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Diversity and Network Coded 5G Wireless Network Infrastructure for Ultra-Reliable Communications

Nabeel Ibrahim Sulieman
University of South Florida, engnis@gmail.com

Diversity and Network Coded 5G Wireless

Network Infrastructure for Ultra-Reliable Communications

by

Nabeel Ibrahim Sulieman

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Department of Electrical Engineering
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University of South Florida

Major Professor: Richard D. Gitlin, Sc.D.
Nasir Ghani, Ph.D.
Zhuo Lu, Ph.D.
Srinivas Katkoori, Ph.D.
Gabriel Arrobo, Ph.D.

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DEDICATION

To my parents, Ameena and Ibrahim, who have taught me invaluable lessons; my beloved wife, Azhaar, who supported me each step of the way; my children, Hasan, Hussein, and Fatima Al-Zahraa, who are my motivation to give and be amongst the best; my siblings, Najlaa, Sulieman, Najwa, Mustafa, Zaineb, and Mohammed, who have helped me whenever I needed them.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This dissertation is directed towards improving the performance of 5G Wireless Fronthaul Networks and Wireless Sensor Networks, as measured by reliability, fault recovery time, energy consumption, efficiency, and security of transmissions, beyond what is achievable with conventional error control technology. To achieve these ambitious goals, the research is focused on novel applications of networking techniques, such as Diversity Coding, where a feedforward network design uses forward error control across spatially diverse paths to enable reliable wireless networking with minimal delay, in a wide variety of application scenarios. These applications include Cloud-Radio Access Networks (C-RANs), which is an emerging 5G wireless network architecture, where Remote Radio Heads (RRHs) are connected to the centralized Baseband Unit (BBU) via fronthaul networks, to enable near-instantaneous recovery from link/node failures. In addition, the ability of Diversity Coding to recover from multiple simultaneous link failures is demonstrated in many network scenarios. Furthermore, the ability of Diversity Coding to enable significantly simpler and thus lower-cost routing than other types of restoration techniques is demonstrated.

Achieving high throughput for broadcasting/multicasting applications, with the required level of reliability is critical for the efficient operation of 5G wireless infrastructure networks. To improve the performance of C-RAN networks, a novel technology, *Diversity and Network Coding (DC-NC)*, which synergistically combines Diversity Coding and Network Coding, is introduced. Application of DC-NC to several 5G fronthaul networks, enables these networks to provide high throughput and near-instant recovery in the presence of link and node failures. Also, the

application of DC-NC coding to enhance the performance of downlink Joint Transmission-Coordinated Multi Point (JT-CoMP) in 5G wireless fronthaul C-RANs is demonstrated. In all these scenarios, it is shown that DC-NC coding can provide efficient transmission and reduce the resource consumption in the network by about one-third for broadcasting/multicasting applications, while simultaneously enabling near-instantaneous latency in recovery from multiple link/node failures in fronthaul networks. In addition, it is shown by applying the DC-NC coding, the number of redundant links that uses to provide the required level of reliability, which is an important metric to evaluate any protection system, is reduced by about 30%-40% when compared to that of Diversity Coding.

With the additional goal of further reducing of the recovery time from multiple link/node failures and maximizing the network reliability, DC-NC coding is further improved to be able to tolerate multiple, simultaneous link failures with less computational complexity and lower energy consumption. This is accomplished by modifying Triangular Network Coding (TNC) and synergistically combining TNC with Diversity Coding to create *enhanced DC-NC (eDC-NC)*, that is applied to Fog computing-based Radio Access Networks (F-RAN) and Wireless Sensor Networks (WSN). Furthermore, it is demonstrated that the redundancy percentage for protecting against n link failures is inversely related to the number of source data streams, which illustrates the scalability of eDC-NC coding. Solutions to enable synchronized broadcasting are proposed for different situations.

The ability of eDC-NC coding scheme to provide efficient and secure broadcasting for 5G wireless F-RAN fronthaul networks is also demonstrated. The security of the broadcasting data streams can be obtained more efficiently than standardized methods such as Secure Multicasting using Secret (Shared) Key Cryptography.

CHAPTER 1: INTRODUCTION

Contemporary wireless and mobile communications began in the last century with a focus on voice communications, and in this century has grown to be the primary, and pervasive, form of communications for many applications such as voice, video and data. Wireless is also projected to be the dominant mode of communication for the emerging domains of the Internet of Things (IoT), Machine to Machine communications (M2M), and many more applications involving healthcare, automobiles, sensor networks, etc. Wireless and mobile communication systems have become the principle means to access information for many people (and machines). According to the Ericsson Mobility Report (November 2017), total global mobile data traffic is expected to reach around 110 Exabytes[1] (EB) per month by the end of 2023, which is 8 times more than that at November 2017 [1]. Simply put, this requires a huge increase in network capacity and reliability, which requires needs new technologies to deploy in the radio access networks in such a way that this amount of data traffic can be reliably delivered to the end user. Cloud Radio Access Networks (C-RANs) [2]-[4] and Fog-Computing-Based Radio Access Networks (F-RANs) [5]-[7] are examples of such technologies. Several applications in 5G wireless communication systems are required to be ultra-reliable, very efficient, and secure with ultra-low latency delivery and recovery time from link and/or node failures [8]. One of the principal factors that decreases network reliability, as well as the system throughput, and increase end-to-end communication delay is the link/node failure. Ultra-reliable, efficient, and very rapid recovery from link/node failures will be required for several applications in 5G (Fifth Generation) mobile communication systems, and solutions need to be

[1] An exabyte (EB) is a billion gigabytes.

developed to address these challenges. Near-instantaneous restoration from link/node failures is essential to improve reliability, efficiency, and enable very low delay networking.

1.1 Radio Access Networks

A radio access network (RAN) is that part of a mobile telecommunication system that implements a radio access technology, that is the air interface with data and control functionality, in a base station (or collection of base stations) and a plurality of mobile phones. The RAN provides connectivity between the mobile and the core network (CN) that interfaces with external networks such as the Internet. A group of base stations in a serving are connected to the core network via a backhaul network, where baseband processing and radio functions are combined within a base station and connected to each other by coaxial cables as shown in Figure 1.1 [4]. Due to the high demand for increasing the network capacity, traditional RANs require the deployment of more base stations, which in turn increases the Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) costs. CAPEX represents the network construction expenditure, including but not limited to RF hardware, civil engineering cost, installation, and software licenses [9]. OPEX refers to the cost of operation, maintenance, upgrading, electricity, and site rental [9]. Not only CAPEX and OPEX will increase by deploying additional base stations, the required amount of power to operate these base stations will also increase dramatically [2].

Cloud Radio Access Networks (C-RANs) were proposed in [2]-[3] to overcome the above challenges. In addition, the C-RAN networks have the ability to enable high bandwidth, accurate synchronization, and very low latency. Therefore, it is considered as one of the evolving 5G wireless network architectures in which distributed Remote Radio Heads (RRHs) are connected to a centralized baseband unit (BBU) via a fronthaul network [2]-[4].

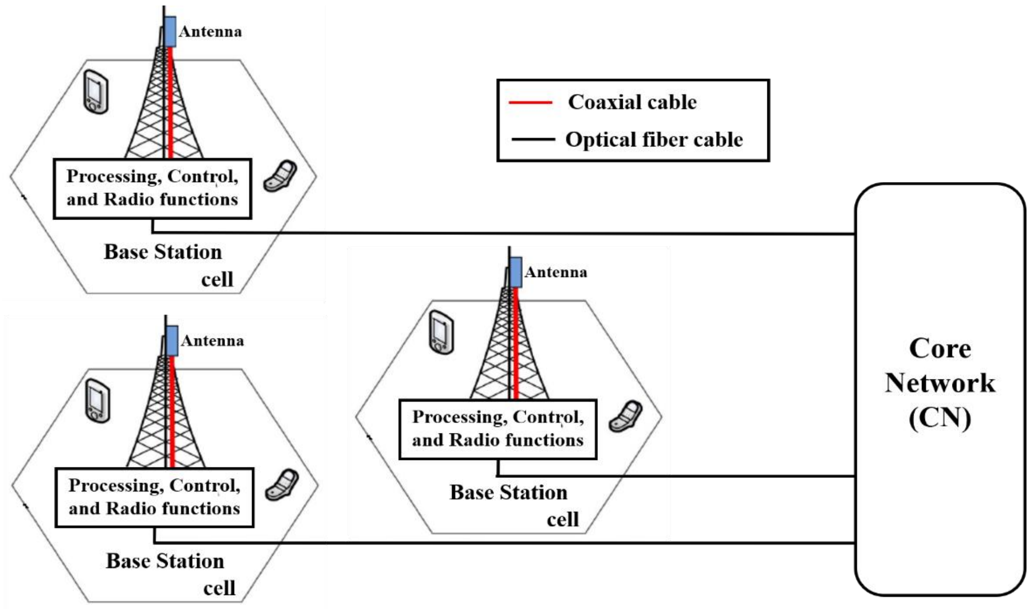


Figure 1.1 Radio Access Network (RAN). [4] © 2015 IEEE. Adapted with permission.

Although the C-RAN architecture solved several challenges, it still has its own challenges such as a restricted centralized baseband unit pool. Fog-Computing-Based Radio Access Networks (F-RANs), which is an enhancement and an alternative to C-RAN, was proposed in [5]-[7] to overcome these problems. The key idea of F-RAN is to employ edge nodes with the ability to store data, control signals, and communicate to each other instead of centralizing processing in the baseband unit (BBU) at the C-RAN. [5]-[7].

1.1.1 Cloud Radio Access Network

The C-RAN separates base station functions into two main parts: the centralized processing and control functions that are processed in the BBU, and the radio functions that are handled by the distributed RRHs located at the cell sites [2]-[4], [10]-[11] as depicted in Figure 1.2 [2]. C-RANs are expected to minimize operating costs, decreases power consumption, and improve spectral efficiency due to its interference management capabilities [2]-[4], [10]-[11]. The main features of C-RAN network are [2]-[4]:

- Flexibility,
- Scalability,
- Adaptability to nonuniform traffic,
- Low cost.

Fronthaul networks connect the BBUs pool and the RRHs and can be wired and/or wireless. Optical fiber is often utilized to deploy fronthaul networks since it can provide high speed up to 10 Gigabit per second (Gbps) and long distances up to 40 Kilometers (Km) communication [10]-[12]. However, the availability of installed optical fiber and the new fiber deployment cost are considered as disadvantages of this option [10]-[12]. Wireless fronthaul is expected to play an essential role in C-RANs due to cost savings and easy implementation in a dense environment such as in campuses or stadiums where optical fiber deployment is difficult [2], [10], [12]. However, wireless fronthaul can only handle up to 2.5 Gbps data capacity and short distances up to 1 Km and mixed fiber and wireless fronthaul networks solutions have been contemplated by many operators [12].

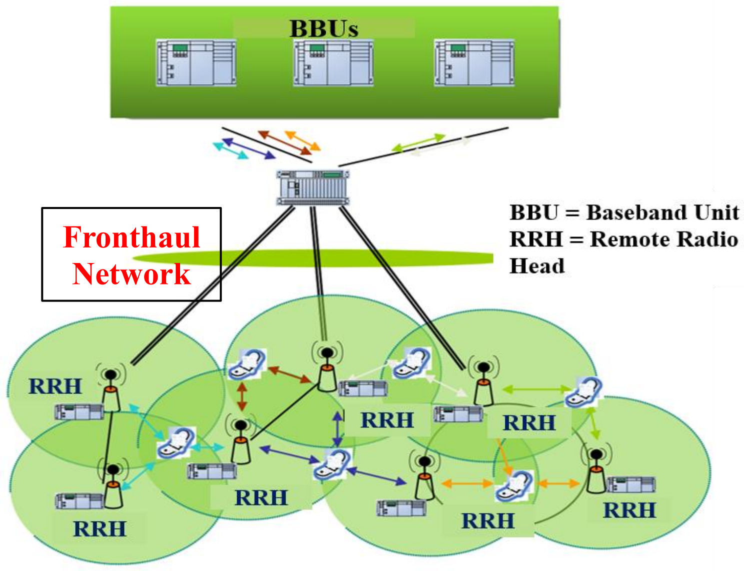


Figure 1.2 C-RAN network architecture. [2] © 2013 China Mobile. Adapted with permission.

In such networks, the RRHs will likely utilize directional antennas or MIMO systems [13] to prevent interference and be able to simultaneously communicate with several RRHs as well as the BBU, in addition to communication with several pieces of user equipment (UEs).

1.1.2 Fog-Computing-Based Radio Access Network

F-RANs were proposed in [5]-[7] to enhance the performance of C-RANs by migrating a significant number of functions to network-edge devices and substantially upgrading the Remote Radio Heads (RRHs). These functions include controlling, communicating, measuring, managing, and data storing and processing. The upgraded RRH is called a Fog Access Point (F-AP), and is able to communicate with other F-APs. One of the benefits of this architecture is decreasing latency by performing functionality at the network edge rather than in the core [5]-[7]. There are three layers in the architecture of F-RANs as illustrated in Figure 1.3 [5]. The network layer contains the BBU pool, centralized storage, and communication and computing cloud. The RRHs and F-APs represent the access layer. The terminal layer includes user equipment (UE) that access RRHs and Fog UE (F-UE) that access F-APs [5]-[6]. Adjacent F-APs can be formed into two topologies: a mesh topology or a tree-like topology. Both topologies can significantly minimize the degrading effects of capacity-constrained fronthaul links [5].

Different transmission modes can be used in a F-RAN such as the C-RAN and Local Distributed Coordination (LDC) modes as illustrated in Figure 1.3 [5]. The core mode for the F-RAN is the LDC mode and the C-RAN mode is similar to that in a C-RAN, where control signals, data storage, and computing processes are centralized in the BBU pool. In LDC, the F-APs communicate with other F-APs to serve the F-UEs. These transmission modes can work together to serve both UEs and F-UEs. For example, when a UE requests data that is stored in one of the F-APs, the RRH will send its request to the BBU then the BBU instead of sending the requested data, which increases the burden on the fronthaul network, will order the F-AP to send the requested data to the UE via the RRH [5]. In this way, the burden on the fronthaul network will be decreased. Hence, the interference can be quickly suppressed, and the required data will be sent to the F-UE and UE (via RRHs) not from the cloud server but from the F-APs [5].

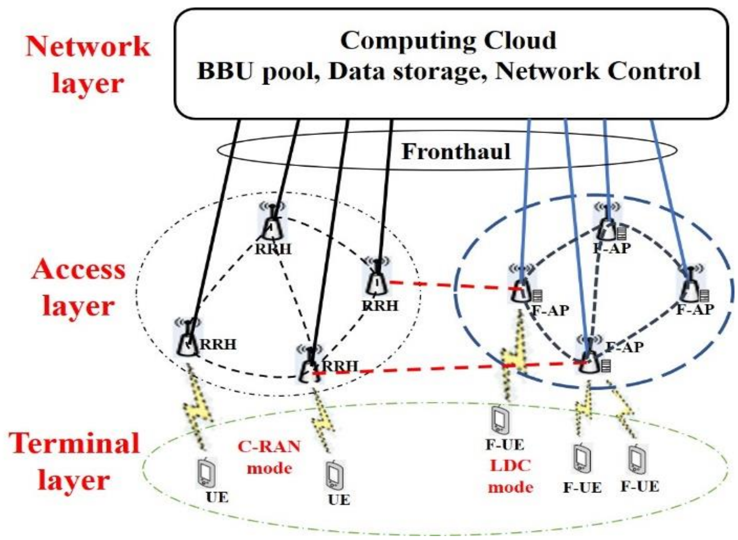


Figure 1.3 F-RAN network architecture. [5] © 2016 IEEE. Adapted with permission.

Similar to fronthaul networks in C-RANs, the fronthaul networks in F-RANs connect the BBUs pool with the RRHs and F-APs and can be wired and/or wireless.

1.2 Wireless Sensor Networks

A Wireless Sensor Network (WSN) is a set of distributed sensors that observes and collects environmental or similar, information and communicates the recorded data to a central position, often referred to as a gateway [14]-[16]. In addition, a WSN might contain one or more gateway nodes (central controllers) and several sensor nodes that are implemented at different locations [14]-[15]. Each sensor node contains a sensor with ability to monitor a specific kind of condition such as temperature, pressure, noise levels, etc. [14]-[15]. A sensor node has the ability to receive and forward the information to the gateway either directly or via other sensor nodes [14]-[15].

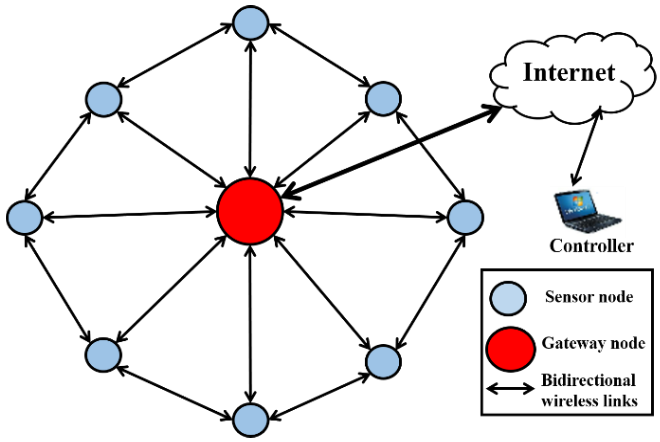


Figure 1.4 Wireless Sensor Network with mesh topology.

The gateway, which works as a bridge between the WSN and the other networks, transmits the collected information to the external network. There are several topologies that can be used to build the WSNs networks such as a star (depicted in Figure 1.4) or mesh topology and a multi-hop wireless mesh topology [14]-[16]. In addition, several wireless techniques can be used for WSN communications such as Zigbee [14], [16]. The WSN can contain a few to several thousands of nodes and a battery is usually utilized as the energy source for these nodes [14]-[16]. Very low energy consumption [14]-[16], as well as increased throughput and ultra-reliability are required for the WSNs [14]. WSNs can be used for different applications, such as healthcare, military (enemy intrusion detection), and smart homes and cities [15].

1.3 Challenges and Constraints in C-RANs, F-RANs, and WSNs

While C-RANs and F-RANs have several advantages that are explained above, they come with their own constraints, which is inherent in the fronthaul network architecture [4]. As mentioned earlier, there are two kinds of fronthaul networks: optical fiber and wireless connections. Although optical fiber is considered more reliable than wireless connections, however, they have limitations in reliability and efficient resource utilization. Since fronthaul networks will deal with very high capacity data transmission and extremely low delay, any link/node failure can effect on the entire network reliability and cause degradation in network throughput.

On the other hand, WSNs suffer from several challenges arising from the wireless sensor nodes. Although these nodes are inexpensive, however, they have limitations in power consumption, computational and processing complexity, and communication capabilities [14]-[17]. Furthermore, they are generally considered as unreliable devices because of their simplicity and how they are deployed (where they may be easily damaged). Moreover, since the power supply of these nodes are generally batteries, a trade-off between their operational lifetime and communication/processing power consumptions must be considered, especially for nodes deployed in inaccessible environments such as the chemical industries or embedded in infrastructures such as bridges, where they are very difficult to replace in case of failure.

Another main parameter in both fronthaul and wireless sensor networks is the traffic characteristics, which is often a real-time traffic in fronthaul networks and some applications of WSNs. Some types of error detection and retransmission techniques, such as Automatic Repeat reQuest (ARQ) cannot be used to achieve reliable transmission because this will increase the network delay for both kinds of networks and increase the burden of fronthaul networks. Therefore, feedforward techniques such as Diversity Coding (DC) [18]-[20] is more appropriate, since it can provide ultra-low delay in fault recovery, at the cost of some redundant transmissions. Regardless of the traffic characteristics, Diversity Coding strives to realize reliable wireless networks using (somewhat) unreliable components such as wireless links and limited resource nodes (RRHs, F-APs, and sensor nodes). As a feedforward network design, Diversity Coding does not need a feedback channel, and consequently enables reliable networking with near-instant recovery from a link failure.

For simplicity, let us assume that we have point-to-point network topology as shown in Figure 1.5 [18], where equal rate data streams $x_1, x_2, \ldots, x_N$ are transmitted over disjoint paths to their destination. Coded data stream c_1, which is equal to the logical XOR summation of the input data streams, is transmitted over another disjoint path. In the case of the failure of link x_i the receiver can immediately use the received data streams and c_1 to form a mod 2 addition between them to recover x_i nearly instantaneously without retransmission and/or rerouting as illustrated in the RX side of Figure 1.5 [18].

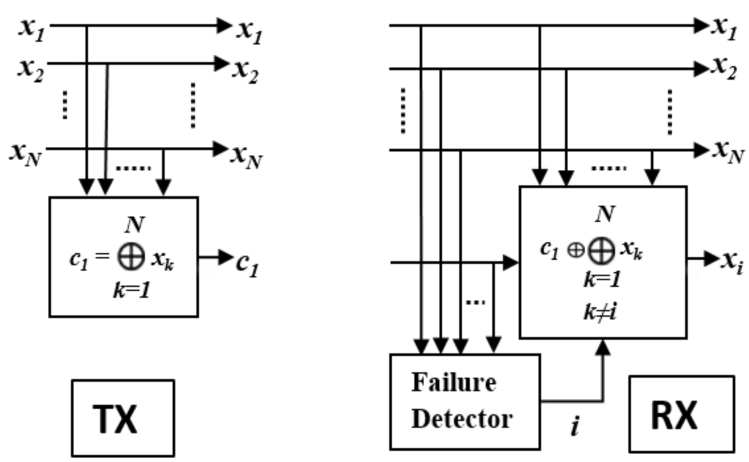
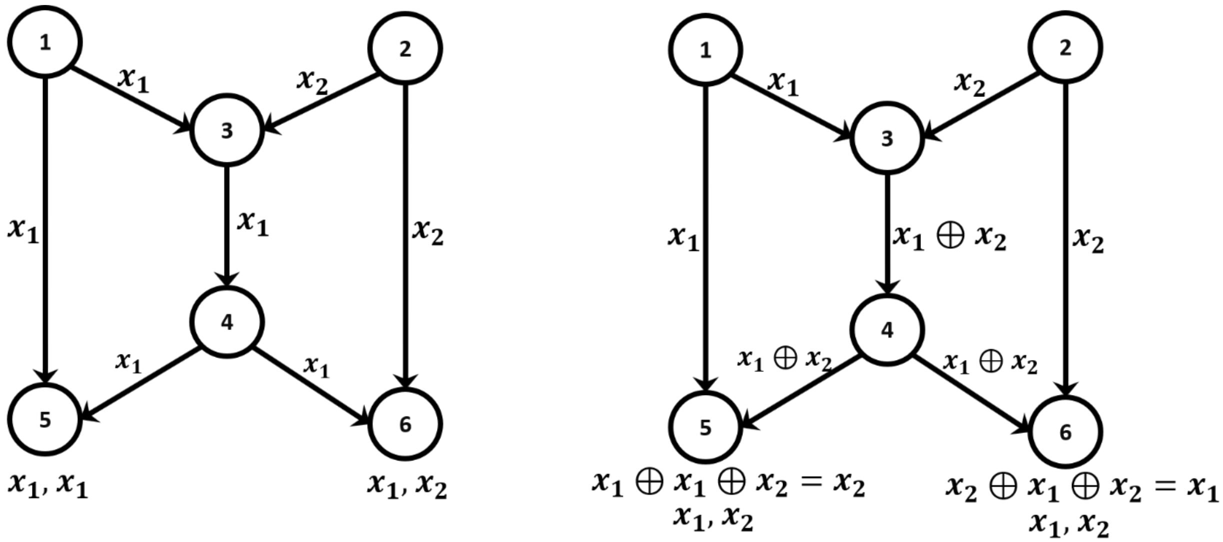


Figure 1.5 The principle of Diversity Coding (DC). [18] © 1993 IEEE. Adapted with permission.

Since C-RANs, F-RANs, and WSNs will often need to broadcast/multicast messages efficiently to several RRHs, F-APs, and sensor nodes respectively, efficient multicasting in wireless networks can be considered as another important challenge in fronthaul and wireless sensor networks. Network Coding [21]-[27], a technology adumbrated from Diversity Coding, can address this challenge by enabling an efficient method of broadcasting information over a lossy wireless medium. Traditionally, to transmit information to several destinations, messages are forwarded or routed from the source node to the destination nodes via the intermediate nodes. For example, if nodes 1 and 2 wants to broadcast data streams x_1 and x_2 respectively to nodes 5 and 6 as shown in Figure 1.6a [21], which represents the well-known butterfly network topology without applying Network Coding, where utilizing direct links, nodes 1 and 2 send x_1 and x_2 respectively to nodes 5 and 6. Node 3 receives x_1 and x_2 then since the central link (connecting nodes 3 and 4) is only able to carry either x_1 or x_2, but not both, node 3 will transmit one of them to node 4 (e.g. x_1). Node 4 sends x_1 to nodes 5 and 6. In this way, node 6 will receive x_1 and x_2, however, node 5 will receive x_1 twice. In this way, the number of transmissions needed for broadcasting messages is increased resulting in increased congestion and decreased throughput. Alternatively, the link emanating from Node 3 can have double the capacity of the other links to carry both x_1 and x_2, with the associated cost. However, in Network Coding, as illustrated in Figure 1.6b [21], the intermediate node (node 3) combines the received data streams, creates coded data stream $(x_1 \oplus x_2)$ and transmits this coded data stream to node 4. Node 5 receives x_1 directly from node 1 and $(x_1 \oplus x_2)$ from node 4, and by forming the mod 2 sum of both streams obtains x_2. Similarly, node 6 receives x_2 directly from node 2 and $(x_1 \oplus x_2)$ from node 4 , and by forming the mod 2 sum of both streams obtains x_1. In this way, the number of transmissions is reduced and the network throughput is increased since fewer transmissions are required to broadcast the required data streams. The features that are provided by Diversity Coding (reliability) and Network Coding (throughput gains) are attractive to increase the performance of different type of networks, especially for wireless fronthaul C-RANs and F-RANs networks who transport real-time traffic and where with high reliability is required.



(a) Without Network Coding (b) With Network Coding (NC)

Figure 1.6 Butterfly network topology. [21] © 2000 IEEE. Adapted with permission.

1.4 Research Motivation

Several time sensitive and high data rate applications such as the Tactile Internet [28] and remote healthcare applications are going to utilize 5G wireless fronthaul, wireless sensor, and other wireless infrastructure, networks. Certainly, one critical element for improving the delivery of required information is the application of technologies that can effectively provide ultra-reliable and highly efficient communications, near-instant recovery form link/node failures, and efficient secure broadcasting. The objectives of this dissertation are to describe and evaluate novel approaches for enhancing reliability, by enabling near-instant recovery from link and node failures, in 5G network infrastructure including Cloud-Radio Access Networks (C-RANs) and Fog-Based-Computing-Radio Access Networks (F-RANs) in addition to Wireless Sensor Networks (WSNs).

5G wireless fronthaul, wireless sensor, and other infrastructure, networks face several research challenges including:

- Being extremely reliable by avoiding a single point of failure and providing near-instant, self-healing capabilities if nodes or links are not operating properly.

- Providing enhanced throughput for broadcasting applications.
- Enabling efficient and secure broadcasting.
- Utilizing low power consumption technology to extend the network's lifetime.
- Extending the prior art of Diversity and Network Coding to mesh and other network architectures.

Since 5G wireless communication systems and time sensitive Wireless Sensor Networks require very low delay in recovering from link and node failures, the most important constraint from our viewpoint is near-instant recovery from any link/node failure.

It is expected that the novel communication techniques presented in this dissertation, will create a paradigm shift in 5G wireless fronthaul, wireless sensor, and other infrastructure, networks to be able to meet the above requirements.

1.5 Contributions and Organization of this Dissertation

The contributions presented in this dissertation are directed towards enhancing the reliability with near-instantaneous fault recovery time, improving throughput, enabling ultra-low energy consumption, and providing efficient secure broadcasting of wireless fronthaul networks in C-RANs and F-RANs and wireless sensor networks. Specific contributions are the following:

- *Application of Diversity Coding to 5G Wireless Fronthaul C-RANs to enable near-instant recover from link and/or node failures* [29]-[30]. The potential applications of Diversity Coding in 5G fronthaul networks where the RRHs in a C-RAN network are connected to the baseband units (BBUs) pool in two scenarios (1) with only wireless links (2) with two tiers of optical and wireless links are presented. In order to avoid retransmissions that incur high transmission and re-routing delays due to link failures in the wireless tier and/or node failures of the fronthaul network, it is demonstrated how

Diversity Coding increases network reliability with near-instantaneous recovery and its ability to recover from multiple simultaneous link failures. In addition, it is shown under what circumstances Diversity Coding could give a lower total routing cost than other types of restoration techniques.

- *The synergistic combination of Diversity and Network Coding (DC-NC) for reliable and efficient broadcasting in wireless fronthaul networks* [31]-[32]. Introduction of a new coding technique, (DC-NC) that synergistically combines Diversity and Network Coding. The performance of DC-NC is evaluated in two 5G fronthaul networks, the first where the RRHs in a C-RAN are connected to the baseband unit with two tiers of optical and wireless links and the second where (most) all RRHs in the C-RAN are connected directly to the BBU via wireless links. In both scenarios, DC-NC coding reduces the required network bandwidth by about 10%-20% and increases throughput by about one-third for broadcasting or multicasting applications, while simultaneously enabling near-instantaneous latency in recovery from multiple link/node failures in fronthaul networks. Also, the number of redundant links is decreased by about 30%-40% by applying DC-NC coding, when compared to that of Diversity Coding. Furthermore, the application of DC-NC coding to downlink Coordinated Multi Point (CoMP) 5G wireless fronthaul networks in a C-RAN is demonstrated to improve performance. In particular DC-NC has the ability to simultaneously recover from multiple link failures when these failures are associated with different RRHs. In addition, DC-NC coding can recover from one intermediate node failure. Furthermore, DC-NC networks can tolerate n link failures for each RRH at the CoMP set that contains j RRHs, where $jn + n$ redundant links are required. In summary, DC-NC coding reduces the resource consumption in the network by about one-third, while simultaneously minimizing the impact on latency of multiple link/node failures in wireless fronthaul network links.

- *Enhanced Diversity and Network Coding, which is the synergistic combination of Diversity Coding and modified Triangular Network Coding for ultra-reliability, efficient broadcasting, and reduced energy cost in wireless fronthaul F-RANs and WSNs networks* [33]-[35]. Further improvement of DC-NC is presented that can tolerate multiple, simultaneous link failures with reduced computational complexity. In this way, reliability will be maximized and the recovery time from multiple link or node failures is dramatically reduced in 5G fronthaul wireless networks. This is accomplished by modifying Triangular Network Coding (TNC) to create enhanced DC-NC (eDC-NC). It is demonstrated that using eDC-NC coding in F-RAN wireless fronthaul networks will provide ultra-reliability and enable near-instantaneous fault recovery while retaining the throughput improvement feature of DC-NC. In addition, a general eDC-NC encoding expression is derived and an explicit algorithm for the eDC-NC decoding process is presented. Furthermore, it is shown that the redundancy percentage for n link failures is inversely related to the number of broadcast data streams, which illustrates the scalability of eDC-NC coding. In addition, the redundancy percentage for complete protection is always less than 50% for the practical cases that were evaluated. Similarly, the application of eDC-NC to improve the performance of WSNs is such that with eDC-NC, WSNs can simultaneously recover from multiple link/node failures nearly-instantaneously with minimum energy consumption. These metrics are very important in evaluating the performance of WSNs.

