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Enhanced Diversity and Network Coded 5G Wireless Fog-Based-Fronthaul Networks

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***Abstract*— The synergistic combination of Diversity and Network Coding (DC-NC) was previously introduced to provide very low end-to-end latency in recovering from a link failure and improve the throughput for a wide variety of network architectures. This paper is directed towards further improving DC-NC to be able to tolerate multiple, simultaneous link failures with less computational complexity. In this way, reliability will be maximized and the recovery time from multiple link or node failures is reduced in 5G fronthaul wireless networks. This is accomplished by modifying Triangular Network Coding (TNC) to create enhanced DC-NC (eDC-NC) that is applied to 5G wireless Fog computing-based Radio Access Networks (Fog-RAN). Our results show that using eDC-NC coding in Fog-RAN fronthaul network will provide ultra-reliability and enable near-instantaneous fault recovery while retaining the throughput improvement feature of DC-NC. In addition, the scalability of eDC-NC coding is demonstrated. Furthermore, it is shown that the redundancy percentage for complete protection is always less than 50% for the practical cases that were evaluated.**

Keywords—5G, Diversity Coding, Fog-RAN, reliability, throughput, Triangular Network Coding

I. Introduction

Wireless 5G networks require extremely high reliability and throughput for many key applications, as well as ultra-low latency communications [1]. Link and node failures reduce reliability, decrease throughput, and increase latency and this issue is addressed in this paper for Fog computing-based Radio Access Networks (Fog-RANs), which is an enhancement and an alternative to Cloud Radio Access Networks (C-RANs) [2]-[4]. The key idea of Fog-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 [2]-[4].

Mobility of user equipment and/or changes in channel state is one of the principle factors that leads to link and node failures in wireless communications. Ultra-low delay and high reliability will be required for several applications in 5G communication systems, and solutions need to be developed to address these two challenges. Near-instantaneous restoration from fronthaul link failures is essential to improve reliability and enable very low delay networking. This can be accomplished by a feedforward technique that uses Diversity Coding (DC) [5], which is a forward error control technology over diverse paths. With DC as soon as the failure is detected near-instantaneous recovery of the lost data is possible with no need to retransmit messages and perform rerouting. It is worth noting that the time to determine the facility loss will be a lower bound on the recovery latency.

It is shown in [6] and [7] that the reliability of a C-RAN network is enhanced by applying Diversity Coding to recover from multiple simultaneous link failures. Although reliability is very important in wireless Fog-RANs, throughput is another important factor in assessing wireless Fog-RANs performance. Network Coding [8], which also called Linear Network Coding (LNC), can increase the throughput of 5G wireless Fog-RAN networks. There are several modes of LNC that can be used for this purpose. One of these modes is Triangular Network Coding (TNC) [9] that reduces the computational complexity of Linear Coding without degrading the throughput performance, with a code rate comparable to that of linear Network Coding.

A synergistic combination of Diversity Coding (DC) and Network Coding (NC) (DC-NC) was introduced in [10] and can simultaneously enhance wireless network reliability, provide high throughput and enable low failure-recovery latency for 5G communications systems.

The contributions of this paper are (1) modifying TNC to enhance DC-NC coding, (2) applying enhanced DC-NC coding (eDC-NC) to Fog-RAN wireless networks to improve reliability. (3) reduce computational complexity, (4) enable extremely low recovery time for simultaneous multiple link failures, and (5) retaining the throughput gains of DC-NC for broadcasting or multicasting applications. In addition, a general eDC-NC encoding expression is derived and a performance analysis in terms of redundancy percentage requirements is presented.

The rest of this paper is organized as follows: Section II describes the network topology based on Fog-RANs. Section III provides background about Triangular Network Coding. The modification to TNC and its utilization to enhance DC-NC coding is presented in Section IV. Section V demonstrates the ability of eDC-NC coding to enable faster recovery from multiple simultaneous link failures in wireless fronthaul networks. The performance analysis of the required redundancy percentage is introduced in Section VI. The paper ends with concluding remarks in Section VII.

