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Ali Alkhansa. Cooperative Wireless Communications in Multi-Source Multi-Relay Network. Other. Université d'Avignon, 2023. English. NNT : 2023AVIG0110 . tel-04105066

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THÈSE DE DOCTORAT D'AVIGNON UNIVERSITÉ

École Doctorale n°536
Agrosciences et Sciences

Mention de doctorat :
Informatique

Laboratoire Informatique D'Avignon

Présentée par
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Cooperative Wireless Communications in Multi-Source Multi-Relay Networks

Soutenue publiquement le 17/01/2023 devant le jury composé de :

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I dedicate my work to my family.

Acknowledgments

I would like to express my deepest appreciation to all those who provided me with the possibility to complete this study.

First and foremost, I would like to express my sincere gratitude to my supervisors: Professor Samson Lasaulce, Professor Ass. Yezekael Hayel, and Doctor Raphaël Visoz. My first contact was with Professor Samson Lasaulce back in my masters at CentraleSupelec where I followed some of the courses he gave there. Being impressed by his work back then, I was lucky and grateful to continue my Ph.D. under his supervision. I am also thankful for him for introducing me to Professor Ass. Yezekael and Doctor Raphaël giving me the opportunity to have their guidance which helped me in all the time of research. Special thanks are to Doctor Raphaël Visoz being a major contributor to my work; I am thankful for his almost daily time on different discussions and ideas exchanging leading to the progress of my Ph.D..

I am deeply grateful to all the jury members for taking interest in my work. I was honoured to have: Professors Didier Le Ruyet and Jean-Pierre Cances as reviewers, who I especially thank for their valuable review of my manuscript, and professors Tijani Chahed and Veronica Belgema as examiners.

I am also thankful to all who influenced me personally and academically over the 3 years at Orange Labs, where I have spent the majority of my time. The kind environment and the supportive colleagues in the RAP team is the needed atmosphere to work in. I have been warmly welcomed since day one, and I would like to thank all its current and former members for their support and the pleasant discussions that we have had, both technical and less formal ones. Despite the hard time of covid, where we had to spend a lot of time teleworking, the continuous support of the team was always present in different forms according to the health and regulations situations.

I am truly grateful to the team manager Pierre Dubois for his continuous support during the whole duration of my Ph.D.. Also, special thanks are to Stefan Cerovic for helping me at the beginning of my Ph.D., sharing with me his codes, and contributing to some of the work of this thesis. His help made it easier for me to understand the new challenging subject I was considering. Particular thanks are for Rita and Meriem and for all my Postdoc/Ph.D. colleagues Nour, Yi, Imene, Romain, Youssef, Amel, Yibo, and Shanglin. I am grateful for your kind company and for all the fun moments that we have spent together.

Finally, it would not be possible to complete my Ph.D. journey without the selfless help and huge support of my family and my friends, here and in Lebanon. Despite the massive situation Lebanon is facing, you were always there for me. Without your love, support, belief, and continuous encouragement, I would not have finished this thesis. Particular patience was needed by my fiancée Walaa to handle the stressful nature of my work and how workaholic I occasionally am. I am eternally grateful for your love and support which helped throughout me this journey.

Special thanks to my friends Hassan Fakih and Ali Wehbe who listened to my mid-thesis presentation and suggested different ideas for the possible directions I can take in the remaining part of my Ph.D.. One suggestion of Ali Wehbe was further discussed leading to the contributions seen in chapter 5. A big thank you is to my sister Rasha, my co-author, and my technical reviewer. Your collaboration helped me accelerate and improve my work. It was really a pleasure to collaborate and publish together.

Abstract

One of the main objectives for 5G and 5G-beyond cellular networks is to allow heterogeneous services to coexist within the same network architecture. Some of these services need a very high peak data rates and a fast adaptation of the channel state, as in enhanced Mobile Broadband (eMBB). In order to meet those needs, we aim at improving the spectral efficiency. Cooperative communication represents one of the key physical layer technologies which aim to optimize the spectral efficiency. The concept is to use the shared resources and information of the users to improve the transmission and reception processes. The cooperation process is performed using relaying nodes. A relaying node can be a dedicated relay node or a source node that performs user cooperation. The difference between a relay node and a source node which implements user cooperation is the fact that the latter has its own message whereas the relay node does not.

An orthogonal Multiple Access Multiple Relay Network (MAMRN) is considered, where at least two sources communicate with a single destination using the help of at least two relaying nodes. Orthogonality is achieved using Time Division Multiplexing (TDM) and all the relaying nodes are assumed half-duplex while all the links experience slow fading. The destination is the central node where the different allocations are performed. In an initialization phase, a Link Adaptation (LA) algorithm is performed where different resources are allocated to the sources. Following this step, the transmission of a frame is divided into two phases. In the first phase, sources transmit in turns in consecutive time slots. In the second phase, the destination schedules relaying node(s) to transmit redundancies. The second phase consists of a limited number of retransmission time slots. Bidirectional limited control channels are available from sources and relays towards the destination to exchange the needed information so that the destination is capable of performing its selections/allocation strategies.

In the first part of this thesis, the LA problem in the initialization phase is considered. Specifically, rate allocation algorithms are studied. Due to the complexity of the exhaustive search approach, sequential algorithms are proposed. The presented algorithms aim at maximizing the Average Spectral Efficiency (ASE) under individual Quality of Service (QoS) targets for a given Modulation and Coding Scheme (MCS) family. The algorithms are applicable in both slow and fast changing radio condition scenarios. The rates are first initialized and then an iterative rate correction step is applied. Furthermore, and in sharp contrast with existing cooperative transmission

schemes, a time-varying packet size at the transmission phase is considered. In other words, the LA process is extended to determine both the rate and the time slot duration for each source. The resulting scheduling and LA algorithms approach the performance of the upper bound as demonstrated by Monte-Carlo (MC) simulations. In addition, the MC results validate the improvements of using relaying nodes and introducing a time-varying packet size.

In the second part of this thesis, the focus is on designing relaying nodes selection strategies that determine which relaying nodes are activated at each time slot in the retransmission phase. One key element in this chapter is to exploit the multi-path diversity of the different relaying nodes. Rather than selecting a single relaying node to help one source node at a given retransmission time slot, the proposed scheduling strategies allocate one source to be helped by multiple relaying nodes. Such a retransmission scheme is called Parallel Retransmission (PR), as the different relaying nodes are retransmitting parallel to each other. Furthermore, and adopting the PR scheme, novel selection strategies are proposed aiming at reducing the overhead of the control exchange process between the destination and the relaying nodes. Numerical results show that these strategies outperform the strategies seen in the prior art that are based on Single Retransmission (SR) and that ignores the effect of control exchange overhead.

In the third part of this thesis, a joint allocation algorithm is presented assuming the presence of the full Channel State Information (CSI) at the destination side. Rather than solving the LA problem and the relaying node scheduling problem separately, an optimal joint allocation method is proposed. The presented joint strategy builds on the fact that for a given scheduling decision, an optimal rate allocation exists. Accordingly, the proposed algorithm selects the scheduling that leads to the optimal rate allocation. Furthermore, due to the complexity of the proposed algorithm, a sequential algorithm is presented. The MC simulations validate the importance of the joint allocation strategy that outperforms the non-joint allocations. Another importance of the joint allocation method is its practicality compared to the non-joint rate allocation which needs to pass exhaustively through all the possible rate values. In addition, the MC simulations validate the performance of the sequential joint allocation being a practical solution that achieves the upper bound.

In the last part of this thesis, future work and other possible directions are presented. Specifically, using online learning algorithms for rate allocation is considered. It is seen that one possible way to tackle this problem is to adopt the methods of the Multi-Armed Bandit (MAB) framework. Another direction presented was the generalization of the considered network to other orthogonality scenarios where Frequency Domain Multiplexing (FDM) is considered. Following the FDM regime, novel selection strategies are proposed. Further mentioned open challenges to the MAMRN are to consider

multiple antennas at the destination node, study non-centralized systems where games are observed, and investigate the methods needed in the non-orthogonal MAMRN.

Résumé

L'un des principaux objectifs des réseaux cellulaires 5G et 5G-beyond est de permettre la coexistence de services hétérogènes au sein d'une même architecture de réseau. Certains de ces services nécessitent des débits crêtes de données très élevés et une adaptation rapide de l'état du canal, notamment dans le cas de l'eMBB (Enhanced Mobile Broadband). Afin de répondre à ces besoins, nous cherchons à améliorer l'efficacité spectrale. La communication coopérative est l'une des principales technologies de la couche physique qui vise à optimiser l'efficacité spectrale. Le concept consiste à utiliser les ressources partagées, et les informations des utilisateurs pour améliorer les processus de transmission et de réception. Le processus de coopération est réalisé à l'aide de nœuds relais. Un nœud relais peut être un nœud relais dédié ou un nœud source qui réalise la coopération entre utilisateurs. La différence entre un nœud relais et un nœud source qui met en œuvre la coopération entre utilisateurs est le fait que ce dernier a son propre message alors que le nœud relais n'en a pas.

On considère un réseau orthogonal à accès multiple et à relais multiples (Multiple Access Multiple Relay Network (MAMRN)), dans lequel au moins deux sources communiquent avec une seule destination à l'aide d'au moins deux nœuds relais. L'orthogonalité est obtenue en utilisant le multiplexage par répartition dans le temps (Time Division Multiplexing (TDM)) et tous les nœuds de relais sont supposés être en semi-duplex alors que toutes les liaisons subissent un affaiblissement lent du signal (slow fading). La destination est le nœud central où les différentes allocations sont effectuées. Dans une phase d'initialisation, un algorithme d'adaptation de lien (Link Adaptation (LA)) est exécuté où différentes ressources sont allouées aux sources. Après cette étape, la transmission d'une trame est divisée en deux phases. Dans la première phase, les sources transmettent à tour de rôle dans des tranches de temps consécutives. Dans la deuxième phase, la destination programme le(s) nœud(s) relais pour transmettre les redondances. La deuxième phase consiste en un nombre limité de tranches de temps de retransmission. Des canaux de contrôle limités bidirectionnels sont disponibles à partir des sources et des relais vers la destination pour échanger les informations nécessaires afin que la destination soit capable d'exécuter ses stratégies de sélection/allocation.

Dans la première partie de cette thèse, le problème de LA dans la phase d'initialisation est considéré. Plus précisément, les algorithmes d'allocation de débits de données sont étudiés. En raison de la complexité de l'approche de recherche exhaustive, des algorithmes séquentiels sont proposés. Les algorithmes présentés visent à maximiser l'efficacité spectrale moyenne (Average Spectral Efficiency (ASE)) sous des objectifs individuels de qualité de service (Quality of Service (QoS)) pour une famille de schémas de modulation et de codage (Modulation and Coding Scheme (MCS)) donnée. Les algorithmes sont applicables dans des scénarios de conditions radio changeant lentement ou rapidement. Les débits sont d'abord initialisés, puis une étape de correction itérative du

débit est appliquée. En outre, contrairement aux systèmes de transmission coopératifs existants, la taille des paquets lors de la phase de transmission est considérée variable dans le temps. En d'autres termes, le processus LA est étendu pour déterminer à la fois le taux et la durée de l'intervalle de temps pour chaque source. L'ordonnancement et les algorithmes qui en résultent se rapprochent des performances de la limite supérieure, comme le démontrent les simulations de Monte-Carlo (MC). De plus, les résultats MC valident les améliorations apportées par l'utilisation de nœuds relais et par l'introduction d'une taille de paquet variable dans le temps.

Dans la deuxième partie de cette thèse, l'accent est mis sur la conception de stratégies de sélection de nœuds relais qui déterminent quels nœuds relais sont activés à chaque slot temporel dans la phase de retransmission. Un élément clé dans ce chapitre est d'exploiter la diversité des chemins multiples des différents nœuds de relais. Plutôt que de sélectionner un seul nœud relais pour aider un nœud source à un intervalle de temps de retransmission donné, les stratégies d'ordonnancement proposées attribuent une source à plusieurs nœuds relais. Un tel schéma de retransmission est appelé retransmission parallèle (Parallel Retransmission (PR)), car les différents nœuds relais retransmettent en parallèle. De plus, en adoptant le schéma PR, de nouvelles stratégies de sélection sont proposées afin de réduire la surcharge du processus d'échange de contrôle entre la destination et les nœuds relais. Les résultats numériques montrent que ces stratégies sont plus performantes que les stratégies de l'art antérieur qui sont basées sur la retransmission unique (Single Retransmission (SR)) et qui ignorent l'effet de la surcharge de l'échange de contrôle.

Dans la troisième partie de cette thèse, un algorithme d'allocation conjointe est présenté en supposant la présence de l'information complète sur l'état du canal (Channel State Information (CSI)) du côté de la destination. Plutôt que de résoudre séparément le problème de LA et le problème d'ordonnancement des nœuds relais, une méthode d'allocation conjointe optimale est proposée. La stratégie conjointe présentée s'appuie sur le fait que pour une décision d'ordonnancement donnée, il existe une allocation de taux optimale. En conséquence, l'algorithme proposé sélectionne l'ordonnancement qui conduit à l'allocation optimale des débits de données. En outre, en raison de la complexité de l'algorithme proposé, un algorithme séquentiel est présenté. Les simulations MC valident l'importance de la stratégie d'allocation conjointe qui surpasse les allocations non conjointes. Une autre importance de la méthode d'allocation conjointe est sa praticité par rapport à l'allocation de débits non conjointe qui nécessite de passer exhaustivement par toutes les valeurs de débits possibles. En outre, les simulations MC valident la performance de l'allocation séquentielle conjointe, qui est une solution pratique permettant d'atteindre la limite supérieure.

Dans la dernière partie, les futurs travaux et d'autres directions d'études possibles sont présentés. Plus précisément, l'utilisation d'algorithmes d'apprentissage en ligne pour l'allocation de debits est envisagée. On voit qu'une façon possible d'aborder ce problème est d'adopter les méthodes de type bandit à bras multiples (Multi-Armed Bandit (MAB)). Une autre direction présentée est la généralisation du réseau considéré à d'autres scénarios d'orthogonalité où le multiplexage dans le domaine des fréquences (Frequency Domain Multiplexing (FDM)) est envisagé. En suivant le régime FDM, de nouvelles stratégies de sélection sont proposées. D'autres défis ouverts pour le

MAMRN sont de considérer des antennes multiples au niveau du nœud de destination, d'étudier des systèmes non centralisés où des jeux sont observés, et d'étudier les méthodes nécessaires dans le MAMRN non orthogonal.

List of Publications

Journal Papers [1, 2]

1. Ali Al Khansa, Stefan Cerovic, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, Dynamic Rate and Channel Use allocation for Cooperative Wireless Networks. In submission in EURASIP Journal on Wireless Communications and Networking.

2. Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, Rasha Alkhansa, Centralized Scheduling for MAMRN with Optimized Control Channel Design. In submission in Annals of Telecommunications.

Conference Papers [3, 4, 5, 6, 7, 8]

1. Ali Al Khansa, Stefan Cerovic, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, (2021, September). Slow-link adaptation algorithm for multi-source multi-relay wireless networks using best-response dynamics. In International Conference on Network Games, Control and Optimization. Springer, Cham.

2. Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, (2021, May). Resource allocation for multi-source multi-relay wireless networks: A multi-armed bandit approach. In International Symposium on Ubiquitous Networking (pp. 62-75). Springer, Cham.

3. Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, Rasha Alkhansa, (2021, December). Fast Link Adaptation with Partial Channel State Information for Orthogonal Multiple Access Multiple Relay Channel (OMAMRC). In 2021 IEEE 3rd International Multidisciplinary Conference on Engineering Technology (IMCET) (pp. 11-16). IEEE.

4. Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, Rasha Alkhansa, (2022, September). Parallel Retransmissions in Orthogonal Multiple Access Multiple Relay Networks. In International Workshop on Resource Allocation and Cooperation in Wireless Networks (RAWNET), 2022.

5. Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, Rasha Alkhansa, (2022, October). Centralized Scheduling for Frequency Domain Orthogonal Multiple Access Multiple Relay Network. In 2022 27th Asia-Pacific Conference on Communications (APCC). IEEE.

6. Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, (2022, December), Joint Rate and Relaying Nodes allocation for Fast Link Adaptation with Full Channel State Information. Accepted in the 5th International Conference on Advanced Communication Technologies and Networking (CommNet 2022).

Patents [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]

1. Ali Al Khansa, Raphael Visoz, Stefan Cerovic, "Procédé et système OMAMRC de transmission avec variation du nombre d'utilisations du canal", Application No: FR2004643. Date de dépôt: 12/05/2020.

2. Ali Al Khansa, Raphael Visoz, "Procédé et système OMAMRC avec transmission FDM", Application No: FR2006623. Date de dépôt: 24/06/2020.

3. Ali Al Khansa, Raphael Visoz, "Procédé de réception d'au moins une trame de données dans un système OMAMRC, destination, programme d'ordinateur et système correspondants", Application No: FR2014132. Date de dépôt: 24/12/2020.

4. Ali Al Khansa, Raphael Visoz, "OMAMRC retransmission par source avec MRT", Application No: FR2205907. Date de dépôt: 16/06/2022.

5. Ali Al Khansa, Raphael Visoz, "Procédé de retransmission coopérative dans un système OMAMRC", Application No: FR2206422. Date de dépôt: 28/06/2022.

6. Ali Al Khansa, Raphael Visoz, "Procédé de transmission et système OMAMRC avec une stratégie de sélection lors de retransmissions tenant compte du débit des sources et d'un unique échange de contrôle Domaine de l'invention", Application No: FR2206443. Date de dépôt: 28/07/2022.

7. Ali Al Khansa, Raphael Visoz, "Procédé de transmission et système OMAMRC avec une stratégie de sélection lors de retransmissions tenant compte du débit des sources et d'un ou plusieurs échanges de contrôle Domaine de l'invention", Application No: FR2206446. Date de dépôt: 28/07/2022.

8. Ali Al Khansa, Raphael Visoz, "Procédé de retransmission coopérative dans un système OMAMRC avec allocation de ressources et sélections des sources à aider conjointes", Application No: FR2210608. Date de dépôt: 14/10/2022.

9. Ali Al Khansa, Raphael Visoz, "Procédé et système OMAMRC avec transmission FDM et coopérations multiples par sous-bande", Application No: FR2210584. Date de dépôt: 14/10/2022.

10. Ali Al Khansa, Raphael Visoz, "Stratégie de sélection optimale à l'aide d'un échange CSI pour l'OMAMRC", Application No: FR2214095. Date de dépôt: 21/12/2022.

11. Ali Al Khansa, Raphael Visoz, "Stratégie de sélection optimale à l'aide d'un échange CSI conditionnel pour l'OMAMRC", Application No: FR2214097. Date de dépôt: 21/12/2022.

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List of Acronyms

AF	Amplify-and-Forward
ASE	Average Spectral Efficiency
AUCB1	Approximated UCB1
AWGN	Additive White Gaussian Noise
BLER	BLock Error Rate
BRD	Best-Response Dynamics
CC	Coded Cooperation
CDI	Channel Distribution Information
CF	Compress-and-Forward
CMAB	Combinatorial MAB
CN	Cellular Networks
CoF	Compute-and-Forward
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSMAB-F	Combinatorial Sleeping MAB model with Fairness constraints
CUR	Channel Use Ratios
DDF	Dynamic Decode-and-Forward
DF	Decode-and-Forward
DMRS	Demodulation Reference Signals
DMT	Diversity-Multiplexing Trade-off
DoF	Degree of Freedom
D2D	Device-to-Device
eMBB	enhanced Mobile Broadband
EE	Energy-Efficient
EGC	Equal Gain Combining

FDM	Frequency Division Multiplexing
FLA	Fast-Link Adaptation
GA	Genie-Aided
HARQ	Hybrid Automatic Repeat Request
IAB	Integrated Access and Backhaul
IR	Incremental Redundancy
JNCC	Joint Network Channel Coding
JNCD	Joint Network Channel Decoding
LA	Link Adaptation
LDPC	Low-Density Parity-Check
MAB	Multi-Armed Bandit
MAMRN	Multiple Access Multiple Relay Network
MARN	Multiple Access Relay Network
MC	Monte-Carlo
MCS	Modulation and Coding Schemes
MRC	Maximum Ratio Combining
MRN	Multiple Relay Network
MRT	Maximum Ratio Transmission
MU	Multi-User
NF	Neuro-Fuzzy
NOAF	Non-Orthogonal Amplify-and-Forward
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OMA	Orthogonal Multiple Access
PR	Parallel Retransmission
QMF	Quantize-Map-and-Forward

QoS	Quality of Service
RBN	Relay Broadcast Network
R-D	Relay-to-Destination
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RP	Relaying Protocols
R-R	Relay-to-Relay
S-D	Source-to-Destination
SDF	Selective Decode-and-Forward
SINR	Signal-to-Interference-and-Noise-Ratio
SLA	Slow-Link Adaptation
SNR	Signal-to-Noise-Ratio
S-R	Source-to-Relay
SR	Single Retransmission
SRS	Sounding Reference Signals
S-S	Source-to-Source
SU	Single-User
SUCB1	Sequential UCB1
TDM	Time Division Multiplexing
TRN	Three-terminal Relay Network
TS	Thompson Sampling
TWFDAF	Two-Way Full-Duplex Amplify-and-Forward
TRN	Three-terminal Relay Network
UCB	Upper Confidence Bound
VCU	Variable Channel Use
WSN	Wireless Sensor Networks

List of Notations and Operations

ϕ	The empty set
$\mathbb{C}$	The set of complex numbers
$\mathbb{R}$	The set of real numbers
$\mathbb{F}_2$	The binary Galois field
$\mathbb{E}\{.\}$	The expected value
$[q]$	The Iverson bracket having the value 1 if q is satisfied, and 0 otherwise
$\lceil q \rceil$	The ceiling function which takes the least integer greater than or equal to q
$\lvert\mathcal{S}\rvert$	Cardinality of set $\mathcal{S}$
$s \in \mathcal{S}$	s is an element of set $\mathcal{S}$
$\mathcal{S} \cup \mathcal{R}$	The union of sets $\mathcal{S}$ and $\mathcal{R}$
$\mathcal{S} \cap \mathcal{R}$	The intersection of sets $\mathcal{S}$ and $\mathcal{R}$
$\mathcal{S} \subset \mathcal{R}$	Set $\mathcal{S}$ is a subset of set $\mathcal{R}$
$\mathcal{S} \subseteq \mathcal{R}$	Set $\mathcal{S}$ is subset or equal to set $\mathcal{R}$
$\mathcal{S} \setminus R$	The minus operation between the sets $\mathcal{S}$ and $\mathcal{R}$ in set theory
$\overline{\mathcal{S}}$	The complement of set $\mathcal{S}$ in set theory
$\mathrm{Pow}(\mathcal{S})$	The power set of $\mathcal{S}$, i.e., the set of all possible subsets of $\mathcal{S}$
$\Pr\{.\}$	The probability of an event
log	Logarithmic function
exp	Exponential function
$\boldsymbol{A}^T$	Transpose of $\boldsymbol{A}$
$\boldsymbol{A}^{-1}$	Inverse of $\boldsymbol{A}$
$\wedge$	The logical and

Chapter 1

Introduction

1.1 Cooperative communication and Relaying Protocols (RP)

Cooperative communication is known to be one of the most effective techniques to improve the coverage and capacity of wireless networks. The research on cooperative systems is widespread and still a hot topic today. Today, users demand to have access to all wireless services no matter the settings they are in (time, location). As wireless networks are now an integral part of our modern society, and as the demand for better quality and availability of wireless services is increasing, cooperative communication is seen as a promising solution to answer the increasing demands. Although wireless technologies are always updating to novel strategies, the increasing number of users in the networks imposes quite big challenges by their nature when it comes to their design (environment, scarce frequency spectrum, etc.). Accordingly, we investigate the concept of cooperative communication being one possible avenue for overcoming those challenges. The main idea is to allow devices to share their available resources in power and/or bandwidth, as well as their antennas, in order to mutually enhance their transmission and reception.

