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Network Coding Enabling Resilient 5G Networks

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Abstract: A resilient 5G Network solution adopting Network Coding in the optical transport with minimum buffering requirements is proposed. Network level modelling results demonstrate a 33% reduction in the overall optical network capacity required and 50% reduction of edge node buffer size.

1. Introduction

Cloud-Radio Access Networks (C-RANs) have been recently proposed as a key concept to address the inefficiencies of traditional RANs and support services requiring very low latency, high reliability, density and mobility. However, C-RAN requires tremendous transport bandwidth and impose strict latency and synchronization constraints [1]-[2] that can only be supported through optical network solutions. The transport capacity problem is further exaggerated in survivable C-RAN solutions [3]-[7]. Several protection schemes require duplication of the optical transport network capacity, making realistic survivable C-RAN deployments impossible [7]. A typical example of systems offering protection to any type of failures (either at the optical transport or the compute domain where Baseband Units (BBUs) are hosted) is shown in Figure 1a). Specifically, in case of a failure in the main paths interconnecting the Remote Units (RUs) with the BBUs (i.e. paths 1-6, 3-5), FH flows are routed to their destination through a set of secondary (protection) paths (1-2-4-5, 3-2-4-6). A similar approach is taken for the C-RAN protection against BBU failures [5]. Under this scenario, multiple FH flows need to be transferred over a set of links, introducing even higher transport bandwidth requirements.

To address this issue the concept of *Network Coding* (NC) [8] is proposed with the aim to offer resilient FH services by multiplexing FH flows and therefore reducing the volume of the transmitted I/Q streams. Using NC, two different FH traffic streams with the same source and destination nodes are routed through the network following diverse paths. These can be protected through their *modulo-two sum* that is generated at the source node and forwarded to the common destination node. This allows reconstruction of each one of the two initial streams at the destination node, in case of a failure along one of the two paths that the initial two streams are traversing reducing the overall protection bandwidth requirement by half (see link 2-4 in Figure 1 b). Adopting this approach, simultaneous protection against optical network and/or compute element failures can be achieved. Although NC has been extensively used to enable protection against link failures, its application in resilient FH networks has not been proposed before. This can be attributed mainly to the overhead that the application of the modulo-two sum and the replication operations of NC introduce in practical systems that may degrade the performance of C-RANs. At the same time, FH flows (i.e. $x, y, x \oplus y$) arriving from the various RUs at the decode nodes (i.e. BBUx, BBUy) should be synchronized.

To address these limitations, we extend optical edge nodes functionalities, currently providing the interface between RANs and optical transport, with a solution that enables them to execute the coding and decoding processes at line rate, complying at the same time with the delay and synchronization requirements of FH flows. In order to evaluate the network level benefits of the proposed approach, an optimization framework has been developed a) that focuses on the design of an NC-enabled architecture that protects the system from possible network and/or compute element failures, *ii)* minimizes buffering at the edge, while ensuring that all FH flows arrive simultaneously at the BBUs.

2. Optimal 5G Network design with resilience considerations

2.1. Traditional Optimization framework

This section provides a description of the modeling framework used to identify the optical network resource requirements for the interconnection of RUs with compute

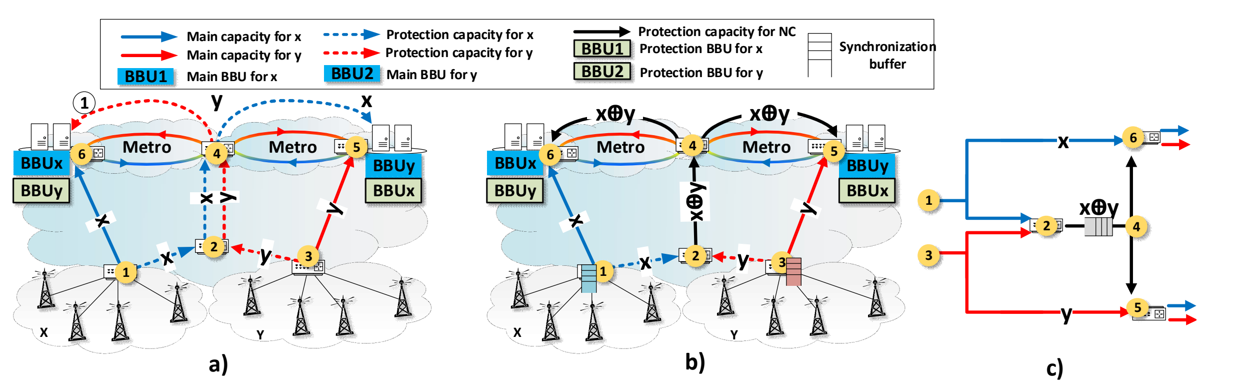

Figure 1. Protection of a C-RAN network from failures of compute and/or network elements. a) Traditional approach: working and protection capacity established over common links causing bottleneck b) C-RAN rotection adoting NC: FH flows from regions x, y are multiplexed ($x \oplus y$) at ingress edge node and replicated reducing bandwidth requirmens by half, c) Optimal Buffer placement for FH flows synchronization.

