SM Thesis Proposal

Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science

Proposal for Thesis Research in Partial Fulfillment
of the Requirements for the Degree of
Master of Science

Title: Network Coding in 5G NR as an Alternative to ARQ and Hybrid ARQ

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Laboratory where thesis will be done: Research Laboratory for Electronics

Brief Statement of the Problem:

Current retransmission-based reliability mechanisms in the link layer of 5G NR correct data erasures at the expense of costly round trip time delays. Network coding is a technique which has the capacity to reduce latency in networks using forward erasure correction. A novel integration of network coding with a commercial 5G NR implementation is proposed which should improve latency and in-order packet delivery relative to existing reliability mechanisms. A system implementing network coding in the network layer will be constructed to test this hypothesis.

Supervision Agreement:

The program outlined in this proposal is adequate for a Master's thesis. The supplies and facilities required are available, and I am willing to supervise the research and evaluate the thesis report.

M. Medard, Prof. of Elec. Eng.

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1 Abstract

Current retransmission-based reliability mechanisms in the link layer of 5G NR correct data erasures at the expense of costly round trip time delays. Network coding is a technique which has the capacity to reduce latency in networks using forward erasure correction. A novel integration of network coding with a commercial 5G NR implementation is proposed which should improve latency and in-order packet delivery relative to existing reliability mechanisms. A system implementing network coding in the network layer will be constructed to test this hypothesis.

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2 Introduction

Computer networks and the internet are widely available in both wired and wireless form. The adaptation of network mechanisms originally designed for a wired medium requires ensuring that the the layers below the network layer mimic the behavior of wired networks. This has necessitated the introduction of a number of reliability mechanisms to compensate for the lossy nature of wireless communication. Two mechanisms used by 5G cellular networks are Automatic Repeat reQuest (ARQ) - which retransmits lost packets - and hybrid ARQ (HARQ) - which allows retransmissions to be combined in case of partial reception.

The use of retransmission to compensate for loss has significant implications for latency. Each retransmission adds a round-trip time (RTT) to the delay of a packet. The longer the RTT, the more severe this delay penalty becomes. In situations where latency is a priority, network coding offers an attractive alternative: Send corrective packets in advance. This document proposes a study of network coding as an alternative to ARQ/HARQ in the context of 5G cellular networks.

2.1 ARQ and Hybrid ARQ

Data corruption in wireless communication occurs primarily in the physical layer of the network protocol stack. As received data are processed and passed to higher layers, each layer has the opportunity to detect and correct errors. The MAC and RLC layers, the next layers after the physical layer, do this by using ARQ and HARQ. ARQ is a simple protocol which discards received data if it detects an error and requests a retransmission. HARQ also requests retransmission of corrupted data, but buffers the current data and combines it with the retransmission using chase combining or incremental redundancy, thus improving the performance of retransmissions [1]. HARQ is implemented on the MAC layer. When the MAC layer is unable to correct an error after several HARQ retransmissions, the failure is passed up to the RLC layer where ARQ clears the buffers and requests a full retransmission.

2.2 Network Coding

Network coding is an approach for ensuring reliability of packets in a network within the stringent latency requirements of 5G use cases [2]. In network coding, multiple packets are combined algebraically in groups of K before being sent and additional $N - K$ packet combinations are added as forward erasure correction (FEC), with the result that the receiver can decode the necessary information with any combination of K packets [3, 4, 5]. If the number of FEC redundant packets is sufficient to compensate for the lost packets, retransmissions are unnecessary. Thus network coding can provide a lower packet service time on average than HARQ where retransmissions are performed based on feedback after a round trip time (RTT).

3 Related Work

The benefits of network coding have been explored in a variety of contexts outside of 3GPP.

3.1 Implementations of Network Coding

The value of forward error correction using block codes as opposed to retransmission has been picked up in latency sensitive contexts such as video streaming, with Microsoft Teams using Reed Solomon block codes [6] and other work suggesting network coding for use with CDNs and peer to peer communications [7]. Network coding as a part of the protocol stack has also been explored, with a proposed protocol called TCP/NC introducing a network coding layer between the transport and IP layers to allow integration of network coding with TCP systems [8]. Two key elements of this design were the use of a window that matched the TCP congestion window and acknowledgments for degrees of freedom rather than specific packets.

Danish company Steinwurf offers software libraries, such as Kodo, implementing random linear network coding algorithms. These libraries have been used by a variety of industry and research organizations for purposes such as content distribution and multi-cloud networking [9].

3.2 Network Coding vs ARQ/HARQ in WIMAX

A 2012 study [10] implemented a study over WIMAX, an early analog to LTE, comparing the performance of network coding to that of HARQ and ARQ, similar to the study I propose over 5G. Their implementation placed a network coding module at the IP layer and compared the throughput, loss, and file transfer delay of configurations using HARQ/ARQ or network coding. It was found that replacing HARQ/ARQ with network coding provides up to 5.9x gain in throughput, decreases packet loss from $11-32\%$ to nearly 0%, and reduces file transfer delay by 5.5x. These results are encouraging when considering replacing HARQ/ARQ with network coding in 5G.

4 Proposed Work

I propose to extend the work of the WIMAX study to 5G and to carry out a broader exploration of what changes and what potential benefits might arise from implementing network coding closer to the physical layer, similar to the location of current HARQ/ARQ mechanisms.

4.1 Required Materials

4.1.1 Access to lower layers.

An exploration of the benefits of implementing network coding closer to the physical layer requires access to source code of those layers. Specifically I will be looking at the 5G MAC layer on both the base station (gNB) and the user equipment (UE).

