Bringing Network Coding into SDN: Architectural Study for Meshed Heterogeneous Communications

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***Abstract*—Modern communications have moved away from point-to-point models to increasingly heterogeneous network models. In this article, we propose a novel controller-based architecture to deploy adaptive causal network coding in heterogeneous and highly-meshed communication networks. Specifically, we consider using Software-Defined-Network (SDN) as the main controller. We first present an architecture for highly-meshed heterogeneous multi-source multi-destination networks that represent the practical communication networks encountered in the fifth generation of wireless networks (5G) and beyond. Next, we present a promising solution to deploy network coding over the new architecture. We also present a new controller-based setting with which network coding modules communicate to attain the required information. Finally, we briefly discuss how the proposed architecture and network coding solution provide a good opportunity for future technologies.**

I. INTRODUCTION

The increasing demand for network connectivity and high data rates requires efficient utilization of all possible resources exploiting existing and new infrastructures. In recent years, connectivity moved forward from point-to-point models to multi-source multi-destination (MS-MD) meshed networks of nodes, where intermediate nodes can cooperate and share physical resources for efficient and reliable communications.

Current state-of-the-art research lacks a comprehensive understanding of the interplay among coding and scheduling within a heterogeneous highly meshed MS-MD network context. Although joint optimization of coding and scheduling has been considered in the literature, efficient allocation of the available resources in heterogeneous networks across all the multiple sources and destinations to obtain the desired performance in terms of high throughput with low in-order delivery delay remains a challenging open problem. To embrace groundbreaking 5G networks with massive scale, dense environments, and requirements of the ultra reliable low latency communications (URLLC), we present an adaptive and causal random linear network coding (AC-RLNC) technique that interplays with a controller-based architecture proposed for effective and reliable communications in highly meshed heterogeneous environments.

We exploit the network information managed by Software-Defined-Network (SDN) [1] controllers to tailor the operation of network coding by learning, in real time, the current erasure pattern and network link rates, using a joint control, to consequently improve the decisions. We note that network coding is already a trend for reaching the capacity of the networks, and we are in fact proposing a communication solution that solves the challenging problem of how to use network coding in practical meshed networks to exploit all available infrastructure/communication mediums. As a promising example, the communication solution presented in this article can be very beneficial for realizing the advanced requirements of Smart Cities. One of the main priorities consists of integration of heterogeneous communication infrastructures and processes to enable the right environment where digital networks and services can prosper, e.g using all physical resources, distributed storage, and computation, see Fig. 1.

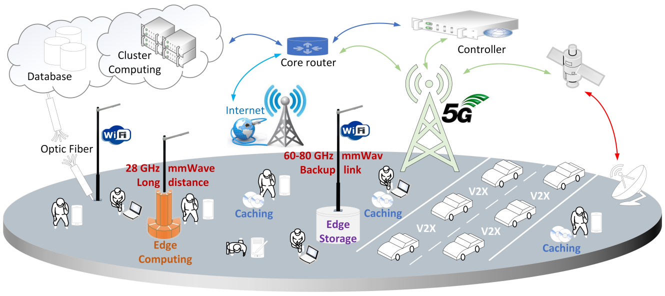

Fig. 1: Heterogeneity in meshed communications.

Upcoming 5G and beyond networks will face stringent capacity and latency requirements. With an impressive growth of new services and devices (consuming and producing huge amounts of data), mobile networks must become ready to grant the expected quality of service to their users. However, achieving the 5G key performance indicators especially in highly dense networks, such as urban areas of major cities, requires complementary solutions. For example, to cope with the lack of connectivity, or simply to increase the backhaul link capacity traditionally supported by fiber links, high frequency and high capacity millimeter-wave (mmWave) communications have proven to be an excellent candidate [2]. In such situations, a multitude of end-to-end paths are provided, bringing multipath (MP) diversity into the network that could be well explored by the network coding techniques.

The adaptive and causal network coding solution presented in this article is extremely helpful in realizing the throughput and delay requirements of the envisioned services in Smart Cities as considered recently in [3] for wireless backhaul solutions in 5G networks. The AC-RLNC can leverage from the availability of multiple paths relying on heterogeneous technologies (e.g. mmWave, fiber) managed by SDN to enhance the resilience of real-time applications. For example, video streaming and vehicle-to-everything are possible applications that can benefit from the proposed communication solution.