resources, hosted at centralized servers performing BBU processing, with resilience considerations. This formulation extends [1] to address resilience and protect the 5G network from possible failures of optical and/or DC network elements. Taking into account both FH network and BBU processing demands, let $\mathcal{P}_r$ be the set of paths interconnecting RU $r \in \mathcal{R}$ with server s where BBUs are hosted with $p \in \mathcal{P}_r$. Now let x_{rp} be the rate at which FH demand originating from r flows through path p and α_{rs} a binary coefficient taking value equal to 1 if the BBU of RU $r \in \mathcal{R}$ is hosted at server s. The following demand constraints should be satisfied:

$$\sum_{s\in\mathcal{S}}\sum_{p\in P_r} \alpha_{rs}x_{rp} = h_r, \qquad \forall\, r \in \mathcal{R} \quad (1)$$

In order to protect the planned network from a possible server failure hosting the BBU, a backup mechanism is introduced. This mechanism ensures that in case of failure of the primary server s hosting BBUs, FH flows are routed to an alternative server s' $(s' \neq s)$ through the candidate path p' $(p' \in \mathcal{P}_r)$ with corresponding flow $x_{rp'}$. The FH flow protection constraints are described through:

$$\sum_{\substack{s',s'\neq s\\ s,s'\in\mathcal{S}}}\sum_{p'\in P_r} \alpha_{rss'}x_{rp'} = h_r, \forall\, r \in \mathcal{R}, s \in \mathcal{S} \quad (2)$$

where $\alpha_{rss'}$ is a binary that equals 1, if BBU of RU r is processed at server s or in case of its failure on server s'; 0 otherwise. Summing all FH flows over the optical network link e $(e \in \mathcal{E})$, the necessary link e capacity, denoted as u_e, is determined:

$$\sum_{r\in R}\sum_{s\in\mathcal{S}}\left[\sum_{p\in\mathcal{P}_r}\beta_{erp}x_{rp} + \sum_{\substack{s'\in\mathcal{S},\\ s'\neq s}}\sum_{p'\in\mathcal{P}_r}\beta'_{erp'}x_{rp'}\right] \le u_e, \quad \forall\, e \in \mathcal{E} \ (3)$$

$$u_e \le \mathcal{C}_e, \quad \forall\, e \in \mathcal{E} \quad (4)$$

In (3), β_{erp} and $\beta'_{erp'}$ are binary coefficients taking values equal to 1 if link e belongs to path p and p', respectively, realizing FH flow r at server s or s'; 0 otherwise. In (4), $\mathcal{C}_e$ is an upper bound of the capacity of link e. Apart from server failures, optical network link failures are also addressed by forwarding FH flows to their destination via alternative paths. Let $\mathcal{Q}_{rp}$ be the set of paths that can be used to protect a path $p \in \mathcal{P}_r$ from a possible failure, y_{rq} the rate at which FH demand originating from r flows through path $q_p \in \mathcal{Q}_{rp}$ protecting main path $p \in \mathcal{P}_r$ (with p, q being disjoint) and $u'_e = \mathcal{C}_e - u_e$ the remaining link e capacity. The path-protection constraints are written as follows:

$$\sum_{s\in\mathcal{S}}\sum_{q\in\mathcal{Q}_{rp}} \alpha_{rs}y_{rq} = h_r, \qquad \forall\, r \in \mathcal{R}, p \in \mathcal{P}_r \quad (5)$$

$$\sum_{\substack{s',s'\neq s\\ s,s'\in\mathcal{S}}}\sum_{q'\in\mathcal{Q}_{rp}} \alpha_{rss'}y_{rq'} = h_r, \forall\, r \in \mathcal{R}, s \in \mathcal{S}, p \in \mathcal{P}_r \quad (6)$$

$$\sum_{r\in R}\sum_{s\in\mathcal{S}}\left[\sum_{q\in\mathcal{Q}_{rp}}\beta_{erq}y_{rq} + \sum_{\substack{s'\in\mathcal{S},\\ s'\neq s}}\sum_{q'\in\mathcal{Q}_{rp}}\beta'_{erq'}y_{rq'}\right] \le u'_e, \forall\, e \in \mathcal{E}, p \in \mathcal{P}_r \ (7)$$