- *Efficiently Secure Broadcasting in 5G Wireless Fog-Based-Fronthaul Networks* [36]. Demonstrated the ability of eDC-NC technology to more efficiently provide secure message broadcasting than standardized methods such as Secure Multicasting using Secret (Shared) Key Cryptography, such that the adversary has no ability to acquire information even if they wiretap the entire F-RAN network (except of course the source and destination nodes). The security of the broadcasting data streams is obtained with lower security cost compared to that of the standard Secure Multicast protocols. It is shown that using secure eDC-NC technology in F-RAN fronthaul network enhances secure broadcasting and provides ultra-reliability networking, near-instantaneous fault recovery, and retains the throughput benefits of DC-NC.

The dissertation is organized as follows:

- CHAPTER 2 presents a literature review of the error correction techniques, which are the standard approaches for improving the reliability and throughput of networks. Well-known techniques such as Automatic Repeat reQuest (ARQ) and channel coding are briefly summarized. Also, Diversity Coding, Network Coding, and Triangular Network Coding, which are the basis for the novel techniques used throughout this dissertation, are described.
- CHAPTER 3 describes the application of Diversity Coding to Wireless fronthaul networks in C-RANs.
- Improving the performance of wireless fronthaul networks in C-RANs using the synergistic combination of Diversity and Network Coding in addition to the application of DC-NC to CoMP systems in C-RANs are presented in CHAPTER 4.

- CHAPTER 5 describes a novel Enhanced Diversity and Network Coding approach to provide ultra-reliability with near-instant fault recovery and efficient broadcasting with less energy consumption in wireless fronthaul F-RANs and WSNs.
- A demonstration of the ability of a new coding technique (eDC-NC) to provide efficient secure message broadcasting in wireless fronthaul networks is described in CHAPTER 6.
- CHAPTER 7 summarizes the research contributions in this dissertation (Chapters 3 to 6), along with recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Error Control

This chapter provides an overview of classic link error control and then provides a tutorial review of prior work in network coding technologies, such as Diversity Coding and related technologies, which create reliable networks that feature near-instant recovery from link and/or node failures. This family of network coding technologies use innovative error control technology to complement the classic encoding of data links in the time domain, by creating spatially, or logically, encoded diverse routes to achieve reliable networks.

Reliable data transmission from one node to one or more nodes is the goal of any wireless, or other, communication system. Due to several wireless channels impairments such as fading and interference, wireless channels are generally considered as unreliable communication channels, relative to other media such as optical fiber, which means frequent errors in transmitted data are expected. Different forms of errors can occur, such as burst errors because of deep fades that persist on wireless channels or isolated single bit error caused by thermal noise, interference, or other impairments. Error control has been used for about 70 years to address this situation and consists of two fundamental approaches Error Detection and Error Correction. Error Detection and retransmission, which detects errors and uses retransmission, is appropriate for data applications where errors at the receiver, after retransmission, are not acceptable. Error Correction, often referred to as Forward Error Control (FEC), is used in applications which are more robust to errors and where delay must be minimized (as in real-time applications such as speech and video applications). Error control may be applied to both link-by-link or end-to-end connections. Many error detection and correction techniques have been developed to enable wireless reliable transmission such as Cyclic Redundancy Check (CRC) error detecting codes and Convolutional error correcting codes [37], [38] respectively.

Not only is reliability very important in communication networks, but throughput is a related and another important factor that effects network performance. In addition, many wired and wireless networks broadcast/multicast messages to a group of receivers, which could have reduced throughput because of the limitation of link capacity.

This dissertation is directed towards the network application of novel network error control technology to achieve reliable networking in the presence of link and/or node failures. The underlying links may use error detection to indicate link/node failures and error correction techniques such as Convolutional Codes [38]-[39] and Polar Codes [40]. The networking technologies that are addressed in this research, such as Diversity Coding [18]-[20], are overlaid on top of the classic error-controlled links across spatially diverse paths to provide a feedforward, near-instant, and robust recovery mechanism from link and/or node failures. Additionally, this research is focused on efficient broadcasting/multicasting techniques at the networking level. In particular, Diversity Coding [18]-[20], Network Coding [21], and Triangular Network Coding [27] are investigated and extended in this dissertation and applied to several wireless networking scenarios.

An overview of classic error control techniques is presented below.

2.2 Classic Error Control Techniques

Error control techniques [37]-[41] are well known and implemented by adding redundant bits to the data message for detecting and correcting the errors that occur during the transmission from the transmitter to the receiver via an unreliable channel.

2.2.1 Error Detection via Cyclic Redundancy Check (CRC) Codes

A Cyclic Redundancy Check (CRC) is a block code, which is also called a polynomial code, where a shift register is used to perform the encoding and decoding processes in error detection. Frames of n bits are represented as coefficients of polynomial ranging from x^{n-1} to x^0. The generator polynomial $g(x)$ that has a degree denoted by c is known at both the sender and receiver. A CRC with c check bits can detect burst errors of length equal to or less than c bits. The CRC is a very efficient technique, and easy to implement, and it is widely used in (wireless) communication systems [41].

2.2.2 Error Correction [Forward Error Control (FEC)]

When errors occur in the transmitted information, error correction techniques strive to recover the original (source) information at the destination without relying on retransmission. Such Feedforward Error Control (FEC) techniques add redundant bits to the original data in such a way that, under most circumstances, the data can be recovered at the receiver. This is appropriate for broadcasting and real-time applications, where no information may be retransmitted. Classic FEC has evolved from early Block Codes and Convolutional Codes, to today's advanced Turbo Codes, Low Density Parity Check Codes (LDPC) [37]-[39], and Polar Codes [40].

2.2.2.1 Linear Block Codes

These codes are processed on a block-by-block basis, where a block of n coded bits is generated from k data bits. Since each block contains n bits, there are 2^k possible codewords among the 2^n possible received blocks of n bits. The coding rate of a block code is $R = \frac{k}{n}$.

The number of errors that the block code decoder can correct is given by:

$$t = \left\lfloor \frac{n-k+1}{2} \right\rfloor \qquad (2-1)$$

where $\lfloor x \rfloor$ is the largest integer smaller than or equal to x.

2.2.2.2 Hybrid ARQ (HARQ) Techniques

To get the benefits of both ARQ and FEC systems, these two error control methods may be combined in hybrid ARQ [42]-[43], which has been dubbed HARQ. FEC is utilized to decrease the frequency of retransmission by correcting some errors that occur most frequently using redundancy bits, whereas ARQ is utilized when errors are detected and cannot be corrected by FEC.

In the standard ARQ communication system, a message is encoded by adding a number of parity bits as error detection codes and then transmitted to the receiver [44]. In HARQ, the message is coded via FEC and parity check bits are either transmitted separately when the receiver detects errors and request retransmission or added to the coded bits before transmission.

2.3 Coding for Networks

As noted above, in this dissertation, the novel use of "classic" error control concepts, such as Diversity Coding [18]-[20], are utilized in various network topologies, to provide reliable communications in the presence of link and node failures. We will refer to this approach as *network coding* to distinguish it from classic link-by-link *channel coding.* As will be demonstrated network coding technologies such as Diversity Coding and Network Coding, can not only provide reliable communications, but other benefits can be achieved such as maximizing network throughput, reducing bandwidth, and increasing network capacity for broadcasting/multicasting applications. In this dissertation, such concepts will be extended and applied to a wide variety of emerging wireless network applications.

2.3.1 Diversity Coding

Diversity Coding is a feed-forward network technique, that uses classic link-by-link error control in a novel way across spatially, or logically, diverse channels to recover from link and/or node failures, and is the main technique investigated throughout this dissertation to improve the reliability of fronthaul and wireless sensor networks. This section describes in detail the advantages of this technique and how it works.

Diversity Coding (DC) [18]-[20] enables robust and reliable networking with near-instant and self-healing recovery from link and/or node failure(s). The feedforward network design uses forward error control across spatially diverse paths that complements the conventional use of classic error control coding in the time domain in the network links. Of course, increased transmission facilities are required. As an example, a Diversity Coding system uses a parity check code for a point-to-point network topology with N data lines and 1 protection line was shown in Figure 1.5 [18], where equal rate data streams $x_1, x_2, \dots, x_N$ are transmitted over disjoint paths to their destination. Parity coded data c_1 equal to

$$c_1 = x_1 \oplus x_2 \oplus \dots \oplus x_N = \bigoplus_{k=1}^{N} x_k \qquad (2-2)$$

is sent on a disjoint route, where $\oplus$ represents the XOR function and the extra link $N+1$ carries the checksum c_1. If a failure occurs in the data stream x_i, then when the receiver detects the line/channel with failure, the receiver can recover x_i easily and quickly by forming:

$$c_1 \oplus \bigoplus_{\substack{k=1 \\ k \neq i}}^{N} x_k = x_i \qquad (2-3)$$

Consequently, by using just one extra link, x_i is recovered, nearly instantaneously, without retransmission, rerouting, or providing a feedback channel. It should be clear that more sophisticated error control, beyond the simple parity check code in the above example, could be used.

As shown in (2 – 2), to implement a $1 - for - N$ Diversity Coding system, one bit is enough (i.e. the minimum number of bits) to be carried at each link because with one bit, a Galois Field of up to two elements $\{0, 1\}$, $GF(2^1)$ can be calculated [18]. The number of coded data streams (protection links) is limited by the number of bits per link (per symbol) in the raw data stream. That is, the larger the number of bits to be carried by each link, the larger the number of coded data streams (i.e., protection links). The number of coded data streams is limited to the Galois Field $[GF(2^m)]$, where $m > 1$ is used to calculate the information that is carried by the protection links.

The above technique can be extended to protect the communication network from simultaneous multiple link failures. For a *M-for-N* Diversity Coding system, the coded data streams are calculated as [18]

$$c_i = \sum_{j=1}^{N} \beta_{ij} x_j \qquad i \in \{1, 2, \dots, M\} \qquad (2-4)$$

where c_i and x_j are the Diversity Coded and raw (uncoded) data streams, respectively, and β_{ij} is the parity generator matrix associated with the coded bits, c_i. In coding theory, the parity generator matrix is used to describe the linear relations that the components of a codeword must satisfy. It can be used to decide whether a received vector is a codeword in the decoding algorithm. Note that multiplication corresponds to the AND operation and summation corresponds to the XOR operation since these are performed in $GF(2^m)$.

The parity generator matrix coefficients are given by:

$$\beta_{ij} = \alpha^{(i-1)(j-1)} \qquad (2-5)$$

where α is a primitive element of a Galois Field $GF(2^m)$, $i = \{1, 2, \dots, M\}$, and $j = \{1, 2, \dots, N\}$.

The total number of transmitted data streams is equal to the number of raw data streams plus the number of coded data streams $(N + M)$, where the number of coded data streams is equal to or less than the number of raw data streams $(M \leq N)$.

At the receiver side, when there is no link failure, the receiver ignores the coded data streams and there is no need for any decoding process. However, in the case of detected link failures, assume that $f_1, f_2, \ldots, f_n$ are the indices of the failed links, where $1 \leq n \leq M$. The receiver generates $\tilde{c}_i$ as follows:

$$\tilde{c}_i = c_i \oplus \sum_{\substack{j=1 \\ j \neq f_1, f_2, \ldots, f_n}}^{M} \beta_{ij}\, x_j \qquad 1 \leq i \leq n \qquad (2-6)$$

The quantity $\tilde{c}_i$ can be easily obtained because β_{ij} are fixed and known at the receiver and x_j for $1 \leq j \leq N, j \neq f_1, f_2, \ldots, f_n$ are available. By applying (2 – 4) to (2 – 6), we obtain

$$\tilde{c}_i = \sum_{j = f_1, f_2, \ldots, f_n} \beta_{ij}\, x_j \qquad 1 \leq i \leq n \qquad (2-7)$$

The coded data streams that generated at the receiver are used to recover the n lost data streams via an inverse linear transform. The parameters of β_{ij}'s should be chosen such that they are linearly independent. This can be determined from the determinant of the matrix $[\beta_{f,j}]_{n\times n}$. Let

$$m = \lceil \log_2(N + 1) \rceil \qquad (2-8)$$

where N is the total number of raw data links and $\lceil y \rceil$ is the smallest integer greater than or equal to y. Since the $[\beta_{f,j}]_{n\times n}$ is a Vandermonde matrix, hence using linear algebra, the well-known result is [18]

$$\det[\beta_{f,j}]_{n\times n} = \prod_{1 \leq j < i \leq n} (\alpha^{f_i - 1} - \alpha^{f_1 - 1}) \qquad (2-9)$$

It is clear that the result of any entries in the product in (2 – 9) cannot be zero because the additive inverse of a member in $GF(2^m)$ is itself i.e. $\alpha^{f_i - 1} = \alpha^{f_1 - 1}$ if and only if $j = i$. Therefore,

$$\det[\beta_{f,j}]_{n\times n} \neq 0 \qquad (2-10)$$

Hence, the inverse of the parity generator matrix exists, and the lost data streams can be recovered as follows:

$$\begin{pmatrix} x_{f_1} \\ x_{f_2} \\ \vdots \\ x_{f_n} \end{pmatrix} = [\beta_{f,j}]_{n\times n}{}^{-1} \begin{pmatrix} \tilde{c}_1 \\ \tilde{c}_2 \\ \vdots \\ \tilde{c}_n \end{pmatrix} \qquad (2-11)$$

Diversity Coding can be applied to other network topologies in addition to point-to-point networks such that the transmitting and/or receiving nodes are not common; Figures 2.1 – 2.3 [18] illustrate the point-to-point with a *M–for–N* DC system, multipoint-to-point and multipoint-to-multipoint topologies respectively, where ***c*** denotes the vector of diversity coded data streams:

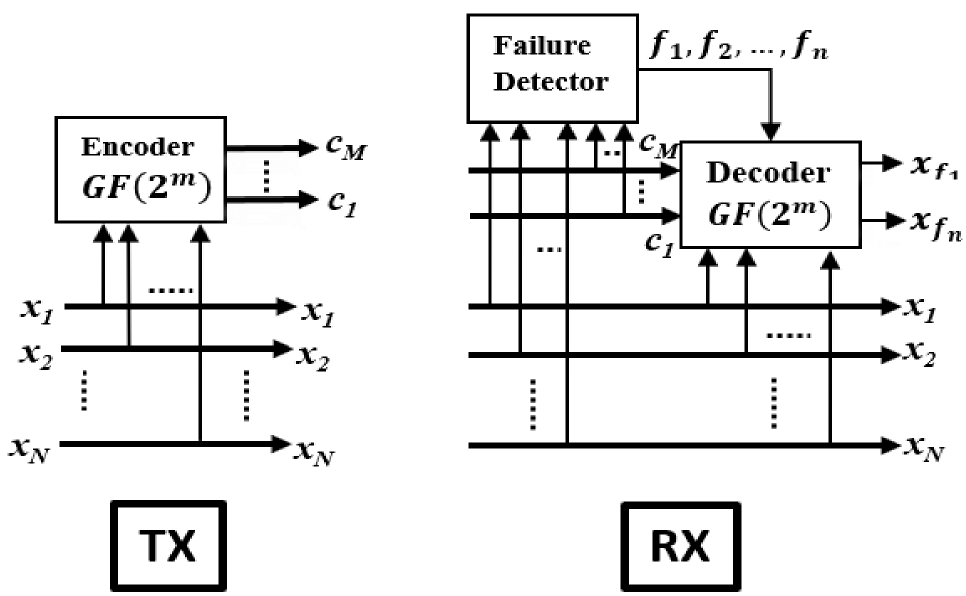


Figure 2.1 Point-to-point network topology with *M* for *N* Diversity Coding. [18] © 1993 IEEE. Adapted with permission.

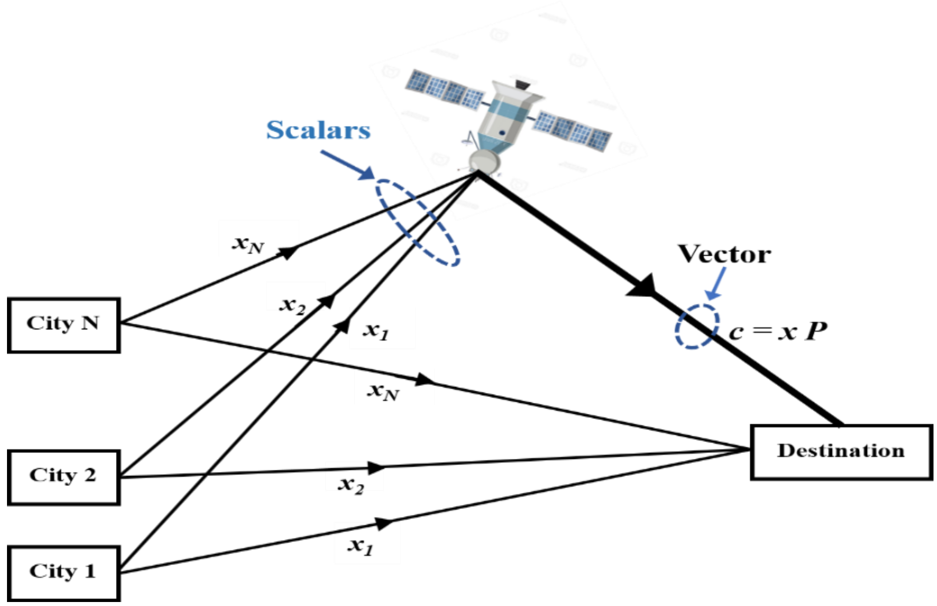


Figure 2.2 Multipoint-to-point Diversity Coding network topology. [18] © 1993 IEEE. Reprinted with permission.

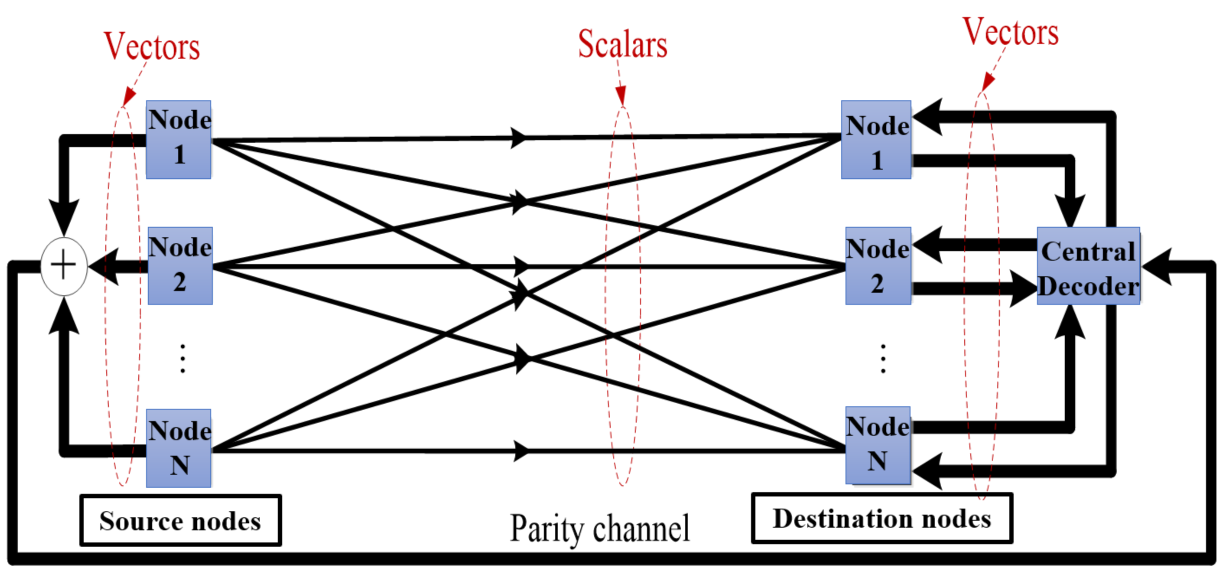


Figure 2.3 Multipoint-to-multipoint Diversity Coding network topology. [18] © 1993 IEEE. Reprinted with permission.

In multipoint-to-multipoint Diversity Coding network topology, the protection routes from each source node form a vector that carries the coded data stream of all the sources. At the destinations, a central decoder receives input (data lines) from the destination nodes. Based on the input from the receivers and with the aid of the parity (protection) vector, the data streams that were lost during the transmission can be recovered if the number of streams that were lost is less than or equal to the number of parity (protection) channels.

In [45]-[46] Diversity Coding was utilized to recover from a single link failure nearly-instantaneously in networks with arbitrary topologies. An algorithm to find groups of links that can be combined efficiently to perform Diversity Coding was presented such that the number of redundant links is minimized.

In addition, Diversity Coding is utilized to introduce a new protection scheme named Coded Path Protection (CPP) [47]. In CPP the sharing structure of the Shared Path Protection technique [48] is transformed into a coding structure. In order to realize this idea, the network is modeled such that both source and destination nodes have data streams to transmit to each other simultaneously. Although the CPP scheme minimizes the required number of redundant links its disadvantage is that it has no ability to recover more than from a single link failure.

In [49], the DC technique is expanded and called Extended Diversity Coding. By applying regular DC to multipoint-to-point network topology to tolerate one link failure, one path is dedicated to carry a coded data stream, which forms from the logical XOR operation of the original data streams. Whereas with Extended Diversity Coding, several paths are enabled to carry coded data streams derived from the mod 2 addition of selected source data streams whose source nodes are close to each other. In some scenarios, this use of Extended Diversity Coding produces greater efficiency i.e. a reduced number of redundant links are required to recover from a link failure. In addition, this technique shortens the routes which leads to significant savings in restoration time. However, the disadvantage of this method is that it cannot tolerate more than a single link failure.

Cooperative Diversity Coding (CDC) with retransmissions is introduced in [50]-[51]. It is demonstrated that CDC with retransmissions significantly enhances wireless sensor network reliability, while reducing the energy consumption for the entire network. In addition, CDC has the ability to further decrease the consumed energy at the transmitter side compared to Cooperative Network Coding (CNC) [52] due to the simplicity of encoding the packets.

Temporal Diversity Coding (TDC) [53]-[54] for wireless body area network applications enhances wireless body area network performance by about 50% in terms of successful reception probability of a message at the receiver side. Also, by utilizing TDC, lower computational complexity and lower delay can be achieved comparing to that of the CNC technique.

As an application example in wireless systems, Diversity Coding may be implemented in wireless Orthogonal Division Frequency Multiplexing (OFDM)-based systems and named DC-OFDM [55]. It achieves reliable communication by using multiple and different sub-channels to transmit the data and protection coded data. It is illustrated that DC-OFDM with only one protection line (subcarrier) can significantly enhance system performance. It is worth noting that DC-OFDM can be utilized in mobile communications to overcome the inherently high symbol error rates.

2.3.2 Network Coding

Network Coding (NC) [21], a technology preceded and derived from Diversity Coding, uses coding in intermediate network nodes to combine several data streams to increase network throughput and save system bandwidth for data broadcasting/multicasting applications. Also, it has the ability to improve the performance of different type of networks. Network Coding also called Linear Network Coding (LNC) can be implemented in different modes, one of them is by selecting deterministic coefficients. Another mode is the Random Linear Network Coding (RLNC)

[56] that performs the coding using randomly chosen coefficients. The coefficients in both modes are transmitted in the header of the data streams. Triangular Network Coding [27] is another mode of network coding that reduces the computational complexity of linear coding without degrading the throughput performance, with a code rate comparable to that of Linear Network Coding.

In addition, the complexity of routing can be reduced by using Network Coding as the same linear combinations of sources' messages are sent through all the links. Therefore, routing the data streams does not need complex formulation. Another advantage of Network Coding is that it efficiently increases security because the transmitted messages through the links are a linear combination of data streams that are arrived from several input links.

The most important advantages of Network Coding are:

- Increasing network capacity for broadcast/multicast applications where the same information is simultaneously received by a single transmission at destination nodes. Hence, the destination nodes receive the information at a maximum rate possible. This means that Network Coding efficiently shares the available network bandwidth.
- Offering higher throughput for both broadcast and multicast applications.
- Increasing the robustness of the network and minimizing the delay by linearly combining the data streams.
- Decreasing the number of transmissions in a wireless network.
- Decreasing congestion in wired networks.

The most common example of the usefulness of Network Coding was shown in Figure 1.6 [21], which represents the well-known butterfly network topology, where the links are considered error-free. (See Section 1.3 for more details).

2.3.2.1 Network Coding Modes

Network Coding can be implemented in different modes, where each mode has its own pros and cons. The appropriate mode is determined based on the applications and networks configuration. One of the important modes is Linear Network Coding [57], where one or many coded data streams are generated by a linear combination of the incoming data streams. Assume that the incoming data streams are $x_1, x_2, \ldots, x_N$, and at the encoding node, each data stream is encoded by Galois Field coefficients (encoding coefficients), which are given as $\beta_{i1}, \beta_{i2}, \ldots, \beta_{iN}$, where i represents the number of generated coded data streams. The coded data stream c_i, which is a linear combination of incoming data streams x_j and encoding coefficients, is given by

$$y_i = \sum_{j=1}^{N} \beta_{ij} x_j \qquad i \in \{1, 2, \ldots, M\} \qquad (2-12)$$

Note that addition corresponds to the XOR operation and multiplication corresponds to the AND operation, since these are performed in $GF(2^m)$. At the receiving end, the number of received data streams have to be equal to or greater than the number of original transmitted data streams to decode the original information at the destination node. The decoding may be performed by using Gaussian elimination to recover the original messages x_j. At this method, the central controller is required to manage the generation of encoding coefficients.

Opportunistic Network Coding [58] is another network coding mode. In this mode, the encoding node decides to encode the incoming data streams based on the status of its queue. If the queue is low, the data streams are encoded and transmitted. Whereas if the queue is high, the data streams are transmitted without encoding. This method was proposed to solve the delay problem associated with encoding and decoding the data streams in Network Coding modes.

Another Network Coding mode is Random Linear Network Coding (RLNC) [25], [56], which is a decentralized method. In this mode, random encoding coefficients are used at the nodes to create the coded messages. This scheme is attractive to implement on wireless networks where the nodes are mobile and the network topology is unknown. Upon receiving the raw data streams, the encoding node uses its own randomly chosen coding coefficients to generate coded data streams. Information concerning the source data streams is contained in the (randomly) encoded data streams, which are calculated as the sum of the products of each of the original raw data stream with a random encoding coefficient. A Cyclic Redundancy Check (CRC, error detecting) field is included at each coded data stream such that data streams in error can be identified.

For wireless networks, Figure 2.4 [26] illustrates the principle of Wireless Network Coding (WNC), where, without Network Coding, nodes A and B need four time slots to interchange two data streams (a and b), as depicted in Figure 2.4 (a). However, with applying Network Coding, only three time slots are used to interchange two data streams (a and b), as shown in Figure 2.4 (b), where $c = a \oplus b$.

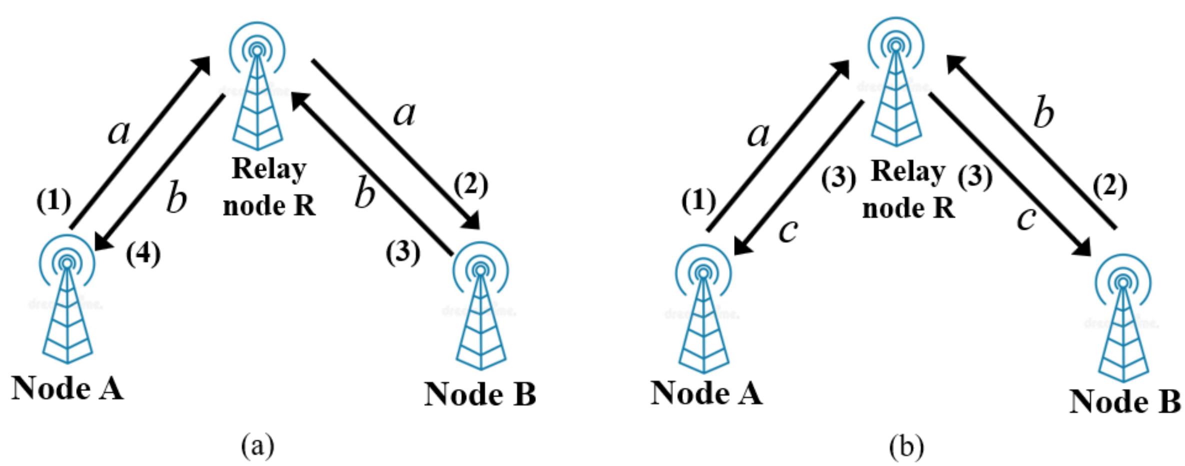


Figure 2.4 The principle of Wireless Network Coding (WNC). [26] © 2008 IEEE. Reprinted with permission: (a) without Network Coding and (b) with Network Coding.

In this scheme, node A transmits a to intermediate (relay) node R during time slot t_1. Then, during the time t_2 node B sends b to node R. After that, node R encodes a and b to create c by. Then, node R sends c to nodes A and B during time slot t_3. By receiving c, node A can obtain b and node B can obtain a.

Triangular Network Coding (TNC) [27] is another important mode of Network Coding that has the ability to decrease the encoding and decoding computational complexity of LNC. The principal idea of TNC is adding a string of “0” bit(s) on each data stream such that the XOR operation between the data streams will result in a new coded data stream [27].

To illustrate the main idea of TNC, it is assumed that the number of data streams $N = 3$, and the data streams are x_1, x_2, and x_3. The bit pattern of each data stream $x_i = \{b_{i,1} \quad b_{i,2} \dots \dots b_{i,B}\}$, where i is the data stream number and B is the total number of bits at each data stream. To generate the first coded data stream, $N - 1$ redundant bits “0”, which is called r_{max} are required. No redundant bit “0” is added at the head of data stream x_1 and hence, it is denoted by $x_{1,0}$. A redundant bit “0” is added at the head of data stream x_2 and hence, it is denoted by $x_{2,1}$. In addition, two redundant bits “0” are added at the head of data stream x_3 and hence, it is denoted by $x_{3,2}$. To equalize the length of all data streams, Two “0” bits are added to the tail of data stream x_1 and a “0” bit is added to the tail of x_2. Therefore, in general, each data stream will be denoted by x_{i,r_i}, where r_i is the number of redundant bit(s) “0” that are added at the head of data stream i. A simple XOR operation between $x_{1,0}$, $x_{2,1}$, and $x_{3,2}$, will generate the first coded data stream, c_1. The unique ID of the encoded data stream is represented as $[r_1, r_2, r_3]$. Thus, the unique ID of c_1 is $[0, 1, 2]$, which in general is given by $[0, 1, \dots, N - 1]$. To generate the second coded data stream, the position of ”0” in the first ID will be fixed and all the other terms will be cyclically rotated. Hence, the second coded data stream’s ID will be $[0, 2, 1]$. In this way, $N - 1$

coded data streams can be generated. To generate another $N-1$ coded data streams, the position of "0" in the first ID will be changed to be in the second position such that the ID will be $[1, 0, \dots, N-1]$ and all other terms except "0" will be rotated. With N positions for "0" to be fixed, $N \times (N-1)$ coded data streams can be generated. So that in this example, $3 \times (3-1) = 6$ coded data streams can be generated. It is shown in [27] that the decoding process can be easily done by bit XOR substitution. Below is a simple example to extract the required raw data streams from codes with IDs $ID_{c_1} = [0, 1, 2]$, $ID_{c_4} = [2, 0, 1]$, $ID_{c_5} = [1, 2, 0]$. The bit representation of each code is shown in Figure 2.5 [27]. Each encoded data stream is represented by a table where each row lists the bits of a data stream involved in the encoding. Starting from the left the first bit of c_1 is encoded by $b_{1,1} \oplus 0 \oplus 0$ which equals $b_{1,1}$. Similarly, $b_{2,1}$ and $b_{3,1}$ can be recovered from the first bit of c_4 and c_5 respectively. Now, the decoding process proceeds to the second bit position of the 3 coded data streams. By substituting $b_{1,1}$ into c_5 and $b_{2,1}$ into c_1 and $b_{3,1}$ into c_4, $b_{3,2}$, $b_{1,2}$, and $b_{2,2}$ can be recovered directly. Going forward to the third bit position, bits $b_{1,3}$, $b_{2,3}$, and $b_{3,3}$ can be instantly obtained by substitution. All unknown bits can be obtained by continuing decoding process. In this way, the bits of all 3 data streams can be decoded by back substitution at the bit level.