When talking about cooperative networks, different factors/metrics are considered. The first factor to take into consideration is the number of sources, relays, and destinations included in the network. Following the number of each of these nodes, different types of networks are formed, and thus, different cooperative scenarios are seen. The second factor to take into consideration is the relaying protocol being used. A relaying protocol represents the rule that the relaying nodes will follow in their retransmissions. The third factor to take into consideration is whether the system is centralized or decentralized. A centralized system, which is adopted in this thesis, means that there is a central node which performs the different allocations needed in the transmission and retransmission. Speaking of which, the fourth factor to take into consideration in a cooperative system is the selection strategy used. The scheduling problem consists in the organization of the retransmission of the relaying nodes. In other words, the scheduling strategy decides which relaying nodes are going to be active and send redundancies and which relaying nodes are not. The fifth factor is resource allocation. The resource allo-

cation problem poses the question of how should we use the available scarce resources in an optimized way depending on the different scenarios of the network. These factors are tackled in this thesis with the goal to propose suitable/practical solutions for the related problems leading to optimal performance.

1.1.1 Different cooperative networks

From a historical point of view, cooperative communication goes back to the year 1970, when van der Meulen derived the upper and lower bounds of the channel capacity of a Three-terminal Relay Network (TRN) [20]. In that reference, and in other works of van der Meulen, we see some fundamental principles and general problems related to cooperative communication. Then, other relay channels and further cooperative networks were investigated as in [21]. Remarkable work on relaying was done by Cover and El Gammal in several publications as in [21, 22, 23]. Using the min-cut max-flow capacity upper bound, the capacity is established for degraded and reversely degraded feedback relay channels. Until today, the main results of these works have not been surpassed.

Basically, the system model of cooperative communication channels is composed of three main components: source, relay, and destination nodes. According to the number of each of these elements, the nature of the cooperative channel is determined. For a multiple number of relays, the TRN can be extended to Multiple Relay Network (MRN) consisting of a single source, a single destination, and multiple relay nodes. Such kind of channels was investigated in [23, 24, 25]. Similarly, a Relay Broadcast Network (RBN) is composed of a single source, a single relay, and multiple destination nodes [26]. As a natural counterpart of the RBN, the Multiple Access Relay Network (MARN) is composed of multiple source nodes, with a single relay, and a single destination [27, 28, 29]. In the mentioned networks, several problems were investigated in the prior art.

In MRN, the reference [24, 26] derived novel achievable rates and capacity upper bounds along with corresponding information-theoretic coding schemes. There, the authors present different types of discrete memory-less and fading channels. In [30], large Gaussian MRN is investigated where the number of relays is assumed very large. It is seen that for an infinite number of relays, the upper and lower bounds on the capacity coincide. In [31], the authors studied the power efficiency of sensory and ad-hoc MRN. The RBN was introduced in [26] where two destinations are considered. In other works, this network is referred to as Dumb Relay Broadcast channel [32]. In the latter reference, the capacity region is derived for fully and partially cooperative RBC. In [33, 34], the case of multiple receivers is provided where new coding schemes and the corresponding achievable rate regions were proposed. Several works targeted the MARN which is seen as an important class of relay networks. Such a network is seen interesting in situations where some sources are too weak to cooperate by can send their data to more powerful nodes. This network was introduced in [27], and the capacity upper bound was derived for Gaussian and discrete memory-less MARN. In [29], the three-tier hierarchical wireless sensor MARN was considered, where the capacity bounds were given for both scenarios with half-duplex and full-duplex relays.

In this thesis, we consider the Multiple Access Multiple Relay Network (MAMRN) composed of multiple source nodes, multiple relay nodes and a single destination. This

Cooperative Network	Reference
Three-terminal Relay Network (TRN)	[20, 21, 22, 23]
Multiple Relay Network (MRN)	[23, 24, 25, 26, 30, 31]
Relay Broadcast Network (RBN)	[26, 32, 33, 34]
Multipl Access Relay Network (MARN)	[27, 28, 29]
Multiple Access Multiple Relay Network (MAMRN)	[26, 36, 37], This Work

Table 1.1: Different cooperative networks.

system can be seen as a generalization of the previously mentioned systems, except for the RBN which includes multiple destination nodes. The considered system is seen in nowadays applications. In [35] for example, it is stated that the considered structure (i.e., the MAMRN) is the main topology structure for UAV cooperative surveillance networks. However, it is seen in [26] that the capacity region of the general MAMRN is still unknown. In MAMRN, the multiple access can be either orthogonal (as considered in this thesis and in other works: check [36]) or non-orthogonal (check [37]), where orthogonality may be achieved through time, frequency, or code division multiplexing.

Throughout the different prior arts that targeted the MAMRN, two major (recent) works are the ones done in the theses [36] and [37]. In [37], the outage analysis of different examples of MAMRN is presented (check [38, 39, 40]). The analysis covers different coding and decoding schemes as well as different transmission scenarios (orthogonal and non-orthogonal). Also in [37], several selection strategies are proposed for the MAMRN (check [41]). In [36], further contributions are presented related to the MAMRN while focusing on orthogonal MAMRN. Three main problems were investigated: resource allocation problems, relaying nodes selection strategies (check [42]), and control exchange process problems (check [43]).

In this thesis, user cooperation is considered, where a user that does not have a message to send, acts as a relay node in order to improve the performance [43]. The relaying nodes (i.e., the sources and the relays) are assumed half-duplex; they can listen to each other while not transmitting. The concept of user cooperation was introduced in the work of Sendonaris et al. [44, 45] where it is sometimes referred to by "cooperative diversity" [46]. In these works, user cooperation is seen as a promising method that have significant gain in various performance metrics (i.e., outage probability, diversity gain, multiplexing gain, diversity-multiplexing trade-off, etc.). We summarize the mentioned cooperative networks in table 1.1.

1.1.2 Different relaying protocols

In our work, the relaying nodes apply the Selective Decode-and-Forward (SDF) relaying protocol, which means that they can forward only a signal representative of successfully decoded source messages. The error detection is based on Cyclic Redundancy Check (CRC) bits that are appended to each source message. The SDF relaying protocol is

an advanced version of the Decode-and-Forward (DF) relaying protocol. The principle of DF protocol is introduced in [21], where unlike SDF, cooperative nodes are obliged to wait to successfully decode all the source messages before starting to cooperate. In [25], an orthogonal multiple DF relaying network was presented, in which a diversity analysis and error probability derivation was carried out. In [47], the problem of resource allocation in DF cooperative communication networks was investigated, considering a limited rate feedback channel. SDF belongs to the category of non-linear (regenerative) relaying protocol.

Other commonly used protocols in the literature that belong to the same category are Compress-and-Forward (CF) [48, 49], Compute-and-Forward (CoF) [50, 51], and Quantize-Map-and-Forward (QMF) [52]. In the CF relaying protocol, the relay transmits an estimated version of its observation of the received signal. The relay node uses source coding to exploit the side information available at the destination. In the CoF relaying protocol, the relay decodes linear equations of the transmitted messages using the noisy linear combinations provided by the channel. Such a protocol is suitable in multi-source networks where more than one source is included. The QMF relaying protocol is another generalization of CF relaying protocol, where the estimated version of the signal is based on quantizing the received signal at the noise level and mapping it to a random Gaussian codeword for forwarding. The final destination decodes the source's message based on the received signal.

The most famous example of the category of the linear relaying protocol is certainly Amplify-and-Forward (AF) [53, 54], while there exist many other interesting RP, such as Coded Cooperation (CC) [55]. In the AF relaying protocol, the relay transmits an amplified version of its received message. It can be seen as a repetition code, where a relay is simply forwarding a scaled version of its received signal. For CC, the principle is to partition the codewords of each transmitting node and transmit each part through an independent channel. Other types of RP are Non-Orthogonal Amplify-and-Forward (NOAF) [56] and Dynamic Decode-and-Forward (DDF). These protocols are evaluated in terms of Diversity-Multiplexing Trade-off (DMT) [57]. In DDF, a certain approach is needed to choose the point where the relay switches from listening to transmitting. As this point is not fixed, fountain codes [58] are considered as they do not have a predetermined rate at the transmitter.

Performance evaluation and comparison of the mentioned protocols are done in the literature (e.g., in [59, 60, 61]), where we can see that there exist some scenarios where the SDF relaying protocol is outperformed by some other protocols. Nevertheless, there is no decisive conclusion in this research area, and rigorous fair comparisons still have to be done for the slow fading half-duplex MAMRN. We summarize the mentioned RP in tables 1.2 and 1.3.

Relaying Protocol	Type	Reference
Decode-and-Forward (DF)	Regenerative	[21, 25, 47]
Selective Decode-and-Forward (SDF)	Regenerative	[43], This Work
Dynamic Decode-and-Forward (DDF)	Regenerative	[57]
Compress-and-Forward (CF)	Regenerative	[48, 49]
Compute-and-Forward (CoF)	Regenerative	[50, 51]
Quantize-Map-and-Forward (QMF)	Regenerative	[52]
Amplify-and-Forward (AF)	Linear	[53, 54]
Coded Cooperation (CC)	Linear	[55]
Non-Orthogonal AF (NOAF)	Linear	[56]

Table 1.2: Relaying protocols summary: retransmission type and protocol.

Method	Reference
Obliged to wait to decode all sources before starting relaying	[21, 25, 47]
Can switch to relaying before decoding all sources	[43], This Work
Switching point between listening and relaying is not fixed	[57]
An estimated version of the received signal is transmitted	[48, 49]
Uses noisy linear combination to decode transmitted messages	[50, 51]
A quantized version of the signal is transmitted	[52]
Repetition code, transmitting amplified version of the signal	[53, 54]
Uses partition of the codewords of each transmitting node	[55]
Uses AF for NOMA to serve primary and secondary users	[56]

Table 1.3: Relaying protocols summary: retransmission method.

1.2 Link adaptation

The Link Adaptation (LA) problems play a major role in the performance of wireless networks. LA relates to how the nodes in the network adapt to the channel gains and the radio conditions. Accordingly, and based on the state of the network, LA includes the process of allocating the resource elements to the different nodes. The LA process includes different allocations such as power allocation, scheduling, sub-carrier allocation, and any possible scarce resource allocation. Upon following cooperative networks, a new Degree of Freedom (DoF) is seen corresponding to the retransmission phase. In other words, the allocation presented in the state of the art for non-cooperative networks is not (always) applicable for cooperative systems. We focus in this thesis on LA problems for MAMRN where Time Division Multiplexing (TDM) is taken for orthogonality. Specifically, we focus on the rate allocation problem, and furthermore, the joint rate and channel use allocation. Note that the generalization to Frequency Domain Multiplexing (FDM) is quite simple, and is going to be investigated in the last chapter of this thesis.

1.2.1 Different link adaptation problems

In the prior art, several works tackled the problem of resource allocation [62, 63]. In [64, 65], the power allocation problem is investigated. In [64], the authors give the power allocation that maximizes the mutual information over parallel channels. The presented policy generalizes the water-filling solution and retains some of its intuition. In [65], the bit and power loading problem is addressed as a constrained multi-variable non-linear optimization problem. The authors present the main classes of loading problems, such as rate maximization and margin maximization. Other works target the power allocation problem in cooperative networks [66, 67]. The reference [66] targets the Device-to-Device (D2D) communication in cellular networks. It aims at optimizing the power allocation in cooperative wireless network localization. The authors decomposed the power allocation problem into infrastructure and cooperation phases, developed several power allocation algorithms, and their numerical results validated the significant improvement in localization accuracy compared to uniform strategies. On the other hand, the reference [67] targets the power allocation problem from the energy-saving perspective.

Concerning the sub-carrier allocation problem, several papers targeted this problem in non-cooperative networks [68, 69, 70, 71] and in cooperative networks [72, 73]. The reference [68] represents a survey of the different heuristic channel allocation methods. Another survey is presented in [70], where the aim of the channel allocation techniques presented was to reduce contention with energy requirements. In [69], a novel channel allocation technique is presented following different non-dominated sets of solutions following different objectives. In a recent publication [71], the authors propose a novel channel allocation technique that uses artificial intelligence and specifically genetic algorithm. It was found that the optimized result with the help of genetic algorithm was better than the results without using genetic algorithm.

On the other hand, a lot of research interest is seen in the rate allocation problem. In [74, 75, 76, 77, 78], the authors present the capacity region of different networks. The capacity region represents the set of source rates of a network that can possibly be decoded by the destination. Following this definition, we see the link between rate allocation and capacity region analysis. On the other hand, and for the networks where the capacity region is not well-known, the rate allocation problem answers the question of what rate each source should use to improve the transmission and reception. In [79], the rate allocation problem from the perspective of energy efficiency is presented for Non-Orthogonal Multiple Access (NOMA) networks. In this letter, statistical state information is assumed, and the energy minimization problem under latency and outage constraints is formulated. The authors propose an iterative water-filling-based rate allocation algorithm that reduces energy consumption. In [80], on the other hand, a dynamic sensor fusion communication network is considered, and the rate allocation is optimized based on a heuristic approach that minimizes a weighted sum of communication costs subject to a constraint on the state estimation error at the fusion center. Furthermore, several works tackled the LA for cooperative networks [81]. The authors of [82] propose a Neuro-Fuzzy (NF) algorithm to perform the relay selection and resource allocation process. More recent works (see [83, 84]) tackled the LA problems for multi-source cooperative systems. In [85], a survey is presented related to the LA problem of

Link Adaptation Problem	Reference
Power Allocation	[64, 65]
Power Allocation for Cooperative Networks	[66, 67]
Channel Allocation	[68, 69, 70, 71]
Channel Allocation for Cooperative Networks	[72, 73]
Rate Allocation	[74, 75, 76, 77, 78]
Rate Allocation for Cooperative Networks	[81, 82, 83, 84, 85, 86, 87, 88]
Joint Power and Channel Allocation	[89, 90, 93, 94, 95]
Joint Channel and Rate Allocation	[91]
Joint Rate Allocation and Power	[92]

Table 1.4: Different link adaptation problems.

cooperative networks.

Most of the papers that deal with an efficient rate allocation problem in the combination with a control exchange process consider a single source, a single or eventually multiple relays, and a single destination. In [86] a presence of a fixed infra-structured relay is considered, and it is shown that large gains in throughput and coverage area can be obtained when the source and the relay are allowed to use different spectral efficiencies, where the simple selection combining technique is used. A scenario of a single ad-hoc relay with no direct link available from the source to the destination where the repetition coding is adopted, i.e. Chase Combining (CC)-type of Hybrid Automatic Repeat Request (HARQ), is studied in [87]. There, a rate allocation strategy of both source and relay is proposed under the outage probability constraint and both finite and infinite allowed number of retransmissions constraint. In [88], a rate adaptation problem is presented as a Markov decision process where dynamic programming is employed for optimization, in a single relay scenario with the feedback available from both the relay and the destination to the source. Incremental Redundancy (IR)-type HARQ technique is adopted in that work, and the advantage in terms of average throughput and the outage probability compared with the non-adaptive HARQ is demonstrated, where the analysis is also extended to multiple relay scenarios.

Other interesting works concerning the link adaptation problems are the ones that target joint allocation strategies. In such works, authors target the optimization of more than one resource element. In [89, 90], the authors target the joint allocation of channel and power for different wireless networks. In [91] on the other hand, a joint allocation of channel and rate is presented. Joint power and rate optimization for multihop relay network (where multiple relays are serially connected from the source to the destination) where the IR-HARQ technique is used is investigated in [92]. It is shown that the proposed scheme outperforms both IR-HARQ scheme with fixed power and rate and CC-HARQ scheme in terms of the long-term average transmission rate. We summarize the mentioned LA works in table 1.4.

1.2.2 Link adaptation problems in learning and decentralized networks

In most of the previously mentioned works, a central node was responsible for the different allocations of resources. Also, in most of the mentioned works the allocation was based on some knowledge of the channel states. Nevertheless, other methods for LA are seen in other frameworks such as game theory (decentralized system) or in learning framework (no knowledge of the channel states). In the learning framework, some of the LA problems can be formulated as Multi-Armed Bandit (MAB) problem. The main issue which MAB framework tackles is the exploration-exploitation dilemma. In scenarios where multiple choices are possible (multiple arms), each with an unknown average reward, MAB algorithms give sequential steps to decide whether we need to learn more (exploration), or to stay with the option that gave the best rewards in the past (exploitation).

There are different types of MAB problems, each based on the assumptions of the problem. In the survey [96], three different fundamental types of MAB problems were mentioned, stochastic, adversarial, and Markovian. In this manuscript, we are more interested in the stochastic MAB problem, as it aligns with the case of the rate allocation problem (the reward is stochastic) as we will see next. From a historical point of view, Lai and Robbins [97] introduced the first analysis of stochastic bandits with an asymptotic analysis of regret. There, the principle of *optimism in the face of uncertainty* (to be optimistic while thinking about the not well explored choices) was used and the Upper Confidence Bound (UCB) algorithm was proposed. This concept is widely used in most of the MAB literature.

In UCB-like algorithms, we favor the exploration of actions with a strong potential to have an optimal value [98], and UCB measures this potential by upper confidence bound of the reward value. Based on this type of literature, a lot of algorithms have been further proposed [99] (section 2.2) and [100]. In [100], the authors proved that the proposed KL-UCB algorithm attains the optimal rate in finite-time. In addition, they proved that this algorithm is optimal for Bernoulli distributions (problems with the reward of Bernoulli distribution).

Another type of algorithms widely used is based on Thompson Sampling (TS) (also known as posterior sampling and probability matching) [101]. Contrary to UCB-type algorithms, the TS algorithms are based on the assumption of posterior distribution for the unknown metric we are trying to learn. The algorithm chooses the arm which maximizes the expected reward based on the current distribution. Then, after each iteration, the posterior distribution is updated. Although this type of algorithms was ignored in the academic literature until recently, several nowadays problems are using these strategies [102]. For interested readers, [103] gives a detailed discussion on when, why, and how to apply TS.

Besides UCB-type and TS-type algorithms, there are also different approaches to tackling the MAB problem. In [104], rather than using the concept of *optimism in the face of uncertainty*, a new general algorithm is proposed aiming at matching the minimal exploration rates of sub-optimal arms as characterized in the derivation of the regret lower bound. In this algorithm, rather than only performing exploration and

exploitation, a third process is taken into consideration as well: estimation. For simpler algorithms, ϵ-greedy is a well-known algorithm, where a fixed value $\epsilon \in [0, 1]$, decides the percentage of time you spend on exploration and exploitation. Since, with a fixed value of ϵ, we will reach a linear (not logarithmic) regret, decreasing ϵ-greedy algorithms are used, taking ϵ as a decreasing variable with time (usually it is in the form of a fraction between a constant and time). We find in the literature several papers comparing the previously mentioned algorithms, as in [105], where the power allocation problem was solved using several algorithms, such as the UCB, TS, and ϵ-greedy.

The MAB selection strategy can be generalized to a case where multiple arms are selected jointly at each decision instance. Such kind of MAB problems is given under the name of Combinatorial MAB (CMAB), where a subset of arms is selected at each step, forming a *Super Arm*. In the literature, CMAB was investigated in several applications. In [106], the problem of beam selection in a vehicular network was solved using CMAB algorithms, based on TS. In [107], CMAB was also presented but this time using UCB-type algorithms. There, two applications were selected, online advertising and social influence maximization for viral marketing. In [108], Combinatorial Sleeping MAB model with Fairness constraints (CSMAB-F) was presented. The concept of sleeping arm is when some arms are not always available.

