NWCRG Closing Report

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***Abstract*—Network Coding Research Group (NWCRG) is concluding itself after 8 years of research. Throughout the years, as a part of the Internet Research Task Force (IRTF), the NWCRG has been exploring the concept of Network Coding, which is a networking technique, where a content of a packet is coded at a network node in a packet network. NWCRG also summarizes the research results and practical implementations related to Network Coding.**

This paper gives an overview and most important concepts of Network Coding and summarizes the efforts undertaken by the NWCRG in Network Coding.

***Index Terms*—Network Coding, NWCRG, IRFT, IEFT, IRSG, Internet Draft, Request For Comments**

1. Introduction

The history of Network Coding dates back to its initial introduction in the seminal paper [1] by Ahlswede et al. and the popularity of Network Coding has been ascending since. Taking notice of the potential power and benefits, researchers commenced to do a research about Network Coding and its possible practical implementations. Following several publications regarding and applications with the usage of Network Coding, the incentive to establish a research group in the IRTF was born.

Since its establishment, the NWCRG has accomplished numerous important works such as researching the principles of Network Coding, summarizing the existing publications and applications, and proposing new ideas. After having fulfilled their main objectives, the NWCRG is coming to an end in 2022 after 8 years of a journey, leaving various contributions to Network Coding.

In this following paper, the most important aspects of Network Coding will be covered and the Network Coding Research Group as well as the efforts undertaken by this group will be showcased. We firstly mention the theory and history behind the Network Coding and its benefits in Section 2. Moreover in Section 3, the history and the initial motivation of the NWCRG and their accomplishments will be explained. Finally, having analyzed the topics of interest, we draw a conclusion of the mentioned topics in Section 4.

2. Network Coding

Considering that Network Coding has had multiple definitions since its birth, it can be challenging to describe the concept with a particular interpretation.

The very first and most general definition of the Network Coding was framed in the seminal paper [1] in year 2000. The authors Ahlswede et al. stated that they will "refer to coding at a node in a network as network coding". The meaning behind coding in this paper was an arbitrary mapping of a data at intermediate network nodes.

According to Ho et al. in their book, Network Coding is a technique, where a content of a packet is coded at a network node in a packet network (a network, in which a data is broken down into packets). The network nodes can take multiple packets, combine them, and output a resulting packet to send it to the next node in the network [2].

2.1. History of Network Coding

In the seminal paper [1], the authors spoke of the potential power and benefits of Network Coding, however, did not disclose the design methods [3].

After 3 years from the first paper on Network Coding, Li, Yeung, and Cai published a new paper [4], which was more about the practical implementation of Network Coding. They showed that applying Network Coding on networks can rely on mathematical functions and suffices to achieve the optimum potential [3].

In the same year, Koetter and Medard issued a paper [5], in which an algebraic framework for analyzing coding approaches was introduced [3].

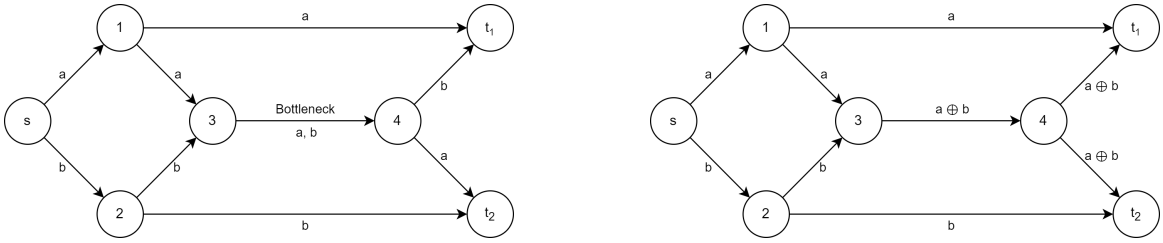
In 2005 and 2006, two important design algorithms were reported. In the first paper [6] from 2005, the authors, Jaggi et al., introduced polynomial time algorithms and randomized algorithms for Network Coding. In the second paper [7] from 2006, the authors Jaggi et al. expressed that randomly chosen network codes are also convenient for multicast networks [3].

2.2. Benefits of Network Coding

Especially in comparison with traditional routing networks, Network Coding can improve the throughput, complexity, robustness, latency, and security of a network. Therefore, in this part, we will go through the most important improvements along with the famous networks such as butterfly network and diamond network.

