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Diversity and Network Coded 5G Fronthaul Wireless Networks for Ultra Reliable and Low Latency Communications

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***Abstract*— This paper is directed towards improving both throughput and reliability of 5G wireless Cloud Radio Access Networks (C-RANs) by the synergistic combination of Diversity Coding and Network Coding (DC-NC). In this paper, we directly apply the concept of DC-NC coding to two network scenarios: first, remote radio heads in a C-RAN connected to the baseband unit in two hierarchical tiers with optical and wireless fronthaul links, second, most remote radio heads are connected directly to the baseband unit via wireless links. Our results show that the combination of Diversity and Network Coding increases the throughput of fronthaul networks for downlink broadcasting or multicasting applications, while enabling reliable networking with near-instant latency in fault recovery by using forward error control across spatially diverse paths. Moreover, the number of redundant links inherent in Diversity Coding can be decreased using the proposed scheme.**

***Index Terms*—5G, Diversity Coding, fronthaul, link/node failures, Network Coding, reliability, throughput.**

I. INTRODUCTION

Contemporary mobile networks require both high throughput and reliability to meet the increasing user expectations, particularly the demand for data-intensive applications. One of the principle factors that decrease network reliability, as well as the system throughput, is link/node failures that are addressed in this paper for Cloud Radio Access Networks (C-RANs). One of the evolving 5G wireless network architectures is based on a C-RAN in which distributed Remote Radio Heads (RRHs) are connected to a centralized baseband unit (BBU) via a *fronthaul* network. The C-RAN, is an appealing architecture since it enables high bandwidth, accurate synchronization, and very low latency.

There are many reasons for link and node failures in wireless communications such as channel changes due to mobility of user equipment, interference, and/or changes in environmental factors. Many technologies have been used to protect communication networks from the link and node failures such as Synchronous Optical Networking (SONET) and *p*-cycle ring [1]-[2]. Although these solutions increase reliability, their delay performance is still considered to be high for the 5G ultra-low latency requirements and, as such, they are not appropriate for wireless fronthaul-network configurations.

Emerging 5G communication systems will support some applications that require very low delay (around 1ms) and high reliability, and solutions need to be developed to address these two challenges. Therefore, it is essential to have near-instantaneous recovery from fronthaul link failures that will improve the reliability and enable very low delay networking. Diversity Coding, which predates Network Coding, was introduced in [3]-[4] and, has the ability to achieve near-instantaneous recovery from link failures, as it is a feedforward technique that uses forward error control technology over diverse links, and consequently does not need to retransmit messages and perform rerouting.

It is shown in [5] and [6] that Diversity Coding improves C-RAN network performance by increasing reliability and providing near-instant link/node failure recovery. Diversity Coding systems can recover from multiple simultaneous link failures up to the total number of data links that are transmitting redundant encoded information. In [7] it is shown that Diversity Coding has competitive spare capacity compared with standard network restoration techniques. Furthermore, Diversity Coding was used in several applications to enhance their reliability such as Network Function Virtualization (NFV) [8] and minimizing energy consumption in sensor networks [9]. Not only is reliability very important in C-RANs, but throughput is another important factor that effects 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. So that in certain circumstances, Network Coding [10], can increase the throughput of 5G fronthaul wireless networks.

The contribution of this paper is to introduce a new coding technique, Diversity Coding-Network Coding (DC-NC), based on the combination of Diversity Coding and Network Coding. DC-NC improves wireless fronthaul network reliability with near-instant recovery from link/node failures and increased throughput for downlink broadcasting or multicasting applications.

Furthermore, the number of redundant links utilized in the proposed coding technique is decreased in comparison to that of Diversity Coding.

The rest of this paper is organized as follows: Section II considers two network topologies based on C-RANs: two hierarchal tiers of RRHs, which are connected to the BBU as a mixed optical fiber and wireless links, and one level RRHs, which are connected to the BBU via wireless links. Section III summarizes Diversity Coding and Network Coding separately and Section IV demonstrates the benefit of synergistic combination of Diversity and Network Coding to enable higher downlink throughput and faster recovery from multiple simultaneous link failures in wireless fronthaul networks. The paper ends with concluding remarks in Section V.