II. System Model

Fog-RANs were proposed in [2]-[4] to improve the performance of C-RANs by migrating a significant number of functions to the edge device and substantially upgrading the

Remote Radio Heads (RRHs). These functions include controlling, communicating, measuring, managing, and storing data. In this way, an upgraded RRH is called a Fog Access Point (F-AP), and will be able to communicate and network with other F-APs and this architecture will reduce latency by performing functionality at the network edge rather than in the core [2]-[4]. The architecture of the Fog-RAN consists three layers as illustrated in Fig. 1 [2]. The BBU pool, centralized storage, and communication and computing cloud represents the network layer. The access layer contains F-APs. The terminal layer contains Fog-user equipment (F-UE) that access F-AP [2]-[3]. The adjacent F-APs can be formed into two topologies: a mesh topology and a tree-like topology. Both of topologies can significantly minimize the degrading effects of capacity-constrained fronthaul links [2].

Although there are different transmission modes in a Fog-RAN, in this paper, it is focused only on the Local Distributed Coordination (LDC) mode as it is the core mode of the Fog-RAN as shown in Fig. 1 [2]. in LDC, the F-APs communicate with other F-APs to serve the F-UEs. This will decrease the burden on the fronthaul network and quickly suppress interference or transmit the required data to the UE not from the cloud server but from the F-APs [2].

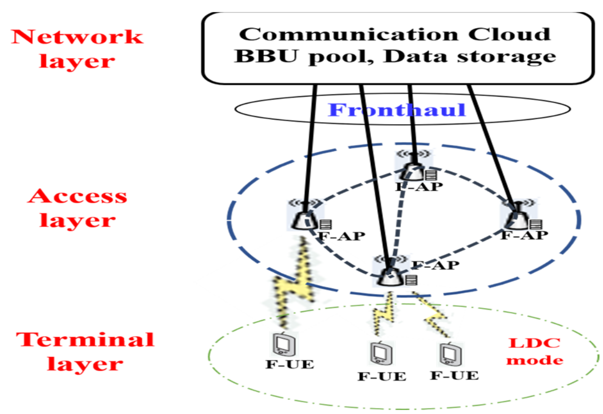


Fig. 1. Fog-RAN network architecture.

In [10], DC-NC coding is applied to a wireless fronthaul C-RANs and in this study, we extend DC-NC, dubbed eDC-NC, to the LDC fronthaul network, where F-APs are connected to each other in a mesh topology as shown in Fig. 2. In this paper, these connections are considered to be wireless links. To minimize interference and be able to communicate with each other, such F-APs will likely utilize MIMO technology.

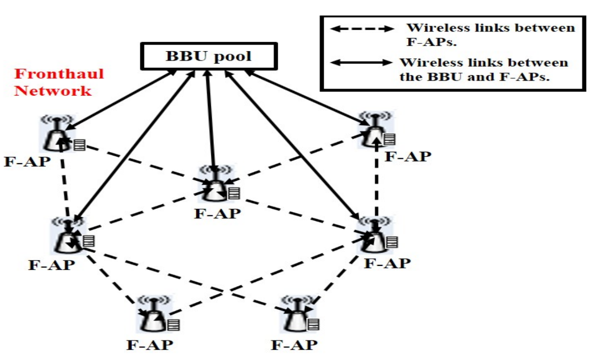


Fig. 2. Example Fog-RAN fronthaul network with wireless links.

III. Triangular Network Coding

Triangular Network Coding (TNC) [9] is a 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 [9].

To illustrate the main idea of TNC, let us assume 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 $[r_1, r_2, r_3]$. Hence, 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 our example, $3 \times (3-1) = 6$ coded data streams can be generated. It is shown in [9] 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 Fig. 3. 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 [9]. However, TNC cannot work as described above if there is a raw (original) data stream in the receiver node as it will be explained in detail in Section IV.

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

Fig. 3. An example of the decoding process in TNC

IV. Enhanced DC-NC Coding

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 ≥ 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. To solve this problem, the DC-NC coding will be modified such that only GF(2) will be utilized at 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. Based on the example that we have given in section III, the first six IDs of the coded data streams 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, let us 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:

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

Coded data stream c_1 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

Coded data stream c_4 after XOR operation with x_1.

It is clear that using the back substitution scheme described above will not work, since only the bit $b_{2,1}$ can be obtained from both tables of coded data streams and hence, x_2 and x_3 cannot be recovered. There are several cases that can lead to the same result, as illustrated in Table I.

