Towards Resilient and Efficient Multi-RAT Operation through Network Coding

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***Abstract*—The usage of network devices equipped with multiple radio access technologies is a promising way to achieve high throughput, low latency, and resilient wireless communication. However, classical scheduling approaches cannot realize the full potential because packet loss on one radio interface can result in resources on the other interfaces to remain unused. This is particularly a problem in situations with asymmetric link data and loss rates. We show that the performance of a multi-RAT system can be significantly improved by the application of intra-flow network coding where the loss of a single or multiple coded packets on one interface does not result in blockage and hence unused radio resources on some other interface. Moreover, it is less sensitive to transmission failures on the backward direction used by automatic repeat request (ARQ). Results from simulations reveal that our approach is able to outperform a classical approach in terms of throughput by factor of up-to $4.4\times$ in certain scenarios.**

***Index Terms*—Multi-radio access technologies, Multi-RAT, network coding, resilience**

I. Introduction

Next generation applications require high throughput, low latency, and resilient wireless communication [1]. The usage of communication devices equipped with multi-RAT (Multiple Radio Access Technology) is very promising to fulfill those goals, as the outage of a single radio interface does not lead to a complete communication outage [2]. In a previous work we revealed how multi-RAT can increase resilience [3]. But, there are disadvantages.

Classical multi-RAT schedulers distribute the packets across the different radio interfaces for the transmission in the next frame according to the expected link data rates. Packets buffered in one radio interface cannot be moved to other otherwise free interfaces in case of packet loss. In case of a higher layer is generating a batch of packets, this leads to resource wastage on those unused radio links, as the next batch of packets can only be generated if the first frame is transmitted successfully. Especially, this problem is particularly serious when the success rates and/or the data rates vary greatly.

In this paper, we show that this problem can be solved by utilizing intra-flow network coding (NC). Therefore, we assume a linear random network encoder placed above the data link layer. By sending coded packets, the loss of a single coded packet on one interface does not result in any blockage as resources on the other interfaces can be used for the transmission of other coded versions of the packets. Thereby, no radio resources remain unused, as all available radio links are used for redundancy.

Contributions: We present `NCM-RAT` which stands for *Network Coded Multi Radio Access Technology* and show that the usage of intra-flow network coding in multi-RAT systems leads to high efficient and resilient solutions. Moreover, our proposed approach is less sensitive to transmission failures on the reverse direction as automatic repeat request (ARQ) is. Using simulations we will show that our proposed approach is able to outperform a classical approach in terms of throughput by 4.4 times in certain scenarios. Moreover, the packet latency remain low and the overall system is very resilient to packet loss and even interface failures.

II. Network Coding Background

The proposed approach is utilizing a technique termed as intra-flow network coding (intra-NC) [4]. In contrast to inter-flow NC only packets from the same flow will be coded. NC allows the sender node to make random linear combinations of packets from a batch of size *N*, so a coded packet is dispensable. There is no packet specific feedback required and the sender keeps transmitting new coded packets, as this can compensate for the losses of previous coded packets. Once the destination receives N independent coded packets, it can decode the N original packets from the batch and acknowledges this. This is an advantage compared to traditional ARQ protocols where block acknowledgment (BA) packets are used to signal whether a specific packet was correctly received by the destination or not. Lost packets require retransmissions, then. In detail, intra-NC works as follows [4]:

Coding at the Source: Given a batch of N original packets as defined as $O_1, O_2, \dots O_N$ and each packet having a length of K bits. Original packets will be divided into several symbols with the same length. The consecutive s bits of a packet are defined as a symbol over the finite field GF(2^s); therefore, each packet consists of $M = K/s$ symbols. In linear network coding, each packet also has a sequence of coefficients $g_1, g_2, \dots, g_N$ in GF(2^s). A coded packet is generated by $C = \sum_{i=1}^{N} g_i O_i$. The summation will occur at every symbol k.

Decoding at the Destination: Assume that the destination receives coded packets $(G^i, C^i), \dots, (G^m, C^m)$. To decode the original packets, the destination node needs to solve the linear system with m equations (no. of received coded packets) and N unknowns. The unknowns are original packets O_i.

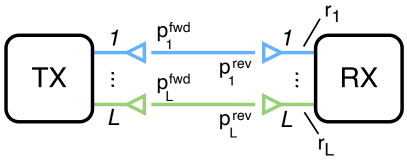

Figure 1. System model of multi-RAT with L radio links.

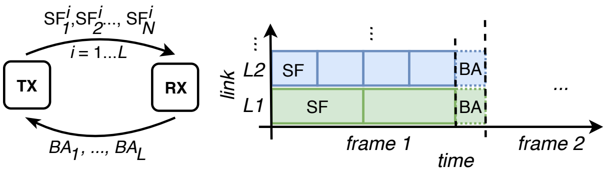

Figure 2. Channel access & scheduling.