$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	....	$b_{1,B}$	0	0
0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....	$b_{2,B}$	0
0	0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....	$b_{3,B}$

The ID of c_1 is $[0, 1, 2]$

0	0	$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	....	$b_{1,B}$
$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....	$b_{2,B}$	0	0
0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....	$b_{3,B}$	0

The ID of c_4 is $[2, 0, 1]$

0	$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	....	$b_{1,B}$	0
0	0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....	$b_{2,B}$
$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....	$b_{3,B}$	0	0

The ID of c_5 is $[1, 2, 0]$

Figure 2.5 An example of the decoding process in TNC. [27] © 2012 IEEE. Adapted with permission.

2.3.2.2 Applications of Network Coding

Network Coding can be utilized to enhance the communications performance in different applications. This dissertation focuses on selected potential applications of novel network coding techniques that are briefly discussed below.

2.3.2.2.1 Wireless Broadcast Networks

Wireless networks generally broadcast/multicast messages to a group of receivers in multiple frequency channels. Since the available frequency bandwidth is limited, interference increases due to an increase in the number of wireless devices used. Also, for the same reason, the system throughput is decreased. Wireless Network Coding (WNC), discussed above, in combination with other modes of network coding can help to overcome above problems since fewer transmissions will be used.

As shown above, in the WNC scheme, a relay node linearly combines data streams from both nodes A and B. As illustrated in Figure 2.4(b), data streams a and b are sent to the relay node R which performs an XOR operation on the data streams and transmits the coded data stream c to both nodes A and B. Since A and B have their own data stream that they transmitted, they decode the coded data stream c and obtain the required information. In this way, only three transmissions (time slots) are used instead of four transmissions to reach both A and B. Thus, using WNC decreases the number of transmissions to three transmissions. This enhances the throughput of the system and efficiently utilizes the available bandwidth.

2.3.2.2.2 Network Security Applications

Network coding has the ability to provide secure communication systems since the original data streams are encoded and transmitted through multiple paths/routes. Thus, as long as the eavesdropper does not acquire all the coded data streams, he/she cannot get any information since the coded data streams are the XOR combination of the original data streams [24].

2.4 Concluding Remarks

Reliable communication and networking over unreliable channels and nodes can be provided by extending classic error control techniques. Error detection techniques may be used with the network coding technology to indicate which links and/or nodes have failed. And, error correction may also be used on individual links.

Building upon the well-known techniques of Diversity Coding and Network Coding and their extension, this dissertation presents novel network coding techniques directed towards improving the network performance of wireless fronthaul and wireless sensor networks in the presence of link and/or node failures. The main advantage of these network coding techniques is that they enable near-instant, self-healing, and fault-tolerance in the presence of link and node failures by transmitting redundant, coded information via spatially diverse routes.

As a preview, in this dissertation, Network Coding is synergistically combined with Diversity Coding to create a new network coding technique, dubbed DC-NC, that enhances network recovery from link and node failures, while providing efficient transmission in wireless fronthaul networks. In broadcast/multicast transmissions, Network Coding provides better performance than unicast transmissions, as is depicted in the well-known Butterfly network topology shown Figure 1.6 [21]. Also, Triangular Network Coding (TNC) is synergistically combined with Diversity Coding to create an extension of DC-NC, dubbed enhanced DC-NC (eDC-NC), which can dramatically decrease computational complexity without degrading throughput performance, with a code rate comparable to that of Linear Network Coding. In addition, these new coding techniques i.e. DC-NC and eDC-NC will be shown to provide ultra-reliable networking with very low latency in recovering from link/node failures and efficient secure broadcasting/multicasting for wireless fronthaul networks such that the adversary has no ability to acquire any information even if they wiretap the entire network excluding of course, the source and destination nodes.

In summary, Table 2.1 compares selected types of prior art Diversity Coding techniques in terms of several important characteristics such as the protection capability, redundancy percentage, and complexity.

Table 2.1 Comparison between selected prior art modes of Diversity Coding technology

Characteristic	**Diversity Coding**	**Coded Path Protection (CPP)**	**Extended Diversity Coding**	**Cooperative Diversity Coding**	**Temporal Diversity Coding**
Network topology	Arbitrary	Arbitrary but both source and destination transmit data streams	Arbitrary but several paths are enabled to carry coded data streams	Arbitrary	Known
Protection*	For N data links, M links can be recovered where $M \leq N$	Single link failure	Single link failure	For N data links, M links can be recovered where $M \leq N$	
Complexity	Low but increases with increasing number of coded data streams	Less since it deals with only one link failure		Low, but increases with increasing number of coded data streams	
Redundancy percentage	Increases with increasing the number of protection links and based on the network topology	Very low	Very low for some network topologies	Increases with increasing the number of protection links and based on the network topology	

Table 2.1 (Continued)

Characteristic	Diversity Coding	Coded Path Protection (CPP)	Extended Diversity Coding	Cooperative Diversity Coding	Temporal Diversity Coding
Restoration time	Near instant				

* Node failure recovery is not mentioned here because it depends on how many links fail and node failure is discussed in the system examples.

CHAPTER 3: DIVERSITY CODED 5G FRONTHAUL WIRELESS NETWORKS[2]

3.1 Introduction

The mobile network has evolved to become a primary form of communications. Therefore, for many applications, ultra-reliable networking is required to be able to serve the increasing user expectations and the demand for data-intensive applications. A principal factor that reduces mobile network reliability is link/node failure. In this chapter this issue is analyzed for the evolving 5G wireless network architecture, where the Remote Radio Heads (RRHs) are connected to the baseband unit (BBU) in a Cloud Radio Access Network (C-RAN) via emerging fronthaul networks. It was mentioned earlier in Section 1.1.1 that in C-RAN architectures, transport between the centralized baseband units (BBUs) and the remote radio heads (RRHs) is referred to as a *fronthaul* network. The main function of the fronthaul network is to enable seamless connections between the baseband units and the remote radio heads without impacting radio performance.

Since optical fiber fronthaul networks are often implemented, several protection schemes are available to react to link and node failures in optical fronthaul networks such as Synchronous Optical Networking (SONET) and *p*-cycle ring [48], [59]. Although these solutions increase reliability, their delay performance is still considered to be high for 5G applications [48]. Of course, they are not appropriate for wireless fronthaul network configurations.

Recovering from fronthaul link and/or node failures nearly-instantaneously will increase the network reliability and provide very low delay. Diversity Coding [18]-[20] has the ability to

[2] The content of this chapter has been published in [29] and [30], and it is included in this dissertation with permission from the IEEE. Permission is included in Appendix A.

achieve near-instantaneous recovery from link/node failures, as it is a feedforward technique that uses forward error control technology on diverse links and consequently does not need to retransmit messages and perform rerouting. In addition, the Diversity Coding technique can recover from a single link failure, as well as from multiple simultaneous link failures up to the total number of data links that are transmitting simultaneously. There are many reasons for link and node failures in wireless communications such as channel changes due to the mobility of user equipment, multiple-access interference, and/or changes in environmental factors (weather, new buildings). The 5G communication systems will support applications that require very low delay (around 1 msec) and high reliability, and solutions need to be developed to address these two challenges even in the presence of link and/or node failures.

Diversity Coding like other types of protection techniques requires extra transmission capacity. In [47]-[48] it is shown that Diversity Coding has competitive spare capacity compared with standard network restoration techniques.

In this chapter, Diversity Coding is applied to wireless fronthaul network to improve reliability with near-instant recovery from link/node failures. In addition, it is shown that Diversity Coding can recover from multiple simultaneous failures. Furthermore, examples where Diversity Coding could give a lower total routing cost than other types of restoration techniques are demonstrated.

3.2 System Model

As it is mentioned earlier in Chapter 1, a C-RAN network is expected to minimize the operating costs and it has the ability to manage the interference, which enhances the spectral efficiency [2], [4]. Optical fiber is usually used to implement long distances, high speed, and reliable fronthaul networks [10]-[12]. Whereas a wireless fronthaul is utilized to provide easy and lower cost deployment in dense environments such as in downtown cities or stadiums where optical fiber deployment is expensive and difficult to install [2], [10], [12]. Furthermore, the mixing of fiber and wireless in fronthaul networks is expected by most operators [12]. In this chapter, two scenarios with wireless fronthaul networks are considered. In the first scenario all links are wireless and the RRHs are connected to each other in a general mesh topology as shown in Figure 3.1 [2].

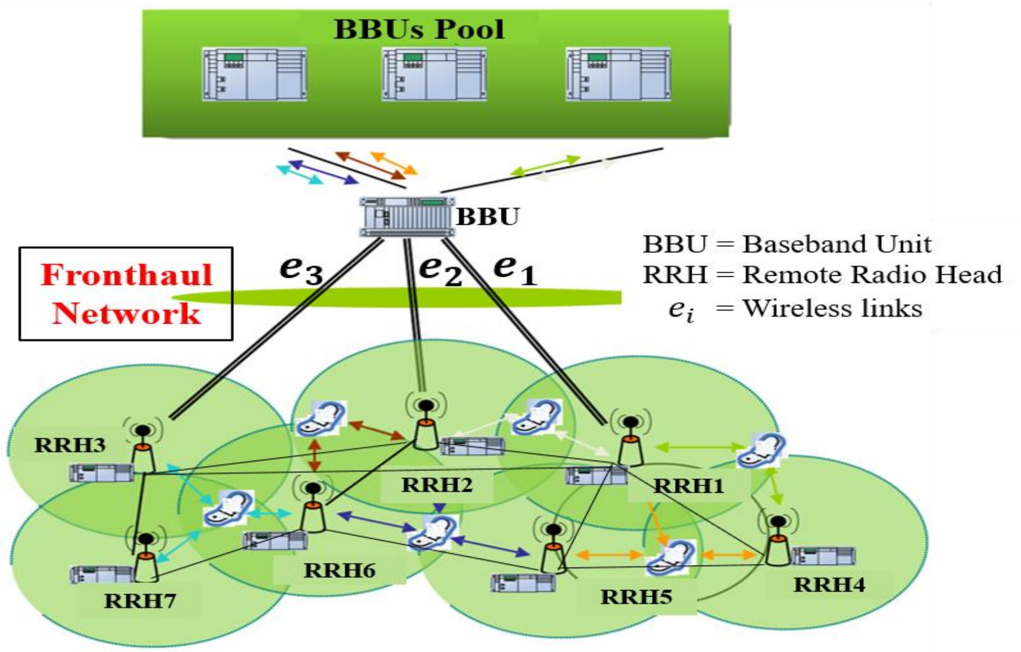


Figure 3.1 C-RAN architecture with a wireless fronthaul network. [2] © 2013 China Mobile. Adapted with permission.

In the second scenario, these connections are divided into two tiers: the first-tier RRHs connect via optical links to the BBU and second-tier RRHs connect via wireless links to the first tier RRHs and thus to the BBU. The second tier RRHs have a general mesh topology as depicted in Figure 3.2. Note that the technique that is described in this chapter are also applicable to the optical tier of the network, as well as the networks with all optical fiber links with a mesh topology. As 5G requires very low delay (around 1 msec for some applications) and high reliability, any link failure generally causes rerouting and/or retransmissions. Diversity Coding has the potential to provide high reliability with near-instantaneous recovery at the expense of redundant transmission facilities.

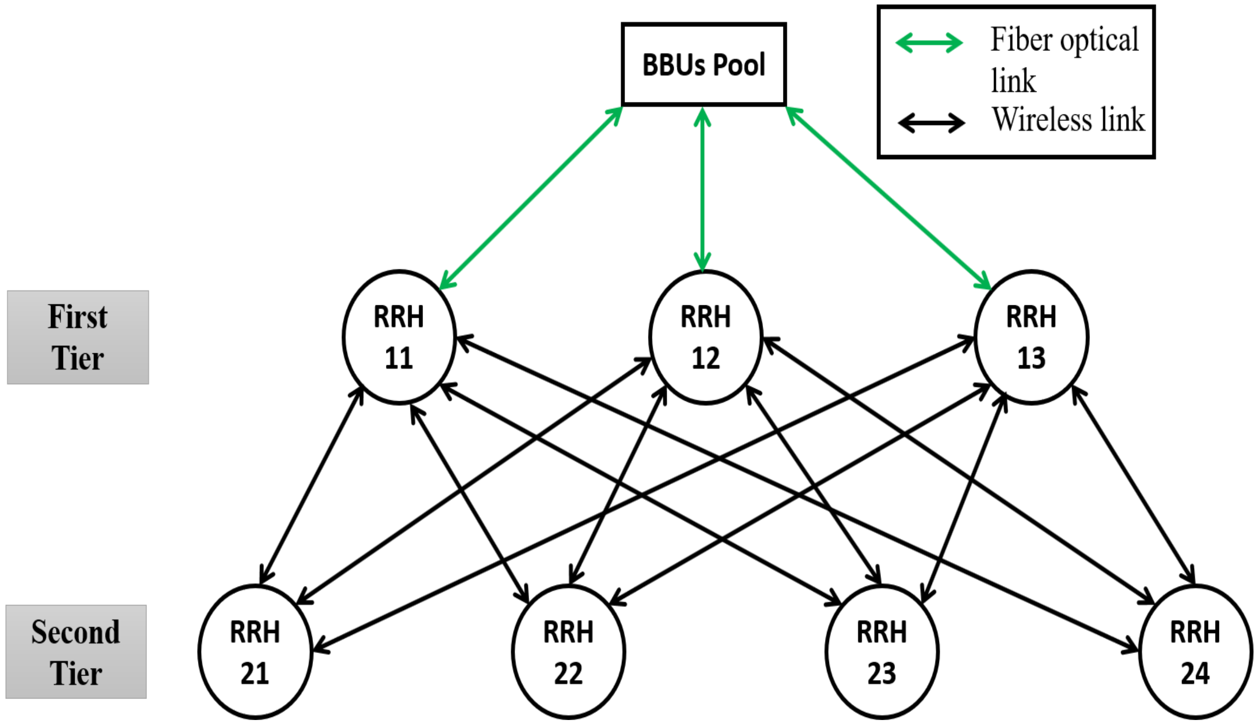


Figure 3.2 C-RAN architecture with a mix of optical and wireless fronthaul network links.

To demonstrate the advantages of applying Diversity Coding in a C-RAN wireless (tier) fronthaul network such as that shown in Figure 3.4 and Figure 3.5, network restoration cost will be described and estimated.

3.2.1 Network Restoration

Generally, a network consists of many nodes (vertices) and links (edges) and has a specific topology. To design a network with the ability to recover from link failures, many factors should be considered such as the traffic between a pair of nodes, which is called a *demand pair* or simply *demand*, the demand volume (i.e. traffic amount) between a demand pair, capacity of each link (i.e. maximum traffic amount that can be carried by the link), and the number of simultaneous link failures that need to be protected. Depending on the network topology, different paths can be used to route each demand. The amount of traffic (flow) in each route depends on the network design objective and the above factors (constraints). Depending on the network design, there are several possible objectives such as minimizing the total routing cost, minimizing the delay, and maximizing the network reliability [60].

To illustrate network routing design, consider a three-node network as depicted in Figure 3.3 [60]. Each pair of nodes has a demand volume such that the total number of demands $D = 3$. The demand between nodes 1 and 2 is $d = 1$, between nodes 1 and 3 is $d = 2$, and between nodes 2 and 3 is $d = 3$. Suppose that the following demand volumes $h_1 = 5, h_2 = 7,$ and $h_3 = 8$ are required.

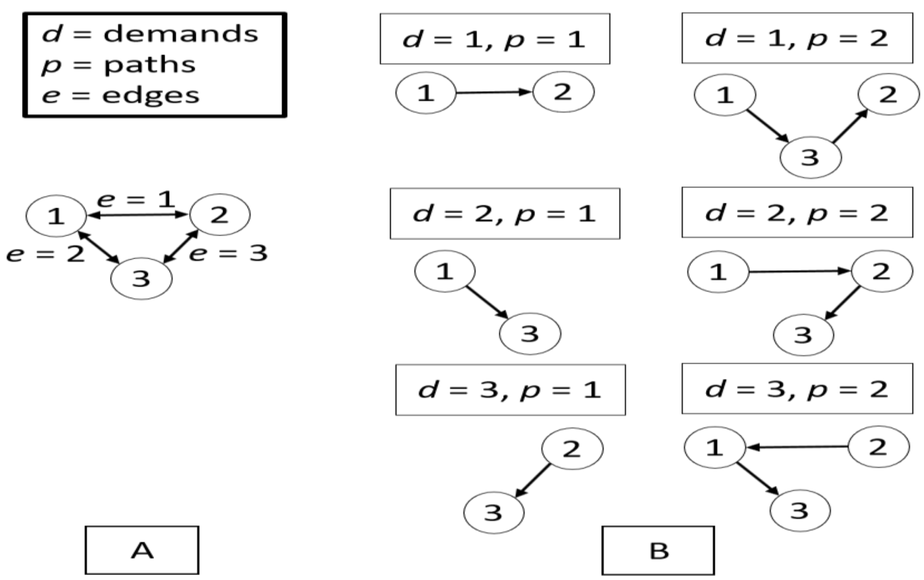


Figure 3.3 A. Example of a three-node network. [60] © 2004 Elsevier. Adapted with permission. B. Possible paths for each demand. [60] © 2004 Elsevier. Adapted with permission.

As shown in Figure 3.3 [60], there are two paths for each demand such that the demand constraints equations can be formulated as

$$x_{11} + x_{12} = h_1, \quad (3-1a)$$

$$x_{21} + x_{22} = h_2, \quad (3-1b)$$

$$x_{31} + x_{32} = h_3, \tag{3 – 1c}$$

where x_{ij} represents the flow x for demand i and path j. Note that all demands utilize joint paths where the common links are considered in each demand. Since each link has a capacity, k_e, which is an important network design parameter and it is considered as a variable in this example network, the number of flows that use the specific link should be determined and the summation of them must be less than or equal to its capacity. Hence, the capacity constraints inequalities are:

$$x_{11} + x_{22} + x_{32} \leq k_1, \tag{3 – 2a}$$

$$x_{12} + x_{21} + x_{32} \leq k_2, \tag{3 – 2b}$$

$$x_{12} + x_{22} + x_{31} \leq k_3, \tag{3 – 2c}$$

Consequently, the objective function to minimize the total routing cost in the network is

$$(F) = \min_{x}(x_{11} + 2x_{12} + x_{21} + 2x_{22} + x_{31} + 2x_{32}). \tag{3 – 3}$$

Note that since the flows x_{12}, x_{22} and x_{32} are used twice in routing, they are multiplied by 2 in the objective function. Using linear programming program, this problem can easily be solved such that the optimal solution is described as follows [60]:

- Flows: $x_{11} = 5,\quad x_{12} = 0,\quad x_{21} = 7,\quad x_{22} = 0,\quad x_{31} = 8,\quad x_{32} = 0.$
- Links capacity: $k_1 = 5,\quad k_2 = 7,\quad k_3 = 8.$
- The minimum total routing cost (*F*) = 20.

It is worth to note that the routing cost is calculated for the network without considering any link failure (normal operation). Therefore, by taking a link failure into account, the routing cost is expected to be increased as will be demonstrated for the same example network shown in Figure 3.3 [60], where the total number of links is 3. By assuming one link failure, there will be three failure states, $s = 1, 2, 3$, where each state corresponds to a specific link failure i.e. in state s, $e = s$ fails and the other links are working properly. Whereas the normal operational state is denoted by $s = 0$. A restoration network is designed by introducing an identifier for s. Hence, the demand constraint in (3 – 1) will be:

$$x_{11s} + x_{12s} = h_1, \qquad s = 0, 1, 2, 3. \qquad (3-4a)$$

$$x_{21s} + x_{22s} = h_2, \qquad s = 0, 1, 2, 3. \qquad (3-4b)$$

$$x_{31s} + x_{32s} = h_3, \qquad s = 0, 1, 2, 3. \qquad (3-4c)$$

Note that with any link failure, the path that utilizes this link fails and the flow that uses this path will be "0". For example, when $s = 1$, the link $e = 1$ fails and the paths $p = 1$ for the demand $d = 1$ and $p = 2$ for the demands $d = 2, 3$ are not satisfied. Thus, the flows x_{111}, x_{221}, and x_{321} will be "0". As shown in (3 – 4) that instead of having one equation for each demand constraint, there will be four (one for the normal state and three for failure states). Thus, there will be twelve equations for the demand constraints in this example network. Similarly, the capacity constraints for $e = 1$ will be four instead of one as follows:

$$s = 0: \quad x_{110} + x_{220} + x_{320} \leq k_1, \qquad (3-5a)$$

$$s = 1: \quad x_{111} + x_{221} + x_{321} \leq 0, \qquad (3-5b)$$

$$s = 2: \quad x_{112} + x_{222} + x_{322} \leq k_1, \qquad (3-5c)$$

$$s = 3: \quad x_{113} + x_{223} + x_{323} \leq k_1, \qquad (3-5d)$$

Note that the capacity of the link $e = 1$ will be "0" when it is in the failed state $s = 1$ as illustrated in (3 – 5b). The capacity constraints for $e = 2$ *and* 3 will be as follows:

$$s = 0: \quad x_{120} + x_{210} + x_{320} \leq k_2, \qquad (3-5e)$$

$$s = 1: \quad x_{121} + x_{211} + x_{321} \leq k_2, \qquad (3-5f)$$

$$s = 2: \quad x_{122} + x_{212} + x_{322} \leq 0, \qquad (3-5g)$$

$$s = 3: \quad x_{123} + x_{213} + x_{323} \leq k_2, \qquad (3-5h)$$

$$s = 0: \quad x_{120} + x_{220} + x_{310} \leq k_3, \qquad (3-5i)$$

$$s = 1: \quad x_{121} + x_{221} + x_{311} \leq k_3, \qquad (3-5j)$$

$$s = 2: \quad x_{122} + x_{222} + x_{312} \leq k_3, \qquad (3-5k)$$

$$s = 3: \quad x_{123} + x_{223} + x_{313} \leq 0, \qquad (3-5m)$$

It is worth noting that the objective function to minimize the total routing cost in the network with the ability to recover from one link failure (i.e. network restoration design) is the same as that shown in (3 – 3) because the network topology has not changed. Again, using linear programming, this problem can be solved for the same demand volumes that are given for the above example network and the optimal flow for each state are described as follows:

$$s = 0: \quad x_{110} = 5, \quad x_{120} = 0, \quad x_{210} = 7, \quad x_{220} = 0, \quad x_{310} = 8, \quad x_{320} = 0.$$
$$s = 1: \quad x_{111} = 0, \quad x_{121} = 5, \quad x_{211} = 7, \quad x_{221} = 0, \quad x_{311} = 8, \quad x_{321} = 0.$$
$$s = 2: \quad x_{112} = 5, \quad x_{122} = 0, \quad x_{212} = 0, \quad x_{222} = 7, \quad x_{312} = 8, \quad x_{322} = 0.$$
$$s = 3: \quad x_{113} = 5, \quad x_{123} = 0, \quad x_{213} = 7, \quad x_{223} = 0, \quad x_{313} = 0, \quad x_{323} = 8.$$

The maximum load of each link over all states $s = 0, 1, 2, 3$, represents the optimal capacity of that link, thus the optimal link capacity is given by:

$$k_1 = 13, \quad k_2 = 15, \quad k_3 = 15.$$

The summation of routing cost for each state represents the minimum total routing cost for the entire network. Hence, the minimum total routing cost (*F*) =100. This shows, not surprisingly, that the network restoration routing cost is more expensive than that of a network design without the ability to recover from a link failure [60].

The complexity and associated cost of network restoration design depend on the number of links that are utilized to transmit the required data to the destination(s), where each link may be shared by several paths i.e. joint paths. Thus, when a link fails, the network optimally reroutes the data that was carried by the failed link to other paths such that all the required demands in the network are met, while also satisfying demand volumes constraints for each failure state, which necessitates enlarged links capacity and in turn leads to increase the total routing cost (summation of routing costs of the normal state operation and all failure states).

Hence, in general, the network restoration design problem can be formulated as:

- *indices*

  $d = 1, 2, \dots, D$ demands

  $p = 1, 2, \dots, P_d$ paths

  $s = 0, 1, \dots, S$ failure states, $s = 0$ means there is no link failure.

  $e = 1, 2, \dots, E$ edges

- *variables*

  x_{dps} flow allocated to path p of demand d for failure states s (non-negative)

  k_e capacity of link e (non-negative).

- *parameters*

  δ_{edp}= 1 if link e belongs to path p realizing demand d; 0, otherwise

  α_{es} = 1 if link e is up; 0 if link e is down in state s

  h_d volume of demand d

  E the total number of links (edges) in the network

  E_f number of link failures at a time

- *objective function to be minimized*

$$(F) = \sum_d \sum_p \delta_{edp}\, x_{dps}, \qquad e = 1, 2, \dots, E \qquad s = 0, 1, \dots, S \qquad (3-6a)$$

- *constraints*

$$S = \frac{E!}{E_f!\,(E - E_f)!}, \qquad (3-6\text{b})$$

$$\sum_p x_{dps} = h_d, \qquad (3-6\text{c})$$

$$\sum_d \sum_p \delta_{edp}\, x_{dps} \leq \propto_{es}\, k_e. \qquad (3-6\text{d})$$

The objective function in $(3-6a)$ represents the minimum routing cost of the network, which is the sum of the flow allocated to path p of demand d for state s times the link incidence relation δ_{edp} (1 if link e belongs to path p realizing demand d; 0, otherwise) [60]. Equation $(3-6b)$ is the total number of simultaneous failure states in the network, which is the combinations of the total number of links in network, E, taking the number of simultaneous link failures at a time, E_f.

The demand constraints are represented by equation $(3-6c)$, which is the sum of all flows for demand d, which equals the volume of demand d, h_d. Finally, inequality $(3-6d)$ represents the capacity constraints. The left side of the equation is the sum of the link incidence relation δ_{edp} (1 if link e belongs to path p realizing demand d; 0, otherwise) times the flow allocated to path p of demand d for states s. In addition, the right side is the link capacity times the constant $\propto_{es}$ (1 if link e is up; 0 if link e is down in state s) [60].

The restoration capability can generally be increased, but it comes at the expense of increasing the total routing cost. In addition, the rerouting delay increases the overall delay in the network [47]-[48], which is undesirable in 5G C-RAN fronthaul networks.

The ideal objective is to improve 5G C-RAN fronthaul network reliability and avoid any rerouting delay, without increasing the total routing cost. Diversity Coding offers a powerful solution to recover the lost data near instantaneously and meet the above objective.

3.3 Link/Node Failure Recovery Nearly-Instantaneously via Diversity Coding

A C-RAN wireless fronthaul network can have a link failure due to multiple-access interference, weather changes or other environmental factors. To provide reliable networking and prevent the delay due to rerouting or retransmission, Diversity Coding is applied as illustrated below.

3.3.1 Single Link Failure Recovery for Completely Wireless Fronthaul Networks

Diversity Coding is applied to a 5G C-RAN wireless fronthaul network as depicted in Figure 3.4. In this example fronthaul network, three wireless links $e_1, e_2,$ and e_3 connect the BBU Pool to RRH1, RRH2, and RRH3 respectively.

In this study, a downlink point-to-point network topology is considered[3]. Therefore, using Diversity Coding, three disjoint paths are used to transmit two data streams from the BBU to RRH1. The link e_1 carries the first data stream x_1 to RRH1 and the second data stream x_2 is transmitted to RRH1 via the links e_2 and e_4. The BBU will sum these data streams using an XOR operation $(x_1 \oplus x_2)$ then transmits the result by e_3 and e_5 to RRH1. Let $(x_1 \oplus x_2)$ be denoted by x_3.

So, if either x_1 or x_2 is not received, RRH1 can recover that signal by summing the received signal with $(x_1 \oplus x_2)$. For example, if the link e_1 fails i.e. the data stream x_1 is lost, RRH1 will

[3] In the uplink, RRH3 receives data streams x_1 and x_2 from RRH1 and RRH2 respectively using the links that are connected with it and performs an XOR summation then transmits the result to the BBU.

sum x_2 and $(x_1 \oplus x_2)$ and obtain x_1. This is how Diversity Coding enables near-instantaneous recovery of the “lost” or errored signals.

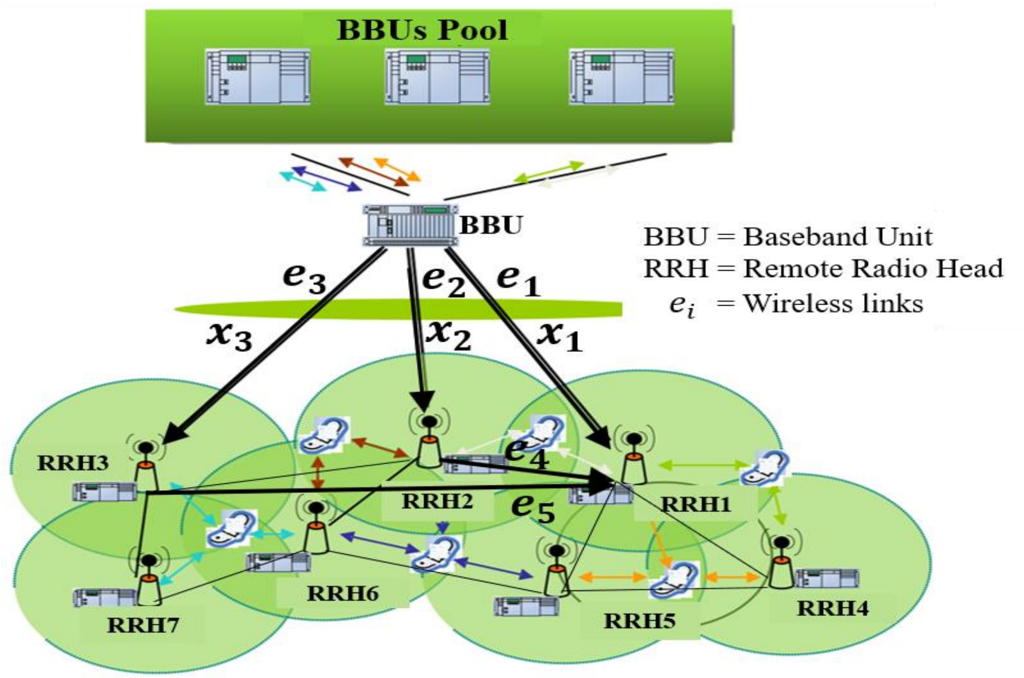


Figure 3.4 Diversity Coded wireless fronthaul network. The fronthaul network is adapted with permission from [2] © 2013 China Mobile.