II. System Model

C-RAN separates base station functions into two main parts: the centralized processing and control functions that are processed in the BBU of the core network, and the radio functions that are handled by the distributed RRHs located at the cell sites [11]-[13]. C-RANs are expected to minimize operating costs and improve spectral effeciency due to its interference management capabilities [11]-[13]. Wireless fronthaul, which is expected to play an essential role in C-RANs, may also be implemented using millimeter waves due to cost savings and easy implementation in a dense environment such as in campuses or stadiums where optical fiber deployment is difficult [11], [13]-[14]. Furthermore, mixed fiber and wireless fronthaul networks solutions has been contemplated by many operators [14].

In this study, we consider two scenarios, the first scenario where RRHs are connected to the BBU in two hierarchical tiers: first-tier RRHs connect via optical links to the BBU and second-tier RRHs connect via wireless links to first tier RRHs, and thus to the BBU. The second tier RRHs have a general mesh topology as shown in Fig. 1. Note that the techniques described in this paper are also applicable to the optical tier of the network as well as to any optical network with a mesh topology. In this

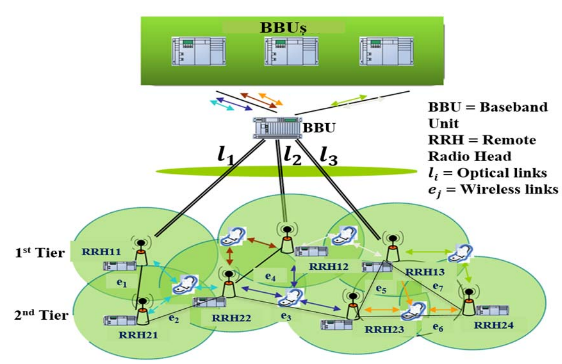


Fig. 1. C-RAN with a mix of optical and wireless fronthaul network links.

scenario, we consider second tier RRHs to be physically distant from the BBU and no optical fiber infrastructure is available to support those RRHs, so they are connected to the first tier RRHs via wireless links and then to the BBU.

The second scenario represents the traditional C-RAN topology where RRHs are connecting to the BBU. However, in this paper these connections are considered to be wireless links. Moreover, RRHs are connected to each other in a general mesh topology as illustrated in Fig. 2.

In both scenarios, 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 communication

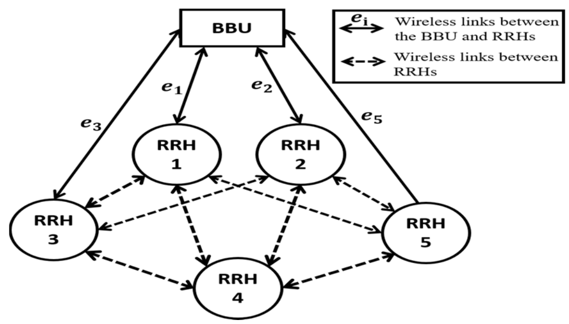


Fig. 2. C-RAN with wireless fronthaul network links.

with several pieces of user equipment (UEs).

III. Diversity and Network Coding Overview

As 5G requires high reliability and very low latency (around 1ms for some applications), any link failure causes rerouting and/or retransmitions. In addition, data broadcasting/multicasting applications will often face link capacity limitations. As shown in the next section, the proposed DC-NC coding scheme has the potential of improving the downlink throughput of C-RAN networks and also providing near-instantaneous recovery from link failures at the expense of redundant transmission.

A. Diversity Coding

The main idea in Diversity Coding is shown in Fig. 3 [3]-[4], for a simple point-to-point network. Here, disjoint routes carry equal rate digital data streams $x_1, x_2, \ldots, x_N$ to their destination. To clarify the idea of Diversity Coding in a simple way, it is assumed that these data streams have been generated from the same source and end at the same destination. Coded data c_1 equal to

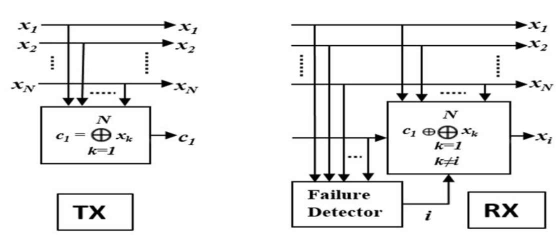


Fig. 3. The principle of Diversity Coding.

