ also have 4 neighbor packets. So the source has to retransmit $P_1$ and $P_2$ independently. In the example we can clearly see that, for the high-packet-loss environment as the packet loss rate increase, more and more lost packet have to be retransmit independently. The disparity of bandwidth efficiency between coding-based scheme and non-coding scheme becomes smaller.

### 2.5 Summary

In this chapter, we propose a network coding-based scheme to increase the bandwidth efficiency of reliable multicast in a wireless network. Our proposed schemes combine different lost packets from different receivers in such a way that multiple receivers are able to recover their lost packets with one transmission by the source. The scheme efficiently
reduces the retransmissions caused by data packet loss. The advantages of the proposed schemes over the traditional wireless multicast are shown through simulation results.
Chapter 3

Enhanced Reliable Multicast Scheme with New Acknowledgement Mechanism

In both non-coding reliable wireless multicast schemes and coding-based reliable multicast schemes, the acknowledgment mechanism works as follows. Once one receiver $R_i$ successfully receives a data packet $P_j$ from the source, it will send one ACK to the source to acknowledge the successful reception of $P_j$. Such acknowledgment mechanism has the following limitation. It is notable that in lossy wireless networks the ACK packets will also suffer from the packet loss, just like the data packets. Once the ACK of packet $P_j$ from $R_i$ is lost, the source will also consider that $P_j$ is lost at $R_i$ although packet $P_j$ is actually received by $R_i$. Thus, the loss of ACK packet will introduce unnecessary retransmission of $P_j$.

Motivated by the above observation, in this chapter we first propose a group-based acknowledgment mechanism, where each ACK can acknowledge all previously received data packets of the current group rather than one single data packet, such that the unnecessary retransmissions are greatly reduced. Then we further propose another group-based acknowledgment mechanism, where receivers will not send ACK for each data packet reception, but start to send acknowledgment from the last two packets in the transmission phase, such that the amount of feedback is greatly reduced. Simulations are conducted to demonstrate that, compared to the current acknowledgment mechanism in network-coding-based reliable multicast schemes, these two proposed mechanisms can achieve much higher bandwidth efficiency. In particular, the former one can achieve better performance over the latter one in the wireless networks with long deep fades, while the second one can outperform the first one in the wireless networks without intermittent long deep fades. Specifically, we provide a few results on the retransmission overhead of the proposed schemes under different channel conditions.

In this chapter, we call the acknowledgment mechanism adopted in the available
coding-based reliable multicast schemes as single-packet based (SPB) mechanism.

**SPB Mechanism:** Once a receiver correctly receives one data packet from the source node, it will send one ACK to acknowledge the reception of this data packet. In the rest of this section, we will introduce two proposed enhanced schemes with new acknowledge mechanisms for the network-coding based reliable wireless multicast.

### 3.1 Coding-based Schemes with New Acknowledgement Mechanisms

Before presenting our acknowledgment mechanisms, we first introduce a definition as follows.

**Definition 1:** For one entry $e_{i,j}$ in the packet-loss table, if it is set to 1 due to the loss of corresponding ACK, we call this packet loss as a pseudo packet loss.

Now, let us introduce the basic idea of our new acknowledgment mechanism below. As previously described, in the coding-based scheme, the source will first transmit one group of packets one by one rather than retransmit one lost packet immediately. In such a transmission process, there actually exist chances to correct the entries that are set to 1 due to the pseudo packet losses. When one receiver $R_i$ receives packet $P_j$, it can acknowledge all successfully received packets among $\{P_1, \ldots, P_j\}$ rather than $P_j$ only. In such a way, once the source receives this ACK, it can correct all pseudo packet losses in the $i$’th row of packet loss table.

In order to implement the function of acknowledging multiple data packets instead of a single packet, we need to slightly revise the ACK packet format, show as **Figure 3.1**, where $L$ additional bytes are added into the current ACK packet format. Denote the bits of these $L$ bytes by $b_1, b_2, \ldots, b_K$ ($K = 8 \times L$ and $b_i \in \{0, 1\}$).

