Network Coding Aware User Plane for Mobile Networks

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***Abstract*—In this paper, we propose a network coding (NC) enabled transmission strategy in the User Plane (UP) of mobile backhaul for networks operators. In the proposed method, NC provides robustness against the transport network failures, so that there will not be any more processing for re-transmission by the User Equipment (UE) in comparison to traditional approaches where re-transmissions are performed by UE applications. Our simulation results indicate that an average 1% loss ratio in the backhaul link creates 59.44% additional total transmission time compared to normal standard GPRS Tunneling Protocol – User Plane (GTP-U) transmission. On the other hand, applying NC at 1% and 2% rates reduces this amount to 52.99% and 56.26% respectively, which is also better than the total transmission time performance of some previously studied dynamic replication schemes as keeping bandwidth utilization at low ratios. Moreover, we also observe a trade-off between total transmission time and NC rate related to expected packet loss ratio such that minimum total transmission time is obtained when NC rate is equal to expected packet loss rate.**

***Index Terms*—User plane, mobile networks, network coding, backhaul.**

I. Introduction

Network Coding (NC) is a networking technique in which certain algebraic operations are performed on data as they traverse through nodes in a network [1]. NC paves the way for the intermediate nodes with the capability of encoding that combines multiple data connections, and thus it protects data against connection dropouts and packet losses. Coding techniques provide improvements and robustness on the network information flow by reducing data congestion in the nodes or connections throughout the network, which can also increase network throughput. NC solutions involve additional practices that go beyond merely applying additional stages of erasure coding in intermediate nodes.

In Long Term Evolution (LTE), end-to-end latency requirements are around 100 msec for video, voice and similar services [2]. This latency value can easily be achieved by the transport networks of many existing Mobile Network Operators (MNOs). However, considering the recommended end-to-end delay times for 5G services, the delay that should be provided by end-to-end mobile network including radio access network (RAN), transport and core networks is much lower [3]. For example, the expected delay defined by the the 3rd Generation Partnership Project (3GPP) for the live streaming services is around 20 msec.

The problem can occur at points when the time sensitive services such as Ultra-Reliable Low-latency Communication (URLLC), Vehicle-to-X (V2X), etc. are provided by the new generation mobile networks. In fact, all newly established services will suffer from the time delay problem, but in the case of time-critical services, the damage will be even higher. For example, in case of a packet loss in the transport network during delivery of a URLLC service at some point as shown in Fig. 1, this service may not work properly. The current utilized GPRS Tunneling Protocol – User Plane (GTP-U) protocol in LTE systems is based on User Datagram Protocol (UDP) and does not provide any re-transmission of GTP-U packets in cases of packet loss or packet drop. A problem in the transport network of a base station may adversely affect the User Plane (UP) packets sent from/to the base station. Actually, these packets belong to user equipments (UEs) that are being served from this base station. Applications used by UEs may be capable for re-transmitting lost packets, however in re-transmission cases, the desired delay times for mission-critical services will be exceeded due to the time consumed by re-transmit process as depicted in Fig. 1. The expected transmission time for a UE application packet will be increased from T to $T + t$ where t represents the time spent between realizing the packet loss and the beginning of re-transmission process.

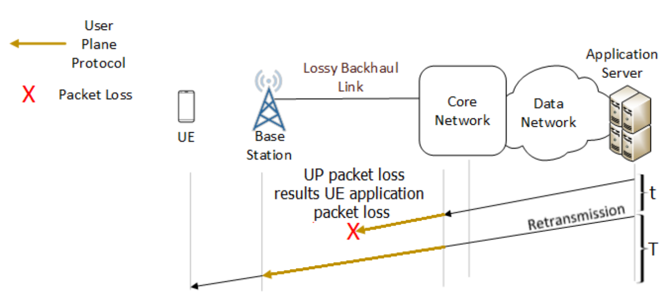

Fig. 1: A packet loss in UP results a re-transmission process in the application layer protocol.