We propose an architecture that fosters the exchange of control information between network coding solutions, SDN, network function virtualization (NFV) management, and orchestration components for general meshed heterogeneous communications.

II. BACKGROUND AND PRELIMINARIES

In this section, we review the most relevant MP communication schemes considered in the literature to our proposed work. We then describe how SDN can accommodate the information needed for MP communication.

A. *RLNC and MPTCP Communication*

Transmission Control Protocol (TCP) and Internet Protocol (IP) were first proposed in the 1970s. The classical TCP in the transport layer was first considered for a single point-to-point connection, and was not capable of efficiently supporting MP communications as it relates applications to their source and destination IP addresses and ports. Moreover, even for a single communication over a lossy link or with varying Round Trip Time (RTT) delay, TCP is known to be sub-optimal with limitations on loss recovery time. Multipath TCP (MPTCP) is considered, allowing a single application to use multiple TCP subflows simultaneously, where each subflow has its own IP/port 4-tuple [4], see top panel of Fig. 2. Although MPTCP provides better utilization of available resources by using several network paths, delay and loss variances may reduce its performance.

Random Linear Network Coding (RLNC) was first introduced in the 2000s and achieves the min-cut max-flow capacity of multipath multi-hop (MP-MH) networks by mixing long blocks of raw information using random coefficient over a large enough field [5]. When the receiver obtains sufficient linear combinations, it can decode all the information by performing a Gaussian elimination on a linear system. Unlike MPTCP, to achieve the capacity of the MP-MH network, the raw data transmitted by the source (in a block) is also mixed and re-encoded at intermediate nodes [5]. In a lossy MP communication network with varying delay, RLNC results in a robust solution in which the decoder, which decodes a block of linear combinations of the raw information, is not highly affected by the loss of specific packets. Fig. 2, middle panel, illustrates the RLNC solution mixing all the raw data at the source and re-mixing all the received data at intermediate nodes using new random coefficients. Unlike MPTCP that operates in transport layer of end nodes, RLNC can perform re-mixing at network layer of intermediate nodes. Although RLNC in the MP-MH network can achieve the maximum throughput in the large blocklength regime, emerging advanced applications demand low in-order delivery delay (using forward error correction), and at the same time, high throughput (maximum utilization of rate resources). Traditional information-theoretic solutions that require large blocklength, e.g., RLNC, are not able to reach a desired trade-off.

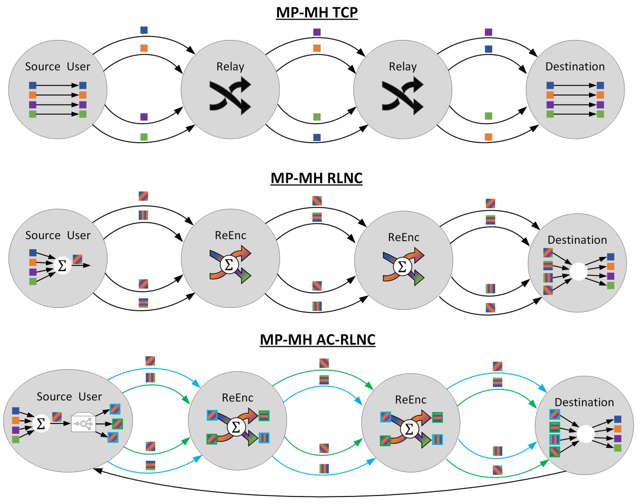

Fig. 2: Communication solutions for a MP-MH network.

Recently, in single path (SP) communication using TCP and MP communication using MPTCP, a-priori forward error correction (FEC) according to the feedback acknowledgments was considered to reduce the in-order delay. In particular, to compensate for erasures in lossy channels, a-priori FEC retransmissions using RLNC are employed [6]. Coded TCP in SP proposes to send a different amount of repair symbols depending on the average loss rate. Recently proposed solutions in the literature are reactive to the feedback acknowledgments, *i.e.*, they are causal, none of them are adaptive to the real-time order of transmissions and FECs to reduce the in-order delivery delay, and are only able to adaptively choose the size of the next coding block. For more details on related literature, refer to [7], [8].