With this new ACK packet format, now we introduce our group based (GB) acknowledgment mechanism.
3.1.1 Group-based Acknowledgment Mechanism

**GB Mechanism:** In both the transmission phase and retransmission phase of coding-based schemes, when one receiver successfully receives one (native or encoded) useful data packet, it will send one ACK packet with the above new format. In the ACK packet to be sent, for each received packet $P_i$ sets its corresponding bit $b_i$ to 0; for each unreceived packet $P_j$, sets bit $b_j$ to 1.
Using this acknowledgment mechanism, the source can know the receiving status of all previous data packets once it receives one ACK from \( R_i \), and then correct those \( e_{i,j} \)'s of previous pseudo packet losses. Let us consider the example in Figure 3. In this example, after the source finishes the transmission of \( P_4 \) and receives the ACK from \( R_1 \), its packet loss table is shown at the top of Figure 3. When the source receives the ACK (shown in the figure) from \( R_2 \), the pseudo packet loss \( e_{2,1} \) is corrected from 1 to 0.

In this acknowledgment mechanism, the \( L \) added bytes in the ACK can represent the receiving status of \( 8L \) packets. We only need to let \( 8L \) be larger than or equal to the group size \( N \) (i.e., \( 8L \geq N \)). As it has already been shown in some literature that setting the group size \( N \) to \( 2M \) is enough for the coding-based scheme to achieve good performance, \( L \) will be a negligible value as compared with the total number of bytes of ACK unless \( M \) is very large, which rarely happens in wireless reliable multicast. In addition, although this mechanism can achieve high bandwidth efficiency, too many ACKs are sent from the receivers to the source node. The number of ACK packets increases linearly with the number of receivers. It is possible for us to reduce the overall amount of feedback while achieving high bandwidth efficiency. Thus, we proceed to present another group-based acknowledgment mechanism.

### 3.1.2 ACK-reduced Group-based Acknowledgment Mechanism

The above GB mechanism can very effectively reduce the number of pseudo packet losses. However, the total number of ACK packets sent from the receivers can be greatly reduced at the cost of slightly increasing the pseudo packet losses. Below, we show another acknowledgment mechanism to achieve this objective, which is called as ACK-reduced group-based (ARGB) acknowledgment mechanism.

**ARGB Mechanism:** In the transmission phase, starting from the \((N-1)\)'th data packet (i.e., \( P_{N-1} \)), once the source sends out one data packet, each receiver will send one ACK no matter it receives this packet or not. In this ACK packet, for each received packet \( P_i \) sets bit \( b_i \) to 0; for each unreceived packet \( P_j \), sets bit \( b_j \) to 1. In the retransmission phase, when one receiver successfully receives one data packet, it will send one ACK to the source node. In
the ACK packet to be sent, for each received packet $P_i$ sets its corresponding bit $b_i$ to 0; for each unreceived packet $P_j$, sets bit $b_j$ to 1.

![GB mechanism](image1)

![ARGB mechanism](image2)

**Figure 3.3** Example of experiencing a long deep fade.

It is easy to know that due to its few ACK packets, ARGB mechanism is scalable to large multicast networks. In addition, compared to the GB mechanism, the ARGB mechanism will lead to a little more pseudo packet losses. However, due to the great reduction of ACK packets, the overall amount of transmitted load may even be smaller than that of GB mechanism. But in the wireless networks with intermittent deep fades, GB mechanism will outperforms ARGB mechanism, because the deep fades may cause the continuous losses of early ACKs in ARGB mechanism and thus leads to the continuous retransmissions of one native packet until the deep fade finishes. This can be illustrated by **Figure 3.3**. In this example, $R_2$ experiences a long deep fade starting from the transmission of $P_4$. Suppose ACK packets are all received by the source except those in the deep fading period, and when using GB mechanism the packet losses are shown in the figure. In the retransmission phase, the source can still conduct packet coding. When using ARGB mechanism, however, as the ACKs from $R_2$ during the transmission of last two packets (i.e., $P_4$ and $P_5$) experiences a deep fade and are lost, in the packet loss table of the source node all packets to $R_2$ are considered to be lost. Thus the source will repeatedly retransmit one native packet until the deep fade passes.
3.2 Performance Evaluation