In the literature, the LA problem is also seen in decentralized networks. In such networks, the notion of games (and game theory) is presented. In LA games, there are multiple players competing on scarce resources with the goal of getting the optimal reward. The reward of each player is a function of the decision of the player itself and the other competing players. In addition, game theory is seen in cooperative networks such as in interference relay networks [109, 110]. In [93], the problem of joint allocation of power and sub-channel is investigated for cooperative networks. There, an AF relay assigns the sub-channels and allocate the different level of power to a set of sources and destinations pairs. Each pair consists of a source node and a destination node, where the source node transmits through the relay to its paired destination node. Joint sub-channel and power allocation is then formulated as a non-convex optimization problem to maximize the total sum-rate. The optimal solution for this problem is NP-hard and requires an exhaustive search. Therefore, an efficient low-complexity resource allocation algorithm is required. In [93], this problem was tackled using matching theory. There, two low-complexity algorithms were proposed. Another method is to tackle the system using game theory perspective, aiming to study the equilibria points of the system (similar to the analysis presented in [111]). The previous problem can be further separated into two sub-problems, a sub-channel allocation problem and a power allocation problem. Such separation can lead to a bi-form problem (check for example [94, 95]), i.e., a problem decomposed into a competitive sub-problem (sub-channel allocation) and a cooperative sub-problem (relay power allocation). In [112], the joint power and rate allocation problem in the game theoretical framework is presented, followed by the analysis of convergence and uniqueness. Finally, in [113], a survey over implementing the game theoretical framework in cognitive radio network for channel allocation. We summarize the mentioned LA learning and game theory works in table 1.5.

Allocation Method	Reference
MAB UCB	[97, 98, 99, 100]
MAB TS	[101, 102, 103]
MAB ϵ-greedy	[105]
CMAB	[106, 107, 108]
Matching theory	[93]
Game theory	[109, 110, 111, 112, 113]
Bi-form problem	[94, 95]

Table 1.5: Different link adaptation problems in learning and decentralized networks.

1.3 Relaying nodes selection strategies

The relaying nodes selection strategy or the retransmission scheduling problem consists in the organization of the retransmission of the relaying nodes. It describes the algorithm that the destination uses to decide which relaying nodes are going to be active and send redundancies and which relaying nodes are not. In the state of the art, several works targeted the selection strategy problem. In [114], the analysis of HARQ mechanism in single relay cooperative networks is presented. In [115], user scheduling for cooperative communication systems is studied. There, a perfect links assumption is adopted between the sources and the relays and which might be unrealistic from a practical point of view. The same assumption is considered in reference [116], where a Two-Way Full-Duplex Amplify-and-Forward (TWFD-AF) paradigm is studied. The authors propose a max-min relay selection strategy which selects the relay that maximizes the minimum Signal-to-Interference-and-Noise-Ratio (SINR) at the respective sources. Besides the unrealistic assumption that the nodes have full knowledge of the channel fading coefficients, another drawback of this work is that the analysis is limited to a scenario with only two sources.

The references [6, 43, 90, 117] consider the relay selection problem for the MAMRN. In [90], a relay ordering algorithm is proposed aiming at exploiting the communication between the relays. In [117], a relaying node selection strategy is proposed which aims at minimizing the common outage while performing Multi-User (MU) encoding. It is meant by MU encoding that a relaying node helps multiple source nodes at the same time. In [43], a novel strategy is used. Rather than minimizing the common outage as in [117], the strategy of [43] selects the relay having the highest mutual information with the destination. It is seen that this strategy outperforms the one proposed in [117]. This can be justified by the fact that although minimizing the common outage might increase the spectral efficiency, it does not necessarily maximize it. A similar method is seen in [118], with the limitation of considering a single source system, with multiple relays. The authors of [43] investigated Single-User (SU) encoding where a selected relaying node only helps a single source node. Although the MU encoding used in [117] is promising, it lacks practicality. SU encoding, on the other hand, is practical as it is a protocol based on existing Low-Density Parity-Check (LDPC) and Turbo codes which are used in the 3GPP LTE standards.

To our interest, the publication [43] shows that the performance of MU and SU

Reference	Network	Encoding	RP	Metric	RT	Control Exchange
[116]	$(2, L, 1)$	MU	AF	OP	SR	not considered
[90]	$(M, L, 1)$	MU	DF	OP	SR	not considered
[117]	$(M, L, 1)$	MU	SDF	ASE	SR	non-Minimal
[43]	$(M, L, 1)$	MU/SU	SDF	ASE	SR	non-Minimal
[6]	$(M, L, 1)$	SU	SDF	ASE	PR	non-Minimal
[118]	$(1, L, 1)$	SU	AF	BER	SR	not considered
[119]	$(1, L, 1)$	SU	AF	EC	PR	not considered
[2]	$(M, L, 1)$	SU	SDF	ASE	PR	Minimal

Table 1.6: Scheduling literature review summary. $M > 1$: number of sources; $L > 1$: number of relays; OP = outage probability; BER = bit error rate, EC = effective capacity; RT = retransmission type; CE = control exchange design.

encoding is quite similar. Following this result, we propose a novel selection scheme based on the practical SU encoding [6] (investigated in detail in chapter 4 section 1). In all the previously mentioned works [43, 114, 115, 117], a single relay is selected at each time slot in the retransmission phase. As SU is being used, the strategy proposed in [6] aims at exploiting the multi-path diversity of the relaying nodes. The idea is based on the fact that each relaying node has its own power budget, and thus, several relaying nodes can be activated at the same time. Thus, [6] proposes a strategy where multiple relaying nodes are activated to help one selected source node. The idea of this strategy which is also called Parallel Retransmission (PR), is that rather than choosing the best relaying node to send redundancies, the destination chooses the best source node which can be helped by multiple relaying nodes. Upon activating several relaying nodes, a better redundancy version of the considered source could be received at the destination. It is seen that PR introduced in [6] outperforms Single Retransmission (SR) used in [43, 117]. In [119], a similar concept is adopted for a two-way communication network. There, the authors consider a one-source multiple-relay network, where the Maximum Ratio Combining (MRC) technique is used at the receiver (i.e., the destination).

In the prior art [6, 43, 117], the authors first design a control exchange strategy to give the destination useful information about the state of the relaying nodes (and their decoding sets: a decoding set is a set which includes the source nodes which a relaying node decoded correctly at a given time instant). Then, they present some relaying nodes selection strategies. The drawback in the prior art is that the control exchange design is heavy (leads to a heavy overhead). There, at each selection, a control exchange process is performed (even if it was not needed at all). In [2] (investigated in detail in chapter 4 section 2), we tackle the relaying node selection problem, aiming at maximizing the Average Spectral Efficiency (ASE) while optimizing the control exchange design in the system. Our intuition is that, upon wisely using the available information at the scheduler, a lighter control exchange design can be used while maintaining good performance. In tables 1.6 and 1.7, we present a summary of comparisons between the prior arts and the current work.

Ref	Selection Strategy
[116]	Max-min of the SINR
[90]	No selection, all relays transmit successively
[117]	Relaying node that minimizes the common OP
[43, 118]	Relaying node with the highest mutual information
[6, 119]	Relaying nodes with the highest equivalent mutual information
[2]	Using [6, 119], select a vector of sources which maximizes the sum-rate

Table 1.7: Different selection strategies of the current and the prior arts.

1.4 Motivation and scope of the thesis

The global aim of this work is to optimize the cooperative communication in the orthogonal MAMRN. This leads to solve the related problems for such networks. The motivation behind adopting a cooperative scheme is due to its potential in achieving some Quality of Service (QoS) constraints and in its ability to improve the communication. On the other hand, the motivation behind targeting a MAMRN is that it can be included in different typical wireless communication scenarios such as:

- Wireless Sensor Networks (WSN)
- Cellular Networks (CN)
- Integrated Access and Backhaul (IAB) in New Radio (NR)
- Relay assisted D2D communications

In WSN (e.g., [29]), a central node receives data from the cooperative sensors, possibly using intermediate nodes with better capabilities (i.e., computation and communication capabilities). In CN, mobile terminals of users in good radio conditions can act as relays helping the base station being the destination in decoding of the transmitted messages of the users in bad ratio conditions. Similar scenario can be used upon using a dedicated relays, where these relays can be fixed in some suitable locations or even can be moving (e.g., a relay can be placed on a moving vehicle). In IAB scenarios [120], the resources are shared between access and backaul links. For example, we can see scenarios where there is a deployment of NR cells with no need of deploying the transport network proportionally. In such scenarios, the IAB-nodes are acting as relays.

We follow a slow fading assumption meaning that channel gains are assumed to be constant during a frame. The transmission of the sources are divided into frames consisting of time slots. Orthogonality between the sources is achieved via TDM. The simplest way to reduce the effect of interference is to avoid it using orthogonality. From theoretical information theory point of view, NOMA is known to be more optimal for slow fading channel. Nevertheless, the required complexity of the NOMA receiver design

is still not used in practice. We define a relaying node as a node which is able to help other nodes. Thus, a relaying node can either be a dedicated relay node, or, on the other hand, a source which performs user cooperation. Such a source acts as a relay when it does not have an own message to transmit. User cooperation acts as an additional DoF in the RP and in the cooperative communication.

In a MAMRN, we have $M > 1$ sources communicating with a single destination with the help of $M + L > 1$ relaying nodes. The first M relaying nodes are the sources which perform user cooperation and the L relaying nodes are dedicated relays which are used only for retransmission aspects (they have no own message to send). The relaying nodes, being half-duplex, are only capable of either receiving or transmitting information flows in the same channel resource. In the literature, the majority of the works that tackle the cooperative networks assume Orthogonal Multiple Access (OMA) and half-duplex relaying nodes. Nevertheless, some approaches proposed to combat the half-duplex constraint such as seen in [121]. We assume that the Channel State Information (CSI) is available at the receiver of each direct link.

Another motivation for considering the MAMRN is that we believe that there are a lot of contributions that could be investigated. Due to the multiple different factors that might be optimized, we seek in this manuscript to propose novel solutions and novel strategies to the problems that are not targeted before. In other words, we suspect that there are many DoF in the considered network that we could explore. This is seen in the different patents we filed throughout this thesis, ensuring the novelty and variety of the different directions of the considered network.

In [41], we see that even advanced RP are limited according to the half-duplex constraint. In other words, the cooperation process using a half-duplex relay depends on the listening/retransmitting process that leads to the problem called "switching problem". The switching problem tackles the issue of when to stop listening and decoding more sources and when to start helping the successively decoded source messages. In fact, a relaying node might prefer to cooperate with a limited number of successfully decoded sources for a longer duration instead of waiting too long to get to cooperate with more number of sources. One way to solve this problem is to use full-duplex relays. Another method is to use limited feedback control channels from the relaying nodes to the destination and from the destination to the relaying nodes. We assume the availability of an unicast forward coordination control channel from all the relaying nodes towards the destination. On the other side, we assume the availability of a broadcast control channel from the destination to the relaying nodes. These control channels are of limited rates. Now, using the exchanged information in the mentioned control channels, the destination could decide for each time slot which node(s) to transmit and which node(s) to listen. Thus, we follow a two phase frame transmission, where sources transmits successively on their dedicated time slots in the transmission phase (first phase). Then, in the second phase (retransmission phase), the destination being the central node, organizes the scheduling process of the relaying nodes choosing which nodes to be activated at each different time slot. An initialization phase occurs before these two phases, where LA process is performed, where different resources are allocated to the different source nodes.

Recalling the goal of this thesis and which is to propose effective cooperation schemes

for the considered MAMRN, we focus in this work on two main problems: 1) Link adaptation, and 2) Scheduling strategies. Each of these two problems branches to different sub-problems. LA, as its name indicates, is the process of adapting of the channel states of the different links of the network. Specifically, it is the process of allocating the different resources available to the different nodes based on the channel conditions. First, we target the problem of rate allocation of the sources which occurs at the initialization phase. We assume the presence of a predefined set of Modulation and Coding Scheme (MCS) rate values. The central node, i.e., the destination, has to allocate for each source a given rate from the predefined set with the aim to optimize the spectral efficiency and respect the QoS constraints. The complexity of the optimal rate allocation comes from the fact that the destination has to allocate the rates of the sources jointly and this makes the exhaustive search algorithm impractical. In other words, the choice of one source effects the choice of other sources as we will see in the expression of the outage events which depends not only on the rates of the sources but also on the retransmission protocol being used in the retransmission phase.

Speaking of which, the other main problem when talking about cooperative MAMRN is the problem of scheduling strategies. This problem tackles the methodology/strategies/protocol followed in the retransmission phase. In this problem, the destination being the central node has to organize the retransmissions occurring in the second phase. In other words, the destination is going to select which relaying nodes are going to be activated and which relaying nodes are going to remain silent. This scheduling process plays a major role in cooperative networks and have a high effect on the performance as we will see next.

Upon tackling these two main problems, other sub-problems arise. For example, the LA problem can be taken into a higher level by including a novel DoF composed of a variable number of channel uses in the transmission phase. This means that the different sources will have different time slot duration in the transmission phase. According to the channel gains, the time slot duration can be optimized when optimizing the rate allocation, leading to better performance. Another sub-problem related to LA concerns the information used while performing the LA algorithms. To this end, we propose different LA algorithm which can be used following different availability of the CSI and the Channel Distribution Information (CDI) of the direct and the indirect links. Specifically, we propose an intermediate LA which performs its allocation using the CSI of the direct links and the CDI of the indirect link. The motivation behind this intermediate LA process is to achieve the performance of the Fast-Link Adaptation (FLA) (which outperforms that of the Slow-Link Adaptation (SLA)) while avoiding its heavy overhead.

Similarly, upon tackling the scheduling strategy problem, several sub-problems arise. One issue which is addressed in the chapters of this thesis is the overhead of the control exchange process. Recalling the assumption of the presence of limited feedback links, it is seen that each different selection strategy needs a different control exchange process. Thus, one important factor to be taken into consideration when analysing a given scheduling strategy is the control exchange process needed by this strategy and the overhead penalty included.

As the goal of the previously mentioned problems is to reach the best possible solu-

tion, the best solution will be to solve the problems jointly. The rate allocation strategy seen in the prior art assumes that there is a certain relaying node scheduling in the retransmission phase, and thus, the rate allocation depends on the scheduling process used in the retransmission phase. Similarly, we see that the selection strategy depends on the rates of the sources, and thus, depends on the rate allocation problem. We notice that when solving any of these two problems (rate allocation or the relaying node scheduling), the second problem is considered fixed and a given solution is adopted. According, solving the two problems jointly is one of the motivations of this thesis at it is the way to reach the best performance. Nevertheless, such allocation is going to be challenging. The issue relates to the constraint that the destination needs the full CSI of the network to perform such a joint allocation.

1.5 Thesis contribution and outline

The organization of the remainder of this thesis is as follows. In **Chapter 2**, we present the common system model assumptions that are adopted throughout the whole thesis. The mentioned description is assumed in all the following chapters unless stated otherwise. In this chapter, the specifications of the network is presented, as well as the process of a frame transmission. In addition, the performance metric and the outage events are given. The main contributions of this thesis are described in four following chapters, which we briefly outline in the following.

In **Chapter 3**, we tackle the problem of LA. In the prior art, this problem consists in allocating a rate value chosen from a MCS family to each source node. In other words, this problem consists in choosing for each source node a rate value taken from a predefined set of possible rate values. In the first section of this chapter, we propose a two-step rate allocation strategy based on the Best-Response Dynamics (BRD) tools. The first step in this algorithm consists in a "Genie-Aided" (GA) starting point, and the second step consists in correcting the previously chosen values. In the second section of this chapter, we propose a new DoF composed of a variable number of channel uses in the transmission phase. This means that each source node will be allocated a different time slot duration during the first phase. Such a modification in the allocation problem is promising due to the improvement it gives in the performance. The numerical results show that the BRD algorithms proposed achieve a good performance and approach the upper bound. This is seen for both: fixed time slot duration and variable time slot duration, and for both: SU and MU encoding methods. Furthermore, the numerical results validate the importance of the SU encoding case, being a practical solution which approaches the MU case. Finally, in the last section of this chapter, we propose an intermediate LA strategy that consists in allocating the rate values based on the CSI of the direct links. This approach aims to achieve the practicality of SLA method, and the optimality of the FLA method while avoiding its heavy overhead.
This chapter lead to the following publications:

- Ali Al Khansa, Stefan Cerovic, Raphael Visoz, Yezekael Hayel, and Samson Lasaulce, (2021, September). Slow-link adaptation algorithm for multi-source multi-relay

wireless networks using best-response dynamics. In International Conference on Network Games, Control and Optimization. Springer, Cham.

- Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, and Rasha Alkhansa, (2021, December). Fast Link Adaptation with Partial Channel State Information for Orthogonal Multiple Access Multiple Relay Channel (OMAMRC). In 2021 IEEE 3rd International Multidisciplinary Conference on Engineering Technology (IMCET) (pp. 11-16).

- Ali Al Khansa, Raphael Visoz, Yezekael Hayel, Samson Lasaulce, and Rasha Alkhansa, R. Dynamic Rate and Channel Use allocation for Cooperative Wireless Networks. In submission in EURASIP Journal on Wireless Communications and Networking.

and the following patent fillings:

- Ali Al Khansa, Raphael Visoz, Stefan Cerovic, "Procédé et système OMAMRC de transmission avec variation du nombre d'utilisations du canal", Application No: FR2004643. Date de dépôt: 12/05/2020.

- Ali Al Khansa, Raphael Visoz, "Procédé de réception d'au moins une trame de données dans un système OMAMRC, destination, programme d'ordinateur et système correspondants", Application No: FR2014132. Date de dépôt: 24/12/2020.

In **Chapter 4**, we tackle second main problem seen in the 2-phase (transmission and retransmission) cooperative system. Specifically, we tackle the problem of relaying nodes scheduling process. In this chapter, we propose a selection strategy based on the practical SU encoding method. We organize the scheduling process in a way that we exploit the multi-path diversity based on the fact that each relay node has its own power budget. In other words, rather than activating a single relaying node in each retransmission time slot, we propose the notion of PR, where multiple relaying nodes are activated to help a single source node. This means that the problem of selecting a relaying node is changed to be a problem of choosing a source node where all the relaying nodes which decoded this source are going to be activated to help the source together. In the second section of this chapter, we further propose a new selection strategy which aims at reducing the control exchange process seen in the prior art. This method builds its selection on an estimation of the number of retransmission time slots needed to decode a given source. Using this estimator, we reduce the number of control exchange processes needed before doing the scheduling strategy. The numerical results validate the optimality of using PR compared to the prior art SR methods. In addition, it present the effect of the overhead of the control exchange process seen in the different scheduling strategies and how we would reduce this overhead using estimation.
This chapter lead to the following publications:

- Ali Al Khansa, Raphael Visoz, Yezelael Hayel, Samson Lasaulce, and Rasha Alkhansa, (2022, September). Parallel Retransmissions in Orthogonal Multiple Access Multiple Relay Networks. In International Workshop on Resource Allocation and Cooperation in Wireless Networks (RAWNET), 2022.

- Ali Al Khansa, Raphael Visoz, Yezelael Hayel, Samson Lasaulce, and Rasha Alkhansa, Centralized Scheduling for MAMRN with Optimized Control Channel Design. In submission in Annals of Telecommunications.

and the following patent fillings:

- Ali Al Khansa, Raphael Visoz, "Procédé de retransmission coopérative dans un système OMAMRC", Application No: FR2206422. Date de dépôt: 28/06/2022.
- Ali Al Khansa, Raphael Visoz, "Procédé de transmission et système OMAMRC avec une stratégie de sélection lors de retransmissions tenant compte du débit des sources et d'un unique échange de contrôle Domaine de l'invention", Application No: FR2206443. Date de dépôt: 28/07/2022.
- Ali Al Khansa, Raphael Visoz, "Procédé de transmission et système OMAMRC avec une stratégie de sélection lors de retransmissions tenant compte du débit des sources et d'un ou plusieurs échanges de contrôle Domaine de l'invention", Application No: FR2206446. Date de dépôt: 28/07/2022.

In **Chapter 5**, we solve the two previously mentioned problems jointly. Rather than assuming a given relaying node strategy when doing the rate allocation (as in chapter 3), and rather than doing the scheduling in the retransmission phase assuming a pre-allocated rates (as in chapter 4), we propose an optimal solution which performs rate allocation and selection scheduling jointly. In this way, we address the problem of sub-optimality of solving the two allocations sequentially. The algorithms proposed in this chapter tackles the complexity of passing through a discrete set of possible rates that is needed in the BRD strategy. The numerical results validate that the joint rate and scheduling allocation outperforms the sequential allocation. Furthermore, it ensure the sub-optimality of following a discrete set of rate values and how this sub-optimality can be reduced using the presented strategy.
This chapter lead to the following publication:

- Ali Al Khansa, Raphael Visoz, Yezelael Hayel, and Samson Lasaulce, Joint Rate and Relaying Nodes allocation for Fast Link Adaptation with Full Channel State Information. Accepted in the 5th International Conference on Advanced Communication Technologies and Networking (CommNet 2022).

and the following patents filling:

- Ali Al Khansa, Raphael Visoz, "Joint Rate and Relaying Nodes allocation for Fast Link Adaptation with Full Channel State Information", Application No: FR2210608. Date de dépôt: 14/10/2022.
- Ali Al Khansa, Raphael Visoz, "Stratégie de sélection optimale à l'aide d'un échange CSI pour l'OMAMRC", Application No: FR2214095. Date de dépôt: 21/12/2022.

- Ali Al Khansa, Raphael Visoz, "Stratégie de sélection optimale à l'aide d'un échange CSI conditionnel pour l'OMAMRC", Application No: FR2214097. Date de dépôt: 21/12/2022.

Finally, in **Chapter 6**, we conclude this work and pave the way for some future works. Specifically, we tackle the rate allocation problem using a different approach. In this approach, we propose a solution when there is no information even for the CDI of the network's links. The solution belongs to online Reinforcement Learning (RL) framework, and specifically, the MAB framework. Other than this direction, we generalize our work to the FDM domain. We first present the utility metric and the outage events in the FDM domain. Then, we propose some solutions for the scheduling strategies when going to the FDM regime.
This chapter lead to the following publications:

- Ali Al Khansa, Raphael Visoz, Yezelael Hayel, and Samson Lasaulce, (2021, May). Resource allocation for multi-source multi-relay wireless networks: A multi-armed bandit approach. In International Symposium on Ubiquitous Networking (pp. 62-75). Springer, Cham.

