NCRAWL: Network Coding for Rate Adaptive Wireless Links

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Abstract

Intersession network coding (NC) can provide significant performance benefits via mixing packets at wireless routers; these benefits are especially pronounced when NC is applied in conjunction with intelligent link scheduling. NC however imposes certain processing operations, such as encoding, decoding, copying and storage. When not utilized carefully, all these operations can induce tremendous processing overheads in practical, wireless, multi-rate settings. Our measurements with prior NC implementations suggest that such processing operations severely degrade the router throughput, especially at high bit rates. Motivated by this, we design NCRAWL, a Network Coding framework for Rate Adaptive Wireless Links. The design of NCRAWL facilitates low overhead NC functionalities, thereby effectively approaching the theoretically expected capacity benefits of joint NC and scheduling. We implement and evaluate NCRAWL on a wireless testbed. Our experiments demonstrate that NCRAWL meets the theoretical predicted throughput gain while requiring much less CPU processing, compared to related frameworks.

Index Terms

Implementation, Measurements, Rate Adaptation, Testbed, Wireless Communications, Wireless Network Coding.

I. INTRODUCTION

Intersession Network Coding (NC) enables the local processing and mixing of independent traffic flows. Combining such flows at wireless routers can increase the available capacity [1], [2], [3]. However, such increase is evident only when: (a) routers (which perform the encoding operations) are able to quickly identify efficient coding opportunities that increase the NC gain; (b) packet decoders are able to correctly decipher the encoded packets and acknowledge the decoded packets that they receive in diverse channel conditions; and (c) the overheads imposed due to the inclusion of additional packet headers as well as packet processing operations [4] are kept minimal. While NC can increase the router throughput in random-access networks [5], prior studies have shown that when the packets are scheduled carelessly, the benefit is reduced [2], [6]. With multi-rate links, and when decisions are made based on statistical information, scheduling is necessary to avoid packet losses. All these factors should be taken into account when designing and developing practical NC algorithms and systems.

Prior NC systems do not consider such effects: Although intersession NC can theoretically offer unprecedented wireless router capacity benefits, realizing these benefits in practical systems is by no means an easy task. Prior implemented efforts towards practical NC [3], [7], [8], [9], have demonstrated throughput benefits at low transmission rates but have also discovered a series of complexity issues arising in such implementations. Our measurements across different testbeds suggest that it is very difficult for such NC implementations to deliver the expected throughput gains in practical multi-rate deployments. This is due to two reasons, which motivate our study. We explain them below.
a. Overhead intensive design: With NC, routers need to be aware of the packets that have been successfully overheard by each neighbor, in order to decide which packets to encode together and when. A method that has been commonly adopted for addressing this requirement, is by enforcing every neighbor into explicitly acknowledging overheard packets. However, in certain practical settings this approach may perform poorly. This is because: (a) the timeliness of information can be severely impaired, as it depends on random medium access; and (b) additional packet processing needs to be performed, which intrusively increases the already imposed processing overhead by NC. Due to such operations, routers become overloaded. Thus, although the channel may be conducive to the use of high bit rates, routers may be incapable of transmitting as many packets in order to meet those rates. Our experiments across two different testbeds(with various approaches such as [3] and [7] running on 1 GHz CPU, 1 GB RAM devices [10]) suggest that in the simple scenario where Alice and Bob exchange packets through an intermediate relay with all links having a PDR (Packet Delivery Ratio) close to 1, the observed CPU utilization was at 100% in 802.11g when bit rates of 36 Mbps or above were used. Moreover, the maximum router throughput for Alice’s and Bob’s flows was approx. 6.5 Mbps on average, compared to approx. 8 Mbps of the pure IEEE 802.11 protocol [5]. These measurements suggest that with such design choices, the benefits due to NC cannot outweigh the performance degradation due to excessive imposed overheads.

b. Absence of scheduling techniques: Previous studies have demonstrated the benefits of jointly applying NC and link scheduling [2], [6]. Prior practical implementations have not incorporated any such techniques, while they have not been designed to host scheduling ideas. This necessitates the design of a broad, although lightweight framework, which can facilitate the efficient coexistence of NC and scheduling.

Our contributions: We present the design and implementation of NCRAWL, our Network Coding framework for Rate Adaptive Wireless Links. NCRAWL has been optimized at each stage of NC operations. It is a modular tool, which can easily host the implementation of intersession NC schemes that are either standalone, or tightly integrated with scheduling algorithms. More specifically, our framework differs from other related systems in the following aspects:

- **NCRAWL is modular:** Algorithms can be easily developed as extensions to NCRAWL modules. These modules manage all the NC operations, such as encoding, decoding, storage and routing in a lightweight manner, which allows for overhead-limited network operations.

- **NCRAWL realizes joint NC and scheduling:** Our framework is the first to facilitate the practical coexistence of NC and scheduling. Theoretically shown throughput benefits can be easily assessed on NCRAWL and adapted for operating on real networks with limited effort.

- **NCRAWL uses solely stochastic information for overhearing:** With this we avoid many overhead intensive processing operations. The practical integration of NC with scheduling provides a well performing lightweight solution.

- **NCRAWL is channel aware:** Routers are aware of all the potential NC opportunities that can take place within their neighborhoods at all times, as well as the maximum transmission rate of the encoded packets that allows for decoding. Routers can also quickly determine which packets should be encoded together to offer the highest performance benefit.

We implement NCRAWL on Click as a Linux kernel module [11]. We evaluate NCRAWL on a wireless testbed through measurements with various indoor and outdoor topological settings. Our experiments
demonstrate that NCRAWL identifies efficient NC opportunities; it offers significant throughput improvements even at high bit rate regimes, where prior schemes are unable to operate, due to the imposed overheads.