We now investigate the bandwidth efficiency for the network coding-based reliable multicast with different acknowledgment mechanisms. In our simulation, the data packet size is 1500 bytes, the ACKs in SPB mechanism have the size of 38 bytes, and the revised ACK packets in the proposed mechanisms have the size of 42 bytes, where 4 bytes are used to record the packet receiving status. For each scenario of parameter setting (number of receivers $M$, Group size $N = 2 \times M$, and link packet loss probabilities), our simulation conducts the multicast transmission of $N \times 10^4$ packets and obtains the ratio of the total number of successfully transmitted data bits ($N \times 10^4 \times 1500 \times 8$ ) to that of the actual transmitted bits (i.e., bandwidth efficiency).

3.2.1 Environments with Only Random Packet Loss

We first investigate the performance of different acknowledgment mechanisms in the wireless networks which suffer from only random packet loss (no long deep fade). The packet losses at each receiver are independent and follow the Bernoulli distribution. The packet losses at different receivers are also independent.

![Figure 3.4 Bandwidth efficiency packet loss rate](image)

Figure 3.4 Bandwidth efficiency packet loss rate
Figure 3.4 shows bandwidth efficiencies of traditional non-coding multicast scheme and coding-based multicast schemes with different acknowledgment mechanisms, under different packet loss rates. First, we can clearly see that for each scheme, the bandwidth efficiency decreases as the packet loss rate increases. High packet loss rate will lead to many retransmissions and thus low bandwidth efficiency. These curves clearly show that even when the packet loss rate is very low there is a significant impact on the bandwidth efficiency. For example, when using the traditional non-coding scheme, the bandwidth efficiency is 0.83 in the absence of packet losses. When the packet loss rate is 0.05 the bandwidth efficiency decreases by 35.2%. Second, compared to the traditional non-coding scheme, the available network-coding-based scheme with SGB acknowledgment mechanism can greatly improve the bandwidth efficiency by using network coding technique for loss recovery. This bandwidth efficiency improvement ranges from several percents to over 40%.

![Figure 3.5 Bandwidth efficiency versus number of receivers](image)

However, when adopting our proposed GB mechanism and ARGB mechanism, the bandwidth efficiency improvement can be further greatly improved. For example, in the scenario where packet loss rate is 0.35, the network-coding-based schemes with GB or ARGB mechanism can further improve bandwidth efficiency by about 35% as compared
with the available network-coding-based scheme. In addition, GB mechanism outperforms ARGB mechanism when the packet loss rate is small. This is because in this case GB mechanism has a little more pseudo packet losses, but has much fewer ACK packets than ARGB mechanism. GB mechanism and ARGB mechanism achieve almost the same bandwidth efficiency when the packet loss rate is not small.

Figure 3.5 shows bandwidth efficiencies of different reliable multicast schemes under different number of receivers. Similar conclusions can be drawn from this figure. Compared to the traditional non-coding scheme, the available network-coding-based scheme with SPB mechanism can greatly improve the bandwidth efficiency by using network coding technique. However, when adopting our proposed GB or ARGB mechanism, the bandwidth efficiency improvement can be further greatly improved.

3.2.2 Environments with Both Random and Bursty Packet Loss

In some wireless networks, due to some factors like buildings blockage, bursty errors (long deep fade) also exist on wireless channels as well as random errors. When a packet is in a deep fade, almost all of the data in the packet are corrupted and thus this packet is lost.

