RATE AWARE NETWORK CODES FOR COORDINATED MULTI BASE-STATION NETWORKS

BY

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Dedication

To my Parents, wife, son, sisters, and brothers for their endless support and love.

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All praise and thanks be to Almighty Allah, the one and only who helps us in every aspect of our lives.

Acknowledgement is due to King Fahd University of Petroleum and Minerals for giving me this precious opportunity to resume my Master degree.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

IDNC	Instantly Decodable Network Coding
RA IDNC	Rate Aware Instantly Decodable Network Coding
ML	Maximum Likelihood
DSNs	Distributed Storage Networks
NC	Network Coding
FNC	Full Network Coding
ONC	Opportunistic Network Coding
BS	Base Station
MMP	Multipoint-to-Multipoint system
RAN	Radio Access Networks
MB-RA IDNC	Multi Base station Rate Aware Instantly Decodable Network Coding

C-RAN	Cloud Radio Access Networks
SFM	State Feedback Matrix
R	Repetition index of the stored files
U	Number of Users
F	Number of Messages
B	Number of Base Stations
N	Message Size
ϵ_u	Message Erasure probability
$\bar{\epsilon}_u$	Average Erasure probability

THESIS ABSTRACT

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TITLE OF STUDY: Rate Aware Network Codes for Coordinated Multi Base-Station Networks

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In this thesis work, we study the problem of minimizing the message download completion delay from multiple base stations system. By utilizing a multi-Base station Rate Aware Instantly Decodable Network Coding (MB-RA IDNC) the completion time is minimized. IDNC can speed up the download process by taking advantage of the users' side information. The different rates of the base-stations to the various users will be thus incorporated in the network coding decisions, so as to schedule the coded messages and transmission rates jointly in order to reduce the overall completion time. This work considers asymmetric rates for users which reflects more practical application scenarios and gives a new trade-off between the selection of message combination for different users and the broadcasting rate to reduce the delivery time of the wanted messages for the users. However, more than

one base station will target the same user simultaneously causing transmission conflicts. This model considers the transmission conflicts among the base stations in finding the optimal message combinations and transmission rates. Using this model, we design a multi-layer heuristic algorithm which is used in solving the download time minimization problem in such systems. The performance of the proposed algorithm (in terms of the completion delay) with perfect channel is compared to that of the classical IDNC and uncoded schemes in which every base station tries to minimize its own completion delay without considering the rate awareness. Also, a message placement policy in the base stations is simulated and compared to the performance of classical IDNC and uncoded schemes when the messages are distributed between base stations without repetitions. The proposed scheme for perfect channel with message placement policy is shown to achieve significant reduction in completion delay as compared to the classical IDNC and uncoded schemes. Furthermore, a channel erasure probability is investigated (i.e., when message loss event occurs). Under such scenario, the uncertainty about message reception at the targeted user would drive the base station to carry out the message combinations selection and re-transmit the lost message. Therefore, the performance of multi-layer MB-RA IDNC algorithm is studied and derived for such scenario.

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الاسم: محمد حميد عبدالله سيف

عنوان الدراسه: دراسة تقليل زمن تحميل المفات في محطات الإرسال بمعرفة معدلات نقل البيانات

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في هذه الأطروحه, نقوم بدراسة تقليل زمن تحميل الملفات من محطات الإرسال Base Stations. من خلال الأستفادة من فكره إرسال ملفات مركبه من محطات الارسال MB-RA IDNC تم تقليل زمن تحميل الملفات. IDNC طريقه مميزه لتسريع عملية تحميل الملفات من خلال الإستفاده من الملفات المستلمه سلفا لدى المستخدمين. لذا بإستخدام اختلاف معدلات النقل Asymmetric Rates من محطات الإرسال الى مختلف المستخدمين يتم اتخاذ قرار تشفير الملفات Network Coding وذالك لجدولة تركيب الملفات File Combination ومعدلات النقل Rates معاَ من أجل تقليل الزمن الكلي لتحميل الملفات Completion Time.

هذا العمل أعتمد على عدم تماثل معدلات الإرسال لكافة المستخدمين الذي يستخدم في عدد من التطبيقات العمليه ويعطي أولويه ومفاضله بين اختيار الملفات المركبه و معدل البث Broadcast Rate لتقليل زمن تسليم الملفات المطلوبه للمستخدمين. أكثر من محطه أرسال تخدم نفس المستخدم بنفس الوقت تسبب تعارض في الإرسال.

لذالك الموديل المستخدم في هذا العمل إعتمد على تعارض الإرسال لعدد من محطات الإرسال لايجاد أفضل اختيار لتركيب المفات ومعدل النقل. استخدام هذا الموديل قمنا بتصميم خوارزمية متعدده الطبقات MB-RA IDNC وذالك لتقليل زمن تسليم المفات. قمنا بمقارنة الخوارزميه المقترحه لعدد من السيناريوهات مع خوارزميات أخرى كخوارزمية Classical IDNC التي لا تعتمد على معدل الإرسال وخوارزميه عدم التشفير Uncoded .بكل السيناريوهات أستنتجنا ان أداء عمل الخوارزميه المقترحه أفضل من خوارزمية Classical IDNC وخوارزميه Uncoded.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the last years, the demand for storing e-mails, photos and videos has increased so this lead to an exponential growth of storage systems capacity. This growth promoted the development of new data storage techniques (i.e cloud) in order to improve the two main performance indicators of the systems: reliability and availability [1, 2]. The exploding number of content requests, e.g., YouTube videos, Instagram pictures, Facebook notes, Dropbox shared files, threatens the ability of wireless networks to provide fast and reliable real-time communication. Cloud-enabled radio access networks (CRANs) have been proposed as a suitable technology to overcome the difficulties mentioned above. CRANs have attracted more interest lately to improve system availability and to efficiently schedule and coordinate the process of downloading data from these storage nodes (base stations) to nodes (mobiles) demand messages. With the emergence of smart phones, the

4G and 5G cellular network architectures, the data download problem has become more attractive in the wireless scenarios. Consequently, the data download problem was modified from a classical full package download problem into a download completion problem [3, 4]. The large storage capabilities of modern user equipment enable these devices to benefit from the already downloaded messages and request only the missed ones. These advances in user equipment gave birth to a new scheduling and routing scheme called Network Coding (NC). The authors in [5, 6, 7] have introduced the idea of NC. The approach gained a considerable attention for its numerous benefits such as throughput enhancement and delay reduction [8], especially in wireless networks. Network coding can be classified into the Random Network Coding (RNC)[9, 10, 11, 12] and the Opportunistic Network Coding (ONC)[13, 14, 15]. RNC mixes messages using random and independent coefficients resulting in an optimality in reducing the number of transmissions and an ability to recover even without feedback. However, it is not suitable for real-time applications of interest in this work as decoding can be performed only after the reception of the whole frame. Consequently, a user should process all the messages of a certain message before decoding. On the other hand, ONC benefits from the diversity of received and lost messages to generate the mixes online which gives a lower decoding delay. Furthermore, ONC utilizes the knowledge of previously downloaded messages at each user to efficiently select the encoded message combinations that would ensure the decodability of encoded messages after each transmission for all users or a subset of them. A particular subclass of ONC, namely Instantly Decodable Network Coding (IDNC). In IDNC the transmitted coded message is decodable at the same instant. IDNC attracted many studies [16]-[23], [24] in the recent years for its instant decodability properties. IDNC is achieved by encoding packets using only XOR-based operations [25, 26, 27]. Such simple encoding scheme allows, not only fast encoding but also simple and progressive XOR decoding at the receivers. The aforementioned instant and fast encoding/decoding properties are essential for real-time applications [28, 27] for interest in this work becasue of its instant decoding. Furthermore, IDNC is well suited for order-insensitive application requiring messages regardless of reception order such as roadside safety messages. To minimize the time required to download other messages, these downloaded messages can be utilized as users side information. Moreover, message transmission from base stations in wireless networks suffer from channel impairments which lead to massage/file corruption. Message corruption introduces an additional downloading overhead in order to request for corrupted messages re-transmission. Previous works have showed that employing well-designed IDNC schemes can minimize either the completion time [23] or the decoding delay experienced by the users [24],[19]. Lately, a recent study [21] on the effect of controlling the decoding delay to minimize the completion time resulted in a multi-layer solution that improved the performance obtained in [24]. Most of the works mentioned above focused on an upper layer view of the network and abstracted the physical layer conditions, e.g., fading, shadowing, reflection, into simple erasure-channel models. Recently, the Rate-Aware

IDNC (RA-IDNC) problem was introduced in [29], which aimed to minimize the completion time of delivering data messages using IDNC to cellular users with heterogeneous physical-layer rates. However, the authors consider the simple setting of a single transmitting base-station (BS) that employs a single transmission rate in each transmission of a coded message. This work aims to extend the result to a more modern paradigm of coordinated multi-BS networks, in which the multiple BSs coordinate in order to serve a set of users with their requested data. In such setting, these users, not only experience heterogeneous channel conditions to each of the BSs but also undergo different channel conditions to each of the BSs due to their different locations within the service area. Thus, each user can be served by each BS with a rate that is different from all the other users/BSs. This schedule should define both the users that each BS should target with its IDNC messages and the rate that the BSs should use in sending them. Consequently, the different rates of the BSs to the various users must be integrated with the IDNC decisions, such that the IDNC messages sent by each BS (and thus their targeted users) and the transmission rate used in each of these transmissions are jointly selected to reduce the overall completion time. Our problem differs from this (classical) IDNC completion time minimization problem in that multiple transmitters (base stations) transmit at the same time with rate awareness. This introduces an additional scheduling challenge to avoid targeting the same user by more than one BS at the same time epoch. To the best of our knowledge, this work introduces a novel Multiple Base station Rate -Aware IDNC (MB-RA IDNC) algorithm suitable for wireless systems involving simultaneous transmissions from multiple transmitters. Given these dual-heterogenous user rates, and their various side-information, a very exciting yet challenging question is *how to identify the optimal schedules of IDNC packets and transmission rates that BSs should follow, so as to complete the delivery of all data messages to all users in the least amount of time*. To answer the aforementioned question, the completion time problem is first formulated and shown to be intractable. We thus relax the problem to an online optimization involving an anticipated version of the completion time. The expression of this anticipated completion time is derived and then used to formulate the online problem as a joint optimization over the set of BSs, achievable rates, and feasible packet combinations. We then prove that this problem can be solved by finding the maximum weight independent set in a newly designed graph without transmission error. An efficient multi-layer heuristic is further proposed to address the problem in polynomial time. Also, a message placement policy in the base stations is simulated and compared to the performance of classical IDNC and uncoded schemes when the messages are distributed at each base station.We extend the study of the completion time minimization problem of MB-RA IDNC by considering the transmission error (the messages maybe erased due to the channel impairments and called erasure probability in the rest of the thesis). Finally, the proposed solution is tested via extensive simulations against Classical IDNC and uncoded schemes. Simulation results suggest that the proposed solution outperforms both the classical IDNC and the uncoded schemes.

1.2 Thesis Contributions

To the best of our knowledge, this thesis introduces the first MB -RA IDNC multi layer algorithm suitable for C-RAN involving transmissions from multiple base stations. Our contributions in this work can be summarized into three points as follows:

- We design a novel "MB-RA IDNC suitable for message download from any wireless system with perfect channel system (error free transmission). The completion delay problem is first formulated and shown to be intractable. We thus relax the problem to an online optimization involving an anticipated version of the completion time. The expression of this anticipated completion time is derived and then used to formulate the online problem as a joint optimization over the set of BSs, achievable rates, and feasible packet combinations. We then prove that this problem can be solved by finding the maximum weight independent set in a newly designed graph. An efficient multi-layer heuristic is further proposed to address the problem in polynomial time. Finally, the proposed solution is tested via extensive simulations against two uncoded schemes. The simulation results show that the proposed MB-RA IDNC achieves a remarkable enhancement in the average download time required to deliver the missed messages, compared to the application of the classical IDNC" and uncoded schemes. This point is published in [38].

- The message placement policy in the base stations is investigated and compared to the performance of classical IDNC and uncoded schemes when the messages are available at each base station with zero repetition. The proposed scheme for perfect channel with message placement policy is shown to achieve highly significant reduction in completion delay as compared to the classical IDNC and uncoded schemes.

- We extend the system model to involve rate aware network coding in erasure channel called erasure probability. The completion problem formulation in error free transmissions is updated to a problem formulation reflecting the uncertainties resulting from unsuccessful reception events due to the channel impairments. This point is submitted to TVT journal and it is under revision.

1.3 Thesis Organization

The rest of the thesis is organized as follows. The background and literature review are explained in chapter 2. Chapter three introduces a novel MB-RA IDNC algorithm based on a graph model that guarantees no conflict- IDNC transmissions, the completion delay problem in Multi point-to-Multi point systems is formulated as an online approximation problem and for solution simplicity the chapter introduces a proposed heuristic algorithm to solve it. The completion delay problem in a C-RAN system with erasure probability is studied in chapter 4. Finally, chapter five concludes the work by highlighting the main contributions and conclusions acquired in this thesis. It also suggests some future works in the field of NC.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Cloud Radio-Access Networks

Radio Access networks (RAN) is a kind of mobile communication systems. It utilizes the radio access technique which is located between a Core Network (CN) and an other terminal such as a mobile, computer or terminal devices. RAN provides a wide-area wireless connection to a cellular users. The major problem that RAN faces is unplanned distributed coordination, which makes radio resource allocation very inefficient and makes the interference hard to manage. The solution for this problem lies in using centralized coordinator or central processer called Cloud RAN (C-RAN) [30]. The cloud storage system is considered as the easiest and the most interesting solution to reliably store and retrieve data where the data is stored over multiple servers with proper redundancy [31]. The continuously increasing demand for high data rates services breakthrough in network system. With the movement towards full spectrum reuse, cloud radio access networks become necessary in large scale interference management for next generation wireless system (5G) [32]. C-RAN can be formed as an architectural evolution based on the distributed base station architecture. Current technology of wireless communication and optical technology such as technology depends on C-RAN in distributing and scheduling the base stations to the users. Hence, cloud enabled networks have the potential of decreasing the interference between base stations using an efficient coordination between them. In other words, the base stations are connected to central processer (cloud) which is responsible for distributing and scheduling the users to base stations. Unlike the previous work where the scheduling is done with no inter-BS coordination, this work considers the coordination level at the central processer and allows base stations to schedule users efficiently.

2.2 Network Coding (NC)

Communication networks are a predominant component of the modern life. Everywhere around us, machines and people exchange information at different scales, speeds and throughput. The network is everywhere: from small number of connected devices such as Bluetooth networks, which are short-range wireless interconnection of computers, cellular phones and other electronic devices, passing by all voice communications that the local phone company offers and all the mobile communication technologies and standards to the wide expanse of connectedness rely on TCP/IP protocols, that literally make the communication networks out of thin air. Regarding the design of communication networks, one fundamental issue should be taken into account: how network traffic is delivered between network terminals. This crucial issue will identify the utilizing efficiency of the network resources. Modern Communication network topologies allow independent data streams to share the same network resources. The transmission nature of wireless networks requires simultaneous transmissions which typically result in some packets being lost, therefore the transmitter is required to re-transmit the missed packets. This paradigm has initiated a new area of research, namely *network coding*. Network coding (NC) is a new technique in communication networks, where the transmitter or the intermediate nodes are allowed to combine (code) the data and perform coding operations on the contents of the packets, normally without changing the packet size to maximize the information utility of each encoded packet. Network Coding attracts the attention of many researchers as a scheduling and routing scheme that can achieve remarkable enhancement in the information flow with different network transmission modes and topologies [5, 6, 33]. Network coding allows the transmitter or the intermediate nodes to perform algebraic operations inside the network. In network coding, the transmitted data does not depend only on a single packet but also on the contents of other packets that happen to be mixed together and share the same channel/route at the same time of transmission. For this reason, communication networks with network coding is more secure and more immune against hacking, eavesdropping and other forms of attack than networks with traditional data transmission. In the literature, two main network coding approaches have been considered, namely Full Network Coding (FNC) [11, 12] and Opportunistic Network Coding (ONC) [13, 15]. In the FNC approach, the wanted packets are coded all together with random or deterministic coefficients. Consequently, in FNC all the wanted packets are encoded and transmitted to the receivers, this leads to high computation complexity. On the other hand, the feedback-based or the ONC approach takes advantage of the receivers side information (the existing and the wanted packets) and then carefully select the suitable packets combination to insure the decodability of encoded packet in each encoded transmission for all the receivers or a subset of them.

2.2.1 Instantly Decodable Network Coding (IDNC)

NC has a great attraction to many studies as a scheduling and routing scheme that can maximize the information flow in a network [16]-[23]. Many studies explained its ability to achieve maximum information flow in several network transmission modes and topologies. The main core of network coding is the idea of packet combination at the sender or the intermediate network nodes in order to get the maximum information usefulness of each coded packet [18, 19]. A subclass of opportunistic network coding is the IDNC in which the received coded packet at any clients are allowed to be decoded only at their reception instant, and cannot be stored for future decoding. IDNC has attractive properties for a wide rang of applications, namely its faster decoding delay and no decoding buffer requirements [23]. Furthermore, IDNC is a type of the feedback-base or the ONC, in which the encoded IDNC packets are selected to be decodable at the same instant by a subset of the receivers (or hopefully all the receivers). IDNC has attractive characteristics for vast range of applications, these characteristics such as its shorter decoding delay and no decoding buffer requirements [34]. Moreover, the encoding and the decoding in the IDNC is done using bitwise binary XOR, which requires simple circuits in both the encoder and the decoder sides. One scheme to find the possible IDNC files combination is the IDNC graph as discussed in the next section.

2.2.2 IDNC Graph

In order to model the completion problem in a system that consists of a transmitter storing a set of files (base stations in our literature) and a set of receivers (users in our literature). The base station aims to deliver a subset of the packets (message or file throughout this work) missed by each user. We need to find an illustration of the possible message combinations, those are decodable at the same instant by all the users or any subset of them. In [34, 35, 36] a graph model was introduced to represent the possible IDNC message combinations called IDNC graph. The IDNC graph $\mathcal{G}$ is a graph that represents all the possible combinations of the messages that are instantly decodable for any subset or all the users. Furthermore, the IDNC graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$ is an undirected graph (An undirected graph is a graph in which edges have no orientation) that consists of a finite set of vertices $\mathcal{V}$ and adjacency edges $\mathcal{E}$, each vertex v_{uf} represents a wanted message f by a given user u and each edge that connects two vertices v_{uf} and $v_{u'f'}$ represents an opportunity to perform XORing between message f and message f'. The base station can build the IDNC graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$ each time it needs to select an IDNC message combination. The *State Feedback Matrix* $SFM(BS_i)$ defined as follows:

$$SFM(BS_i) = [l_{j,k}] = \begin{cases} 0, & \text{user } u_j \text{ already has file } f_k \\ \\ 1, & \text{user } u_j \text{ wants file } f_k \end{cases} \tag{2.1}$$

Then the base station will construct a graph $\mathcal{G}$ as a set of vertices, each vertex represents a wanted message and any two vertices $v_{u,f}$ and $v_{u',f'}$ will be set adjacent by an edge if one of the following conditions is true:

- C1: $f = f'$
- C2: $f \in H_{u'}$ and $f' \in H_u$

where H_u is the set of files that already received by user u. Condition (C1) implies that the base station can target two different users u and u' by a message f if the two vertices represent the same message, whereas condition (C2) implies that the base station can target two different users u and u' by the encoded message $f \oplus f'$ and each user will be able to extract its wanted message from it. So, This graph represents all the encoding opportunities. Once the graph is formulated, the base station will find the Maximum Clique $\mathbf{M}$ (a clique in a graph is a set of pairwise adjacent vertices) [37] and XOR all the messages represented by $\mathbf{M}$.