- Ali Al Khansa, Raphael Visoz, Yezelael Hayel, Samson Lasaulce, and Rasha Alkhansa, (2022, October). Centralized Scheduling for Frequency Domain Orthogonal Multiple Access Multiple Relay Network. In 2022 27th Asia-Pacific Conference on Communications (APCC). IEEE.

and the following patent fillings:

- Ali Al Khansa, Raphael Visoz, "Procédé et système OMAMRC avec transmission FDM", Application No: FR2006623. Date de dépôt: 24/06/2020.

- Ali Al Khansa, Raphael Visoz, "OMAMRC retransmission par source avec MRT", Application No: FR 2205907. Date de dépôt: 16/06/2022.

- Ali Al Khansa, Raphael Visoz, "Procédé et système OMAMRC avec transmission FDM et coopérations multiples par sous-bande", Application No: FR2210584. Date de dépôt: 14/10/2022.

Chapter 2

System Model

2.1 Chapter summary

In this chapter, we present the system model considered in this thesis as well as some common assumptions adopted throughout the manuscript. The mentioned description is assumed in all our work unless stated otherwise. In the first section, we present the TDM orthogonal MAMRN considered and we describe the different nodes included in the network followed by the assumptions of the radio conditions investigated. In addition, we describe the transmission of a frame with all the needed elements: the retransmission strategy used and the control exchange process between the destination and the relaying nodes. In the second section, we present the analytical expression of the utility metric considered as well as the outage events.

2.2 System description

We consider an (M, L, 1) system with M sources, L relays, and one destination node. The M sources communicate with a single destination, using the help of $M+L$ relaying nodes. The relaying nodes consist of L half-duplex dedicated relays in addition to the M sources, where the latter sources perform user cooperation. User cooperation means that sources act as relays when they have no messages of their own to send. A message $\mathbf{u}_s \in \mathbb{F}_2^{K_s}$ of a source s has a length of K_s information bits, where $\mathbb{F}_2$ represents the binary Galois field. In addition, the length K_s depends on the MCS for that source. The messages of all sources are mutually independent. It is assumed that all nodes transmit with the same power, where each node is equipped with one antenna only. To be clear with the notations, we define the source nodes set as $\mathcal{S} = \{1, \ldots, M\}$, the relay nodes set as $\mathcal{R} = \{M+1, \ldots, M+L\}$, and all cooperative nodes set as $\mathcal{N} = \mathcal{S} \cup \mathcal{R} = \{1, \ldots, M+L\}$. In other words, a source s_i is the node i in set $\mathcal{N}$, and a relay r_i is the node $i+M$ in set $\mathcal{N}$.

In Fig. 2.1, we present a simple realization of the considered MAMRN. In this figure, we see that all the nodes (sources, relays, and the destination) can listen to each other. Furthermore, we see that there is a link from the destination (the central node) toward the different relaying nodes (sources and relays) representing the feedback information

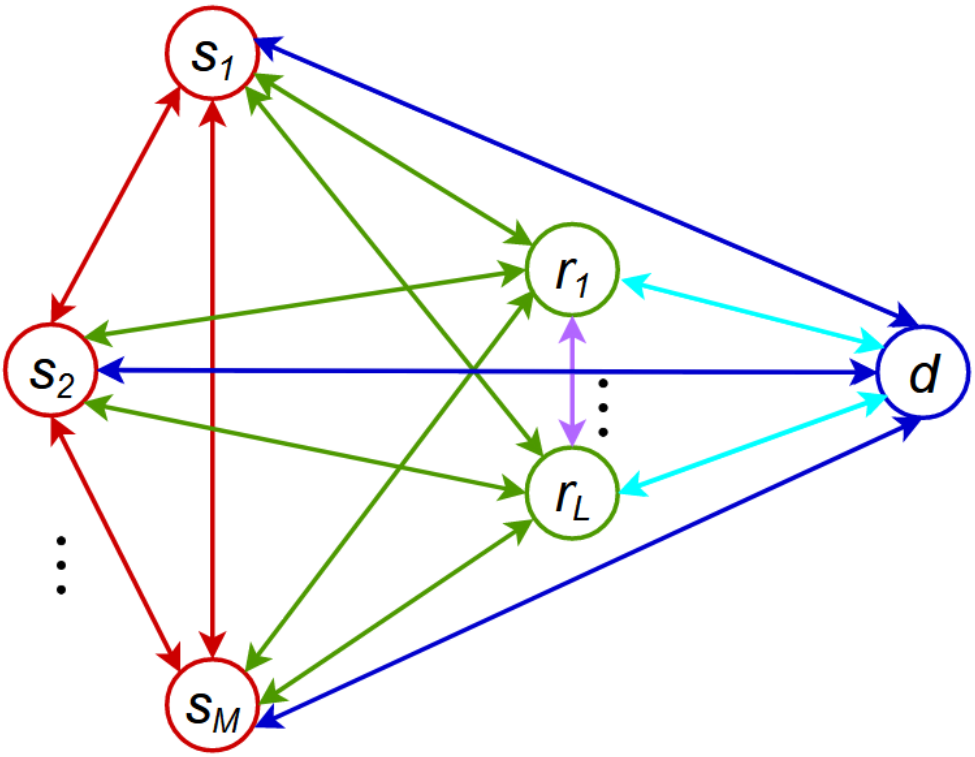


Figure 2.1: The MAMRN consists of a wireless network with multiple sources, multiple relays, and a single destination.

flow. Accordingly, the destination uses these links to share its different decisions and allocations with the different relaying nodes (e.g., allocated rates, selected relaying node, etc.).

We follow a slow fading assumption which means that the radio links between the nodes do not change within a frame transmission. The channel realization is considered independent from frame to frame. It simplifies the analysis and the convergence of the system, and it captures the performance of practical systems assuming ergodicity of the underlying random processes. We assume that the CSI of only the direct links is available at the receiver, i.e., $\mathbf{H}_{\text{dir}} = [\mathbf{h}_{\text{s,d}}, \mathbf{h}_{\text{r,d}}] = [h_{1,d}, \ldots, h_{M+L,d}]$ of Source-to-Destination (S-D), and Relay-to-Destination (R-D) links are perfectly known by the destination. On the other hand, the knowledge of the CSI of other indirect links, Source-to-Source (S-S), Source-to-Relay (S-R), and Relay-to-Relay (R-R), might not always be possible. Basically, based on the cost of the control overhead, the source and the relay nodes might be able to report the CSI of these indirect links. In the case where the overhead of reporting the exact CSI is high, the relaying nodes (sources and relays) will only report the CDI of these indirect links. The overhead is mainly correlated to the mobility of the system, and the destination accordingly chooses which information is reported from the other relaying nodes (CSI or CDI).

In other words, we investigate two scenarios :

1- Fast changing radio conditions: where the acquisition of the CSI of all the links is too

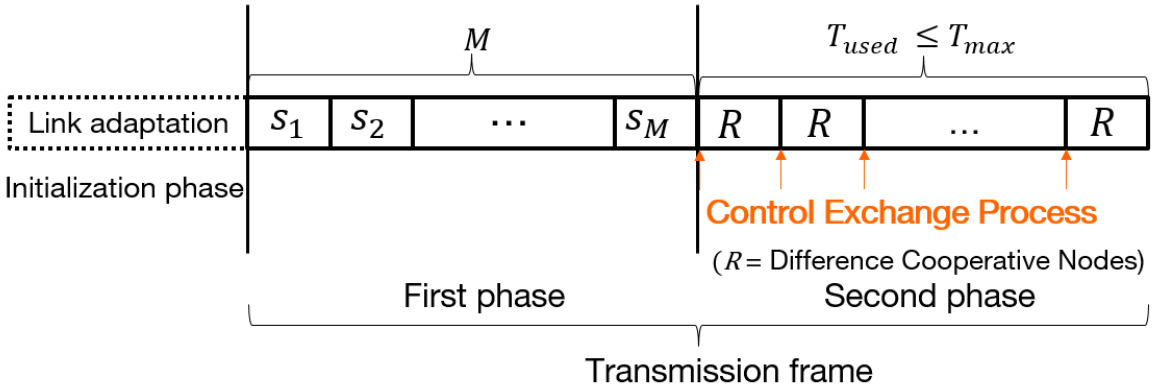


Figure 2.2: Transmission of a frame: initialization, first and second phases. A control exchange process is seen before each retransmission time slot.

costly in terms of the feedback overhead. Instead, CDI (e.g., average Signal-to-Noise-Ratio (SNR) of the corresponding links) is used in the allocation process, and we call this type of LA **Slow-Link Adaptation (SLA)**. It follows that the initial phase occurs once every few hundred frames, once the CDI of network links changes. Between two occurrences of the initial phase, the sources' rates are kept fixed.
2- Slow changing radio conditions: where the acquisition of the CSI of all the links is assumed given. This can be practical in scenarios where channel states of all the links change slowly and can be assumed constant during tens of frames. We call this type of LA **Fast-Link Adaptation (FLA)**.

The transmissions and retransmissions of source messages occur in time frames structured as shown in Fig. 2.2. Following an initial LA phase, where a rate allocation process is performed (the rates of the sources are allocated), a time frame is divided into two phases. The first phase is the transmission phase during which the sources transmit their messages in turn over U channel uses. The second phase, called retransmission, is composed of $T_{\text{used}} \in \{0, ..., T_{\text{max}}\}$ retransmissions scheduled by the destination using Q channel uses. T_{max} represents the maximum number of possible retransmissions before declaring an outage event (event of not decoding messages of some source nodes). Thus, the whole frame size is $M + T_{\text{used}}$ which is limited to $M + T_{\text{max}}$ where T_{max} is a fixed system parameter.

In our work, relaying nodes apply the SDF relaying protocol, which means that they can forward only a signal representative of successfully decoded source messages. The error detection is based on CRC bits that are appended to each source message. The SDF relaying protocol is an advanced version of the DF relaying protocol. The principle of DF protocol is introduced in [21], where unlike SDF, cooperative nodes are obliged to wait to successfully decode all the source messages before starting to cooperate.

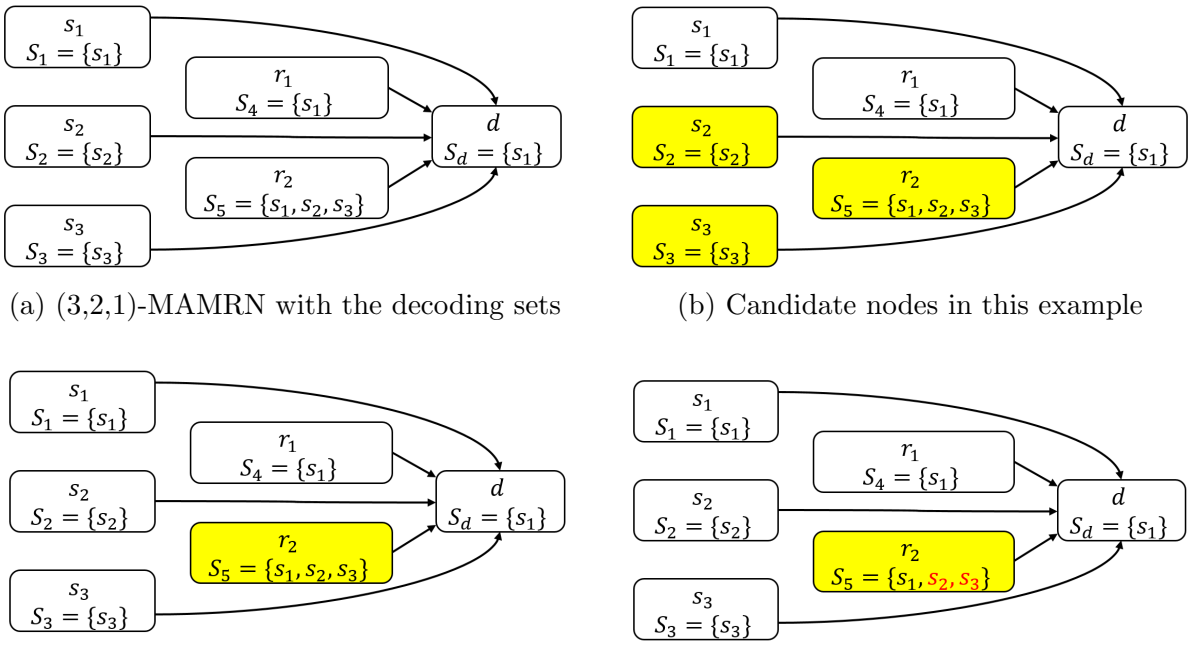
Furthermore, we investigate both MU encoding and SU encoding. The reference [43] investigated different cooperative HARQ protocols for MAMRN. To our interest, the authors of [43] tackled both MU encoding and SU encoding, and both schemes gave promising results. While our work in the next chapter is mainly based on the MU encoding where Joint Network Channel Coding (JNCC) is used, we analyze as well the

performance of our algorithms for the SU encoding sub-case. In MU encoding, a relaying node sends an IR-type of HARQ. This IR signal is representative of all its successfully decoded source messages $\mathcal{S}$. From both a practical and an information theory viewpoints, the signal sent can help the destination to decode any subset $\mathcal{S}' \subseteq \mathcal{S}$ knowing $\mathcal{S} \backslash \mathcal{S}'$ where $\backslash$ is the minus in set theory. In SU encoding on the contrary, the relaying node chooses (randomly) one source message from its decoding set to retransmit. From a practical point of view, and following the state of the art punctured codes, the SU encoding sub-case is attractive being compatible with codes such as LDPC codes or Turbo codes.

A control exchange process represents the steps that the nodes and the destination do in order to exchange useful information so that the destination is able to perform its selection algorithm. As seen in Fig. 2.2, a control exchange process between the destination and the relaying nodes runs before each retransmission scheduling. As the destination does not know the CSI of the indirect links of the networks (S-S links, S-R links, and R-R links), it does not know the decoding set of the relaying nodes. In other words, the decoding sets at the relaying nodes depend on the channel state between the relaying nodes, and thus, the destination needs to know the CSI of these links to deduce the decoding set of the relaying nodes. Accordingly, and as it lacks this information, a control exchange process is needed to give the destination useful information to perform its scheduling strategy. We note that K_s is assumed large enough to neglect the effect of control channels on the transmission rate (that is why we see no time slot reserved for the control exchange process). In other words, we assume the presence of "limited control channels" with a large enough packet length. For short packet lengths, however, the control channel overhead cannot be neglected. Nevertheless, this will not change the contribution of this manuscript.

The control exchange process depends on the selection strategy used in the retransmission phase. In this chapter, we present the control exchange process which is used when using the selection strategy of [43]. This selection strategy (and this control exchange process) are adopted in chapter 3 and further optimized in chapter 4. First, we recall the selection strategy used in [43], then, we describe the needed control exchange process when using this selection strategy. In [43], in each retransmission round, the destination selects the node with the highest mutual information between itself and that node, among all nodes which were able to decode at least one source from the set of non-successfully decoded sources at the destination. It is demonstrated that using the described strategy, we can reach the ASE close to the upper bound obtained by an exhaustive search for the best possible node activation sequence, under much smaller computational complexity.

We present in Fig. 2.3 a toy example that shows how the selection strategy of [43] works. In Fig. 2.3a, we consider a $(3, 2, 1)$-MAMRN. At the considered time slot (any time slot in the retransmission phase), the decoding sets of all the nodes are presented. We see that the destination decoded the message of source s_1, the sources did not decode any source message (but their own message), and the relays r_1 and r_2 decoded respectively the set of sources $\{s_1\}$ and $\{s_1, s_2, s_3\}$. In [43], the candidate relaying nodes to be selected are the nodes that can help at least one source which is not decoded by the destination. As the destination decoded source s_1, the candidate nodes (in this example) are the relaying nodes that can help either source s_2 or s_3 or both. Following



(a) (3,2,1)-MAMRN with the decoding sets

(b) Candidate nodes in this example

(c) Selected node in this example

(d) Candidate sources in this example

Figure 2.3: A toy example describing the process of the selection strategy used in the following chapter.

the toy example, the candidate relaying nodes are s_2, s_3, and r_2 (highlighted in Fig. 2.3b). After fixing the set of candidate relaying nodes, the destination chooses the node with the highest mutual information. Such a relaying node is the node having the best direct link with the destination. In Fig. 2.3c, we assume that the best direct link is the link between r_2 and the destination, and thus, r_2 is going to be selected. Finally, in Fig. 2.3d, we see that r_2 is going to send a symbol representative of all correctly decoded sources which are not decoded yet by the destination, i.e., sources s_2 and s_3. This process is repeated at the beginning of each retransmission time slot while using the updated decoding sets of the nodes.

Now, following the described selection strategy, the control exchange process needed before a retransmission time slot $t \in \{1, \ldots, T_{\max}\}$ can be described as seen in Fig. 2.4.

- The destination first shares its decoding set $S_{d,t-1}$ with the relaying nodes. Thus, it broadcasts M bits that indicate its decoding set.

- If the destination decoded all the sources, i.e., if the decoding set of the destination consists of all source messages, a new frame begins. Otherwise, each relaying node which was able to decode at least one source message that is not included in the decoding set of the destination sends 1 bit on a dedicated unicast forward coordination control channel. Each relaying node which did not decode any message needed by the destination, i.e., any message that is not included in the decoding set of the destination after round $t-1$, remains silent.

- Using the described selection strategy and the information exchanged with the

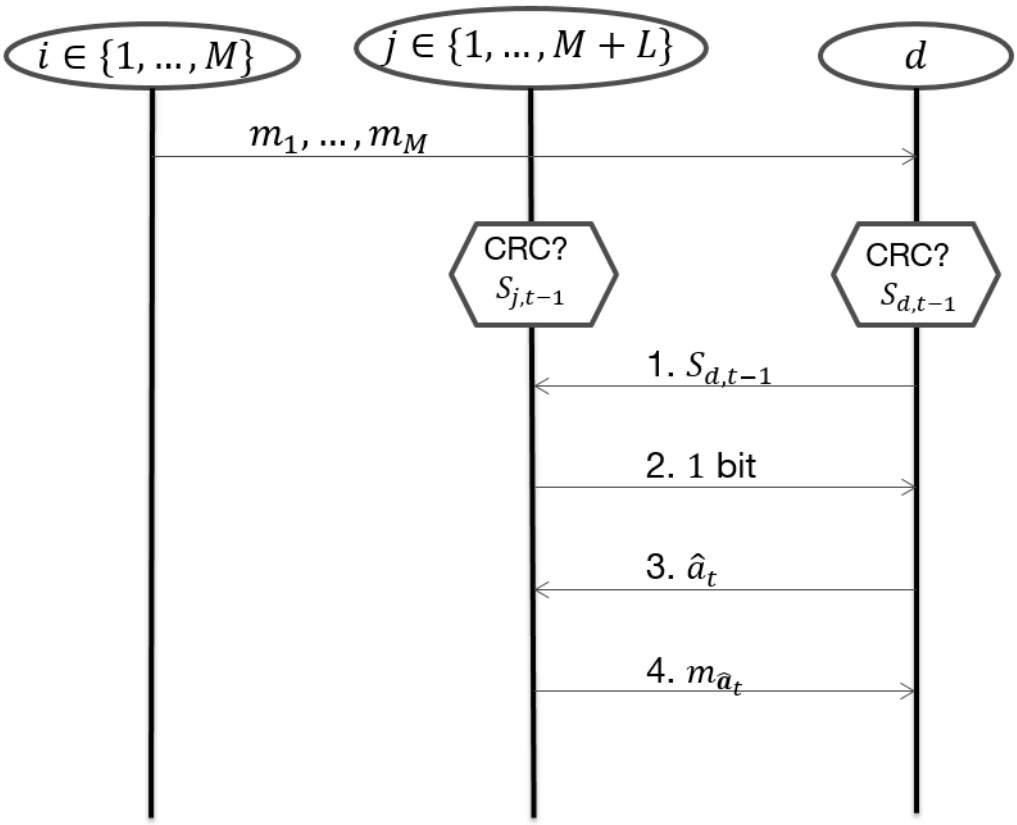


Figure 2.4: Control exchange process used in the following chapter.

relaying nodes, the destination chooses the relaying node $\widehat{a}_t$ with the highest mutual information between itself and that node. Its decision is broadcasted using the feedback broadcast control channel. Note that the candidate relaying nodes at this step are only the nodes which were not silent in step 2. In other words, only the relaying nodes which were able to decode at least one source message that is not included in the decoding set of the destination.

- The selected relaying node transmits redundancies using MU encoding with the messages of the source that it was able to decode.

Now, for a given transmitting node $a \in \mathcal{S} \cup \mathcal{R}$, and a receiving node $b \in \mathcal{S} \cup \mathcal{R} \cup \{d\}$, at a given channel use k, the received signal $y_{a,b,k}$ can be written as:

$$y_{a,b,k} = h_{a,b} m_{a,k} + n_{a,b,k}, \tag{2.1}$$

where

- $m_{a,k} \in \mathbb{C}$ is the coded modulated symbol whose power is normalized to unity.
- $h_{a,b}$ are the channel fading gains, which are independent and follow a zero-mean circularly symmetric complex Gaussian distribution with variance $\gamma_{a,b}$.
- $n_{a,b,k}$ represents the independent and identically distributed Additive White Gaussian Noise (AWGN) samples, which follow a zero-mean circularly-symmetric complex Gaussian distribution with unit variance.