In addition to the near-instantaneous recovery capability of Diversity Coding, the optimality of the scheme in terms of total routing cost for this example is demonstrated. The example network of Figure 3.4 is considered, where the demand volumes are $h_1 = 3, h_2 = 7$, and $h_3 = 7$ (h_3 equals the highest demand between h_1 and h_2 as it is the result of the XOR operation between the two data streams).

The objective function can be expressed as

$$(F) = \min_{x}(x_1 + 2x_2 + 2x_3), \qquad (3-7)$$

such that the amount of each data stream will be $x_1 = 3, x_2 = 7$, and $x_3 = 7$. The total routing cost will be 31. Note that since the data streams x_2 and x_3 are used twice in the routing, they are multiplied by 2 in the objective function.

However, using the general network restoration method that is described in Section 3.2.1, applying $(3-6)$ for two data streams and one link failure at a time will increase the total routing cost to 70. Note that the cost of the network restoration scheme is more than double compared to that for the Diversity Coding scheme because the former considers all joint paths in the network and all normal operation and failure states $s = 0, 1, \dots, 5$, whereas Diversity Coding employs only the disjoint paths, where there are only three disjoint paths in this example. In addition, with Diversity Coding, only minimal change to normal operation is required since the Diversity Coding technique itself recovers the lost data nearly instantaneously.

The differences in formulation between the Diversity Coding scheme and the general network restoration method of Section 3.2.1 are summarized in Table 3.1.

Table 3.1 Protection schemes comparisons

Protection Scheme	**Diversity Coding**	**Network restoration**
Total routing cost	31	70
Number of data streams	3	2
Number of disjoint paths	3	-
Number of nodes (vertices)	4	4
Number of links (edges)	5	5

3.3.2 Multiple Links Failure Recovery for Two-Tier Mixed Fronthaul Networks

The application of Diversity Coding in a 5G C-RAN mixed (optical and wireless) fronthaul network is shown in Figure 3.5, where recovery from two simultaneous wireless link failures are considered. The BBU pool is connecting to the first tier RRHs (RRH11, RRH12, RRH13) via three optical links (green arrows). In addition, the first and second tiers RRHs are connecting to each other by several wireless links (black arrows). Furthermore, there is no direct connection between the BBU pool and the second tier RRHs. Here, an uplink multipoint-to-point network topology is considered[4]. In this fronthaul network, each link is bi-directional. The optical connections in the first tier are considered to be a reliable connection. So that in order to transmit three data streams from second tier RRHs: RRH21, RRH22, and RRH23 to the BBU pool via the first tier RRHs and protect against two simultaneous wireless link failures using Diversity Coding, five wireless disjoint paths are required. RRH21 transmits x_{21} to the BBU pool via RRH11, RRH22 transmits x_{22} to the BBUs pool via RRH12, and RRH23 transmits x_{23} to the BBU pool via RRH12.

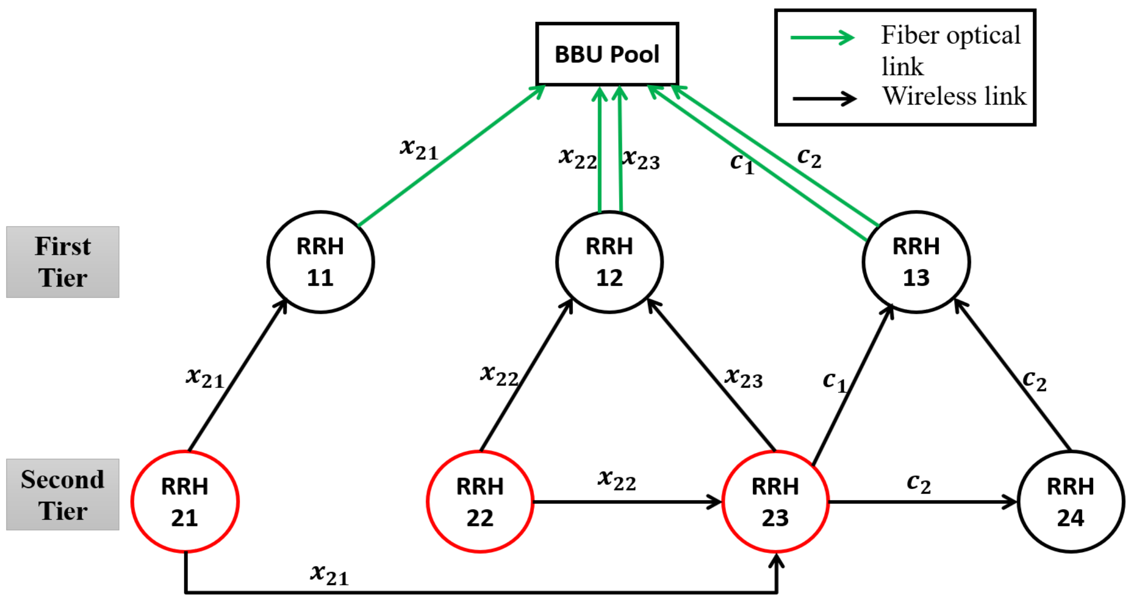


Figure 3.5 Diversity Coded mixed optical and wireless fronthaul network. The red RRHs are the source nodes.

To apply Diversity Coding, RRH21 will send x_{21} to RRH23, RRH22 will send x_{21} to RRH23, RRH22 will transmit x_{22} to RRH23, and RRH23 will form coded data streams c_1 and c_2 as follows:

$$c_1 = \beta_{11}x_{21} + \beta_{21}x_{22} + \beta_{31}x_{23} \quad (3-8a)$$

$$c_2 = \beta_{12}x_{21} + \beta_{22}x_{22} + \beta_{32}x_{23}, \quad (3-8b)$$

[4] In the downlink, the BBU performs XOR summations and transmit the results using the optical links to the first tier RRHs which then uses wireless links to RRH24, which performs Diversity Decoding.

where $\begin{bmatrix}\beta_{11} & \beta_{12}\\ \beta_{21} & \beta_{22}\\ \beta_{31} & \beta_{32}\end{bmatrix}$ is the parity generator matrix. As noted earlier, in coding theory, the parity generator matrix is used to describe the linear relations that the components of a codeword must satisfy. In the decoding process, the generator matrix is used to decide whether a particular vector is a codeword. Note that since multiplication and summation are performed in $GF(2^m)$, they correspond to AND and XOR operations respectively. The message c_1 will be transmitted to the BBUs pool via RRH13 and c_2 will be transmitted to the BBUs pool via RRH24 and RRH13.

At the receiver (BBU pool), assume that two data links (x_{21} and x_{22}) fail and the BBU pool detects the failures. Let f_1 and f_2 be the indices of the links that failed, so tha $x_{f_1} = x_{21}$ and $x_{f_2} = x_{22}$. Hence, the BBU will generate $\tilde{c}_1$ and $\tilde{c}_2$ as follows:

$$\tilde{c}_1 = c_1 + \beta_{31}x_{23}, \qquad (3-9)$$

and applying $(3-8a)$ to $(3-9)$, we obtain

$$\tilde{c}_1 = \beta_{11}x_{f_1} + \beta_{21}x_{f_2} + \beta_{13}x_{23} + \beta_{31}x_{23},$$

$$\tilde{c}_1 = \beta_{11}x_{f_1} + \beta_{21}x_{f_2}. \qquad (3-10)$$

Similarly, we have

$$\tilde{c}_2 = c_2 + \beta_{32}x_{23}. \qquad (3-11)$$

and applying $(3-8b)$ to $(3-11)$, it results in

$$\tilde{c}_2 = \beta_{12}x_{f_1} + \beta_{22}x_{f_2} + \beta_{32}x_{23} + \beta_{32}x_{23}$$

$$\tilde{c}_2 = \beta_{12}x_{f_1} + \beta_{22}x_{f_2}. \qquad (3-12)$$

Finally, $(3-10)$ and $(3-12)$ can be expressed in a matrix form as

$$\begin{bmatrix}\tilde{c}_1\\ \tilde{c}_2\end{bmatrix} = \begin{bmatrix}\beta_{11} & \beta_{21}\\ \beta_{12} & \beta_{22}\end{bmatrix}\begin{bmatrix}x_{f_1}\\ x_{f_2}\end{bmatrix}. \qquad (3-13)$$

The quantities $\tilde{c}_1$ and $\tilde{c}_2$ can be easily obtained because β_{ij} are fixed and known at the BBU pool. In addition, $\tilde{c}_1$ and $\tilde{c}_2$ are used to recover x_{f_1} and x_{f_2}via an inverse linear transform [18]-[20]. The parameters β_{ij}'s should be chosen such that $\beta_{11}, \beta_{21}, \beta_{12}$ and β_{22} are linearly independent. This can be checked by finding the determinant of the matrix

$$\begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}. \qquad (3-14)$$

Let $\propto$ be a primitive element of $GF(2^m)$ and express $\beta_{ij} = \propto^{(i-1)(j-1)}$. Also, let

$$m = \lceil \log_2(N+1) \rceil, \qquad (3-15)$$

where *N* is the total number of data links that is three in this example and $\lceil y \rceil$ is the smallest integer greater than or equal to *y* so that $m = 2$. Hence, the determinant will be $(\propto -1)$, and it cannot be zero since $\propto$ is a primitive element of $GF(2^2) = GF(4)$ [18]-[20].

Therefore, the BBU obtains the failed data streams as follows:

$$\begin{bmatrix} x_{f_1} \\ x_{f_2} \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{c}_1 \\ \tilde{c}_2 \end{bmatrix}. \qquad (3-16)$$

Note that this method can apply for any two simultaneous data link failures such as x_{22} & x_{23} and x_{21} & x_{23}, as well as above example.

Furthermore, not only link failures can be recovered, in the example network. First tier node failures that receive and transmit data streams may be recovered, but not the node that transmits and receives the Diversity Coded data. So, if RRH11 failed, only x_{21} will be lost and it can be recovered even with one simultaneous link failure. In addition, if RRH12 fails two data streams x_{22} and x_{23} will be lost simultaneously. Hence, they can be recovered easily by the BBU. However, if RRH13 fails, the protection of the network i.e. c_1 and c_2 will be lost, but successful data communication will still occur. Unfortunately, second tier node failures are not recoverable, since these nodes generate the data streams.

The above illustrates how Diversity Coding enables near-instantaneous recovery of the "lost" or errored signals. Now, the optimality of the Diversity Coding scheme, compared to the network restoration method described in Section 3.2.1, in terms of total routing cost for this example is demonstrated. The example network of Figure 3.5 is considered, where the demand volumes are $h_1 = 5, h_2 = 4$, $h_3 = 3, h_4 = 5$, and $h_5 = 5$, (h_4 and h_5 equal the highest demand between h_1, h_2 and h_3 as it is the result of the XOR operation between the three data streams).

The objective function can be expressed as

$$(F) = \min_{x} \ (3x_{21} + 3x_{22} + 2x_{23} + 2c_1 + 3c_2), \qquad (3-17)$$

such that the amount of each data stream will be $x_{21} = 5, x_{22} = 4, x_{23} = 3, c_1 = 5$, and $c_2 = 5$. The total routing cost using diversity coding will be 58. Note that since the data streams x_{21}, x_{22} and c_2 are used three times in the routing, they are multiplied by three in the objective function and the data streams x_{23} and $c_1$are used twice in the routing, they are multiplied by two in the objective function.

Next, using the general network restoration scheme that is described in Section 3.2.1, applying $(3-6)$ for three data streams and one link failure protection will increase the total routing cost to 225. Note that the cost of this network restoration scheme is very high compared to that using Diversity Coding because the network restoration scheme considers all joint paths in the network and all normal operation and failure states $s = 0, 1, \dots, 8$, whereas Diversity Coding employs only the disjoint paths. Also, note that there are only five disjoint paths in this example network. Also, by applying Diversity Coding, substantially normal operation is required since the Diversity Coding technique itself recovers the lost data nearly instantaneously.

The differences in formulation between the Diversity Coding scheme and the general network restoration method of Section 3.2.1 are summarized in Table 3.2.

Table 3.2 Protection schemes comparisons

Protection Scheme	Diversity Coding	Network restoration
Total routing cost	58	225
Number of data streams	5	3
Number of disjoint paths	5	-
Number of nodes (vertices)	8	8
Number of links (edges)	11	11

In addition to the near instantaneous link failure recovery, an example where Diversity Coding has a lower routing cost than the general network restoration scheme is provided. As with all restoration methods, there is an increase in the number and utilization of links.

3.4 Concluding Remarks

The potential applications of Diversity Coding in 5G fronthaul networks was presented, where the RRHs in a C-RAN network are connected to the BBU in two scenarios, the first with wireless links and the second with two tiers of optical and wireless links. In order to avoid retransmissions that incur high transmission and re-routing delays due to link failures in wireless links of the fronthaul network, it was demonstrated how Diversity Coding increases network reliability with near-instantaneous recovery and the ability to recover from multiple simultaneous link failures. In addition, examples where Diversity Coding gives a significantly lower total routing cost than other types of restoration techniques are depicted.

CHAPTER 4: IMPROVING THE PERFORMANCE OF 5G CLOUD RADIO ACCESS NETWORKS[5]

4.1 Introduction

Wireless 5G networks require ultra-low latency communications for many key applications, as well as high throughput and ultra-reliability [8]. Link/node failure is one of the main contributors that increases latency, reduces system throughput, and decreases reliability. It was mentioned in Section 3.1 that link failures in wireless communications may occur due to channel changes and/or interference. While node failures might happen due to a power issue or buffer overflow. Emerging 5G communication systems will support some applications that require very low delay and high reliability. Therefore, it is very desirable to have near-instantaneous recovery from link failures that will improve the reliability and enable very low delay networking in the presence of link and/or node failures. As it is mentioned in Section 2.3.1 Diversity Coding [18]-[20] can achieve near-instantaneous recovery from link/node failures, as it uses forward error control technology over diverse links, and hence, there is no need to retransmit messages and perform rerouting.

In the previous chapter, Diversity Coding was applied to a Cloud Radio Access Network (C-RAN) network to enhance performance by improving the reliability with near-instant link/node failure recovery. C-RANs are one of the evolving 5G wireless network architectures, which enables very low latency, high bandwidth, accurate synchronization, and interference management

[5] The content of this chapter has been published in [31] and [32], and it is included in this dissertation with permission from the IEEE. Permission is included in Appendix A.

[4]. Also, it was shown that multiple simultaneous link failures can be recovered via Diversity Coded systems.

Furthermore, Diversity Coding was used in several applications to enhance their reliability such as Network Function Virtualization (NFV) [61] and minimizing energy consumption in sensor networks [51].

Although ultra-low latency and high reliability are very important in C-RANs, network throughput and high data rate coverage are other important factors that effect C-RAN performance. However, broadcasting/multicasting data applications that will utilize C-RAN networks could have reduced throughput because of the limitation of fronthaul link capacity. Moreover, to improve the high data rate coverage, Coordinated Multi Point (CoMP) technology [4] is used to manage and mitigate interference. Coordinated Multi Point (CoMP) shares both data and channel state information (CSI) among neighboring cellular base stations (BSs) to coordinate their transmissions in the downlink and jointly process the received signals in the uplink. In this way, harmful inter-cell interference is transformed into useful signals, enabling significant power gain, channel rank advantage, and/or diversity gains [4], [62]. A challenge in the implementation of CoMP is reducing the additional network resources that are used for simultaneous redundant transmissions to several RRHs. Enhanced throughput and efficient implementing for CoMP to improve high data rate coverage of 5G fronthaul wireless networks can be achieved via Network Coding [21].

In this chapter, a new coding technique, Diversity Coding-Network Coding (DC-NC), is introduced based on the synergistic combination of Diversity Coding and Network Coding. DC-NC can enable ultra-low latency communications systems, enhance network throughput for broadcasting/multicasting applications, and improve wireless fronthaul network reliability. Latency is lowered owing to the open-loop nature of DC-NC coding. In addition, the application of DC-NC coding is investigated for downlink CoMP within a C-RAN to decrease wireless fronthaul resource consumption, enhance wireless fronthaul C-RAN reliability, and enable ultra-low recovery time. Furthermore, the number of redundant links utilized in the proposed coding technique is decreased in comparison to that required by Diversity Coding.

4.2 System Model

Similar to the system model described in Section 3.2, in this chapter, the new coding technique (DC-NC coding) is applied to two wireless fronthaul network scenarios to enhance the performance of C-RANs. In the first scenario, the RRHs are connected to the BBU in two hierarchal tiers: first-tier RRHs connect via optical links to the BBU and second-tier RRHs connect via wireless links to the first tier RRHs and thus to the BBU. The second tier RRHs have a general mesh topology as shown in Figure 3.2.

The second scenario represents the traditional C-RAN topology where RRHs are directly connected to the BBU, where these connections are wireless links. And, the RRHs are connected to each other in a general mesh topology as illustrated in Figure 3.1 [2].

In both scenarios, the RRHs will likely utilize directional antennas or MIMO systems to prevent interference and be able to simultaneously communicate with several RRHs as well as the BBU, in addition to communicate with several pieces of user equipment (UEs).

Note that the technique that is described in this work is also applicable to the optical tier of the C-RAN network, as well as to networks with all optical fiber links with a mesh topology.

As discussed in Section 4.1, CoMP may be used to improve interference management capabilities in C-RANs. CoMP has been standardized in Release 11 of the LTE mobile network specifications [62]. To implement CoMP, a set of cells, called a CoMP set, where each cell is served by a RRH, team up to serve single or multiple user equipment (UEs) based on feedback from the user(s). As all RRHs are controlled by the same BBU pool, very tight synchronization and coordination among the RRHs in a CoMP set can be easily achieved [4], [63]- [64].

There are three ways to deploy downlink CoMP: the simplest way is called Coordinated Scheduling/ Coordinated Beamforming (CS/CB) where the UE deals with only one RRH (called the serving RRH) while other RRHs in the CoMP set help in preventing interference [4], [63]. The second type of CoMP is an extension of the above scheme which is called Dynamic Point Selection (DPS). In this scheme, the required data for a particular UE is made available to all RRHs in a CoMP set. However, only one RRH deals with a mobile at a given point of time. The BBU decides which one should do the actual transmission based on the quality of its transmission path to the UE [4], [63].

The last and the most advanced CoMP scheme is Joint Transmission (JT), referred to as JT-CoMP. Here, all RRHs in the CoMP set receive the required data and they simultaneously transmit the same information with accurate timing to the user(s) with the expectation of achieving a high SINR as illustrated in Figure 4.1 where three cells (1, 2, and 3), each represented by a RRH, are grouped as a CoMP set to serve a UE. Although this scheme generally guarantees high data rate coverage, it consumes several RRHs resources [4], [63].

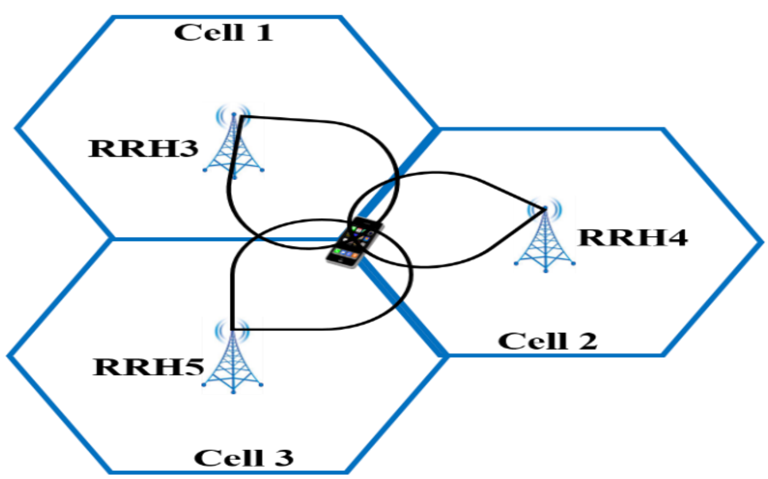


Figure 4.1 JT-CoMP mode in a wireless fronthaul C-RAN.

In this chapter, the new coding technique (DC-NC) is applied to downlink JT-CoMP in a wireless fronthaul C-RAN to enhance resource utilization and improve the reliability with ultra-low recovery time. The C-RAN topology investigated is one in which most RRHs connect directly to the BBU pool via wireless links. Moreover, RRHs are connected to each other in a general mesh topology as illustrated in Figure 4.2. Furthermore, downlink JT-CoMP is used, where CoMP set cells are represented by RRH3, RRH4, and RRH5. This CoMP set serves a UE as shown in Figure 4.1.

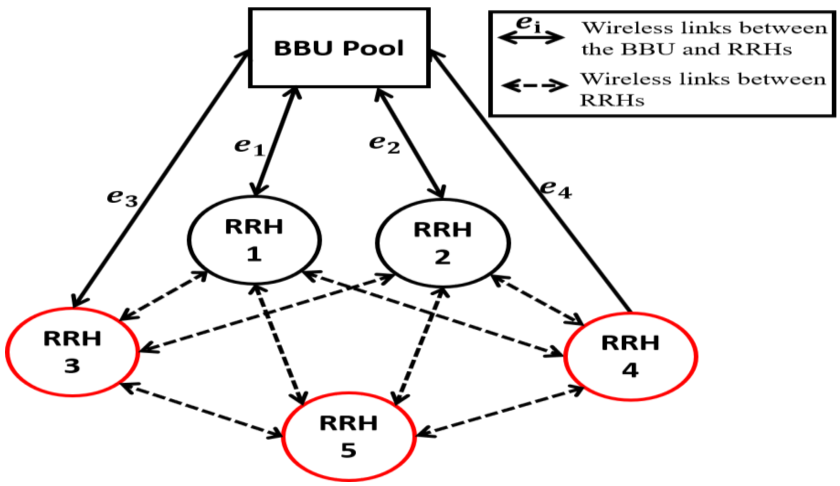


Figure 4.2 Example C-RAN with wireless fronthaul network links. Red RRHs represent the CoMP set cells.

4.3 Synergistic Combination of Diversity and Network Coding (DC-NC)

In this Section, the synergy of Diversity and Network Coding, referred to as DC-NC coding is described. In the DC-NC network shown below in Figure 4.3(a), nodes 1 and 2 broadcast equal rate digital data streams x_1 and x_2 respectively to nodes 6 and 7. Node 3 receives x_1 and x_2 and then encodes them and forms c_1 and c_2 as follows:

$$c_1 = \beta_{11}x_1 + \beta_{21}x_2, \quad (4-1)$$

$$c_2 = \beta_{12}x_1 + \beta_{22}x_2, \quad (4-2)$$

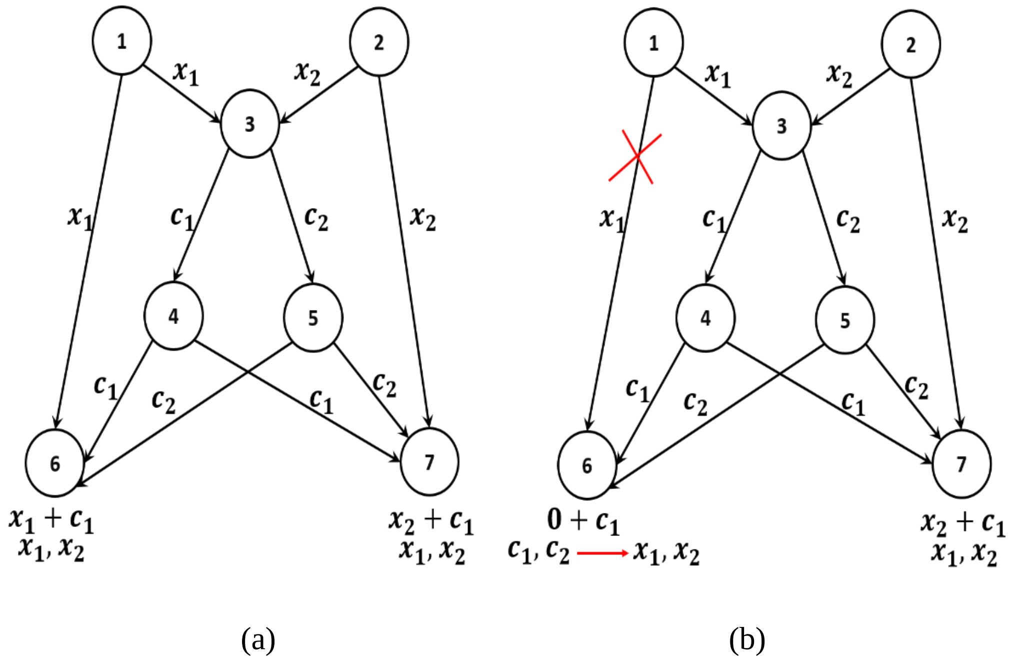


Figure 4.3 (a) DC-NC network (b) DC-NC network with a link failure.

where $\begin{bmatrix}\beta_{11} & \beta_{12}\\ \beta_{21} & \beta_{22}\end{bmatrix}$ is the parity generator matrix for c_1 and c_2. In coding theory, the parity generator matrix is used to describe the linear relations that the components of a codeword must satisfy. It can be used in decoding to decide whether a particular vector is a codeword. Note that multiplication corresponds to the AND operation and summation corresponds to the XOR operation, since these are performed in $GF(2^m)$. Node 3 is the DC-NC encoding node. The coded data c_1 and c_2 then will be sent to nodes 4 and 5 respectively. Node 4 sends c_1 to nodes 6 and 7. Node 6 receives x_1 directly from node 1 and c_1 from node 4 so, it decodes these streams and recovers x_2 as follows:

$$\tilde{c}_1 = c_1 + \beta_{11}\, x_1, \qquad (4-3)$$

and applying (4 – 1) to (4 – 3),

$$\tilde{c}_1 = \beta_{11}x_1 + \beta_{21}x_2 + \beta_{11}x_1 \; = \beta_{21}x_2, \qquad (4-4)$$

$$x_2 = \tilde{c}_1/\beta_{21}\,. \qquad (4-5)$$

Hence, Node 6 can recover both x_1 and x_2. Note that the coefficients β_{ij} are fixed and known at all nodes. Similarly, node 7 receives x_2 directly from node 2 and c_1 from node 4 so, it decodes them and recovers x_1 as follows:

$$\tilde{c}_1 = c_1 + \beta_{21}\, x_2, \qquad (4-6)$$

and applying (4 – 1) to (4 - 6),

$$\tilde{c}_1 = \beta_{11}x_1 + \beta_{21}x_2 + \beta_{21}x_2 = \beta_{11}x_1, \qquad (4-7)$$

$$x_1 = \tilde{c}_1/\beta_{11}\,. \qquad (4-8)$$

Hence, Node 7 can also recover x_1 and x_2. Note that each link in the network has the same link capacity, which is equal to the data rate of one of the broadcast data streams.

To illustrate the throughput gain of DC-NC coding, which is similar to that of Network Coding, let us assume that each data stream's data rate is half of the maximum link capacity. So, if two data streams are sent in each link, then four data streams can be broadcast to nodes 6 and 7. However, without coding, only three data streams can be broadcast to nodes 6 and 7 because the link between nodes 3 and 4 cannot carry more than two data streams i.e. one data stream from node 1 and another from node 2. Therefore, as in Network Coding, the throughput is increased by one-third using DC-NC coding [21]. However, any link failure can strongly impact reliability and nodes 6 and 7 will not receive targeted data streams.

To improve network reliability, node 5 transmits c_2 to nodes 6 and 7. When there is no link failure, nodes 6 and 7 ignore c_2.

In case of a link failure (for example, the link from node 1 to node 6 fails) as shown in Figure 4.3(b), node 6 detects the failure then utilizes c_1 and c_2 to recover x_1 and x_2 as follows: Expressing (4 – 1) and (4 – 2) in a matrix form

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad (4-9)$$

Data streams x_1 and x_2 can be easily recovered using the inverse matrix transform. The parameters β_{ij}'s should be chosen such that $\beta_{11}, \beta_{21}, \beta_{12}$ and β_{22} are linearly independent. This can be checked by finding the determinant of the matrix

$$\begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}, \quad (4-10)$$

Let $\propto$ be a primitive element of $GF(2^m)$ and let $\beta_{ij} = \propto^{(i-1)(j-1)}$. Also, let

$$m = \lceil \log_2(N+1) \rceil, \quad (4-11)$$

where N is the total number of data links, which is two in this example, and $\lceil x \rceil$ is the smallest integer greater than or equal to x so that $m = 2$. Hence, the determinant will be $(\propto -1)$, and it cannot be zero since $\propto$ is a primitive element of $GF(2^2) = GF(4)$ [18]-[20]. Therefore, node 6 obtains x_1 and x_2 as follows:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}^{-1} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}. \quad (4-12)$$

Furthermore, if c_1 fails, node 6 has x_1 and c_2 then can easily form

$$\tilde{c}_2 = c_2 + \beta_{12} x_1, \quad (4-13)$$

and applying (4 – 2) to (4 – 13)

$$\tilde{c}_2 = \beta_{12} x_1 + \beta_{22} x_2 + \beta_{12} x_1 = \beta_{22} x_2, \quad (4-14)$$

$$x_2 = \tilde{c}_2 / \beta_{22}\,. \quad (4-15)$$

Similarly, node 7 can recover x_1 and x_2. Note that the proposed DC-NC coding scheme can simultaneously recover from one link failure at each receiver node (nodes 6 and 7). Also note that if only Diversity Coding is used in this multipoint-to-multipoint network topology with two source nodes and two destination nodes (i.e. there is no broadcasting, hence, no need to use Network Coding), the receiver nodes cannot recover the data stream in the presence of a link failure. In this case, the receiver nodes need to transmit whatever they directly received from the transmitters to node 5 which will decode them with Diversity coded data. In case of a link failure, the decoding process will produce the failed data stream, which will be transmitted to the receiver node. So that by applying Diversity Coding alone, only one link failure in the entire network can be recovered and more links must be used for recovering the failed data stream. However, as mentioned, one link failure for each receiver node can be recovered at the same time with about 40% fewer redundant links by applying DC-NC coding. This illustrates the power of DC-NC networking.

Furthermore, not only data associated with link failures can be recovered. If node 4 fails, c_1 will be lost, the DC-NC coding scheme can recover the required data streams as shown in (4 – 13) - (4 – 15). However, if node 5 fails, network protection will be lost i.e. c_2, but data communication can still be made. In this way, both reliability and throughput are improved with DC-NC networking.

The superiority of DC-NC coding over Diversity Coding is illustrated in Table 4.1 for the above network.