The scope of our work: Our focus is not on proposing optimal scheduling policies for NC, but on developing an accurate, lightweight and easy-to-deploy system that can host NC and/or scheduling schemes. NCRAWL can be applied on routers, keeping their functionality simple and fast, given that they need to process and route many thousands of packets per second. We provide a practical and realistic design, by considering cases where encoded packets are decoded at the next hop.

The rest of the paper is structured as follows. In section II we discuss relevant previous studies. In section III we provide a high level overview of the considered NC scheme. In section IV we present the modular design and implementation of NCRAWL. In section V we demonstrate the strengths of our design through a scheduling-driven case study. In section VI we assess the performance of NCRAWL via extensive measurements. Our conclusions form section VII.

II. RELATED WORK

In this section we discuss previous related NC studies and differentiate our work.

Experimental studies on wireless coding: Katti et al. [3] propose COPE, the seminal implementation of wireless NC. With COPE, routers are fully aware of packets that have been overheard by every neighbor. For this, each node is required to inform the router about overheard packets. Experiments with COPE on a wireless testbed show that even with very simple encoding operations, intersession NC can provide significant capacity gains. They also study the interactions of network coding with the routing and the higher layer protocols. We provide more details about COPE later in this paper, where we differentiate our design and implementation. Rozner et al. in [7] present ER, a scheme that adopts the design of COPE and employs NC to perform efficient packet retransmissions. With ER, packets that need to be retransmitted are coded together, such that one retransmission can recover multiple packet losses. The authors show that the problem of selecting the optimal set of packets to code together is NP-hard; they propose a set of heuristics that can be followed to make coding decisions. Kim et al. [12] extend the design of COPE to include NC-aware bit rate control and clever selection of nodes that acknowledge the reception of encoded packets. Rayanchu et al. [8] propose CLONE, a suite of algorithms for NC that take into account losses on wireless links. However, [7], [12] and [8] all follow COPE’s logic regarding the dissemination of information about which packets have been stored as keys. Moreover, these studies do not make online decisions about whether to enable coding or not, based on the link quality. MORE [9] is a routing protocol where routers perform random mixing of packets before forwarding them. Routers that overhear the same transmission may decide not to forward the same packets. Sources keep sending linear combinations of a batch of packets, until receiving an ACK from the destination. MIXIT [13] encodes symbols rather than packets. Similarly to MORE, batches of packets are coded together. However, since a packet is a sequence of symbols, Intermediate relays use hints from the PHY layer in order to infer which symbols within a packet are correctly received with high probability. Relays choose a vector of coefficients at random and encode packets symbol by symbol, using only the clean symbols at a certain position.

The above experimental approaches differ from ours in that we use solely stochastic information for overhearing instead of acknowledging each particular packet. This allows for efficient implementation and avoids computationally expensive packet processing operations. Our work offers a valuable tool for
studying problems regarding joint NC and scheduling with feedback, and can potentially be intertwined with an optimal algorithm to provide the best solution within the class of implicit ACK schemes. We showcase the operation of NCRAWL with various heuristic lightweight algorithms. As we show in section VI there are cases of implicit ACK schemes where NC incurs throughput loss, unless careful scheduling is used. Making decisions based on multiple rates is another important innovation of our framework. To the best of our knowledge, our work is the first to provide a coherent, lightweight framework for practically assessing joint NC and scheduling schemes.

Analytical and simulation NC studies: Chaporkar and Proutiere [2] show that systems with NC may actually have smaller throughputs than if coding is not applied. They show that unless appropriate scheduling is applied, NC may lead to performance degradation. We support this claim by identifying an additional example when implicit ACKs are used. In the same work, Chaporkar and Proutiere propose a generic framework that characterizes the throughput region with NC and enables the design of adaptive joint NC and scheduling schemes. Finally, they propose XOR-Sym, a computationally simple NC scheme that can be applied to symmetric routes. With XOR-Sym, packets are decoded at their destinations only and not at intermediate nodes along a path. This protocol considers only symmetric flows disregarding opportunistic listening. On the contrary we focus on exploiting opportunistic listening. Liu and Xue in [14] consider NC for two-way relaying in a three-node network. They analytically characterize the achievable rate regions for the traditional Alice-Relay-Bob topology, and they find the theoretically optimal end-to-end sum rates. Scheuermann et al. [6] propose noCoCo, a deterministic packet scheduling scheme for NC within two-way multihop traffic flows. Their scheme involves per-hop packet scheduling, NC and congestion control. Seferoglu and Markopoulou in [15] provide an understanding of the interplay between application data rate control and NC. Finally, Vieira et al. [16] provide observations on how the combination of NC and bit rate diversity affects the performance of practical broadcasting protocols. They show that it is possible for multi-rate link layer broadcasts and NC to jointly increase the network throughput in multicast applications. More theoretical results can be found in [17] with the list being non-exhaustive.

III. NETWORK CODING SCHEME

We study the generalized $N$–wheel topology having $N + 1$ nodes as shown in figure 1. The central node, called the relay (or router), is connected to all other $N$ nodes, called neighbors. Links between neighbors may exist as well. Each link connecting nodes $i$ and $j$ is characterized by two channel rates $r_{ij}$, $r_{ji}$ and two probabilities $q_{ij}$, $q_{ji}$ which correspond to the packet delivery ratios in each direction.