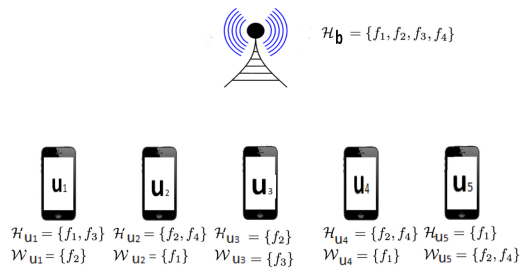

Figure 2.1: BS content and the users' requests and contents.

$$SFM(\mathbf{b}) = \begin{array}{c} \\ \\ \\ \\ \\ \end{array}\begin{array}{cccc} f_1 & f_2 & f_3 & f_4 \\ \end{array}$$

$$SFM(\mathbf{b}) = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}\begin{array}{l} \mathbf{u}_1 \\ \mathbf{u}_2 \\ \mathbf{u}_3 \\ \mathbf{u}_4 \\ \mathbf{u}_5 \end{array}$$

Figure 2.2: The corresponding SFM matrix.

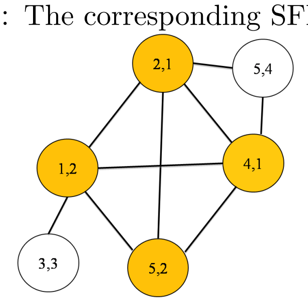

Figure 2.3: IDNC graph with maximum clique shown in darker colour

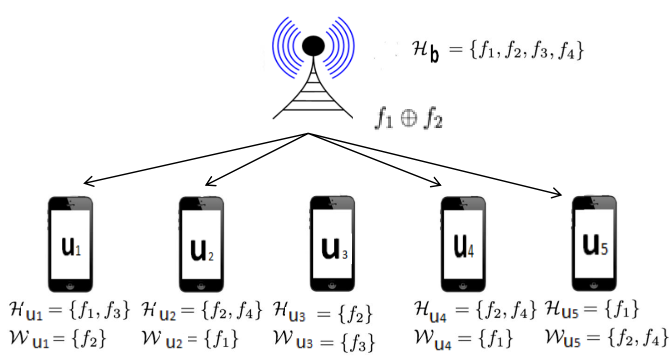

Figure 2.4: Message Combination corresponding to the maximum clique in the IDNC graph.

The above figures show a numerical example of the IDNC graph formulation. A BS stores $\{f_1, f_2, f_3, f_4\}$ and 5 users with the following requests and contents:

user u_1 already has $\{f_1, f_3\}$, and wants to download $\{f_2\}$.

user u_2 already has $\{f_2, f_4\}$, and wants to download $\{f_1\}$.

user u_3 already has $\{f_2\}$, and wants to download $\{f_3\}$.

user u_4 already has $\{f_2, f_4\}$, and wants to download $\{f_1\}$.

user u_5 already has $\{f_1\}$, and wants to download $\{f_2, f_4\}$.

Based on these contents and requests the BS builds the SFM matrix as shown in Fig. 2.2. The IDNC graph for the system at the state shown in Fig. 2.3. The vertices that represent the maximum clique are marked by darker colour. The selected vertices are induced by messages f_1, f_2. Hence, The IDNC combination $f_1 \oplus f_2$ will be sent by the base station to inform the users that this combination represents $f_1 \oplus f_2$. The corresponding download schedule is shown in Fig.2.4 and each user will decode the IDNC file as follows :

- Users u_1 and u_5 already have f_1, so they can XOR the combination $(f_1 \oplus f_2)$ with f_1 to retrieve f_2.

- Users u_2 and u_4 already have f_2, so they can XOR the combination $(f_1 \oplus f_2)$ with f_2 to retrieve f_1.

- User u_3 already has f_2 and the wanted message is f_3, so the combination $f_1 \oplus f_2$ will not serve this user because the wanted message f_3 is not in the combination.

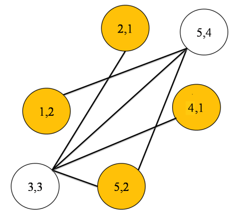

Figure 2.5: IDNC Conflict graph, dark colour represents vertices of the maximum independent set.

The download schedule of the IDNC requires 3 transmissions to deliver all the required messages.

2.2.3 IDNC Conflict Graph

The IDNC conflict graph is a graph that represents all the encoding conflicts. The IDNC conflict graph is the complement of the IDNC graph. The base station generates the IDNC conflict graph as a set of vertices. Each vertex represent a wanted messages and any two vertices $v_{u,f}$ and $v_{u',f'}$ will be set adjacent by a conflict edge if both of the following conditions apply:

- C1: $f \neq f'$
- C2: $f \notin H_{u'}$ OR $f' \notin H_u$

These conditions are the complement of the conditions in the previous subsection. The base station finds its maximum independent set (an independent set or stable set in a graph is a set of pairwise non-adjacent vertices) [37]. The maximum independent set of the IDNC conflict graph is equivalent to the maximum clique of the IDNC graph.

The maximum independent set (An independent set is a group of pairwise nonadjacent vertices [37].) of the IDNC conflict graph is represented by the same set of vertices which forms the maximum clique in the IDNC opportunities graph. Hence, the download patterns corresponding to the maximum independent set of the IDNC conflict graph and the maximum clique of the IDNC graph are identical. Fig. 2.5 shows the IDNC conflict graph for the system in Fig.2.2. The base station find its maximum clique and the combination message corresponding to the maximum clique in the IDNC graph is the same as the download pattern shown in Fig. 2.4.

2.3 Thesis Scope

2.3.1 Important Definition

In this subsection we collect the important definitions which will be used throughout the thesis.

Definition 1 (Instantly Decodable Transmission). *The transmission of a packet $\kappa_b(t)$ from the b-th BS at a rate $R_b(t)$ (which we denote by $(\kappa_b(t), R_b(t))$) is said to be instantly decodable for the u-th user if and only if $R_b(t) \leq R_b^u(t)$ and $\kappa_b(t)$ contains exactly one message from the Wants set of that user. Where R_b^u is the rate of user u when its associated to base station b.*

To make these definitions in this section easy to understand, let us explain this numerical example [43]. Figure 2.6 illustrates an example of an IDNC transmission

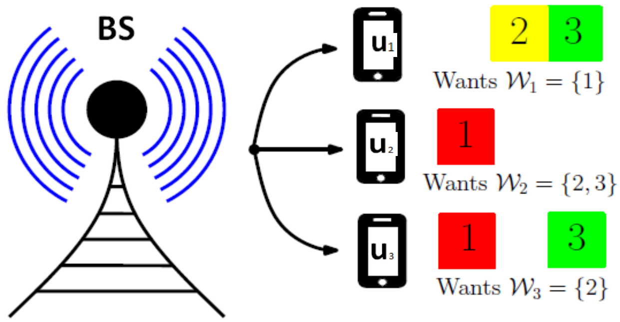

Figure 2.6: A network composed of 3 users and 3 messages and one base station.

in a network composed of 3 users and 3 messages and for simplicity we assume one base station and assuming that transmission rate is less than the capacities of all users. The message combination $2 \oplus 3$ is:

- Non-instantly decodable for user 1 as all the messages are in his Has set. The message does not bring new information.

- Non-instantly decodable for user 2 as it contains 2 messages from his Wants set. User 2 discards the message upon successful reception.

- Instantly decodable for user 3 as it contains only one message from $\mathcal{W}3$. Indeed, users 3 can XOR the combination $2 \oplus 3$ with message 3 to retrieve message 2.

Definition 2 (Individual Completion Time). *The individual completion time $\mathcal{C}_u$ of the u-th user is the absolute time required until this user gets all the messages in $\mathcal{F}$.*

Definition 3 (Overall Completion Time). *The overall completion time is the time required until all the users receive all the messages in $\mathcal{F}$ and its equal to the maximum individual completion time of any user i.e.,* $\mathcal{C} = \max_{u \in \mathcal{U}}\{C_u\}$.

Definition 4 (Transmission Schedule). *A transmission schedule* $\mathcal{S} = (\kappa_b(t), R_b(t))$, $\forall\ t \in \{1, 2, ..., |\mathcal{S}|\}$, and $\forall\ b \in \{1, 2, .., |\mathcal{B}|\}$ is the set of chosen packets and rates at every time index t until all users successfully receive all messages.

Definition 5 (Minimum Rate). *The minimum rate $R_{\min}(t)$ at the t-th transmission is the minimum rate among those used by the different BSs to transmit their chosen packets in this transmission, i.e.,* $R_{\min}(t) = \min_{b \in \mathcal{B}} R_b(t)$.

Definition 6 (Time Delay). *In the t-th transmission, a user with non-empty Wants set, experience $N/R_{\min}(t)$ seconds of time delay increase if the transmissions from all the BSs are not instantly decodable for that user. Further, the sum of all such time delays experienced by that user during the schedule $\mathcal{S}$ is called the accumulated time delay $\mathcal{T}_u(\mathcal{S})$.*

Assuming no erasure occurs at transmissions at a rate of 1 bit/sec that is less than the capacities of all users in the example illustrated in Figure 2.6 the schedule of messages $\mathcal{S} = \{2 \oplus 3, 1, 1 \oplus 3, 2\}$ yields the following:

- Individual completion time: user 1 received two transmissions, one is non-instantly decodable and the other is instantly decodable, i.e $\mathcal{C}_1 = 2N$, user 2 received four transmissions, so its completion time is $\mathcal{C}_2 = 4N$, and user 3 received just one instantly decodable so its completion time is $\mathcal{C}_3 = N$ seconds.

- Overall completion time is the maximum individual completion time of any user. In our example user 2 has the maximum individual completion time so $\mathcal{C} = \mathcal{C}_2 = 4N$ seconds.

- Time delay: user 1 experiences one time delay increases $\mathcal{T}_1 = N$, user 2 experiences two time delay increases, $\mathcal{T}_2 = 2N$, and user 3 does not experience any time delay increases becasue it receives one Instantly Decodable transmission, $\mathcal{T}_3 = 0$ seconds.

On the other hand, for a fixed rate $R = 1$, the optimal schedule $\mathcal{S}^* = \{1 \oplus 2, 3\}$ provides the least individual and overall completion time of $\mathcal{C} = 2N$ and zeros delay for all users. It can be easily seen that the message combination $1 \oplus 2$ provides a new packet for all users.

2.3.2 System Model and Parameters Definition

Network and Data Model

In our system model shown in Fig. 2.7, we consider the downlink of a radio access network with a set $\mathcal{B}$ of B coordinating BSs. These BSs are required to transmit the entire set $\mathcal{F}$ of F messages to the whole set $\mathcal{U}$ of U users. All messages in $\mathcal{F}$

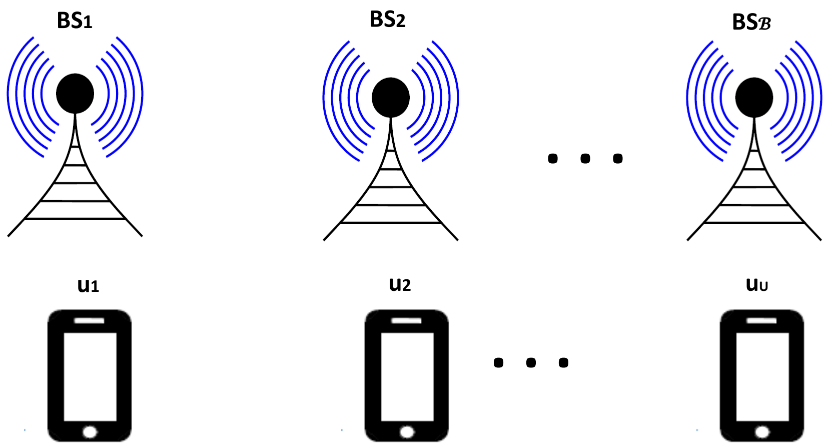

Figure 2.7: The System Model

have the same size of N bits and may represent any data such as files, executable instructions, frames from a video stream, ..., etc. The time is indexed by $t \in \mathbb{N}^+$. This work assumes that users do not initially have any side information. In other words, at $t = 0$, the users do not possess any single message $\mathcal{F}$, and thus these messages are solely available at the BSs. When the transfer process starts, the users start accumulating knowledge of different subsets of $\mathcal{F}$. Consequently, the messages can be classified into one of the following options for each user for any $t > 0$:

- The *Has* set $\mathcal{H}_u$ containing the messages successfully received by the u-th user.
- The *Wants* set $\mathcal{W}_u = \mathcal{F} \backslash \mathcal{H}_u$ containing the messages missing at the u-th user.

The base station builds its own State Feedback Matrix $SFM(BS_i)$, defined as in (2.1). At each transmission, the BSs can either send uncoded messages (especially at the start of the transfer phase) or exploit the diversity of the Has and Wants sets of the different users to transmit an IDNC combination of these messages using binary XOR. Note that an uncoded message is simply a special case of an IDNC combination, having only one message XORed with no other messages. Thus, we will use the term "packet" to describe either and use the same notation $\kappa_b(t)$ to denote either when sent by BS b at time t.

It is important to note that we assume in this work that all packets are non-fragmentable (i.e. are not dividable into smaller units) when being transmitted. Thus, a BS that starts sending a packet must complete its transmission, and in no instance is it allowed for multiple BSs to send different parts of the same packet.

In the rest of the thesis, the term "t-th transmission" represents the starting time of t-th transfer of a packet from any BS. The term "transmission" denotes both the process and the duration time of transmitting any message by any BS. Further, we will always use the notation $|\mathcal{X}|$ to represent the cardinality of the set $\mathcal{X}$.

Physical Layer Model

Let $h_b^u(t)$ be the complex channel gain from the b-th BS to the u-th user at the t-th transmission. The work assumes that the complex channel gain $h_b^u(t)$, $\forall\ u \in \mathcal{U}$, and $\forall\ b \in \mathcal{B}$ remains fixed during the transmission time of a single message or a single IDNC packet. Let P_b be the transmitted power of the b-th BS, assumed to be fixed during the entire transfer process. The achievable rate or capacity of the

u-th user during the t-th transmission can be expressed as:

$$R_b^u(t) = \log_2(1 + \text{SINR}_b^u), \tag{2.2}$$

where SINR_b^u is the corresponding signal-to-interference plus noise-ratio experienced by the u-th user when it is associated with the b-th BS. The SINR can be expressed by the following formula:

$$\text{SINR}_b^u = \frac{P_b|h_b^u\,|^2}{\sigma^2 + \sum\limits_{b' \neq b} P_{b'}|\ h_{b'}^u\ |^2}, \tag{2.3}$$

where σ^2 represents the complex gaussian noise variance. During the t-th transmission the achievable capacities of all users for the b-th BS can be represented by the set $\mathcal{R}^b(t) = \{R_b^1(t), ..., R_b^{|\mathcal{U}|}(t)\}$.

The time required to deliver a packet of size N in the t-th transmission using a transmission rate $R(t)$ is $N/R(t)$, called the absolute time.

For a reception of a packet transmitted by the b-th BS to be successful at the u-th user, the transmission rate $R(t)$ must be smaller than or equal to the user capacity, i.e., $R(t) \leqslant R_b^u(t)$.

2.3.3 Problem Statement

In this section we will discuss the main motivations that lead to this work and how they are important to the field of research in network coding area. As can be noticed from the literature, all the previous studies have considered IDNC network coding scheme to minimize the completion delay in wireless networks without rate adaptation. In our study, we are only interested in IDNC network coding with rate adaptation due to its very attractive features and becasue it has a good performance as explained in the next chapters. Our focus in this study is on how to reduce the completion time of the users in radio access networks using MB-RA IDNC graph. Since, our system model consists of multiple base stations, the encoding conflicts is a major resources waste. Same user may receive two different messages from two different base stations that represent unpleasant redundancy. Hence, Our target is to formulate our MB- RA IDNC selection such that the scheduling process leads to the reduction of the completion time with less complexity. So, the optimum schedule to reduce the completion time of users is comes from the best selection of message combination and transmission rates as we will see in the next chapter.

CHAPTER 3

PERFECT CHANNEL SCENARIO

3.1 Motivation

This chapter introduces a systematic approach that enables the transmitted BS to select MB-RA IDNC message combination in a multi point-to-multi point systems. A heuristic multi layer algorithm is designed to solve the completion delay problem based on maximum independent set search scheme. The proposed algorithm can be implemented in centralized forms. For example, assume we have a central processor, 2 base stations, 2 users and 2 messages as shown in figure 3.1. Moreover, assuming error-free transmissions at a rate of 1 bit/sec that is less than the capacities of all users in the example illustrated in Figure 3.1, the schedule of message $\mathcal{S} = \{1, 2\}$ concludes the following:

- Individual completion time: $\mathcal{C}_1 = N$, $\mathcal{C}_2 = 2N$ seconds.

- Overall completion time: $\mathcal{C} = 2N$ seconds. In other words, the overall completion time is the maximum individual completion time which is the completion time of user 2.

- Time delay: $\mathcal{T}_1 = 0$, $\mathcal{T}_2 = N$ seconds. User 2 experience N seconds time delay because the first schedule $\mathcal{S} = \{1\}$ is non-instantly decodable for that user becasue the first message is already in $\mathcal{H}_2$.

On the other hand, for a transfer rate $R = 1$, the schedule $\mathcal{S} = \{1 \oplus 2\}$ provides the least individual and overall completion time of $\mathcal{C} = N$ and zero delay for all users. However, due to the rate asymmetry between users, it may not be optimal with the above rate as shown in Figure 3.2. Therefore, the schedule $\mathcal{S}$ must be selected efficiently to achieve the optimum of the completion delay problem. This can be achieved by a heuristic multi layer algorithm with a significant reduction in the average completion time compared to using the classical IDNC and uncoded approaches. Also in this chapter we study the message placement policy in base stations and compare it to the performance of classical IDNC and uncoded schemes when the messages are available and distributed between base stations without repetition.