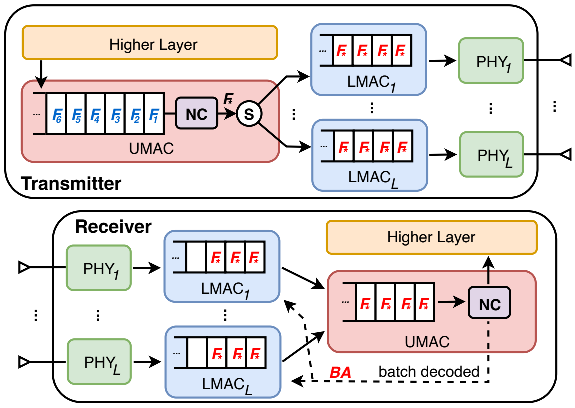

Figure 3. Architecture of NCM-RAT.

III. Problem Statement

The envisioned scenario consisting of a single transmitter (TX) and receiver (RX) connected over L many radio links on possibly different technologies is shown in Figure 1. We assume a scheduled channel access as shown in Figure 2. The packet length is assumed to be fixed. Here, for each link the radio resources are allocated by scheduling transmissions within subframes (SF). Depending on the link data rate r_l the number of subframes that can be transmitted within a single frame varies. In the example from Figure 2 we can see that the data rate of link $L2$ is twice as high as of $L1$. We also assume that a transmitted subframe on link l might get lost due to weak signal and/or interference which is described by an average subframe success rate for the forward (p_l^{fwd}) and reverse (p_l^{rev}) direction respectively. Finally, there is an ARQ scheme in place where the RX node is signaling about successful subframe transmissions at the end of each frame so that unsuccessful subframe transmissions can be repeated in the subsequent frame.

IV. NCM-RAT in a Nutshell

In the classical multi-RAT architecture the packet received from the network layer are stored in the upper MAC (UMAC) before distributing them over the L lower MAC (LMAC) layers. Here the packets are scheduled using a proportional fair scheduler to take into account the different link data rates. The number of packets dequeued from the UMAC corresponds to the expected amount of subframes which can be transmitted during the next frame duration.

Our proposed NCM-RAT approach is different as it utilizes infra-flow NC for better utilization of the multi-RAT. Figure 3 shows the architecture. We can identify the additional component termed as **NC** inside the UMAC which is responsible for the coding and decoding of packets. In contrast to the classical approach packets from the same batch are not transmitted in plain but instead are coded with each other. In the shown example the batch size is 6, hence 6 packets are coded using random linear network coding creating coded versions of the packets (F_*) which are distributed over the LMACs. Here the scheduler from the UMAC makes sure that sufficient number of coded packets is stored in the LMAC queues so that a fully loaded frame can be transmitted. In contrast to the classical approach the ARQ mechanism works slightly different. In case the RX node receives a sufficient number of linear independent coded packets it informs the TX node by sending a block-acknowledgment (BA) on each radio link. On reception of the BA the sender node stops sending further coded packets from the same batch. Instead the LMAC queues are emptied and a new batch of encoded packets are created and distributed by the UMAC. In case decoding was not successful, indicated by missing BA(s), additional linearly encoded packets are generated by the NC component so that the LMAC queues remain full to make sure all links are fully utilized in the next frame. Note, with NC it does not matter via which radio link the coded packets were received. What matters is that enough linearly independent packets are received.

The advantage of the proposed approach is evident in Figure 4. It is much more efficient than the classical approach in case of subframe losses. Consider the illustrated example where six packets are transmitted within six subframes which are scheduled for transmission over the two links. In the classical approach a failed subframe on $L2$ leads to blockage on $L1$ resulting in waste of radio resources, i.e., unused radio resources (Figure 4 A). With the proposed approach the situation is different (Figure 4 B), as the scheduler is able to fully load all radio links by generating sufficient new linear independent coded packets F_*. Hence a failed subframe on one link does to impact the operation on another link resulting in more efficient operation without wastage of radio resources.

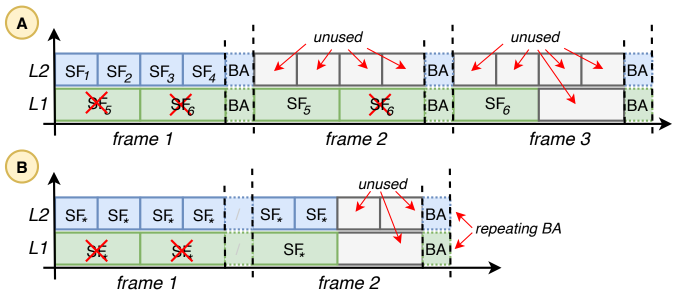

Figure 4. Illustration of schedules from classical (A) and proposed approach (B) under subframe loss in forward direction.