![Bandwidth efficiency comparison of using GB mechanism and ARGB mechanism, in the wireless networks with long deep fades.](image)

Figure 3.6 Bandwidth efficiency comparison of using GB mechanism and ARGB mechanism, in the wireless networks with long deep fades.
Now we investigate the performance of different acknowledgment mechanisms in this type of wireless networks. In our simulation, each packet will experience the deep fade with a probability $p_F$, and once one packet experience the deep fade its consequent 9 packets also experience the deep fade (i.e., will be lost).

Figure 3.6 shows the bandwidth efficiency of using GB mechanism and ARGB mechanism in the wireless networks with long deep fades. We can clearly see that in this type of wireless networks, GB mechanism outperforms ARGB mechanism. Take the case of $p_F = 0.02$ as the example. When the random packet loss rate is 0.2, compared to using ARBB mechanism, using GB mechanism enhances the bandwidth efficiency by 8.8%.

Figure 3.7 Bandwidth efficiency versus packet loss rate $M = 8$, $N = 16$ and $p_F = 0.02$.

Figure 3.7 and Figure 3.8 show the bandwidth efficiency of the non-coding multicast scheme and the network-coding-based schemes with different acknowledgment mechanisms. From two graphs, the similar conclusion we can draw is that GB mechanism can achieve higher bandwidth efficiency than ARGB mechanism in the wireless networks.
with intermittent deep fades. Compared to ARGB mechanism, the bandwidth efficiency improvement from using GB mechanism can be as large as 10%.

![Figure 3.8](image)

**Figure 3.8** Bandwidth efficiency versus number of receivers. Packet loss rate is 0.3

### 3.2.3 Comparison between Available Scheme and Proposed Scheme

There already exists one coding-based reliable scheme proposed by D. Nguyen, et al. [24]. There are two differences between this one and our proposed schemes.

First we consider different scenarios. The existing scheme assumes that all the ACK/NAKs are instantaneous (never be lost). In contrast, for the first time, we investigate network coding-based reliable wireless multicast scheme under the condition that the acknowledgments packets (ACKs) suffer from loss.

Second in the existing scheme, during the retransmission phase, the sender forms a new packet by XORing a maximum set of the lost packets from different receivers before
retransmitting this combined packet for all the receivers. It has been proved in [33] that, 
maximizing the number of lost packets for XORing, which is the key part of existing 
scheme, is actually a complex NP-complete problem. Clearly we can know the coding 
algorithm has exponential complexity. On the other hand, as above we have talked that our 
proposed schemes have polynomial complexity.

We conduct simulations under the scenarios both ACKs never be lost and can be lost. 
And investigate the bandwidth efficiency under different packet loss rates.

\[ \text{Figure 3.9} \] Comparison between available coding-based scheme and proposed scheme. ACK 
packet loss rate \( p_a = 0 \).

Let \( p_a \) denotes the ACK packet loss rate. \textbf{Figure 3.9} shows that when \( p_a = 0 \), our proposed 
schemes have almost the same bandwidth efficiency. And the two schemes can slightly 
outperform the available high-complexity coding-based one. For example, in the 
environment of \textbf{Figure 3.9}, compared to the available coding-based scheme the proposed 
coding based scheme can improve the bandwidth efficiency by 13\% when \( p_i = 0.6 \).
In **Figure 3.10** it can be clearly observed that our proposed schemes have higher bandwidth efficiency than the available scheme. Especially our proposed coding-based scheme with GB mechanism has a significant improvement than the available coding-based scheme. For example, in the environment of **Figure 3.10**, compared to the available coding-based scheme the proposed coding-based scheme with enhanced ACK can improve the bandwidth efficiency by 29% when $p_i=0.3$.