B. *SDN and Multiple Paths Communication*

Multipath communication combined with SDN has been used to enhance performance and reliability in data centers and communication networks. When a node intends to communicate with another one using MPTCP, SDN can help providing information of the underlying infrastructure between the two nodes, which can be employed to determine the number of TCP connections to be created to leverage the availability of MP network resources. Indeed, the combination of SDN and MPTCP leads to an efficient network resource utilization and congestion reduction, since the usage of idle and overloaded links is reduced. In addition, it also overcomes the challenges associated with the multipath routing approaches relying on Equal Cost Multipath (ECMP), which randomly selects a path for load balancing.

Other protocols, such as Stream Control Transmission Protocol (SCTP) and QUIC can also leverage the benefits of employing SDN, which allows them to establish a mapping between the routing information and the application streams. SDN controller can manage the configuration of devices, with OpenFlow or P4, to assign the transmission of packets from each stream over different paths [1].

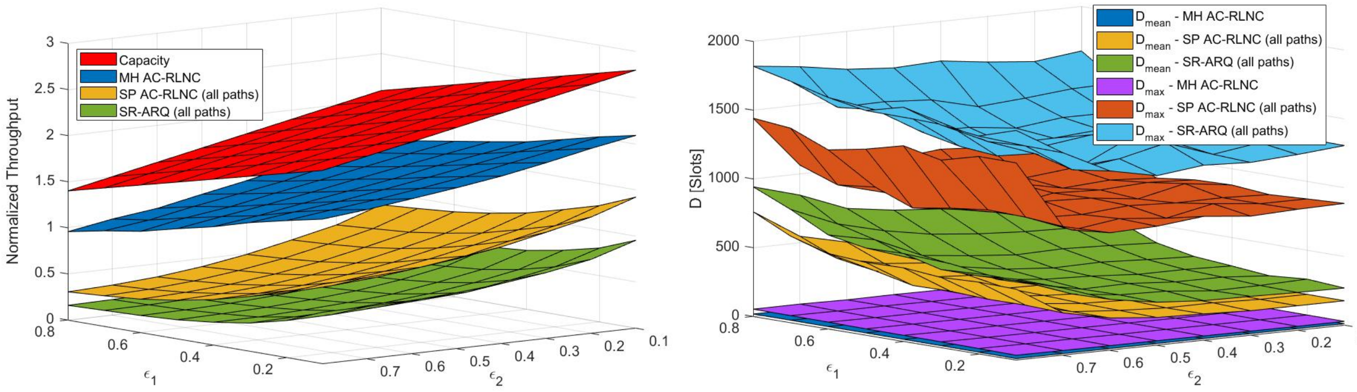

Fig. 3: Performances of the AC-RLNC solution as in [8] over an MP-MH network with 4 paths and 3 hops. The erasure probabilities, ϵ_1 and ϵ_2, in two paths per hop vary in the range of $[0.1, 0.8]$. The remaining paths have fixed erasure probabilities as given in [8]. The throughput in the left is measured as the normalized amount of information packets delivered in order at the receiver. Mean and max in-order delivery delay D in the right are measured as the difference between the time (in slots) an information packet is first transmitted and the time that the same information packet is decoded in order.

III. AC-RLNC CLOSES TRADE-OFF BETWEEN HIGH THROUGHPUT AND LOW-DELAY

Here, we review AC-RLNC algorithm which is the base of the MS-MD communication proposed scheme. To achieve the desired delay-throughput trade-off demanded by emerging applications and technologies, we recently proposed an adaptive and causal solution for communication with one source user and one destination over SP [7] and over MP-MH [8] networks. AC-RLNC is adaptive to link conditions, and it is causal since data transmissions from the source depend on the particular erasure realizations, as reflected in the feedback acknowledgments from the destination. That is, AC-RLNC can track the erasure pattern of links in the network and adaptively adjust retransmission rates, using RLNC for a-priori and posteriori FEC, based on the quality of connections.