Increased throughput is one of the easiest-to-demonstrate benefits of Network Coding [2]. In the seminal paper [1], the potential gain in throughput is explained with a butterfly network. As in the paper, we will use s for the source, and t_1, t_2,..., t_n, the sinks of a graph. In both Figures 1a and 1b, the source s transmits two packets

doi: 10.2313/NET-2022-07-1_14



(a) Routing with Multicast (b) Network Coding

Figure 1: Butterfly Network

(a, b) to the sink nodes t_1 and t_2 and the capacity of each edge is one packet per unit time.

With routing, the edge (3, 4) of Figure 1a poses a bottleneck, and it can carry either the packet a or b per unit time. Hence, it must be used twice so that both sinks can get the packets a and b. As seen in the Figure 1a, it is not possible to feature a multicast from one source node to two sink nodes simultaneously.

Through the medium of Network Coding, the node 3 in the Figure 1b is coded and takes both packets, a and b, combines them by taking the **xor** operation and sends out the new packet. The sink nodes t_1 and t_2 can decode the missing packets by taking the **xor** operation again with the two received packets. In this case, t_1 performs the **xor** operation between packets a and $a \oplus b$ and receives the missing packet, b. Likewise, t_2 performs the **xor** operation between packets b and $a \oplus b$ and receives the missing packet a. Thus, we see that using Network Coding in the butterfly network saves one transmission by coding an intermediate node and therefore increases the throughout [2].

Network Coding can reduce the complexity of a network in certain cases. In article [2], Ho and Lun state that although routing can gain comparable performance as Network Coding, Network Coding can reduce the complexity and consequently provides better performance in the fields such as Gossip-data dissemination protocol and Wireless Ad Hoc Network (WANET) [2], [8].

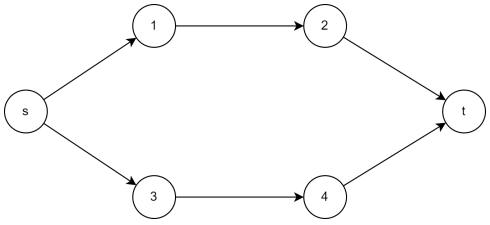


Figure 2: Diamond Network

Network Coding can have both advantages and disadvantages in terms of network security. On the one hand, Network Coding can make a network more vulnerable to attacks like Pollution Attacks or Byzantine Attacks. Mixing packets at the intermediate nodes can result in packet pollution and one polluted packet can easily spread the pollution to many other packets. Considering that this pollution attack is one of the dangerous attacks against a network, it may cause a failure of the decoding at the sink nodes [9].

However, on the other hand, Network Coding can ensure a secure communication within a network by preventing eavesdropping. For example, in the Figure 2, the source node s wants to transmit a packet p to the sink node t, but it is aware that one of the 4 intermediate nodes in the network is malicious and operated by an eavesdropper. With routing, there is a 1/2 chance that the eavesdropper obtains the packet. With Network Coding, s can split the packet s into 4 equal packets p_1, p_2, p_3 and p_4 and then combine these packets again by taking the **xor** operation:

$$c_1 = p_1 \oplus p_2, c_2 = p_3 \oplus p_4 \quad (1)$$

$$c_3 = p_1 \oplus p_4, c_4 = p_2 \oplus p_3 \quad (2)$$

Then, s sends these combined packets c_1 and c_2 over node 1 and the other packets c_3 and c_4 over node 2. If the malicious node cannot calculate the content of at least one coded packet, decoding the packet p is impossible [2], [8].

3. Network Coding Research Group

Network Coding Research Group (also known as Coding for efficient NetWork Communications Research Group) is one of the 14 active and chartered research groups of the IRTF.

Before going into the particulars of the NWCRG, we would like to refer briefly to the IRTF and its significance.

3.1. Internet Research Task Force

IRTF is an organization that is administered by the IRTF-Chair in deliberation with the Internet Research Steering Group (IRSG) and targets research-issues connected to the Internet such as Internet protocols, applications, architecture, and technology, by establishing long term research groups working on these fields [10]. The roles of research groups can be listed as [11]:

- Finding new ideas about their field
- Exploring new academic and industrial areas with global Internet potential
- Expert-supporting the Internet Engineering Task Force (IETF)

On the contrary, the parallel organization IETF focuses on issues of engineering and standards making in the short term [10].