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II. Related Works & Motivation

Our previous work in [4] concentrates on evaluating effect of replication of the lost UP packets when failures occur on mobile backhaul links of transport network. Although some of the advantages are presented in [4], the amount of generated bandwidth usage is too high during the replication process. Therefore, NC in the UP side may be more advantageous in terms of bandwidth usage when compared to making replication. In this sense, resilience and performance capabilities of NC applications in critical infrastructure systems are examined in [5].

The study [6] deals with the throughput decrease in wireless networks occurring due to Transmission Control Protocol (TCP), and presents an Intra-flow network coding technique with the objective of increasing this performance degradation in lossy networks such that Multipath TCP (MPTCP) is used as dividing data into multiple paths with a NC application implemented at IP level. Another study [7] uses Inter-session Network Coding based Clustering Routing (INCC) where the messages are encoded from different flows using broadcasting to improve transmission efficiency. The nodes are clustered and this proposed technique is applied to Delay Tolerant Network (DTN). The average delay is shown lower while INCC is used compared to other algorithms. The research of [8] put forth the implementation of NC and Diversity Coding (DC) in 5G wireless Cloud Radio Access Network (C-RAN). It appears that the combined usage of NC and DC leads to an increase in throughput of fronthaul networks for downlink broadcasting and multicasting. At the same time these methods enable reliable networking with low latency. In a recent study [9], the authors proposed an adaptive and causal random linear network coding method with forward error correction for a point-to-point communication channel.

The main contributions of the paper is as follows:

- We propose a NC-enabled transmission strategy in the User Plane (UP) of mobile backhaul for networks operators, which operates in an iterative manner without requiring extra buffer for NC operations,
- We derive analytical analysis and asymptotic behaviour of our proposed method,
- Our simulation results in NS3 reveal that an average 1% loss ratio in the backhaul link creates 59,44% additional total transmission time compared to normal standard GTP-U transmission. In case NC is applied, the total transmission time increases by 52,99% and 56,26% for 1% and 2% NC ratio respectively compared to no coded transmission , and
- In comparison with dynamic replication scheme presented in [4] with two replicated UP packets, the performance of proposed approach in terms of the total transmission time is better when coding rates are %1 and %2 while keeping bandwidth utilization at much lower ratios. Moreover after NC ratio of 5%, NC creates too much total transmission time which also match with our analytical calculations.

III. System Architecture

A. System Model

In our proposed online coding method, we construct an additional coding packet (p_{nc}), at the transmitter side, based on XOR operations of previously transmitted data packets. This extra coding packet is kept at hand without sending to the receiver side and updated recursively as new data packets arrive. It is transmitted to the receiver only when a certain number (i.e. threshold) of data packets are processed. This threshold level is determined in an adaptive manner, depending on link quality or expected packet loss ratio. After transmitting the coding packet p_{nc} upon reaching to the threshold, the whole cycle of coding process is repeated by starting with an all-zero coding packet initially. This is illustrated in Figure 2.

The network coding process in our approach is expressed formally as a recursive function in Equation 1.

$$C(p_i, p_k) = \begin{cases} p_i & i = k \\ C(p_i, p_{k-1}) \oplus p_k & \text{otherwise} \end{cases} \quad (1)$$

where $k \geq i \geq 1$ and k, i are integers.