Matlab. Matlab's 5G Toolbox implements a full simulation of the 3GPP layers, the source code of which is accessible with a Matlab license. Matlab is a very accessible tool for initial exploration of the 3GPP protocol stack. This is in large part thanks to its debugging feature - since the Matlab 5G Toolbox is a simulator, operations can be paused at any time and traced throught the stack. Matlab allows for easy preliminary tests to determine what tests should be carried out on real-world devices.

JMA devices. Our industry collaborator, JMA wireless, supplies 5G networks in the form of gNBs, and is able to give our lab access to the lower layers of these devices in the form of an Amarisoft callbox (gNB) and UE emulator. Our collaborators at JMA are very knowledgeable in the MAC and RLC layers of the 3GPP protocol stack and able to provide support. However, the UE emulator does not allow access to the lower layers. Therefore the UE emulator will be useful in tests involving network coding at the IP layer but not at lower layers.

OAI. Some time has been spent seeking a UE device with access to lower layers but none was found. An alternative exists in the form of Open Air Interface (OAI), an open source project to implement the 3GPP standard. OAI can be run with a software defined radio to operate as a UE. Open Air Interface is a valuable contribution to the field of 5G research, but the nature of open source means that it has limited support and not all features are fully implemented. HARQ and its associated features in the MAC layer are less of a priority in the OAI research space and therefore little is documented about how it is designed and might be controlled. For this reason, OAI may be something to use in the future, but at present we will focus on the other available resources.

4.1.2 Steinwurf API

Steinwurf's Kodo libraries will be used to implement network coding as this implementation is both efficient and tested for correctness. A license to use these libraries has been obtained by MIT and JMA.

4.2 Procedure

4.2.1 Assess the benefit and feasibility of implementing network coding at various levels of the MAC layer

As defined in the 3GPP standard [1], there are three main data units used in the MAC layer: transport blocks (TBs), composed of code block groups (CBGs), composed of code blocks (CBs). The benefit of network coding increases as it is applied on smaller and smaller increments of data, because the corrupted data is more localized to the actual corrupted bits. In practice, the devices we have access to do not make a distinction between CBs and CBGs, leaving one subunit below TB.

4.2.2 Use JMA traces to characterize the potential for network coding in the MAC layer

JMA devices log each instance of packet failure and retransmission. The next step after Matlab simulation is to use these logs as traces to determine how network coding would compare to HARQ/ARQ on industry devices once implemented. This involves an analysis of implementation delays, beginning with the extraction of HARQ delays from JMA's implementation, followed by calculating and simulating the corresponding network coding (NC) delays, examining both jitter and total delay characteristics. To ensure a robust investigation, the analysis will be conducted across multiple traffic models, including the full buffer model, video streaming traffic, and gaming traffic, as delineated in [11].

4.2.3 Implement network coding at higher layers (application and network) on JMA machines

JMA has obtained a Steinwurf trial license, allowing use of Steinwurf's implementation of network coding on JMA devices. Initial proof of concept will implement network coding fully end-to-end, monitoring the latency and throughput from programs on the application layer. If the results of this are positive, I will replicate the implementation on the network layer for more fine-grained results. A packet manipulation tool such as `netfilter` or `scapy` will be used to extract data packets from the IP layer, network code them, and reinsert the modified packets into the stream of data. I will use `iperf` to compare the results in the same categories specified in the WIMAX study: throughput, loss rate, and file transfer delay. In addition, jitter will be calculated to compare to the values derived in the trace comparisons outlined in the previous step.

4.3 Preliminary Results

4.3.1 Network coding at various levels of the MAC layer

I ran experiments this summer implementing network coding across CBs within a TB in a Matlab simulation which indicated that when one code block in a TB is corrupted, most likely every CB of that TB is also corrupted. This leaves little room for improvement by network coding within TBs, because block network coding (where each block is one TB) relies on the assumption that errors are scattered across blocks, and this is not the case here.

Implementing network coding across TBs is likely the more beneficial and realistic approach. One complication here is that TBs vary in size, while network coding requires that each data unit be the same size. This difficulty can be overcome using similar methods to [8], in which a network coding buffer was created to take in TCP packets and add dummy zeros to pad packets to be the same length.

Simulation using the cross-TB network coding approach was used to experiment with adaptive bitrate (ABR) schemes to determine how modulation and coding scheme (MCS) should vary to work well with network coding. In the course of this investigation, a coding pipeline approach was proposed to increase efficiency in the presence of limited HARQ processes. A conference paper was published and a patent submitted based on this work. These results demonstrated that network coding results in lower wait times than HARQ and that creative application of network coding (the coding pipeline) have even greater potential for latency reduction, lending credence to the future benefits which may be discovered by this master's thesis.

4.4 Timeline

Currently Complete	Tested effectiveness of network coding within a single TB (intra-TB). Performed experiments comparing wait times of HARQ vs network coding across TBs in simulation as well as a proposed coding pipeline approach. Published and presented on a conference paper documenting these results and submitted a patent on the same.
Dec 2024	Use JMA traces to characterize the potential for network coding in the MAC layer using different traffic patterns (video, gaming).
Jan 2025	Implement network coding at application layer. Design system to test network coding at the network layer on JMA machines.
Feb 2025	Gather preliminary comparison of network coding (in network layer) vs HARQ performance for multiple traffic models (full buffer, video, etc.).
March 2025	Make adjustments to experiments in accordance with results found in Feb.
April 2025	Complete first draft of thesis and submit title by April 11 (title deadline). Revise and submit thesis by May 9.

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