The IRTF also organizes the Applied Networking Research Workshop and the Applied Networking Research Prize in collaboration with the Association for Computing

doi: 10.2313/NET-2022-07-1_14

Machinery (ACM) and Internet Society (ISOC), where the applied networking research results are reviewed and discussed by the researchers, vendors, and many other operatives in the field [12].

3.2. History of NWCRG

Following the first introduction of the concept of Network Coding in the article [1], the interest in the field increased consistently. After taking action on practical implementations and design algorithms throughout the years, the involvement in pursuing an IRTF activity came on stage.

In November 2012, researchers from Lincoln Laboratory, MIT, Caltech, and many other institutions from all around the globe were invited to constitute an IRTF research group led by Victor Firoiu from BAE Systems, and Brian Adamson from U.S. Naval Research Laboratory. By the end of 2012, the research group was formed and had planned a meeting at the IETF-86 Meeting in Orlando in order to introduce the research group's objectives and plans for the future. Succeeding the primary meeting, the group decided to plan a second meeting in the next IETF-87 Meeting in Berlin. Having reintroduced the research group and its objectives in IETF 87 and IETF 88 Meetings, the IETF chair officially chartered the research group, and the Internet Architecture Board (IAB) approved the charting on the 13^{th} of November 2013 [13].

One year after laying the foundation for a research group, the Network Coding Research Group was officially one of the chartered research groups of the IRTF.

3.3. Initial Motivation

As industrial and commercial applications enhanced their interest in Network Coding after few years of research, the Network Coding Research Group was established as mentioned. According to the presentation of Firoiu and Adamson in their first IETF Meeting, one of the initial motivations of the NWCRG was to analyze the research advancements, proved performance improvements and the practical algorithms in the publications [14]. For instance, analyzing the achievements of multicast with Network Coding on Max-flow Min-cut problem in the seminal paper of Ahlswede et al. [1] as well as analyzing the coding schemes for reliable communication from the article of Lun et al. [15].

Additionally, one of the initial motivations of the research group was to do a research regarding the practical applications of Network Coding as the studies on Network Coding expanded and developed over the years and began to appear on manifold platforms [14].

3.4. Objectives

Every research group affiliated with the IRTF is founded based on a peculiar requirement and has a specific objective. As declared in the charter [16], the main goal of the Network Coding Research Group is to analyze principles and utilities of Network Coding in order to improve the Internet communication. NWCRG examines the research results on Network Coding and aims to advance its practical applications. In addition, the group also focuses on the existing practical implementations and targets to achieve the standardization of the Network Coding enabled communication [16].

3.5. Interest Areas of the NWCRG

As stated above, the two main interest areas of the Network Coding Research Group are Network Coding Research and Practical Applications of Network Coding. In these sections, we will see the primary subjects, in which the NWCRG is interested.

NWCRG is mainly devoted to the following topics in Network Coding Research [16]:

- Performance and efficiency: Analyzing performance improvements, computational complexity of Network Coding, trade-offs between different Network Coding techniques.
- Security, privacy, and robustness: Evaluating the advantages and disadvantages of Network Coding in network security, analyzing the interactivity of Network Coding and encryption.
- Application Layer: Exploring the interactions between Network Coding and application-specific Coding.
- Data Link Layer: Searching for the interaction between Network Coding and data link protocols such as optical, wireless, and satellite links.
- Costs of Network Coding: Determining the ways to price services, for instance, network usage or information rate.

NWCRG is mainly interested in the following matters in Network Coding practical application [16]:

- Architectural Considerations: Analyzing different design techniques and requirements for extensive networks.
- End-to-end vs. hop-by-hop: Evaluating the two different transport principle.
- Intra-flow and inter-flow: Researching the two different protocols Intra-flow Network Coding and Inter-flow Network Coding.
- Service Paradigms: Analyzing the service paradigms such as best effort and time bounded utility.
- Encoding – Decoding algorithms, packet formats: Examining the benefits of Network Coding in common encoding and decoding algorithms and packet formats.