To illustrate packet level operation in the proposed method, we provide an example as depicted in Figure 3, where the threshold is assumed as of 8. In the context of this example, p_{nc} becomes equal to p_1 initially, and then gets updated as $p_1 \oplus p_2$, $p_3 \oplus p_2 \oplus p_1$, and so on respectively, and finally gets the following value:

$$p_{nc} = p_8 \oplus p_7 \oplus p_6 \oplus p_5 \oplus p_4 \oplus p_3 \oplus p_2 \oplus p_1 \quad (2)$$

The iterative XORing eliminates the need for extra memory to perform network coding over a set of data. Suppose now that one of the transmitted packets in streamed data set of $\{p_i, p_{i+1}, ..., p_k\}$ is lost, and let p_m be the lost packet where $i \leq m$ and $m \leq k$. Then, the receiver can recover this lost packet p_m by XORing the remaining received $k-1$ data packets and the coding packet p_{nc}. In other words,

$$p_m = p_{nc} \oplus \{p_1 \oplus p_2 \oplus .... \oplus p_{m-1} \oplus p_{m+1} \oplus ..... \oplus p_k\} \quad (3)$$

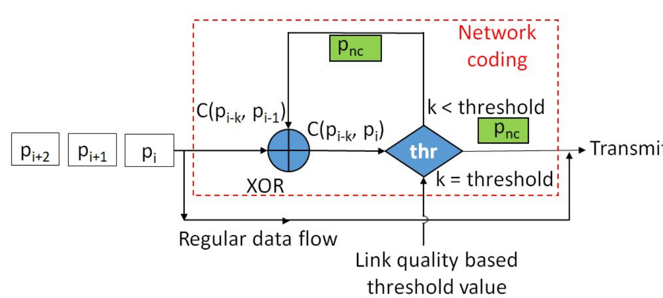


Fig. 2: Encoding function defined in the system model.

The ratio of overhead incurred due to coding packet is proportional with the threshold level. If there is no lost packets at the receiver side or lost packet were not successfully recovered, this additional network code packet is discarded. The decoder is able to recover a lost packet iff the receiver has exactly one lost packet in the set of k packets. If the packet loss rate is higher than the network coding capacity, then the transmitter re-transmits all lost packets except an arbitrary one.

B. Establishing a Network Coded UP Session

In our proposed approach, the interface (S1 in LTE, NG in 5G), where the transmission between Base Station (BS) and Core Network (CN) flows, needs to be aware of whether the UP packets are sent in encoded fashion both from the BS side and the CN side. The purpose of this awareness is that the UP packets will not be encoded and buffered in the receiver if the receiver does not have any knowledge about the ongoing encoding process. As an alternative solution, we recommend to insert a flag in the header of the 3GPP standardized UP packet as shown in Fig. 4. This flag will occupy 1-bit area in the UP header. The proposed flag of the UP can be positioned anywhere in the packet header and we will call this flag, the *"NC-flag"* throughout the text. Its purpose is to inform the receiving end node whether the UP packets are sent in encoded fashion or not.

For example, if the backhaul is not lossy, then there may no need to apply NC process. The UP packets then can be sent to the BS or CN side with the *NC-flag* set to 0 by the transmitter node. This means that no coding process is performed with the UP packets, hence the normal communication continues without any modification. However, if there is a problem in the transport network, then one of the nodes (that may be BS or CN) needs to set the *NC-flag* of the UP header to 1 to prevent the loss of the packet. In this case, the transmission will be performed with the *NC-flag* of 1 and the receiving end node will be aware that NC operation has started, since it detects the *NC-flag* is set to 1 on the UP header. Afterwards, the receiving node will execute the decoding process by running the *N(x)*

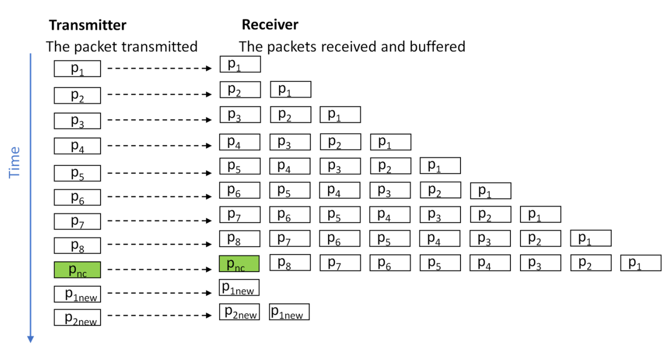


Fig. 3: An illustration of NC example for threshold value equals to 8.