Table 4.1 Protection schemes comparisons

Protection Scheme	**Diversity Coding**	**DC-NC coding**
Number of data streams	2	2
Number of coded data stream(s)	1	2
Number of broadcast data streams	0	2
Number of utilized links	9	10
Number of redundant links	7	3

Table 4.1 (Continued)

Protection Scheme	Diversity Coding	DC-NC coding
Failed data recovery time	Low	Ultra-Low
Number of tolerant link failures	1 link for whole network	1 link for each receiver node

4.4 Throughput and Reliable Enhancement via DC-NC Coding

A 5G C-RAN wireless network may need to broadcast/multicast downlink information to all/some RRHs. Improving throughput is critical due to wireless link capacity limitations. In addition, link failures can occur due to weather changes or other environmental factors. To increase its throughput and improve the reliability with minimal delay without rerouting or retransmission, the DC-NC technique is very appealing as illustrated in the following.

4.4.1 DC-NC Coding for Two-Tier Mixed Fronthaul Networks

The application of DC-NC coding to a 5G C-RAN mixed (optical and wireless) fronthaul network, where a wireless link failure is considered, is illustrated in Figure 4.4. Four optical links (green arrows) connect between the BBU and the first tier RRHs (RRH11, RRH12, RRH13, RRH14). In addition, several wireless links (black arrows) connect the first and second tiers RRHs. In this fronthaul network, each link is bi-directional. Furthermore, there is no direct connection between the BBU and second tier RRHs.

As it is mentioned in Section 4.2, in this scenario, the second tier RRHs are assumed to be distant from the BBU and they are connected to the first tier RRHs via wireless links and thus to the BBU. In this study, a downlink point-to-multipoint network topology is considered[6]. The optical connections in the first tier are considered to be reliable. So that in order to broadcast two data streams from the BBU to the second tier RRHs: RRH21, RRH22, and RRH23 via the first tier

[6] In the uplink, DC-NC coding would generally not be used, as there is typically no broadcasting or multicasting from RRH to other RRHs. However, Diversity Coding alone can apply as shown in Chapter 3.

RRHs using the DC-NC coding scheme, four disjoint paths are used. The BBU transmits data streams x_1 and x_2 to RRH11 and RRH14 respectively. In addition, the BBU encodes them and forms c_1 and c_2 as shown in (4 – 1) and (4 – 2) then transmits them to RRH12 and RRH13 respectively. RRH11 sends data stream x_1 to RRH21 and RRH22. Similarly, RRH14 sends data stream x_2 to RRH22 and RRH23. Hence, RRH22 has x_1 and x_2. RRH12 sends c_1 to RRH21 and RRH23. RRH21 decodes c_1 and x_1 then gets x_2 as shown in (4 – 3), (4 – 4), and (4 – 5). Similarly, RRH23 decodes c_1 and x_2 then gets x_1 as shown in (4 – 6), (4 – 7), and (4 – 8). Here, RRHs may use directional antennas or MIMO systems to prevent interference.

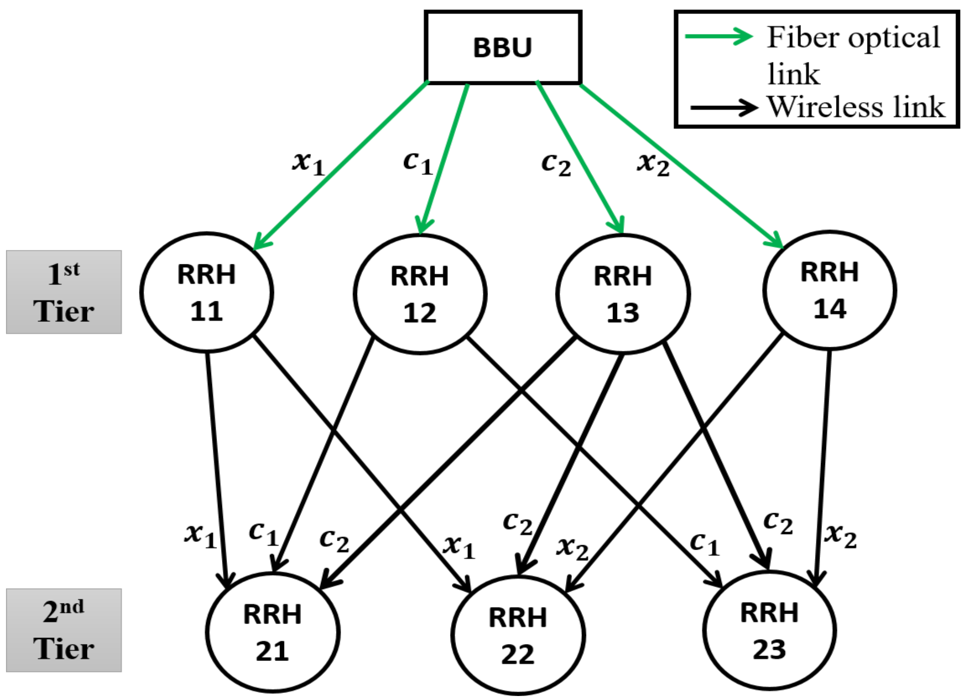


Figure 4.4 DC-NC coding applied to mixed optical and wireless fronthaul network.

To improve network reliability, RRH13 transmits c_2 to all second tier RRHs. When there is no link failure, the second tier RRHs ignore c_2. In case of a link failure (for example, the link from RRH11 to RRH21 fails), RRH21 detects the failure then utilizes c_1 and c_2 to recover x_1 and

x_2 as shown in (4 – 9) through (4 – 12). Furthermore, if c_1 fails, then RRH21 has x_1 and c_2 and can easily recover x_2 as shown in (4 – 13), (4 – 14), and (4 – 15).

Similarly, RRH23 can recover x_1 and x_2. However, RRH22 does not have c_1 so, if x_2 fails, data stream x_2 can be easily recovered as shown in (4 – 13), (4 – 14), and (4 – 15). Also, if x_1 fails, data stream x_1 can be easily recovered as follows:

$$\tilde{c}_2 = c_2 + \beta_{22}x_2, \qquad (4-16)$$

and applying (4 – 2) to (4 – 16)

$$\tilde{c}_2 = \beta_{12}x_1 + \beta_{22}x_2 + \beta_{22}x_2 = \beta_{12}x_1, \qquad (4-17)$$

$$x_1 = \tilde{c}_2/\beta_{12}\,. \qquad (4-18)$$

Note that DC-NC coding scheme can simultaneously recover from one link failure for each second tier RRH. Furthermore, not only link failures can be recovered. In Figure 4.4, if RRH11, RRH12, or RRH14 fails, the proposed coding scheme can recover the required data streams. However, if RRH13 fails, protection of the network will be lost i.e. c_2, but, if this is the only failure, data communication can still be achieved. In this way, reliability is improved with simultaneous multi-link failures tolerance. Hence, both reliability and throughput are improved using DC-NC coding**.**

As with all restoration methods, there is an increase in the number and utilization of links. However, DC-NC coding can decrease the number of redundant links compared with that in Diversity Coding on average by about (30%-40%).

4.4.2 DC-NC Coding for Completely Wireless Fronthaul Networks

Figure 4.5 shows the application of DC-NC coding to a 5G C-RAN with a completely wireless fronthaul network, where a link failure is considered. In this scenario, the BBU has a direct wireless link with most RRHs (four of them are shown in Figure 4.5). In addition, several wireless links connect the RRHs.

RRH4 is considered to be distant from the BBU so, it has no direct link with the BBU but connected to other RRHs and thus to the BBU (If this link exists, DC-NC coding can also be applied, but without throughput gain). In this fronthaul network, each link is bi-directional. Similarly, to the previous subsection, a downlink point-to-multipoint network topology is considered. So that in order to broadcast two data streams from the BBU to RRHs: RRH3, RRH4, and RRH5 using the DC-NC coding scheme, four disjoint paths are used. BBU transmits data streams x_1 and x_2 to RRH3 and RRH5 respectively. In addition, it encodes them and forms c_1 and c_2 as shown in (4 – 1) and (4 – 2) then transmits them to RRH1 and RRH2 respectively. RRH3 and RRH5 send x_1 and x_2 respectively to RRH4. Hence, RRH4 has both broadcast data streams. RRH1 sends c_1 to RRH3 and RRH5. RRH3 decodes c_1 and x_1 then gets x_2 as shown in (4 – 3), (4 – 4), and (4 – 5). Similarly, RRH5 decodes c_1 and x_2 then gets x_1 as shown in (4 – 6), (4 – 7), and (4 – 8). Directional antennas or MIMO systems may be used by the RRHs to prevent any interference.

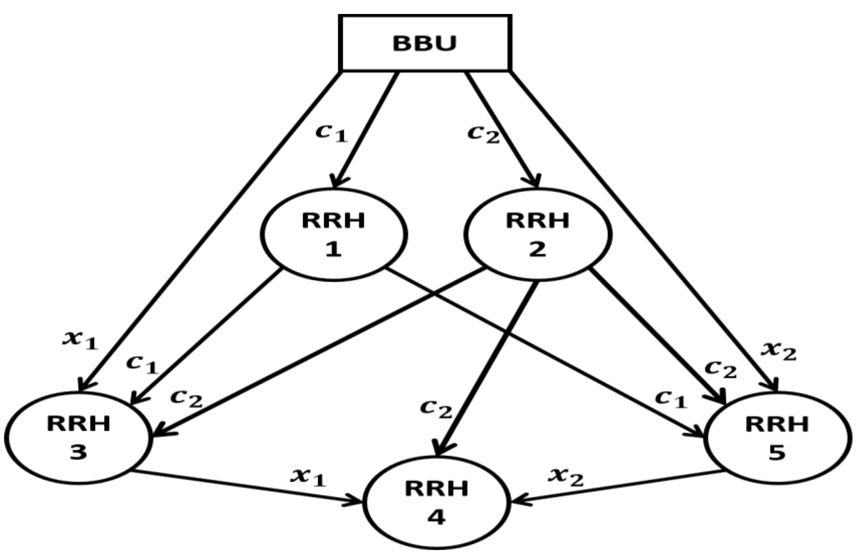


Figure 4.5 DC-NC coding applied to a wireless fronthaul network.

To improve network reliability, RRH2 transmits c_2 to RRH3, RRH4, and RRH5. When there is no link failure, the targeted RRHs ignore c_2. In case of a link failure (for example, the link from BBU to RRH3 fails), RRH3 detects the failure then utilizes c_1 and c_2 to recover x_1 and x_2 as shown in (4 – 9) through (4 – 12). Furthermore, if c_1 fails, RRH3 has x_1 and c_2 then can easily recover x_2 as shown in (4 – 13), (4 – 14), and (4 – 15). Similarly, RRH5 can recover x_1 and x_2. However, since RRH4 will not receive c_1 , so, if x_2 fails, data stream x_2 can be easily recovered as shown in (4 – 13), (4 – 14), and (4 – 15). Also, if x_1 fails, data stream x_1 can be easily recovered as shown in (4 – 16), (4 – 17), and (4 – 18).

Note that the DC-NC coding scheme can simultaneously recover one link failure for each targeted RRH. Furthermore, not only data associated with link failures can be recovered. In the example network, if RRH1 fails, c_1 will be lost, the proposed coding scheme can recover the data streams for all targeted RRHs. However, if RRH2 fails, protection of the network will be lost i.e. c_2, but data communication can still be achieved. In this way, reliability is improved with simultaneous multi-link failures tolerance. Hence, both reliability and throughput are improved using the proposed coding scheme.

As it is mentioned above, with all restoration methods, there is an increase in the number and utilization of links. However, the number of redundant links is decreased using the proposed coding technique comparing to that in Diversity Coding as described earlier in this section.

Although in this chapter, it is solely focused on applying DC-NC coding in a wireless fronthaul network that can tolerate multi-link failures, future work will investigate this approach to more general and complex network topologies that include optical and wireless links.

4.5 Applying DC-NC Coding to CoMP in C-RAN

A 5G wireless C-RAN that utilizes downlink JT-CoMP to mitigate inter-cell interference, needs to broadcast downlink information to several RRHs called a CoMP set. The redundant transmission consumes network resources. Reducing overall network resource consumption is important to overcome the limitations of wireless link capacity. In addition, due to weather changes or other environmental factors such as blockage, link failures can occur. To enhance resource utilization and improve the reliability with near instant link/node failure recovery, the DC-NC technique is very appealing, as depicted below.

The application of DC-NC coding to downlink JT-CoMP in a 5G wireless fronthaul C-RAN network, where a link failure is considered is depicted in Figure 4.6. In this scenario, a direct wireless link between the BBU pool and most RRHs is considered. In addition, RRHs are connected to each other by wireless links. However, when the distance between RRH5 and BBU pool is considered to be too great, no direct link exists with the BBU pool, but RRH5 is connected to other RRHs and thus can reach the BBU pool. For simplicity, the connections between the user(s) and the CoMP set RRHs are not shown in Figure 4.6. However, it is similar to that in Figure 4.1. Each fronthaul link is bi-directional. In this study, a downlink point-to-multipoint network topology is considered to model the application of downlink JT-CoMP. The CoMP set RRHs are RRH3, RRH4, and RRH5. So that using the DC-NC coding method, four disjoint paths are needed to broadcast two data streams (for the same user or each one for a different user) from the BBU pool to all RRHs in the CoMP set. Utilizing direct links, data streams x_1 and x_2 are sent from the BBU pool to RRH3 and RRH4 respectively. In addition, coded data c_1 and c_2 are formed in the BBU/BBUs pool as shown in $(4-1)$ and $(4-2)$ then sent to RRH1 and RRH2 respectively. RRH5 receives x_1 and x_2 directly from RRH3 and RRH4 respectively. Hence, RRH5 receives both broadcast data streams. RRH1 sends c_1 to RRH3 and RRH4. Coded data c_1 and data stream $x_1$are decoded in RRH3 to obtain x_2 as illustrated in (4 – 3), (4 – 4), and (4 – 5). Similarly, c_1 and x_2 are decoded in RRH4 to get x_1 as depicted in (4 – 6), (4 – 7), and (4 – 8).

If only standard routing were allowed, then the link that connects the BBUs pool and RRH1 would be only able to carry x_1 or x_2, but not both. Suppose x_1 is sent through this link; then RRH3 would receive x_1 twice and not have x_2 at all. Similarly, Sending x_2 poses the same problem for the RRH4. So that routing is insufficient because no routing scheme can transmit both x_1 and x_2 simultaneously to both destinations. Hence, by encoding the data x_1 and x_2 at the BBU, the throughput is improved by one-third in this application. This illustrates the network resource utilization enhancement of DC-NC coding, which is similar to that of Network Coding.

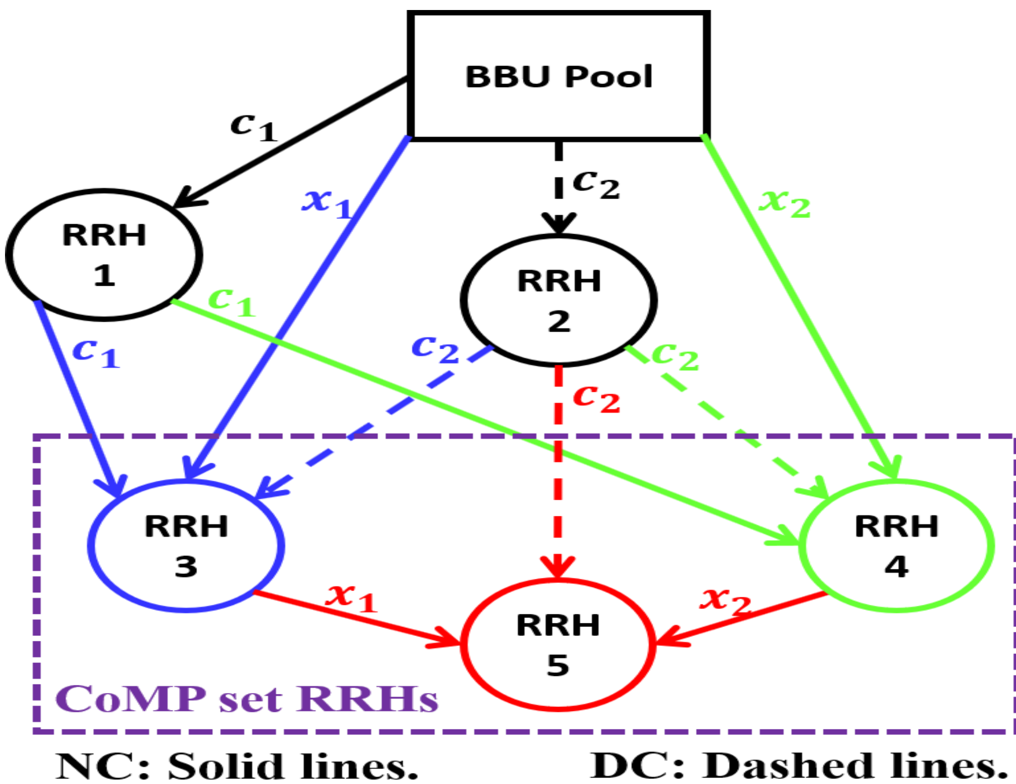


Figure 4.6 DC-NC coding applied to downlink JT-CoMP in wireless fronthaul C-RAN, where the CoMP set RRHs are RRH3, RRH4, and RRH5.

Wireless fronthaul network reliability can be improved by transmitting c_2 from RRH2 to the CoMP set RRHs. The coded data c_2 will be ignored when there is no link failure. In the presence of a link failure, for example, if the link from the BBU pool to RRH3 fails, RRH3 detects the failure then recovers x_1 and x_2 by utlizing c_1 and c_2 as shown in (4 – 9) through (4 – 12). Furthermore, if c_1 lost, RRH3 has x_1 directly and c_2 then can quickly and easily recover x_2 as illustrated in (4 – 13), (4 – 14), and (4 – 15).

Similarly, data streams x_1 and x_2 can be recovered at RRH4. However, since c_1 will not be received by RRH5, if x_2 is lost, data stream x_2 can be easily and quickly recovered as shown in (4 – 13), (4 – 14), and (4 – 15). Also, if x_1 is lost, data stream x_1 can be easily and quickly obtained as shown in (4 – 14), (4 – 17), and (4 – 18).

As DC-NC coding has the ability to simultaneously recover from one link failure at each destination node, hence, in this example fronthaul network, DC-NC can recover from three link failures simultaneously (one failure for each targeted RRH), but NOT from two or more failed links for the same RRH. In general, if link failures are associated with different RRHs, then DC-NC can recover from these simultaneous failures. For example, when c_1 at RRH3, x_2 at RRH4, and x_1 at RRH5 fail simultaneously, DC-NC can recover from all these simultaneous failures since each failure belongs to a different RRH. However, when more than one failure belongs to the same RRH, DC-NC *cannot* recover from these failures. For example, when c_1 and x_1 fail simultaneously at RRH3, DC-NC cannot recover because both failures belong to the same RRH.

Furthermore, in addition to link failure recovery, DC-NC coding can recover from one intermediate node failure, such as RRH1, because this corresponds to simultaneous link failures that are associated with different CoMP set RRHs. Also, when RRH2 fails, protection of the network will be lost i.e. c_2, but, if this is the only failure, successful data communication can still be achieved. However, when more than one node failure occurs, DC-NC *cannot* recover from these failures because this will cause two or more link failures at the same targeted RRH. For example, when RRH1 and RRH2 fail simultaneously, DC-NC cannot recover since c_1 and c_2 will be lost simultaneously.

In this example network, four redundant links are utilized to protect from one link failure at each CoMP set RRH, which consists of three RRHs. To protect the JT-CoMP network completely, another set of four links should be utilized as shown in Figure 4.7 (note the addition of RRH6 and distribution of coded data c_3). Here, each RRH in the CoMP set has the ability to tolerate two simultaneous link failures. In general, to tolerate n link failures for each RRH at the CoMP set that contains j RRHs, $jn + n$ redundant links are required.

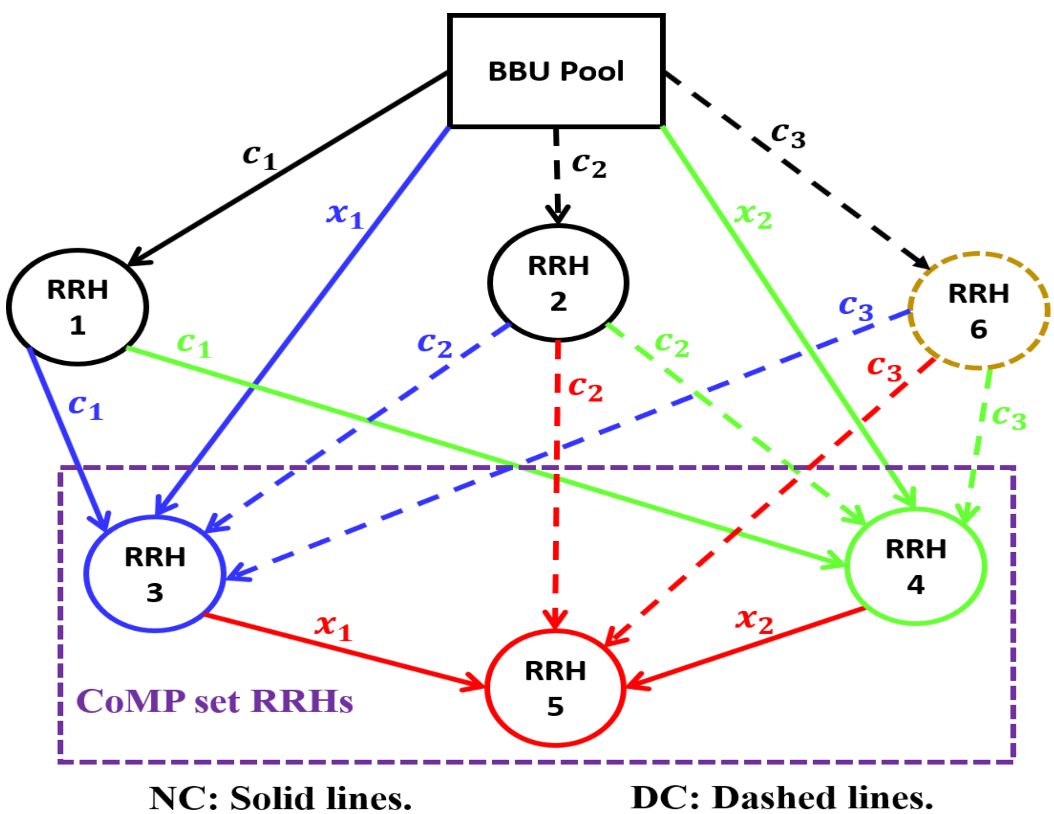


Figure 4.7 DC-NC coding applied to downlink JT-CoMP in wireless fronthaul C-RAN. Two simultaneous link failures can be tolerated (Complete protection).

It is clear that simulation of these algorithms is not necessary, since the link failure is taken into account regardless of the failure reason and it is shown mathematically how the fronthaul network and the JT-CoMP operation can be enhanced and protected by the DC-NC coding scheme. The recovery latency is lower bounded by the time it takes to detect a facility failure, which will vary from system to system.

The technology proposed in this chapter has the potential to enhance network reliability with the ability to tolerate multi-link failures in addition to near-instant link/node failure recovery. Therefore, both reliability and network resource utilization are improved by applying the DC-NC coding scheme.

Although in this study, we solely focused on applying the DC-NC coding scheme in a downlink JT-CoMP with a wireless fronthaul network, an area for future research is to investigate this approach to more general and complex network topologies that include optical and wireless links.

4.6 Concluding Remarks

This chapter presented a new coding scheme, DC-NC that synergistically combines Diversity and Network Coding. The performance of DC-NC is evaluated in two 5G fronthaul networks, the first where the RRHs in a C-RAN are connected to the baseband unit with two tiers of optical and wireless links and the second where (most) all RRHs in the C-RAN are connected directly to the BBU via wireless links. Also, the application of DC-NC coding to improve the performance of downlink JT-CoMP in 5G wireless fronthaul C-RANs is introduced. In all scenarios, DC-NC coding increases throughput and reduces the resource consumption in the network by about one-third for broadcasting or multicasting applications, while simultaneously enabling near-instantaneous latency in recovery from multiple link/node failures in fronthaul networks. Also, the number of redundant links is decreased by applying DC-NC coding by about 30%-40%, when compared to that of Diversity Coding.

Furthermore, DC-NC networks can tolerate n link failures for each destination RRH at the CoMP set that contains j RRHs, where, $jn + n$ additional links are required to provide protection.

CHAPTER 5: ULTRA-RELIABLE, NEAR-INSTANT FAULT RECOVERY IN WIRELESS FRONTHAUL AND SENSOR NETWORKS[7]

5.1 Introduction

Several applications in 5G wireless communications systems are required to be ultra-reliable and very efficient with ultra-low latency communications [8]. This chapter describes a methodology for rapid recovery from link and/or node failures in the fronthaul networks of 5G Fog Radio Access Networks (F-RANs) and in Wireless Sensor Networks (WSNs). F-RANs are an enhancement and an alternative to Cloud Radio Access Networks (C-RANs) [5]-[7]. The key idea of a F-RAN is to employ edge nodes with the ability to store data, control signals, and communicate to each other instead of centralizing processing in the baseband unit (BBU) at the C-RAN [5]-[7]. In contrast a WSN contains one or more gateway nodes (central controllers) and several sensor nodes that are implemented at different locations [14]-[15]. Each sensor node contains a sensor with the ability to monitor specific conditions such as temperature, pressure, noise levels, etc. [14]-[15]. Very low energy consumption [14]-[16], efficient transmission, and ultra-reliability are required for the WSNs [14]. As mentioned in Section 2.3.1, Diversity Coding (DC) [18]-[20], an open loop coding technique, can help address this challenge and is a forward error control networking technology over diverse routes. With DC, once the failure is detected the lost message can be rapidly recovered without performing rerouting and/or retransmission. It is

[7] The content of this chapter has been accepted for publication in [33] and has been published in [34] and [35], and it is included in this dissertation with permissions from the IEEE. Permissions are included in Appendix A.

worth noting that the time to determine the facility loss will be a lower bound on the recovery latency.

In Chapter 3, DC is used to improve the reliability of a C-RAN network with the ability to tolerate multiple simultaneous link/node failures. Also, Diversity Coding was described as a means to improve the reliability of OFDM-based vehicular systems [55] and wireless body area networks [53]-[54]. Although reliability is extremely important in F-RANs and WSNs, efficient transmission, and very low energy consumption are other important factors that affect the F-RANs and WSNs performance. Network Coding (NC) [21] has the ability to further improve 5G wireless F-RAN performance by increasing its throughput. Triangular Network Coding (TNC) [27] is another mode of NC that can be used for this purpose with less computational complexity. Hence, TNC has the ability to provide minimum energy consumption with higher throughput.

A synergistic combination of Diversity Coding (DC) and Network Coding (NC) (DC-NC) was introduced in Chapter 4 and can simultaneously improve wireless network reliability, provide high throughput, enhance energy consumption, and enable low failure-recovery latency for 5G wireless fronthaul networks. DC-NC coding can be easily integrated into the-state-of-art F-RAN by deploying relay nodes that are configured to enable DC-NC coding. However, the DC-NC coding scheme depends on deterministically chosen coefficients from a finite (Galois) field and the computational complexity will increase dramatically with an increased number of broadcast data streams and/or the number of link failures that need to be protected. This will increase the energy cost of link failure recovery, as DC-NC coding requires increasing the finite field (GF) size. Consequently, the coding process will consume more energy, as it includes matrix inversion.

DC-NC coding like other types of protection techniques requires extra transmission capacity. In Chapter 4 it is shown that DC-NC coding has better spare capacity compared with that of Diversity Coding.

In this chapter, (1) Triangular Network Coding (TNC) is modified to enhance DC-NC coding and realize the benefits of enhanced Diversity and Network Coding (eDC-NC) for F-RAN wireless networks by improving their reliability, (2) reduce computational complexity, (3) enable extremely low recovery time for simultaneous multiple link failures, (4) enable ultra-low energy consumption systems, (5) retaining the throughput gains of DC-NC for broadcasting or multicasting applications, and (6) extend the application of eDC-NC coding to WSNs. In addition, a general eDC-NC encoding expression is derived, an explicit algorithm for eDC-NC decoding is derived, and a performance analysis in terms of redundancy percentage requirements is presented. Furthermore, solutions for a synchronization problem in eDC-NC are discussed.

5.2 System Model

5.2.1 Fog-Computing-Based Radio Access Network (F-RAN)

As it is mentioned earlier in Chapter 1, with F-RANs, a significant number of functions such as controlling, communicating, and data storing and processing are migrated from the BBU pools to the network-edge devices to enhance the performance of C-RANs. This requires the RRHs to be upgraded and are called Fog Access Points (F-APs). In addition, they are able to communicate with each other. Since functionality is performed at the network edge rather than in the core, it is shown that this architecture reduces communication latency [5]-[7].

Several transmission modes can be utilized in F-RANs, such as the C-RAN and Local Distributed Coordination (LDC) modes as depicted in Figure 1.3 [5]. The core mode for the F-RAN is the LDC mode, whereas the C-RAN mode is similar to that in a classic C-RAN. In LDC, the F-APs cooperate with each other to serve the Fog-User Equipment (F-UE). Furthermore, these transmission modes can work together to serve both User Equipment (UE) and F-UE. This will decrease the burden on the fronthaul network. Therefore, the required data can be transmitted to the F-UE and UE (via RRHs) not from the cloud server but from the F-APs [5].

In this chapter, the new coding technique (eDC-NC coding) is applied to two scenarios involving wireless fronthaul networks to improve the performance of F-RANs. In the first scenario, eDC-NC is applied to the LDC fronthaul network, where F-APs are connected to each other in a mesh topology as shown in Figure 5.1, where these connections are considered to be wireless links.

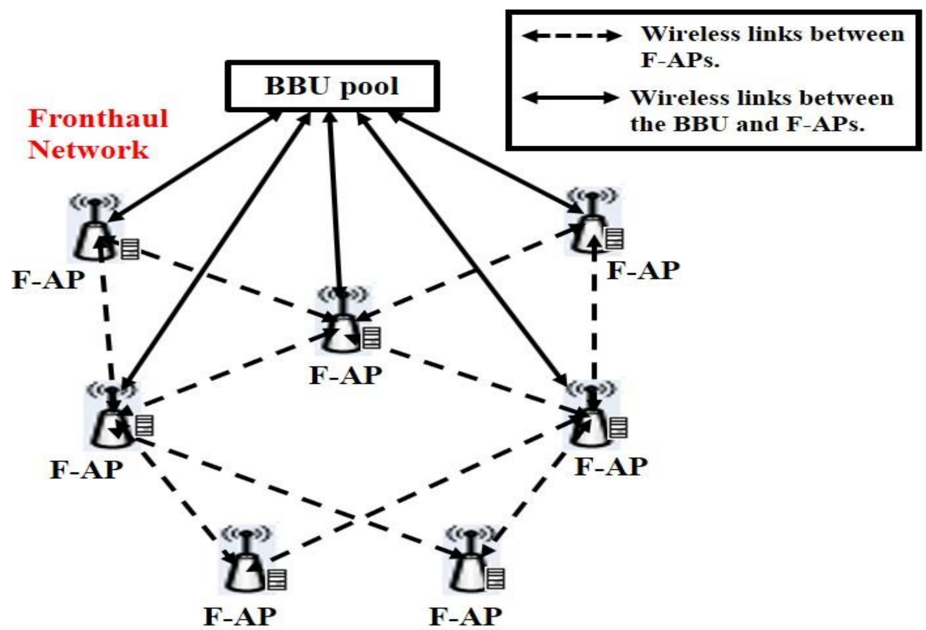


Figure 5.1 LDC transmission mode in a F-RAN fronthaul network with wireless links.