2.3 Performance metric and outage events

2.3.1 Average spectral efficiency

In this subsection, we present our utility metric called average spectral efficiency η which is maximized for both FLA and SLA. It is defined as the limit of the average of the ratio between the number of successfully received bits and the number of channel uses when the number of frame transmissions tends to infinity ($\eta = \mathbb{E}\{\eta^{\text{frame}}\}$). Our analysis relies on the definition of the outage event $\mathcal{O}_{i,t}$ which occurs when source i is not decoded correctly after the transmission phase ($t = 0$) and at each retransmission l up to t ($l = 1, ..., t$). We define, accordingly, $\mathrm{O}_{i,t}$ as a binary Bernoulli random variable which indicates an outage event. In other words, $\mathrm{O}_{i,t}$ takes the value 1 if the event $\mathcal{O}_{i,t}$ happens, and 0 otherwise. Or, in mathematical terms, for any elementary event w, $\mathrm{O}_{i,t}(w) = [w \in \mathcal{O}_{i,t}]$ where [q] denotes the Inverson bracket which takes the value 1 if q is true, and 0 otherwise.

The metric η is derived from the spectral efficiency per frame η^{frame} and which depends on the channel realization $\mathbf{H}$, and the LA strategy used (strategy of allocating the rate of the source nodes) denoted P. Also, it depends on the relaying protocol used, relaying nodes selection strategy, and the parameters of the system (e.g., M; L; $T_{\max}$).

For simplicity, we only include within the following equations the dependency on $\mathbf{H}$ and P. Now, η^{frame} is defined as:

$$\begin{aligned}\eta^{\text{frame}}(\mathbf{H}, P) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} K_i(1 - \mathrm{O}_{i,T_{\text{used}}})}{MU + QT_{\text{used}}} \\ &= \frac{\sum_{i=1}^{M} R_i(1 - \mathrm{O}_{i,T_{\text{used}}})}{M + \alpha T_{\text{used}}}, \end{aligned} \tag{2.2}$$

where

- $R_i = K_i/U$ is the rate of a source i, with K_i being the number of bits that can be transmitted by source i given U channel uses.
- $T_{\text{used}} \in \{0, \ldots, T_{\max}\}$ is the number of retransmission time slots activated in a frame.
- $\mathrm{O}_{i,T_{\text{used}}}$ is a binary Bernoulli random variable which indicates an outage event $\mathcal{O}_{i,t}$. In other words, $\mathrm{O}_{i,t}$ takes the value 1 if the event $\mathcal{O}_{i,t}$ happens, and 0 otherwise.
- $\alpha = Q/U$ is the ratio of number of channel uses in a retransmission time slot by that in a transmission slot.

2.3.2 Outage events

Now, we present the outage events of the system which are the individual outage event for a given source, and the common outage event for a subset of sources. The latter occurs when at least one user in the subset of sources is in outage. In [39], Mohamad et al provide an outage analysis for various cooperative schemes. Here, we build on that work and we present the outage derivations for our considered system. In general, the "individual outage event of a source s after round t", $\mathcal{O}_{s,t}(a_t, S_{a_t,t-1}|\mathbf{h}_{\text{dir}}, \mathcal{L}_{t-1})$, depends directly on the rates we are scheduling. In addition, it depends on the selected node $a_t \in \mathcal{N}$ and its associated decoding set $S_{a_t,t-1}$. It is conditional on the knowledge of $\mathbf{h}_{\text{dir}}$ and $\mathcal{L}_{t-1}$, where $\mathcal{L}_{t-1}$ denotes the set collecting the nodes $\widehat{a}_l$ which were selected in rounds $l \in \{1, \ldots, t-1\}$ prior to round t together with their associated decoding sets $S_{\widehat{a}_l,l-1}$, and the decoding set of the destination $S_{d,t-1}$ ($S_{d,0}$ is the destination's decoding set after the first phase).

Similarly, we define $\mathcal{E}_t(a_t, S_{a_t,t-1}|\mathbf{h}_{\text{dir}}, \mathcal{L}_{t-1})$ the "common outage event after round t" as the event that at least one source is not decoded correctly at the destination at the end of round t. The probability of the individual outage event of source s after round t, $\Pr(\mathrm{O}_{s,t}(a_t, S_{a_t,t-1}|\mathbf{h}_{\text{dir}}, \mathcal{L}_{t-1}) = 1)$, for a candidate node a_t using the expectation operator $\mathbb{E}\{.\}$ can be formulated as $\mathbb{E}\{\mathrm{O}_{s,t}(a_t, S_{a_t,t-1}|\mathbf{h}_{\text{dir}}, \mathcal{L}_{t-1})\}$. We can similarly define the probability of the common outage event. In the rest of the manuscript, and in order to simplify the notation, the dependency on $\mathbf{h}_{\text{dir}}$ and $\mathcal{L}_{t-1}$ is omitted.

Analytically, the common outage event of a given subset of sources is declared if the vector of their rates lies outside the corresponding MAC capacity region. We recall that

although this is an orthogonal transmission framework, the outage events encounter the interference effects. Clearly, this follows the JNCC used, where a retransmitted message can include information about different source messages. Now, for some subset of sources $\mathcal{B} \subseteq \overline{S}_{d,t-1}$, where $\overline{\mathcal{S}}_{d,t-1} = \mathcal{S} \setminus S_{d,t-1}$ is the set of non-successfully decoded sources at the destination after round $t-1$, and for a candidate node a_t, this event can be expressed as:

$$\mathcal{E}_{t,\mathcal{B}}(a_t, S_{a_t,t-1}) = \bigcup_{\mathcal{U}\subseteq\mathcal{B}} \Big\{ \sum_{i\in\mathcal{U}} R_i > \sum_{i\in\mathcal{U}} I_{i,d} + \alpha \sum_{l=1}^{t-1} I_{\widehat{a}_l,d}\mathcal{C}_{\widehat{a}_l}(\mathcal{U}) + \alpha I_{a_t,d}\mathcal{C}_{a_t}(\mathcal{U}) \Big\}, \tag{2.3}$$

where $I_{a,b}$ denotes the mutual information between the nodes a and b (the mutual information is defined based on the channel inputs, check numerical results sections in the following chapters for Gaussian inputs example), and where $\mathcal{C}_{\widehat{a}_l}$ and $\mathcal{C}_{a_t}$ have the following definitions:

$$\begin{aligned} \mathcal{C}_{\widehat{a}_l}(\mathcal{U}) &= \Big[(S_{\widehat{a}_l,l-1} \cap \mathcal{U} \neq \emptyset) \wedge (S_{\widehat{a}_l,l-1} \cap \mathcal{I} = \emptyset) \Big], \\ \mathcal{C}_{a_t}(\mathcal{U}) &= \Big[(S_{a_t,t-1} \cap \mathcal{U} \neq \emptyset) \wedge (S_{a_t,t-1} \cap \mathcal{I} = \emptyset) \Big]. \end{aligned} \tag{2.4}$$

In (2.4), the sources that belong to $\mathcal{I} = \overline{\mathcal{S}}_{d,t-1} \setminus \mathcal{B}$ are considered as interference, with $\wedge$ standing for the logical and. In (2.3), for each subset $\mathcal{U}$ of set $\mathcal{B}$, we check if the sum-rate of sources contained in $\mathcal{U}$ is higher than the accumulated mutual information at the destination (since IR-type of HARQ is used). The accumulated mutual information is split into three summations, which originate from:

- The direct transmissions from sources contained in $\mathcal{U}$ towards the destination during the first phase: $\sum_{i\in\mathcal{U}} I_{i,d}$.
- The transmission of previously activated nodes during the second phase: $\alpha \sum_{l=1}^{t-1} I_{\widehat{a}_l,d}\mathcal{C}_{\widehat{a}_l}(\mathcal{U})$. Node $\widehat{a}_l$ for $l = \{1, \ldots, t-1\}$ is involved in the calculation only if it was able to successfully decode at least one source from the subset $\mathcal{U}$ (JNCC is used), but at the same time, if it does not belong to the set $\mathcal{I}$ (otherwise, the signal would represent an interference).
- The transmission of the candidate node a_t during the second phase: $\alpha I_{a_t,d}\mathcal{C}_{a_t}(\mathcal{U})$, under the same conditions as for the previously activated nodes.

The individual outage event of a source s after round t for a candidate node a_t can be defined as:

$$\begin{aligned} \mathcal{O}_{s,t}(a_t, S_{a_t,t-1}) &= \bigcap_{\mathcal{I}\subset\overline{S}_{d,t-1}, \mathcal{B}=\overline{\mathcal{I}}, s\in\mathcal{B}} \mathcal{E}_{t,\mathcal{B}}(a_t, S_{a_t,t-1}) \\ &= \bigcap_{\mathcal{I}\subset\overline{S}_{d,t-1}} \bigcup_{\mathcal{U}\subseteq\overline{\mathcal{I}}: s\in\mathcal{U}} \Big\{ \sum_{i\in\mathcal{U}} R_i > \sum_{i\in\mathcal{U}} I_{i,d} + \alpha \sum_{l=1}^{t-1} I_{\widehat{a}_l,d}\mathcal{C}_{\widehat{a}_l}(\mathcal{U}) + \alpha I_{a_t,d}\mathcal{C}_{a_t}(\mathcal{U}) \Big\}, \end{aligned} \tag{2.5}$$

where $\overline{\mathcal{I}} = \overline{S}_{d,t-1} \setminus \mathcal{I}$. The detailed analysis behind the relation between the individual outage event and the common outage event can be revisited in [39].

We finally define the outage events equations for the SU encoding sub-case. Since the relaying node transmits redundancies of a single source (which is chosen randomly from its decoding set), the individual outage event of a source s after round t for a candidate node a_t can be written as:

$$\mathcal{O}_{s,t}^{\mathrm{SU}}(a_t, S_{a_t,t-1}) = \Big\{ R_i > I_{i,d} + \alpha_i \sum_{l=1}^{t-1} I_{\widehat{a}_l,d} \mathcal{C}_{\widehat{a}_l}^{\mathrm{SU}} + \alpha_i I_{a_t,d} \mathcal{C}_{a_t}^{\mathrm{SU}} \Big\}, \tag{2.6}$$

where $\mathcal{C}_{\widehat{a}_l}^{\mathrm{SU}}$ (respectively $\mathcal{C}_{a_t}^{\mathrm{SU}}$) takes the value 1 if the source s is chosen by $\widehat{a}_l$ (respectively a_t) and zero otherwise. For the common outage event, in the SU encoding sub-case, it is simply the union of the individual outage events of all the sources included in the considered subset $\mathcal{B}$, and can be written as:

$$\mathcal{E}_{t,\mathcal{B}}^{\mathrm{SU}}(a_t, S_{a_t,t-1}) = \bigcup_{s \in \mathcal{B}} \mathcal{O}_{s,t}^{\mathrm{SU}}(a_t, S_{a_t,t-1}). \tag{2.7}$$

In the outage equations, we see that the expressions depend on the mutual information between the nodes and the destination. The definition of the mutual information is based on the channel inputs, e.g. Gaussian inputs, discrete inputs, etc.. With no loss of generality, we used Gaussian inputs in our simulations. Nevertheless, other channel inputs might be used without changing the findings of this thesis.

Chapter 3

Dynamic Rate and Channel Use Allocation Algorithms

3.1 Chapter summary

In this chapter, we aim at studying LA in the TDM orthogonal MAMRN presented in the previous chapter. As using cooperative systems aims to optimize spectral efficiency, the LA problem is always an open challenge to achieve better spectral efficiency and to satisfy QoS demands. LA is a fundamental mechanism allowing the source nodes to adapt the coding and modulation scheme depending on the radio channel conditions. The destination has to choose a rate for each source from a finite set of rates with the objective to maximize the spectral efficiency. In addition, the system is subject to QoS constraints on individual Block Error Rate (BLER) per source.

In the first section, we present the GA initialization algorithm followed by the BRD correction algorithm used for rate allocation assuming a fixed time slot duration in the transmission phase. In the second section, we investigate a new DoF represented by a variable time slot duration in the transmission phase. Following the new DoF, we present the updated utility metric and the outage events, followed by the new algorithms that perform LA for both rate and time slot duration. The presented algorithms can be used in SLA and FLA. In the third section, we validate our proposals via MC simulations. Our numerical analysis validates the gain of using a variable time slot duration in the transmission phase and the performance of the proposed BRD algorithm in different scenarios. Finally, in section four, we propose an intermediate practical LA that combines the benefits of SLA and FLA. The novel LA is based on a FLA strategy with partial CSI.

3.2 Fixed time slot duration

In the literature, in non-cooperative scenarios, where nodes are competing on sparse resources, the BRD appears as a natural approach to solving game theory problems. In BRD, a player chooses his most favorable outcome taking other players' choices as given. Such tools are seen in several domains [122], especially in decentralized wireless

problems, such as rate and power allocation in decentralized cellular networks [123, 124, 125]. In our system, on the contrary, we use a centralized LA, where the destination is the center node that determines the source choices. Accordingly, we have a typical multi-variable optimization problem that aims at optimizing the total ASE, subject to QoS constraints. In our considered problem, and due to the high complexity of its exact solution, we adopt here the methodology used in the BRD tools trying to give a substantial solution/algorithm to the given centralized multi-variable problem. The main idea is to decrease the complexity of the problem by considering each variable independently while taking the other variables as known information. In our approach, rather than choosing the rates of all the sources at the same time, each source will be handled by the destination successively. Such sequential strategy is sometimes referred to as the Gauss-Seidel procedure (e.g., [126]) when used in cooperative scenarios (which is our case).

In MAMRN, the knowledge of instantaneous CSI of all the links allows the LA algorithm to allocate the rates of the sources in the most accurate way (FLA). Since the number of channels in such a network grows exponentially with the number of sources and relays, frequent changes in the channel states (for ex. in a high mobility scenario) can incur an excessive amount of control signaling on the forward coordination control channels. In that case, FLA is deemed impractical, and SLA is a more suitable solution. The idea of SLA is to adapt the source rates to the CDI of all links, which remain constant for longer periods of time. It is important to stress that the time-scale of the SLA differs from the one used by the retransmission algorithm.

Following the considered orthogonal MAMRN system model, the individual outage event (resp. the probability of outage event) of any node depends on the vector of rates allocated for all the source nodes considered in the system. In other words, $\mathcal{O}_{s,T_{\text{used}}}$ (resp. $\Pr(\mathcal{O}_{s,T_{\text{used}}})$) depends on the vector of rates $\{R_1, \ldots, R_M\}$. To understand this dependency, we should be aware that at a given retransmission time slot, the decoding set of the selected node to retransmit, depends on all the rates allocated. Also, with a small observation of the analytical definition of the individual outage event, i.e., equation (2.5), we see that theoretically, the vector of pairs should be jointly optimized. Now, before we present the optimization problem, we define the corresponding notations:

- n_{MCS} is the number of different MCS available.
- $\widetilde{\mathbb{R}} = \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$ is the set of possible rates available.
- $\widehat{R}_i$, is the rate of source i after the optimization.
- R_i, one possible value of $\widehat{R}_i$ taken from the set of possible rates available.

Using these notations, our given optimization problem can be written as:

$$\begin{aligned}
&\{\widehat{R}_1, \ldots, \widehat{R}_M\} = \underset{\{R_1,\ldots,R_M\}\in\widetilde{\mathbb{R}}^M}{\operatorname{argmax}} \mathbb{E}\left\{\frac{\sum_{i=1}^{M} R_i(1-\mathrm{O}_{i,T_{\text{used}}})}{M+\alpha T_{\text{used}}}\right\}, \\
&\text{subject to:} \\
&\Pr(\mathrm{O}_{i,T_{\text{used}}}=1) \leq BLER_{\text{QoS},i},\ \forall i \in \{1,\ldots,M\}, \\
&R_i \geq R_{\min,i},\ \forall i \in \{1,\ldots,M\}.
\end{aligned} \tag{3.1}$$

In SLA, a QoS constraint *per source* is introduced as a minimum rate with an outage probability threshold (BLER). For FLA, since the full CSI is known at the destination, it is possible to avoid any individual outage per frame by simply not transmitting or, equivalently, transmitting with zero rate. Furthermore, we chose not to introduce any constraint on minimum rates in order to have a benchmark on the maximum achievable spectral efficiency.

To our knowledge, a closed-form solution for this multi-variable optimization problem is not found yet. Indeed, there is always the possibility to find the solution to such a problem by checking exhaustively all n_{MCS}^{M} possible combinations of allocated rates, and choosing the one which maximizes the ASE subject to individual QoS constraints. Clearly, such an approach is computationally very expensive. Accordingly, sub-optimal solutions are needed to relax the complexity of the problem, and thus we resort to BRD tools.

Another reason for looking for sub-optimal solutions is the fact that even in case there is a closed-form solution, this solution would be different from one cooperative network to another. This is seen as another difficulty in the considered problem. In other words, the optimal rate allocation of the cooperative network depends on the assumptions of the given network (e.g., relaying protocol used, selection strategy adopted, etc.). Thus, we investigate here the BRD approach, being a solution that can be used in different cooperative networks and not only the considered one. As mentioned in chapter 1, most of the papers that deal with efficient rate allocation strategies consider a single source, a single or eventually multiple relays, and a single destination; which ensures the novelty of the targeted problem in the considered MAMRN.

Following the BRD approach, the problem is solved in two steps: in step one, the destination chooses the initial source rates, then in step two, the destination uses the BRD methods to update the initial allocations by searching for a better result. The correction is done iteratively for each source node (not jointly), and the correction process is repeated until convergence to the "optimal" solution is reached. In the following subsection, we attempt to find a clever algorithm to reach a good starting point, since the optimal solution and the convergence speed will depend on it. Thus, rather than using random source rate values, we follow a GA assumption and try to find a suitable initialization algorithm.

3.2.1 Starting point using the "Genie-Aided" assumption

In order to reduce the complexity, we can resort to an approach that is based on a GA assumption, where all the sources $s \in \mathcal{S} \setminus i = \{1, 2, \ldots, i-1, i+1, \ldots, M\}$ except the one for which we want to allocate the rate, i, are assumed to be decoded correctly at the destination and the relaying nodes. Following this relaxation of the problem, the dependence of the decoding set of potentially cooperating nodes on sources other than the considered one is avoided. From a viewpoint of a source i, the MAMRN reduces to (1,$L + M - 1$,1) multiple relay network. An example is given in Fig. 3.1 for $i = s_1$, where the sources $\{s_2, \ldots, s_M\}$ are symbolically denoted by $\{r_{L+1}, \ldots, r_{L+M-1}\}$, as they only serve as relays. Under such an assumption, the node selection strategy will give a different sequence of selected nodes than the case where the GA assumption is not taken.

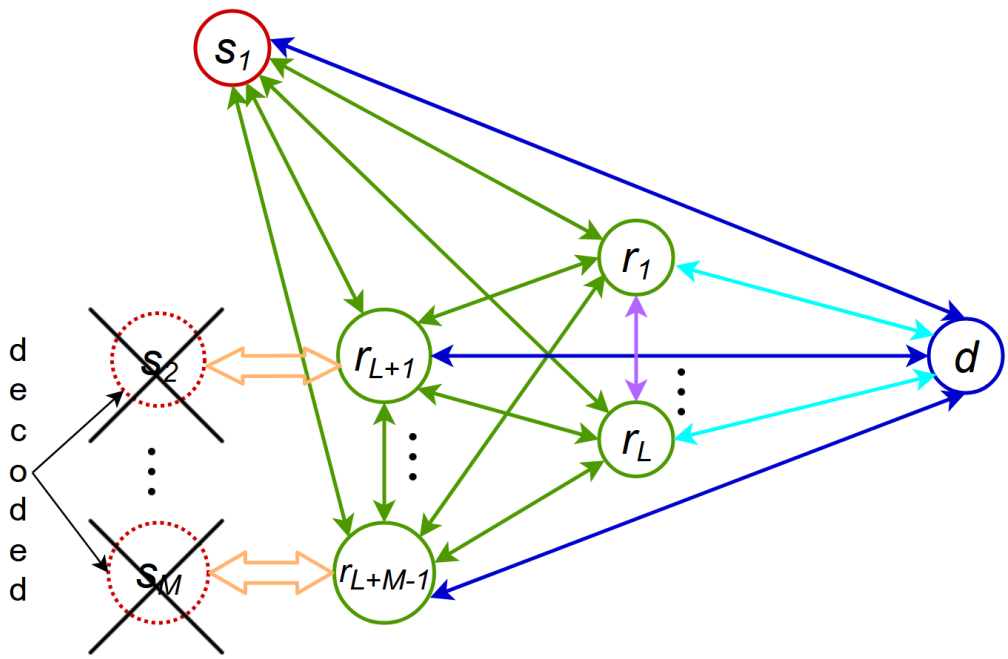


Figure 3.1: Illustration of the "Genie-Aided" assumption.

Indeed, since source i is the only one that is not decoded correctly at the destination, all the scheduling decisions are oriented towards helping this source exclusively, which results in an allocated rate higher than the optimal one. Possibly a better approximation of the realistic node selection sequence while evaluating rate R_i in the GA algorithm, is a random node activation sequence, and that approach is adopted in the rest of the manuscript when using GA.

Hence, although the initial rates found under the GA assumption are not the exact solutions to the maximization problem (3.1), they can serve as a good starting point for finding the optimal solutions. Indeed, even though we always consider that only one source is not decoded correctly, which is not a realistic assumption, and that the node activation sequence is purely random, we take into account the quality of all the links which can potentially help the transmission of a given source in the calculation.