In the above topology we focus only on 2–hop flows having neighbors as source and destination and the relay as the intermediate node. In the uplink part (the first hop of these flows), the packets are transmitted without NC towards the relay. In the downlink part, the relay selects a number of packets, applies the XOR operator and transmits the encoded packet. If a receiver recognizes its address in the header, it attempts to decode the packet in order to obtain the intended packet. To achieve this, it should have all the other packets in its buffer, in order to apply the XOR operator again. These packets are known to the receiver either because they have been generated by it (in case of symmetric flows) or they have been obtained by means of opportunistic listening, as explained above. Whenever the packet is successfully decoded, an acknowledgment message is sent back to the relay at layer-3.
Coming back to the $N$–wheel topology, in order to experiment on high gain topologies, we can impose the extra constraint that $N$ symmetric flows are defined by splitting the neighbors in two equal sets, the source and the destination set, selecting a matching of these two sets which corresponds to $N/2$ flows, and finally create another $N/2$ flows by inverting the roles of source and destination. If only the initial $N/2$ flows are enabled, we refer to $\frac{N}{2}$–wheel setting else if all $N$ flows are enabled, we refer to $x$–wheel setting. Evidently, 2–wheel corresponds to the well known Alice-Relay-Bob topology. Throughout the paper, we also use $\frac{1}{2}$–wheel referred to as half-cross and $4$–wheel referred to as cross, as well as a 6–wheel where we activate the flows one after the other. It should be noted that NCRAWL supports any random subgraph of the $N$–wheel topology with any possible set of flows activated on top of it. In addition, it supports settings with any possible combination of link qualities and/or channel rates. The wheel topology is the most general topology to be considered around a single node. Any actual network topology can be reduced to a wheel topology if nodes and links irrelevant to NC on a relay are removed. Since our scheme runs on all nodes in the network, this implies that our scheme works with any arbitrary network topology. The encoding opportunities at each node are automatically discovered by the combination of NCRAWL and SRCR. Thus NCRAWL operates under any assumed graph providing opportunistically throughput gains. We study the wheel setting where the maximum such gain arises in order to showcase that NCRAWL can achieve it in many cases.

We have incorporated the following features in order to enhance the practicality of NCRAWL. As a tradeoff, such features may limit the performance of our framework against the maximum theoretical performance of intersession coding.

- The XOR operator is used instead of linear coding. It is known that the capacity region of XOR NC schemes is a subset of the one achieved with linear coding.
- We enforce the decoding of encoded packets at the next hop, since this is practically the most possible case in today’s wireless access deployments.
- Only native packets are allowed to be stored as keys. This might reduce the capacity region as well.
- We use implicit ACKs of overheard packets. The capacity region is reduced in comparison to explicit ACKs whenever the overhearing probabilities are small.

The decision on imposing these features is justified by the necessity to keep the NC scheme simple, practical, implementable and efficient in terms of processing overhead.

IV. Architectural Blueprint

In this section, we describe the modular design and implementation of NCRAWL.
Employing Click as the basis of our framework: The main NCRAWL system has been developed in the Click modular router framework [11]. Click can be used to develop primarily OSI layer 3 packet processors, which can be directly deployed inside the standard Linux network stack. A Click processor is mainly comprised of (a) processing stages which are called elements and (b) an element interconnection configuration that indicates the processing flow. Execution in Click is event-driven with 4 different types of asynchronous events, namely the incoming packet event, the ready-to-forward packet event, the timer expire event and the external read or write events to Click memory. The first two events require some handling code to deal with network packets; this is not always necessary for serving the rest of the event types. Since all Click events are asynchronous, a Click packet processor typically features internal queues to temporarily store incoming packets.

In what follows, we describe the NCRAWL system design and implementation. We also present the NCRAWL interface that can be used to develop new algorithms, as well as for deploying and managing experiments on wireless testbeds.

A. Design preliminaries

NCRAWL realizes an OSI layer 2.5 protocol that lies immediately under the routing layer. More specifically, it can be considered as an extension to the Click modular router implementation of the SRCR protocol [18], which is the heart of the MIT Roofnet wireless network. Since NCRAWL operates below the routing layer, encoded packets are not forwarded by a node-relay; they are decoded at the next hop. This simplifies the format of the NCRAWL packet headers: they are now used only to encapsulate encoded packets and transfer the respective acknowledgments for successful decoding back to the sender. Both types of the NCRAWL header format are depicted in figure 2. Network wide unique 32-bit packet identifiers are made by applying the sdbm [19] hashing algorithm on data tuples, comprised of packet source IP, the IP header sequence number and the respective offset.
B. NCRAWL System Description

Next, we discuss the modular design of NCRAWL in detail.

The big picture: The main NCRAWL system is a Click network packet processor that includes the SRCR routing protocol implementation for wireless networks \(^{[18]}\). We have included two additional processing stages: the NCRAWL decoder and the NCRAWL encoder. We have developed these stages as individual Click elements, and we have placed them before the beginning and after the end of the SRCR processing flow, respectively, as depicted in figure 3.

a. The packet decoder: The main tasks of the decoder module are the following:
   - To use the available (from overhearing or ownership) key packets in order to decode the received encoded packet.
   - To schedule the transmission of layer-3 acknowledgments (ACKs) for the correctly retrieved native packets, derived by the decoding operation.
   - To determine any potential pending acknowledgments, as well as to verify any received acknowledgments.
   - To tag and store all the correctly overheard data packets as potential keys; as discussed above, these will be potentially used in the near future for decoding received encoded packets. Moreover the key repository is used for packet retransmissions, in case an expected acknowledgment never arrives.

The decoder resides at the packet receiving side of the system and is invoked by the corresponding packet arrival event.

b. The NC packet encoder: The NCRAWL encoder element resides at the sending side of the system and is more complicated, since it maintains and manages the processor packet queues. A part of the element handles incoming packet events, another part deals with outgoing packet events, and there is also code that gets invoked upon timer expiry as well as read and write Click configuration events (figure 3). It is this element that exports the framework API which can be used to develop NC algorithms. Specifically, the main assigned tasks for this module are the following:
• To process and place incoming native packets (keys) into particular maintained queues. Our system supports a plurality of queueing operations, which can be configured as per the requirements of the NC algorithm under development.
• To identify and combine packets together, towards forming encoded packets. The selection of the appropriate packet set follows the directions of the NC algorithm under consideration, supported by NCRAWL.
• To piggyback any acknowledgments (through the use of scheduled, upcoming data packet transmissions) that have been scheduled by the decoder element.
• To generate potentially expected acknowledgment tokens for each of the packets of an encoded combination.