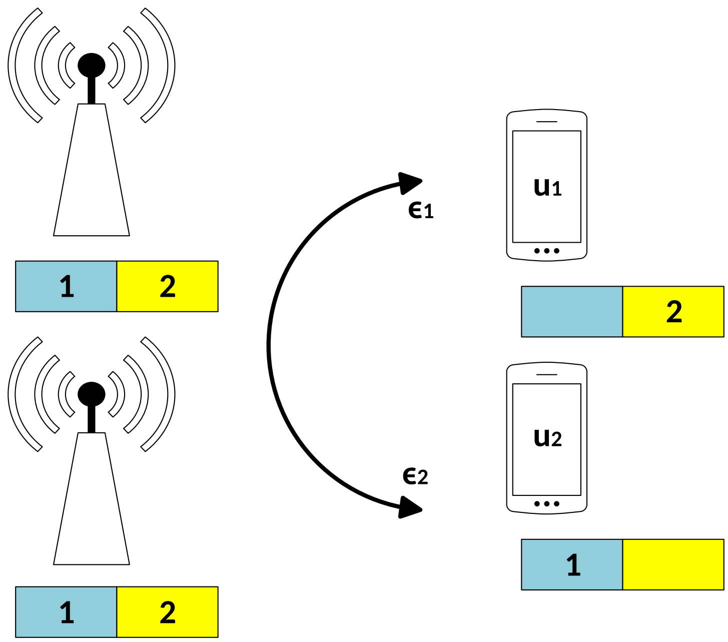

Figure 3.1: Shows A network composed of 2 users and 2 messages and 2 base stations.

3.2 Problem Formulation

3.2.1 Problem Description

In this subsection, we follow a similar approach to that used in [29] to formulate the minimum overall completion time problem for rate-aware IDNC in coordinated multi-BSs networks. The following theorem introduces this formulation by deriving an expression for the optimal schedule $\mathcal{S}^*$ to reduce the overall completion time.

Theorem 1. *The minimum overall completion time problem in multiple base stations rate-aware IDNC with perfect channel reduces to finding the opti-*

mal schedule $\mathcal{S}^*$, such that:

$$\mathcal{S}^* = \arg\min_{S \in \mathbb{S}} \{\max_{u \in \mathcal{U}} \{\frac{N|\mathcal{F}|}{\tilde{R}_{u\min}(\mathcal{S})} + \mathcal{T}_u(S)\}\}, \tag{3.1}$$

where $\mathcal{T}_u(S)$ is the accumulated time delay for the u-th user in $\mathcal{S}$. and $\tilde{R}_{u\min}(\mathcal{S})$ *is the harmonic mean of the minimum transmission rates during the transmissions that are instantly decodable for u-th user in $\mathcal{S}$. In other words, $\tilde{R}_{u\min}(\mathcal{S})$ is the harmonic mean of $\{R_{\min}(t)\}_{t \in \alpha_u(s)}$ where $\alpha_u(\mathcal{S})$ is the set of transmission indices that is instantly decodable for user u.*

Proof: Appendix A shows the proof of theorem 1. As a sketch of the proof, we first show that, for any schedule $\mathcal{S}$, the cardinality of $\alpha_u(\mathcal{S})$ is $|\mathcal{F}|$. Then we show that the sum of all time delay increases experienced by user u during the schedule $\mathcal{S}$ until its individual completion time is $\mathcal{T}_u(\mathcal{S})$. Finally, we conclude the proof by substituting $\{R_{\min}(t)\}_{t \in \alpha_u(s)}$ with its harmonic mean $\tilde{R}_{u\min}(\mathcal{S})$.

From the above theorem, it is clear that finding the optimal schedule $\mathcal{S}^*$ is very difficult, due to the channel realization nature and the dependence of the optimal schedule on them. This makes the problem in (3.1) intractable and anti-causal (i.e., current results depend on future input). Given the complexity of finding the optimal schedule, the next section first presents an approximation of the completion times, called the "anticipated completion times", and then reformulates a relaxed online version of the problem using this approximation.

3.2.2 Anticipated Completion Time Formulation

The anticipated completion time $\mathcal{C}_u(t)$ of the u-th user is the completion time of that user if it does not experience any additional increases in its accumulated time delay (i.e. if the u-th user does not receive any non-instantly decodable transmission after the t-th transmission). Clearly, if this condition indeed occurs, then this anticipated completion time will be the actual exact completion time of that user. Given this definition, $\mathcal{C}_u(t)$ can be approximated by:

$$\mathcal{C}_u(t) = \frac{N|\mathcal{F}|}{\tilde{R}_{u\,\min}(t)} + \mathcal{T}_u(t) \tag{3.2}$$

where $\tilde{R}_{u\text{min}}(t)$ is the harmonic mean of the minimum transmission rates for the transmissions at times $t' \leqslant t$ that are instantly decodable for the u-th user, and $\mathcal{T}_u(t)$ is the accumulated time delay by that user until t-th transmission.

3.2.3 Relaxed Problem Formulation

Based on the definition of the anticipated completion time in the above subsection, we relax the optimization problem in (3.1) to a more tractable version. Assume that u^* is the user with the highest anticipated completion time compared to the other users after transmission $t-1$, i.e., $u^* = \arg\max_{u \in U}\{\mathcal{C}_u(t-1)\}$.

let $\mathcal{K}_{R(t)}$ be the set of users that can increase the maximum anticipated overall completion time after the t-th transmission, which could be defined as follows:

$$\mathcal{K}_{R(t)} = \left\{ u \in \mathcal{U} \;\middle|\; \mathcal{C}_u(t-1) + \frac{N}{R_{\text{min}}(t)} \geqslant \mathcal{C}_{u^*}(t-1) \right\}. \tag{3.3}$$

It is clear from (3.3) that, if the t-th transmission is non-instantly decodable for that set of users in $\mathcal{K}_{R(t)}$, they will experience time delay increases of $\frac{N}{R_{\min}(t)}$, which will make their anticipated completion times after the t-th transmission surpass $C_{u^*}(t-1)$. We can thus relax the completion time minimization problem to an online version, by reducing the chance of occurrence of this event, i.e. increasing the maximum overall anticipated completion time after each transmission compared to its value before it. Defining $\tau_b\left(\kappa_b(t)\right)$ as the set of targeted users by the transmitted packet $\kappa_b(t)$ from the b-th BS at time t, i.e. the set of receives for which the transmission by the b-th BS with rate $R_b(t)$ is instantly decodable, we can formulate this relaxed problem as introduced in the following theorem.

Theorem 2. *The completion time reduction problem in (3.1) can be relaxed to an online version, in which, at any transmission t, the following joint optimization problem over the packet $\kappa_b(t)$, transmission rates $R_b(t)$ of BSs, $\forall\ i \in \mathcal{B}$:*

$$(\kappa^*(t), R^*(t)) = \arg \max_{\substack{\kappa(t)\in\mathcal{P}(\mathcal{F}) \\ R(t)\in\mathcal{R}(t)}} \sum_{b\in\mathcal{B}} \sum_{u\in(\mathcal{K}_{R(t)}\cap\tau_b(\kappa_b(t)))} \log(R_{\min}(t)/N), \tag{3.4}$$

where $\mathcal{P}(\mathcal{F})$ is the power set of the set $\mathcal{X}$.

Proof: The proof can be found in Appendix B. As a sketch of the proof, we first show the expression of anticipated completion time of the user u for the instantly and non-instantly decodable transmissions. The probability of the event that the maximum anticipated completion time increases by the product of all time delays is approximated. Finally, we conclude that the completion time reduction problem is approximated by joint optimization over the packet $\kappa_b(t)$, transmission rates $R_b(t)$ of BSs, $\forall\, b \in \mathcal{B}$.

3.3 Proposed Solution

This section proposes solving the anticipated completion time problem proposed in (3.4). The solution relies on the construction of the multi-BS rate-aware IDNC (MB-RA-IDNC) graph. Afterward, the completion time reduction problem is shown to be equivalent to finding the maximum weight independent set in the MB-RA-IDNC graph. Finally, the solution being potentially not unique, an efficient multi-layer packet selection heuristic is proposed.

3.3.1 Multi-BS Rate-Aware IDNC Graph

In [29], the RA-IDNC graph was introduced for the single BS scenario as a tool to represent all possible message combinations, transmission rate, and users that can instantly decode the transmission. For their considered single BS situation, they show that the completion time reduction problem is equivalent to finding the maximum weight clique in the RA-IDNC graph.

This subsection extends the formulation of the RA-IDNC graph to include the general scenario of multiple BSs of interest in this work.

Let the MB-RA-IDNC graph be denoted by $\mathcal{G}(\mathcal{V}, \mathcal{E})$ wherein $\mathcal{V}$ and $\mathcal{E}$ refer to the set of vertices and edges, respectively. In order to represent the potential IDNC message combinations, the transmission rate of each base-station in the network and the intended user, a vertex $v_{b,u,f,r}$ is generated for each BS $b \in \mathcal{B}$, for each user $u \in \mathcal{U}$, for each wanted message $f \in \mathcal{W}_u$ and for each achievable rate for that user $r \in \mathcal{R}_u = \{R \in \mathcal{R} \mid R \leq R_b^u\}$.

The construction of the set of edges $\mathcal{E}$ relies on the fact that two vertices v and v' are adjacent if and only if the transmission represented by both vertices is non-instantly decodable to one of them. In other words, adjacent vertices represent a violation of one of the IDNC conditions. In particular, the set of edges can be decomposed into coding-conflict and transmission-conflict edges wherein the coding-conflict are related to vertices represented by the same base-station whereas the transmission-conflict are those representing different base-stations.

Two vertices $v_{b,u,f,r}$ and $v_{b',u',f',r'}$ representing the same base-station b are linked with a coding-conflict edge if the resulting combination violates the instant decodability constraint. Such event occurs if one of the following holds:

- The transmission rate is different, i.e., $r \neq r'$.
- The combination is not-instant decodable, i.e., $f \neq f'$ with $f \notin \mathcal{H}_{u'}$ or $f' \notin \mathcal{H}_u$.

Similarly, two vertices $v_{b,u,f,r}$ and $v_{b,u',f',r'}$ representing different base-stations $b \neq b'$ are conflicting if and only if:

- The transmission rate is different, i.e., $r \neq r'$.
- The same user is targeted, i.e., $u = u'$.

Without loss of generality, the condition can be extended to all vertices (even

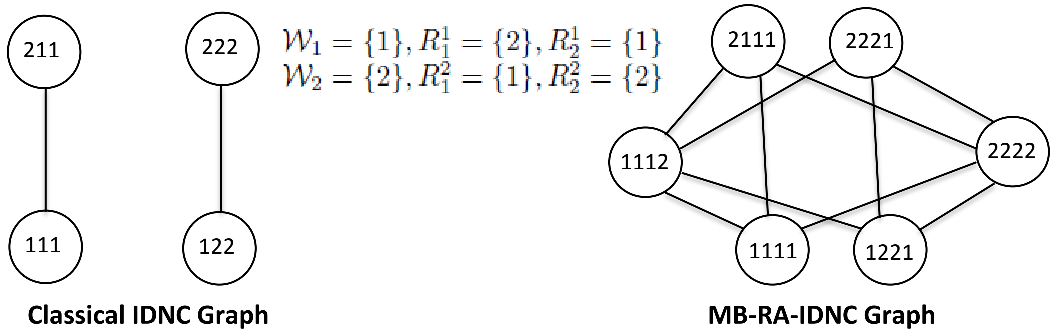

Figure 3.2: Comparison between the classical IDNC graph and the MB-RA-IDNC graph.

those belonging to different BSs). Therefore, two vertices $v_{b,u,f,r}$ and $v_{b',u',f',r'}$ are adjacent by an edge if they satisfy the following connectivity conditions:

- CC1: $r \neq r'$.
- CC2: $b = b'$ AND $f \neq f'$ with $f \notin \mathcal{H}_{u'}$ OR $f' \notin \mathcal{H}_u$.
- CC3: $b \neq b'$ and $u = u'$.

An example of the MB-RA-IDNC graph is depicted in Fig. 3.2 for a simple network consisting of 2 users, 2 messages and 2 BSs. It can be shown that all feasible combinations of packets and transmission rates of the different BS can be represented by the maximal independent set in the MB-RA-IDNC graph, wherein an independent set in a graph is a set of pairwise nonadjacent vertices [37]. In a weighted graph, the maximum weight independent set problem is the one of finding the independent set with the maximum weight, where the weight of a set is defined as the sum of the individual weights of its vertices. An example of the MB-RA-IDNC graph is depicted in Fig. 3.2 for a simple network consisting of 2 users, 2 messages and 2 BSs. Therefore, from definition 1, the transmission represented by each clique in the MB-RA-IDNC graph is instantly decodable for all the users designated by the cliques vertices. In Figure 3.2. the maximal independent sets of classical IDNC graph are: {211, 222}, {211, 122} ,{222, 111} and {111, 122}. Each one of these sets serves two users and provide 2 bits/s. The maximal independent sets of MB-RA IDNC graph are: {1111, 1221}, {1111, 2221}, {2111, 1221}, {2111, 2221} and {1112, 2222}. Each one of the first four maximal independent sets serves two users and provides 2 bits/s. The last one {1112, 2222} is selected because it serves 2 users and provides 4 bits/s so its the best clique. Hence, {1112, 2222} is called the maximum weight independent set. The following theorem characterizes the optimal solution to. The following theorem relates the optimal solution to the relaxed completion time reduction problem in (3.4) to the independent sets in the MB-RA-IDNC graph.

Theorem 3. *The optimal solution to the anticipated completion time reduction problem (3.4) is the maximum weight independent set in the MB-RA-IDNC graph in which the weight* $w(v_{b,u,f,r})$ *of each vertex* $v_{b,u,f,r}$ *can be expressed as:*

$$w(v_{b,u,f,r}) = \begin{cases} log(\frac{r}{N}) & \text{if } u \in \mathcal{K}_r \\ 0 & \text{otherwise.} \end{cases} \tag{3.5}$$

3.3.2 Multi-Layer Solution

As explained in the previous subsection, finding the maximum independent set among all maximal independent sets in MB-RA-IDNC graph is the optimal solution to the optimizing problem (3.4). However, the maximum independent set or the optimal solution of (3.4) is not unique. This is mainly due to the vertices that have a zero weight. It is clear that their inclusion/exclusion produces the same objective function and thus the maximum may not be unique. Hence in this subsection, we provide an efficient method, similar to the one proposed in [29], for selecting one of the points that achieve the optimum of (3.4). Such point is chosen by focusing on message combinations serving users that are the most likely to be decisive users in the next transmissions. First, define the set of " k-th critical users $\mathcal{K}_R^k$ as the set of users that can potentially increase the anticipated overall completion time if and only if they experience $k \geqslant 1$ consecutive time delay increases. In other words, users in $\mathcal{K}_R^k$ increase the anticipated completion time if they receive k subsequent non-instantly decodable transmissions at a rate R, starting from t-th" transmission. This set can be defined mathematically as follows:

$$\mathcal{K}_R^k = \left\{ u \notin \ \mathcal{K}_R^{k-1} \middle| C_u(t-1) + \frac{kN}{R} \geqslant C_{u^*}(t-1) \right\} . \tag{3.6}$$

Let $\mathcal{G}^k$" be the MB-RA-IDNC graph containing only vertices belonging to the users in layer k with rate R, i.e $\mathcal{K}_R^k$. From the definition of critical sets $\mathcal{K}_R^k$, vertices belonging to $\mathcal{G}^i$ have higher chance to increase the anticipated overall completion time than vertices in $\mathcal{G}^j$, $j > i$. In other words, the vertices belong to users in the first layer have higher chance to increase the anticipated completion time than those belong to the second layer. Hence, the idea is to divide the graph into layers $\mathcal{G}^k$ with decreasing order of criticality. The algorithm first finds the maximum independent set among all the maximal independent sets in layer $\mathcal{G}^1$ as mandated in Theorem 2. Let $\mathbf{M}^1$ be the maximum independent set among all maximal independent sets in $\mathcal{G}^1$. Hence, the selected independent set $\mathbf{M}$ is initialized to $\mathbf{M} = \mathbf{M}^1$. We then construct $\mathcal{G}^2(\mathbf{M})$ using vertices in $\mathcal{K}_R^2$ that are adjacent to all the vertices in $\mathbf{M}$ (i.e., forms a bigger maximum independent set with $\mathbf{M}$), where R is the rates of users chosen in $\mathbf{M}$. After two transmissions, such vertices can potentially become critical users with weight equal to $\log(\frac{R}{N})$. Therefore, the weight of all the vertices in $\mathcal{G}^2(\mathbf{M})$ is $\log(\frac{R}{N})$. The maximum independent set $\mathbf{M^2}$ in $\mathcal{G}^2(\mathbf{M})$ is found and merged with $\mathbf{M}$ to form the updated independent set $\mathbf{M} = \mathbf{M}^1 \cup \mathbf{M}^{2}$". The process is repeated for all layers in the graph. We use the same heuristic algorithm proposed by the authors in [29] but with the difference that it is applied for multiple BSs with different rates.

In [39], it is shown that the maximum weight independent set problem is NP-hard and hard to approximate. In [40] and [41], methods were proposed for solving the problem more efficiently than the $\mathcal{O}(|\mathcal{V}|^2.2^{|\mathcal{V}|})$ naive exhaustive search methods. In [42], an approximate solution with satisfactory results was suggested.

3.4 Simulation Results

In all simulations in this chapter, all base stations have the same information. In other words, all messages $\mathcal{F}$ are stored in the base stations and no user has any of these messages. The BSs are placed in a hexagonal cell in which users are distributed randomly. To study the performance of the proposed solution in various scenarios, we change the number of users, messages, and the message sizes in the simulation. We assume that the total number of base stations is fixed to 3 in all simulations.

Table 4.1 summarized our simulation parameters. In this section, we compare, through extensive simulation, the performance of our proposed cross-layer algorithm for multiple base stations network in the downlink of radio access network to the following schemes:

- The classical IDNC: In this scheme, the message combination is chosen according to the strategy proposed in [21]. The transmission rate is the minimum rate/achievable capacity of the users included in the maximum independent set. Hence, the transmission is instantly decodable for all users in the maximum independent set.

- The uncoded: In this scheme, base-stations broadcast the packets sequentially. Users are assigned to base-stations according to their maximal achievable capacity. Each base-station broadcasts the packets using the minimum rate of its assigned users. Such scheme requires F transmissions that necessitate F time slots.

Fig. 3.3 plots the average completion time versus the number of users U for a network composed of $F = 20$ messages with a message size $N = 1$ Mb. We note from Fig. 3.3 that our proposed rate aware IDNC scheme outperforms both the classical IDNC and uncoded schemes for all simulated number of users. This is mainly due to the rate awareness in the message selection process. Whereas

Table 3.1: SIMULATION PARAMETERS

Cellular Layout	Hexagonal
Cell Diameter	500 meters
Channel Model	SUI-Terrain type B
Channel Estimation	Perfect
High Power	-42.60 dBm/Hz
Background Noise Power	-168.60 dBm/Hz
Bandwidth	10 MHz

classical IDNC only considers the minimum achievable rate , the broadcast scheme sacrifices the rate optimality by selecting the maximum number of users. The proposed scheme strikes a balance between these two aspects by jointly selecting the number of targeted users and the transmission rate such that the overall completion time is minimized. As the number of users increases the gap between our proposed and the classical schemes increases. This can be explained by the fact that as the number of users increases, the classical IDNC scheme targets more and more users at the expense of a lower transmission rate that explains the degradation in performance as the number of users increases. The proposed scheme, however, balances this effect for all number of users. The same thinking applies to the broadcast scheme.