According to the network link rates, the source sends, a-priori, an adaptive amount of RLNC FEC retransmissions periodically. Then, at each time step, according to a posteriori retransmission criterion, the source adaptively and causally decides over which paths to send retransmissions and over which paths to send RLNC coded packets that contain new data information, see [9, Section III] for more details. The proposed retransmission criterion tracks the actual network packet receiving rate and the missing Degree of Freedom (DoF) rate required at the destination to decode the received linear combination packets, which can be inferred from the feedback information. To minimize the computational overhead due to the decoding process, in the AC-RLNC scheme, the number of information packets that are encoded together is bounded.

For MP, a new *adaptive discrete water-filling algorithm* is proposed at source nodes for allocation of the new coded packets of information and the retransmissions over the available global paths [8]. This algorithm balances between two objectives, maximizing throughput and minimizing the in-order delivery delay. Fig. 2, bottom panel, illustrates the adaptive allocation scheme at the source nodes, and blue and green packets denote new and retransmission packets, respectively.

In MP-MH, the rates in the naive connections between source and destination are limited by the link with the lowest rate. This causes a bottleneck if the rate of constituent links of a path have dramatic variations. Hence, for MP-MH, a decentralized *balancing algorithm* is proposed that avoids the throughput degradation of bottleneck effects [8]. This is obtained by reorganizing the selection of the naive global paths between source and destination to a new decentralized *global path* selection optimization at the intermediate nodes (called ReEnc nodes), considering the rates of the incoming and outgoing links at each ReEnc node.

For the non-asymptotic regime, in [8] analytically demonstrated that the AC-RLNC solution over an MP-MH network achieves more than 90% of the network capacity with zero error probability under mean and maximum in-order delay constraints. That is, a mean delay smaller than three times the optimal genie-aided one and a maximum delay within eight times the optimum. Fig. 3 presents the performance of the AC-RLNC solution over the same MP-MH network comparing to SR-ARQ, showing a dramatic performance improvement using AC-RLNC.

Moreover, AC-RLNC solution over SP networks is already implemented for QUIC protocol to transport layer using TCP, showing significant performance improvements. In case AC-RLNC cannot be deployed over the whole network parts, especially when one end is outside the controlled network, the single-path version of AC-RLNC can be deployed at the transport layer to protect the traffic over these parts of the network using a single connection. Fig. 4 shows a simulation on how the AC-RLNC behaves with QUIC in such scenarios, *i.e.*, sending FEC-protected messages that need to arrive before 250ms to the destination. We simulate a video use-case, where messages are generated from h264-encoded Big Buck Bunny movie with 25 frames per second (one message every 40ms). We considered a 250ms deadline as it is the median RTT for

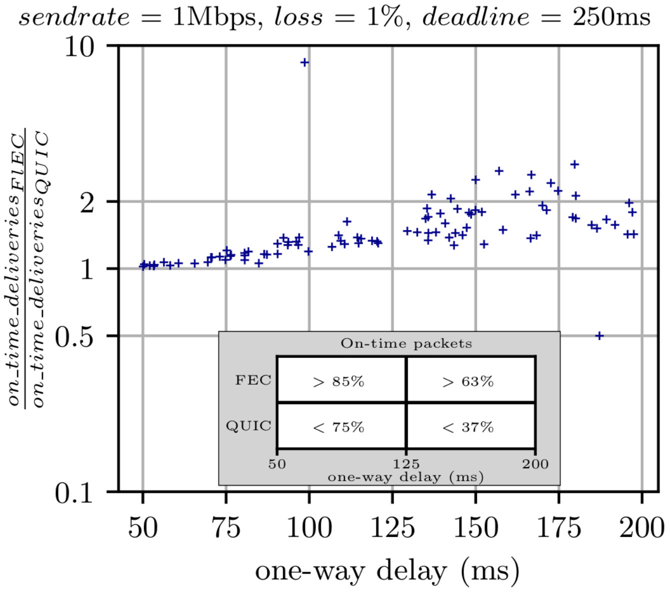

Fig. 4: Ratio of the number of messages delivered for QUIC with SP AC-RLNC compared to the number for regular QUIC.

all the scenarios and thus a fast retransmission in QUIC takes roughly one RTT to be triggered. The FEC-enabled solution in Fig. 4 is more robust against loss and delivers more than twice messages within 250ms compared to QUIC. The table in Fig. 4 shows the proportion of messages received on-time, averaged for experiments with one-way delay both smaller and greater than 125ms.