In the second scenario, eDC-NC is applied to a mixture of the C-RAN and LDC transmission modes in a fronthaul network, where F-APs and RRHs are connected to each other in a mesh topology as shown in Figure 5.2. Here, these connections are also assumed to be wireless links. In both scenarios, MIMO technology will likely be used by the F-APs and RRHs to decrease interference and to realize communicate with each other.

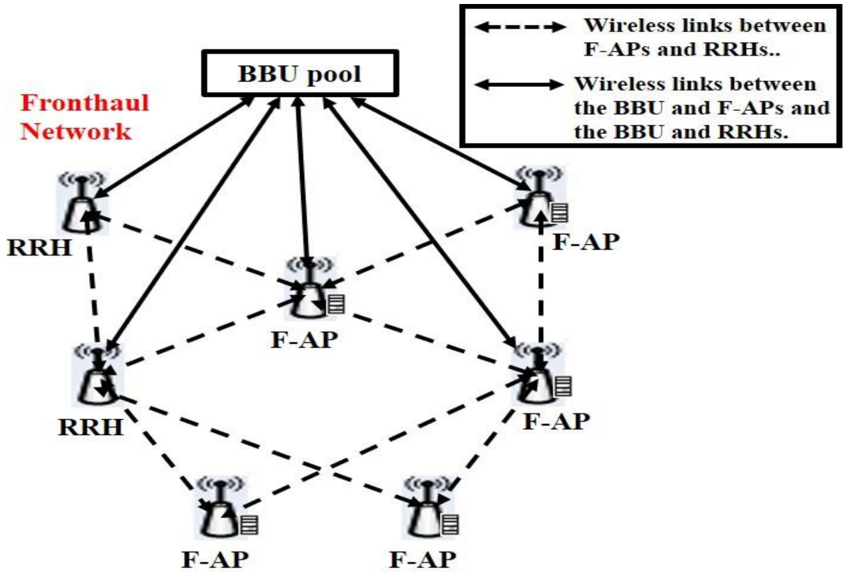


Figure 5.2 LDC and C-RAN transmission modes in a F-RAN fronthaul network with wireless links.

5.2.2 Wireless Sensor Networks

Since eDC-NC has very low computational complexity and ultra-low energy cost, eDC-NC may be applied to a WSN to increase the reliability in a network with a multi-hop mesh topology, where sensor nodes are connecting to each other by wireless links as shown in Figure 1.4. The collected data is transmitted from sensor nodes to the gateway node, and commands and other information is transmitted from the gateway to the sensor nodes. Here, the focus is on an uplink scenario, where a sensor node sends the collected information to the gateway nodes.

5.3 Enhanced DC-NC Encoding and Decoding Algorithms

As the number of broadcast data streams and/or the number of coded data streams increases, a large finite Galois field, denoted by $GF(2^m)$ where $m \geq 1$, is required to select the coefficients for coding data streams over DC-NC coding. Consequently, this will result in high encoding and decoding computational complexity. This will also increase the fault recovery time and energy consumption. To solve this problem, DC-NC coding will be modified such that only *GF(2)* i.e. a simple XOR operation will be utilized in the encoding and decoding processes.

In this section, the modification of TNC is explained and utilized to enhance DC-NC coding (dubbed eDC-NC). First, it will be shown that TNC cannot work as desired with a raw data stream present at the receiver node.

Recall from Section 2.3.2.1, that the unique ID of the encoded data stream is represented as $[r_1, r_2, \ldots, r_N]$, where r_i is the number of redundant "0" bit(s) that are added at the head of the i^{th} raw data stream and N is the number of broadcast data streams.

As an example of a regular TNC, where the number of broadcast data streams, N, is 3, the unique ID of the coded data stream is represented as $[r_1, r_2, r_3]$, hence, the unique ID of the first coded data stream, c_1, is $[0, 1, 2]$, which in general is given by $[0, 1, \ldots, N-1]$. The second coded data stream, c_2, is generated by fixing the position of "0" in the first ID and cyclically rotating the other terms. Hence, the second coded data stream's ID will be $[0, 2, 1]$. In this way, only $N-1$ coded data streams can be generated. To generate another $N-1$ coded data streams, the position of "0" in the first ID will be changed to be in the second position such that the ID will be $[1, 0, \ldots, N-1]$ and all other terms except "0" will be rotated. With N positions for "0" to be fixed, $N \times (N-1)$ coded data streams can be generated. So that in this example, $3 \times (3-1) = 6$ coded data streams can be generated, and their unique IDs will be as follows:

$$ID_{c_1} = [0, 1, 2], \quad ID_{c_2} = [0, 2, 1], \quad ID_{c_3} = [1, 0, 2],$$

$$ID_{c_4} = [2, 0, 1], \quad ID_{c_5} = [1, 2, 0], \quad ID_{c_6} = [2, 1, 0].$$

Now, assume that the receiver node has the raw data stream x_1 and it received c_1 and c_4. To extract x_2 and x_3, XOR operation between x_1 and c_1 and x_1 and c_4 will be done, the result will be as shown in the tables below:

Table 5.1 Coded data stream c_1 after XOR operation with x_1

0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$			....	$b_{2,B}$	0
0	0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$			....	$b_{3,B}$

Table 5.2 Coded data stream c_4 after XOR operation with x_1

$b_{2,1}$	$b_{2,2}$	$b_{2,3}$			....	$b_{2,B}$	0	0
0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$			....	$b_{3,B}$	0

It is clear that both data streams are similar and hence, the bit level back substitution scheme described in Section 2.3.2.1 will not work, since only the bit $b_{2,1}$ can be obtained from both tables of coded data streams. Therefore, x_2 and x_3 cannot be recovered. Table 5.3 shows other cases that can lead to the same problematic result.

Table 5.3 Other problematic cases for TNC

Available raw data stream	**Coded data streams**	
	First code & its ID	**Second code & its ID**
$\boldsymbol{x_1}$	c_2 [0, 2, 1]	c_6 [2, 1, 0]
$\boldsymbol{x_2}$	c_2 [0, 2, 1]	c_3 [1, 0, 2]
$\boldsymbol{x_2}$	c_4 [2, 0, 1]	c_5 [1, 2, 0]
$\boldsymbol{x_3}$	c_1 [0, 1, 2]	c_5 [1, 2, 0]
$\boldsymbol{x_3}$	c_3 [1, 0, 2]	c_6 [2, 1, 0]

To enhance TNC such that it works with a raw data stream present at a destination node, it is noted that the coded data streams with a zero that is fixed in only one position in their IDs can recover the other required raw data streams. However, with only one position for a fixed "0", only

$(N-1)$ coded data streams can be generated. Using the same method used in TNC to generate another group of coded data streams, will not work with a raw data stream in the destination nodes for the same reason that is discussed above. Hence, to generate another group of $(N-1)$ coded data, let the new ID will be [0, the smallest integer greater than r_{max} at the previous group (r_{2_α}), $r_{2_\alpha}+\alpha, \ldots, r_{2_\alpha}+\alpha(N-2)$], where α represents the group number. This represents the general coded data stream IDs for $\alpha > 1$.

A general notation to generate the encoded data streams such that they can work perfectly with or without raw data stream may be derived. The coded data stream can be expressed as:

$$c_i = x_{1,0} \bigoplus_{r=1}^{N-1} x_{[i-(\alpha-1)(N-1)+r+\delta]mod(N),[\alpha r+(\alpha-1)(N-2)]} \qquad (5-1)$$

for $1 \leq i \leq 2(N-1)$, where $\delta = \begin{cases} 0 & if\ i-(\alpha-1)(N-1)+r \leq N \\ 1 & elsewhere \end{cases}$,

In addition, x is the raw data stream and α is either 1 or 2. In this way, $2(N-1)$ coded data streams can be generated. Generally, in DC-NC coding, only $(N-1)$ coded data streams for NC are required to realize the throughput gain and N coded data streams for DC are required to get a fully protected network (i.e. the system can recover from a number of link failures equal to the number of transmitted data streams at each destination node). However, using (5 – 1), $(N-1)$ coded data streams are generated for NC and another $(N-1)$ coded data streams are generated for DC, which means one more coded data stream must be generated to get a fully protected DC-NC network. The last coded data stream, which belongs to the third group of coded data streams can be generated, when it is required, from the general coded data stream's ID representation that is shown above. Note that the fully protected network is not always required or preferred because it requires additional redundant transmission facilities. For example, to broadcast 3 data streams i.e. $N = 3$ and tolerate 2 link failures for each destination node, 4 coded data streams will be required, which can be generated as follows:

$$c_i = x_{1,0} \bigoplus_{r=1}^{2} x_{[i-(\alpha-1)2+r+\delta]mod(3),[\alpha r+(\alpha-1)]} \quad (5-2)$$

for $1 \leq i \leq 4$, where $\delta = \begin{cases} 0 & if\ i-(\alpha-1)2+r \leq 3 \\ 1 & elsewhere \end{cases}$,

For $\alpha = 1$, first group of coded data streams will be

$$c_1 = x_{1,0} \oplus x_{2,1} \oplus x_{3,2}, \quad (5-3)$$

$$c_2 = x_{1,0} \oplus x_{2,2} \oplus x_{3,1}, \quad (5-4)$$

For $\alpha = 2$, second group of coded data streams will be

$$c_3 = x_{1,0} \oplus x_{2,3} \oplus x_{3,5}, \quad (5-5)$$

$$c_4 = x_{1,0} \oplus x_{2,5} \oplus x_{3,3}, \quad (5-6)$$

where x_{i,r_i} represents the i^{th} raw data stream and r_i is the number of redundant “0” bit(s) that are added at the front of the raw data stream.

For the decoding process, although it is similar to that used in TNC, an algorithm and general notation for the decoding process are derived as follows:

1) Selection of the coded data stream that will be used to extract a specific raw data stream:
   a) The IDs of $(N-1)$ available coded data streams at the destination node will be checked after neglecting $r_{\text{available raw data stream}}$ from there. Note that the unique ID of the coded data stream is represented as $[r_1, r_2, \dots, r_N]$.
   b) For each required raw data stream position in each coded data stream’s ID, r_i will be compared. The coded data stream with smaller r_i in its ID will be selected to extract the i^{th} raw data stream.

Example 1: For $N = 3$, x_1, the first raw data stream, c_1, and c_2 are available at the destination node. The IDs of c_1 is $[0, 1, 2]$ and c_2 is $[0, 2, 1]$, where the general ID of the coded data stream for $N = 3$ is $[r_1, r_2, r_3]$. Now, r_1 from each ID will be neglected because x_1 is available, then it is noted from comparing the IDs of c_1 and c_2 that r_2 in the ID of c_1 is less than that in the ID of c_2. Similarly, r_3 in the ID of c_2 is less than that in the ID of c_1. Hence, c_1 will be used to extract x_2, the second raw data stream, as its ID has the smaller r_2, and c_2 will be used to extract x_3, the third raw data stream, as its ID has the smaller r_3.

c) In case where r_i, r_{i-1}, and so on in the ID of the same coded data stream are less than those in the ID of the second (others) coded data stream(s), the results of differences between r_i in the IDs of the coded data streams will determine which code will be used to extract the raw data streams. The larger the difference between r_i in the ID of the coded data streams indicates that the i^{th} data stream will be extracted from the coded data stream that has a smaller r_i in its ID.

Example 2: For $N = 3$, x_1, c_1, and c_3 are available at the destination node. The IDs of c_1 is $[0, 1, 2]$ and c_3 is $[0, 3, 5]$, where the general ID of the coded data stream for $N = 3$ is $[r_1, r_2, r_3]$. Now, r_1 from each ID will be neglected because x_1 is available. It is noted that r_2 and r_3 in the ID of c_1 have smaller values than those in the ID of c_3. Hence, the difference of r_2 in the IDs of c_1 and c_3 is calculated. Similarly, the difference of r_3 in the IDs of c_1 and c_3 is calculated.

$$|r_2 \; in \; the \; ID \; of \; c_1 - \; r_2 \; in \; the \; ID \; of \; c_3| = |1 - 3| = 2,$$

$$|r_3 \; in \; the \; ID \; of \; c_1 - \; r_3 \; in \; the \; ID \; of \; c_3| = |2 - 5| = 3.$$

Since the larger the difference between r_3 in the IDs of c_1 and c_3 is obtained and the ID of c_1 has the smaller r_3, hence, c_1 will be used to extract x_3 and c_3 will be used to extract x_2.

2) After selecting the coded data streams that will be used to decode the raw data streams, the required raw data stream is extracted using *the general decoding notation* as follows:

$$b_{i,k} = c_{s,(k+r_i \ in \ c_s)} \oplus b_{m,(k+(r_i-r_m) \ in \ c_s)} \oplus b_{l,(k+(r_i-r_l) \ in \ c_s)} \oplus \dots \qquad (5-7)$$

where $b_{i,k}$ is the bit k of raw data stream x_i, c_s is the selected coded data stream, $b_{m,(k+\cdots)}$, $b_{l,(k+\cdots)}$, and so on (based on the number of broadcasted data streams) are the known bits from other raw data streams. For $N = 3$ with one available raw data stream at destination node, the decoding processes are expressed in Table 5.4 while the decoding processes with *no* raw data stream at destination node, are expressed in Table 5.5.

Table 5.4 Enhanced DC-NC decoding scheme with one raw data stream at destination node

Available x_i	**Coded data**		**Raw data streams after decoding (bit level)**
	1st code & its ID	**2nd code & its ID**	
x_1	c_1 [0, 1, 2]	c_2 [0, 2, 1]	$b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{1,(k+1)} \oplus b_{2,(k-1)}$
x_1	c_1 [0, 1, 2]	c_3 [0, 3, 5]	$b_{2,k} = c_{3,(k+3)} \oplus b_{1,(k+3)} \oplus b_{3,(k-2)}$ $b_{3,k} = c_{1,(k+2)} \oplus b_{1,(k+2)} \oplus b_{2,(k+1)}$
x_1	c_1 [0, 1, 2]	c_4 [0, 5, 3]	$b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$ $b_{3,k} = c_{4,(k+3)} \oplus b_{1,(k+3)} \oplus b_{2,(k-2)}$
x_1	c_2 [0, 2, 1]	c_3 [0, 3, 5]	$b_{2,k} = c_{3,(k+3)} \oplus b_{1,(k+3)} \oplus b_{3,(k-2)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{1,(k+1)} \oplus b_{2,(k-1)}$
x_1	c_2 [0, 2, 1]	c_4 [0, 5, 3]	$b_{2,k} = c_{2,(k+2)} \oplus b_{1,(k+2)} \oplus b_{3,(k+1)}$ $b_{3,k} = c_{4,(k+3)} \oplus b_{1,(k+3)} \oplus b_{2,(k-2)}$
x_1	c_3 [0, 3, 5]	c_4 [0, 5, 3]	$b_{2,k} = b_{3,(k+3)} \oplus b_{1,(k+3)} \oplus b_{3,(k-2)}$ $b_{3,k} = c_{4,(k+3)} \oplus b_{1,(k+3)} \oplus b_{2,(k-2)}$
x_2	c_1 [0, 1, 2]	c_2 [0, 2, 1]	$b_{1,k} = c_{1,k} \oplus b_{2,(k-1)} \oplus b_{3,(k-2)}$ $b_{3,k} = c_{1,(k+2)} \oplus b_{2,(k-1)} \oplus b_{1,(k+1)}$
x_2	c_1 [0, 1, 2]	c_3 [0, 3, 5]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{3,k} = c_{1,(k+2)} \oplus b_{2,(k+1)} \oplus b_{1,(k+2)}$
x_2	c_1 [0, 1, 2]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{3,k} = c_{1,(k+2)} \oplus b_{2,(k+1)} \oplus b_{1,(k+2)}$
x_2	c_2 [0, 2, 1]	c_3 [0, 3, 5]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{2,(k-1)} \oplus b_{1,(k+1)}$

Table 5.4 (Continued)

Available x_i	**Coded data**		**Raw data streams after decoding (bit level)**
	1st code & its ID	**2nd code & its ID**	
x_2	c_2 [0, 2, 1]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{2,(k-1)} \oplus b_{1,(k+1)}$
x_2	c_3 [0, 3, 5]	c_4 [0, 5, 3]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{3,k} = c_{4,(k+3)} \oplus b_{2,(k-2)} \oplus b_{1,(k+3)}$
x_3	c_1 [0, 1, 2]	c_2 [0, 2, 1]	$b_{1,k} = c_{2,k} \oplus b_{2,(k-2)} \oplus b_{3,(k-1)}$ $b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$
x_3	c_1 [0, 1, 2]	c_3 [0, 3, 5]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$
x_3	c_1 [0, 1, 2]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$
x_3	c_2 [0, 2, 1]	c_3 [0, 3, 5]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{2,k} = c_{2,(k+2)} \oplus b_{1,(k+2)} \oplus b_{3,(k+1)}$
x_3	c_2 [0, 2, 1]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{2,k} = c_{2,(k+2)} \oplus b_{1,(k+2)} \oplus b_{3,(k+1)}$
x_3	c_3 [0, 3, 5]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{2,k} = c_{3,(k+3)} \oplus b_{1,(k+3)} \oplus b_{3,(k-2)}$

Table 5.5 Enhanced DC-NC decoding scheme with no raw data stream at destination nodes

Coded data			**Raw data streams after decoding (bit level)**
1st code & its ID	**2nd code & its ID**	**3rd code & its ID**	
c_1 [0, 1, 2]	c_2 [0, 2, 1]	c_3 [0, 3, 5]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{1,(k+1)} \oplus b_{2,(k-1)}$
c_1 [0, 1, 2]	c_2 [0, 2, 1]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{1,(k+1)} \oplus b_{2,(k-1)}$
c_1 [0, 1, 2]	c_3 [0, 3, 5]	c_4 [0, 5, 3]	$b_{1,k} = c_{3,k} \oplus b_{2,(k-3)} \oplus b_{3,(k-5)}$ $b_{2,k} = c_{1,(k+1)} \oplus b_{1,(k+1)} \oplus b_{3,(k-1)}$ $b_{3,k} = c_{4,(k+3)} \oplus b_{1,(k+3)} \oplus b_{2,(k-2)}$
c_2 [0, 2, 1]	c_3 [0, 3, 5]	c_4 [0, 5, 3]	$b_{1,k} = c_{4,k} \oplus b_{2,(k-5)} \oplus b_{3,(k-3)}$ $b_{2,k} = c_{3,(k+3)} \oplus b_{1,(k+3)} \oplus b_{3,(k-2)}$ $b_{3,k} = c_{2,(k+1)} \oplus b_{1,(k+1)} \oplus b_{2,(k-1)}$

In Table 5.4 and Table 5.5, for $b_{i,(k-a)}$, where a is any number between 0 and r_{max},

$$b_{i,(k-a)} = 0 \qquad 0 > (k-a) > B \qquad (5-8)$$

In this way, eDC-NC coding can provide maximum reliability, ultra-low recovery time and minimal computational complexity, and high throughput.

Table 5.6 shows the performance differences between eDC-NC and DC-NC.

Table 5.6 The comparison between enhanced DC-NC and regular DC-NC

Criteria	eDC-NC	DC-NC
Encoding and decoding complexity	Less and same for any number of coded data	High and increases with increasing the number of coded data
Decoding scheme	bit by bit XOR substitution	Matrix inversion
Failed data recovery	Near-instant	Fast but decreases with increased number of coded data streams
Energy cost	Very low due to less complexity	Low but increases with increasing the number of coded data

5.4 Applying Enhanced DC-NC Coding

5.4.1 Applying Enhanced DC-NC Coding to F-RANs

Improving throughput and reliability in 5G F-RANs is critical due to wireless link capacity limitations. In addition, due to weather changes or other environmental factors, such as blockage, or excessive multiple access interference, link failures can occur. Enhanced DC-NC is a promising technology to improve the reliability of wireless F-RAN fronthaul networks and enable ultra-low recovery time from link/node failures while retaining the throughput enhancement feature of DC-NC for broadcasting applications.

5.4.1.1 Applying Enhanced DC-NC Coding to the LDC Transmission Mode in F-RANs

Figure 5.3 illustrates the application of eDC-NC coding to a wireless fronthaul F-RAN, where F-APs are connected to each other in a mesh topology by wireless links. Each fronthaul link is bi-directional. Here, a multipoint-to-multipoint network topology models the application of broadcasting three data streams from three F-APs to two destination F-APs. With the enhanced DC-NC coding method, five disjoint paths are needed to broadcast three data streams from three F-APs to other two F-APs. Utilizing direct links, data streams x_1 and x_3 are sent from F-AP1 and F-AP3 to F-AP7 and F-AP8 respectively. In addition, coded data c_1, c_2, c_3 and c_4 are formed as shown in (5 – 3)-(5 – 6) in F-AP4 then sent to F-AP5, F-AP6, F-AP9 and F-AP10 respectively. F-AP5 sends c_1 to F-AP7 and F-AP8. Also, F-AP6 sends c_2 to F-AP7 and F-AP8. Coded data streams $c_1$and c_2 in addition to data stream x_1 are decoded in F-AP7 to obtain x_2 and x_3 as described in Section 5.3. Similarly, c_1, c_2 and x_3 are decoded in F-AP8 to get x_1 and x_2. The throughput gains in this example network improve by at least one-fifth [31]. However, any link failure can strongly impact F-RAN reliability.

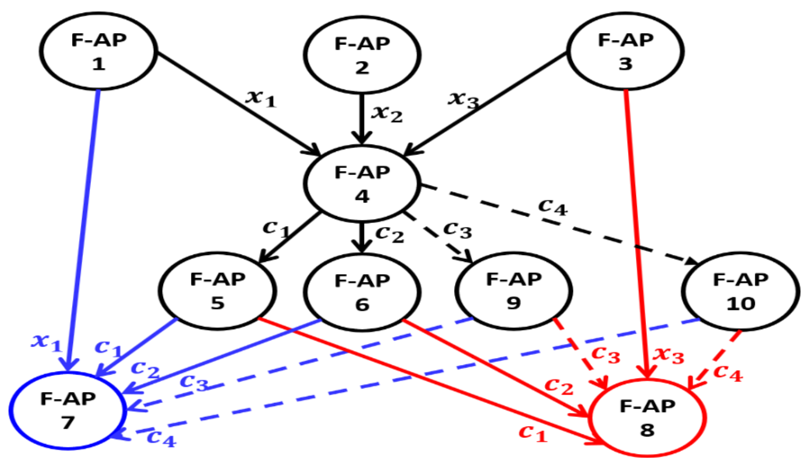


Figure 5.3 Example wireless fronthaul F-RAN network with eDC-NC coding that broadcasts three data streams to F-AP7 and F-AP8 and protects each stream from two simultaneous link failures. The solid lines represent the links that carry coded data streams and are used to improve network throughput whereas dashed lines represent the links that carry coded data streams and are used to maximize network reliability. The blue and red links distinguish the different destinations.

Wireless fronthaul network reliability can be improved by transmitting c_3 and c_4 from F-AP9 and F-AP10 to F-AP7 and F-AP8 respectively. The coded data c_3 and $c_4$will be ignored when there is no link failure. In the presence of a link failure, for example if the link from the F-AP1 to

F-AP7 that carries x_1 fails, F-AP7 detects the failure then recovers x_1, x_2 and x_3 by utilizing c_1, c_2 and c_3 as explained in Section 5.3 and shown in Table 5.5. In addition, if c_1 is lost, F-AP7 has x_1, c_2 and c_3 then can quickly and easily recover x_2 and x_3. Furthermore, if two link failures at F-AP7 occur, for example x_1 and c_2, F-AP7 detects the failures and then recovers x_1, x_2 and x_3 by utlizing c_1, c_3 and c_4 as illustrated in Section 5.3 and Table 5.5. Similarly, any two link failures can be recovered in the same way.

Furthermore, in addition to multiple link failure recovery, in this example fronthaul network enhanced DC-NC coding can recover from two intermediate node failures such as F-AP5 and F-AP6 because this corresponds to four simultaneous link failures, where two of them are associated with different destination F-APs. Also, when F-AP9 and F-AP10 fail, protection of the network will be lost i.e. c_3 and c_4, but, if these are the only failures, successful data communication can still be achieved.

5.4.1.2 Applying Enhanced DC-NC Coding to a Mix of the C-RAN and LDC Transmission Modes in F-RANs

The application of eDC-NC coding to a mixing of the C-RAN and Local Distributed Coordination (LDC) transmission modes in F-RAN network is illustrated in Figure 5.4. Here, wireless links are connecting F-APs and RRH to each other in a mesh topology, where each fronthaul link is bi-directional. To model the application of broadcasting three data streams from the BBU pool and two F-APs to one RRH and one F-AP, a multipoint-to-multipoint network topology is considered. With eDC-NC, five disjoint paths are needed to broadcast three data streams from the BBU pool and two F-APs to two destination nodes. Utilizing direct links, data streams x_2 and x_3 are sent from F-AP2 and BBU pool to F-AP6 and RRH1 respectively. In addition, F-AP3 receives data streams x_1, x_2, and x_3 and form coded data c_1, c_2, c_3 and c_4 as shown in (5 – 3)-(5 – 6) that are then sent to F-AP4, F-AP5, F-AP7 and F-AP8 respectively. F-AP4 and F-AP5 send c_1 and c_2 respectively to RRH1 and F-AP6. Coded data streams c_1 and c_2 in addition to data stream x_1 are decoded in RRH1 to obtain x_2 and x_3 as described in Section 5.3 and shown in Table 5.4. Similarly, c_1, c_2 and x_3 are decoded in F-AP6 to get x_1 and x_2. The throughput gains in this example network improve by at least 20% [31].

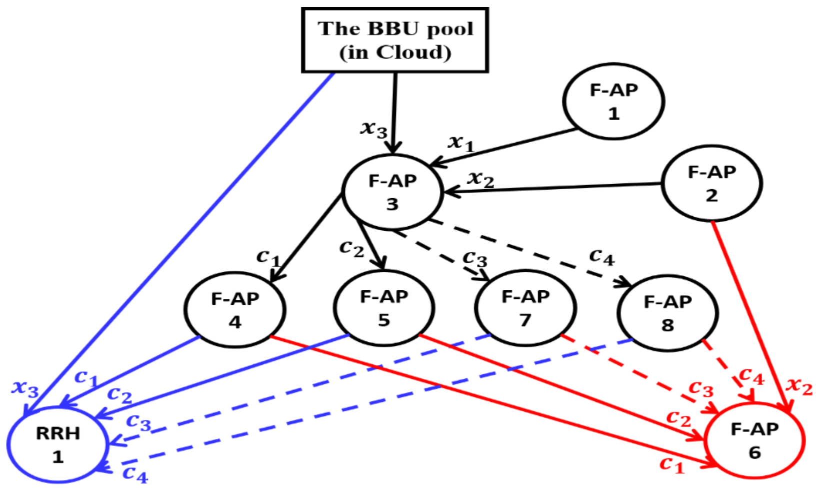


Figure 5.4 Example of eDC-NC coding applied to a 5G wireless fronthaul F-RAN, where solid lines represent the links that carry coded data streams and are used to improve network throughput whereas dashed lines represent the links that carry coded data streams and are used to maximize network reliability. The blue and red links distinguish the different destinations.

Wireless fronthaul network reliability can be improved by transmitting c_3 and c_4 from F-AP7 and F-AP8 respectively to RRH1 and F-AP6. The coded data c_3 and c_4 will be ignored when there is no link failure. In the presence of a link failure, for example if the link from the F-AP2 to F-AP6 fails, F-AP6 detects the failure then recovers x_1, x_2 and x_3 by utilizing c_1, c_2 and c_3 using the decoding algorithm described in Section 5.3 and shown in Table 5.5. In addition, if c_1 is lost, F-AP6 has x_2, c_2 and c_3 then can quickly and easily recover x_1 and x_3. Furthermore, if two link failures at F-AP6 occur, for example x_1 and c_2, F-AP6 detects the failures then recovers x_1, x_2 and x_3 by utlizing c_1, c_3 and c_4 as illustrated in Table 5.5. Similarly, any two link failures can be recovered in the same way. Note that the BBU can transmit x_3 directly to F-AP6 using the direct link between them instead of sending it to F-AP3, but in this case, x_3 will not be recoverable since it will be not included in coded data streams. In addition, the BBU pool can send x_3 to both destination nodes RRH1 and F-AP6 and to F-AP3. However, this will increase the burden on the fronthaul network, while the F-RAN was introduced to decrease fronthaul complexity. As shown in Figure 5.4, only two links from the BBU pool to the RRH1 and F-AP3 are enough to transmit the required data stream and make it recoverable.

Moreover, not only multiple link failures can be recovered by eDC-NC coding in this example fronthaul network. Two intermediate node failures such as F-AP4 and F-AP5 can be tolerated since this corresponds to four simultaneous link failures that each pair is associated with different destination node. Also, when failures occur on F-AP7 and F-AP8, c_3 and c_4 will be lost i.e. protection of the network but, if these are the only failures, successful data communication can still be achieved.

It is observed that for three broadcast data streams, any combination of link and node failures can be tolerated as long as the receiver nodes have at least three error free links. Recovery is near-instant, once the fault is detected, since the desired information is present, in coded form, at the destination node.

In general, eDC-NC networks can tolerate n link failures for each destination node with k destination nodes, however, $kn + n$ redundant links are required, where $n \leq$ the number of broadcast data streams.

These results in this section do not need to be simulated because the link failure is taken into account regardless of the failure reason and it is mathematically demonstrated how the F-RAN network can be improved and protected by eDC-NC.

5.4.2 Applying Enhanced DC-NC Coding to WSNs

Wireless Sensor Network resource limitations such as energy and transmission bandwidth, in the presence of link/node failures, can cause degradation in throughput and reliability. Enhanced DC-NC is a promising technology to maximize the reliability of WSNs with enabling ultra-low energy cost for link/node failures recovery and increased throughput in broadcast applications.

The eDC-NC coding technique is applied to a WSN network as illustrated in Figure 5.5. Here, bi-directional wireless links connect sensor nodes and gateway nodes to each other in a mesh topology. An uplink point-to-multipoint network topology models the broadcasting of three data streams from the sensor node S1 to two gateways G1 and G2. It is assumed that these two gateways are working in active/stand by (ACT/STBY) mode to eliminate single points of failure and to make sure that the required information is collected from sensor nodes i.e. even if one gateway fails for any reason, the collected data will still arrive to the user. Utilizing the eDC-NC coding scheme, four disjoint routes are needed to broadcast three data streams from the sensor node to two gateway nodes. In addition, two more disjoint paths are used to tolerate two link failures at each gateway node. Using direct links, data streams x_1 and x_3 are transmitted from S1 to G1 and G2 respectively. To obtain the throughput gain and tolerate 2 link failures for each destination node, four coded data streams, $c_1 – c_4$ are formed at S1 as shown in (5 – 3)-(5 – 6) and then sent to S2, S3, S4 and S5 respectively. To obtain the throughput gains, S2 and S3 transmit c_1 and c_2 respectively to G1 and G2. Coded data streams $c_1$and c_2, in addition to the data stream x_1, are decoded at G1 to obtain x_2 and x_3 as described in Section 5.3. Similarly, c_1, c_2 and x_3 are decoded at G2 to obtain x_1 and x_2. In this way, the throughput gains in this example network improve by at least 20% [31].