**c. Maintaining up-to-date topological information:** The link metrics updater is responsible for collecting information about the current neighbors as well as the corresponding link transmission rates and PDR values. This information is gathered and passed to the rest of the system via the Click memory write event mechanism. Furthermore, the code that configures the encoding combination policies is invoked as needed.

**Gathering link quality information:** The NCRAWL updater relies on the existing SRCR protocol component, which maintains link connectivity information and performs periodic measurements on all links. SRCR sends probe packets at all rates to determine the PDR for each link and chooses the highest rate that performs well. PDR information is then used by SRCR to calculate the ETX or ETT metric [20], [21], which provides information about entire routing paths (not just 1-hop links). This information is kept in the SRCR link table, and is accessible by our Click components. The SRCR measurement period can be set as desired (the default value, also used in our work, is 3 sec).

**Managing neighbor information:** Based on the information stored in the SRCR link table, the link updater maintains its own so-called Neighbor Table (NT), which includes information for its neighbors. Initially, the NT is empty. The updater periodically reads the SRCR link table and updates NT as needed. The NT contents are updated whenever (i) a new neighbor appears, (ii) an existing neighbor disappears, or (iii) a certain link quality changes. In such cases, the NCRAWL updater broadcasts a packet with the new NT contents and sets a timer. When such a NT packet is received (overheard), the updater replies by broadcasting its NT, provided it has not done so recently. The reply suppression threshold is set equal to the SRCR period. The NT packets are used by the NCRAWL updater to maintain the so-called Received NT Table (RNTT). This table complements the NT, holding information about the link quality as measured by the neighbor nodes themselves. When an NT packet arrives, the corresponding RNTT entry is updated. Packets from nodes that are not in the NT are ignored; a node must be “officially” reported as a direct neighbor by SRCR in order to be considered by NCRAWL.

**Feeding NC algorithms with updated topological information:** Each time the updater modifies the contents of the NT or RNTT (i.e., each time it proactively sends or receives a NT packet which leads to an update of the RNTT) a timer is set. Upon timer expiry, the new link qualities are passed to the main NCRAWL system, where they will potentially drive adaptive NC decisions, based on the NC designer’s needs. This timeout is (generously) set to 1 sec, providing ample time for any NT reply packets to arrive.

**Keeping overheads low:** The NCRAWL updater employs its own threads of execution to perform these information maintenance tasks (the current implementation uses 2 threads), but these remain suspended
most of the time, making this component quite unintrusive in terms of CPU occupancy. Moreover, only a small fraction of the wireless bandwidth is typically used to collect the required link quality information from the neighboring nodes. Finally, the “reactiveness” of the updater is a function of the SRCR period. If a smaller period is used, link changes can be tracked faster (and more accurately) but the processing and communication overhead will increase too. Note that the implementation of the NCRAWL updater can be trivially adjusted to cooperate with other link information gathering protocols as well, i.e., it is not tied to SRCR.

d. NCRAWL logger: The read events are used by another application, the NCRAWL logger, which gathers various statistics that are generated online by both the encoder and decoder.

e. NCRAWL acknowledgments: NCRAWL acknowledges individual (native) data packets, but also groups packet acknowledgments per encoded combination. With this, if the same encoded packet has been successfully decoded at one recipient but failed at another, the sender can figure out which of the undelivered packets can be reused in encoded combinations, based on whether they have been logged successfully as keys by fellow recipient nodes. Note that NCRAWL provides this support; however, it expects that the user algorithm will make the final scheduling decisions. NCRAWL uses by default a user defined timeout threshold to resend packets that have not been acknowledged. Note also that a timer-expire event triggers the transmission of acknowledgments in separate packets when there is not enough outgoing traffic to piggyback them (figure 3). NCRAWL also reschedules packets from the key repository for which acknowledgments have not arrived.

Utilizing resources effectively: Efficient resource utilization is an inherent property of NCRAWL. The repository that stores copies of packets uses a FIFO queue as the main indexing mechanism and can host up to a user defined quantity. After the storage limit is reached, the oldest packet is removed in order for a new one to get stored. The same packets are also indexed in a hash table based on their network-wide unique identifiers, as we previously discussed. The hash table is used to quickly retrieve packets either as keys for decoding, or for resending them in case an expected ACK token expires. The same indexing approach has been used for the ACKs and expected ACK tokens as well.

C. Implementing NC algorithms

NCRAWL exports an API (Application Programming Interface) that can be used to implement scheduling algorithms for intersession NC. This API is a library of functions that can be used to carry out NCRAWL common tasks and mandatory function extensions to the handling code of each event. Points of extensibility and/or programmability are denoted in figure 3 with shadowed boxes.

Implementing packet handling operations: Regarding the incoming packet event, the designer should account for placing arriving packets into proper queues. In particular, each flow is associated with a queue and the scheduler checks all available controls, i.e. activates a set of queues by combining one packet from each queue. It maintains a list with the expected score (reward) of all controls and selects one of those controls at each time instance. The controls that activate only one queue correspond to the case of transmitting non coded packets. It is always possible to deactivate NC by imposing the use of only those latter controls. With this, the developer may implement logic that disables NCRAWL when needed. Furthermore, after the placement of the incoming packet, the developer may: (a) invoke the function that chooses the next encoded packet queue combination according to the NC algorithm, (b) retrieve the
packets from the respective queues, (c) encode them and schedule the encoded packet for transmission by placing it into the outgoing queue. This operation may be repeated until the outgoing queue contains a user defined number of packets. Apart from the queue combination retrieval function, which needs to be implemented by the algorithm developer, the rest of the required functionality is already seamlessly provided by NCRAWL.

**Implementing the core NC logic:** The main algorithm implementation takes place in the context of the Click memory write event, generated by the NCRAWL updater. The latter provides the user with a table of single direction links with entries denoted by the corresponding source and destination IP combinations. Each entry holds the link direction PDR and transmission rate. The provided information can be used by the network coding algorithm to decide the valid NC combinations by selecting the queues to activate together. Since this part of the code runs periodically, the developer is encouraged to implement any complex algorithm steps here and thoroughly index the NC available combinations. With such an approach, the overhead of choosing the most beneficial packet combination during the incoming or outgoing packet events will be minimized.