Finally, server s should have adequate capacity φ_s for BBU processing. To determine φ_s, RU r network demands, h_r are mapped to computing requirements through parameter $\mathcal{M}_{rs}$. This parameter specifies the computational requirements (usually in Instructions Per Second - IPS) to process FH flow r on server s. Estimation of $\mathcal{M}_{rs}$ for various wireless access network configurations is provided in [10]. The total volume of BBU processing performed at s is given by:

$$\mathscr{v}_s(x) = \sum_{r\in\mathcal{R}}\sum_{p\in P_r} \alpha_{rs}\,\mathcal{M}_{rs}, \quad s \in S \quad (8)$$

Finally, servers' capacity protection constrains are expressed through

$$\mathscr{v}'_{s'}(x) = \sum_{r\in\mathcal{R}}\sum_{p'\in P_r}\sum_{\substack{s\in\mathcal{S}\\ '\neq s}} \alpha_{rss'}\,\mathcal{M}_{rs'}, \qquad s' \in \mathcal{S} \ (9)$$

The primary objective of the proposed scheme is to minimize the total power consumption of the resulting network configuration. Let k_e being the cost of the capacity of link e of the optical network and PC_s the power consumed at server s, then the following cost function is minimized:

$$min\ O(\boldsymbol{p}, \boldsymbol{x}) = \sum_{e\in\mathcal{E}_o} k_e(u_e(\boldsymbol{x}) + u'_e(\boldsymbol{x})) + \sum_{s\in\mathcal{S}} PC_s(\mathscr{v}_s(\boldsymbol{x}) + \mathscr{v}'_s(\boldsymbol{x})) \quad (10)$$

subject to constraints (1)-(9) and end-to-end delays

2.2. Extension: Integration of NC

To reduce the very high bandwidth requirements of resilient C-RAN deployments the concept of *NC* is employed. Using NC, FH streams originating from the two RUs can be multiplexed reducing network requirements. This is demonstrated in Figure 1 b) where the replicated FH streams are replicated (nodes 1, 3) and transmitted through disjoint paths 1-2, 1-3. Then, at node 2 instead of forwarding protection FH flows from regions x and y, the modulo-two sum $x \oplus y$ is transmitted over links 2-4, 4-6 and 4-5. At the egress nodes where BBUs are connected, the operations $x \oplus (x \oplus y)$ and $y \oplus (x \oplus y)$, are performed for BBU1 and BBU2, respectively, recovering FH flows y and x, respectively. In order to apply this concept in realistic environments, the pairs $x, x \oplus y$ as well as $y, x \oplus y$ should arrive at the BBUs simultaneously. At the same time, placement of the modulo-two sum and replication operations at the edge is a critical aspect that needs to be resolved. To this end, a multi-stage optimization framework is proposed.

In the first stage, equations (5)-(7) of the original problem are dropped and replaced by a suitable set of constraints enabling NC. Let $\mathcal{N}_1$, $\mathcal{N}_2$, be the set of nodes where the modulo-2 sum and replication operations are performed. To keep the analysis tractable, we assume that RUs are located in regions, x, y, as shown in Figure 1b), however, it can be easily extended to multiple nodes. Now, let $\mathcal{R}_x, \mathcal{R}_y$ be the set of RUs belonging to regions x, y, respectively with $\mathcal{R} = \mathcal{R}_x \cup \mathcal{R}_y$ and δ_{n1} a binary variable taking value equal to 1 if the protection flows of RUs originating from regions x, y are multiplexed at node $n_1 \in \mathcal{N}_1$. The following flow constraints should be satisfied:

$$\sum_{n_1\in\mathcal{N}_1}\sum_{q\in\mathcal{Q}_{rn_1}} \delta_{n1}y_{rq} = h_z, \qquad \forall\, r \in \mathcal{R}_z, z = x, y \ (11),$$

$$\sum_{n_1\in\mathcal{N}_1} \delta_{n1} = 1 \quad (12)$$

where $\mathcal{Q}_{rn_1}$ denotes the set of paths interconnecting an RU r with node n_1 and h_z denotes network requirements of all RUs belonging to region $z = \{x, y\}$. (12) ensures that