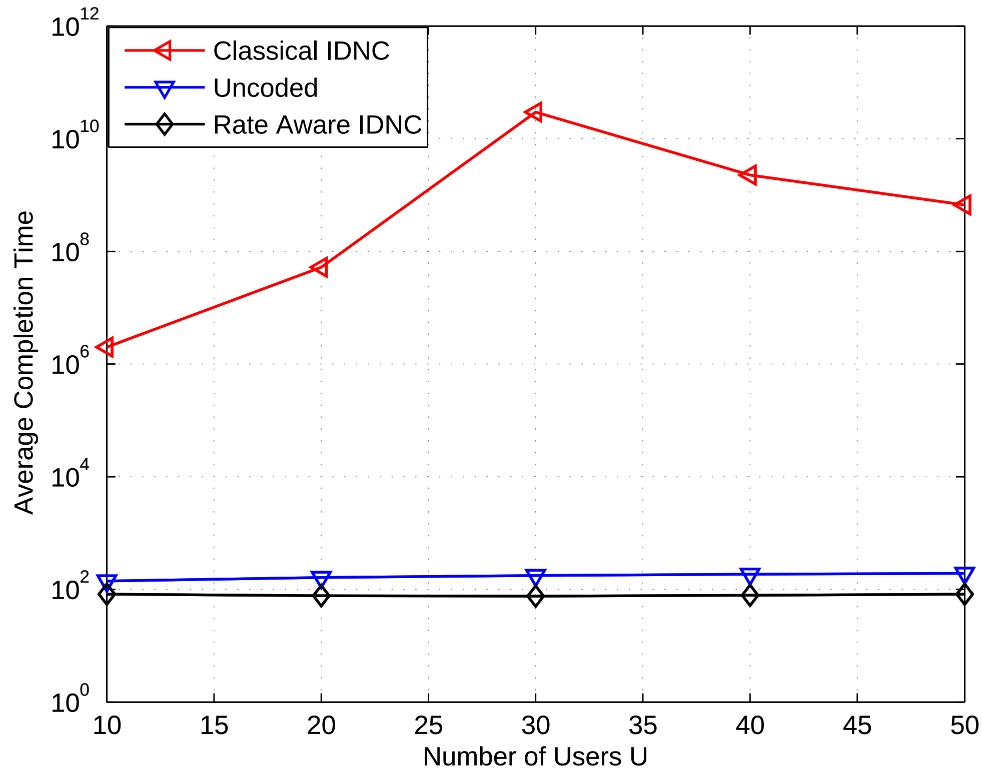

Figure 3.3: Completion time in sec. vs the number of users U.

Fig. 3.4 illustrates the performance of the different schemes against the number of messages F for a network composed of $U = 20$ users and a message size $N = 1$ Mb. The figure shows that our proposed MB-RA-IDNC outperforms the schemes without rate adaptation. The classical IDNC scheme in both figures has the highest completion time, and this is because of the nature of this scheme. In each transmission, different users are targeted, and the number of total transmission in this scheme before completion is different but the transfer rate is the minimum rate as compared to F transmissions for uncoded scheme with maximum achievable capacity of each user to the assigned BS.

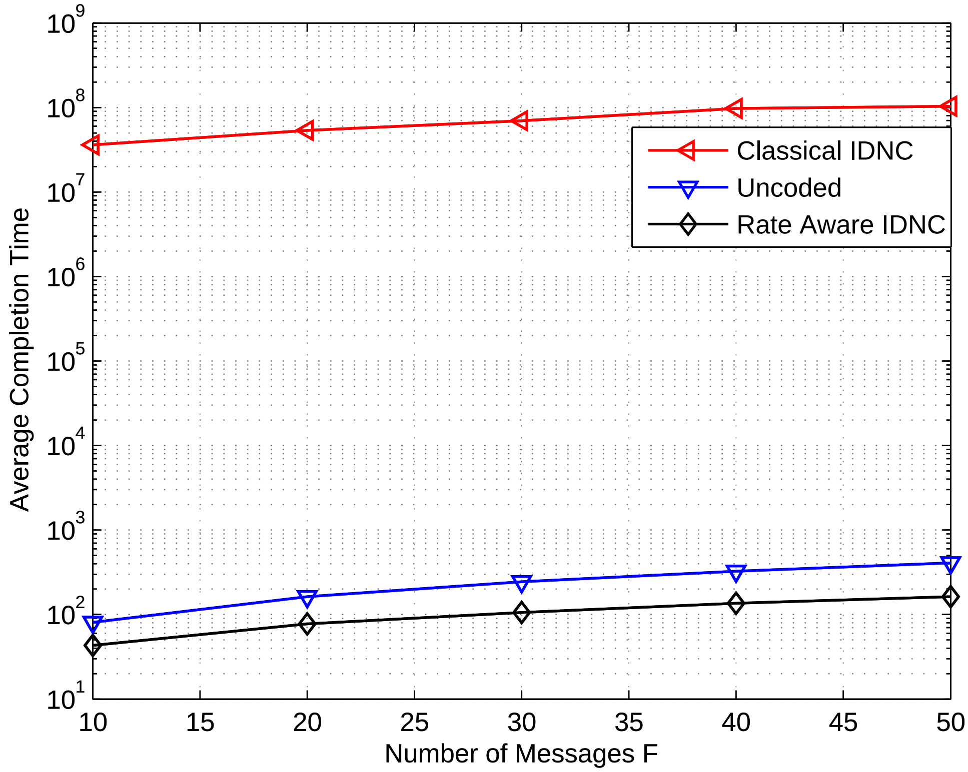

Figure 3.4: Completion time in sec. vs the number of messages F.

Fig. 3.5 illustrates the completion time versus the message's size N in bits for a network composed of $U = 20$ users and $F = 30$ messages. From Fig. 3.5, we note that all schemes increase linearly with the size of the message. This can be explained by the expression of the completion time. In fact, as hinted by the anticpated completion time equation, the completion time is the sum of two linear functions in the message size. Therefore, the whole function is linear in such parameter independently of the adopted transmission scheme.

Also to study the performance of the proposed solution in perfect channel system with message placement policy, we change the number of users, messages, and the message sizes in the simulation. It is can be inferred from figures 3.6, 3.7

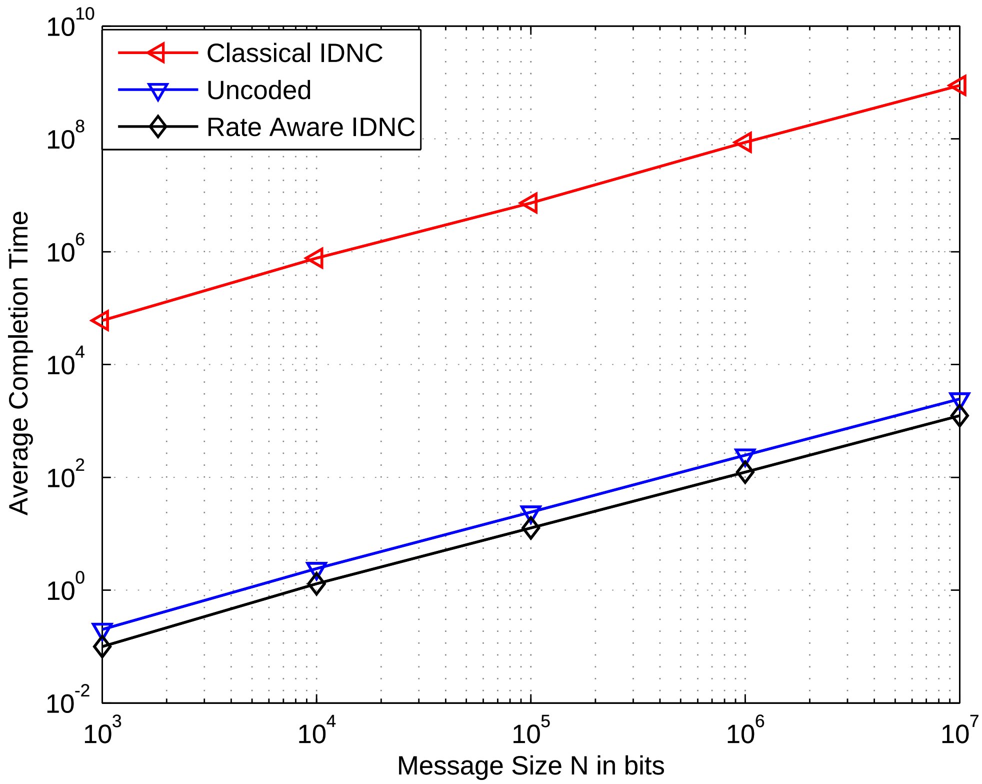

Figure 3.5: Completion time in sec. vs the message's size N in bits.

and 3.8 that the proposed work shows highly significant performance comparing to classical IDNC and uncoded scheme. The uncoded scheme affected from this policy due to that there are no more opportunities for users to have their messages with maximum capacity from base stations.

3.5 Summary and Conclusions

In this section we introduced a novel graph model that represents in one paradigm both the transmission conflicts and the coding conflicts in the global system called the MB-RA IDNC graph. We can generate MB-RA IDNC coded transmission

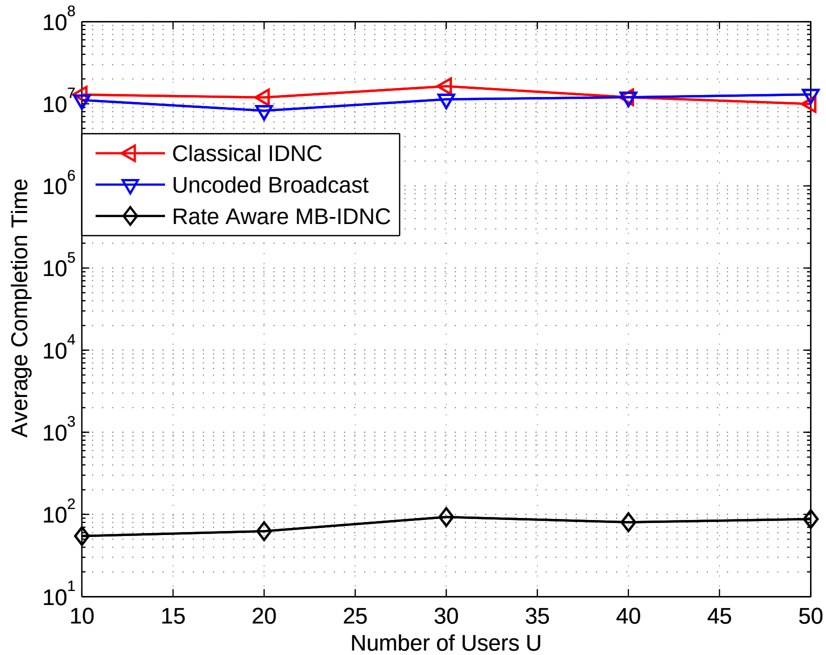

Figure 3.6: Completion time in sec. vs the number of users U.

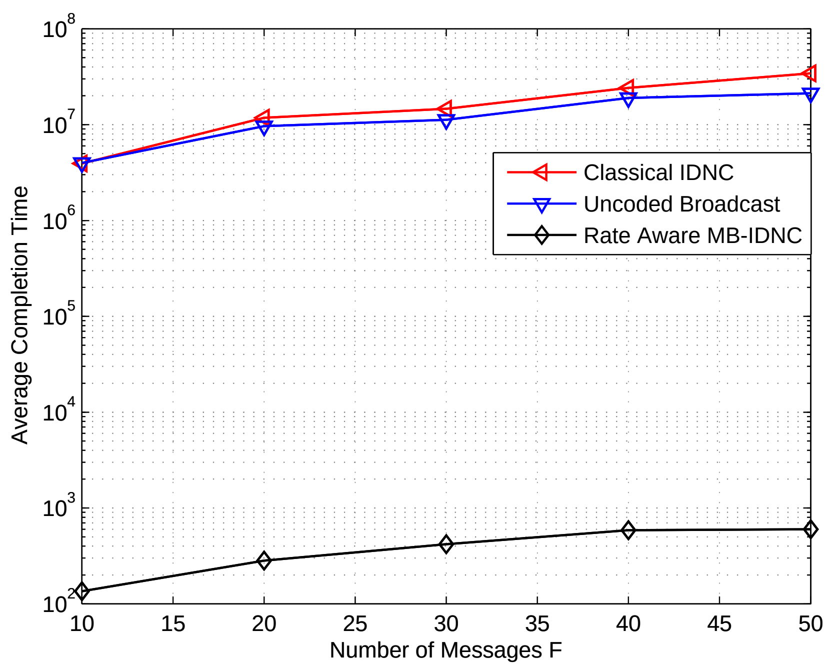

Figure 3.7: Completion time in sec. vs the number of messages F.

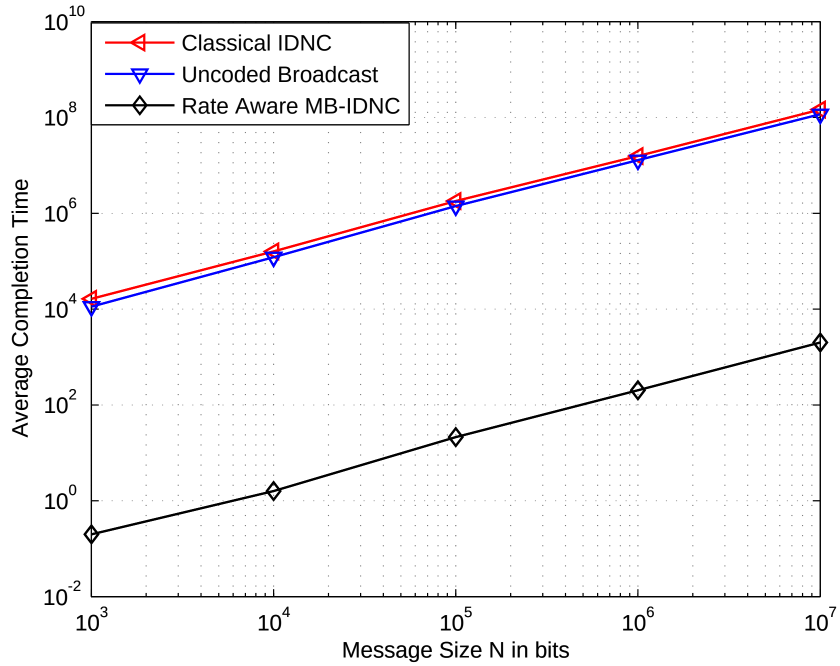

Figure 3.8: Completion time in sec. vs the message's size N in bits.

scheduling that can provide more efficient scheduling scheme to serve the users, these transmissions are generated by finding maximum independent sets in this proposed graph model. To find the maximum independent set in this graph we proposed a heuristic MB-RA IDNC multi layer algorithm and solve the download time minimization problem after showing that its optimal solution is intractable. Simulation results illustrated that our proposed MB-RA IDNC algorithm outperforms the classical IDNC and uncoded schemes in reducing the overall download time. Moreover, the message placement policy of the proposed work shows highly significant performance comparing to classical IDNC and uncoded scheme. When the messages are stored in all BSs, the user assign to the BS based on its maximum achievable capacity. On the other hand, when the messages are stored in BSs without repetition, the user assign to the BS based on where its message stored. The next chapter introduces the same MB-RA IDNC algorithm as in section 3.3 but with erasure channel. We will investigate the lossy environment and its effect on the MB-RA IDNC multi layer algorithm. We will investigate the centralized scenario and study the different transmission schemes.

CHAPTER 4

IMPERFECT CHANNEL SCENARIO

4.1 Motivation

In this chapter we introduce, based on the analysis of MB-RA IDNC graph in chapter 3 and based on the analysis in [43], the MB-RA IDNC network coding with consideration of channel impairments. In other words, we formulates the minimum overall completion time problem for rate-aware IDNC in coordinated multi-BSs networks with forward channel erasures.. Therefore, the performance of the MB-RA IDNC algorithm with erasure probability is compared with the classical IDNC and uncoded schemes. The reminder of this chapter is organized as follows: Section 4.2 formulates the completion problem in multi rate aware IDNC with erasure channel. In Section 4.3 the proposed work of MB-RA IDNC graph is derived. Section 4.5 illustrates the simulation results which show that the performance of our proposed work outperforms the classical IDNC and uncoded schemes. Finally, section 4.6 concludes the chapter by highlighting the main contributions and results.

4.2 Problem Formulation

4.2.1 Problem Description

This subsection formulates the minimum overall completion time problem for rate-aware IDNC in coordinated multi-BSs networks with forward channel erasures or called erasure channel probability ϵ_u. Let ϵ_u be the message erasure probability at u-th user. Its clear that the message is erased with a probability of ϵ_u and received correctly with a probability of $1 - \epsilon_u$. The particular case of the erasure probability gives the perfect channel estimation scenario explained in chapter 3 as follows:

$$\epsilon_u = \begin{cases} 1 & \text{if } R \leqslant R_b^u \\ 0 & \text{otherwise} \end{cases} \tag{4.1}$$

Let $\mathcal{S}^*$ be the optimal schedule of packet combinations and transmission rates for each base-station that minimizes the completion time. The completion time minimization problem in coordinated multiple base-stations rate-aware IDNC with forward channel erasures can be expressed as follows:

$$\mathcal{S}^* = \arg\min_{\mathcal{S}\in\mathbf{S}} \mathcal{C}(\mathcal{S}) = \arg\min_{\mathcal{S}\in\mathbf{S}} \left\{ \max_{u\in\mathcal{U}} \{C_u(\mathcal{S})\} \right\}, \tag{4.2}$$

where $\mathbf{S}$ is the set of all feasible schedules. The following lemma reduces the search space for the optimal schedule:

Lemma 1: *The optimal schedule $\mathcal{S}^*$ to reduce the completion time can be expressed as follows:*

$$\mathcal{S}^* = \arg\min_{\mathcal{S}\in\mathbf{S}} \mathcal{C}(\mathcal{S}) = \arg\min_{\mathcal{S}\in\tilde{\mathbf{S}}} \mathcal{C}(\mathcal{S}), \tag{4.3}$$

where $\tilde{\mathbf{S}}$ is the set of all feasible schedule with the same transmission rate for all base-stations sampled from the achievable capacities of all users. The definition of the set is given by:

$$\tilde{\mathbf{S}} = \left[\mathcal{P}(\mathcal{F})^B \times \mathcal{R}(t)\right]_{t\in N}, \tag{4.4}$$

where $\mathcal{P}(\mathcal{F})$ represents the power-set of the set messages $\mathcal{F}$ and $\mathcal{R}(t)$ is the set of achievable capacities of all users to all base-stations defined as:

$$\mathcal{R}(t) = \bigotimes_{(u,b)\in\ \mathcal{U}\times\mathcal{B}} R_b^u(t). \tag{4.5}$$

Proof. This lemma is proved in two steps. First, it is shown that the search space can be reduced without loss of optimality by assuming that all base-stations are using the same transmission rate. Secondly, it is demonstrated that the search space can be reduced further by considering only the set of achievable capacities of each user. A complete proof can be found in Appendix C. ∎

Following the result of lemma 1, the rest of the thesis assumes that all base-stations are using the same transmission rate at each transmission t denoted by $R(t)$, i.e., $R_b = R_{\min}, \forall\ b \in \mathcal{B}$. Unlike error-free transmission scenarios, the individual completion time $C_u(\mathcal{S})$ depends not only on the schedule $\mathcal{S}$ but also on the channel impairments.