3.6. Achievements

Since its establishment in 2013, the Network Coding Research Group has made many contributions to Network Coding by encouraging studies on Network Coding and improving network performance, developing codes, and coding libraries, offering new protocols to promote the usage of Network Coding in existing and future systems. The group published many Internet-Drafts (I-Ds) and Request For Comments (RFC) over the years [17].

Before going into the details of the most important achievements and proposed protocols of the NWCRG, we

will briefly clarify the terms Internet-Drafts (I-Ds) and Request For Comments (RFC).

An Internet-Draft is a short-lived working document of the Internet Engineering Task Force (IETF). It is the primary input with technical standards and research findings which then may be approved as a Request For Comments. Since I-Ds are ongoing documents and do not embody any formal status, they should not be cited or acknowledged as authoritative sources [18], [19].

On the other hand, a Request For Comments is a publication with technical specifications and organizational notes, which poses more formality. Furthermore, an RFC can have different IETF statuses based on the maturity level [18], [20].

Immediately below, we will introduce one Internet-Draft and one RFC of the Network Coding Research Group.

Network Coding for Content-Centric Networking / Named Data Networking: Considerations and Challenges is one of the three Internet-Drafts of the NWCRG. The I-D was sent to Internet Research Steering Group (IRSG) in March 2021 and currently, this group is still in the process of approval and taking a poll on whether the document fulfills the requirements to be published [21].

The first version of the I-D was approved in October 2018. In this document, the authors Matsuzono, Asaeda and Westphal summarize the current research in Network Coding for Content-Centric Networking (CCN) Named Data Networking (NDN) and technical issues and challenges when applying Network Coding to the CCN and NDN such as content naming, transport, congestion control and security. Matsuzono et al. state that, the application of Network Coding in CCN and NDN can help with large-scale content/information dissemination effectively. Combining Network Coding and CCN/NDN may also cause security issues such as malevolently requesting or injecting network packets and thereby resulting in amplification attacks [21].

The RFC *Taxonomy of Coding Techniques for Efficient Network Communications* [22] is the first RFC of the Network Coding Research Group which was approved by the IRSG and was published in 2018. The purpose behind this RFC was to create a Network Coding terminology which would assist the future research on Network Coding, and instead of proposing specific solutions offering the common Network Coding concepts, constructs and set of terms. It was the first document to be published about the taxonomy of Network Coding and 14 researchers from the NWCRG contributed to this RFC.

In this RFC, the general definitions and concepts of the Network Coding such as Packet Erasure Channel, End-to-End Coding, Source Node, Coding Node and surely the Network Coding are clarified. The authors refer to Network Coding as: "A system where coding can be performed at the source as well as at intermediate forwarding nodes (all or a subset of them)." [22]. The different coding types and the technical details are also discussed in the document.

In substance, the RFC *Taxonomy of Coding Techniques for Efficient Network Communications* summarizes the recommended terminology for Network Coding and the most common definitions of Network Coding that many of the researchers use and come across while researching or developing practical applications [22].

3.7. Current Situation

After 8 years of doing research, developing practical applications, positing new questions, and publishing many I-Ds and RFCs, the Network Coding Research Group organized their last meeting at the online IETF 111, led by the co-chairs Marie-Jose Montpetit and Vincent Roca.

The group has 3 active I-Ds at the moment. The I-Ds, *Coding and congestion control in transport* and *Network Coding for CCN / NDN: Considerations and Challenges*, are sent to the IRSG and the latter is currently in IRSG poll and will be published according to the results of the poll. The third I-D, *BATS Coding Scheme for Multi-hop Data Transport*, which analyzes and discusses the BATS coding schemes for multi-hop networks communications, has not been sent to the IRSG [21]–[23].

After sending all I-Ds to the IRSG, and publishing these I-Ds as RFCs, the Network Coding Research Group will be closed in 2022, after 9 years of the establishment.

4. Conclusion

To conclude this paper, we have provided an overview of Network Coding theory and its most important benefits. We have also shown that the Network Coding Research Group has complied with its initial motivations and accomplished their fundamental objectives by making research concerning the Network Coding, summarizing publications and applications, and proposing newfangled ideas.

Furthermore, the prospective individual research and implementations on Network Coding from the researchers of the NWCRG can be of interest in the future.

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