**Sending data and ACK packets:** The outgoing packet event checks the size of the outgoing packet queue. If this is below the defined threshold, the functions that choose and encode combinations are called in the exact same way as for the incoming packet event. Then the next packet on the outgoing queue gets transmitted. The developer may also add logic for the handling of ACKs. By default, NCRAWL resends packets that have not been acknowledged, by directly placing them on the outgoing queue. It is possible, however, that an algorithm deals with the failed packets (see section 5 for an example). Since the ACK scheme groups ACKs that belong to the same encoded packet, the developer knows which packets have been decoded successfully at which destination, and may extend the NC algorithm to decide whether a packet should be resent directly, or reconsidered for encoding combinations.

**System monitoring:** Our framework allows for user defined timer events. Statistics for incoming–outgoing packet activity as well as queue lengths are all logged using counters. The NCRAWL logger periodically retrieves statistics and notifies the user at runtime about the flow stability and the corresponding queue lengths. The latter are also available for use in the NC algorithm if needed. Finally, the developer may also implement additional debugging support for inspecting the algorithm configuration at runtime, using the standard Click support for the read handler.

**D. Deploying NCRAWL Experiments**

We have integrated NCRAWL deployment scripts with the OMF framework [10] for wireless testbeds. OMF is a Control, Management and Measurement Framework that provides users with tools to describe, execute and collect experimental results in a straightforward manner. There are three main components that comprise OMF; we describe them below:

- **Gridservices:** This is a set of web services that are used by OMF to fetch information and perform actions remotely on the nodes. These services can be used for loading the system image to nodes, executing experiments and collecting results.
- **Nodehandler:** This component resides on the central server that interacts with the user for the experiment submission. Moreover, it provides the necessary applications for node system image loading, experiment execution, image saving and node status check. This component communicates with both the gridservices
and the nodeagent to get the required information and perform actions. Regarding the experiment deployment, nodehandler contains a set of prototypes that can be used for experiment definition. It also notifies the user for any problems that may arise.

- **Nodeagent:** The task of this constantly active component is to wait for information that contains instructions for the experiment deployment, arriving from the nodehandler.

NCRAWL extensions have been written for both nodehandler and nodeagent. The former performs transfers of the Click executable along with user defined parameters. The latter retrieves local node information (e.g. the network interface name and MAC address) and then parametrizes a generic NCRAWL deployment script that gets immediately invoked to start the local Click NCRAWL instance. Finally, the nodehandler is notified if the deployment was successful; Upon success, experiments can start. We have written nodeagent scripts to deploy *iperf* instances and collect results at the nodehandler. With OMF, NCRAWL experiments can be deployed with minimal user effort.

V. Case Study

As discussed above, the relay maintains a queue for each pair of source-destination in the neighborhood that lacks direct connection (2-hop flows traversing the relay). At each transmission slot, the scheduler should select a number of packets, encode them and send the encoded packet to the MAC layer for transmission. The problem is then of scheduling nature; to select a number of packets for transmission. Note that selecting only one packet corresponds to transmission without NC. This section demonstrates by example how the NCRAWL framework allows for easy implementation of scheduling algorithms and presents a case study to be used for the performance comparison of the next section.

A well known family of optimal algorithms for scheduling is the maximum weighted matching algorithms, applied in the stability theory of stochastic networks and input queues switches, see for example [22], [23]. In these algorithms, the available control actions are chosen to maximize a reward which depends on link rates and queue lengths. The application of such algorithms for the solution of the joint NC and scheduling problem with arbitrary rates is then promising (see [24] and papers in which it appears as a reference).

For the case of the implicit ACKing scheme, used by our framework, one observes that the rate of service for packets of a particular source-destination pair is actually random. The randomness comes from the fact that some packets needed for decoding may be missing because of an overhearing failure. Nevertheless, a NCRAWL equipped relay owns the probabilistic information of overhearing and is then in position to determine the probability of decoding and thus the average service rate. A control action consists of selecting a number of queues to serve at a single decision instance. The reward of each control is the sum of queue length times the average service rate for each queue activated by the control. The average service rate is the expected number of successfully serviced packets times the transmission rate for which the encoded packet can be received by all intended receivers. This rate is the minimum of the reception rates of all intended receivers. We write:

\[ \mu_i(C) = \prod_{j \in C} q_{s_j,d_i} \min\{r_C\}, \]

where \( C \) is the control, \( q_{s_j,d_i} \) is the probability that the destination of flow \( i \) overhears the source of flow \( j \) at the uplink phase, \( \min\{r_C\} \) is the transmission rate of the control and \( \mu_i(C) \) is the expected
service rate of flow $i$ when the control $C$ is selected. Here we have assumed that the overhearing events are independent. This is a realistic assumption since the time and space for each overhearing event is different. Collisions and Rayleigh fading may be the causes for this randomness.

A. Algorithm 1

Let $Q_i$ be the queue backlog at the relay for the flow $i$. We are then in position to design our first algorithm.

**Input:** $Q_i, \mu_i(C)$

**Output:** $C^*$

$w_{\text{max}} := 0$

for $C \in C$ do

$w(C) := \sum_{i \in C} Q_i \mu_i(C)$;

if $w(C) > w_{\text{max}}$ then

$C^* := C$;

end

end

Algorithm 1: MaxWeight Algorithm without feedback

An issue raised in this algorithm is the fact that the number of possible encoding combinations to be examined is exponential in nature. If, for example, we assume that overhearing is possible for all receivers except the destinations, then the number of combinations is actually $2^N - 1$ where $N$ is the number of source-destination pairs (or 2-hop flows). The question is then whether the computational overhead for the weights is prohibitively high. In subsection V-D, we explain how the list of weights is maintained in order to reduce the number of calculations per slot.