In order to derive an expression for the optimal schedule to reduce the completion time, the following theorem proposes approximating the individual completion time $C_u(\mathcal{S})$ given a schedule $\mathcal{S}$ by an expression involving the time delay defined in the previous subsection.

Theorem 4. *The individual completion time $C_u(\mathcal{S})$ of the u-th user given a schedule $\mathcal{S}$ of packet combinations and transmission rates for each base-station can be approximated by the following quantity:*

$$C_u(\mathcal{S}) \approx \left(\frac{N|\mathcal{F}|}{\tilde{R}_u(\mathcal{S})} + \mathcal{T}_u(\mathcal{S}) \right) \frac{1}{1 - \bar{\epsilon}_u(\mathcal{S})}, \tag{4.6}$$

where $\mathcal{T}_u(\mathcal{S})$ is the cumulative time delay experienced by the u-th user after receiving the schedule $\mathcal{S}$, $\bar{\epsilon}_u$ is the average erasure probability for user u from all base-stations, and $\tilde{R}_u(\mathcal{S})$ is the harmonic mean of the transmission rates in the schedule $\mathcal{S}$ that are instantly decodable for u-th user in $\mathcal{S}$ defined as:

$$\frac{|\alpha_u(\mathcal{S})|}{\tilde{R}_u(\mathcal{S})} = \sum_{t \in \alpha_u(\mathcal{S})} \frac{1}{R(t)}, \tag{4.7}$$

with $\alpha_u(\mathcal{S})$ being the set of transmission indices that are instantly decodable for the u-th user.

Proof. : The expression is derived by writing the completion time as the sum of the times receiving useful, useless, and erased packets. The number of useful transmissions corresponds to the number of wanted packets. Similarly, the number of unnecessary transmission matches the previously defined time delay. Finally, the number of erased transmissions is approximated using the law of large number in combination with the apriori distribution of the channel realization and the expected erasure probability.
A complete proof can be found in Appendix D. ∎

The individual completion time as expressed in (4.6) depends on the dynamic channel realizations. Therefore, obtaining the optimal schedule requires an optimization over all such possible channel realizations which is clearly intractable for any moderately sized network. To efficiently solve the above problem, the rest of this thesis suggests reformulating the completion time reduction problem using a more tractable quantity called herein the "anticipated completion time".

4.2.2 Anticipated Completion Time Formulation

Given the NP-hardness of reducing the completion time for the whole session, this section introduces an anticipated version that can be computed at each time instant t. The anticipated completion time $\mathcal{C}_u(t)$ of the u-th user would be equal to the actual completion time $\mathcal{C}_u(\mathcal{S})$ if and only if the user does not experience any additional increases in its accumulated time delay and the transmission rate, and average erasure remain constant (The rest of this work assumes that the transmission rates vary slowly enough so that both the average transmission rate and erasure can be considered to be constant) for the remaining transmissions in the schedule $\mathcal{S}$. In other words, the approximation would be exact if the user does not receive any non-instantly decodable transmission after the t-th transmission. The expression of an anticipated completion time that satisfy the aforementioned conditions is the following:

$$C_u(t) = \left(\frac{N|\mathcal{F}|}{\tilde{R}_u(t)} + \mathcal{T}_u(t)\right)\frac{1}{1-\tilde{\epsilon}_u(t)}, \tag{4.8}$$

where $\mathcal{T}_u(t)$ is the cumulative time delay experienced by the u-th user until the t-th transmission, $\tilde{\epsilon}_u(t)$ is the average erasure experienced by the user until the t-th transmission, and $\tilde{R}_u(t)$ the harmonic mean of the transmission rate that are instantly decodable for the u-th user until the t-th transmission defined in a similar fashion than in (4.7).

4.2.3 Relaxed Problem Formulation

Let $\mathcal{K}_{R(t)}$ be the set of users that can increase the maximum anticipated overall completion time after the t-th transmission, The mathematical definition of such set if given in the following lemma:

Lemma 2: The set of critical users $\mathcal{K}_{R(t)}$ can be defined as follows:

$$\mathcal{K}_{R(t)} = \left\{ u \in \mathcal{U} \;\middle|\; \mathcal{C}_u(t-1) + \frac{N}{R_{\min}(t)(1-\widetilde{\epsilon}_u(t-1))} \geqslant \mathcal{C}_{u^*}(t-1) \right\}. \tag{4.9}$$

Proof. The complete proof can be found in Appendix E. The proof steps of the above lemma are as follows: the completion time of the critical set of users $\mathcal{K}_{R(t)}$ that can potentially increase the anticipated version of is first identified. The expected completion time is derived based on the different events that can occur of each user. Using a mean field approximation of the rates and erasures, the expression in (4.9) is established. Defining $\tau_b(\kappa_b(t))$ as the set of targeted users by the transmitted packet $\kappa_b(t)$ from the b-th BS at time t, i.e. the set of receives for which the transmission by the b-th BS with rate $R_b(t)$ is instantly decodable, we can formulate this relaxed problem as introduced in the following lemma.

Theorem 4: *The completion time reduction problem in (4.2) can be relaxed to an online version, in which, at any transmission t, the following joint optimization problem over the packet $(\kappa_b(t))$, transmission rates R of BSs, $\forall\ b \in \mathcal{B}$:*

$$\max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log\left(\frac{R}{N\epsilon_u(R, R_b^u)}\right). \tag{4.10}$$

where $\mathcal{P}(\mathcal{F})$ is the power set of the set $\mathcal{X}$.

Proof: The fundamental concept in relaxing the completion time reduction problem is choosing the packet combination and the transmission rate so as to reduce the probability that the anticipated completion time increases in the next time steps. Hence, the relaxed problem is derived by first expressing the event of maximum anticipated completion time increase as a function of the critical set. Afterward, the expression is used to formulate the completion time reduction problem. The complete proof can be found in Appendix F.

The relaxed optimization problem in the special setting of perfect forward channels, i.e., no erasures in the forward link, is given in the following corollary.

Corollary: *The completion time reduction problem in perfect forward channel can be expressed as follows:*

$$\max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log\left(\frac{R}{N}\right). \tag{4.11}$$

Furthermore, in a single base-station setting, the optimization is further reduced to $\max\limits_{\substack{\kappa \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum\limits_{u \in (\mathcal{K}_R \cap \tau(\kappa))} \log\left(\frac{R}{N}\right)$.

proof: To show this corollary it is sufficient to note that the message combination κ_b from base-station b at rate R is instantly decodable for all targeted users $u \in \tau_b(\kappa_b)$ as $R \leq R_b^u$. Using the the expression of the erasure probability in perfect channel estimation scenario as (4.1), the quantity does not depend on the packet combination or the transmission rate.Therefore, the joint optimization problem can be written as:

$$\begin{aligned}
&\max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log\left(\frac{R}{N}\right) - \log(\epsilon_u(R, R_b^u)) \\
&= \max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log\left(\frac{R}{N}\right). \qquad (4.12)
\end{aligned}$$

Furthermore, for a single base-station setting, the optimization problem can be simplified as follows:

$$\max_{\substack{\kappa \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{u \in (\mathcal{K}_R \cap \tau(\kappa))} \log\left(\frac{R}{N}\right). \qquad (4.13)$$

4.3 Proposed Solution

In this section we follow the same explanation of the proposed solution using MB-RA IDNC graph with perfect channel in section 3.3. Given the construction rules explained in section 3.3, it can be readily inferred that each clique. in the MB-RA-IDNC graph represents a transmission with following properties:

- All the users designated by the cliques vertices receive an instantly decodable transmission. Therefore all users in the maximum independent set benefit from the transmission.

- The transfer rate is smaller than the capacities of all the users identified by the cliques vertices.

Therefore, the transmission represented by each clique in the RA-IDNC graph is instantly decodable for all the users designated by the cliques vertices.

The following lemma characterizes the optimal solution to the approximated completion time reduction problem in (4.10) using the MB-RA IDNC graph:

Theorem 5: *The optimal solution to the anticipated completion time reduction problem (4.10) is the maximum weight independent set in the MB-RA-IDNC graph in which the weight $w(v_{b,u,f,r})$ of each vertex $v_{b,u,f,r}$ can be expressed as:*

$$w(v_{b,u,f,r}) = \begin{cases} log(\frac{r}{\epsilon_u N}) & \text{if } u \in \ \mathcal{K}_r \\ \\ 0 & \text{otherwise.} \end{cases} \tag{4.14}$$

Proof: The proof of the theorem is demonstrated by showing a one-to-one mapping between the set of maximal independent sets in the MB-RA-IDNC graph and the feasible transmissions. Afterward, the weight of each independent set is shown to be equivalent to the objective function. Therefore, the maximum weight independent set is the optimal solution to the optimization problem (4.10). A complete proof can be found in Appendix G.

The authors in [39] show the NP-hardness of finding the maximum weight independent set problem in a given graph. However, efficient polynomial-time algorithms, e.g., [41, 42], are suggested to discover a satisfactory solution more efficiently that the naive exhaustive search methods. Furthermore, the solution may not be unique due to the existence of vertices of weights zeros. Indeed, their inclusion/exclusion produce the same objective function. This section proposes using a method similar to the one in [29] to select one of the points that achieve the optimum of theorem (4). The fundamental concept of the heuristic is to arrange users in multiple layers in descending order of criticality and to heuristically solve the maximum weight independent set in each layer. This work further proposes to improve the performance of the maximum weight independent set heuristic by updating the weight of each vertex.

Reference [29] suggests a satisfactory solution to the maximum weight independent set by iteratively selecting vertices and updating the graph. The algorithm first selects the vertex with the highest weight and then updates the graph to keep only vertices that are connected to the selected one. This process guarantees that the final set is an independent set and hence a feasible solution. This work proposes using a similar method with the exception of modifying the original weights. The weight update is motivated by the fact that the original weight may be negative and that it does not reflect the connectivity of that vertex.

Let w_v be the original weight of vertex v in the MB-RA IDNC graph as defined in theorem 3. Let $w^* = \max_{v \in \mathcal{V}} w_v$ be the maximum weight in the graph. The modified weight $\tilde{w}_v$ of vertex v can be expressed as:

$$\tilde{w}_v = (w_v - w^*) \sum_{v' \in \mathcal{V}_v} w_{v'}, \tag{4.15}$$

$\mathcal{V}_v$ is the set of vertices not adjacent to vertex v. By construction, it can be seen that all weights $\tilde{w}_v$ are negative and that a large value represents a large initial weight and a low connectivity to other vertices with large weights.

4.4 Complexity Computation by using SSP

4.4.1 SSP Formulation

Stochastic Shortest Path is a class of probabilistic planning problems which describe a wide range of possible scenarios where the purpose of the active agent is to reach a goal state in the minimum costly way from any non-goal state using actions with probabilistic outcomes. The problem of reducing the completion time in MB-RA IDNC graph can be formulated as an SSP problem as follows:

1. *State Space:* Due to the fact that the user can receive from a single BS at each time slot, states space can be considered as all the possibilities of the SFM that could take place until completion. Based on this concept, the states space has a size of $O(2^{UM})$.

2. *Action Space:* The action space for each states s can be defined as the set that contains all possible MB-RA IDNC graph's maximal independent sets that can be generated from SFM of state space s.

3. *State-Action Transition Probabilities:* The system will stay at the same state s or move to another state s' based on the action (i.e., transmission pattern corresponding to a message combination and transmission rate selection taken at any state). The system will transit to another state depending on

the users targeted by the base stations and the message corruption probability between each of these users and the base station which receiving its message from.

4. *Action Cost:* Similar to [44] , each action costs the system one transmission towards completion time.

By using SSP the MB-RA IDNC needs both action space of size $O(2^{UMB\mathcal{R}})$ (upper pound), where $\mathcal{R}$ is the rate set from all base stations to all users, and state space of size $O(2^{UM})$. So, the optimal policy of MB-RA IDNC is computed using iteration algorithm, its complexity $O(2^{UMB\mathcal{R}})$, but for classical IDNC the complexity is $O(2^{UMB})$, and for uncoded scheme the time complexity until completion is $O(UM)$. Accordingly, we conclude that computing the optimal policy in real-time is very difficult for typical values of U and M.

4.4.2 Complexity Analysis of the Proposed Work

For each transmission selection, the base stations require two steps, namely building the MB-RA IDNC graph after receiving the feedback and determining the maximum independent set for this transmission. In the proposed work we have two scenarios: One is when all users belong to the same layer and the other is when each user forms a separate layer.

We can construct the graph by generating $O(UMB)$ vertices, representing different messages loss from different users with different base stations. To build the adjacency matrix of the graph, we need to check the coding conflict and transmission conflict adjacency conditions for each pair of vertices to determine whether they should be connected with an edge. Hence, we need a $O(U^2M^2B)$ operations for the coding conflict and needs the same operations for transmission conflict. This means that we need a total of $O(U^2M^2B)$ operations to build the adjacency matrix.

However, we can minimize this complexity by exploiting the following properties of the coding conflict adjacency conditions between each pair of users in the same base station.

- P1: if $f \in \mathcal{W}_{u'}$, v_{uf} can be adjacent to each vertex u', becasue they satisfy the coding conflict condition, except for vertex $v_{u'f}$.

- P2: if $f \in \mathcal{H}_{u'}$, v_{uf} can be adjacent to any vertex of u' based on the coding conflict condition, except for all vertices $v_{u'l}$ for which l is in the has set of u.

Consequently, after constructing the vertices in $O(UMB)$ operations, the adjacency matrix can be built as follows. For each pair of receivers, we can compute for each message f.

$$|f_{uf}| + |f_{u'f}| = \begin{cases} 0, & \text{Both users have } f \text{ or both want } f \\ 1 & \text{Exactly one of users has } f. \end{cases} \tag{4.16}$$

Therefore, for each pair of users, we can identify the vertices representing a coding conflict conditions by M operations. Thus, according to properties P1 and P2, different messages required by different users, but at least one user does not has the other requested message or both of the users do not have the other requested messages. Since we have to execute the above action for every pair of users without repetition, the edge set is built in $O(U^2MB)$ operations. Hence, the total complexity reduces to $O(U^2MB + UMB + U^2M^2B) = O(U^2M^2B)$ operations.

In the first scenario, when all users are in the same layer, the complexity of the vertex search algorithm can be computed as follows. Since a maximal clique can have at most U vertices (we can target each user with one message per transmission), and since we have at most $|\mathcal{R}|$ maximal independent sets in this scenario and each iteration in the algorithm requires weight recomputations for the $O(UMB)$ graph vertices, the complexity of the algorithm is $O(U^2M^2B\mathcal{R})$ operations. Therefore, the total complexity of building the graph and finding an independent set for a transmission is $O(U^2M^2B\mathcal{R})$ operations.

In the second scenario, when each user forms a separate layer, the maximal independent set in each layer can have at most 1 vertex. Let us assume that the maximum number of layers is k, so the total complexity of building the graph and finding an independent set for a transmission is $O(kUMB)$. This complexity is experienced by the base stations, and thus does not represent a severe problem due to energy abilities of BSs [44].

On the other hand, this complexity comes at a cost of simplifying both the coding complexity at the BS and most importantly the receivers' decoding complexity and buffer requirements. Indeed, for IDNC the decoding complexity and buffer size at the users are $O(M)$ and $O(1)$, respectively. We conclude that the MB-RA IDNC algorithm has an overall complexity of $O(\mathcal{R}U^2M^2B)$ compared to Classical IDNC which has an overall complexity $O(U^2M^2B)$.

4.5 Simulation Results

This section shows the performance of the proposed solution in a coordinated enabled multi-BSs network with forward channel erasures. The simulations consider a network comprising 3 base-stations each placed in the center of a hexagonal cell. Users are randomly and uniformly distributed among the cell. To study the performance of the proposed solution in various scenarios, the number of users, messages, and the message sizes change in the simulation. In all simulations, the time delays due to the used protocols are not considered as they are negligible as compared to the file transfer period.

The message erasure probabilities of each user to each base-station are drawn randomly and uniformly from the interval $[0.3, 0.6]$. For simplicity, the erasure probability of each user remains constant during the whole transmission schedule.Table 4.1 summarizes additional system parameters.

Table 4.1: SIMULATION PARAMETERS

Cellular Layout	Hexagonal
Cell Diameter	500 meters
Channel Model	SUI-Terrain type B
Channel Estimation	Imperfect
High Power	-42.60 dBm/Hz
Background Noise Power	-168.60 dBm/Hz
Bandwidth	10 MHz

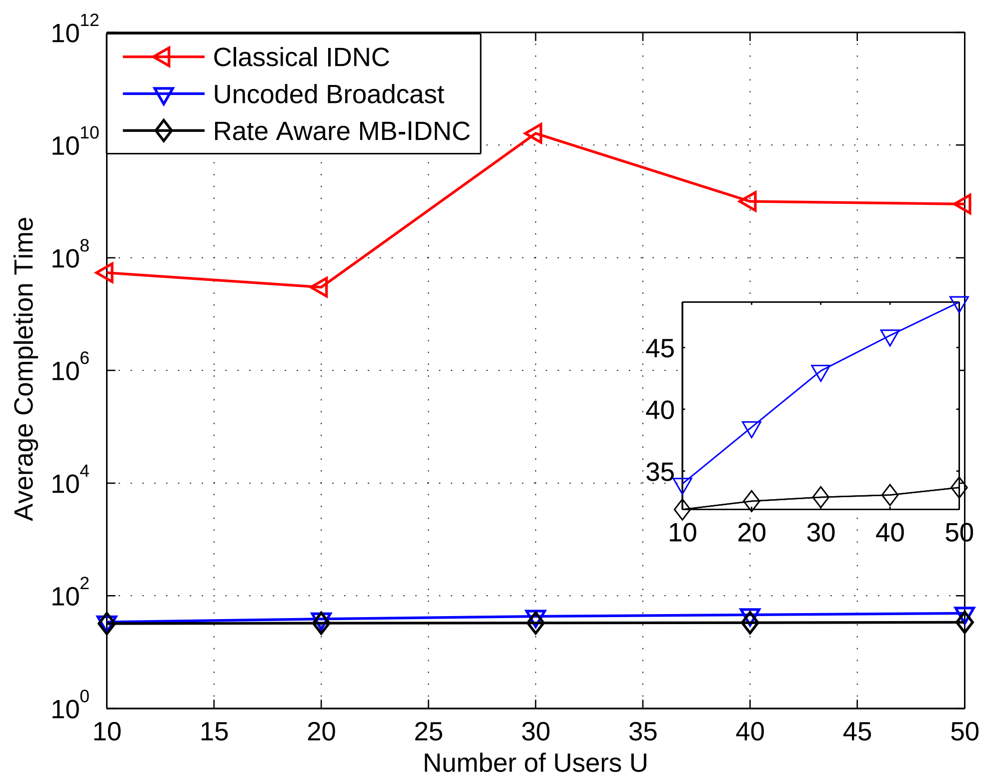

Figure 4.1: Completion time in sec. vs the number of users U for a network composed of $F = 20$ users and a messages size N = 1 Mb.