In this manuscript, in the SLA scenario, we assume that the channel statistics of each link follow a centered circularly complex Gaussian distribution. Since the links are independent of each other, the average SNR of each link is sufficient as an input to trace back the statistics of each link. Given the simplified, $(1,L+M-1,1)$ network, the problem of finding the optimal rate $\widehat{R}_i$ for the source i subject to a $BLER_{\mathrm{QoS},i}$ constraint has the following form:

$$\begin{aligned}
&\widehat{R}_i^{\mathrm{SLA}} = \underset{R_i \in \widetilde{\mathbb{R}}}{\operatorname{argmax}}\, \mathbb{E}\left\{\frac{R_i(1-\mathrm{O}_{i,T_{\mathrm{used}}})}{M+\alpha T_{\mathrm{used}}}\right\}, \\
&\text{subject to} \\
&\Pr\{\mathrm{O}_{s,T_{\mathrm{used}}}=1\} \leq BLER_{\mathrm{QoS},s},\ \forall s \in \{1,\ldots,M\}, \\
&\text{and } R_i \geq R_{\min,i},
\end{aligned} \tag{3.2}$$

where $\Pr\{\mathrm{O}_{i,T_{\text{used}}}=1\} = \Big(1 - \int \Big[R_i > I_{s,d} + \sum_{l=1}^{T_{\text{used}}} \alpha I_{\widehat{a}_l,d}[s \in S_{\widehat{a}_l,l-1}]\Big] \Pr(\mathbf{H})\mathrm{d}\mathbf{H}\Big)$ with $\Pr(\mathbf{H})$ is the joint probability of channel realizations of all the links in the network. Note that equation (3.2) is reached after a direct simplification of equation (3.1). Simply, only one source node is considered. The problem of finding the maximum rate R_i for source i in the case of FLA simplifies to the following:

$$\widehat{R}_s^{\text{FLA}} = \underset{R_i \in \widetilde{\mathbb{R}}}{\operatorname{argmax}} \Big\{ \frac{R_i}{M + \alpha T_{\text{used}}} \Big(1 - \Big[R_i > I_{s,d} + \sum_{l=1}^{T_{\text{used}}} \alpha I_{\widehat{a}_l,d}[s \in S_{\widehat{a}_l,l-1}]\Big]\Big)\Big\}. \tag{3.3}$$

A detailed step-by-step algorithm in which a rate is allocated to source i under GA assumption with CDI available at the destination (SLA) is given by Algo. 1. First, we set the initial best efficiency. Then, each possible candidate rate from the set $\{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$ is considered one after another in the first "for loop" on j. We only consider the rates satisfying the minimum rate constraint $R_j \geq R_{\min,i}$. The second "for loop" allows to average out the $\Pr(\mathrm{O}_{i,T_{\text{used}}}=1)$, for the given rate R_j over Nb_MC realizations of all channels. The averaging is done according to statistics given by the average SNRs of all links. Hence, inside the loop *cnt*, the quality of each channel is known, since they result from the random realization of all channels. Therefore, in order to calculate the probability of outage seen in equation (3.2), it is sufficient to use the Monte-Carlo (MC) simulations approach, where the integral is replaced by the sum:

$$\int \Big[R_i > I_{i,d} + \sum_{l=1}^{T_{\text{used}}} \alpha I_{\widehat{a}_l,d}[i \in S_{\widehat{a}_l,l-1}]\Big] \Pr(\mathbf{H})\mathrm{d}\mathbf{H} =$$
$$\frac{1}{\text{Nb_MC}} \sum_{cnt=1}^{\text{Nb_MC}} \Big[R_i > I_{i,d}(\mathbf{H}_{cnt}) + \sum_{l=1}^{T_{\text{used}}} \alpha I_{\widehat{a}_l,d}(\mathbf{H}_{cnt})[i \in S_{\widehat{a}_l,l-1}]\Big].$$

The FLA algorithm is very similar to the SLA one, so it is left out of the text. The main difference is the absence of the averaging of the individual outage probability over Nb_MC realizations of all channels. For that reason, variables *out*, $\overline{T}$, and P_{i,R_j}^{out} are not used, nor is the "for" loop on *cnt*. Additionally, instead of drawing the channels $\mathbf{H}_{cnt}$, it is assumed that $\mathbf{H}$ is already known at the destination due to available CSI information of all channels.

3.2.2 Sequential Best-Response Dynamic solution

After setting up the starting point of the rates (using GA approach), the BRD algorithm follows. The idea is to modify, iteratively, the chosen rates. Since the joint allocation is very complex, we will correct the starting point chosen for each source node successively. In that case, the rate of source i is a function of the sources' rates updated in the same iteration prior to source i (sources with index $i' < i$), and the rates updated for the last time in the previous iteration, $t-1$ (sources with index $i'' > i$). The correction is repeated until the algorithm converges when no source node modifies its rate any further.

Algorithm 1 Slow-link adaptation algorithm based on "Genie-Aided" assumption for source i s.t. $BLER_{\text{QoS},i}$ target.

$S_{\text{best}} \leftarrow -1$. ▷ Initialize the best efficiency to -1.
for $j \leftarrow 1$ **to** n_{MCS} **do** ▷ Number of candidate rates.
  Pick sequentially $R_j \in \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$ s.t. $R_j \geq R_{\min,i}$.
  $S \leftarrow 0$ ▷ Initialize the efficiency sum to 0.
  $\overline{out} \leftarrow 0$. ▷ Counter of MC samples leading to outage.
  $\overline{T}_{used} \leftarrow 0$. ▷ Accumulated nb. of rounds used in the 2. phase.
  for $cnt \leftarrow 1$ **to** Nb_MC **do** ▷ Max. number of MC samples
    $out \leftarrow 0$
    Draw $\mathbf{H}_{cnt}$ based on $\Pr(\mathbf{H})$.
    Calculate $I_{a,b}(\mathbf{H}_{cnt})$ for $\forall a \in \mathcal{N}, \forall b \in \{\mathcal{N} \cup \{d\} \setminus \{a\}\}$.
    if $R_j \leq I_{i,d}$ **then**
      $S_{d,0} \leftarrow S_{d,0} \cup \{i\}$.
      continue. ▷ out and $\overline{T}_{used}$ do not change.
    end if
    for $t \leftarrow 1$ **to** $T_{\max}$ **do** ▷ For each round we do:
      Random node selection by the scheduler: $\widehat{a}_t$.
      $C_1 \leftarrow I_{i,\widehat{a}_t} + \alpha \sum_{k=1}^{t-1} I_{\widehat{a}_k,\widehat{a}_t} \mathbf{1}_{\{i \in S_{\widehat{a}_k,k-1}\}}$. ▷ Acc. mut. inf. between i and $\widehat{a}_t$.
      if $R_j \leq C_1$ **then** ▷ Check if $\widehat{a}_t$ has decoded i.
        $S_{\widehat{a}_t,t-1} \leftarrow S_{\widehat{a}_t,t-1} \cup \{i\}$.
      end if
      $C_2 \leftarrow I_{i,d} + \alpha \sum_{k=1}^{t} I_{\widehat{a}_k,d} \mathbf{1}_{\{i \in S_{\widehat{a}_k,k-1}\}}$.
      if $R_j \leq C_2$ **then** ▷ Check if the dest. has decoded i.
        $S_{d,t} \leftarrow S_{d,t} \cup \{i\}$.
        $T_{\text{used}} \leftarrow t$. ▷ Nb. of rounds used for the current MC sample.
        break. ▷ out does not change.
      end if
      if $t = T_{\max}$ **then**
        $\overline{out} \leftarrow \overline{out} + 1$.
        $out \leftarrow 1$.
        $T_{\text{used}} \leftarrow T_{\max}$.
      end if
    end for
    $\overline{T}_{used} \leftarrow \overline{T}_{used} + T_{\text{used}}$.
    $S \leftarrow S + \left\{ \frac{R_j(1-out)}{M+\alpha T_{\text{used}}} \right\}$ ▷ Compute the current efficiency.
  end for
  $P^{out}_{i,R_j} \leftarrow \frac{\overline{out}}{\text{Nb_MC}}$ ▷ The avg. outage prob. of i with R_j.
  if $S > S_{\text{best}}$ **and** $P^{out}_{i,R_j} \leq BLER_{\text{QoS},i}$ **then**
    $S_{\text{best}} \leftarrow S$ **and** $\widehat{R}_i \leftarrow R_j$
  end if
end for

Algorithm 2 Best-Response algorithm under the QoS constraints on individual BLER targets $BLER_{\text{QoS},i}, \forall i \in \{1, \ldots, M\}$.

1: $t \leftarrow 0$. ▷ Counter of iterations.
2: Set the candidate rates: $\widetilde{\mathbb{R}} = \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$.
3: Rate initialization under GA assumption with a random node selection: $\{\widehat{R}_1(0), \ldots, \widehat{R}_M(0)\} \leftarrow \{R_1^{\text{GA}}, \ldots, R_M^{\text{GA}}\}$
4: $\widehat{R}_i(-1) \leftarrow 0$ for all $i \in \{1, \ldots, M\}$ ▷ To force loop to start
5: **while** $(|\widehat{R}_i(t) - \widehat{R}_i(t-1)| > 0$ for some $i \in \{1, \ldots, M\}$ **do**
6: $\quad t \leftarrow t + 1$.
7: $\quad$ **for** $i \leftarrow 1$ **to** M **do** ▷ for all sources, choose the rate that maximizes the ASE
8: $\quad\quad \widehat{R}_i(t), \leftarrow \text{argmax}_{R_i \in \widetilde{\mathbb{R}}}\, \eta\big(\widehat{R}_1(t), \ldots, \widehat{R}_{i-1}(t), R_i, \widehat{R}_{i+1}(t-1), \ldots, \widehat{R}_M(t-1)\big)$ such that $\Pr\{\text{O}_{s,T_{\text{used}}} = 1\} \leq BLER_{\text{QoS},s}$ for all $s \in \{1, \ldots, M\}$ and $R_i \geq R_{\min,i}$ ▷ while satisfying the constraints
9: $\quad$ **end for**
10: **end while**

In the correction method described above, a given source i chooses the best rate corresponding to the maximum spectral efficiency while meeting the QoS constraints. Based again on equation (3.1), we write the optimization problem for a given source node i as:

$$\begin{aligned} &\widehat{R}_i = \underset{R_i \in \widetilde{\mathbb{R}}}{\text{argmax}}\, \mathbb{E}\left\{ \frac{\sum_{j=1, j\neq i}^{M} \widehat{R}_j(1 - \text{O}_{j,T_{\text{used}}}) + R_i(1 - \text{O}_{i,T_{\text{used}}})}{M + \alpha T_{\text{used}}} \right\}, \\ &\text{subject to:} \\ &\Pr(\text{O}_{s,T_{\text{used}}} = 1) \leq BLER_{\text{QoS},s},\ \forall s \in \{1, \ldots, M\}, \\ &\text{and } R_i \geq R_{\min,i}. \end{aligned} \tag{3.4}$$

Algo. 2 presents the BRD algorithm in the case of the SLA scenario. The same modifications mentioned in the algorithm of the GA approach are needed here to adapt to the algorithm of the FLA. The destination first initializes the rates following the result of the GA approach, and then it performs the correction process for all the M source nodes. The algorithm terminates once we have no further changes in the rate choices for all the source nodes. A small remark should be mentioned about step 8 of the BRD algorithm. By this step, we have captured all the details previously mentioned in the GA algorithm (between step 7 and step 35), i.e., the details of the MC simulation used to obtain the outage probability and the average number of rounds used. This is done for the sake of brevity, but both algorithms do individual outage tests to achieve the QoS constraint while allocating the rates.

By performing MC simulations, where the results are presented next, we witness that the number of iterations needed for the algorithm to converge is relatively small. In addition, we witness that the MC method is robust to the number of samples, as the degradation seen with decreasing the number of samples is not significant i.e., the results barely change even when simulations were based on only 10 samples. Moreover, we have demonstrated that the utility function is not always convex since the BRD, when

initialized with other starting points than the GA, can converge to a local optimum far from the global one depending on the simulation scenario (not presented for brevity). It confirms that the convergence analysis is simulation scenario dependent, which makes it extremely difficult to tackle analytically. In the next subsection, we talk about the convergence and the complexity of the BRD algorithm used.

3.2.3 Convergence and complexity

Convergence:

Theorem 3.2.1. *The BRD algorithm converges to an optimal (local or global) rate allocation after a limited number of iterations.*

Proof: The BRD is composed of an initialization step and an iterative correction step. The initialization step is always fixed to 1 iteration. Concerning the correction step, the stopping condition (step 5 in Algo. 2) happens when the allocation of all the sources' rates is not changed from the previous iteration for all sources $i \in \{1, ..., M\}$. Since the number of possible rate for all sources is finite (n_{MCS}), and since the *argmax* at step 8 only updates the rates if η strictly increases, the process of BRD completes with a finite number of iterations.
Complexity:
The complexity of the proposed BRD algorithm is much smaller than the case of the exhaustive search approach algorithm. In the latter, the calculation of each $\Pr(\mathrm{O}_{i,T_{\text{used}}} = 1)$ is performed $(n_{\text{MCS}})^M$ times, while in the proposed algorithm, in one iteration the same calculation is performed $n_{\text{MCS}} \times M$ times. Note that the GA algorithm is only an initialization phase where rates are fixed. Thus, we need $n_{\text{MCS}} \times M$ times of the same calculation. As we will see next, the number of BRD iterations is relatively small, ensuring the practicality of the used BRD algorithm.

3.3 Variable time slot duration

In this section, we consider LA for both rate and channel use allocation. In sharp contrast with existing cooperative transmission schemes, we consider the packet size to be time-varying. Although this assumption extends the complexity of the allocation problem, it is an interesting DoF which plays an important role in improving the efficiency of the network. The idea is that based on the channel conditions of different sources, it would be better to give more channel uses for a given source in good radio conditions and fewer channel uses for another source in bad radio conditions. Thus, we propose in this section to generalize the previously presented algorithms to tackle both rate and channel use allocation.

3.3.1 Novel system model

In the prior art [38, 39, 40, 41, 42, 43], the number of channel uses at each of the transmission phase U and the retransmission phase Q was fixed, and accordingly, the

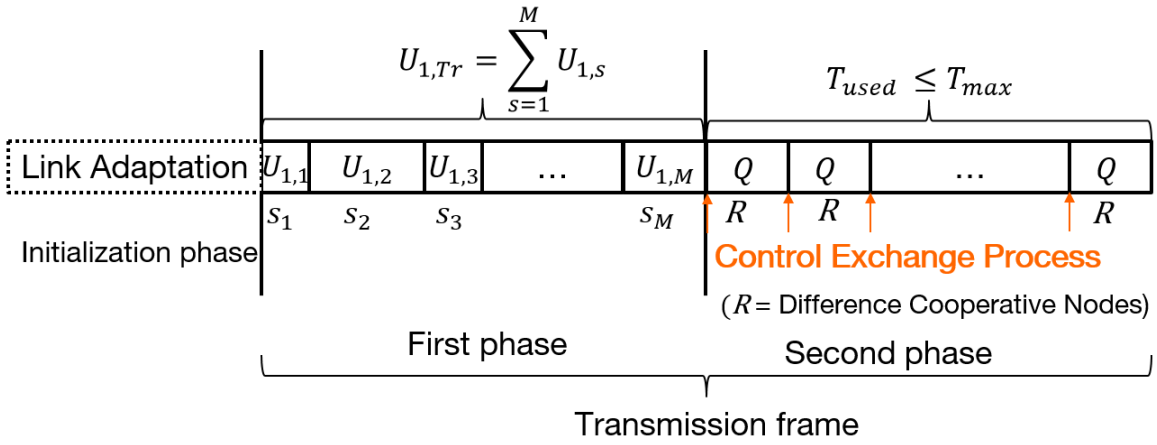


Figure 3.2: Proposed frame structure with variable packet size in the transmission phase.

ratio of channel uses between the two phases was also fixed. Here, we introduce a new DoF composed of a variable ratio of the number of channel uses. In particular, we fix the number of channel uses at the retransmission phase, and we define a variable number of channel uses for the transmission phase for each different source node s. In other words, the ratio of channel uses for a source node $s \in \{1, \ldots, M\}$ is denoted as $\alpha_s = \frac{Q}{U_{1,s}}$.

As a result of the introduced variable parameter, the LA problem we are investigating gets more complex. Indeed, rather than adapting source rates at the initial phase before starting the transmission of a new frame, the destination should now allocate both the rate and the ratio for each given source node. In figure 3.2, we see the initialization phase where rates are initialized, the transmission phase where a different number of channel uses is used for each different source node and the retransmission phase where there is a fixed number of channel uses and different allocated relaying nodes. A key assumption of our work is that the sources can use packets with variable sizes at the transmission phase (i.e., $U_{1,i}$ in the first phase), accordingly, the initialization phase includes both rate and channel use allocation. Fixing Q and varying U (and not the contrary) is simpler since during the retransmission phase a time slot is not dedicated to a specific node (being a relay or a source).

3.3.2 Performance metric and outage events for variable channel uses

Upon making the channel use in the transmission phase variable, we define

- n_{CUR} is the number of different Channel Use Ratios (CUR) available.
- $\widetilde{\mathbb{A}} = \{\widetilde{\alpha}_1, \ldots, \widetilde{\alpha}_{n_{\text{CUR}}}\}$ is the set of possible channel use ratios available.
- $\widehat{\alpha}_s$, is the channel use ratio of source s after the optimization.

- α_i, one possible value of $\widehat{\alpha}_s$ taken from the set of possible channel use ratios available.

Now, the spectral efficiency per frame with Variable Channel Use (VCU) $\eta^{\text{frame-VCU}}$ can be written as:

$$\begin{aligned}\eta^{\text{frame-VCU}}(\mathbf{H}, P) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} K_i(1-\mathrm{O}_{i,T_{\text{used}}})}{\sum_{l=1}^{M} U_{1,l} + QT_{\text{used}}} \\ &= \frac{\sum_{i=1}^{M} \frac{R_i}{\alpha_i}(1-\mathrm{O}_{i,T_{\text{used}}})}{\overline{\alpha} + T_{\text{used}}} \end{aligned} \tag{3.5}$$

where $\overline{\alpha} = \sum_{l=1}^{M} 1/\alpha_l$ denotes the sum of inverse of all the channel use ratios, and $R_i = K_i/U_{1,i}$ represents the rate of a source i. Note that R_i and α_i have a fixed value for SLA, while they change from frame to frame for FLA. In [39], Mohamad et al provide an outage analysis for various cooperative schemes. Nevertheless, the analysis was based on a fixed channel uses in the transmission phase. Accordingly, we present here the outage derivations when the number of channel uses in the transmission phase is considered variable. Specifically, and in the case of a variable number of channel uses, the equations that represent the common and the individual outage events for MU and SU cases (i.e., equations (2.3-2.7) can be generalized to:

$$\mathcal{E}_{t,\mathcal{B}}^{\text{VCU}}(a_t, S_{a_t,t-1}) = \bigcup_{\mathcal{U}\subseteq\mathcal{B}} \Big\{ \sum_{i\in\mathcal{U}} \frac{R_i}{\alpha_i} > \sum_{i\in\mathcal{U}} \frac{I_{i,d}}{\alpha_i} + \sum_{l=1}^{t-1} I_{\widehat{a}_l,d}\mathcal{C}_{\widehat{a}_l}(\mathcal{U}) + I_{a_t,d}\mathcal{C}_{a_t}(\mathcal{U}) \Big\}, \tag{3.6}$$

$$\begin{aligned}\mathcal{O}_{s,t}^{\text{VCU}}(a_t, S_{a_t,t-1}) &= \bigcap_{\mathcal{I}\subset\overline{S}_{d,t-1}, \mathcal{B}=\overline{\mathcal{I}}, s\in\mathcal{B}} \mathcal{E}_{t,\mathcal{B}}^{\text{VCU}}(a_t, S_{a_t,t-1}) \\ &= \bigcap_{\mathcal{I}\subset\overline{S}_{d,t-1}} \bigcup_{\mathcal{U}\subseteq\overline{\mathcal{I}}: s\in\mathcal{U}} \Big\{ \sum_{i\in\mathcal{U}} \frac{R_i}{\alpha_i} > \sum_{i\in\mathcal{U}} \frac{I_{i,d}}{\alpha_i} + \sum_{l=1}^{t-1} I_{\widehat{a}_l,d}\mathcal{C}_{\widehat{a}_l}(\mathcal{U}) + I_{a_t,d}\mathcal{C}_{a_t}(\mathcal{U}) \Big\},\end{aligned} \tag{3.7}$$

$$\mathcal{O}_{s,t}^{\text{SU-VCU}}(a_t, S_{a_t,t-1}) = \Big\{ \frac{R_i}{\alpha_i} > \frac{I_{i,d}}{\alpha_i} + \sum_{l=1}^{t-1} I_{\widehat{a}_l,d}\mathcal{C}_{\widehat{a}_l}^{\text{SU}} + I_{a_t,d}\mathcal{C}_{a_t}^{\text{SU}} \Big\}, \tag{3.8}$$

$$\mathcal{E}_{t,\mathcal{B}}^{\text{SU-VCU}}(a_t, S_{a_t,t-1}) = \bigcup_{s\in\mathcal{B}} \mathcal{O}_{s,t}^{\text{SU-VCU}}(a_t, S_{a_t,t-1}). \tag{3.9}$$

We see that the ratio values are included in the outage events, and thus, the optimal allocation of ratios should be performed jointly. Similarly, we generalize the optimization

equations to the VCU case (i.e., the equations (3.1) and (3.4)) as:

$$
\begin{aligned}
&(\{\widehat{R}_1, \widehat{\alpha}_1\}, \ldots, \{\widehat{R}_M, \widehat{\alpha}_M\}) = \underset{\{(R_1,\alpha_1\},\ldots,\{(R_M,\alpha_M\})\in\{\widetilde{\mathbb{R}},\widetilde{\mathbb{A}}\}^M}{\operatorname{argmax}} \mathbb{E}\left\{\frac{\sum_{i=1}^{M}\frac{R_i}{\alpha_i}(1-\mathrm{O}_{i,T_{\text{used}}})}{\overline{\alpha}+T_{\text{used}}}\right\}, \\
&\text{subject to:} \\
&\Pr(\mathrm{O}_{i,T_{\text{used}}}=1) \leq BLER_{\text{QoS},i},\ \forall i \in \{1,\ldots,M\}, \\
&R_i \geq R_{\min,i},\ \forall i \in \{1,\ldots,M\}.
\end{aligned}
\tag{3.10}
$$

$$
\begin{aligned}
&\{\widehat{R}_i, \widehat{\alpha}_i\} = \underset{\{R_i,\alpha_i\}\in\{\widetilde{\mathbb{R}},\widetilde{\mathbb{A}}\}}{\operatorname{argmax}} \mathbb{E}\left\{\frac{\sum_{j=1,j\neq i}^{M}\frac{\widehat{R}_j}{\widehat{\alpha}_j}(1-\mathrm{O}_{j,T_{\text{used}}})+\frac{R_i}{\alpha_i}(1-\mathrm{O}_{i,T_{\text{used}}})}{\overline{\alpha}+T_{\text{used}}}\right\}, \\
&\text{subject to:} \\
&\Pr(\mathrm{O}_{s,T_{\text{used}}}=1) \leq BLER_{\text{QoS},s},\ \forall s \in \{1,\ldots,M\}, \\
&\text{and } R_i \geq R_{\min,i},
\end{aligned}
\tag{3.11}
$$

where (3.10) represents the joint (rate-ratio) pair optimization and (3.11) represents the (rate-ratio) pair optimization per source (when using the BRD to be presented next). The difference seen in the latter two equations as compared to the case of fixed channel use allocation is that we are optimizing now $\eta^{\text{frame-VCU}}$ which includes not only the rate values but also the ratios.