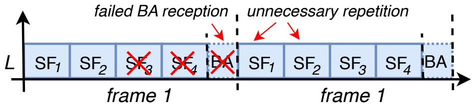

Figure 5. The classical multi-RAT suffers from missing BAs.

Even in case of a full outage on $L1$ the six coded packets can be delivered over the other link in just 2 frames.

Another advantage is the more reliable ARQ mechanism. From Figure 5 we can see that a missing BA in the classical approach leads to unnecessary subframe retransmissions resulting in reduction in throughput and increase in latency. This is because in the classical approach a BA transmitted on link l can only acknowledge subframes being transmitted on that link l. This is different in NCM-RAT as the BA is transmitted redundantly on all interfaces. This is because the BA carries only the information about whether the RX node received sufficient number of independent coded packets regardless of the used interface. The BA mechanism only fails if the BA could not be delivered successfully on any of the interfaces. Hence, the reliability is increased with increased number of interfaces L which stands in contrast to the baseline approach.

V. Performance Evaluation

A. Methodology

We evaluated NCM-RAT and compared it to the classical scheduler approach by means of simulations. As performance metric we selected the overall throughput. For our study we consider five scenarios:

- **Scenario 1**: variation of number interfaces L with erroneous forward and perfect backward links,
- **Scenario 2**: variation of forward link success rate p_l^{fwd} on two links of same link data rate and assuming perfect backward links,
- **Scenario 3**: variation of link data rate on two links $r_l, l \in [1,2]$ of same forward success rate and assuming perfect backward links,
- **Scenario 4**: extending Scenario 1 by taking also transmission errors on the backward links into account.
- **Scenario 5**: variation of link success rate p_l on two links of asymmetric link data rates and erroneous backward links.

In all scenarios the frame duration was set to 5 ms and the subframe size was 6250 Bytes. Moreover, a total number of 1e6 frames was simulated.

B. Results

1) Scenario 1: We start with the study of the impact of the number of interfaces L on the overall throughput. Here we set the same forward link success rate on all links, i.e., $\forall l \in L : p_l^{\text{fwd}} = 0.9$. The backward links assumed to be perfect, i.e., no loss of BA packets transmitted by the RX node. Moreover, all links had the same data rate, i.e., $\forall l \in L : r_l = 100$ Mbps. The results are shown in Figure 6. We can clearly see that gain from the proposed approach increases with L. With $L = 3$ NCM-RAT offers a 11% higher throughput as compared to the baseline as it is more resilient to subframe loss.

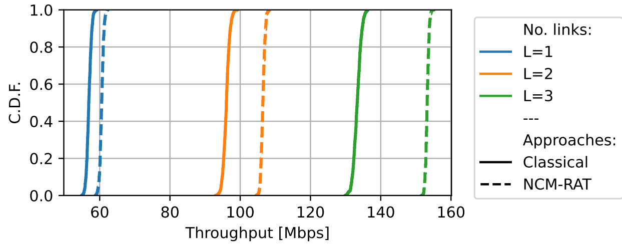

Figure 6. Impact of number of links.

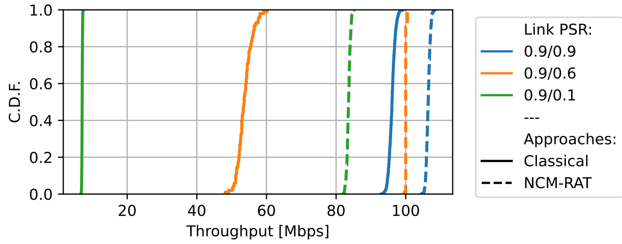

Figure 7. Impact of link success asymmetry.

2) Scenario 2: Next, we analyze the impact of having asymmetric forward link success rates. Specifically, we set $L = 2$ and $p_1^{\text{fwd}} = 0.9$ while varying the loss rate on the second link $p_2^{\text{fwd}} \in \{0.9, 0.6, 0.1\}$. From the results in Figure 7 we can clearly see that the gain from NCM-RAT is highest when having very asymmetric forward link success rates. In the specific case of $p_1^{\text{fwd}} = 0.9$ and $p_2^{\text{fwd}} = 0.1$ NCM-RAT outperforms the baseline by $12\times$.

3) Scenario 3: Additionally, in a multi-RAT configuration with very asymmetric data rates the advantage from NCM-RAT is very high. As can be seen from Figure 8 for the data rate configuration $100/1000$ Mbps where the data rate on the second link is $10\times$ higher the gain from NCM-RAT is 41%.

