Diversity Coded 5G Fronthaul Wireless Networks

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***Abstract* — In this paper we study the application of Diversity Coding to enable near-instantaneous recovery from link failures in 5G wireless Cloud Radio Access Network (C-RAN) networks. We focus on networks where remote radio heads in a C-RAN are connected to the baseband unit in two hierarchical tiers with optical and wireless fronthaul links. In order to avoid retransmissions and re-routing delays due to link failures in wireless links, we investigate the use Diversity Coding where a feedforward network design uses forward error control across spatially diverse paths to enable reliable networking with minimal delay.**

Keywords —5G wireless; Diversity Coding; Fronthaul; link failures; reliability

I. Introduction

As the mobile network has evolved to a primary form of communications for many, increased reliability is needed to be able to serve the increasing user expectations and the demand for data-intensive applications. One of the principal factors that decrease reliability is the link/node failure. We revisit this issue for the evolving 5G wireless network architecture, where Remote Radio Heads (RRHs) are connected to a cloud radio access network (C-RAN) via emerging fronthaul networks (see Fig 1 below). In C-RAN architectures, transport between the centralized baseband units (BBUs) and the remote radio head (RRH) units is referred to as *fronthaul*. Its function is to enable the baseband units to seamlessly connect to the remote radio units without impacting radio performance. In LTE C-RAN architectures, backhaul is via the Internet Protocol (IP) network from the centralized baseband units to the Evolved Packet Core (EPC). We consider the scenario where these connections are divided into two tiers: first-tier RRHs that connect via optical links to the BBU and second-tier RRHs that connect via wireless links to first tier RRHs and thus to the BBU. Note that the techniques we describe in this paper are also applicable to the optical tier of the network as well as the networks with all optical fiber links.

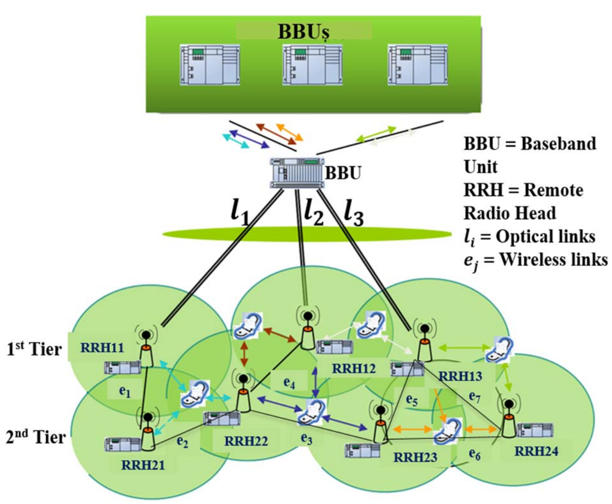

Fig.1 C-RAN with a mix of optical and wireless fronthaul network links.

Many technologies have been used to protect communication networks from link and node failures such as Synchronous Optical Networking (SONET) and *p*-cycle ring [1]. Although these solutions increase reliability, their delay performance is still considered to be high for 5G applications [1] and is not appropriate for wireless fronthaul network configurations.

Near-instantaneous recovery from fronthaul link failures will improve reliability and provide very low delay. Diversity Coding technique, which was introduced in [2] and [3], has the ability to achieve near-instantaneous recovery from link failure, 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, Diversity Coding technique can be applied to recover from a single link failure as well as from multiple simultaneous link failures up to the total number of data links that transmitting simultaneously. 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 (weather, new buildings). Nevertheless, 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.

Diversity Coding like other types of protection techniques require extra transmission capacity. In [4] it is shown that Diversity Coding has competitive spare capacity compared with standard network restoration techniques.

This paper is organized as follows: First, we describe the Diversity Coding technique in Section II. In Section III, we apply Diversity Coding with ability to recover multiple simultaneous link failures to wireless tier in fronthaul networks. Finally, we conclude the paper in Section IV.

II. Diversity Coding

The main idea in Diversity Coding is showing in Fig. 2 [2], [3] for a simple point-to-multipoint network. Here, disjoint routes carry equal rate digital flows $x_1, x_2, \dots, x_N$ to their destination. To clarify the idea of Diversity Coding in a simple way, we assume that these flows have been generated from the same source and end at the same destination. A coded flow "c_1" equal to

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

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

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

since $x_1, x_2 \ldots, x_{i-1}, x_{i+1}, \ldots, x_N$ 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.