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

is sent on a disjoint route. If a failure occurs in data stream x_i, the receiver can easily and quickly form

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

since $x_1, x_2 \dots, x_{i-1}, x_{i+1}, \dots, x_N$ are available at the receiver and $x_k \oplus x_k = 0$ (logical XOR operation). Consequently, x_i is recovered, *nearly instantaneously, without retransmission, or rerouting.* It should be clear that more sophisticated error control, beyond the simple parity check code in the above example, could be used.

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; see the extensions for the point-to-multipoint, multipoint-to-point and multipoint-to-multipoint topologies in [7].

It should be evident that Diversity Coding is a feedforward technology and does not need feedback messages to recover from link or node failures, since near-instantaneous recovery of the lost data is possible as soon as a failure is detected.

B. *Network Coding*

The basic idea of Network Coding was presented in [10]. Network Coding uses coding at a network node to increase network throughput and save system bandwidth for data broadcasting/multicasting application [10]. Fig. 4 [10] illustrates Network Coding in the standard way. Here, nodes 1 and 2 broadcast equal rate digital data streams x_1 and x_2 respectively to nodes 5 and 6. Node 3

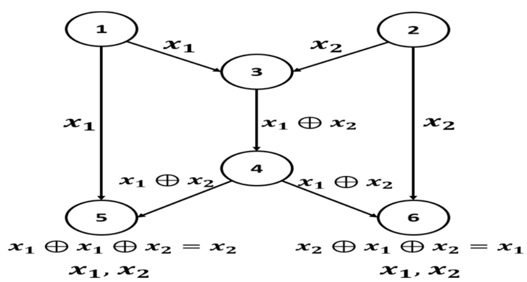


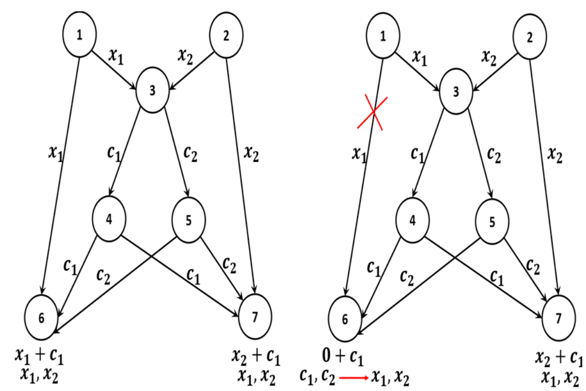
Fig. 4. The principle of Network Coding.

receives x_1 and x_2 then encodes them as $(x_1 \oplus x_2)$ and sends the result to node 4. Node 4 sends$(x_1 \oplus x_2)$ to nodes 5 and 6. Node 5 receives x_1 directly from node 1 and $(x_1 \oplus x_2)$ from node 4 so, it decodes them and obtains x_2 as shown in Fig. 4. Hence, node 5 receives x_1 and x_2. Similarly, node 6 receives x_2 directly from node 2 and $(x_1 \oplus x_2)$ from node 4 so, it decodes them and obtains x_1. Hence, it has x_1 and x_2. Note that each link in the example network has the same link capacity, which is equal to the data rate of the broadcasted data. In this example network, the throughput is increased by encoding the data x_1 and x_2 at node 3 instead of sending each stream on separate links. However, single points of failure can strongly impact reliability,since nodes 5 and 6 will only receive either one data stream or no data at all. For example, if the link between nodes 1 and 5 fails, node 5 will only receive coded data $(x_1 \oplus x_2)$, which is niether x_1 nor x_2, so node 5 has no data at all. Also, if the link between nodes 4 and 5 fails, node 5 will only receive x_1, and then there is no way to obtain x_2, so node 5 has only one data stream.