TABLE I. 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 in the destination nodes, it is noted the coded data streams with a zero that fixed in only one position in their IDs can perfectly recover other required raw data streams. However, with 1 position for "0" to be fixed, 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, 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. In DC-NC coding, only $(N-1)$ coded data streams for NC are required to get the throughput gain and N coded data streams for DC are required to get full protection of the network. By doing several experiments, we derived a general notation to generate the encoded data stream such that they can work perfectly with or without raw data stream. Hence, coded data stream can be expressed as:

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

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, we can always generate $(N-1)$ coded data streams for NC and another $(N-1)$ coded data streams for DC. Furthermore, we can always generate one more coded data stream to get a fully protection DC-NC network. For example, to broadcast 3 data streams i.e. $N = 3$ and tolerate 2 link failures for each destination node, we will need for 4 coded data streams that can be generated as follows:

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

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

$$c_1 = x_{1,0} \oplus x_{2,1} \oplus x_{3,2}, \quad (3)$$
$$c_2 = x_{1,0} \oplus x_{2,2} \oplus x_{3,1}, \quad (4)$$

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

$$c_3 = x_{1,0} \oplus x_{2,3} \oplus x_{3,5}, \quad (5)$$
$$c_4 = x_{1,0} \oplus x_{2,5} \oplus x_{3,3}, \quad (6)$$

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

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

TABLE II. THE COMPARISON BETWEEN ENHANCED DC-NC AND REGULAR DC-NC

Criteria	eDC-NC	DC-NC
Encoding and decoding complexity	Less and same for any # of coded data	High and increases with increasing the # of coded data
Decoding scheme	bit by bit XOR substitution	Matrix inversion

V. APPLYING ENHANCED DC-NC CODING TO FOG-RANS

Improving throughput and reliability in 5G Fog-RANs is critical due to wireless link capacity limitations. In addition, due to weather changes or other environmental factors, such as blockage, link failures can occur. Enhanced DC-NC is a promising technology to improve the reliability of Fog-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.

Fig. 4 illustrates the application of eDC-NC coding to a wireless fronthaul Fog-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 (3)-(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 III. Similarly, c_1, c_2 and x_3 are decoded in F-AP8 to get d_1 and d_2. The throughput gains in this example network improve by at least one-fifth [10]. However, any link failure can strongly impact Fog-RAN reliability.

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 using simple back substitution method. 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 are happened, for example x_1 and c_2, F-AP7 detects the failures then recovers x_1, x_2 and x_3 by utlizing c_1, c_3 and c_4 using bit by bit substitution method. Similarly, any two link failures can be recovered in the same way.

Furthermore, in addition to multiple link failures recovery, enhanced DC-NC coding in this example fronthaul network can recover from two intermediate node failures such as F-AP5 and F-AP6 because this corresponds to four simultaneous link failures that each 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.

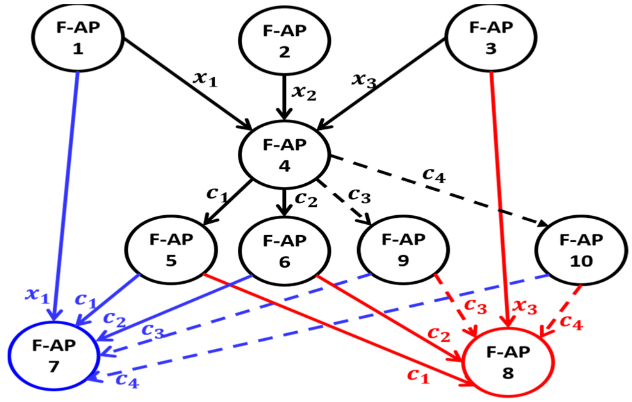


Fig. 4. Example wireless fronthaul Fog-RAN network with eDC-NC coding that broadcasts three data streams to F-AP7 and F-AP8 and protects each stream from two simultaneous link failures. The solid lines represent the links that carry coded data streams and are used to improve network throughput whereas 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.

These results in this paper 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 Fog-RAN network can be improved and protected by eDC-NC.