The previous AC-RLNC solution can reach the desired throughput-delay trade-off for an MP-MH network with one source and one destination. Sections IV and V describe a novel controller-based architecture to demonstrate how to deploy AC-RLNC solution in heterogeneous MS-MD networks.

IV. Scalable, Secure and Efficient SDN Controller for Meshed MS-MD Communication

In this section, we introduce an SDN-based scheme for providing necessary control information for the components of the meshed heterogeneous network. Keeping up with rapid evolution and dynamism of network traffic, SDN is a crucial element of 5G networks and for MS-MD nodes empowered with the AC-RLNC for optimal use of the available links. An SDN controller provides flexible management and control of network devices, thus having the necessary information for the AC-RLNC over heterogeneous MS-MD meshed networks. The Scalable, Secure and Efficient SDN Controller (SSE-SDNC) hereby proposed for mesh communications relies on multiple SDN controllers to attain an improved fault tolerance. The controllers are organized in a cluster, to avoid single point of failure, where a master node can be easily replaced by other slaves, see Fig. 5, or even to distribute the load between controllers. The cluster of SDN controllers can be managed using available solutions like Atomix ONOS cluster [10], without incurring in additional delay regarding response time.

The SSE-SDNC, using multiple SDN controllers, manages the topology information of the virtual networks through the southbound interface (SBI), for instance, by supporting OpenFlow, P4, or NETCONF protocols. Such protocols allow to control the forwarding plane (e.g. flow rules in devices) and to manage devices (e.g. software configuration and updates). Low overhead mechanisms to gather statistics through the SBI are considered, as well as the P4 in-band network telemetry. The SSE-SDNC also includes management applications responsible to exchange information with other components through the messaging system. The information is obtained through the controller northbound API (NBI).

V. Controller-based Architecture for AC-RLNC in Meshed Heterogeneous Communications

We present an AC-RLNC solution for the heterogeneous MS-MD network architecture. Although a base approach was previously introduced in [7], [8], we propose a practical implementation for an MS-MD network, where modularization, modification, and interplay with main controller are incorporated, thus resulting in a decentralized implementation, for a practical utilization of network coding in meshed heterogeneous networks, as each module requires specific information and needs to be implemented in a specific part of the meshed network.

A. *Architecture for a heterogeneous MS-MD network*

Fig. 5 illustrates the main parts of the proposed architecture through an example setup, with two sources and destinations and each source aims to send messages to a subset of destinations. In this example, Source 1 transmits information to both destinations; Source 2 only transmits information to Destination 2. The network is divided into several *Virtual Networks (VNs)*, each with one communication channel (e.g. MP-MH in the general case) to transfer the received packets. Each source is associated with one *User*, one *Enc node*, and one *Net node*, and each destination is associated with one *Dec node* and one *Dest node*. Each source is aware of the available paths and routing information for the current application to its desired destinations through the interaction with messaging systems, where the SSE-SDNC provides the updated values of paths and links characteristics.

A user generates the application/service information, and it can be located at the same place as the source node that generates the RLNC coded data, see Source User 1, or it can be physically apart, see Source User 2. In the latter, User may deploy traditional communication methods to transmit the information to the first place on paths to its desired destination that supports the AC-RLNC solution, *i.e.*, *Enc* and *Net nodes*. An *Enc node* prepares the RLNC-coded packets based on the received feedbacks and the tracked channel status. A *Net node* selects the global paths over which the new-transmissions are performed, called global paths of type 1, and subsequently, global paths over which the retransmissions are transmitted, called global paths of type 2. *Dec node* is the closest to the destination that can perform decoding, provides necessary feedback, and transmits the decoded packets to the destination. Finally, we resort to a traditional communication protocol from