Fig. 4.1 plots the average completion time versus the number of users U for a network composed of $F = 20$ messages with a message's size $N = 1$ Mb. The figure shows that the proposed rate aware IDNC scheme outperforms both the broadcast and the unicast for all simulated number of users. This is mainly due to the rate awareness in the message selection process. Whereas classical scheme selecting a maximum number of users at the expense of a minimum achievable rate, the broadcast scheme sacrifices the rate optimality by selecting the maximum number of users. The proposed scheme strikes a balance between these two aspects by jointly selecting the number of targeted users and the transmission rate such that the overall completion time is minimized. As the number of users increases, the gap between our proposed and the broadcast scheme increases. This can be explained by the fact that as the number of users increases, the broadcast scheme targets more and more users at the expense of a lower transmission rate that explains the degradation in performance as the number of users increase. The gap between our RA-IDNC and the classical IDNC increases as the number of users increases. This due to the fact that as the number of users increases, the conventional IDNC scheme have more coding opportunities and thus the number of targeted users increases. This results in a lower transmission rate as it represents the minimum of an increasing set.

The performances of the algorithms versus the number of messages, the fixed numbers of users ($U = 20$), is depicted in Fig. 4.2. We note our proposed rate aware IDNC scheme outperforms the other two schemes. The performance of the uncoded strategy is also linear with the number of messages since it requires F transmissions to deliver all the messages. Figure 4.3 displays the completion time versus the messages size N for a network composed of $U = 20$ users, and $F = 30$

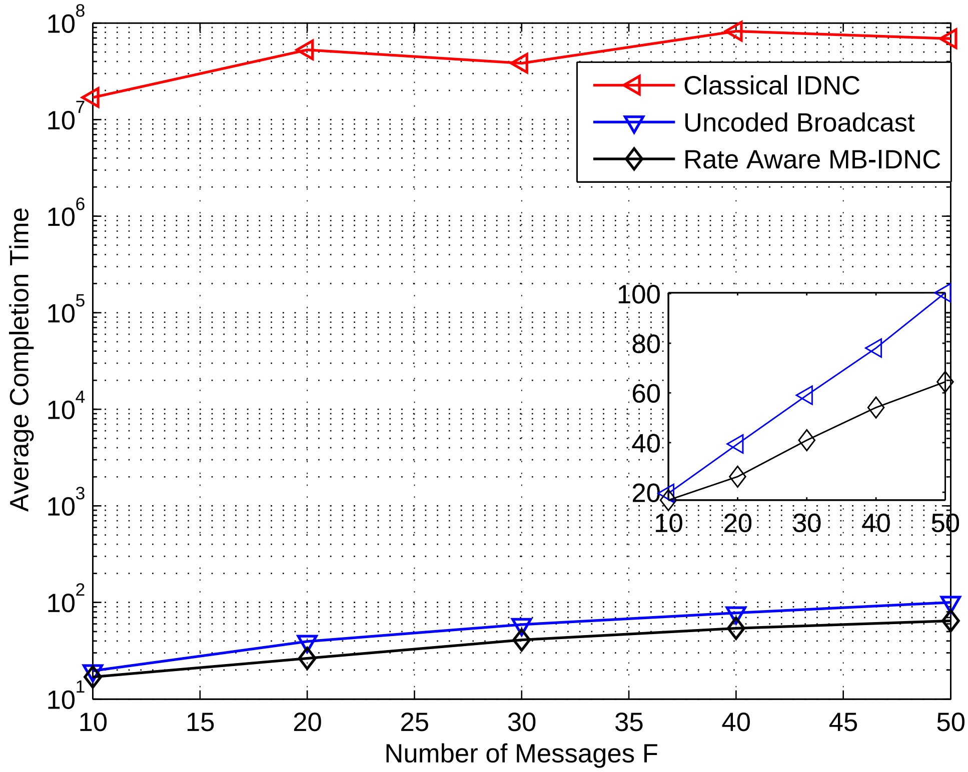

Figure 4.2: Completion time in sec. vs number of messages F for a network composed of $U = 20$ users and a messages size $N = 1Mb$.

messages. As hinted by (4.6), the completion time is the sum of a linear function of the message size and the time delay that is also linear with the message size. This result applies for any transmission scheme that explains that all the policies are linear with respect to such parameter. Table 4.2 shows the achieved gain of our proposed scheme with comparison to the uncoded scheme.

Table 4.2: Results Comparison between MB RA-IDNC and Broadcast scheme

Messages Size N in bits	Rate Aware MB RA-IDNC	Uncoded Broadcast
10ˆ3	0.041	0.0514
10ˆ4	0.4540	0.6367
10ˆ5	4.5905	5.9140
10ˆ6	46.3727	61.14367
10ˆ7	461.805	583.0678

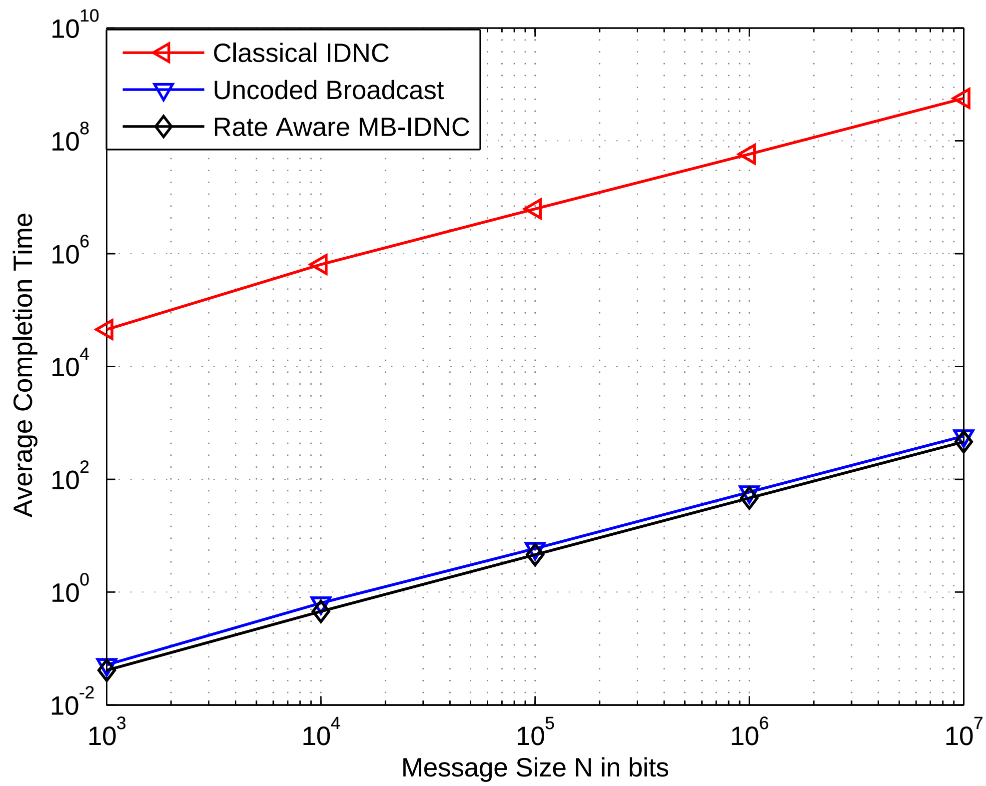

Figure 4.3: Completion time in sec. vs the messages size N bits for a network composed of $U = 20$ users, and $F = 30$ messages.

4.6 Summary and Conclusions

This chapter studies the problem of completion time reduction in multi-base-station enabled network using Rate Aware Instantly Decodable Network Coding. The focus is to jointly determine the packet combination and the transmission rate of each base-station so as to minimize the total recovery time. The completion time minimization in a multi-BS network with forward channel erasures is derived. Being intractable, the problem is approximated by a joint online optimization involving an anticipated version of the completion time. The paper introduces the multi-BS RA-IDNC graph and shows that the relaxed problem can be formulated as a maximum weight independent set search. A multi-layer approach is exploited to discover the solution and shown through extensive simulations to outperform existing schemes in literature.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this work, the minimization problem of the download time in PMP using IDNC with perfect and imperfect channel is considered. Applying the conventional (Classical) IDNC algorithm is shown to results in multiple transmissions conflicts, which reduce the downloading efficiency. Consequently, we proposed a novel graph model which provides multi-layer scenario. The completion time problem is first formulated and shown to be intractable. We thus relax the problem to an online optimization involving an anticipated version of the completion time. The expression of this anticipated completion time is derived and then used to formulate the online problem as a joint optimization over the set of BSs, achievable rates, and feasible packet combinations. We then prove that this problem can be solved by finding the maximum weight independent set in a newly designed graph. An efficient multi-layer heuristic is further proposed to address the problem in polynomial time. The proposed solution is tested via extensive simulations against Classical IDNC and uncoded schemes. Simulation results suggest that the proposed solution outperforms both the Classical IDNC and the uncoded schemes. In addition to study the problem in perfect channel we studied the problem with message placement in the base stations. Simulation results showed that the proposed MB-RA IDNC scheduling with message placement in BS outperformed the classical IDNC and uncoded schemes.

We extended the problem formulation in perfect channel estimation to a lossy environment formulation which include the erasure probability or the channel estimation error. We then used this formulation to identify the erasure channel events, and employed it to MB-RA IDNC algorithm with channel estimation error. Simulation results showed that the proposed MB-RA IDNC scheduling outperformed the classical IDNC and uncoded schemes in both perfect and imperfect channel.

5.2 Future Work

There are many open research problems for MB-RA IDNC field that need to be investigated and evaluated under different system parameters and new designs have to be proposed. Here we are enumerating some of these areas of research as follows:

Power Optimization in IDNC : All previous works in the network coding focused on the completion time and decoding delay problems and how to minimize them by using conventional IDNC and rate aware IDNC with fixed power assumption. To the best of our knowledge no one studied the power optimization problem in IDNC. Therefore, our future work will be focused on optimizing the BS power with minimizing the delivery time of the wanted messages to the users.

Adaptive message size IDNC transmissions : The main condition of the IDNC network coding is the equally sized messages. If the message size varies from one user to another, the implementation of the IDNC will be unattainable. However, our "MB-RA IDNC graph model can be developed to enable the base station to deal with a groups of users each group share the same message size. The base station can represent each wanted message by a vertex, in addition to the IDNC conflicts among the vertices induced by messages with the same size, any two vertices induced by messages with different size should be set connected by an undirected edge to indicate these two messages can not be encoded together. In this case, the problem will be graph partitioning problem instead of the problem of selecting the maximum weighted independent set in the MB-RA IDNC" graph.

Appendices

Appendix A: Proof of theorem 1

In this section, we follow the same steps used in proving theorem 1 in [29] with small modification. "The optimal schedule is illustrated as an optimization problem involving the time delay of users.

$$\mathcal{S}^* = \arg\min_{\mathcal{S}\in\mathbb{S}}\{\mathcal{C}(\mathcal{S})\} = \arg\min_{\mathcal{S}\in\mathbb{S}}\{\max_{u\in\mathcal{U}}\{\mathcal{C}_u(\mathcal{S})\}\}. \tag{A.1}$$

Hence", to explain this theorem its necessary to show that:

$$\mathcal{C}_u(\mathcal{S}) = \frac{N|\mathcal{F}|}{\tilde{R}_{u\min}(\mathcal{S})} + \mathcal{T}_u(S) \tag{A.2}$$

The completion time of user u at any schedule $\mathcal{S}$ of message combinations $\kappa(t)$ and transmit rates $R(t)$ is the sum of all download time until the first transmission achieving that no wanted messages of user u, $\mathcal{W}u = \phi$, $1 \leqslant t \leqslant |\mathcal{S}|$ and this completion time can be mathematically expressed as:

$$C_u(\mathcal{S}) = \sum_{t=1}^{n_u(\mathcal{S})} \frac{N(\kappa(t))}{R_{\min}(t)}, \tag{A.3}$$

where $N(\kappa(t))$ is the message combination size. Since the messages size are equal and they are mixed using binary XOR, therefore the size of any mixed messages is N. Such that, $N(\kappa(t)) = N$, and $n_u(\mathcal{S})$ is the initial transmission index achieving that no wanted messages in the Wants set of that user, $\mathcal{W}u = \phi$. The side information of the BSs be stored in State Feedback Matrix $SFM(BSi) = [l_{j,k}]$ and expressed mathematically as follows:

$$s.t. \quad l_{j,k} = \begin{cases} 0 & u_j \text{ downloaded } f_k \\ \\ 1 & u_j \text{ wants } f_k \end{cases}, \forall (u, f) \in \mathcal{U} \times \mathcal{F} \tag{A.4}$$

where "$\mathcal{U} \times \mathcal{F}$ is the Cartesian product of the two sets $\mathcal{U}$ and $\mathcal{F}$. Let l_j be the side information of user u. such that, l_j is the uth row of matrix SFM".

The transmission can be instantly decodable or non-instantly decodable for user u. Hence, the expression (A.3) can be written as follows:

$$\mathcal{C}_u(S) = \sum_{t \in \alpha_u(\mathcal{S})} \frac{N(\kappa(t))}{R_{\min}(t)} + \sum_{t \in \beta_u(\mathcal{S})} \frac{N(\kappa(t))}{R_{\min}(t)}, \tag{A.5}$$

where $\alpha_u(\mathcal{S})$ and $\beta_u(\mathcal{S})$ represent the sets of transmission index that are, instantly decodable and non-instantly decodable for user u, respectively. The mathematical definition of the above two sets is expressed as:

$\alpha_u(\mathcal{S}) = \{t \leqslant n_u(\mathcal{S}) \mid l_j(t)^T k(t) = 1 \text{ and } R(t) \leqslant R_b^u(t)\}$

$\beta_u(\mathcal{S}) = \{t \leqslant n_u(\mathcal{S}) \mid l_j(t)^T k(t) \neq 1 \text{ or } R(t) > \ R_b^u(t)\}$

where Z^T is the transpose of vector Z.

To prove this theorem, we "first show that, for any schedule $\mathcal{S}$, the cardinality of the set $\alpha_u(\mathcal{S})$ is $|\mathcal{F}|$. Then we show that the sum of all time delay increases experienced by user u during the schedule $\mathcal{S}$ until its individual completion time is $\mathcal{T}_u(\mathcal{S})$. Finally, we conclude the proof by substituting $\{R_{\min}(t)\}_{t\in\alpha_u(s)}$ of its harmonic mean $\tilde{R}_{u\,\min}(\mathcal{S})$. Let t^0_α be the smallest time index in the set $\alpha_u(\mathcal{S})$. Hence, for any transmission has time index less than the smallest time index in $\alpha_u(\mathcal{S})$, $t < t^0_{\alpha_u}$, is non instantly decodable for user u. So, the Wants set of user u is still the same as no message is received at t-th transmission, i.e., $\mathcal{W}_u(t) = \mathcal{F}$. Now lets take two consecutive time indices in $\alpha_u(\mathcal{S})$, t_α and t'_α". Using the same procedures as we did above.

For any $t_\alpha \leqslant t < t'_\alpha$ $\mathcal{W}_u(t) = \mathcal{W}_u(t_\alpha)$. In other words, at transmission t_α user u does not receive any instantly decodable transmission and starts receiving an instantly decodable transmission at t'_α. Therefore, user u reduces its Wants set by one unit, i.e., $\mathcal{W}_u(t'_\alpha) = \mathcal{W}_u(t_\alpha) - 1$. Finally, as mentioned above from the definition of $n_u(\mathcal{S})$, we have empty Wants set as $n_u(\mathcal{S})$ is the initial transmission index verifying the Wants set empty, $\mathcal{W}_u = \phi$. At the end of our first part in the proofing, it is easy to note that $n_u(\mathcal{S}) \in \alpha_u(\mathcal{S})$ which concludes that:

$$|\alpha_u(\mathcal{S})| = |\mathcal{F}| \tag{A.6}$$

Let $t < n_u(\mathcal{S})$ be a time index before the user u gets all its Wanted messages. From the above two sets, time index t will be in two scenarios:

- $t \in \alpha_u(\mathcal{S})$: The user does not experience any time delay increases since the message is instantly decodable.

- $t \in \beta_u(\mathcal{S})$: The user experience time delay $N/R_{\min}(t)$ increases since the message is non-instantly decodable and $\mathcal{W}_u \neq \phi$ (since $t < n_u(\mathcal{S})$.