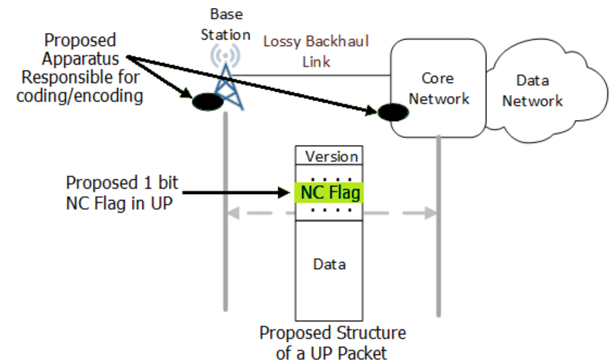


Fig. 4: The proposed apparatus in network nodes communicates with newly introduced NC flag of the UP packet.

decoding function that is pre-configured on both sides. The coding and encoding operations can be done via an apparatus based on software or hardware in the mobile network nodes. When a UP packet is decided to be sent to the network, if there is no need to perform NC, the apparatus does not take any action. Also, the *NC-flag* will be set as 0.

IV. Experimental Analysis

We conducted experiments in Network Simulator 3 (NS3) to demonstrate the benefits of our proposed NC approach in the UP. We utilized the Lena EPC module [10] in NS3 to simulate the S1 interface and we applied the NC implementation in that interface. The parameters used for the simulation are presented in Table I. In our experimental setup, we compare no coding scheme (i.e. regular UE application re-transmission in case of data loss), NC with 1%, 2%, 5% and 10% coding rate and dynamic replication scheme of [4] with 2 packets replicated in the mobile backhaul network. The relevant metrics used for comparisons are total processing time and bandwidth utilization.

Figure 5a presents the obtained results for the backhaul link with different average packet loss ratios. Note that if the exact packet loss ratio of a link is known, then the optimum NC ratio can be applied to combat the packet loss efficiently. However, in practice, we assume that the loss ratio can not be that stable, so we used the average of the packet loss ratio of a backhaul link. In Fig. 5a, the *x-axis* shows the transmission with different NC ratios implemented and also the performance of replication scheme for comparison purposes. The *y-axis* represents the increase (percentage) in the required total End-to-End (E2E) transmission time to transfer the same data when compared with the lossless link with standard GTP-U transmission, which is taken as baseline, i.e. %100.