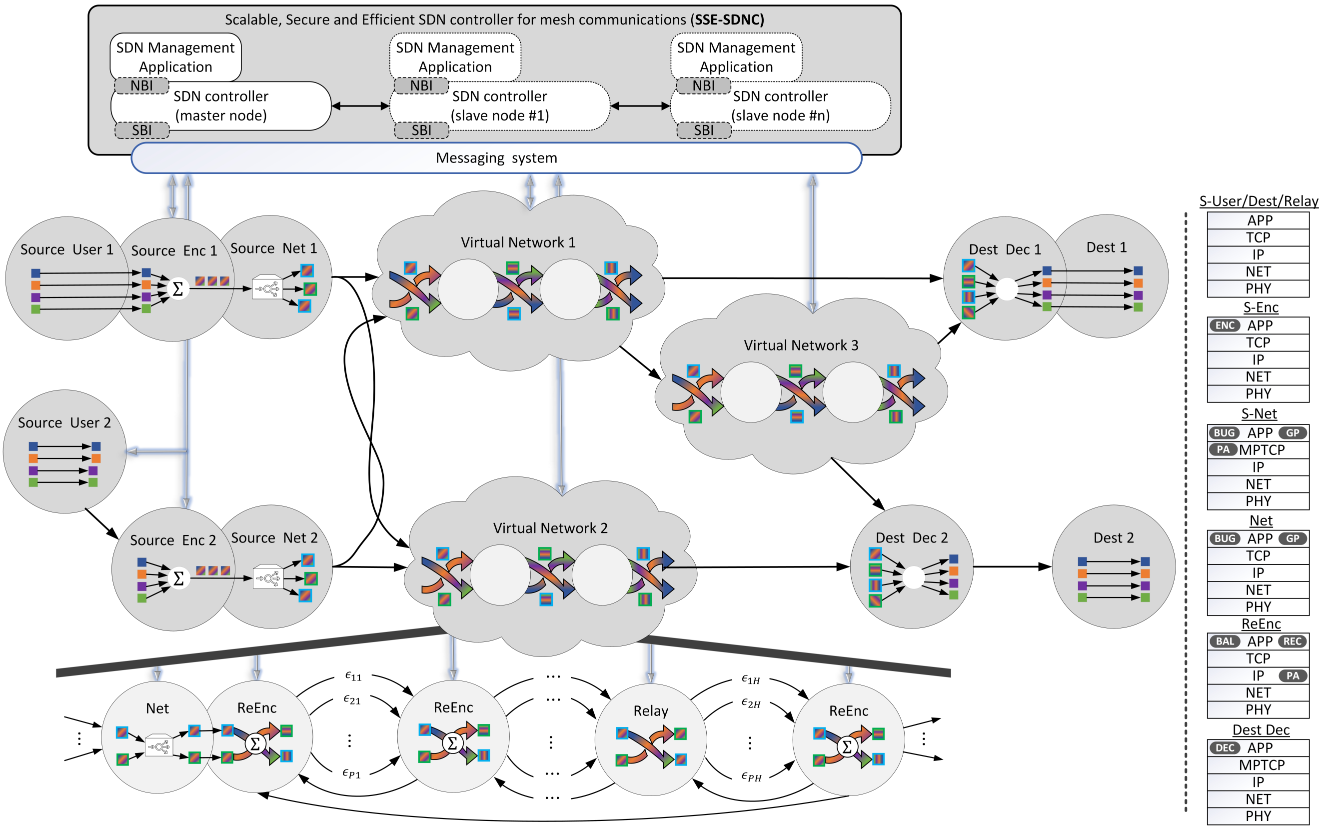

Fig. 5: A simple network architecture that is composed of three virtual networks, and has two sources and two destinations.

Dec node to the destination, whereby *Dest node* represents the physical location of the final destination.

In a VN, *Net node* is responsible to select global-paths of type 1 (dedicated to new-transmissions) and type 2 (dedicated to retransmissions). Then, other nodes are either a *ReEnc node* or a *Relay node*. A *ReEnc node* performs mixing over the received RLNC packets and transmits the re-encoded RLNC packets on appropriate global-paths. *Relay nodes* forward the received packets on their global paths, using their routing table.