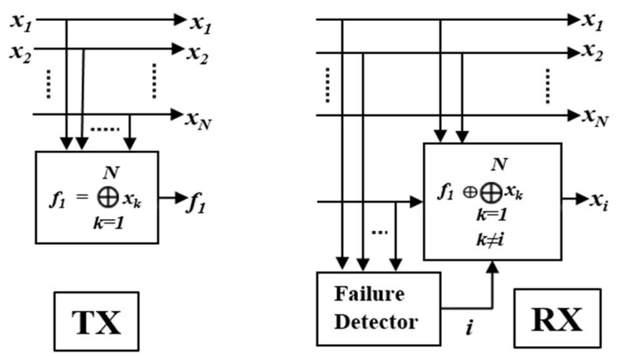

Fig.2 Illustrating the principal of Diversity Coding.

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; for example, we consider multipoint-to-point in Section III-C, and see the extensions for the point-to-multipoint and multipoint-to-multipoint topologies in [4].

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

III. NETWORK APPLICATIONS OF DIVERSITY CODING

A. Cloud Radio Access Networks (C-RANs)

C-RANs are expected to minimize the operating costs and improve spectral effeciency due to its interference management capabilities [5], [6]. The C-RAN separates base station functions into two main parts: the centralized processing and control functions that are processed in the baseband unit (BBU) of the core network, and the radio functions that are handled by the remote radio heads (RRHs) located at the cell sites [6], [7]. Wireless fronthaul may also be implemented using millimeter waves [6]. Wireless fronthaul is expected to play an essential role in C-RAN due to its cost saving and easy implementation in a dense environment such as campuses or stadiums where optical fiber deployment is difficult [6], [8]. Furthermore, mixing of fiber and wireless in fronthaul networks is expected by most operators [8]. We consider the situation where the fronthaul connections between BBU and RRHs are divided into two tiers: first-tier RRHs that connect via optical links to the BBU and second-tier RRHs that connect via wireless links to first tier RRHs and thus to the BBU. The second tier RRHs have a general mesh topology as illustrated in Fig. 1.

As 5G requires very low delay (around 1 msec for some applications) and high reliability, any link failure causes rerouting and/or retransmitions. As we demonstrate in the next section, Diversity Coding has the potential to provide near-instantaneous recovery at the expense of redundant transmission facilities.

In order to show the advantages of applying Diversity Coding in a C-RAN wireless tier fronthaul network, we will describe network restoration cost and show the benefits of applying Diversity Coding to a fronthaul networks such as that shown in Fig. 3.

B. Network Restoration

A C-RAN wireless fronthaul network can have a link failure due to weather changes or other environmental factors. To prevent the delay due to rerouting or retransmission, the standard approach is to protect the system by duplicating the number of links that carry the same information (full protection). Although this will increase the reliability of the network, it will increase the redundancy by 100%, so it is not a very attractive solution.

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 demand between nodes, capacity of each link (i.e. traffic amount), and the number of simultaneous link failures that need to be protected at a time. Depending on the network topology, different paths can be used to route each demand. The amount of traffic (flow) in each route depends on network design objective and 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 [9].

Network restoration design can be formulated as:

indices:

$d = 1, 2, \ldots, D$ demands
$p = 1, 2, \ldots, P_d$ paths
$s = 1, 2, \ldots, S$ failure states
$e = 1, 2, \ldots, E$ edges

variables:

x_{dps} flow allocated to path p of demand d for failure states s (non-negative)
y_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
ζ_e unit cost of link e

objective function to be minimized:

$$\boldsymbol{F} = \sum_e \zeta_e \, y_e, \quad (3a)$$

constraints:

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

$$\sum_p x_{dps} = h_d, \quad (3c)$$

$$\sum_d \sum_p \delta_{edp} \, x_{dps} \leq \propto_{es} y_e. \quad (3d)$$

The objective function in $(3a)$ represents the capacity cost of the network, which is the sum of the link capacity times the link unit cost [9]. Equation $(3b)$ 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 $(3c)$, which is the sum of all flows for demand d, which equals the volume of demand d, h_d. Finally, inequality $(3d)$ 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 failure 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) [9].

