Link Failure Recovery via Diversity Coding in 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 Centralized Radio Access Network (C-RAN) networks. We focus on networks where remote radio heads in a C-RAN are connected to the baseband unit with wireless fronthaul links. In order to avoid retransmissions and re-routing delays due to link failures, we investigate 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; Diversity Coding; 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 network, where Remote Radio Heads (RRHs) are connected to a centralized radio access network (C-RAN) in the "cloud" 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 the Internet Protocol (IP) network from the centralized base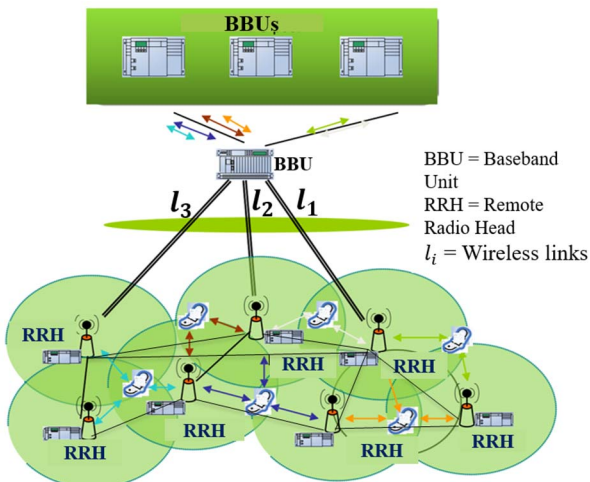band units to the Evolved Packet Core (EPC). We consider the scenario where these connections are with wireless links. Note that the techniques we describe in this paper are also applicable to the networks with optical fiber links.

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. 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). 5G communication systems require very low delay (1 msec) and high reliability.

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 to wireless 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 simple way, we assume that these flows have been generated from the same source and end in the same destination. A coded flow "f_1" equal to

$$f_1 = x_1 \oplus x_2 \oplus \cdots \oplus x_N = \bigoplus_{k=1}^{N} x_k \tag{1}$$

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

Fig. 1. C-RAN with a wireless fronthaul network.

$$f_1 \oplus \bigoplus_{\substack{k=1 \\ k \neq i}}^{N} x_k = x_i \oplus \bigoplus_{\substack{k=1 \\ k \neq i}}^{N} (x_k \oplus x_k) = x_i \qquad (2)$$

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.
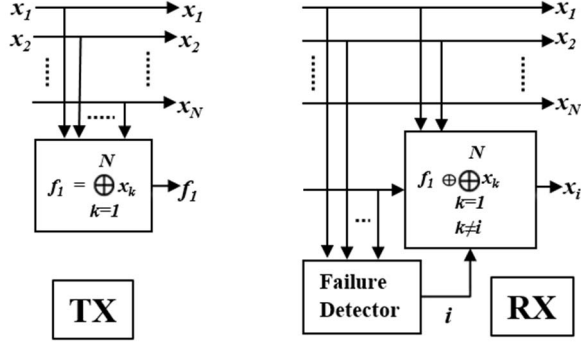

Fig. 2. Illustrating the principal of Diversity Coding.

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, multipoint-to-point, point-to-multipoint and multipoint-to-multipoint topologies [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. C-RANs

Centralized radio access networks (C-RAN) are expected to minimizing operating costs and improve spectral efficiency due to its interference management capabilities [5]. The C-RAN separates base station functions into two main parts the centralized processing and control function, which is located in the center of network and is called the baseband unit (BBU) and the radio function, which is located at the cell site and is called the remote radio head (RRH) [6]. We consider the situation where the fronthaul connections between BBU and RRHs are with wireless links and RRHs have a general mesh topology as illustrated in Fig. 1.

As 5G requires very low delay (1 msec) 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 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, but it will increase the redundancy by 100%, which is not a practical 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 [7].

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:

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

constraints:

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

$$\sum_p x_{dps} = h_d, \tag{3c}$$

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

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 [7]. 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) [7].