### 3.3 Summary

In this chapter we presented two acknowledgment mechanisms for network coding-based wireless reliable multicast. In these two mechanisms, rather than acknowledging only one data packet, each ACK packet acknowledges all previous received data packets of the current group such that the feedback loss is effectively mitigated. Simulation results demonstrate that compared to the acknowledgment mechanism in the current network-coding-based wireless reliable multicast, the bandwidth efficiency improvement achieved by using proposed mechanisms can be as large as 40%.
Among these two mechanisms, the first one can achieve better performance over the second one in the wireless networks with long deep fade, while the second one can outperform the first one in the wireless networks without intermittent long deep fades.
Chapter 4

Conclusion and Future Work

Until now all of the network coding-based schemes on reliable multicast over wireless networks based on the assumption that each receiver can send ACK timely and successfully to the source node. Different from these schemes, for the first time, we investigate network coding-based reliable wireless multicast scheme under the condition that the acknowledgments packets (ACKs) should be lost. Based on this thought, in this research, we focus on the network coding-based recovery scheme for reliable one-hop multicast in wireless networks. The thesis contributions are summarized below.

4.1 Restatement of The Main Proposals and Contributions

- Application of network coding technique

We apply network coding technique to wireless reliable multicast where ACKs will loss and design a network coding-based reliable multicast scheme to reduce retransmissions caused by packet loss, aiming to address how to apply network coding in reliable wireless multicast to achieve high-level bandwidth efficiency. Specifically, we present an efficient heuristic algorithm for finding an approximately optimal solution of in terms of the number of packets for coding. We conduct extensive simulations under different parameter settings. The advantage of the proposed scheme over the traditional wireless multicast is shown through simulations. The scheme can efficiently improve the bandwidth efficiency by reducing retransmissions which caused by data packets loss.

- Enhanced reliable multicast scheme with new acknowledgement mechanism

Further challenge the problems of dealing with the ACK-loss problem in practice. In our research, we presented two acknowledgment mechanisms for network coding-based wireless reliable multicast. Effectively solve the problem that unnecessary retransmissions caused by ACK loss. In these two mechanisms, rather than acknowledging only one data
packet, each ACK packet acknowledges all previous received data packets of the current group such that the feedback loss is effectively mitigated. Simulation result demonstrates that compared to the acknowledgment mechanism in the current network coding-based wireless reliable multicast, the bandwidth efficiency improvement achieved by using proposed mechanisms can be as large as 40%. Among these two mechanisms, the first one can achieve better performance over the second one in the wireless networks with long deep fade, while the second one can outperform the first one in the wireless networks without intermittent long deep fades.

4.2 Future Work

In the thesis, we studied the application of network coding in wireless reliable multicast and proposed a group-based acknowledgment mechanism. The future work will focus on the following issues:

- Notice that all the previous and our coding-based reliable multicast schemes do not take the packet delay issue into account. The delay is not so important for some applications like file distribution. However, for some applications like real-time stock quotes, the delay is an important performance metric. Thus, we believe that it is worth our effort to design delay-guaranteed schemes and the packet delay should be used as one of performance metrics to evaluate network coding-based reliable multicast schemes.

- As we emphasized before that there exists the ACK explosion problem in multicast communication, which makes the multicast schemes not scalable to large multicast groups. Although we made the first attempt to address problem, the design of a simple and effective acknowledgment mechanism is still an important issue in the network coding-based multicast.

- We have noticed that in some wireless networks, due to some factors bursty errors (long deep fade) also exist on wireless channels as well as random errors. In our algorithms, we did not consider about how to efficiently deal with the bursty errors, and only conducted some simulations under such kind of scenario. One possible
solution for this problem is that design a receiver-cooperative scheme. In the receiver-cooperative scheme, for the receiver suffering from bursty losses, we can select one near neighbor receiver whose loss rate is not large and let this selected neighbor receiver send the received packets to this receiver. More careful consideration on this problem can be the future work.

- To the best of my knowledge, it is impossible to recover more than one lost packets at one receiver by one retransmission. However, we might can further reduce the retransmissions by conducting network coding in more general coding operations (i.e., in a larger finite field than GF(2)), which can combine together the lost packets which have comment intended receivers.
References


exchanges in wireless mesh networks,”, in WiMesh, 2006.


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