This is recognized as a linear programming program. 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 [4], 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 total routing cost. As we now demonstrate, Diversity Coding offers a powerful solution to recover the lost data near instantaneously and meet the above objective.

C. Diversity Coding in 5G Fronthaul Networks

Fig. 3 illustrates the application of Diversity Coding in a 5G C-RAN mixed (optical and wireless) fronthaul network. where two simultaneous wireless link failures are considered. Three optical links (green arrows) connect between the BBU and the first tier RRHs (RRH11, RRH12, RRH13). 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. In this study, an uplink multipoint-to-point network topology is considered[1]. We consider the optical connection in the first tier 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 via first tier RRHs using Diversity Coding, five wireless disjoint paths are used. RRH21 transmits r_{21} to BBU via RRH11, RRH22 transmits r_{22} to BBU via RRH12, and RRH23 transmits r_{23} to BBU via RRH12. To apply Diversity Coding, RRH21 will transmit r_{21} to RRH23, RRH22 will transmit r_{22} to RRH23, and RRH23 will form coded data streams c_1 and c_2 as follows:

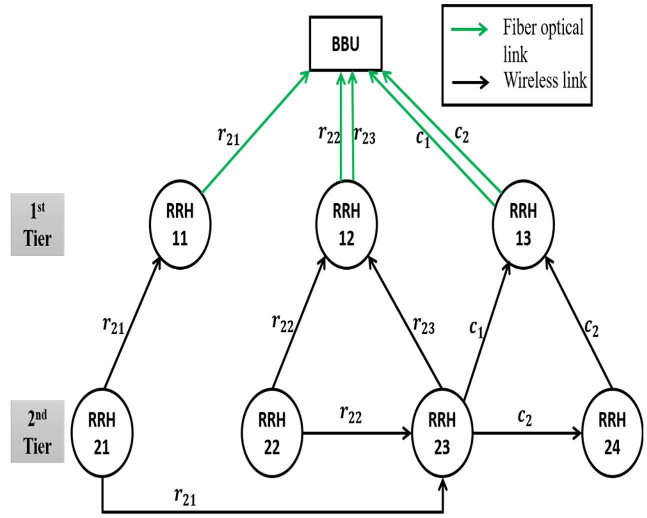

Fig.3 Diversity Coded mixed optical and wireless fronthaul network. The green lines are fiber optical links and black are the wireless links

$$c_1 = \beta_{11}r_{21} + \beta_{21}r_{22} + \beta_{31}r_{23} \quad (4a)$$
$$c_2 = \beta_{12}r_{21} + \beta_{22}r_{22} + \beta_{32}r_{23}, \quad (4b)$$

where $\begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \\ \beta_{31} & \beta_{23} \end{bmatrix}$ is the parity generator matrix. 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 AND operation and summation corresponds to XOR operation since they are performed in $GF(2^m)$. The message c_1 will be transmitted to the BBU via RRH13 and c_2 will be transmitted to the BBU via RRH24 and RRH13.

At the receiver (BBU) it is assumed that two data links (r_{21} and r_{22}) fail and that the BBU detects the failures. Let f_1 and f_2 be the indices of the links that failed, so that

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

$r_{f_1} = r_{21}$ and $r_{f_2} = r_{22}$. Hence, the BBU will generate $\tilde{c}_1$ and $\tilde{c}_2$ as follows:

$$\tilde{c}_1 = c_1 + \beta_{31} r_{23}, \tag{5}$$

and applying $(4a)$ to (5), we obtain

$$\begin{aligned} \tilde{c}_1 &= \beta_{11} r_{f_1} + \beta_{21} r_{f_2} + \beta_{13} r_{23} + \beta_{31} r_{23}, \\ &= \beta_{11} r_{f_1} + \beta_{21} r_{f_2}. \end{aligned} \tag{6}$$

Similarly, we have

$$\tilde{c}_2 = c_2 + \beta_{32} r_{23}. \tag{7}$$

When we use $(4b)$ to (7), it results in

$$\begin{aligned} \tilde{c}_2 &= \beta_{12} r_{f_1} + \beta_{22} r_{f_2} + \beta_{32} r_{23} + \beta_{32} r_{23} \\ &= \beta_{12} r_{f_1} + \beta_{22} r_{f_2}. \end{aligned} \tag{8}$$