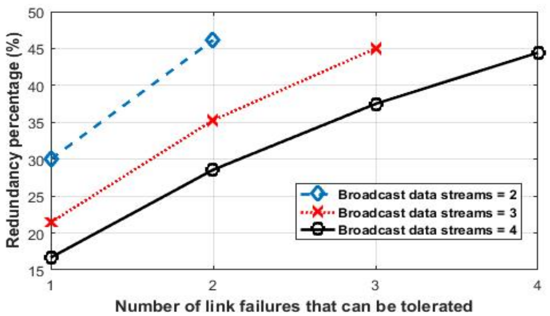
Although in this study, we solely focused on applying the enhanced DC-NC coding scheme in a Fog-RAN with a wireless fronthaul network, our future work will investigate the application of this approach to more general and complex network topologies that include optical and wireless links.

VI. REDUNDANCY PERCENTAGE ANALYSIS

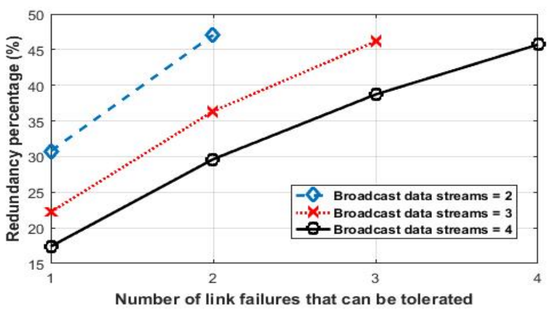
In general, eDC-NC networks have the ability to tolerate n link failures for each F-AP at j destination F-APs, however, $jn + n$ redundant links are required. Furthermore, for multipoint-to-multipoint topology, the number of overall utilized links for k source F-APs can be expressed as $kj + (2k - 1) + jn + n$. One of the important parameters that can determine 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) can be expressed as:

$$R = \frac{jn + n}{kj + (2k - 1) + jn + n} \times 100 \quad (7)$$

Using (7), the relationship between the redundancy percentage versus number of link failures that can be tolerated for two and three destination F-APs respectively in Fog-RAN networks with various broadcast data streams is plotted and depicted in Fig. 5a and 5b. 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.



(a) Number of destination F-APs = 2



(b) Number of destination F-APs = 3

Fig. 5. Enhanced DC-NC coding redundancy percentage versus number of link failures that can be tolerated.

Similarly, Fig. 6, illustrates the redundancy percentage versus number of link failures that can be tolerated, number of broadcast data streams, and the number of destination F-APs. 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[1] is always less than 50% for the practical cases that were evaluated.

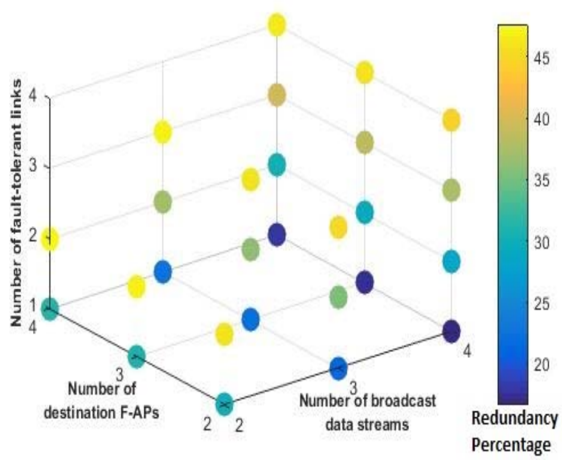


Fig. 6. Enhanced DC-NC coding redundancy percentage versus number of fault-tolerant links, destination F-APs, and broadcast data streams.

VII. CONCLUSIONS

This paper presented the application of enhanced DC-NC, which synergistically combines Diversity and modified Triangular Network Coding, to improve the performance of 5G wireless fronthaul Fog-RANs. It is shown that enhanced DC-NC can simultaneously recover from multiple link/node failures. Furthermore, enhanced DC-NC networks can tolerate n link failures for each F-AP at j destination F-APs, with $jn + n$ redundant links. Moreover, it is shown that the redundancy percentage for n link failures is inversely related to the number of source F-APs, which illustrates the scalability of eDC-NC coding. In addition, the redundancy percentage for complete protection is always less than 50%. Applying eDC-NC coding minimizes the impact on latency of multiple link/node failures in wireless fronthaul network links and significantly improves the reliability of Fog-RAN networks.

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[1] 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.