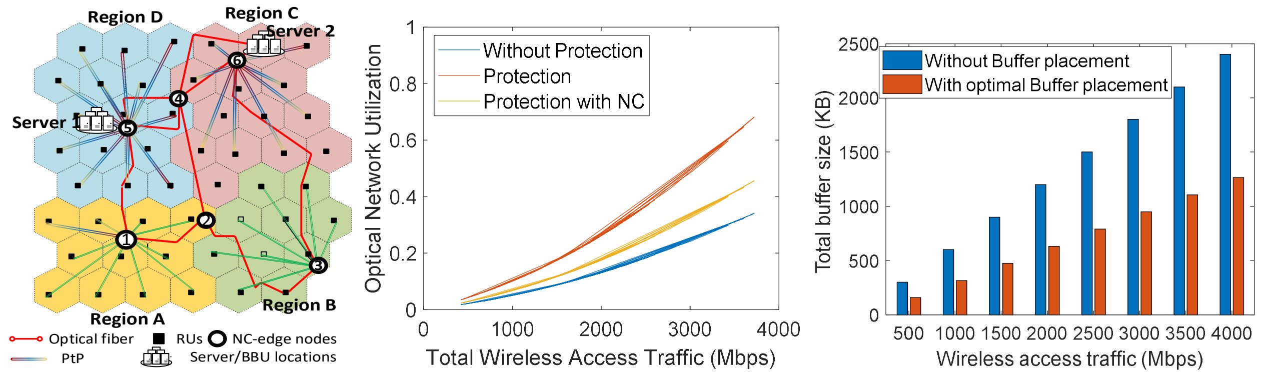

Figure 2. a) Bristol topology with NC enabled nodes, b) Optical network utilization with and w/o NC, c) Impact of optimal buffer placement at the optical edge

the encoding process of all RUs will be performed at a single node. The multiplexed stream $y_{n1} = y_{rq} \oplus y_{kq}$ is then forwarded to node $n_2 \in \mathcal{N}_2$ where the replication operation is performed. Flows are transmitted over candidate paths $q \in \mathcal{Q}_{n1n2}$ interconnecting nodes n_1 and n_2 with capacity z_q, $q \in \mathcal{Q}_{n1n2}$. The replicated flows z_q are then routed to the locations where BBU are hosted over the shorted available paths. Finally, taking the summation of all FH flows over the optical network link e, the necessary protection capacity at e, u'_e, is determined. The NC-enabled C-RAN network is determined by minimizing the cost function (10) subject to the constraints mentioned above.

The output of the first-stage optimization problem is used as input in the second stage problem that tries to identify the total buffer length. Let $G = \{E, V\}$ be the NC enabled graph determined through the first stage problem, with E and V represent the sets of all edges and nodes in G. Let also (u, v) denote a graph edge from node u to node v. Synchronizing the NC system is equivalent to assigning a value to d_{uv} at link (u, v) so that the delays from an RU to node $u \in V$ are identical for all nodes u. The synchronization-buffer minimization problem can be expressed as [9]:

$$\min \sum_{(u,v)\in E} d_{uv}$$

subject to $-D_u + D_v - d_{uv} = T_u, u, v \in V, (u, v) \in E,$

where T_u is the known transmission delay at node u.

3. Network level evaluation

To evaluate the performance of the overall system, the processing requirements of the virtualized BBUs, and, consequently parameter $\mathcal{M}_{rs}$, are determined. To achieve this, an extensive set of experiments has been carried out using OAI. Once BBU requirements have been determined, the performance of the overall system with and without NC considerations is examined for the Bristol City topology shown in Figure 2a. In this topology, RUs are attached to the edge node through point to point links. For this topology, BBU processing for Regions A and D will be provided by Server 1 whereas BBU processing for Regions B and C by Server 2. At the same time, the main FH connectivity will be provided through links 1-5 and 3-6 for regions A, B, respectively. Protection of FH flows will be provided through paths 1-2-4-6 for Region A, 3-2-4-5 for region B, 5-4-6 for region D and 6-4-5 for region C. The encoding (replication) processes for regions A, B will be performed at node 2 (4), while for Regions C and D decoding and replication operations will be both formed at node 4. A comparison of the optical network utilization for the Bristol City network for the provisioning of resilient C-RAN services is shown in Figure 2b, with and without the adoption of NC. It is observed that when NC is adopted, optical network utilization is reduced by approximately 33% leading to an overall reduction of the power consumption. The impact of the optimal placement of the buffering functionality at the optical nodes is shown in Figure 2c). When the ILP scheme that minimizes buffering size for synchronization is adopted, the size of the buffers at the optical edge nodes can be reduced by 40%.

4. Conclusions

The problem of provisioning of C-RAN services over optical transport networks with resilient considerations has been studied. Recognizing the high bandwidth requirements that emerge from this type of services, a novel approach based on NC has been proposed. Network level modeling results demonstrate a reduction of the total optical network capacity required for this type of applications by 33% keeping buffering requirements at minimum.

5. Acknowledgment

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