IV. Combining Diversity and Network Coding

In this section, the synergy of Diversity and Network Coding is explained. As noted above, we refer to this as DC-NC coding. In the DC-NC network shown below in Fig 5(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:

$$c_1 = \beta_{11}x_1 + \beta_{21}x_2, \quad (3)$$
$$c_2 = \beta_{12}x_1 + \beta_{22}x_2, \quad (4)$$



(a) (b)

Fig. 5. (a) DC-NC network (b) DC-NC network with 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 to decide whether a particular vector is a codeword and is also used in decoding algorithms. 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:

$$\tilde{c}_1 = c_1 + \beta_{11}\, x_1, \quad (5)$$

and applying (3) to (5),

$$\tilde{c}_1 = \beta_{11}x_1 + \beta_{21}x_2 + \beta_{11}x_1 = \beta_{21}x_2, \quad (6)$$
$$x_2 = \tilde{c}_1/\beta_{21}\,. \quad (7)$$

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:

$$\tilde{c}_1 = c_1 + \beta_{21} x_2, \tag{8}$$

and applying (3) to (8),

$$\tilde{c}_1 = \beta_{11}x_1 + \beta_{21}x_2 + \beta_{21}x_2 = \beta_{11}x_1, \tag{9}$$

$$x_1 = \tilde{c}_1/\beta_{11} . \tag{10}$$

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 the braodcasted data.

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 [10]. 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 link failure (for example, the link from node 1 to node 6 fails) as shown in Fig. 5(b), node 6 detects the failure then utlizes c_1 and c_2 to recover x_1 and x_2 as follows:

Expressing (3) and (4) in a matrix form

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \tag{11}$$

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

$$\begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}, \tag{12}$$

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

$$m = \lceil \log_2(N+1) \rceil, \tag{13}$$

where N is the total number of data links, two in our 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 $GF(2^2) = GF(4)$ [3][4]. Therefore, node 6 obtains x_1 and x_2 as follows:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}^{-1} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}. \tag{14}$$

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

$$\tilde{c}_2 = c_2 + \beta_{12}x_1, \tag{15}$$

and applying (4) to (15)

$$\tilde{c}_2 = \beta_{12}x_1 + \beta_{22}x_2 + \beta_{12}x_1 = \beta_{22}x_2 \tag{16}$$

$$x_2 = \tilde{c}_2/\beta_{22} . \tag{17}$$

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, the receiver nodes cannot recover the data stream. In this case, they 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 we 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 synergies possible with DC-NC networking.

Furthermore, not only 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 (15)-(17). 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 I for the above network.

TABLE I. PROTECTION SCHEMES COMPARISONS

Protection Scheme	**Diversity Coding**	**DC-NC coding**
# of data streams	2	2
# of coded data stream(s)	1	2
# of broadcasted data streams	0	2
# of utilized links	9	10
# of redundant links	7	3
Failed data recovery time	Low	Ultra-Low
# of tolerant link failures	1 link for whole network	1 link for each receiver node

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.

1) *DC-NC Coding for Two-Tier Mixed Fronthaul Networks:*

Fig. 6 illustrates the application of DC-NC coding in a 5G C-RAN mixed (optical and wireless) fronthaul network, where a wireless link failure is considered. Four optical links (green arrows) connect between the BBU and the first tier RRHs (RRH11, RRH12, RRH13,

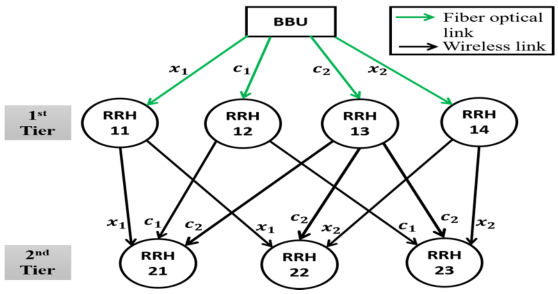


Fig. 6. DC-NC coding applied to mixed optical and wireless fronthaul network.

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 we mentioned in section II, in this scenario, we consider second tier RRHs are 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[1]. It is considered the optical connection in the first tier to be a reliable connection. So that in order to broadcast two data streams from the BBU to the second tier RRHs: RRH21, RRH22, and RRH23 via first tier RRHs using the DC-NC coding scheme, four disjoint paths are used. BBU transmits data streams x_1 and x_2 to RRH11 and RRH14 respectively. In addition, it encodes them and forms c_1 and c_2 as shown in (3) and (4) 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 (5), (6) and (7). Similarly, RRH23 decodes c_1 and x_2 then gets x_1 as shown in (8), (9) and (10). Here, RRHs should utilize directional antennas or MIMO systems to prevent interference.