As explained above that the time index t is grater than or equal the smallest time index $n_u(\mathcal{S})$ then the user u will not experience any time delay increases as its have an empty Wants set. Therefore, we conclude that:

$$\sum_{t \in \beta_u(\mathcal{S})} \frac{N}{R_{\min}(t)} = \mathcal{T}_u(\mathcal{S}). \tag{A.7}$$

Let $\tilde{R}_{u\,\min}(\mathcal{S})$ be the harmonic mean of $\{R_{\min}(t)\}_{t \in \alpha_u(\mathcal{S})}$. The two quantities can be linked as follows:

$$\frac{|\alpha_u(\mathcal{S})|}{R_{u\,\min}(\mathcal{S})} = \sum_{t \in \alpha_u(\mathcal{S})} \frac{1}{R_{\min}(t)} \tag{A.8}$$

By substituting (A.6), (A.7) and (A.8) in (A.5) we conclude:

$$\mathcal{C}_u(\mathcal{S}) = \frac{N|\mathcal{F}|}{\tilde{R}_{u\,\min}(\mathcal{S})} + \mathcal{T}_u(\mathcal{S}). \tag{A.9}$$

Appendix B: Proof of theorem 2

Let $\mathbf{B}$ be the event that the highest anticipated completion time at " t-th transmission is greater than the anticipated completion time at the previous transmission $t-1$. Thus, the probability of this event can be written as follows:

$$\begin{aligned}\mathbb{P}(\mathbf{B}) &= \mathbb{P}(\max_{u\in\mathcal{U}}(\mathcal{C}_u(t)) > \max_{u\in\mathcal{U}}(\mathcal{C}_u(t-1))) \\ &= 1 - \mathbb{P}(\max_{u\in\mathcal{U}}(\mathcal{C}_u(t)) = \mathcal{C}_{u^*}(t-1)).\end{aligned} \tag{B.1}$$

Let $\mathcal{K}_{R(t)}$ be the set of critical users that can be potentially increase the anticipated overall completion time in the t-th transmission at the rates $R(t)$. This set can be mathematically expressed as:

$$\mathcal{K}_{R(t)} = \{u \in \mathcal{U} \mid \mathcal{C}_u(t) > \mathcal{C}_{u^*}(t-1)\}. \tag{B.2}$$

Assume that the transmission at time t is non-instantly decodable for user u. We can note that the minimum harmonic mean for user u at the current transmission equal to the harmonic mean for the same user at the previous transmission, $\tilde{R}_{u\min}(t-1) = \tilde{R}_{u\min}(t)$. Then, the anticipated time of user u can be expressed as:

$$\mathcal{C}_u(t) = \mathcal{C}_u(t-1) + N/R_i(t) + T_{iwait}(t) \tag{B.3}$$

where $R_i(t)$ is the transmission rate of BS b when its connected to user u at t-th transmission and $T_{iwait}(t)$ is the waiting time of BS b to be synchronized with other BSs at t-th transmission, $\forall i \in \mathcal{B}$ and can be expressed in terms of $R_i(t)$ and $R_{\min}(t)$ as follows in lemma 3:

Lemma 4. *Given the no-fragmentation constraint on message and packet transmissions, using the lowest scheduled BS rate in all BSs is equivalent to using different rates in each of them.*

***proof*:** Its easy to proof this lemma. We assume that each BS send its packet at its own rate. In other words, assume that the BSs send the combination at different transmission rates $\mathcal{R}(t)$. Hence, at t-th transmission the transmission time is expressed as follows:

$$T_{itransmit}(t) = N/R_i(t) + T_{iwait}(t), \tag{B.4}$$

where the waiting time is expressed as follows:

$$T_{iwait}(t) = \frac{N}{R_{\min}(t)} - \frac{N}{R_i(t)} \tag{B.5}$$

Hence, by substituting (B.5) in (B.4) we get:

$$T_{itransmit}(t) = N/R_{\min}(t) \tag{B.6}$$

Therefore, this result lead to the same as using the same rate (lower rate). Based on the above explanation the waiting time is equivalent to use the same rate.

By substituting (B.5) in (B.3) we get the final expression of the anticipated time of user u as follows:

$$\mathcal{C}_u(t) = \mathcal{C}_u(t-1) + N/R_{\min}(t) \tag{B.7}$$

If the transmission is instantly decodable, the relation that connected between the harmonic mean of the current transmission $\tilde{R}_{\min}(t)$ and the harmonic mean of the previous transmission $\tilde{R}_{\min}(t-1)$ is mathematically expressed as:

$$\frac{1}{\tilde{R}_{\min}(t)} = \frac{n-1}{n\tilde{R}_{\min}(t-1)} + \frac{1}{nR} \tag{B.8}$$

where n is the number of transmission received that are instantly decodable by user u. Assuming that $R_{u\min}(t-1) \approx R_{u\min}(t)$, the anticipated completion time in (B.7) of user u remains unchanged, such that $C_u(t) = \mathcal{C}_u(t-1)$.

Based on the above analysis, we conclude that the individual completion time of user u after the transmission of the message $\kappa(t)$ with the rate $R(t)$ from multiple BSs can be expressed as:

$$\mathcal{C}_u(t) = \begin{cases} \mathcal{C}_u(t-1) & \text{if } u \text{ targeted} \\ \mathcal{C}_u(t-1) + N/R_{\min}(t) & \text{otherwise} \end{cases} \tag{B.9}$$

Therefore, the mathematical expression of the critical set of users in (B.2) can be written as:

$$\mathcal{K}_{R(t)} = \{u \in \mathcal{U} \ \mid \mathcal{C}_u(t-1) + \frac{N}{R_{\min}(t)} \geqslant \mathcal{C}_{u^*}(t-1)\}. \tag{B.10}$$

By the structure of the above set in (B.10) any user is not targeted from any base station at t-th transmission such that $u \notin \mathcal{K}(t)$ can increase the highest individual completion time in the transmission t-th at rate $R(t)$.

Therefore, the probability of the event $\mathbf{B}$ is:

$$\begin{aligned} \mathbb{P}(\mathbf{B}) &= 1 - \mathbb{P}(\max_{u \in \mathcal{K}_{R(t)}} (\mathcal{C}_u(t)) = \mathcal{C}_{u^*}(t-1)) \\ &= 1 - \prod_{u \in \mathcal{K}_{R(t)}} \mathbb{P}(\mathcal{C}_u(t) - \mathcal{C}_u(t-1) = 0) \\ &= 1 - \prod_{i \in \mathcal{B}} \prod_{u \in (\mathcal{K}_{R(t)} \cap \mathcal{N}) \setminus \tau_i(\kappa_i(t))} N/R_{\min}(t) \end{aligned} \tag{B.11}$$

where $\mathcal{N} = \{u \in \mathcal{U} \mid \mathcal{W}_u \neq \phi\}$ is the set of users with non-empty Wants set. Hence, the completion time reduction problem can be approximated by the following joint optimization over the message combination $\kappa(t)$ and the transmission rate $R(t)$.

$$
\begin{aligned}
&(\kappa^*(t), R^*(t)) = \\
&= \arg \max_{\substack{\kappa(t)\in\mathcal{P}(\mathcal{F}) \\ R(t)\in\mathcal{R}(t)}} \sum_{i\in\mathcal{B}} \sum_{u\in(\mathcal{K}_{R(t)}\cap\mathcal{N})\setminus\tau_i(\kappa_i(t))} \log(N/R_{\min}(t)) \\
&= \arg \min_{\substack{\kappa(t)\in\mathcal{P}(\mathcal{F}) \\ R(t)\in\mathcal{R}(t)}} \sum_{i\in\mathcal{B}} \sum_{u\in(\mathcal{K}_{R(t)}\cap\tau_i(\kappa_i(t)))} \log(N/R_{\min}(t)) \\
&= \arg \max_{\substack{\kappa(t)\in\mathcal{P}(\mathcal{F}) \\ R(t)\in\mathcal{R}(t)}} \sum_{i\in\mathcal{B}} \sum_{u\in(\mathcal{K}_{R(t)}\cap\tau_i(\kappa_i(t)))} \log(R_{\min}(t)/N)\text{”},
\end{aligned}
\tag{B.12}
$$

Appendix C: Proof of lemma 1

The proof of this lemma can be decomposed in two steps. In the first step, we show that the search space can be reduced without loss of optimality by assuming that all base-stations are using the same transmission rate. In the second phase, we demonstrate that it can be reduced further by considering only the set of the achievable capacity of each user.

The completion time minimization problem in coordinated multiple base-stations rate-aware IDNC with forward channel erasures can be expressed as follows:

$$\mathcal{S}^* = \arg\min_{\mathcal{S} \in \mathbf{S}} \mathcal{C}(\mathcal{S}) = \arg\min_{\mathcal{S} \in \mathbf{S}} \left\{ \max_{u \in \mathcal{U}} \{C_u(\mathcal{S})\} \right\}, \tag{C.1}$$

where $\mathbf{S}$ is the set of all feasible schedules of packet combinations and transmission rate. This part focus only on the t-th (for ease of notations, the time index t is dropped from all variables in this proof) transmission. The generalization to the whole schedule is straightforward. The transmission time from the b-th base-station can be expressed as follows:

$$T_b = \frac{N}{R_b}. \tag{C.2}$$

However, for the various base-stations to be synchronized, the next transmission is only possible after all base-stations finish the t-th transfer. Therefore, the total time of the t-transmission is:

$$T = T_b + T_b^w, \ \forall\, b \in \mathcal{B}, \tag{C.3}$$

where T_b^w is the waiting time that can be expressed as:

$$T_b^w = \frac{N}{R_{\min}} - \frac{N}{R_b}. \tag{C.4}$$

By combining C.2 and C.3, it can readily be seen that using the same transmission rate, i.e., $R_{\min} = \min_{b \in \mathcal{B}} R_b$, yields the same total transmission time. (This work assumes that the erasure probability is an increasing function of the transmission rate. Hence, decreasing the transmission rate of some base-stations results in a lower erasure probability). The analysis above can be generalized to any transmission in the schedule $\mathcal{S}$. Hence, the search space can be reduced to all base-stations using the same transmission rate without loss of optimality.

Let R be the optimal transmission rate of all base-stations during the t-th transfer corresponding to packets κ_b, $b \in \mathcal{B}$, and assume that $R \notin \mathcal{R}$, where $\mathcal{R}$ is the set of achievable capacities of all users defined as:

$$\mathcal{R} = \bigotimes_{(u,b)\in\ \mathcal{U}\times\mathcal{B}} R_b^u. \tag{C.5}$$

As shown in C.3, the transmission time only depends on the chosen rate. Let $\tau_b(\kappa_b)$ be the set of users that are targeted by packet κ_b transmitted from the b-th base-stations at the transmission rate R. Since the transmission is instantly decodable for all users in τ_b, then it can be concluded that:

$$R \leq R_b^u,\ \forall\ u \in \tau_b. \tag{C.6}$$

Define $R_b = \min_{u\in\tau_b} R_b^u$ as the minimum achievable capacity of the targeted users and $R_{\min} = \min_{b\in\mathbb{B}} R_b$. From the definition in C.4, we have $R \leq R_{\min}$. Therefore, the transmission rate $R_{\min}$ serves the same set of users for a lower total transmission time. This can be generalized to all transmission in the optimal schedule $\mathcal{S}^*$, then the new schedule have a lower completion time. Given that the transmission rate R is the optimal one at the t-th transmission, then $R = R_{\min}$ which is in contradiction with the initial assumption that $R \notin \mathcal{R}$. Finally, we conclude that the optimal schedule $\mathcal{S}^*$ to reduce the completion time can be expressed as follows:

$$\mathcal{S}^* = \arg\min_{\mathcal{S}\in\tilde{\mathbf{S}}} \mathcal{C}(\mathcal{S}), \tag{C.6}$$

where $\tilde{\mathbf{S}}$ is the set of all feasible schedule with the same transmission rate for all base-stations sampled from the achievable capacities of all users. The definition of the set is given by:

$$\tilde{\mathbf{S}} = \left[\mathcal{P}(\mathcal{F})^{B} \times \mathcal{R}(t)\right]_{t \in N}, \tag{C.7}$$

where $\mathcal{R}(t)$ is the set of achievable capacities of all user to all base-stations defined as:

$$\mathcal{R}(t) = \bigotimes_{(u,b) \in \mathcal{U} \times \mathcal{B}} R_b^u(t). \tag{C.8}$$

Appendix D: Proof of theorem 4

The proof of this theorem extends the results of Theorem 1 to an imperfect channel scenario. Note that the individual completion time of the u-th user can be expressed as the first time instant in which the user experience an empty Wants set. Indeed, we have $\mathcal{W}_u(t) = \varnothing$, $1 \leq t \leq n_u(\mathcal{S})$ where $n_u(\mathcal{S})$ is the initial transmission index achieving $\mathcal{W}_u(t) = \varnothing$. The individual completion time can be expressed as:

$$\begin{aligned} \mathcal{C}_u(\mathcal{S}) &= \sum_{t=1}^{n_u(\mathcal{S})} \frac{N(\kappa(t))}{R(t)} \\ &= \sum_{t \in \alpha_u(\mathcal{S})} \frac{N(\kappa(t))}{R(t)} + \sum_{t \in \beta_u(\mathcal{S})} \frac{N(\kappa(t))}{R(t)} + \sum_{t \in \gamma_u(\mathcal{S})} \frac{N}{R(t)}, \end{aligned} \tag{D.1}$$

where

- $\alpha_u(\mathcal{S})$ is the set transmission index such that user u successfully receives an instantly decodable packet combination from one of the base-stations.
- $\beta_u(\mathcal{S})$ is the set of transmission index in which all packet combinations from all base-stations are not instantly decodable for the u-th user.
- $\gamma_u(\mathcal{S})$ is the set transmission index such that an instantly decodable trans-

mission from one of the base-stations is erased at the u-th user.

Given that the packets are combined using binary XOR, then the resulting packet combination has the same size as the original source packets. In other words, we have $N(\kappa) = N$ for any combination κ. Therefore, the first step of the proof is to show the following equalities for any schedule $\mathcal{S}$:

- $\alpha_u(\mathcal{S}) = |\mathcal{F}|$.
- $\sum\limits_{t \in \beta_u(\mathcal{S})} \frac{N}{R(t)} = \mathcal{T}_u(\mathcal{S})$.

For time indices $t \in \alpha_u(\mathcal{S})$, the transmission is instantly decodable for the u-th user. Since each user can be targeted by a single base-station at each time instant, then by rearranging the order of base-stations users can be considered to be served by a single BS for each instantly decodable packet. Therefore, the proof of the first equality is omitted as it mirrors the steps used in proving the same equality in Appendix A.

Let $t < n_u(\mathcal{S})$ be a time index before the user u gets all its wanted messages. From the above three sets, time index t can be in three scenarios:

- $t \in \alpha_u(\mathcal{S})$: The user does not experience any time delay increases since the message is instantly decodable.
- $t \in \beta_u(\mathcal{S})$: The user experiences time delay increase of $N/R(t)$ since the message is non-instantly decodable and $\mathcal{W}_u \neq \varnothing$.
- $t \in \gamma_u(\mathcal{S})$: The message is erased, and hence the users do not experience any time delay.

Furthermore, for time indices t grater than or equal to $n_u(\mathcal{S})$, user u does not experience any time delay increases as its Wants set is empty. Therefore, it can readily be concluded that the cumulative time delay can be expressed as follows:

$$\sum_{t \in \beta_u(\mathcal{S})} \frac{N}{R(t)} = \mathcal{T}_u(\mathcal{S}). \tag{D.2}$$

Finally, let $\varepsilon_u(\mathcal{S})$ be the cumulative absolute time of the erased packet defined as follows:

$$\sum_{t \in \gamma_u(\mathcal{S})} \frac{N}{R(t)} = \varepsilon_u(\mathcal{S}) \tag{D.3}$$

Combining the equalities above, the individual completion time of the u-th user can be formulated as:

$$\mathcal{C}_u(\mathcal{S}) = \frac{N|\mathcal{F}|}{\tilde{R}_u(\mathcal{S})} + \mathcal{T}_u(S) + \varepsilon_u(S), \tag{D.4}$$

where $\tilde{R}_u(\mathcal{S})$ is the harmonic mean of the transmission rates in the schedule $\mathcal{S}$ that are instantly decodable for u-th user in $\mathcal{S}$ defined as:

$$\frac{|\alpha_u(\mathcal{S})|}{\tilde{R}_u(\mathcal{S})} = \sum_{t \in \alpha_u(\mathcal{S})} \frac{1}{R(t)}. \tag{D.5}$$

By approximating the cumulative absolute time of the erased packets by its mean value and using steps similar to the one provided in the proof of Theorem 1 in Appendix A, it can be shown that for a large number of messages and/or a large number of users, the following holds:

$$\begin{aligned}\varepsilon_u(\mathcal{S}) \approx E[\varepsilon_u(\mathcal{S})] &= \hat{\epsilon}_u \sum_{t=1}^{n_u(\mathcal{S})} \frac{N}{R(t)} \\ &\approx \bar{\epsilon}_u \sum_{t=1}^{n_u(\mathcal{S})} \frac{N}{R(t)} = \bar{\epsilon}_u \mathcal{C}_u(\mathcal{S}),\end{aligned} \tag{D.6}$$

where $\hat{\epsilon}_u$ is the average erasure of the erased transmissions that are instantly decodable from the base-station that targeted the user and $\bar{\epsilon}_u$ is the average erasure from all base-stations. The definition of these averages is given below:

$$\hat{\epsilon}_u = \frac{1}{|\gamma_u(\mathcal{S})|} \sum_{t \in \gamma_u(\mathcal{S})} \epsilon_u(R(t), R^u_{b(t)}(t)), \tag{D.7}$$

where $b(t)$ is the base-station that targets user u during the t-th transmission. The average erasure probability is defined as:

$$\bar{\epsilon}_u = \frac{1}{B} \sum_{b \in \mathcal{B}} E_{R(t) \leqslant R^u_b(t)}[\epsilon_u(R(t), R^u_b(t))] \tag{D.8}$$

Therefore, substituting D.11 in D.9 and rearranging the terms as following:

$$\begin{aligned}
\mathcal{C}_u(\mathcal{S}) &= \frac{N|\mathcal{F}|}{\tilde{R}_u(\mathcal{S})} + \mathcal{T}_u(S) + \varepsilon_u(S) \\
\mathcal{C}_u(\mathcal{S}) &\approx \frac{N|\mathcal{F}|}{\tilde{R}_u(\mathcal{S})} + \mathcal{T}_u(S) + \bar{\epsilon}_u \mathcal{C}_u(\mathcal{S}) \\
\mathcal{C}_u(\mathcal{S})(1-\bar{\epsilon}_u) &\approx \frac{N|\mathcal{F}|}{\tilde{R}_u(\mathcal{S})} + \mathcal{T}_u(S) \\
\mathcal{C}_u(\mathcal{S}) &\approx \left(\frac{N|\mathcal{F}|}{\tilde{R}_u(\mathcal{S})} + \mathcal{T}_u(S)\right)\frac{1}{(1-\bar{\epsilon}_u)}. \qquad \text{(D.9)}
\end{aligned}$$

Appendix E: Proof of lemma 2

Let "$\mathcal{K}_R$ be the set of critical users that can be potentially increase the anticipated overall completion time in the t-th transmission at the rate R. This set can be mathematically expressed as":

$$\mathcal{K}_{R(t)} = \{u \in \mathcal{U} \mid \mathcal{C}_u(t) > \mathcal{C}_{u^*}(t-1)\}. \tag{E.1}$$

The t-th transmission for user u can be either erased or successfully received. This first part of the proof shows that the anticipated completion time remains the same for erased transmission and increases according to the instant decodability of the received transmissions.

Assume that the transmission at time "t is erased for user u. Hence, the harmonic mean for user u at the current transmission is equal to its the harmonic mean at the previous transmission, i.e., $\tilde{R}_u(t-1) = \tilde{R}_u(t)$. The relationship linking the average transmission erasures $\tilde{\epsilon}(t-1)$ and $\tilde{\epsilon}(t)$ of the u-th user is:

$$\begin{aligned}\tilde{\epsilon}(t) &= \frac{1}{t}\sum_{j=1}^{t}\epsilon(R(j), R_b^u(j)) \\ &= \frac{t-1}{t}\frac{1}{t-1}\sum_{j=1}^{t-1}\epsilon(R(j), R_b^u(j)) + \frac{\epsilon(R(t), R_b^u(t))}{t} \\ &= \frac{t-1}{t}\tilde{\epsilon}(t-1) + \frac{\epsilon(R(t), R_b^u(t))"}{t}\end{aligned} \tag{E.2}$$

For a huge number of transmissions and as the erasure $0 \leqslant \epsilon(R(t), R_b^u(t)) \leqslant 1$, $\forall\ t > 0$, we approximate the below quantities as follows:

- $\frac{t-1}{t} \approx 1$, for large t.
- $\frac{\epsilon(R(t), R_b^u(t))}{t} \approx 0$, for large t.