In a network, the total transmission time (T_{e2e}) is defined as

$$T_{e2e} = T_{proc} + T_{queue} + T_{trans} + T_{prop} \tag{4}$$

TABLE I

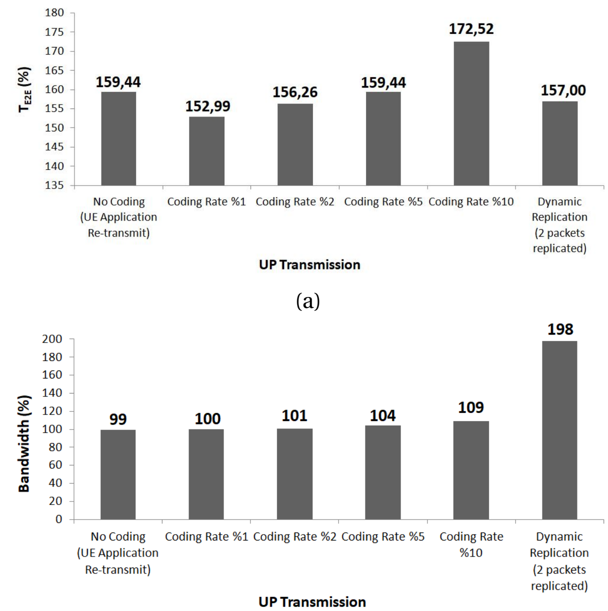
SIMULATION PARAMETERS

Parameters	Value
Test Duration	20 s
S1 Packet Size	1500 bytes
Inter-packet Interval	0 ms
S1 Transport Bandwidth	1 Gbps
S1 Transport Delay	10 ms
Carrier Frequency	1800 Mhz
Bandwidth	20 Mhz
3GPP Channel Scenario	Urban
UE Mobility	Constant
MAC Scheduler	Proportional Fair (PF)
Subframe duration	1 ms
RLC buffer size for UEs	1 ms
eNodeB Power	46 dBm
Antenna Configuration	1x1
UE Traffic Type	TCP DL

where T_{prop} is the time for a signal to propagate through the communication media and T_{trans} is the time required to put an entire packet into the communication media. T_{proc} is the time that is spent to process a packet in the node, T_{queue} is the time that a packet spends in a queue. Note that, in our experimental tests, (T_{trans} + T_{prop}) is constant and does not change when NC coding rate varies, but the sum of (T_{queue} + T_{proc}) increases when NC ratio increases.

As seen from Fig. 5a, if there is no coding applied to the UP, average 1% loss ratio in the backhaul link creates 59,44% additional more T_{e2e} time when compared to normal standard GTP-U transmission. When the NC is applied in the ratio of 1% (which means XOR every 100 packets and send the XORed packet) the T_{e2e} becomes 152.99% with an increase of 52,99%, and this saves nearly 7% time when compared with no coded transmission. NC ratio of 2% generates 56,26% more T_{e2e}, but still saves 3.5% time when compared with no coded transmission. In a backhaul link where average 1% loss ratio exists, NC ratio of 5% seems upper limit providing benefit and after 5% NC ratio, coding creates too much T_{e2e} time when compared with no coded transmission that allows re-transmission in the TCP session of the UE for the lost packets. Dynamic replication scheme presented in [4] with two replicated UP packets sent to the backhaul has T_{e2e} of %157 and its performance is worse than coding rate %1 and %2. Additionally, the tested dynamic replication scheme doubles the used bandwidth.

Fig. 5b presents the throughput/bandwidth characteristics of the compared methods. For the comparisons, we define the bandwidth usage of the UP transmission in a lossless link as 100%. Then, the lossy link with no coding enabled has the bandwidth usage of %99. NC coding ratio of 1% sends 1% more packet and has the same throughput as the normal lossless transmission. However, as the NC coding ratio increases from 2%, to 10%, the bandwidth utilization values increases slightly. On the other hand, the bandwidth utilization of dynamic replication scheme [4] increases by 98% in comparison with normal lossless



(a)

(b)

Fig. 5: Performance comparisons of different NC ratios under backhaul link with %1 average packet loss ratio a) End-to-end transmission time b) Bandwidth occupation.

transmission. These results indicate that together with NC-enabled backhaul, major gains in terms of bandwidth utilization can be obtained for network operators.

V. CONCLUSIONS & FUTURE WORK

In this paper, we propose a NC enabled transmission strategy in the UP interface for mobile backhaul networks of MNOs. In the proposed method, NC provides robustness against the transport network failures, so that there will not be any re-transmission process by the UEs in comparison to traditional approaches where re-transmissions are performed by UE applications. On the other hand, the proposed system requires only a minor improvement in the packet structure of the UP protocol. We validate our proposed approach via NS-3 based simulation environment. Our simulation results indicate that while an average 1% loss ratio in the backhaul link creates 59,44% additional total transmission time compared to normal standard GTP-U transmission, applying NC at 1% and 2% rates reduces this amount to 52,99% and 56,26% respectively, which is also better than the total transmission time performance of some previously studied dynamic replication schemes while keeping bandwidth utilization at low ratios. Moreover, we also observe a tradeoff between total transmission time and NC rate relative to expected packet loss ratio such that minimum total transmission time is obtained when NC rate is equal to expected packet loss rate.

VI. Acknowledgements

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