The algorithm 1 is throughput optimal under the condition that the knowledge of the aforementioned probabilities of overhearing cannot be altered during transmissions. This happens when (i) the probabilities are 0 or 1, as in Alice-Relay-Bob topology (and any other symmetric flow setting) or (ii) upon a decoding failure we reschedule the uplink transmission for the failed flow. The latter may arise in a TCP scenario. In the general case, however, whenever a particular encoded packet is not correctly decoded, the packet remains in the queue at the relay but extra feedback information is obtained. If for example $P_1 \oplus P_2$ is not decoded by both receivers, the relay knows that these two packets are not overheard by receiver 2 and 1 respectively, and the proper action is to correct the overhearing probabilities to zero and never encode these two specific packets again. The impact of feedback clearly biases the probabilities of decoding. The knowledge state of each packet evolves in a such a way that future states depend on the control action selected at present and as a result, in the general case, not only algorithm 1 is not optimal but it might perform quite badly when the overhearing probabilities are quite small.

B. Algorithm 2: the case of two queues

Another idea is to propose an algorithm which is not necessarily optimal, but manages to handle the feedback information successfully. In general, an algorithm should be able to predict the future effects of current control actions. Here we restrict our search to the category of the so-called myopic algorithms,
trying to solve the problem given only the current state and disregarding the future. We consider the problem of mixing only two flows.

In order to cope with feedback, we add two more knowledge states. Apart from newly arrived (unknown) packets whose behavior is captured by known probabilities, we have a state for “good” packets (overheard by the other receiver) and one for “bad” packets (those not overheard by the other receiver). Thus, the system maintains the queues \( Q_i^s \) where \( i \in \{1, 2\} \) signifies the flow and \( s \in \{u, g, b\} \) signifies the state. The set of controls \( C \) contains all controls that activate one or two queues with the constraint that no two queues from the same flow can be activated. The packets are initially injected in the queues at the

\[
\text{Input: } Q_i^s, \mu_i^s(C) \\
\text{Output: } C^* \\
\text{At feedback time:} \\
\quad \bullet \text{ For each packet that was not correctly decoded define whether it is good or bad.} \\
\quad \bullet \text{ Bad packets are directly sent to the MAC layer for transmission without coding.} \\
\quad \bullet \text{ Good packets are sent to the corresponding queue at the good state.} \\
\text{At decision time:} \\
\quad w_{\text{max}} := 0; \\
\quad \text{for } C \in C \text{ do} \\
\quad \quad w(C) := \sum_{C'} Q_i^s \mu_i^s(C'); \\
\quad \quad \text{if } w(C) > w_{\text{max}} \text{ then} \\
\quad \quad \quad C^* := C; \\
\quad \text{end} \\
\text{end}
\]

\textbf{Algorithm 2: Myopic Algorithm with feedback}

unknown state. Once a packet is not decoded properly, the relay classifies it as either good or bad based on feedback information. If bad, it is retransmitted without encoding (thus the queues \( Q_i^b \) are not needed actually). If it is deemed as good, it is transferred to the corresponding queue at the good state (\( Q_i^g \) or \( Q_2^g \) depending on the flow it belongs to). When calculating average service rates, the packets at the good state have probability of overhearing equal to one. Apart from these alterations, algorithm 2 works in the same way as algorithm 1.

In [25] it is shown that an enhanced queue length based algorithm solves optimally the joint NC and scheduling problem arising in intersession coding at the relay node. This solution might be costly in terms of resources, and therefore suboptimal algorithms might be preferred. For this reason, our framework serves as an ideal substrate for performing measurements of such algorithms.

C. Algorithm 3: fixed threshold policy

For reasons of performance comparison we define a third algorithm. This algorithm operates only with implicit ACKs and makes decisions based on principles used in the COPE framework. In this sense, it emulates COPE in its probabilistic mode. The important differences to our algorithm are that instead of calculating average service rates, the \( \delta \)–Fixed Threshold Policy (\( \delta \)–FTP) simply marks the incoming packets with information about decoding opportunities. In order to do so, overhearing probabilities \( q_{i,j} \) are compared with a fixed threshold \( \delta \in [0, 1] \) and set to 1 if they exceed the threshold or zero otherwise. The algorithm selects at each decision instance the control that maximizes the number of transmitted packets.
D. NCRAWL algorithm implementation

Next, we demonstrate how to implement the three above algorithms on NCRAWL. For all three cases, we configure NCRAWL at each node to maintain one queue per flow for incoming packets.

Implementing algorithm 1: We first describe how one may organize queues in an efficient manner. Subsequently, we show how to utilize the queue information to apply NC.

- **Organizing packet queues:** To begin with, we dedicate one vector per control which contains the identity of the involved queues (e.g. the flow it belongs to and/or the state) and the identities of the packets enqueued at the involved queues. The formed vectors are stored in a double linked list. Each vector is assigned a weight (or reward); the higher this weight, the higher the preference of the encoder for using the combination. This weight is recalculated every time the backlog size of a member queue changes. The linked list is formed such that the head of the list contains always the current maximum weight. For the sake of low processing overhead, vectors are also directly indexed by their member queues; with this, the weight update process is fast. As one may expect, vectors as well as their linked list are all constructed during the NCRAWL updater write event.

- **Applying NC operations:** Given the construction of the control list, the encoder event examines the head of the list, and further: (a) retrieves packets from their respective queues, (b) updates the vector weights (since the respective backlogs are decremented), and (c) sets the vector with the highest weighted combination as the head of the list. The latter is actually a process with slowly scaling complexity with the number of vectors-combinations, since each updated vector weight is just compared against the weight of the current head, and only takes its place if it is higher. Retrieved packets are subsequently combined using the NCRAWL encode library call, and the resulting encoded packet is scheduled for transmission.