B. Modularized AC-RLNC for MS-MD Architecture

The main modules of the proposed AC-RLNC solution for heterogeneous MS-MD networks are the following:

- **Agent (AGN):** Present in all network nodes that require interaction with the controller, it is responsible to retrieve necessary information from SSE-SDNC through the messaging system, e.g., Fairness Table, RTT, Link Rates, and/or to determine the information locally (e.g., Routing Table).
- **Balancing (BAL):** Matches the incoming and outgoing links, such that the bottleneck effect is minimized over each global path. This module is implemented at *ReEnc nodes*.
- **Global Path Identification (GP):** Identifies global paths between two parts of the network, and it is implemented at *Net nodes*.
- **Budgeting (BUG):** Splits the rate budget (decides which global-paths are type 1 and which are type 2) for an application/service into retransmissions and new-transmissions, and it is implemented at *Net nodes*.
- **Encoding (ENC):** Performs RLNC encoding on the information packets of an application/service and prepares RLNC packets (either retransmission or a new-transmission). It is implemented at Source *Enc nodes*.
- **Packet Allocation (PA):** Allocates to each global path of type 1 a new-transmission packet and each global path of type 2 a retransmission packet. This module is implemented at Source *Net nodes* and *ReEnc nodes*.
- **Re-encoding (REC):** Linearly mixes the received RLNC packets and produces new RLNC packets. It is implemented at *ReEnc nodes*.
- **Decoding (DEC):** Decodes the RLNC packets associated with the service/application that is desired by the destination and transmits necessary acknowledgment feedback messages. It is implemented at *Dec nodes*.

The SSE-SDNC is aimed to be deployed with a set of distributed controllers to ensure low-delay module-controller communication with the AGN modules. The AGN module communicates with the SSE-SDNC to synchronize updates in the network topology. In case a subset of AC-RLNC modules cannot be performed in parts of the network nodes due to their overhead, in terms of computation or memory, etc., the SSE-SDNC controller can perform the task of the missing modules and make necessary changes accordingly. For instance, by supporting a low-overhead push mechanism to retrieve information from network elements. The SSE-SDNC has more information that the one required by the AGN module and the AC-RLNC solution, but the one that is demanded by the AC-RLNC solution from the controller includes the following items:

1) Routing Table (RT): Each RT is associated with a Net node, and contains routing information (constituent links) between two IP addresses. In our solution, we need an RT per Net node. For example, an RT table that is requested by a Source Net node of an application/service contains all routing information from the source to the destination, however, an RT table that is requested by a VN Net node has all routing information from the first node to the last node in that VN. The AGN module retrieves this information from the SSE-SDNC through the messaging systems, upon new communications in a network node.

2) Fairness Table (FT): There is one FT per Net node that shows how to split the available rate resources among several applications/services based on their priorities. For example, one can assign rate per application/service that is a real number in $[0,1]$ such that these real numbers sum up to 1. The SSE-SDNC is responsible for setting the weights/costs associated with the network resources (e.g. by considering the link technology). Then, the AGN module presents this information to AC-RLNC modules at Net nodes.

3) Local-Path Routing Table (LPRT): There is one LPRT per ReEnc node. An LPRT shows the matching between incoming and outgoing links, and it is constructed and updated by the BAL module of a ReEnc node to minimize the bottleneck effect. ReEnc nodes update their LPRTs based on dynamism of the network condition where the link qualities may change over time, thus the inputs from the SSE-SDNC are required for an updated network information. Traditional Relay nodes do not need to update their LPRTs, and this provides heterogeneity by using traditional nodes along with the nodes that are capable of performing the AC-RLNC solution.

4) Global-Path Routing Table (GPRT): There is one GPRT per Net node of an application service. A GPRT includes all global paths routing information and rate between a pair of IP address, *i.e.*, source and destination of an application/service when requested by a Source Net node, or first and last nodes of a VN when requested by a VN Net node. A GPRT is constructed and updated by the GP module with the assistance of the AGN module.

5) Round Trip Time (RTT) and Link Rates: The SSE-SDNC is responsible for providing updated values of the RTTs and link rates, which are determined through the probing/monitoring mechanisms implemented in the SDN management applications.