Finally, (6) and (8) can be expressed in matrix form as

$$\begin{bmatrix} \tilde{c}_1 \\ \tilde{c}_2 \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix} \begin{bmatrix} r_{f_1} \\ r_{f_2} \end{bmatrix}. \tag{9}$$

The quantities $\tilde{c}_1$ and $\tilde{c}_2$ can be easily obtained because β_{ij} are fixed and known at BBU. In addition, $\tilde{c}_1$ and $\tilde{c}_2$ are used to recover r_{f_1} and r_{f_2} via an inverse linear transform [2], [3]. 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

$$\begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}. \tag{10}$$

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

$$m = \lceil \log_2(N+1) \rceil, \tag{11}$$

where N is the total number of data links that is three 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 $GF(2^2) = GF(4)$ [2], [3].

Therefore, BBU obtains the data streams in failure as follows:

$$\begin{bmatrix} r_{f_1} \\ r_{f_2} \end{bmatrix} = \begin{bmatrix} \beta_{11} & \beta_{21} \\ \beta_{12} & \beta_{22} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{c}_1 \\ \tilde{c}_2 \end{bmatrix}. \tag{12}$$

Note that this can apply for any two simultaneous data link failures such as r_{22} & r_{23} and r_{21} & r_{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 r_{21} will be lost and it can be recovered even with one link failure exist simultaneously. In addition, if RRH12 failed two data streams r_{22} and r_{23} will be lost simultaneously. Hence, they can be recovered easily by BBU. However, if RRH13 fails, we will lose the protection of the network i.e. c_1 and c_2, but the data communication can still be made. Unfortunately, we cannot recover second tier node failures because these nodes generate the data streams.

The above illustrates how Diversity Coding enables near-instantaneous recovery of the "lost" or errored signals. In addition to the near-instantaneous recovery capability of Diversity Coding, we now demonstrate the optimality of the scheme in terms of total routing cost for this example. Let us consider the example network of Fig. 3, 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 link capacities that will be used in the network are given as $k_1 = 10, k_2 = 10, k_3 = 10, k_4 = 10, k_6 = 10, k_6 = 10, k_7 = 10, k_8 = 10$.

The objective function can be expressed as

$$(\boldsymbol{F}) = \min_{r} \ (3r_{21} + 3r_{22} + 2r_{23} + 2c_1 + 3c_2), \tag{13}$$

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

Next, we solve the network restoration scheme that is described in Section III-B and use the problem formulated in (3) for three data streams and one link failure protection. It can be seen that the total routing cost increases to 367. 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, whereas Diversity Coding employs only the disjoint paths. Note that there are only five disjoint paths in our example.

The differences in formulation between the Diversity Coding scheme and the general network restoration scheme of Section III-B are summarized in Table I.

TABLE I. PROTECTION SCHEMES COMPARISONS

Protection Scheme	**Diversity Coding**	**Network restoration**
Total routing cost	58	367
# of data streams	5	3
# of disjoint paths	5	-
# of nodes (vertices)	8	8
# of links (edges)	11	11

In addition to the near instantaneous link failure recovery, we provided an example where Diversity Coding has a lower routing cost than the general network restoration scheme. In future work, we will explore the bounds for the difference between the routing costs of the two protection schemes. As with all restoration methods, there is an increase in the number and utilization of links, but finding the optimal restoration scheme depends on the network design, objectives, and constraints. Although in this paper, we solely focused on applying Diversity Coding in a wireless tier in fronthaul network that can tolerate two data link failures at a time as illustrated in Fig. 3, our future work will extend it to more general and complex network topologies such that Diversity Coding is applied to the whole network (optical and wireless tiers) and can tolerate more link failures at a time.

IV. CONCLUSIONS

In this paper, we studied the potential applications of Diversity Coding in 5G fronthaul Networks, where the RRHs in a centralized radio access network are connected to the baseband unit 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 tier of the fronthaul network, we demonstrated how Diversity Coding increases network reliability with near-instantaneous recovery and its ability to recover from multiple simultaneous link failures. In addition, we demonstrated an example where Diversity Coding could give a lower total routing cost than other types of restoration techniques. Future work will investigate the problem of dynamic joint resource allocation and routing in 5G Fronthaul networks, as well as the development of distributed Diversity Coding schemes. Also, the application of Diversity Coding to the entire fronthaul network (optical and wireless tiers) is of interest.

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