3.3.3 Rate and channel use allocation

In this subsection, we present the BRD algorithm that allocates both the rate and the ratios of the sources (i.e., the $\{R_i, \alpha_i\}$ pairs). The methodology of the BRD algorithm remains the same. First, we have an initialization step. Then, a sequential correction follows. As seen in the optimization equations (3.10) and (3.11), upon including the VCU DoF, the ratios are included jointly in the optimizations. In other words, in order to reach the optimal allocation, the rates and the ratios of all sources should be allocated jointly (3.10). Again, and to avoid the exponential number of possible allocations, BRD is used to perform allocations sequentially (3.11).

For the initialization step, we use a similar algorithm as that presented in Algo. 1. Concerning the ratios, we set each source ratio as the average value of the possible ratios. In other words, for all sources $i \in \{1, \ldots, M\}$, we set α_i to $\alpha_{\text{average}} \leftarrow \frac{1}{|\widetilde{\mathbb{A}}|}\sum_{q=1}^{|\widetilde{\mathbb{A}}|}\widetilde{\alpha}_q$ where $\widetilde{\mathbb{A}} = \{\widetilde{\alpha}_1, \ldots, \widetilde{\alpha}_{\text{CUR}}\}$. In case α_{average} is not in the set of possible ratios, we choose the closest one to it: $\alpha_i \leftarrow argmin_{\tilde{\alpha}\in\widetilde{\mathbb{A}}}|\tilde{\alpha} - \alpha_{\text{avgerage}}|$. Concerning the rates, the same steps as Algo. 1 are performed. So, to sum up, the initialization steps are the same as in the case of fixed channel use case, while using the average ratio for all the sources.

For the BRD correction step, the algorithm goes in a similar manner as Algo. 2. The difference here is that we are allocating both, the rate and the ratio of each source successively. In addition, the algorithm terminates when there is no change in either

Algorithm 3 Best-Response algorithm under the QoS constraints on individual BLER targets $BLER_{\mathrm{QoS},i}, \forall i \in \{1,\dots,M\}$ for VCU case.

$t \leftarrow 0.$ ▷ Counter of iterations.
Set the candidate rates and ratios: $\widetilde{\mathbb{R}} = \{\widetilde{R}_1,\dots,\widetilde{R}_{n_{\mathrm{MCS}}}\}, \widetilde{\mathbb{A}} = \{\widetilde{\alpha}_1,\dots,\widetilde{\alpha}_{n_{\mathrm{CUR}}}\}$.
Rate and Ratio initialization under GA assumption with a random node selection:
$[\widehat{R}_1(0),\dots,\widehat{R}_M(0)] \leftarrow [R_1^{\mathrm{GA}},\dots,R_M^{\mathrm{GA}}]$,
$[\widehat{\alpha}_1(0),\dots,\widehat{\alpha}_M(0)] \leftarrow [\alpha_1^{\mathrm{GA}},\dots,\alpha_M^{\mathrm{GA}}]$.
$\{\widehat{R}_i(-1),\widehat{\alpha}_i(-1)\} \leftarrow \{0,0\}$ for all $i \in \{1,\dots,M\}$ ▷ To force loop to start
while $(|\widehat{R}_i(t)-\widehat{R}_i(t-1)|>0$ or $|\widehat{\alpha}_i(t)-\widehat{\alpha}_i(t-1)|>0)$, for some $i \in \{1,\dots,M\}$ **do**
  $t \leftarrow t+1.$
  for $i \leftarrow 1$ **to** M **do** ▷ for all sources, choose the pair which maximizes η
    $\{\widehat{R}_i(t),\widehat{\alpha}_i(t)\} \leftarrow \mathrm{argmax}_{\{R_i,\alpha_i\}\in\{\widetilde{\mathbb{R}},\widetilde{\mathbb{A}}\}}\, \eta\big(\{\widehat{R}_1(t),\widehat{\alpha}_1(t)\},\dots,\{\widehat{R}_{i-1}(t),\widehat{\alpha}_{i-1}(t)\},$
    $\{R_i,\alpha_i\},\{\widehat{R}_{i+1}(t-1),\widehat{\alpha}_{i+1}(t-1)\},\dots,\{\widehat{R}_M(t-1),\widehat{\alpha}_M(t-1)\}\big)$
    such that $\Pr\{\mathrm{O}_{s,T_{\mathrm{used}}}=1\} \le BLER_{\mathrm{QoS},s}$ for all $s \in \{1,\dots,M\}$
    and $R_i \ge R_{\min,i}$ ▷ while satisfying the constraints
  end for
end while

the rates nor the ratios of all the sources. The steps of this algorithm are presented in Algo. 3. The convergence of the BRD algorithm for the VCU case holds following the same explanations of 3.2.1. Concerning the complexity, upon following a VCU case, the complexity increases. Nevertheless, the increase is not exponential. The only difference is that rather than passing through n_{MCS} possible rates, we have to pass through $n_{\mathrm{MCS}} \times n_{\mathrm{CUR}}$ pairs of rates and ratios. Thus, and as we will see in the numerical results section, using a VCU transmission is seen as a trade-off between complexity and performance.

In table 3.1, we summarize the complexity of different allocation methods to be presented in the next section. This table includes the allocation using exhaustive search, BRD, GA allocations with fixed and variable channel use ratios. In this table, we present the complexity and the performance of these methods showing the importance of the BRD algorithm being a practical method with lower complexity and that approaches the benchmark of the complex exhaustive search approach.

3.4 Numerical results

In this section, we present the performance results of several scenarios using MC simulations. We consider the (3,3,1)-MAMRN, with $T_{\max}$ fixed to 4. In addition, we assume independent Gaussian distributed channel inputs (with zero mean and unit variance), with $I_{a,b} = \log_2(1+|h_{a,b}|^2)$. Note that some other formulas could be also used for calculating $I_{a,b}$ where for example discrete entries, finite length of the codewords, non-outage achieving Joint Network Channel Coding/Joint Network Channel Decoding

Allocation Method	Complexity	Properties
Exhaustive with variable α	$\Omega((n_{\text{MCS}} \times n_{\text{CUR}})^M)$	Optimal but complex: exponential with M and linear with n_{MCS} and n_{CUR}
Exhaustive with fixed α	$\Omega((n_{\text{MCS}})^M)$	Optimal (for fixed α) but complex: exponential with M and linear with n_{MCS}
BRD with variable α	$\Omega(n_{\text{MCS}} \times n_{\text{CUR}} \times M \times n_{\text{BRD}})$	Approaches the exhaustive method with lower complexity (linear with M)
BRD with fixed α	$\Omega(n_{\text{MCS}} \times M \times n_{\text{BRD}})$	Approaches the exhaustive method with lower complexity (linear with M)
GA with variable α	$\Omega(n_{\text{MCS}} \times n_{\text{CUR}} \times M)$	Low complexity but with mediocre performance
GA with fixed α	$\Omega(n_{\text{MCS}} \times M)$	Low complexity but with mediocre performance
Fixed allocation	$\Omega(1)$	Unacceptable performance

Table 3.1: Different allocation methods with their corresponding complexities and performance.

(JNCC/JNCD) architectures, etc. would be taken into account. In addition, we can calibrate the mutual information by using weight factors as in [127]. As mentioned in [128], our main conclusions would still apply to these different functions of mutual information. Moreover, we adopt an asymmetric link configuration setting, where each link has a different average SNR. The average SNR of each link is obtained from a unique value γ following the ordered steps:

1. All links are set to γ.
2. Links including source 2 are set to γ-4dB.
3. Links including source 3 are set to γ-7dB.
4. Links including both sources 2 and 3 are set to γ-5dB.

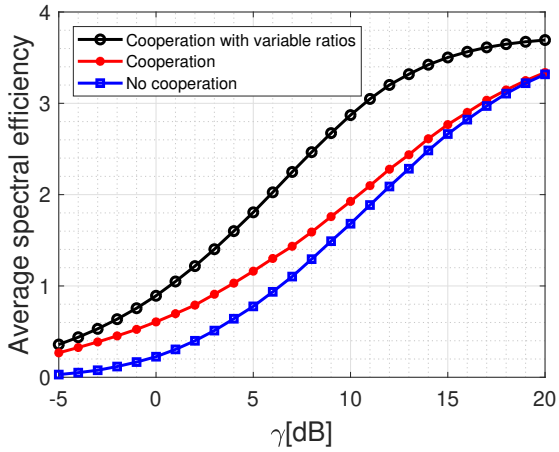
We carefully chose such kind of asymmetric configuration in order to make source 1 the source with the best links, followed by source 2, and source 3 is the source in the worst conditions. We recall that the destination scheduling strategy is the one described in [43], i.e., in each retransmission round the selected node is the one that has i) the highest mutual information with the destination and ii) which can help (its decoding set includes at least one message that has not yet been decoded correctly by the destination). The set of rates and ratios used are {0,0.75,1.5,2.25,3,3.75} [bits per channel use], and {0.1,0.55,1,1.45,1.9}, respectively.

We define two QoS scenarios. QoS^1: $\Pr(\mathrm{O}_{i,T_{\text{used}}} = 1) \leq BLER_{\text{QoS},i} = 1$, and $R_i \geq R_{\min,i} = 0$ [bits per channel use], $\forall i \in \{1, \ldots, M\}$. QoS^2: where $R_{\min,i} = 0.5$ [bits per channel use] and $BLER_{\text{QoS},i} = 10^{-3}$ $\forall i \in \{1, \ldots, M\}$. Clearly, with QoS^1, no constraint is taken into consideration. Note that although we investigated many different QoS constraints, we chose these two QoS scenarios since we believe they cover two representative cases: no constraint and a severe constraint. As mentioned before, for FLA, we only use QoS^1. This is due to the fact that since the full CSI is known at the destination, it is possible to avoid any individual outage per frame by simply not transmitting or, equivalently, transmitting with zero rate. In SLA on the contrary, we investigate both cases, no constraint (i.e., QoS^1) and a severe constraint (i.e., QoS^2).

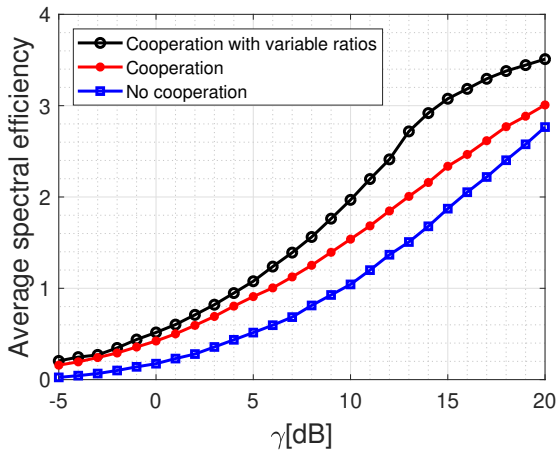
We divide the results into two main parts. In part 1, we investigate the effect of the new DoF of variable number of channel uses at the transmission phase. There, we check the gain of the proposed idea, and we investigate how this gain is changing with respect to the channel conditions and the system parameters (e.g., number of sources and number of relays). In part 2, we investigate the performance of the BRD algorithm allocating the rate and the channel uses for the sources. The performance is compared with an exhaustive search approach for both MU and SU encoding. We also test the practicality of the algorithm with respect to the channel conditions, number of samples needed, and the system parameters.

In the first part, we compare the ASE with respect to γ of 3 communication schemes, namely, no cooperation, cooperation, and cooperation with variable ratios. In the case of no cooperation, $T_{\max}$ is fixed to zero, meaning that we only have a transmission phase, and no notion of cooperation or retransmission is included. For the case of cooperation, the ratios of all the sources are fixed to 1 (the average value of the possible ratio set). Then, at each retransmission time slot, the scheduling strategy is the one recalled above [43]. Finally, for the case of cooperation with variable ratios, the channel use ratios are optimized per source exploiting the proposed DoF.

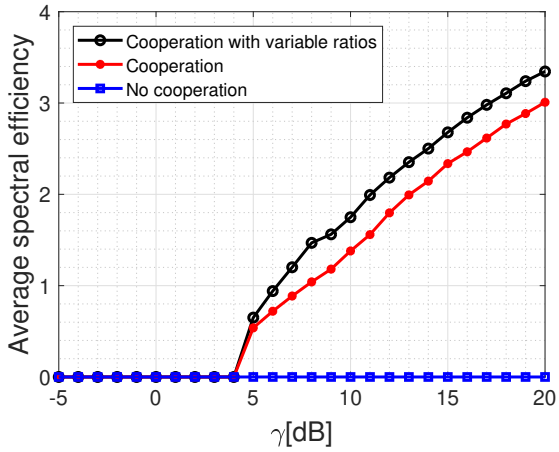
In Fig. 3.3, we see the performance of the three schemes: no cooperation ($T_{\max} = 0$), cooperation ($T_{\max} = 4$) with fixed ratios ($\alpha = 1$), and cooperation with variable ratios (α is optimized per source node) with: a) FLA with QoS^1, b) SLA with QoS^1, and c) SLA with QoS^2. In the FLA scenario (i.e., in Fig. 3.3 (a)), the gain of cooperation with fixed ratios compared with no cooperation increases for low SNR values (low γ). This gain decreases for high SNR values. On the other hand, and upon introducing variable ratios at the transmission phase, the gain of cooperation increases and become significant over all the considered SNR range (-5dB to 20dB). In Fig. 3.3 (b), a similar performance is seen with SLA with QoS^1. Once again, optimizing the channel use at the transmission phase is leading to a significant gain compared with fixed channel use and with no cooperation at all. Finally, in Fig. 3.3 (c), the performance of the three schemes is presented for SLA with QoS^2. Upon using this severe constraint, we see that with no cooperation, the system is always in outage. In other words, no possible allocation can be used to achieve the required constraint. On the other hand, upon using cooperation and cooperation with optimized channel use allocation, we see that starting from $\gamma = 4$dB, the system is not in outage. Here again, optimizing α per source is leading to better performance over all the considered SNR range larger than $\gamma = 4$dB. To summarize, Fig. 3.3 gives the following findings: 1- using cooperation can help improve the performance,



(a) FLA with QoS^1 target



(b) SLA with QoS^1 target



(c) SLA with QoS^2 target

Figure 3.3: ASE that corresponds to the proposed link adaptation algorithm for different scenarios.

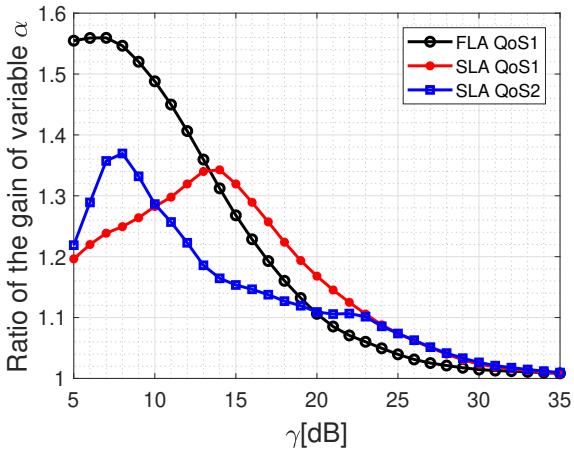


Figure 3.4: The ratio of the ASE with variable α and fixed α with respect to γ.

and is necessary with severe QoS constraints; 2- optimization of the channel use ratio can further improve the performance leading to a significant gain compared to fixed ratios scheme.

To our interest, we aim to investigate the operational conditions under which the gain of the proposed DoF (variable ratio) is significant. Also, we aim to investigate this gain for different channel conditions (e.g., high SNR), and different system parameters. Accordingly, in the next two figures, we present the ratio of the (ASE with optimized α) and the (ASE with the fixed α). We present this ratio for the three cases: FLA, SLA with QoS^1, and SLA with QoS^2.

In Fig. 3.4, the ratio presenting the gain of variable α compared with fixed α is seen over the SNR range (5dB to 35dB). We aim here to investigate how the gain is changing for high SNR values. We see that for the three different LA considered, the gain is acting in a similar way. The gain starts to increase from low SNR values reaching its peak at an intermediate SNR value, and then it decreases for high SNR reaching the ratio 1 (meaning that we have no gain). To explain this asymptotic behavior, we recall that at high SNR, the destination is able to decode all the messages sent by all the sources no matter what rate or ratio is being used. Accordingly, the difference between the channel conditions of the different sources is insignificant (all sources are facing similar channel conditions of high SNR). Moreover, having a fixed possible rates and possible channel ratios sets, will lead to a limitation of the gain. For the rates, the destination will select the highest possible rate for all the sources. And finally, upon having a fixed rate for all the sources, the channel use allocation will be indifferent.

Such analysis can also be deduced directly by analyzing the spectral efficiency per frame equation (i.e., equation (3.5)). Following that equation, and at high SNR, we can fix R_i to $R_{\max}$, and we can fix the outage and the T_{used} to zero (at high SNR there is no outage and no need for retransmission phases). Then, it is directly seen that the ASE is limited to $R_{\max}$ which justifies why we reach no gain at high SNR.

A final comment about the ratio at low SNR. As we see in the previous figure (i.e., Fig. 3.3) the ASE at low SNR is very small (and sometimes equal to zero), accordingly

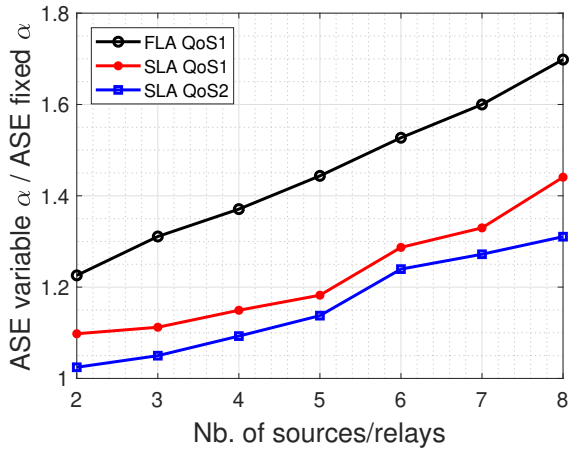


Figure 3.5: The ratio of the ASE with variable α and fixed α with respect to network size.

checking the ratio (ASE variable α/ASE fixed α) for such small values is not important. In other words, at low SNR, we might have a gain which is big, just because the ASE is very small. This might mislead the conclusion that the proposed DoF is important at low SNR. On the contrary, we say that after checking both the ASE and the ratio (ASE variable α/ASE fixed α), the proposed DoF is most significant at intermediate SNR values.

Following Fig. 3.4, the gain is most significant in the range of 5dB to 15dB. Accordingly, in Fig. 3.5, we fix γ to 10dB and we investigate the effect of the number of sources and relays on the gain of the VCU case. The x-axis represents the value of M and L considered. In other words, for a given x, we consider a (x,x,1) MAMRN. Note that we are still in an asymmetric link configuration, and for any value of M/L, the links of the sources are organized in a way making source i in better channel conditions from source j for $i < j$. Specifically, for a (x,x,1) system, the average SNR of each link is obtained from a unique value $\gamma = 10$ following the ordered steps:

1. All links are set to γ.

2. The links including source $i \in \{1, ..., x\}$ are set to γ - $2(i-1)$dB.

For the three considered schemes (FLA, SLA with QoS^1, SLA with QoS^2), we see that the gain of using variable ratios increases with the increase of the number of sources and relays. Also, we notice that the gain is approximately linear with respect to the size of the system. For FLA, the gain ratio reaches 1.7 with (8,8,1) system, whereas for SLA, the ratio is 1.45 and 1.3 with QoS^1 and QoS^2 respectively. This concludes the first part of the simulations. So to summarize, our findings are

- Using cooperation (with fixed ratios or variable ratios) can improve the spectral efficiency and is a must for severe QoS constraints.

- Using a variable number of channel uses at the transmission phase can help improve the spectral efficiency.

- The gain of using the new DoF is mostly significant for intermediate SNR values. This gain is limited at high SNR following the highest possible rate value in the set of possible rates considered.

- The gain of VCU increases with the increase in the system considered (i.e., with an increase in the number of sources and relays).

Keeping the same parameter settings used in the first part of simulations, and specifically, the configurations used inf Fig. 3.3, we now evaluate the performance of the BRD LA algorithm for α optimized per source with respect to other possible LA strategies including the LA utility metric optimization based on the exhaustive search approach. In particular, seven algorithms are presented:

- Exhaustive search approach: acting as the performance upper bound (exhaustive search over the possible vectors of pairs $\{\alpha$, rate$\}$). This algorithm is presented for the MU and the SU encoding.