Implementation considerations for algorithm 2: This algorithm is similar to algorithm 1, however it involves an additional acknowledgment scheme logic. Therefore, for each flow NCRAWL now maintains two queues: (a) one with new incoming packets, and (b) one with packets that have been successfully logged as keys by fellow nodes, but have not reached their ultimate destination. Algorithm 2 exploits the NCRAWL acknowledgment scheme facility; this process groups the packet acknowledgment tokens, which have been created for outgoing packets combined together in the same encoded packet. This information is provided by NCRAWL to the developer. Algorithm 2 directly sends packets that have not yet reached their destinations; such packets are not reconsidered for encoding. However, the algorithm considers favorable queues and “unknown” queues for the same flow separately, when forming vectors. Note that the vectors formed with this algorithm scale intrusively, compared to the simple maxweight algorithm described previously. Throughout our measurements we only consider the scenario of two flows and thus avoid the arising complexity. This issue is expected to be resolved in the future using the NCRAWL framework.

Algorithm 3 in NCRAWL: For the implementation of the third algorithm we simply need to create vectors, (i.e. controls or queue combinations) for which the decoding probability is nonzero, according to the user-defined threshold $\delta$ and the channel quality. As soon as packets are available in all queues that constitute a vector, they are combined and transmitted at once, without considering or updating the queue backlogs. This algorithm selects controls that mix the largest possible number of packets each time.

We should note here that NCRAWL does not use any time-threshold policy towards increasing the backlog size of the incoming packet queues, before deciding to send outgoing packets. On the other hand,
COPE adopts such a design decision. With NCRAWL, queue backlogs will increase when the relay’s outgoing packet rate is smaller than the incoming packet rate. In such cases, NC proves to be a panacea for the router stability; if the NC algorithmic operations are supported by a lightweight implementation, the router capacity can be truly increased, as our measurements suggest.

VI. EVALUATING OUR FRAMEWORK

In this section, we evaluate NCRAWL in conjunction with scheduling algorithms (NCRAWL + alg1, NCRAWL + alg2 and δ–FTP) described in section V, in terms of both throughput and resource utilization. We begin by describing the wireless testbed infrastructure and the configurations that we used to deploy experiments. Next, we quantify the CPU overhead that is introduced by each NCRAWL processing stage, under maximum traffic loads, and we compare total CPU utilization to: (i) the public COPE implementation that uses an explicit acknowledgment scheme and (ii) legacy IEEE 802.11b-g. Following, we demonstrate that NCRAWL can support theoretical gains even when coding opportunities lead to more than 2-packet combinations. Finally, we deploy experiments that demonstrate how the proposed algorithms perform in cases with variable link qualities and different rates.

A. Experimental setup

Our testbed is comprised of 20 ORBIT-like nodes, deployed both indoors and outdoors. Each node consists of one 1GHz 386 processor, 512MB of RAM, two ethernet ports and two miniPCI slots which are used to host two AR5212 Atheros 802.11a/b/g WiFi cards. All the nodes are connected through wired Ethernet with the testbed’s server - console. On console, we have all the required testbed services running as well as the NCRAWL deployment scripts that we described in section IV-D. For conducting throughput measurements we use the iperf bandwidth meter tool. For CPU occupancy measurements we appropriately instrument NCRAWL with the Linux getrusage system call, which accurately estimates CPU usage time. We place several getrusage calls at the borders of each processing stage, we record the average usage time of each stage and we compare it to the whole NCRAWL system usage time. We have repeatedly performed all of our experiments late at night, in order to avoid interference from collocated networks.

B. CPU occupancy measurements

In order to measure the efficiency of our framework in terms of CPU occupancy, we compare it to the case of running COPE, as well as the legacy IEEE 802.11 protocol.

NCRAWL is much more CPU friendly than COPE-based approaches: We invoke the Alice-Relay-Bob setting (see section III) and we inject fully saturated traffic in both flows. We compare NCRAWL + alg1, NCRAWL + alg2, COPE and the plain 802.11, for the case of 802.11b; figure 4-a depicts the results. Note that COPE can support at most the IEEE 802.11b rate set as discussed in section I; for the sake of a fair comparison here, we use this mode of operation for NCRAWL as well. We observe that NCRAWL makes use of the CPU resources in a very efficient manner: it reduces the CPU utilization by at least 2 and as much as 7 times compared to COPE (we have validated these observations for the case

Our motivating experiments discussed in section IV-D were performed on 2 different testbeds. We have evaluated NCRAWL on both testbeds; here we present results for one of them.
of ER [7] as well, which is based on COPE). Furthermore, we test NCRAWL for the case of 802.11g. Our measurements (figure 4-b) suggest that NCRAWL does not need to occupy more than 37% of the CPU resources for NC operations at 54 Mbps, with fully saturated UDP traffic! This implies that the design of NCRAWL includes low additional overhead functions (as opposed to legacy 802.11).

**Evaluating individual operations of NCRAWL:** Next, we deploy getrusage calls and measure the breakdown of CPU occupancy per processing stage (figure 4-c). The most CPU intensive operation is the SRCR stage (it contains legacy IEEE 802.11 operations as well). The most computationally heavy pieces of NCRAWL are the encode stage and the key house-keeping. Note here that these two lie at the heart of any NC system and in a way represent unavoidable costs. It should also be noted that the processing
stage of the scheduler remains at very low values and there is a certain percentage dedicated to dealing with ACKs. Furthermore, as depicted in figure 4-d, by increasing the channel rate (and thus the number of packets into the system per unit time), the coding stage increases in complexity disproportionally with the SRCR stage. This implies that the coding complexity increases faster than SRCR as the rate increases. Nevertheless, for high channel rates the differences are reduced. This suggests that NCRAWL could potentially operate efficiently at much higher channel rates, such as with 802.11n systems. We plan to test NCRAWL on MIMO networks in our future work.

C. Throughput measurements with UDP

Next, we assess the ability of NCRAWL to approach the theoretically expected benefits of NC.