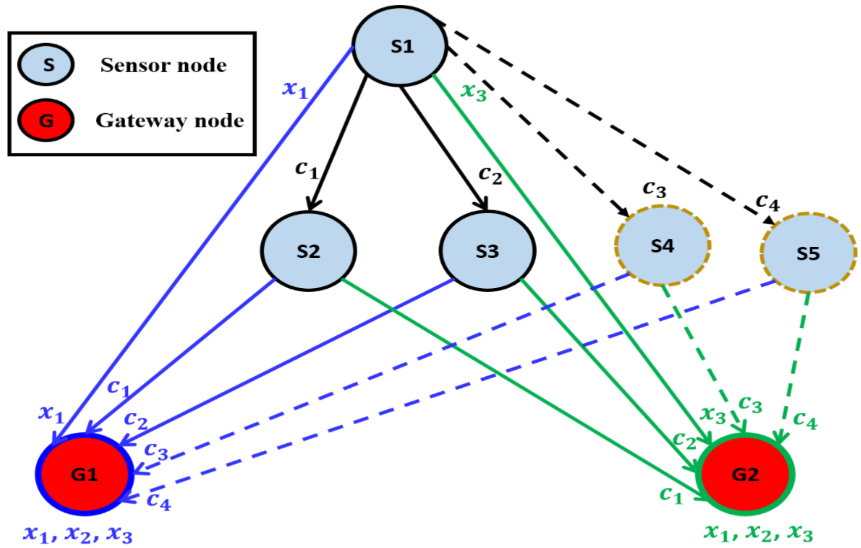


Figure 5.5 Example of eDC-NC coding to broadcast three packets to nodes G1 and G2 applied to a WSN, where solid lines represent the links that carry coded data streams and are used to improve network throughput whereas dashed lines represent the links that carry coded data streams and are used to maximize network reliability. The blue and green links distinguish the different destinations.

Wireless sensor network reliability in the presence of link failures, can be improved by transmitting c_3 and c_4 from S4 and S5 respectively to G1 and G2. The coded data streams c_3 and c_4 will be ignored when there are no link failures. In the presence of a link failure, for example if the link from the S1 to G1 fails, G1 detects the failure then recovers x_1, x_2 and x_3 by utilizing c_1, c_2 and c_3 as shown in Table 5.5. In addition, if c_1 is lost, G1 has x_2, c_2 and c_3 then can quickly and easily recover x_1 and x_3. Furthermore, if two links fail at G1, for example x_1 and c_1, G1 detects the failures and then recovers x_1, x_2 and x_3 by utilizing c_2, c_3 and c_4 in the same manner that is illustrated in Section 5.3 and Table 5.5. Similarly, any two link failures can be recovered in the same way.

Moreover, not only multiple link failures can be recovered by eDC-NC coding in this example WSN network. Two intermediate node failures such as S2 and S3 can be tolerated since this corresponds to four simultaneous link failures, where each pair is associated with a different destination node. Also, when failures occur at S4 and S5, c_3 and c_4 will be lost i.e. protection of the network is lost, but, if these are the only failures, successful data communication can still be achieved.

There is no need to simulate the results in this section because the link failure is considered independently of the failure mode and it is mathematically proven how the WSN network can be enhanced and protected by eDC-NC. Of course, the recovery time is lower bounded by the time to detect a failure.

5.5 Redundancy Percentage Analysis

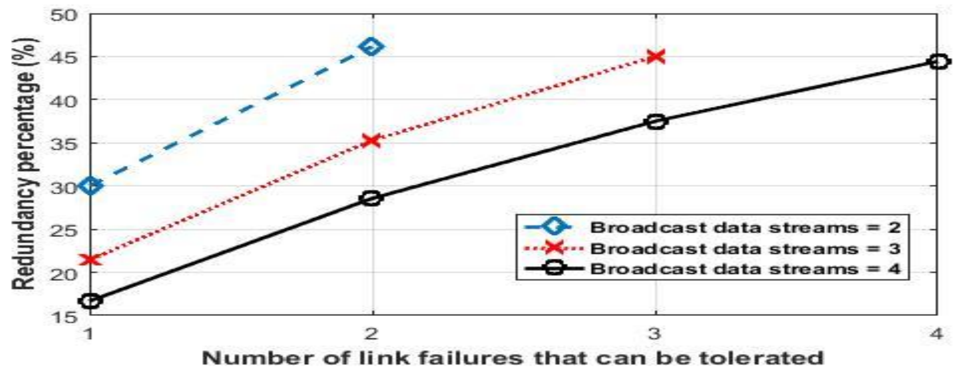
In general, eDC-NC networks have the ability to tolerate n link failures for each F-AP at j destination F-APs, where $jn + n$ redundant links are required. Furthermore, for a multipoint-to-multipoint topology, the number of overall utilized links for k broadcast data streams can be expressed as $kj + (2k - 1) + jn + n$. While for a point-to-multipoint topology, this will be $kj + (k - 1) + jn + n$. One of the important parameters that determines the scalability of any protection method is the redundancy link percentage, which is equal to the number of required redundant links divided by the number of overall utilized links. Hence, the redundancy percentage (R) for multipoint-to-multipoint network topology can be expressed as:

$$R = \frac{jn + n}{kj + (2k - 1) + jn + n} \times 100 \qquad (5-9)$$

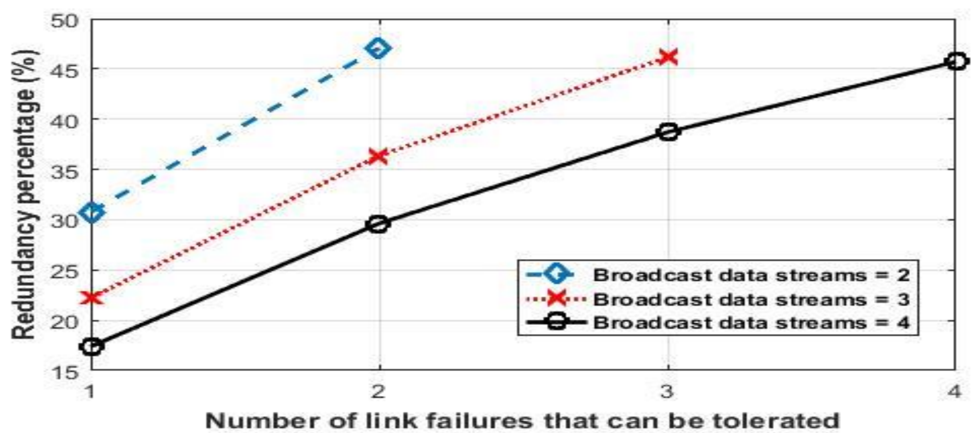
whereas for point-to-multipoint network topology, the redundancy percentage (R) can be determined from:

$$R = \frac{jn + n}{kj + (k - 1) + jn + n} \times 100 \qquad (5-10)$$

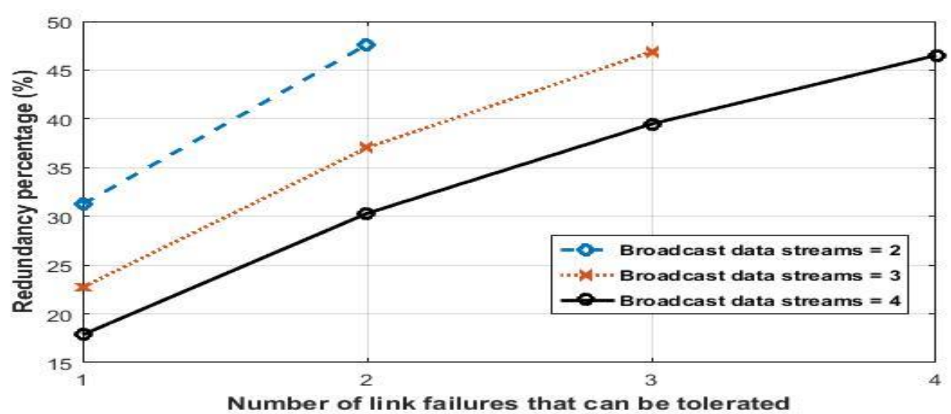
Using (5 – 9) and (5 – 10), the relationship between the redundancy percentage versus the number of link failures that can be tolerated for two, three, and four destination F-APs respectively in F-RAN networks with various broadcast data streams for multipoint-to-multipoint and point-to-multipoint network topologies respectively are plotted and depicted in Figure 5.6 and Figure 5.7.



(a) Number of destination F-APs = 2

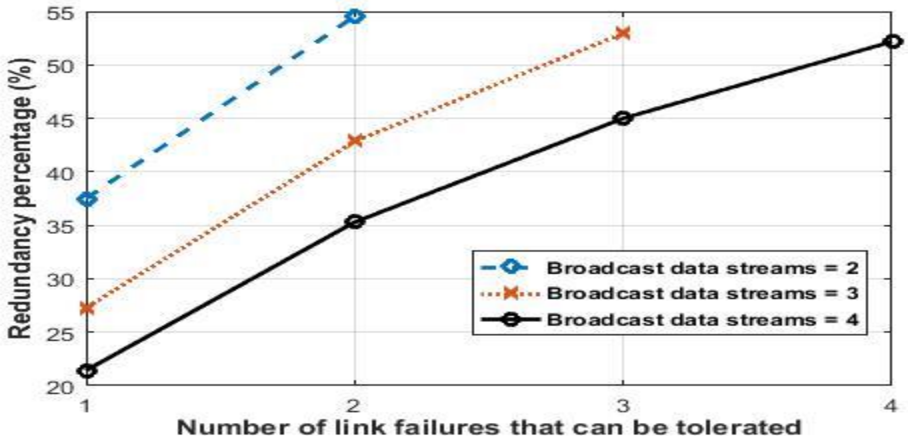


(b) Number of destination F-APs = 3

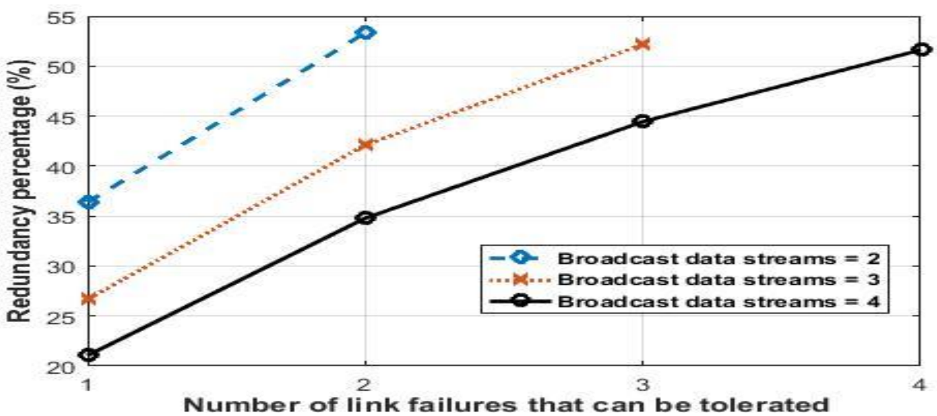


(c) Number of destination F-APs = 4

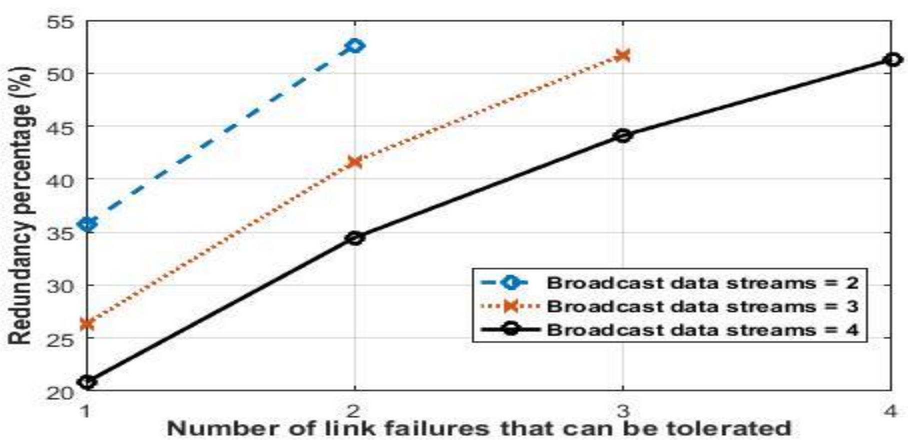
Figure 5.6 Enhanced DC-NC coding redundancy percentage versus number of link failures that can be tolerated for multipoint-to-multipoint network topology.



(a) Number of destination F-APs = 2



(b) Number of destination F-APs = 3



(c) Number of destination F-APs = 4

Figure 5.7 Enhanced DC-NC coding redundancy percentage versus number of link failures that can be tolerated for point-to-multipoint network topology.

It is shown that the number of destination nodes has *no* significant effect on the required redundancy percentage. Furthermore, the figures illustrate the inverse relationship between the required redundancy percentage (*R*) to tolerate *n* link failures and the number of broadcast data streams.

Similarly, Figure 5.8 and Figure 5.9, illustrate the redundancy percentage versus number of link failures that can be tolerated, number of broadcast data streams, and the number of destination F-APs for multipoint-to-multipoint and point-to-multipoint network topologies respectively.

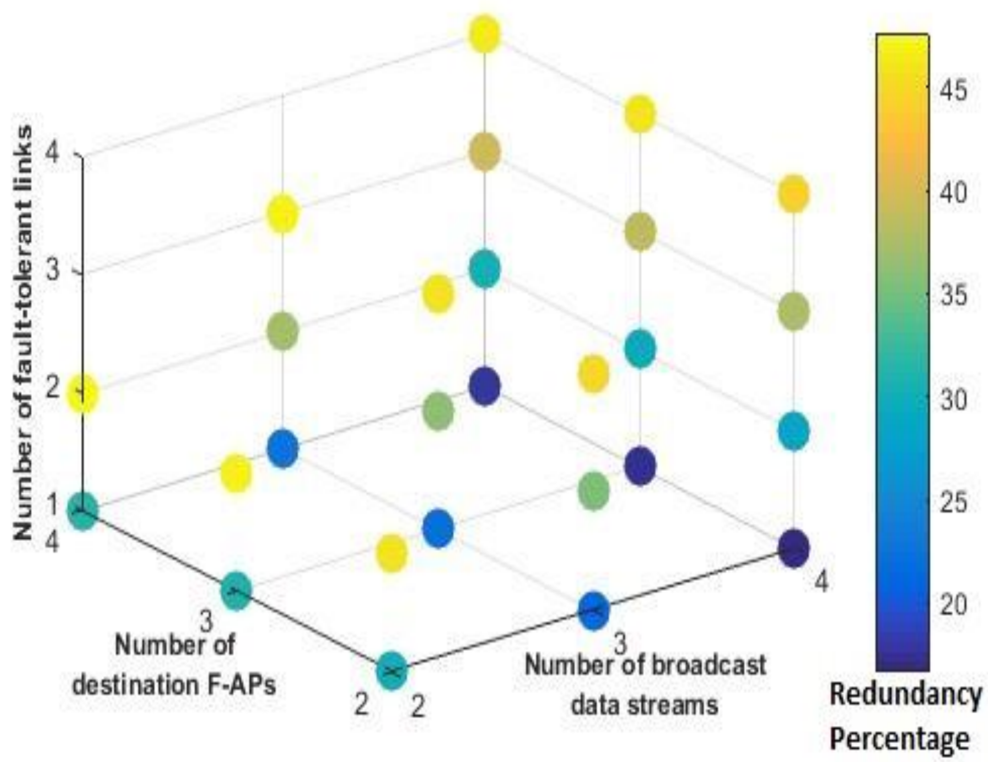


Figure 5.8 Enhanced DC-NC coding redundancy percentage versus number of fault-tolerant links, destination F-APs, and broadcast data streams for multipoint-to-multipoint network topology.

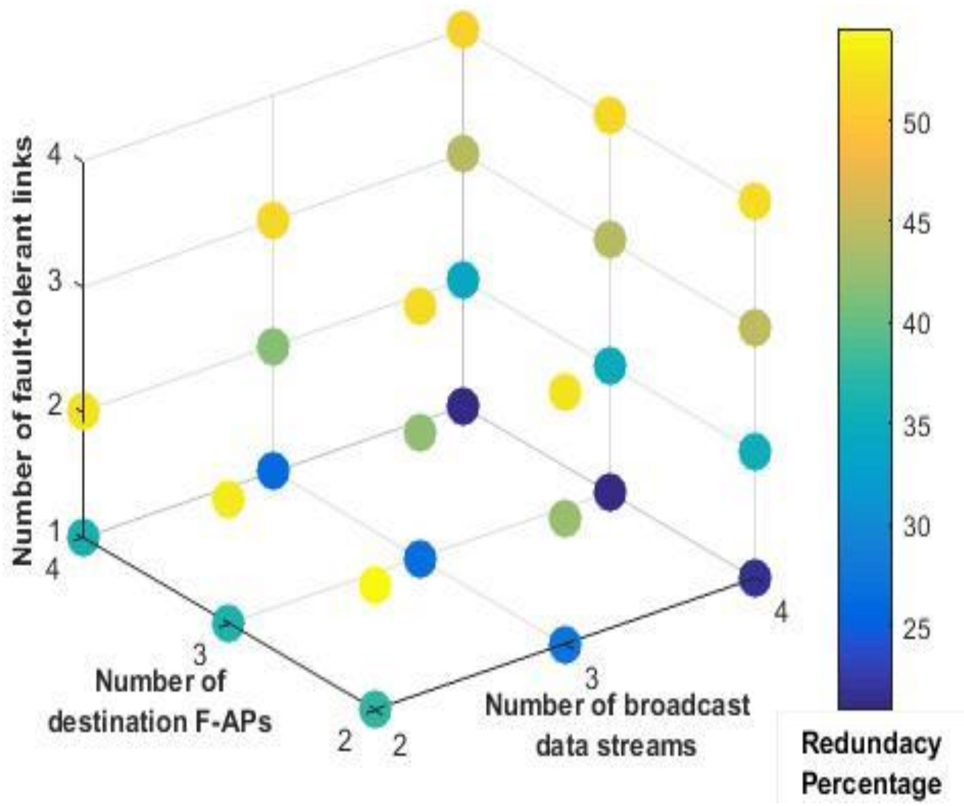


Figure 5.9 Enhanced DC-NC coding redundancy percentage versus number of fault-tolerant links, destination F-APs, and broadcast data streams for point-to-multipoint network topology.

Again, it is noted that the required redundancy percentage for tolerance of n link failures is inversely related to the number of broadcast data streams, which clearly demonstrates the scalability of eDC-NC coding. In addition, the redundancy percentage for complete protection[8] is always less than 50% and 55% for multipoint-to-multipoint and point-to-multipoint network topologies respectively.

[8] Complete protection means that the system can recover from a number of link failures equal to the number of transmitted data streams at each destination node.

5.6 Synchronized Broadcasting

In Chapter 4 and this chapter, it is assumed that the transmitted messages arrive simultaneously at the destination node, which is not the case in real life. Hence, solutions to the synchronization problem must be addressed and are discussed in this section.

Here, eDC-NC is applied to the point-to-multipoint network topology as shown in Figure 5.10, where node 1 (the source) broadcasts two data streams x_1 and x_2 to destination nodes 5 and 6. With eDC-NC, node 1 transmits x_1 and x_2 to nodes 5 and 6 respectively via nodes 2 and 3 respectively. In addition, it forms c_1 and c_2 as shown in (5 – 11)-(5 – 12) and sends them to the destination nodes 5 and 6 via nodes 4 and 7 respectively.

$$c_1 = x_{1,0} \oplus x_{2,1} \qquad (5-11)$$

$$c_2 = x_{1,0} \oplus x_{2,2} \qquad (5-12)$$

where x_{i,r_i} represents the data stream i and r_i is the number of redundant bit(s) “0” that are added at the head of data stream i, and c_i represents the coded data stream i.

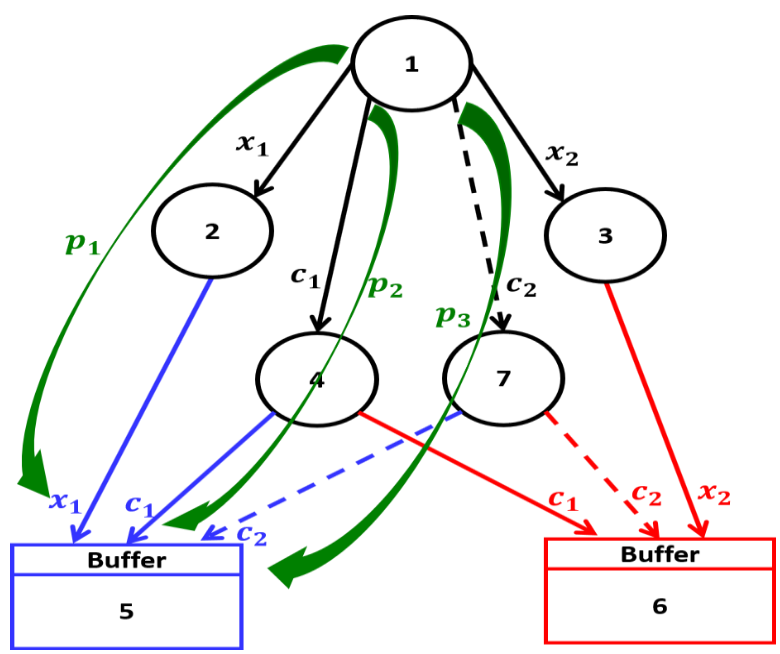


Figure 5.10 Synchronized broadcasting via eDC-NC.

The coded data stream c_1 will be used to increase the network throughput while c_2 will improve the reliability of the network as illustrated in Section 5.3.

In order to broadcast data streams x_1 and x_2 to destination nodes 5 and 6 such that the transmitted data streams are processed simultaneously at the destination node, the most distant node should have a buffer to collect the raw and coded data streams. In order to calculate the required waiting time at each destination node, the following is required.

The source node will broadcast a scout data stream to all destination nodes using all the required paths. The scout data stream contains the timestamp of the transmission time instant, the number of broadcast data streams that will be transmitted , and the number of coded data streams that will be transmitted for reliability (For example, two broadcast data streams and one coded data stream for reliability as shown in Figure 5.10).

It is shown that there are three paths between the source (node 1) and the destination (node 5). The delay for each path is represented by d_{p_i}, where p_i is the path (i) and measured in seconds. Each destination node can determine the delay for each path, so it can calculate the difference between the lowest and the highest delays. It is assumed that $d_{p_3} > d_{p_2} > d_{p_1}$. Hence, the waiting time at destination node 5 will be $d_{p_3} - d_{p_1}$. Node 5 sets its buffer based on this calculation. Also, in this way, the destination nodes do not need to reply with any information concerning the delays to the source node. In addition, the nodes will know that the broadcast session will start soon and how many data streams they should receive. One more important thing is that each destination node will work independently re the waiting time at its buffer.

Whenever the destination node receives the first data stream and storing it in its buffer, it will wait for $d_{p_3} - d_{p_1}\ seconds$ to make sure all required data streams have arrived and stored in its buffer then it will start processing them. In this way, the synchronization problem is solved without experiencing any higher delay than what is actually required.

Since the delay through a network change dynamically, so this method can work when the data rate of the broadcasting message equals to the link capacity or twice of the link capacity (assuming that the link capacity of each link in the network is similar) so one scout data stream will be enough.

However, if the data rate of the broadcasting message is large, one scout data stream will NOT be sufficient and sending several scout data streams with a certain frequency based on the data rate of the broadcasting message will be necessary.

In case the delay through the network changes very rapidly and the data rate of the broadcasting message is very large, scout data streams will be sent with each broadcasting session until the end of the broadcast message. Furthermore, the synchronization problem in this situation can be solved in another way as follows:

1) Assuming that the TX and RX clocks are synchronized, in order to start a broadcasting session, the scout data stream will be sent, which contains the timestamp and source/destination for each link. So that the destination nodes will set their buffers and be ready to receive the data streams.
2) Then, instead of sending scout data streams with each broadcasting session, each data stream will include the timestamp hence, the destination node will continuously set its buffer based on the newly arrived data streams. In this way, for the whole broadcasting sessions, there will be no need to more than one scout data stream.

5.7 Concluding Remarks

Enhanced DC-NC, which synergistically combines Diversity and modified Triangular Network Coding, is introduced in this chapter to improve the performance of 5G wireless fronthaul F-RANs and Wireless Sensor Networks. It was demonstrated that eDC-NC can simultaneously recover from multiple link/node failures nearly-instantaneously with minimum energy consumption. In addition, a general eDC-NC encoding expression was derived and an algorithm and a general notation for the eDC-NC decoding process were presented. Furthermore, eDC-NC networks can tolerate n link failures, where $n \leq$ number of broadcast data streams for each receiver node, with j receiver nodes and with $jn + n$ redundant links. Moreover, it is shown that the redundancy percentage for protecting against n link failures is inversely related to the number of source data streams, which illustrates the scalability of eDC-NC coding. In addition, the redundancy percentage for complete protection is always less than 50% (multipoint-to-multipoint topology) - 55% (point-to-multipoint topology). Moreover, solutions to synchronized broadcasting are proposed for different situations. Applying eDC-NC coding minimizes the impact on latency of multiple link/node failures in wireless fronthaul network links and WSNs and decreases the energy cost of recovering from multiple wireless link/node failures due to its less computational complexity, while simultaneously improving the throughput in the network by at least 20% for three broadcast data streams.

CHAPTER 6: EFFICIENT AND SECURE BROADCASTING IN 5G WIRELESS FOG-BASED-FRONTHAUL NETWORKS[9]

6.1 Introduction

Many wired and wireless networks securely broadcast/multicast messages to a group of receivers. Several studies [65]-[68] have theoretically analyzed the ability of Network Coding [21] to provide secure broadcasting/multicasting in wired and wireless networks. These papers assume that the number of channels that the eavesdropper can wiretap is equal to or less than the number of tolerated[10] wiretapped channels in the network, which is a design parameter [65]-[68]. However, this assumption is not valid in real networks, as the eavesdropper might have the ability to wiretap the entire network of channels. To overcome this vulnerability, this chapter is directed towards demonstrating that Secret (Shared) Key Cryptography in combination with Network Coding may be utilized to provide efficient, secure message broadcasting. It is also shown that Enhanced Diversity and Network Coding (eDC-NC) [33]-[34], which is the synergistic combination of Diversity Coding [18]-[20] and modified Triangular Network Coding [27], can efficiently and securely broadcast messages in 5G wireless fog-computing-based Radio Access Networks (F-RANs). It is mentioned early in Chapter 1 that F-RANs are an alternative network architecture to Cloud Radio Access Networks (C-RANs) [5]-[7] that are under consideration for 5G networks,

[9] The content of this chapter has been published in [36], and it is included in this dissertation with permission from the International Journal of Wireless and Mobile Networks (IJWMN). Permission is included in Appendix A.
[10] Tolerated denotes the maximum number of channels that can be wiretapped without acquiring any information, which is always less than the number of channels in the entire network.

where the centralized processing in the baseband unit (BBU) of the C-RAN are replaced by edge nodes with the ability to control, process and store data, and communicate with each other [5]-[7].

It is shown in Chapter 5 that eDC-NC can simultaneously improve the network reliability, reduce computational complexity, enable extremely fast recovery from simultaneous multiple link/node failures, and retain the throughput improvement of Diversity and Network Coding (DC-NC) for broadcasting/multicasting applications of F-RAN wireless fronthaul networks and wireless sensor networks.

In this chapter the ability of eDC-NC technology to more efficiently provide secure messages broadcasting than standardized methods such as Secure Multicasting [69], such that the adversary cannot acquire any information even if they can wiretap the entire F-RAN network (except of course the source and destination nodes) is demonstrated. In this way, eDC-NC can enhance secure broadcasting and provide ultra-reliability networking, near-instantaneous fault recovery, and retain the throughput gain of DC-NC coding.

6.2 System Model

Similar to the system model described in Section 5.2.1, this chapter is focused on the core mode of the F-RAN, which is the Local Distributed Coordination (LDC) mode as illustrated in Figure 1.3 [5].

In Chapter 5, eDC-NC coding was applied to a wireless fronthaul F-RAN network and a wireless sensor network to provide ultra-reliable with near-instant fault recovery and efficient energy consuming system, and here the ability of eDC-NC to provide efficient secure messages broadcasting and apply secure eDC-NC coding to the LDC fronthaul network is demonstrated, where F-APs are connected to each other via wireless links in a mesh topology as shown in Figure 5.1. Here, these wireless links are considered to be wiretapped by an eavesdropper. To minimize interference and be able to communicate with each other, such F-APs will likely utilize MIMO technology.

6.3 Secure Enhanced DC-NC Broadcasting Network

In order to illustrate how Secret (Shared) Key Cryptography is used in eDC-NC type networks and to provides secure broadcasting, consider the point-to-multipoint network topology depicted in Figure 6.1.

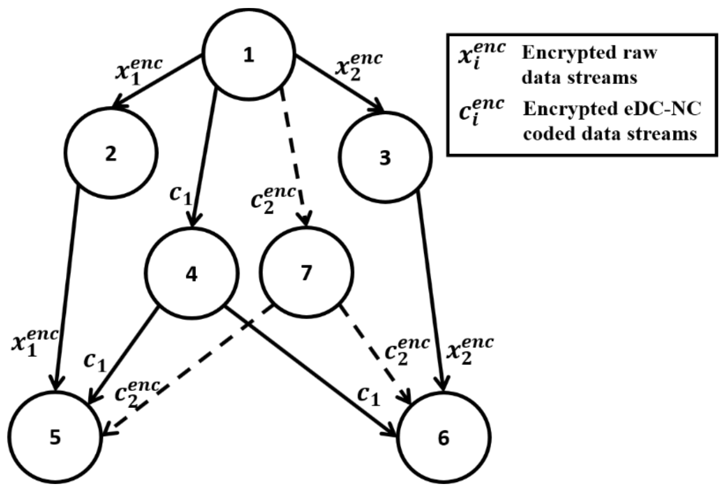


Figure 6.1 Example wireless network with secure broadcasting via eDC-NC coding that broadcasts two data streams to nodes 5 and 6 and protects each stream from one link/relay node failure. The solid lines represent the wireless links that carry (eDC-NC) coded data streams and are used to improve network throughput whereas dashed lines represent the wireless links that carry (eDC-NC) coded data streams and are used to maximize network reliability.

Each broadcasting session is assumed to have its own secret (shared) session key. The source node (node 1) and the receiver nodes (nodes 5 and 6) will share the broadcasting session key. Controlling the distribution of the keys between the source and the legitimate receivers is a primary issue in any communication network. The IETF Group Domain of Interpretation (GDOI) protocol defined in Request for Comments (RFC-6407) [70] may be used to facilitate connecting the source and the destinations to a key server, where using Public Key Cryptography (PKC) the keys are encrypted and distributed to the members of secure multicast group. The source and the destinations can be authenticated and authorized to form a specific multicast group by the key server such that the shared key is utilized to encrypt and decrypt messages between members of the group [70]. In this way, the broadcasting session (shared) key will be distributed securely to the source and destination nodes.