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 utlizes c_1 and c_2 to recover x_1 and x_2 as as shown in (11) through (14). Furthermore, if c_1 fails, RRH21 has x_1 and c_2 then can easily recover x_2 as shown in (15), (16) and (17).

[1] 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 [5] and [6].

Similarly, RRH23 can recover x_1 and x_2. However, RRH22 has no c_1 so, if x_2 fails, it can be easily recovered as shown in (15), (16) and (17). Also, if x_1 fails, it can be easily recovered as follows:

$$\tilde{c}_2 = c_2 + \beta_{22}x_2, \quad (18)$$

and applying (4) to (18),

$$\tilde{c}_2 = \beta_{12}x_1 + \beta_{22}x_2 + \beta_{22}x_2 = \beta_{12}x_1 \quad (19)$$

$$x_1 = \tilde{c}_2/\beta_{12}\,. \quad (20)$$

Note that DC-NC coding scheme can simultaneously recover one link failure for each second tier RRH. Furthermore, not only link failures can be recovered. In Fig. 6, 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 tolorence. 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%).

2) *DC-NC Coding for Completely Wireless Fronthaul Networks:*

Fig. 7 shows the application of DC-NC coding in 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 Fig. 7). In addition, several wireless links connect RRHs between each other.

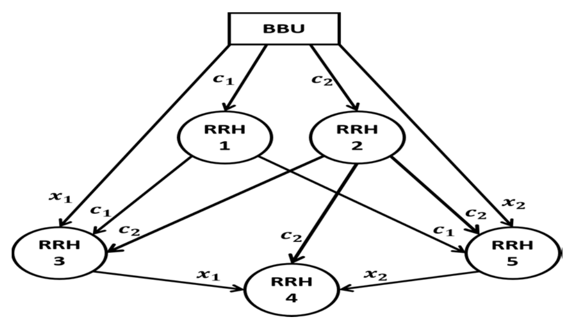


Fig. 7. DC-NC coding applied to wireless fronthaul network.

However, 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 is existed, 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 (3) and (4) then transmits them to RRH1 and RRH2 respectively. RRH3 and RRH5 send x_1 and x_2 respectively to RRH4. Hence, RRH4 has both broadcasted data streams. RRH1 sends c_1 to RRH3 and RRH5. RRH3 decodes c_1 and x_1 then gets x_2 as shown in (5), (6) and (7). Similarly, RRH5 decodes c_1 and x_2 then gets x_1 as shown in (8), (9) and (10). directional antennas or MIMO systems should be utilized in RRHs to prevent any interference.

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 utlizes c_1 and c_2 to recover x_1 and x_2 as as shown in (11) through (14). Furthermore, if c_1 fails, RRH3 has x_1 and c_2 then can easily recover x_2 as shown in (15), (16) and (17). Similarly, RRH5 can recover x_1 and x_2. However, since RRH4 will not receive c_1 , so, if x_2 fails, it can be easily recovered as shown in (15), (16) and (17). Also, if x_1 fails, it can be easily recovered as shown in (18), (19), and (20).

Note that DC-NC coding scheme can simultaneously recover one link failure for each targeted RRH. Furthermore, not only link failures can be recovered. In the example network, if RRH1 fails, c_1 will be lost, the proposed coding scheme can recover required 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 tolorence. Hence, both reliability and throughput are improved using the proposed coding scheme.

As we 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 we described early in this section.

Although in this paper, is solely focused on applying the DC-NC coding scheme in a wireless fronthaul network that can tolerate multi-link failures, our future work will investigate this approach to more general and complex network topologies that include optical and wireless links. Future work will also investigate determining the optimal disjoint paths for DC-NC coding fronthaul networks.

V. Conclusions

This paper introduced 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. 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 applying DC-NC coding by about 30%-40%, when compared to that of Diversity Coding.

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