This is recognized as a linear programming program. The restoration capability can generally be increased, but 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 wireless fronthaul networks.

The ideal objective is to improve 5G C-RAN wireless 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 to a 5G C-RAN wireless fronthaul network. In our example, there are three wireless links $l_1, l_2,$ and l_3 that connect between the BBUs and RRH1, RRH2, RRH3 respectively.
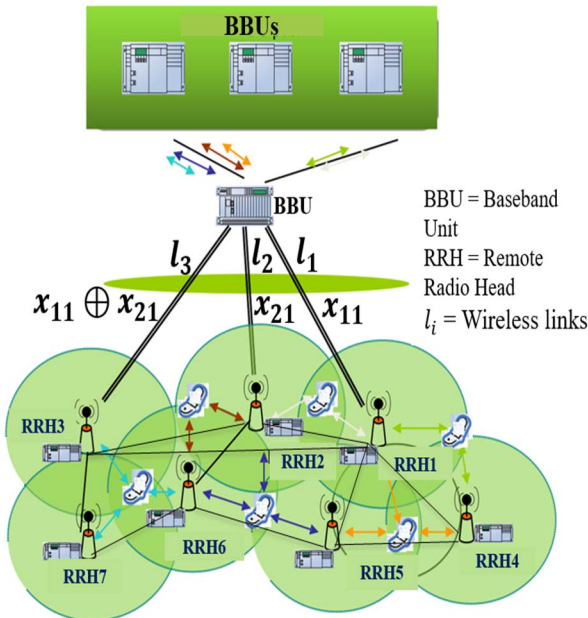

Fig. 3. Diversity Coded wireless fronthaul network.

In this study, a downlink point-to-multipoint network topology is considered[1]. So that in order to transmit two data streams from BBU to RRH1 and RRH2 using Diversity Coding, three disjoint paths are used. The link l_1 carries the first data stream x_{11}, l_2 carries the second data stream x_{21}. The BBU will sum these data streams using XOR operation $(x_{11} \oplus x_{21})$ then transmit the result by l_3 through RRH3. Let $(x_{11} \oplus x_{21})$ denoted by x_{31}.

So, if either x_{11} or x_{21} are not received, the receiver can recover that signal by summing the received signal with $(x_{11} \oplus x_{21})$. **This is 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 $h_1 = 3, h_2 = 7,$ 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 link capacities that will be used in the network are given as $c_1 = 10, c_2 = 10, c_3 = 10, c_4 = 10, \ c_5 = 10$.

The objective function can be expressed as
$$(F) = \min_x(x_{11} + x_{21} + 3x_{31}), \tag{4}$$
such that the amount of each data stream will be $x_{11} = 3, x_{21} = 7,$ and $x_{31} = 7$. The total routing cost will be **31**. Note that since the data streams x_{21} and x_{31} are used twice in the routing, they are multiplied by 2 in the objective function.

However, using the general network restoration scheme that is described in section III-B, applying equation (3) for two data streams and one link failure at a time will increase the total routing cost to **293**. Note that the cost of the network restoration scheme is very high compared to the one for the Diversity Coding scheme because the former considers all joint paths in the network, whereas Diversity Coding employs only the disjoint paths, where there are only three 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	31	293
# of data streams	3	2
# of disjoint paths	3	-
# of nodes (vertices)	4	4
# of links (edges)	5	6

[1] In the uplink RRH3 performs XOR summation and transmit the result using the links that connected it with RRH1 and RRH2.

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 simple network topology as illustrated in Fig. 3, our future work will extend it to more general and complex network topologies (see the mesh network topology shown with green color in Fig. 3), where Diversity Coding is applied to connect the RRHs.

III. 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 a wireless link. In order to avoid retransmissions that incur high transmission and re-routing delays, we demonstrated how Diversity Coding increases network reliability with near-instantaneous recovery. 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 developing distributed Diversity Coding schemes. Also, the application of Diversity Coding to wireless mesh networking between RRHs is of interest.

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