Therefore, the average erasure probability at the t-th transmission is approximately equal to $\tilde{\epsilon}(t-1)$. We conclude that the erased packets do not change the anticipated completion time, i.e., $\mathcal{C}_u(t) = \mathcal{C}_u(t-1)$.

Now assume that the t-th transmission is successfully received at the u-th user. Depending on the instant decodability of the packet combinations, two scenarios can be distinguished:

- If the transmission is "non-instantly decodable for user u, then the harmonic mean for the rate of instantly decodable transmission is unchanged, i.e., $\tilde{R}_u(t-1) = \tilde{R}_u(t)$. Furthermore, using a similar approximation than the one in E.2, the anticipated completion time can be written as:

$$\mathcal{C}_u(t) = \mathcal{C}_u(t-1) + N/R(t) \tag{E.3}$$

- If the transmission is instantly decodable for user u, the relation that connected between the harmonic mean of the current transmission $\tilde{R}(t)$ and the harmonic mean of the previous transmission $\tilde{R}(t-1)$" is mathematically expressed as:

$$\frac{1}{\tilde{R}(t)} = \frac{n-1}{n\tilde{R}(t-1)} + \frac{1}{nR} \tag{E.4}$$

where "n is the number of transmission received that are instantly decodable by user u. Assuming that $\tilde{R}_u(t-1) \approx \tilde{R}_u(t)$ and the approximation in E.2, the anticipated completion time of user u remains unchanged, i.e., $C_u(t) = \mathcal{C}_u(t-1)$".

time of user u after the transmission of the message combinations κ with the transfer rate R can be expressed as:

$$\mathcal{C}_u(t) = \begin{cases} \mathcal{C}_u(t-1) & \text{if } u \text{ targeted} \\ \mathcal{C}_u(t-1) + \frac{N}{R_{\min}(t)(1-\tilde{\epsilon}_u(t))} & \text{otherwise} \end{cases}$$

Therefore, the mathematical expression of the critical set of users in E.1 can be written as:

$$\mathcal{K}_R = \left\{ u \in \mathcal{U} \;\middle|\; \mathcal{C}_u(t-1) + \frac{N}{R_{\min}(1-(\tilde{\epsilon}_u(t)))} \geq \mathcal{C}_{u^*}(t-1) \right\}. \tag{E.5}$$

Appendix F: Proof of Theorem 4

The fundamental concept in relaxing the completion time reduction problem is choosing the packet combination and the transmission rate so as to reduce the probability that the anticipated completion time increases in the next time steps. Hence, the relaxed problem is derived by first expressing the event of maximum anticipated completion time increase as a function of the critical set. Afterward, the expression is used to formulate the completion time reduction problem.

Let "$\mathbf{X}$ be the event that the highest anticipated completion time at t-th transmission is greater than the anticipated completion time at the previous transmission $t-1$". According to the analysis in Appendix B, the probability of the event $\mathbf{X}$ can be expressed as function of the critical set as follows:

$$\begin{aligned}\mathbb{P}(\mathbf{X}) &= 1 - \mathbb{P}(\max_{u \in \mathcal{K}_{R(t)}} (\mathcal{C}_u(t)) = \mathcal{C}_{u^*}(t-1)) \\ &= 1 - \prod_{u \in \mathcal{K}_{R(t)}} \mathbb{P}(\mathcal{C}_u(t) - \mathcal{C}_u(t-1) = 0)\end{aligned} \tag{F.1}$$

As shown in lemma 2, for a transmission at the rate R, the anticipated completion time of critical non-targeted users, i.e., $u \notin \bigcup_{b \in \mathcal{B}} (\mathcal{K}_R \cap \tau_b(\kappa_b))$, increases according to the realization of the erasure channel as follows:

$$\mathcal{C}_u(t) - \mathcal{C}_u(t-1) = \begin{cases} 0 & \text{w.p., } \epsilon(R(t), R_b^u(t)) \\ \\ N/R(t) & \text{w.p., } 1 - \epsilon(R(t), R_b^u(t)) \end{cases} \tag{F.2}$$

Therefore, "the probability that the maximum anticipated completion time increases at the t-th transmission as compared with the $t-1$-th transmission can be expressed as follows":

$$\mathbb{P}(\mathbf{X}) = 1 - \prod_{b \in \mathcal{B}} \prod_{u \in (\mathcal{K}_R \cap \mathcal{N}) \setminus \tau_b(\kappa_b)} \epsilon(R, R_b^u) \tag{F.3}$$

where "$\mathcal{N} = \{u \in \mathcal{U} \mid \mathcal{W}_u \neq \phi\}$ is the set of users with non-empty Wants set". Hence, the packet combinations κ_b and the transfer rate R that minimizes the probability of increase in the anticipated completion time for the transmission can be expressed as follows:

$$\begin{aligned} & \min_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} 1 - \prod_{b \in \mathcal{B}} \prod_{u \in (\mathcal{K}_R \cap \mathcal{N}) \setminus \tau_b(\kappa_b)} \epsilon(R, R_b^u) \\ & = \max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \prod_{b \in \mathcal{B}} \prod_{u \in (\mathcal{K}_R \cap \mathcal{N}) \setminus \tau_b(\kappa_b)} \epsilon(R, R_b^u) \end{aligned} \tag{F.4}$$

Finally, the expected increase in the completion time reduction problem can be approximated by the following joint online optimization over the message combination κ_b and the transmission rate R as follows":

$$
\begin{aligned}
& \max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \prod_{b \in \mathcal{B}} \prod_{u \in (\mathcal{K}_R \cap \mathcal{N}) \setminus \tau_b(\kappa_b)} \frac{\epsilon(R, R_b^u) N}{R} \\
= & \max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \mathcal{N}) \setminus \tau_b(\kappa_b)} \log(\frac{\epsilon(R, R_b^u) N}{R}) \\
= & \min_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log(\frac{\epsilon(R, R_b^u) N}{R}) \\
= & \max_{\substack{\kappa_b \in \mathcal{P}(\mathcal{F}) \\ R \in \mathcal{R}(t)}} \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log\left(\frac{R}{N \epsilon(R, R_b^u)}\right) ".
\end{aligned} \tag{F.5}
$$

Appendix G: Proof of Theorem 5

To theorem is demonstrated by showing a one-to-one mapping between the set of maximal independent sets in the MB-RA-IDNC graph and the feasible transmissions. Afterward, the weight of each independent set is shown to be equivalent to the objective function. Therefore, the maximum weight independent set is the optimal solution to the optimization problem in theorem 4.

The authors in [29] show that there exists a one-to-one mapping between the set of feasible transmissions and the set of independent sets (reference [29] considers the complementary graph and formulates the optimization problem as a maximum weight clique search) in the RA-IDNC graph. Hence, to extend the results of [29] to the MB-RA-IDNC graph, we only need to show that the feasible transmissions between different transmissions are not adjacent, i.e., the extra constraint CC3. Since each feasible transmission by a base-station is an independent set and they are not connected, then the union of both sets is also an independent set.

From the connectivity condition CC3 of the MB-RA-IDNC graph, the same user cannot be targeted by distinct base-stations. Therefore, all vertices of in the sub-graph representing BS b are not connected to vertices in the sub-graph of BS b' as long as the targeted users are distinct. Therefore, each feasible combination of targeted users, message combinations, and the transmission rate is represented by a maximal independent set.

Conversely, it can readily be seen that each independent set represents a feasible condition as it does not violate the connectivity conditions CC1, CC2, and CC3. Indeed, for an independent set $\mathbf{M}$, the transmission of the packet $\kappa_b = \oplus_{v_{b,u,f,r} \in \mathbf{M}} f$ by base-station b at rate r is instantly for all users $\tau_b(\kappa_b) = \cup_{v_{b,u,f,r} \in \mathbf{M}} u$.

To finish the proof, we show that the weight of the independent set is the objective function of theorem 4. Let the weight of vertex $v_{b,u,f,r}$ be defined as in theorem 5. The weight of a maximal independent set $\mathbf{M}$ with its corresponding message mix τ_k and transmission rate R is:

$$
\begin{aligned}
w(\mathbf{M}) &= \sum_{v_{b,u,f,r} \in \mathbf{M}} w(v) \\
&= \sum_{u \in \tau_k} w(v_{b,u,f,r}) \\
&= \sum_{b \in \mathcal{B}} \sum_{u \in (\mathcal{K}_R \cap \tau_b(\kappa_b))} \log \left(\frac{R}{N \epsilon(R, R_b^u)} \right).
\end{aligned}
$$

Therefore, the problem of reducing the completion time (theorem 4) in MB-RA IDNC-enabled networks is equivalent to the maximum weight independent set problem among the maximal independent sets in the MB-RA IDNC graph.

REFERENCES

[1] A. G. Dimakis, K. Ramchandran, Y. Wu, and C. Suh, "A survey on network codes for distributed storage," *Proceedings of the IEEE*, vol. 99, no. 3, pp. 476–489, 2011.

[2] D. S. Papailiopoulos, J. Luo, A. G. Dimakis, C. Huang, and J. Li, "Simple regenerating codes: Network coding for cloud storage," in *INFOCOM, 2012 Proceedings IEEE.* IEEE, 2012, pp. 2801–2805.

[3] M. S. El Bamby, M. Bennis, W. Saad, and M. Latva-aho, "Content-aware user clustering and caching in wireless small cell networks," in *Wireless Communications Systems (ISWCS), 2014 11th International Symposium on.* IEEE, 2014, pp. 945–949.

[4] N. A. P. S. Yousef Shnaiwer, Sameh Sorour and T. Al-Naffouri, "Network-coded content delivery in femtocaching-assisted cellular networks," in *accepted for presentation and publication in the IEEE Globecom 2015*, 2015.

[5] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *Information Theory, IEEE Transactions on*, vol. 46, no. 4, pp. 1204–1216, 2000.

[6] J. Huang, L. Wang, W. Cheng, and H. Li, "Polynomial time construction algorithm of bcnc for network coding in cyclic networks," in *Computer and Information Science, 2009. ICIS 2009. Eighth IEEE/ACIS International Conference on*. IEEE, 2009, pp. 228–233.

[7] S. Sorour and S. Valaee, "On densifying coding opportunities in instantly decodable network coding graphs," in *Information Theory Proceedings (ISIT), 2012 IEEE International Symposium on*. IEEE, 2012, pp. 2456–2460.

[8] T. Ho and D. Lun, *Network Coding: An Introduction*. New York, NY, USA: Cambridge University Press, 2008.

[9] T. Ho, R. Koetter, M. Medard, D. Karger, and M. Effros, The benefits of coding over routing in a randomized setting, in Proc. of IEEE International Symposium on Information Theory (ISIT 2003), Yokohama, Japan, June 2003, pp. 442448.

[10] J.-S. Park, M. Gerla, D. Lun, Y. Yi, and M. Medard, Codecast: a network-coding-based ad hoc multicast protocol, IEEE Wireless Communications, vol. 13, no. 5, pp. 7681, October 2006.

[11] T. Ho, M. Medard, J. Shi, M. Effros, and D. R. Karger, "On randomized network coding," in *Proceedings of the Annual Allerton Conference on Communication Control and Computing*, vol. 41, no. 1. The University; 1998, 2003, pp. 11–20.

[12] L. Junhai, Y. Danxia, X. Liu, and F. Mingyu, "A survey of multicast routing protocols for mobile ad-hoc networks," *Communications Surveys & Tutorials,*

IEEE, vol. 11, no. 1, pp. 78–91, 2009.

[13] S. K. D. K. W. Hu and H. R. M. Médard, "The importance of being opportunistic: Practical network coding for wireless environments," *Newsletter ACM SIGCOMM Computer Communication Review*, vol. 36, no. 4, 2006.

[14] L. Georgiadis and L. Tassiulas, Broadcast erasure channel with feedback - capacity and algorithms, in Proc. of Workshop on Network Coding, Theory, and Applications (NetCod 2009), Lausanne, Switzerland, June 2009, pp. 5461.

[15] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard, and J. Crowcroft, "Xors in the air: practical wireless network coding," *IEEE/ACM Transactions on Networking (ToN)*, vol. 16, no. 3, pp. 497–510, 2008.

[16] M. Muhammad, M Berioli, G. Liva, and G. Giambene, "Instantly decodable network coding protocols with un equal error protection," *in proc. of IEEE international conference on communications (ICC' 2013), Sydeny, Australia,* June 2013, pp. 5120-5125.

[17] S. Tajbakhsh P. Sadeghi, and N. Aboutorab, "Instantly deocdable network codes for cooperative index coding problem over general topologies," *in proc. of Australia Communication Theory Workshop (AusCTW' 2014), Sydney, Australia,* Feb 2014, pp. 84-89.

[18] N. Aboutorab, P. Sadeghi, and S. Tajbakhsh,"Instantly decodable network coding for delay reduction in cooperative data exchange systems," *in proc.*

of IEEE international Symposium on Information Theory (ISIT' 2013), Istanbul, Turkey, July 2013, pp. 3095-3099.

[19] A. Douik, S. Sorour, M.S. Alouini, and T. Y. Al-Naffouri,"On minimizing the maximum broadcast decoding delay for instantly decodable network coding," *submitted to proc of IEEE Vehicular Technology Conference, (VTCFall 2014), available ArXiv e-prints,* Apr, 2014.

[20] L. Lu. M. Xiao, and L. K. Rasmussen, "Design and analysis of relay-aided broadcast using binary network codes," *Journal of communications*, vol. 6, no. 8, pp. 610-617, 2011.

[21] A. Douik, S. Sorour, M.-S. Alouini, and T. Y. Al-Naffouri, "Completion time reduction in instantly deocdable network coding through decoding delay control," *in proc. of IEEE Global Telecommunications Conference (GLOBECOM' 2014), Austin, Texas, USA*, Dec. 2014.

[22] S. Sorour, A. Douik, S. Valaee, T. Al-Naffouri, "Partially blind instantly decodable network codes for lossy feedback environment," *IEEE Transaction on wireless communications,* vol. 13, no. 9, pp. 4871-4883, Sept 2014.

[23] S. Sorour and S. Valaee, "Completion delay minimization for instantly decodable network codes," *IEEE/ACM Transaction on networking*, vol. PP, no. 99, pp. 1-4, 2014.

[24] S. Sorour and S. Valaee, "Minimum broadcast decoding delay for generalized instantly decodable network coding," *in proc. of IEEE Global Telecommuni-*

cations Conference (GLOBECOM' 2010), Miami, Florida, USA, Dec 2010, pp. 1-5.

[25] P. Sadeghi, D. Traskov, and R. Koetter, "Adaptive network coding for broadcast channels," in *Proc. 5th Workshop on Network Coding, Theory and Applications*, 2009, pp. 80–86.

[26] P. Sadeghi, R. Shams, and D. Traskov, "An optimal adaptive network coding scheme for minimizing decoding delay in broadcast erasure channels," *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, p. 4, 2010.

[27] D. Nguyen, T. Tran, T. Nguyen, and B. Bose, "Wireless broadcast using network coding," *Vehicular Technology, IEEE Transactions on*, vol. 58, no. 2, pp. 914–925, 2009.

[28] A. Le, A. S. Tehrani, A. G. Dimakis, and A. Markopoulou, "Instantly decodable network codes for real-time applications," in *Network Coding (NetCod), 2013 International Symposium on.* IEEE, 2013, pp. 1–6.

[29] A. Douik, S. Sorour, M. S. Alouini, and T. Y. Al-Naffouri, "Rate aware instantly decodable network codes," *submitted to IEEE Global Telecommunications Conference (GLOBECOM' 2015), San, Deigo, California, USA, available Arxiv e- prints.*

[30] Wenfei Wu, Li Erran Li, Aurojit Panda and Scott Shenker, "PRAN: Programmable Radio Access Networks," *HotNets-XIII Proceedings of the 13th*

*ACM Workshop on Hot Topics in Networks Pages 6.*October 2728, 2014, Los Angeles, CA, USA. 187–196.

[31] B. Lampson and H. Sturgis, *Crash recovery in a distributed data storage system.* Xerox Palo Alto Research Center Palo Alto, California, 1979.

[32] J. G. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *To appeare in IEEE J. Sel. Areas Commun. issue on 5G Wirless Commun. Systems, Sep. 2014, on achive: http://arxiv.org/pdf/1405.2957v1.pdf*

[33] E. Erez and M. Feder, "Efficient network code design for cyclic networks," *Information Theory, IEEE Transactions on*, vol. 56, no. 8, pp. 3862–3878, 2010.

[34] ——, "On minimizing broadcast completion delay for instantly decodable network coding," in *Communications (ICC), 2010 IEEE International Conference on.* IEEE, 2010, pp. 1–5.

[35] M. A. R. Chaudhry and A. Sprintson, "Efficient algorithms for index coding," in *INFOCOM Workshops 2008, IEEE.* IEEE, 2008, pp. 1–4.

[36] S. Y. El Rouayheb, M. A. R. Chaudhry, and A. Sprintson, "On the minimum number of transmissions in single-hop wireless coding networks," in *Information Theory Workshop, 2007. ITW'07. IEEE.* IEEE, 2007, pp. 120–125.

[37] D. B. West *et al.*, *Introduction to graph theory.* Prentice hall Upper Saddle River, 2001, vol. 2.

[38] M. Saif, A. Douik, and S. Sorour, “Rate aware network codes for coordinated multi Base-Station networks,” in *Proc. of IEEE International Conference on Communications (ICC' 2013)*, Kuala Lumpur, Malaysia, May 2016.

[39] M. Garey and D. Johonson, ”Computers and Intractability - A Guide to the Theorey of NP-Completeness.” *Freeman, New York*, 1979.

[40] K. Yamaguchi and S. Masuda, ”A new exact algorithm for the maximum weight clique problem,” *in proc. Of the 23rd International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC' 2008), Yamaguchi, Japan.*

[41] Z. Akbari, ”A polynomial-time algorithm for the maximum weight clique problem,” *in proc. of IEEE/ACIS 12th International Conference on Computers and Information Science (ICIS' 2013), Niigata, Japan*, June 2013,pp. 503-507.

[42] V. Vassileevska, ”Efficient algorithms for clique problems.” *Inf. Process. Lett.*, vol. 109, no. 4 pp. 254-257, 2009.

[43] A. Douik, S. Sorour, M. S. Alouini, and T. Y. Al-Naffouri, ”Rate aware instantly decodable network codes,” *submitted to IEEE Global Telecommunications Conference (GLOBECOM' 2015), San, Deigo, California, USA, available arXiv:1504.03985v2 [cs.IT] 28 Jul 2015.*

[44] Sameh Sorour, Member, IEEE, and Shahrokh Valaee, Senior Member, IEEE, ”Completion Delay Minimization for Instantly Decodable Network Codes,”

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