More detail about the algorithmic implementation of the AC-RLNC modules proposed for the new MS-MD architecture along with practical considerations can be found in the full version of this article [9].

VI. CONCLUSIONS AND VISIONS FOR ENABLING TECHNOLOGIES

In this paper, we presented a controller-based architecture for network coding, where a SDN is employed to enable flexible management and control of devices, as well as provide information about the underlying infrastructure (e.g. the mmWave backhaul) to network components. This calls for mechanisms to secure the controller, discussed in Section VI-A. Moreover, the dynamic of mmWave mesh network and how the interplay of the SDN and AC-RLNC can provide a reliable and efficient communication solution over this setting are discussed in Section VI-B. Lastly, we note that emerging technologies, such as distributed storage and caching [11], distributed computation [12], and post-quantum cryptography security for data transmission [13] that may utilize network coding can benefit from the proposed techniques in this paper.

A. Securing SDN Controllers

Current SDN security challenges [14] include proper authentication, access control, data privacy and integrity among the orchestration components of SDN. In addition, (Distributed) Denial of Service attacks can be performed if centralized approaches for deploying SDN controllers are followed, for example due to limitations on management of flow tables that can be filled up by malicious/erroneous applications. Protection for other attacks like Man-in-the-Middle or replay require enhancements in protocols like OpenFlow (to avoid changes in control messages).

The SSE-SDNC herein proposed, tackles these security vulnerabilities by employing replication of controllers to avoid single point of failure (SPOF) and implements authentication, encryption and access control mechanisms to establish trust between the diverse components. The AC-RLNC modules and the SDN controllers can be configured in a trust chain, where AC-RLNC modules provide proofs of their identity (*i.e.* perform authentication) to use the information available in SDN. The SDN controller(s) perform access control (e.g. privileges to modify or only to retrieve information) for the authenticated applications. For that, the SSE-SDNC will perform replication of controllers with dynamic load distribution among controllers according to traffic conditions and network load. Authentication, access control and data privacy and integrity are achieved by integration with the Software-Defined Perimeter (SDP) security approach [14], that employs TLS mechanisms for mutual authentication and encryption of communications between clients (e.g. applications, network devices) and servers (e.g. controllers). In addition, SDP features such as SDP control, responsible by determining which devices/applications can connect to a given component (e.g. SDN controller), manage access control between clients and servers. The SSE-SDNC can interoperate with an SDP controller to only communicate with authenticated and trustworthy devices/applications.

B. AC-RLNC and SDN for mmWave Mesh Networks

The AC-RLNC solution requires knowledge of the throughput and delay of the links and global paths, so that global paths of type 1 and 2 can be determined. In a radio-based communication, the throughput and delay may depend on several different parameters beyond the link capacity and the data rate, since wireless links are very prone to interference. The uncertainty on these parameters is increased with mmWave, because of its sensitivity to high co-channel interference, the lack of line of sight, and the low propagation and penetration of the signal in outdoor environments. Therefore, the sudden and dynamic change in the throughput and delay requires a close interaction with the SDN controller not only to determine new global paths, but also incorporating link stability in the choice of these paths.

To achieve the resiliency and agility needed at the mmWave backhaul, our approach is to collect additional metrics about the mmWave mesh network and link properties (i.e., packet loss, delay, RSSI, LQI, antenna direction [15]), in order to ensure faster recovery (in the presence of link failure), and optimized service selection. This information will be available to the SDN controller, and used to compute the link rates. With the metrics collected about the mmWave link state, the controller will be able not only to react to link failures, but also to predict them in advance, bringing the possibility of reconfiguring the flows and forwarding tables according to the needs of the applications/services.

The mmWave technology, on the other hand, provides great diversity on the establishment of different paths, achieving a multitude of end-to-end paths, and bringing multipath diversity to the network that can be well explored by the controller-based AC-RLNC solution. The configuration of the mmWave mesh can therefore be autonomously performed to accommodate the users and services needs over time, and to optimize the overall network conditions, providing higher throughput on the paths by optimal balancing in order to improve delay and service performance metrics.

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