In our example network the source broadcasts two data streams x_1 and x_2 to destination nodes 5 and 6 using relay nodes 2, 3, 4, and 7.

The system proceeds as follows:

1) The streams c_1 and c_2 are created using eDC-NC encoding [33]-[34], which will be referred to as eDC-NC coded data streams to distinguish them from the encrypted data streams as follows:

$$c_1 = x_{1,0} \oplus x_{2,1} \qquad (6-1)$$

$$c_2 = x_{1,0} \oplus x_{2,2} \qquad (6-2)$$

where x_{i,r_i} represents the raw data stream i and r_i is the number of redundant "0" bit(s) that are added at the head of raw data stream i, c_i represents the eDC-NC coded data stream i. Note that the eDC-NC coded data stream, c_2, will be encrypted using the shared key at the source node 1 then it will be transmitted. Therefore, it appears in the figure as c_2^{enc}.

2) The source node (node 1) encrypts the streams x_1, x_2, and c_2 using the Secret (Shared) Key Cryptography algorithm.

Node 1 transmits x_1^{enc} and x_2^{enc} to nodes 5 and 6 respectively via relay nodes 2 and 3 respectively. In addition, node 1 transmits c_1 in order to realize the throughput gain provided by eDC-NC networking [33]-[34] and c_2^{enc} to be able to tolerate one link/relay node failure [33]-[34] to the destination nodes 5 and 6 via relay nodes 4 and 7 respectively.

3) At the destination side, for example, node 5 will use the broadcasting session shared key to decrypt the received data streams using the Secret (Shared) Key Cryptography algorithm depending on the following situations:

   a) If all data streams are correctly received (by checking the CRC), c_2^{enc} is ignored and x_1^{enc} will be decrypted to find x_1. Next, x_2 will be recovered by applying x_1 to c_1 using the eDC-NC decoding algorithm that was explained in detail in Chapter 5.

   b) If one data stream is either incorrectly received or not received at all (either c_2^{enc} or x_1^{enc}), the receiver will decrypt the one that is correct (correct CRC) and then apply it to c_1 to obtain x_2 similarly to step a.

   c) If c_1 fails, the receiver will decrypt both c_2^{enc} and x_1^{enc} to get c_2 and x_1 then similarly to step a apply x_1 to c_2 to obtain x_2.

It is worth noting that the intermediate (relay) nodes will not need to decrypt the encrypted raw and eDC-NC coded data streams because they only need to forward them to the destination nodes. Hence, they do not have to be secured. Also, they *cannot* decrypt the encrypted raw and eDC-NC coded data streams because they do not have the broadcasting session secret (shared) key.

Now, suppose that the adversary wiretaps the entire network, he/she will have x_1^{enc}, x_2^{enc}, c_1, and c_2^{enc}. Only c_1 is not encrypted but it will not disclose any information because it is a XOR combination of raw data streams x_1 and x_2. The other data streams are encrypted so, the adversary will need to know the broadcasting session secret (shared) key to decrypt them.

In this way, as long as the adversary does not possess the broadcasting session key, it will not be able to get any information even if he/she wiretaps the entire network (except of course the source and destination nodes).

6.4 Applying Secure Enhanced DC-NC Coding to F-RANs

Enhancing the security (privacy) of transmitted information in 5G wireless F-RAN fronthaul networks is critical due to the vulnerability of wireless links. In addition, although F-APs have specific resources, but these should be used efficiently. Enhanced DC-NC technology was recently utilized to improve the efficiency and reliability of 5G wireless F-RAN fronthaul networks and provide rapid recovery time from multiple simultaneous link/node failures while retaining the throughput enhancement feature of Network Coding for broadcasting applications [33]-[34]. Here, secure eDC-NC technology is applied to Local Distributed Coordination (LDC) transmission mode in an F-RAN network to achieve the above benefits and to efficiently improve its security, as depicted in Figure 6.2.

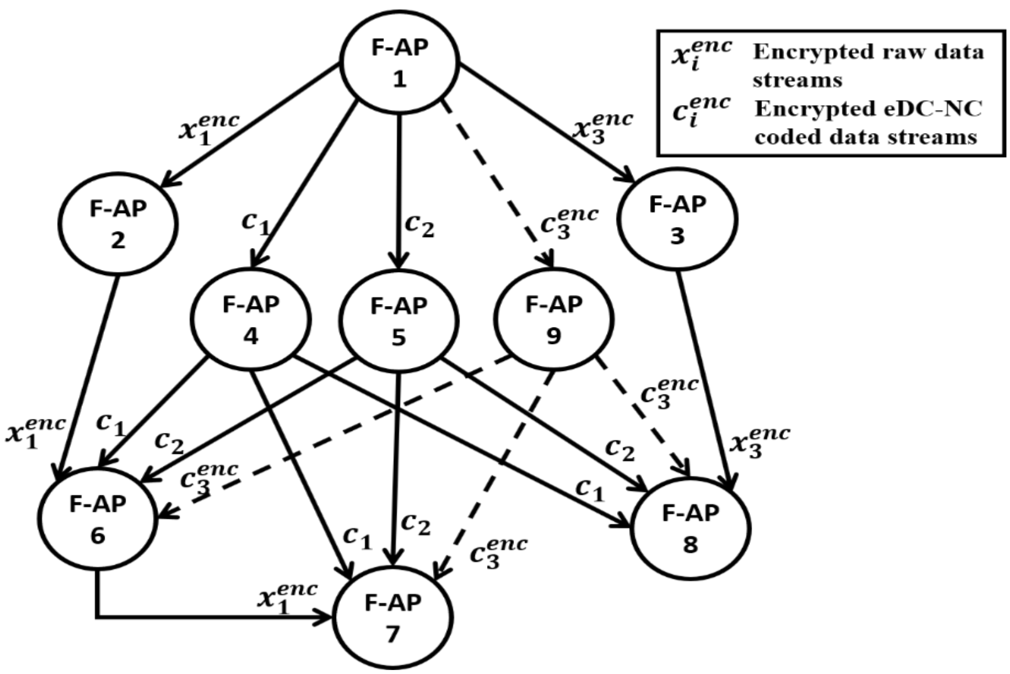


Figure 6.2 Example wireless fronthaul Fog-RAN network with secure eDC-NC coding that broadcasts three data streams to F-AP6, F-AP7, and F-AP8 and protects each stream from one link failure. The solid lines represent the links that carry (eDC-NC) coded data streams and are used to improve network throughput whereas dashed lines represent the links that carry (eDC-NC) coded data streams and are used to maximize network reliability.

In this example, F-APs are connected to each other in a mesh topology by bi-directional wireless links. Here, a point-to-multipoint network topology models the application of securely broadcasting three data streams x_1, x_2, and x_3 from one F-AP (F-AP1) to three F-APs (F-APs 6, 7, and 8) using intermediate relay nodes F-APs 2, 3, 4, 5, and 9. As mentioned in Section 6.3, each broadcasting session will have its own secret (shared) session key. The source node (F-AP1) and the receiver nodes (F-APs 6, 7, and 8) will share the broadcasting session key using the GDOI protocol.

The system proceeds as follows:

1) The coded data streams c_1, c_2, and c_3 are created using eDC-NC encoding [33]-[34] as follows:

$$c_1 = x_{1,0} \oplus x_{2,1} \oplus x_{3,2} \quad (6-3)$$

$$c_2 = x_{1,0} \oplus x_{2,2} \oplus x_{3,1} \quad (6-4)$$

$$c_3 = x_{1,0} \oplus x_{2,3} \oplus x_{3,5} \quad (6-5)$$

Note that the eDC-NC coded data stream (c_3) will be encrypted using the shared key at F-AP1 then it will be transmitted. Therefore, it appears in the figure as c_3^{enc}.

2) F-AP1 encrypts the streams x_1, x_3, and c_3 using the Secret (Shared) Key Cryptography algorithm. Note that data stream x_2 does not need to be encrypted because there is no need to transmit it in a separate link. However, it can be recovered from the coded data streams at the destination F-APs.

F-AP1 transmits x_1^{enc} and x_3^{enc} to F-AP6 and F-AP8 respectively via relays F-APs 2 and 3 respectively. In addition, c_1 and c_2 are transmitted to realize the throughput gain provided by eDC-NC [33]-[34] and c_3^{enc} to be able to tolerate one link/relay F-AP failure via eDC-NC [33]-[34] to the destination F-APs 6, 7, and 8 via relays F-APs 4, 5, and 9 respectively.

3) At the destination side, for example, F-AP6 will use the broadcasting session shared key to decrypt the arrived data streams via Secret (Shared) Key Cryptography algorithm based on the following situations:

   a) If all data streams are correctly received (by checking the CRC), c_3^{enc} is ignored and x_1^{enc} will be decrypted to find x_1. Next, x_2 and x_3 will be recovered using the eDC-NC decoding algorithm that was explained in detail in Chapter 5.

   b) If one data stream is either incorrectly received or not received at all (either c_3^{enc} or x_1^{enc}), the receiver will decrypt the one that is correct (by checking the CRC) and then obtain all data streams in similar way of step a.

   c) If c_1 or c_2 fails, the receiver will decrypt both c_3^{enc} and x_1^{enc} to recover c_3 and x_1 then similarly as in step a obtain x_2 and x_3.

As it is mentioned in Section 6.3, the intermediate (relay) F-APs will not need to decrypt the encrypted raw and eDC-NC coded data streams because they only need to forward the streams to the destination F-APs. Also, they *cannot* decrypt the encrypted raw and eDC-NC coded data streams because they do not have the broadcasting session secret (shared) key.

Now, assuming that the eavesdropper wiretaps the entire network, he/she will have x_1^{enc}, x_3^{enc}, c_1, c_2 and c_3^{enc}. Although c_1 and c_2 are not encrypted, no information can be disclosed because they are XOR combinations of raw data streams x_1, x_2, and x_3. Other data streams are encrypted so, the eavesdropper will need to know the broadcasting session secret (shared) key to decrypt them.

In this way, as long as the adversary does not have the broadcasting session key, it will not be able to get any information even if he/she wiretaps the entire network (except, of course, the source and destination nodes).

Consequently, secure eDC-NC will efficiently enable secure broadcasting and provide ultra-reliability networking, near-instantaneous fault recovery, and re the throughput gain of DC-NC coding of 5G wireless F-RAN fronthaul networks.

6.5 Efficiency Analysis

Normally, when standard Secure Multicast [69] is utilized to provide network security, the source has to encrypt all transmitted data streams. However, by applying eDC-NC, the source node does not need to encrypt all the streams as shown in Sections 6.3 and 6.4. In the example network in Section 6.3, only three out of four data streams have to be encrypted, namely x_1, x_2, and c_2. The reason for encrypting only three data streams is that the eDC-NC coded data streams c_1 and c_2 are not plaintext but the mod 2 combination of the raw data streams x_1 and x_2. So, encrypting one stream (c_2^{enc}) in this example network will make recovering the raw data streams impossible without knowledge of the broadcasting session key to decrypt c_2^{enc} and thus be able to recover both raw data streams via the eDC-NC decoding algorithm [33]-[34]. In this way, the cost/complexity of encryption will be decreased by 25%. At the receiver, each destination node has only to decrypt two out of three data streams at a maximum as illustrated in case c in Section 6.3 above. Hence, the cost of decryption will be maximum and for two broadcast data streams, there will be no cost benefits in decryption, (however, for three broadcast data streams, the decryption cost will be decreased by 33%) which is referred to as a minimum decryption cost benefit (*Min. DecCB*). However, in some cases, the destination node has only to decrypt one data stream (cases a and b in Section 6.3) which decreases the decryption cost by 50%. In this case, the cost of decryption will be a minimum and there will be 50% decryption cost benefit, which is referred to as a maximum decryption cost benefit (*Max. DecCB*). Note that the encryption cost benefit will not vary once the system parameters are fixed because the source node always needs to encrypt only two raw data streams and once the number of eDC-NC encoded data stream(s) that will be used to improve the system reliability has been selected (that is, the number of link failures that can be tolerated) the benefit will be determined.

In general, for point-to-multipoint network topology, in order to quantify the security cost benefits, we need to define the following variables:

D_{total}: Number of overall transmitted data streams.

D_{enc}: Number of encrypted (raw and eDC-NC coded) data streams.

D_{raw}: Number of broadcast raw data streams.

L_f: Number of link failures that can be tolerated in the network.

D_{dec}: Number of decrypted data streams.

Therefore, the security cost benefit can be calculated as follows.

The encryption cost benefits (*EncCB*) in percentage is:

$$EncCB\ \% = \frac{D_{total} - D_{enc}}{D_{total}} \times 100 \qquad (6-6)$$

where

$$D_{total} = D_{raw} + L_f + 1 \qquad (6-7)$$

and

$$D_{enc} = L_f + 2 \qquad (6-8)$$

Hence,

$$EncCB\ \% = \frac{D_{raw} - 1}{D_{raw} + L_f + 1} \times 100 \qquad (6-9)$$

The decryption cost benefits (*DecCB*) in percentage at each destination node is:

$$DecCB\ \% = \frac{D_{raw} - D_{dec}}{D_{raw}} \times 100 \qquad (6-10)$$

where

$$D_{dec} = \begin{cases} 1 & \textit{if destination node has no link failure OR only one encrypted data stream is lost} \\ L_f + 1 & \textit{otherwise} \end{cases},$$

Table 6.1 shows the security cost benefits in percentage for tolerance of one link failure and different numbers of broadcast data streams.

Table 6.1 The security cost benefits in percentage for one link failure tolerance.

Number of broadcast data streams	**Number of overall data streams**	**Number of encrypted data streams**	***EncCB* (%)**	**Min. *DecCB* (%)**	**Max. *DecCB* (%)**
2	4	3	25	0	50
3	5	3	40	33.33	66.67
4	6	3	50	50	75
5	7	3	57.14	60	80
6	8	3	62.5	66.67	83.3

Figures 6.3 and 6.4 illustrate the relationship between the encryption and decryption cost benefits percentage respectively and the number of broadcast data streams. Note that by applying Secure Multicast [69], all data streams have to be encrypted at the source and decrypted at the destination nodes. However, Figure 6.3 and Figure 6.4 show that by applying Secret (Shared) Key Cryptography to the eDC-NC broadcast networks, there are always security cost benefits (except in the case of minimum decryption cost for broadcasting two data streams). Also, they depict the scalability of eDC-NC by the decreasing of the security costs with the increasing the number of broadcast data streams.

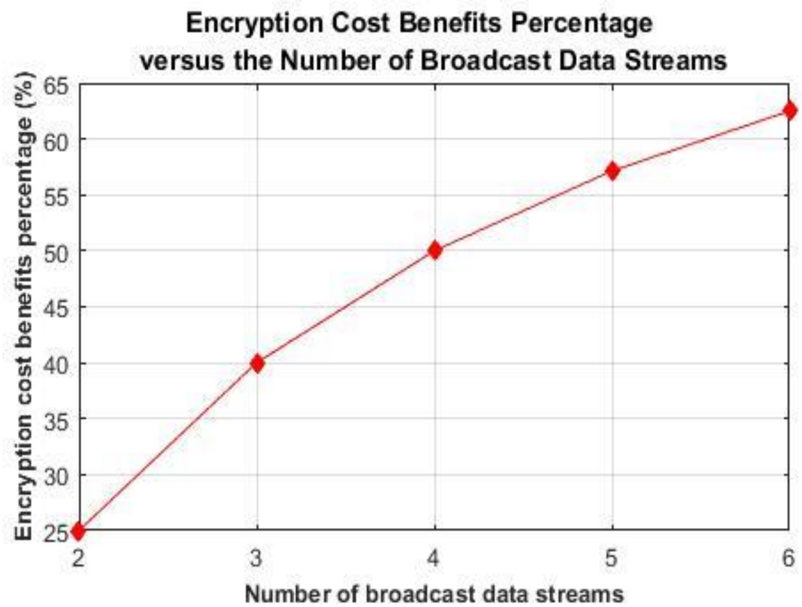


Figure 6.3 eDC-NC encryption cost benefits.

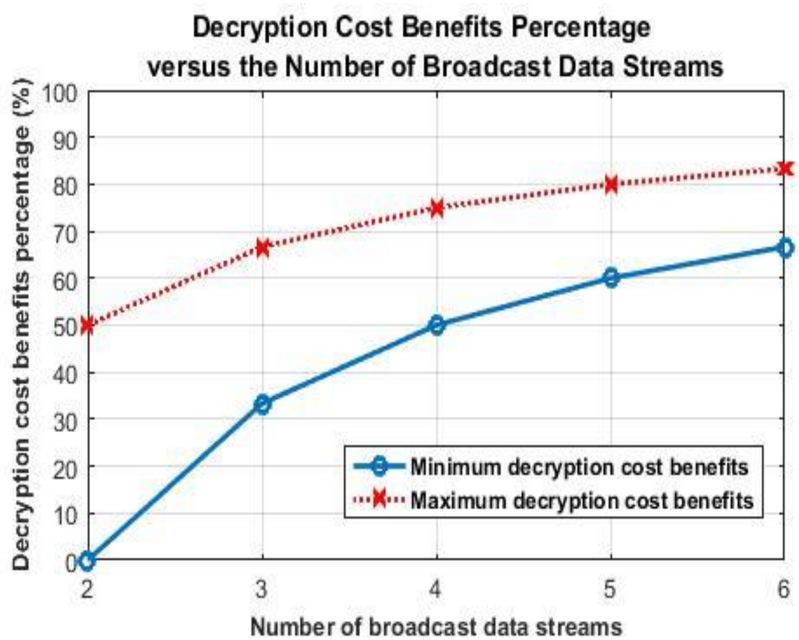


Figure 6.4 eDC-NC decryption cost benefits.

However, the security costs will increase with increasing the number of link failures that need to be tolerated as shown in Figure 6.5 and Figure 6.6.

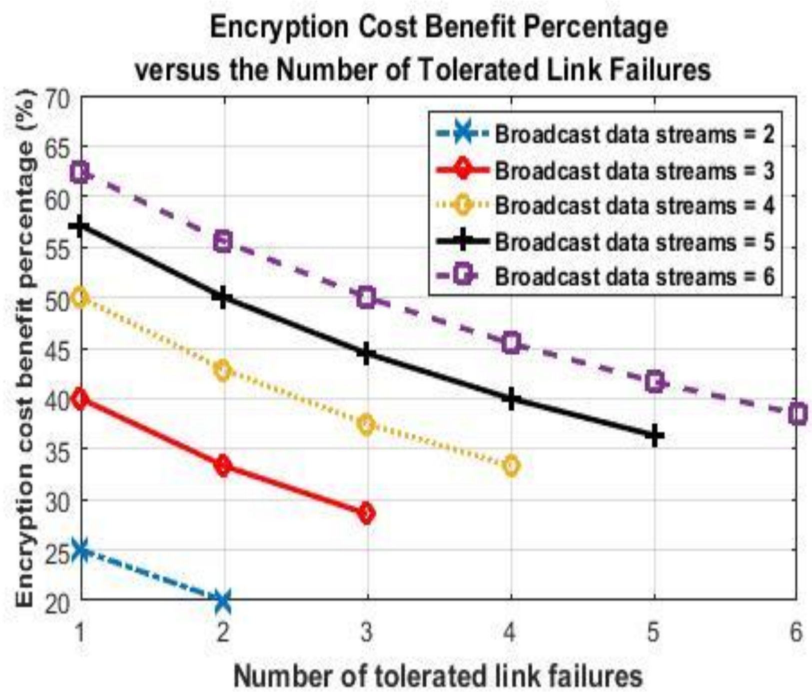


Figure 6.5 eDC-NC encryption cost benefits for different number of tolerant links.

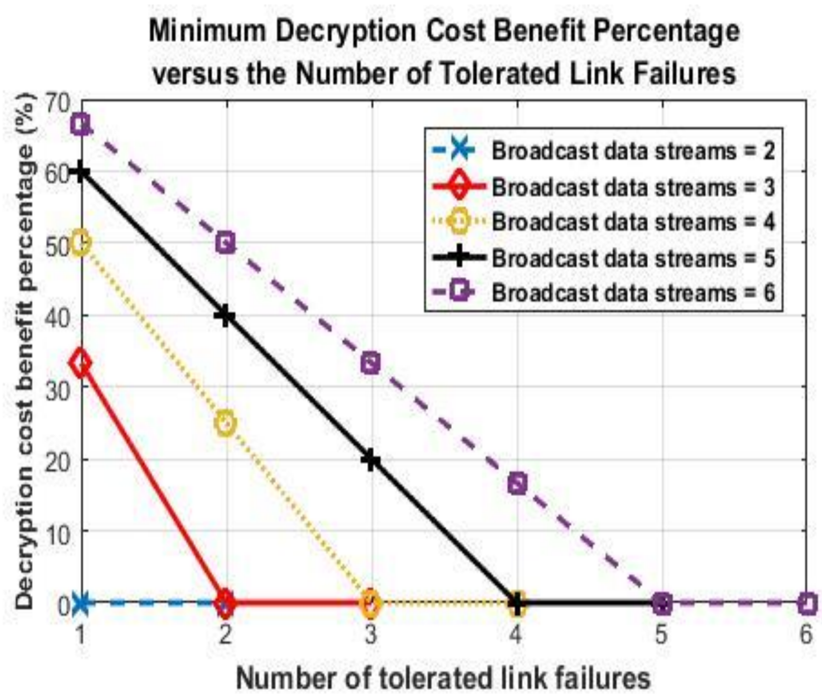


Figure 6.6 eDC-NC minimum decryption cost benefits for different number of tolerant links.

6.6 Conclusions

This chapter presented a means to achieve efficient and secure broadcasting via eDC-NC technology for 5G wireless F-RAN fronthaul networks, such that the adversary has no ability to acquire any information even if they wiretap the entire fronthaul network (except of course the source and destination F-APs). The security of the broadcasting data streams is obtained with lower security cost compared to that of the standard Secure Multicast protocols. Enhanced secure broadcasting using eDC-NC in F-RAN wireless fronthaul networks provides ultra-reliable communications, near-instantaneous link/node failure recovery, and retains the throughput gains of DC-NC coding.

CHAPTER 7: CONCLUSIONS AND FUTURE DIRECTIONS

Wireless and mobile communication systems have emerged as the principal means to access information not only for people but for machines as well. The widespread use of wireless networks has imposed some very demanding requirements such as huge network capacity, ultra-high reliability, and very low end-to-end latency. In order to meet these requirements, new technologies such as C-RANs and F-RANs will be deployed in the radio access networks such that a huge amount of data traffic can be reliably delivered to the end user.

Wireless Sensor Network (WSN) are another example of pervasive wireless networks and are widely deployed in several applications, such as smart homes and cities and wireless body area networks in recreational and medical applications. The latter application definitely required efficiency and ultra reliability. Link and/or node failures are one of the main contributors that reduces network reliability, as well as the system throughput and increase end-to-end communication latency. Very rapid recovery from link/node failures is essential to achieve reliability, efficiency, and enable very low latency networking.

The technologies that are used in this Dissertation to enhance the performance of C-RANs, F-RANs and WSNs are based on Diversity Coding, Network Coding, and Triangular Network Coding. These technologies are utilized synergistically to introduce new coding techniques such as Diversity and Network Coding (DC-NC) and Enhanced DC-NC (eDC-NC), which simultaneously improve systems reliability, provide efficient communications, and enable ultra-low fault recovery time with very low energy consumption.

7.1 Main Contributions and Conclusions

The main contributions of this dissertation are described below.

7.1.1 Near-Instant Fault Recovery in 5G Wireless Fronthaul C-RANs via Diversity Coding

The reliability of 5G wireless fronthaul networks was improved with near-instant fault recovery via Diversity Coding [29]-[30]. The applications of Diversity Coding in wireless fronthaul C-RANs networks were presented, where the RRHs in a C-RAN network are connected to the BBU in two scenarios, the first with wireless links and the second with two tiers of optical and wireless links. It was demonstrated that Diversity Coding enables reliable networking with near-instantaneous fault recovery. Also, the ability of Diversity Coding to recover from multiple simultaneous link failures was shown. Hence, the retransmissions that incur high transmission and re-routing delays due to wireless link/node failures of the fronthaul network can be avoided. In addition, it was explicitly demonstrated that Diversity Coding has the ability to significantly provide lower total routing cost than other types of restoration techniques.

7.1.2 Efficient and Ultra-Reliable Broadcasting in Wireless Fronthaul Networks via Diversity and Network Coding (DC-NC)

A new coding technique, (DC-NC) that synergistically combines Diversity and Network Coding was introduced [31]-[32]. The DC-NC performance was evaluated in two 5G fronthaul networks, the first where the RRHs in a C-RAN are connected to the baseband unit with two tiers of optical and wireless links and the second where (most) all RRHs in the C-RAN are connected directly to the BBU via wireless links. Also, the application of DC-NC coding to enhance the performance of downlink JT-CoMP in 5G wireless fronthaul C-RANs was demonstrated. In all scenarios, DC-NC coding provides efficient transmission and reduces the resource consumption in the network by about one-third for broadcasting and/or multicasting applications, while simultaneously enabling near-instantaneous latency in recovery from multiple link/node failures in fronthaul networks. In addition, it was shown that by applying DC-NC coding, the number of redundant links is reduced by about 30%-40% when compared to that of Diversity Coding. Furthermore, n link failures can be tolerated via DC-NC networks for each destination RRH at the CoMP set that contains j RRHs, where, $jn + n$ additional links are required to provide protection.

7.1.3 Enhanced Diversity and Network Coded 5G Wireless Fronthaul F-RANs and Wireless Sensor Networks

Enhanced DC-NC, which synergistically combines Diversity Coding and modified Triangular Network Coding, was introduced to improve the performance of 5G wireless fronthaul F-RANs and Wireless Sensor Networks [33]-[35]. It was described how eDC-NC can simultaneously recover from multiple link/node failures nearly-instantaneously with minimum energy consumption. In addition, a general eDC-NC encoding expression was derived and an explicit algorithm and a general notation for the eDC-NC decoding process were presented. Furthermore, it was shown that eDC-NC networks have the ability to tolerate n link failures, where $n \leq$ number of broadcast data streams for each receiver node, with j receiver nodes and with $jn + n$ redundant links. Moreover, it was demonstrated that the redundancy percentage for protecting against n link failures is inversely related to the number of source data streams, which illustrates the scalability of eDC-NC coding. In addition, the redundancy percentage for complete protection is always less than 50% (multipoint-to-multipoint topology) - 55% (point-to-multipoint topology). Moreover, solutions to enable synchronized broadcasting were proposed for different situations. When the data rate of the broadcast message is less than or equal to the link capacity, a *scout* data stream, typically with a time stamp, is broadcast to all destination nodes via all the required routes. At each destination node, the delay is calculated for each route then the buffering time of each destination node is set based on this calculation. In case the delay through the network changes very rapidly and the data rate of the broadcasting message is very large, scout data streams will be sent with each broadcasting session until the end of the broadcast message or instead of sending scout data streams with each broadcasting session, each data stream will include a timestamp hence, the destination node will continuously set its buffer based on the newly arrived data streams. Applying eDC-NC coding minimizes the impact on latency of multiple link/node failures in wireless fronthaul network links and WSNs and decreases the energy cost of recovering from multiple wireless link/node failures due to its less computational complexity, while simultaneously improving the throughput in the network by at least 20% for three broadcast data streams.

7.1.4 Efficient and Secure Broadcasting in 5G Wireless Fog-Based-Fronthaul Networks

The ability of eDC-NC coding scheme to provide efficient and secure broadcasting for 5G wireless F-RAN fronthaul networks was demonstrated [36], such that the adversary has no ability to acquire any information even if he/she wiretaps the entire fronthaul network (except of course the source and destination F-APs). The security of the broadcasting data streams was obtained with lower security cost compared to that of the standard Secure Multicast protocols [69]. It was demonstrated that by applying Secret (Shared) Key Cryptography to the eDC-NC broadcast networks, there are always encryption cost benefits starting from 25% for broadcasting two data streams and increase with an increasing the number of broadcasting data streams. Similarly, there are always decryption cost benefits (except in the case of minimum decryption cost for broadcasting two data streams). Also, the scalability of eDC-NC was demonstrated by the decreasing the security costs with an increasing the number of broadcast data streams. However, the security costs increased with increasing the number of links that need to be protected. Therefore, applying secure eDC-NC technology to wireless F-RAN fronthaul network enhances secure broadcasting and enables ultra-reliability networking, near-instantaneous fault recovery, and retains the throughput benefits of DC-NC.

7.2 Future Directions

Beyond what has been presented throughout this dissertation, there are topics that can be further explored. For example:

- Applying Enhanced DC-NC (eDC-NC) coding technology to wireless multi-hop networks and Diversity Coding to each link within the wireless multi-hop networks such that each link can tolerate losing one data stream (one for each hop) and one link failure can be tolerated for each destination node.
- Applying Diversity Coding and/or eDC-NC coding scheme to Cellular Networks with Mobile Cells (MCs) in order to enable ultra-reliable networking with near instant fault recovery.
- Analyzing and simulating the application of Machine Learning and Diversity Coding to Cellular Networks with Mobile Cells (MCs) communications to predict when links/nodes will fail in order to provide ultra-reliable networking with instant multi-fault recovery capabilities.
- Emulating the application of eDC-NC coding technology to Software Defend Network (SDN) to improve its performance using the Mininet program, which is a network emulator that creates a network of virtual hosts, switches, links, and controllers.
- Studying and analyzing the ability of using mobile Fog-Access Points within what is envisioned as Mobile Fog-Computing-Based Radio Access Networks (mF-RAN) then using Diversity Coding and/or Enhanced DC-NC to this new architecture to provide

ultra-reliable networking with instantaneous fault recovery and improve system efficiency.

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ABOUT THE AUTHOR

Nabeel Ibrahim Sulieman was born in Baghdad, Iraq in 1976. He received his B.S. degree in Electrical Engineering from University of Baghdad, Baghdad – Iraq in 1998, he was one of the ten highest ranked students in the Electrical Engineering Department, and he received his M.S. degree with merit in wireless communication systems from Brunel University, London – UK in 2008. From 2002 until 2014, he worked for Iraqi Telecommunication and Informatics Company as a technical support engineer. In addition, he worked as an instructor for short technical courses in Higher Institute of Telecommunications, Baghdad – Iraq. He received several training certifications from Lucent Technologies (Alcatel-Lucent) in Operations, Maintenance, and Management of Lucent landline switches. Also, he received two certifications from the Cisco Academy (CCNA1 and CCNA2). He was Assistant Head of Engineering when he traveled to the USA to pursue a Ph.D. in Electrical Engineering at the University of South Florida in the Innovations in Wireless Information Networking Laboratory (*i*WINLAB) under the supervision of Dr. Richard Gitlin, and his research interests include Diversity Coding, Network Coding, Triangular Network Coding, 5G Wireless Fronthaul Networks, Coordinated Multipoint Processing (CoMP), Synchronization of Diversity and Network Coding, Wireless Sensor Networks (WSNs), Moving Cells, Software Defined Networking (SDN), and Network Function Virtualization (NFV). He is a student member of IEEE.