4) Scenario 4: Finally, we again analyze the impact of the number of available radio links. However, we no longer assume perfect backward links so that BA packets used by ARQ protocols can get lost. Therefore, we set the same forward and backward link success rate on all links, i.e., $\forall l \in L : p_l^{\text{fwd}} = p_l^{\text{rev}} = 0.9$. All links had the same data rate of 100 Mbps. The results are shown in Figure 9. We can observe that a classical approach is very sensitive to losses of BAs as a single missing BA leads to unnecessary retransmission of a variety of subframes which were already successfully received. This is not the case with NCM-RAT where the loss of a single

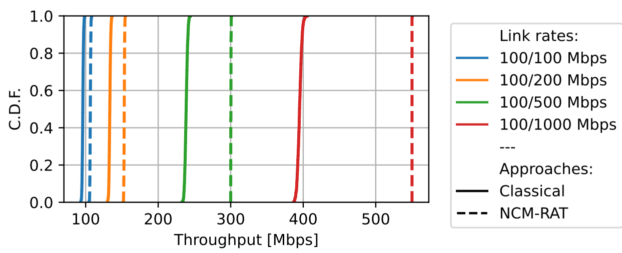

Figure 8. Impact of data rate asymmetry.

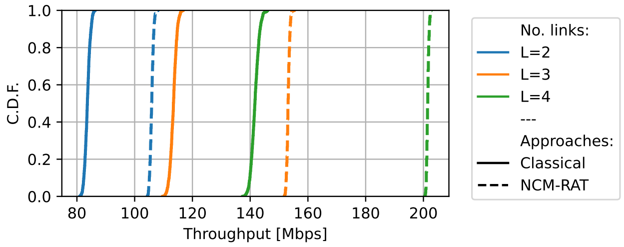

Figure 9. Impact of non-reliable backward links.

BA is not critical as long as there is at least one successful BA regardless of the used link. In terms of throughput our approach is able to outperform the baseline in terms of throughput by up-to 43%. Moreover, the gain is increasing with the number of interfaces L.

5) Scenario 5: Finally, we analyze a scenario with very asymmetric data rates and asymmetric success rates on both forward and backward links. Here we set $L = 2$ and the data rate was set to 100 Mbps and 500 Mbps respectively. Moreover, we analyzed different forward and backward link success rate configurations. As can be seen from Figure 10 the throughput for NCM-RAT is nearly constant at around 300 Mbps and independent of the link success rates on both radio links. This is not the case with the baseline where a low link success rate on the fast link leads to significant throughput degradation by 77% as compared to proposed approach.

VI. Related Work

Zhang et al. [4] showed that the combination of opportunistic routing and network coding (NC) leads to performance improvements in multi-hop wireless networks due to the utilization of the broadcast nature of wireless media. Wang et al. [5] showed that routing optimization improves NC in satellite networks with single source and multiple destinations as it maximizes the entire network's transmission capacity. Gomes et al. [6] showed that the reliability of a vehicular ad-hoc network can be improved through the use of NC. The proposed multi-technology architecture distributes the original and coded data packets over multiple WiFi interfaces. Wang et al. [7] studied the impact of asymmetric links in an industrial IoT butterfly network where the downlink provides a higher data rate than the uplink. Nguyen et al. [8] studied throughput and energy consumption of different NC techniques in a ZigBee network. Barla et al. [9] showed that resources can be saved when NC is used in a multi flow scenario. The usage of NC for inter-datacenter bulk transfers was proposed recently by Tseng at al. [10]. Here a custom flow control mechanism on top of existing transport protocols was introduced. Förster et al. [11] showed that the use of NC can improve the performance of distributed cloud systems. This is achieved by increasing the reliability while trading off storage and bandwidth costs, which provides high download speeds for data without centralized protocols. Finally, Dias et al. [12] demonstrated that the lossy behavior of mmWave channels can be effectively mitigated by implementing sliding window network coding.

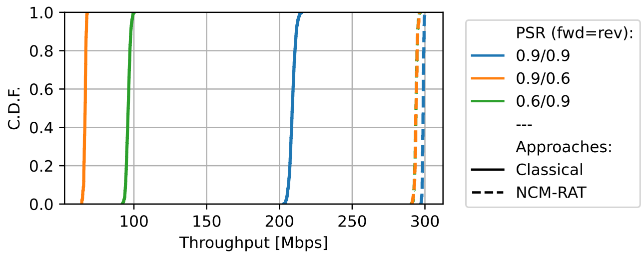

Figure 10. Impact of link success asymmetry on a multi-RAT with asymmetric link data rate.

VII. Conclusion

We have demonstrated that the performance of a multi-RAT can be improved by the usage of intra-flow network coding. This is because the available radio resources can be more efficiently used. As future work we plan prototype NCM-RAT which would allow us to validate our approach under real channel and network conditions. In particular, the realization of an efficient network coding block together with effective queue management and the possibility to deal with variable frame sizes is essential to support high link data rates.

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