**Experiments with the simple Alice-Relay-Bob topology:** We calculate and measure the maximum throughput for both symmetric flows, such that the system remains stable (i.e. the queues do not rise more than a large permissible number). Figures 4-e, 4-f, 4-g and 4-h show the results. Note that since the receivers always have the proper keys (these are the keys from their own transmitted packets [2]), decoding is always possible and thus algorithm 1, algorithm 2 and COPE are optimal in this setting. In each case, a gain in throughput of \( \frac{4}{3} \) is identified, which matches the theoretical for this topology. Our measurements suggest that COPE achieves the theoretical throughput for small rates, but it fails to do so in higher rates. Note that the public COPE code was initially available for 802.11b only; while we carefully modified COPE to operate at 802.11g rates, we observed that such modifications lead to a very unstable system when rates higher than 18 Mbps are used. A closer look at certain individual components of the COPE implementation revealed that the reason for this instability is the excessive overhead induced by the NC system operations (as discussed earlier). For this reason we do not explicitly compare COPE here at these high rates. Nevertheless, from these measurements one can realize that COPE cannot provide benefits at rates higher than 18 Mbps, due to the tremendous CPU processing overheads that its design incurs. In contrast, NCRAWL manages to reach the theoretical gain at high channel rates (e.g. at 54 Mbps), as shown in figures 4-f and 4-h.

**The case for wheel topologies:** Furthermore, we scale the number of flows (see figures 5-a and 5-b); the topology is an \( \frac{x}{2} \)-wheel. The theoretical gain in this case is \( \frac{2x}{x+1} \) where \( x \) is the number of flows combined at the downlink. Our measurements support the theoretically predicted gain at the channel rate of 54 Mbps. We observe the per flow throughput naturally drops, as the number of flows increases, but the aggregate throughput increases. The gain (figure 5-b) is an increasing function of flows and approaches asymptotically 2; note that this is perfectly aligned with the findings in [2] as well. Note also that in \( \frac{x}{2} \)-wheel topologies, piggybacking is not available since there is no return flow from the receivers. NCRAWL is able to select the appropriate ACKing method and the results show that the overhead incurred is negligible.

**Experiments with cross topologies:** We now present two more cases of interest that can appear in realistic environments. We setup various cross topologies with nodes in different locations across our testbed; we activate the flows Alice-Relay-Chloe and Bob-Relay-David. The arrivals are again chosen in a symmetric way, i.e. the arrival rate of the one flow is equal to the other.

- In the first case (figure 5-c), David overhears Alice’s uplink transmissions with probability 1 and Chloe hears Bob with probability \( q \). The rates of all links are equally set to 12Mbps (the channel rate
is not important in this experiment). We measure the highest throughput that guarantees queue stability while varying the probability $q$, by considering different node locations. We compare NCRAWL+alg1, NCRAWL+alg2 and IEEE 802.11g as well as $\delta$–FTP for $\delta = \{0.7, 0.8, 0.9\}$ (see section V for description). The results demonstrate the superiority of NCRAWL+alg2, which is able to deliver the maximum throughput in each case. Evidently, our framework in combination with the proposed scheduling algorithms is able to effectively handle the several link quality conditions.

- In the second case (figure 5-d), the overhearing probability from Bob to Chloe is set to $q = 0.7$. All channel rates are set to 24Mbps with the exception of the link Relay-Chloe which is varied. Our measurements demonstrate the inefficiency of policies oblivious to rates like the $\delta$–FTP. In this case, the choice of a small value for $\delta$ is penalized when the Relay-Chloe link is slow enough. Instead NCRAWL+alg2 is able to handle in an effective way the several rate and link conditions and deliver important throughput gains. From figures 5-c and 5-d we also observe that given that overhearing links are not perfect in terms of PDR, NCRAWL+alg2 always outperforms NCRAWL+alg1, since it is able to use feedback information.

D. Performance with TCP traffic

Finally, we assess the efficacy of NCRAWL in scenarios with TCP traffic. In [3], experiments with TCP have demonstrated a loss in efficiency due to packet losses and reordering. First, throughout our experiments with the Alice-Relay-Bob topology, where no losses or delays are incurred, the throughput is reduced due to the additional TCP overheads. We observe that when the 54 Mbps rate is used, the per flow throughput rate is 7 Mbps for plain 802.11 and 8.5 Mbps for NCRAWL+alg1. A slight loss in NC gain is observed; this is the result of mixing TCP ACKs with data packets. The same gain is obtained for all the other available bit rates.

Furthermore, we perform experiments with half-cross topologies, where flows are unidirectional (from Alice to Chloe and from Bob to Dave), with probabilities of overhearing $q_{AD} = q_{BC} = 0.7$ and several channel rates. In this case, NCRAWL+alg1 achieves a slightly lower throughput than IEEE 802.11. This is due to the fact that some packets are not correctly decoded at the destination and therefore they arrive delayed and out of order. This causes abrupt reactions from TCP and leads to throughput reduction. When adding the reordering module of COPE [3], the packets arrive always in order, however this module increases the delay for each packet. This in turn is interpreted by TCP as congestion; it ends up in TCP window increments, and thereby decreases performance. NCRAWL is not optimized to cooperate with TCP at this point and thus, it faces the common problems of TCP in wireless networks. Improving this component is the main goal of our future work.

VII. CONCLUSIONS

We design and develop NCRAWL. Our framework is an extended, generic NC framework that can be used to quickly develop networking systems in order to evaluate intersession NC and/or scheduling algorithms, entirely based on the implicit (probabilistic) acknowledgment that a packet can get decoded at the destination. The design of NCRAWL involves all the common processing steps that are always needed to implement such algorithms; these steps have been abstracted such that designers need to simply focus only on the implementation of their algorithms. Our measurements demonstrate that NCRAWL is a powerful NC development system. It offers significant throughput benefits even at high channel rates.
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