- Best-Response Dynamic algorithm. Again, this algorithm is presented for the MU and the SU encoding.

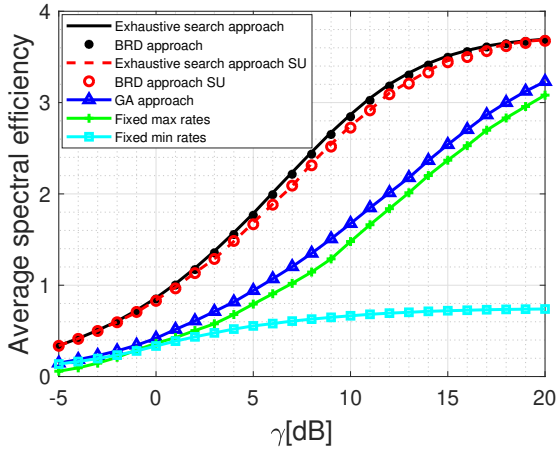
- Genie Aided approach: being the starting point of the BRD algorithm in the MU case.

- Maximum Rate approach: a trivial approach using the average α and the maximum rate available (3.75 [bits per channel use]).

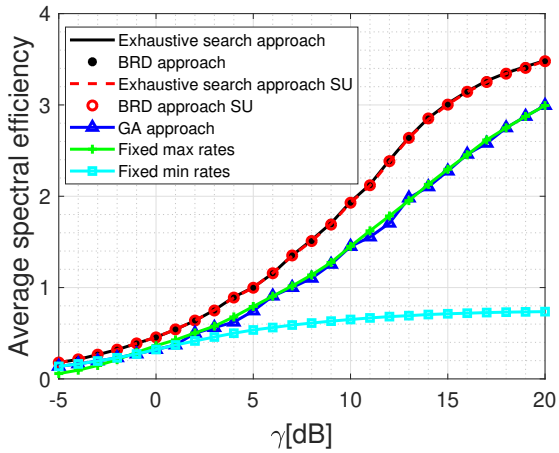
- Minimum Rate approach: a trivial approach using the average α and the minimum positive rate available (0.75 [bits per channel use]).

Here again, we present the results of FLA, SLA with QoS^1 target, and SLA with QoS^2 target. It is evident that in the three different scenarios, the proposed BRD algorithm converges to the optimal exhaustive search approach in both cases: the MU and the SU encoding. In addition, we notice that the GA approach leads to a loss of around 7dB in the FLA case (Fig. 3.6 (a)), at most 5dB in the SLA with QoS^1target (Fig. 3.6 (b)), and at most 5dB in the SLA with QoS^2 target (Fig. 3.6 (c)). Concerning the fixed allocation strategies, the minimum rate approach is always left behind. On the other hand, the fixed max rate approach gives a close performance to the GA approach when there is no QoS constraint (as in Fig. 3.6 (a) and 3.6 (b)) and an unacceptable performance with a severe QoS constraint (as in Fig. 3.6 (c)) except for very high SNR.

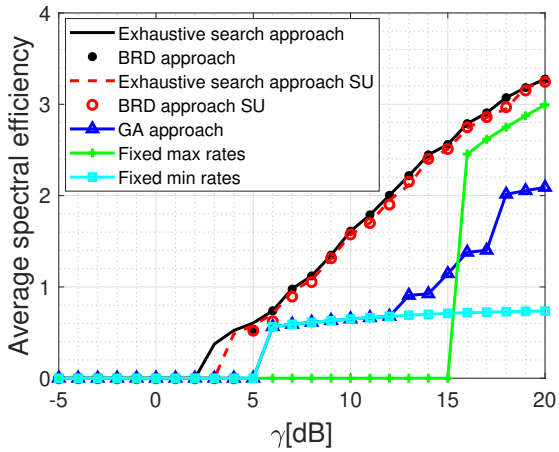
This result confirms the performance of the practical low-complexity BRD algorithm. Even with a varying number of channel uses at the transmission phase, the BRD algorithm is approaching the complex exhaustive search approach. In addition, this result validates the observation in [43] that the SU encoding strategy while being much simpler behaves similarly to its MU counterpart, and thus presents a great interest in practice since the shelves capacity approaching IR codes can be used. Shorty, this result validates the performance of the BRD for both the MU and the SU case. In the next two figures, we investigate two other aspects of the BRD. In Fig. 3.6, we validate its performance,



(a) FLA with QoS^1 target



(b) SLA with QoS^1 target



(c) SLA with QoS^2 target

Figure 3.6: ASE that corresponds to the different algorithms with a variable α.

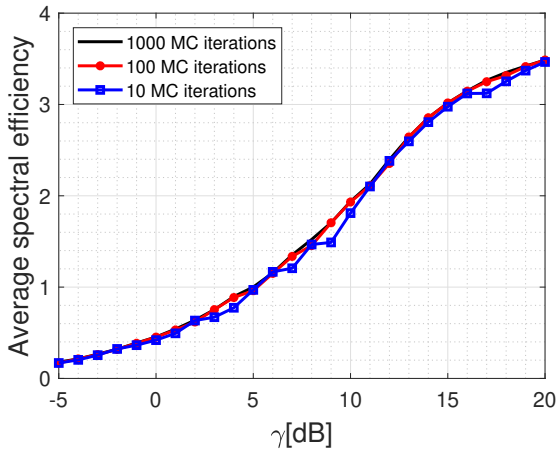


Figure 3.7: ASE of BRD approach under SLA QoS^1 for different number of MC samples.

which gives an ASE close to the upper bound. Next, we investigate its practicality, in terms of the needed number of MC iterations and the number of BRD iterations.

In SLA, the BRD algorithm is performed based on the CDI of the channel conditions. According, a number of samples are needed to be simulated at the destination in order to calculate the *argmax* seen in step 8 of Algo. 2. In Fig. 3.7, we present the ASE for SLA with QoS^1 while using 10, 100, and 1000 MC samples. As we see in this figure, the ASE is slightly changing with respect to the number of MC samples used. Specifically, even 10 iterations were enough to reach acceptable performance. We conclude that the MC method is robust to the number of samples. Note that this results is also seen with different QoS constraints (e.g., QoS^2), but we just show it with QoS^1.

Finally, in Fig. 3.8, we vary again the size of the system by varying the number of sources and relays used. The link configuration is similar to the one described in Fig. 3.4. Here, we investigate the number of BRD iterations used before reaching convergence. It is well known that the BRD algorithm will converge since the number of possible rates and ratios is finite. In the previous results (Fig. 3.6), we validate that the BRD convergence value is approaching the optimal value. In Fig. 3.7, we validate the practicality of the BRD algorithm being able to be performed using a low number of MC simulations. Finally, in Fig. 3.8, we validate the convergence speed by presenting the number of iterations the BRD algorithm is using for each $(x, x, 1)$-MAMRN.

In Fig. 3.8, we see that for the three scenarios (FLA, SLA with QoS^1, and SLA with QoS^2) the number of BRD iterations is relatively small. Since in FLA the LA is performed at each new CSI, we present the average number of BRD iterations used. On the contrary, since in SLA the LA is performed over a fixed CDI, we present the exact number of BRD iterations used. In both FLA, SLA QoS^1, and SLA with QoS^2, the number of iterations used is robust. For FLA, we see that the average number of iterations used is less than 3 iterations in all the considered systems up to (8,8,1)-MAMRN. Similarly in SLA, we see that with QoS^1, the highest number of iterations used was 4, and for SLA with QoS^2, the number of iterations used was always 2. It is seen that upon having a constraint, fewer options are available to the BRD algorithm,

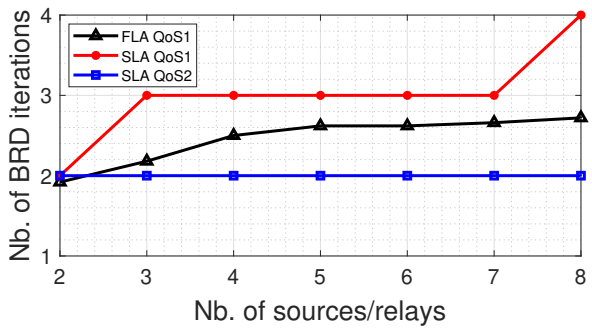


Figure 3.8: The (average) number of BRD iterations with respect to sources/relays included in the system.

leading to a faster convergence than no constraint scenario.

This concludes the second part of the simulations. So to summarize, our findings are

- The BRD algorithm is approaching the exhaustive search approach while tackling both rate and ratio allocation.
- The performance is similar for the MU and the SU encoding, which is interesting due to the practicality of the SU encoding case.
- In SLA, the MC method is robust to the number of samples needed, where only 10 iterations were sufficient in the presented scenario.
- The number of BRD iterations is slow in all the considered systems (up to (8,8,1)) which again validates the practicality of the considered algorithm.

3.5 FLA with partial CSI

In the previous three sections, two cases were mentioned: SLA and FLA. SLA relies on the CDI of all links at the destination, while FLA relies on the CSI of all links. Clearly, SLA is less demanding in terms of channel information acquisition control overhead while FLA provides closer-to-optimum scheduling decisions. In this section, we propose and analyze a novel practical LA algorithm combining the benefits of both. It is based on a FLA strategy with partial CSI.

The proposed LA strategy is a FLA algorithm in the sense that the rates are allocated at the beginning of each frame based on the partial CSI of the direct link. However, it relies on the average values of the unknown indirect links to avoid their heavy acquisition (in terms of signaling overhead). Note that this strategy can be adopted for both fixed channel use or variable channel use cases. For brevity, and to capture the performance of FLA with partial CSI, we present and investigate this proposal for fixed channel use allocation. Nevertheless, the proposal can be generalized to VCU case intuitively.

The proposed scheme is therefore an intermediate LA strategy which outperforms SLA but does not require the control overhead in FLA. Table 3.2 summarizes and compares the control exchange process of the three adaptation schemes, where the first two

rows correspond to FLA and SLA proposed in the previous sections, while the last row corresponds to our proposed intermediate solution. Clearly, we see how the proposed LA reduces the information needed at the destination while exploiting all the available information.

From an overhead perspective, the proposed strategy acts similarly to SLA, i.e., it incurs a small overhead. We neglect the overhead of the channel acquisition of the direct links and the one related to the allocation of the rates per frame. We focus on the overhead of the indirect links which is the most costly. In a given $(M, L, 1)$-MAMRN, the number of the indirect links corresponds to the number of possibilities to select two nodes among $M+L$ which is C_2^{M+L} where C is the combination operator. This means that the overhead can be calculated as $C_2^{M+L} \times$ nb bits per CSI/CDI $\times$ update percentage. As an example, we consider a $(3, 3, 1)$-MAMRN where 9 bits are needed for the quantification of a real value. In the case of high mobility, where the CSI is changing after each frame, the overhead of FLA is $C_2^6 \times 18 \times 1 = 270$ bits. On the other hand, and since SLA and the proposed strategy depend on the CDI which is assumed fixed for a long time (for example 1000 frames) and corresponds to a real value like the SNR, the overhead is $C_2^6 \times 9 \times 0.001 = 0.135$ bits. Clearly, FLA overhead quickly becomes prohibitive for a high number of nodes and/or high mobility. Note that in the example above, the 18 bits correspond to the real and imaginary parts of the CSI quantification, while the 9 bits correspond to the real value of the CDI quantification.

3.5.1 Framework

In figures 3.9 and 3.10, we see an illustration of the framework. The control exchange between the transmitting nodes (sources and relays) and the destination is presented within a frame transmission. First, the destination broadcasts Sounding Reference Signals (SRS) request to acquire the CSI of the direct links. Next, after receiving the partial CSI, the destination allocates and broadcasts the rates of the sources. The allocation process is based on the channel distribution of the indirect links. Then, each source transmits its message with its allocated rate while including Demodulation Reference Signals (DMRS) which are necessary for demodulating the signal coherently at the destination and which help update the partial CSI knowledge. Finally, there are two cases. The first case is that the destination decodes all the sources before $T_{\max}$ and then broadcasts an ACK which triggers the flushing of the source buffers. The second case is when there is at least one source node that is not decoded after $T_{\max}$ in which case the sources flush their buffers (based on timers). In both cases, we reach the initialization of a new frame. On the other hand, and every few hundreds of frames, we see in figure 3.10 the CDI update event, where the destination requests and receives CDI of the updated nodes before performing the rate allocation process, and occasionally the CDI update is event-driven and initiated by the source/relay (when the CDI changes).

3.5.2 Utility of FLA with Partial CSI and the proposed algorithm

The ASE can now be derived from η^{frame} for SLA/FLA as:

SLA • **LA occurrences:** Once the CDI of any link needs to be updated • **Channel information:** Based on the CDI of the links, the allocation is determined using MC simulations, over the probability distribution of the links
FLA • **LA occurrences:** Once the CSI of any link changes • **Channel information:** Based on the exact CSI of the links, the allocation is performed
FLA with partial CSI • **LA occurrences:** Once the CSI of any direct link or the CDI of any indirect link need to be updated • **Channel information:** Based on the CSI of the direct links, and the CDI of indirect links

Table 3.2: Description of the different link adaptation schemes.

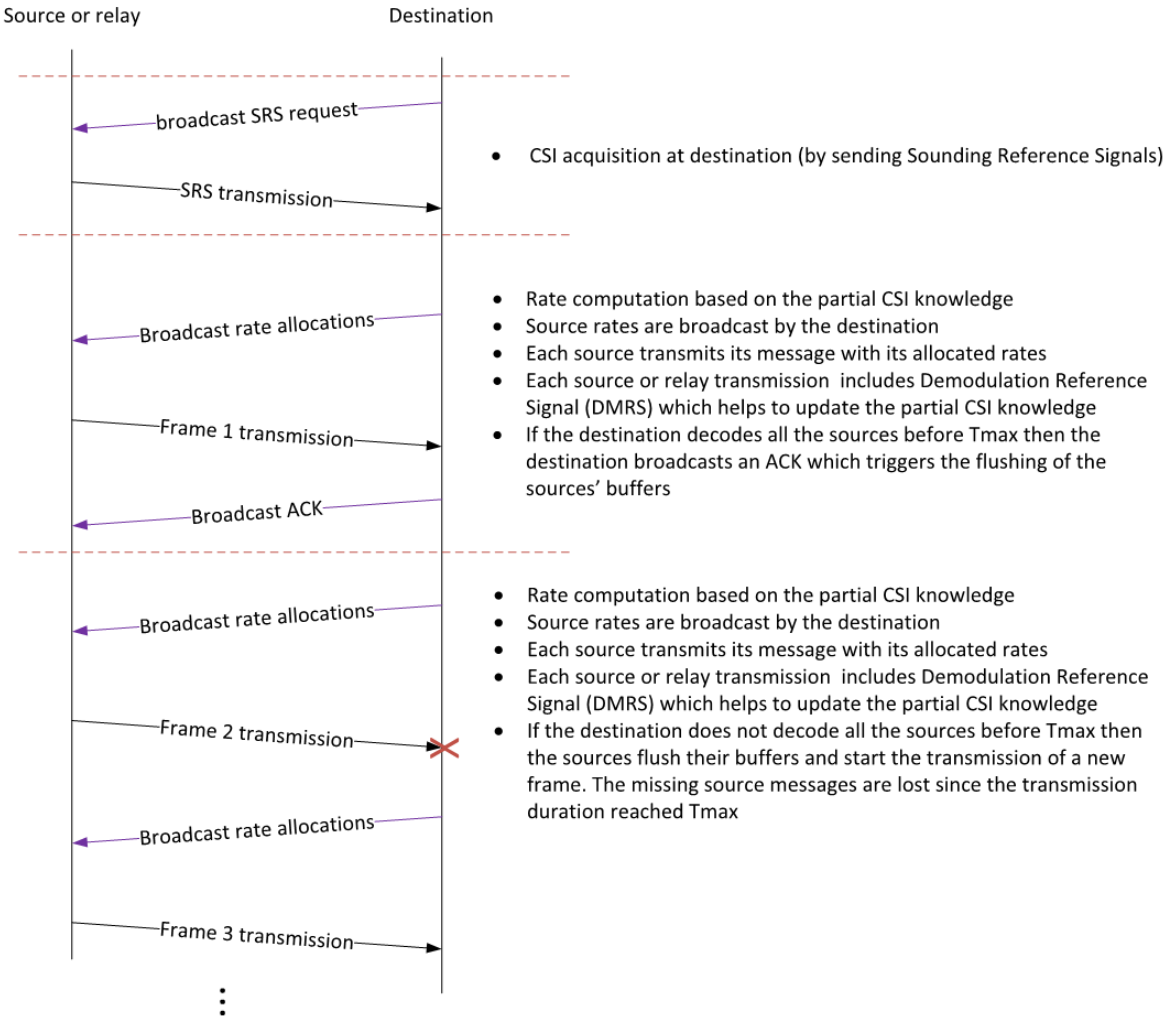


Figure 3.9: FLA with partial CSI knowledge for orthogonal MAMRN.

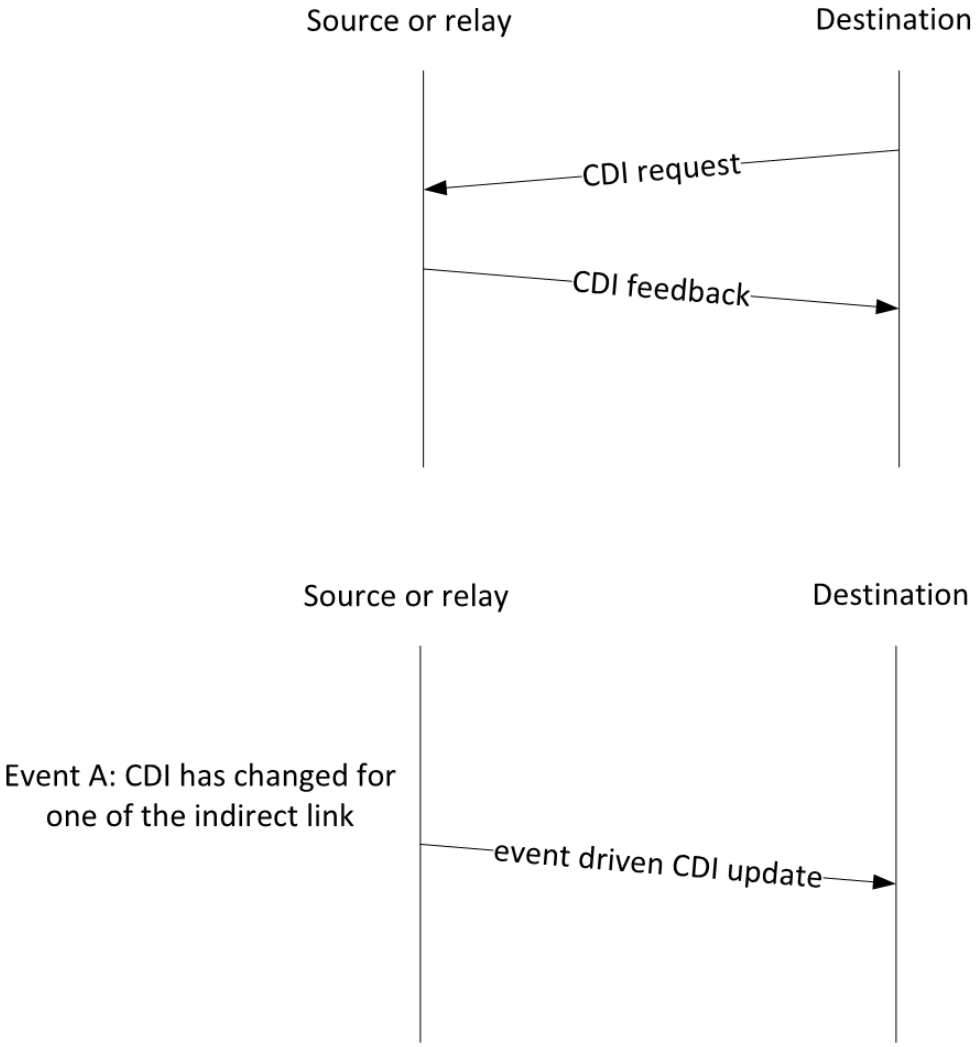


Figure 3.10: The CDI update event steps.

$$\eta^{\text{SLA/FLA}}(\mathbf{H}, P_{\text{SLA/FLA}}) = \mathbb{E}\{\eta^{\text{frame}}\}$$
$$= \mathbb{E}\left\{\frac{\sum_{i=1}^{M} R_i(1 - \text{O}_{i,T_{\max}})}{M + \alpha T_{\text{used}}}\right\}. \tag{3.12}$$

In SLA, the rates are allocated based on the CDI which are fixed within hundreds of frames, and thus, the rates are fixed within the expectation. On the other hand, in FLA, the rates are allocated based on the CSI which is updated frequently, and thus, the rates are random variables.

We now present the updated utility metric and rate allocation scheme for the proposed FLA with the partial CSI assumption. Following the strategy description mentioned before, the rate allocation process is based on the knowledge of the channel distribution of the direct links. In other words, for each given CSI of the direct links, the destination will allocate the rates of the sources based on the CDI of the indirect links. Here too, the aim is to maximize the ASE per frame. The channel information of the direct links is conveyed over unicast forward coordination control channels (from sources and relays towards the destination) that are assumed to be error-free. Similarly, the CDI of the indirect links is forwarded to the destination once there is any change in it (every few hundred frames). The source nodes forward the CDI of the S-S and S-R links, and the relays forward the CDI of the R-R links.

Using the law of total expectation, i.e., $\mathbb{E}\{X\} = \mathbb{E}\{\mathbb{E}\{X|Y\}\}$, we update the expression for the FLA utility metric:

$$\eta^{\text{FLA}}(\mathbf{H}, P_{\text{new}}) = \mathbb{E}\left\{\frac{\sum_{i=1}^{M} R_i(1 - \text{O}_{i,T_{\max}})}{M + \alpha T_{\text{used}}}\right\},$$
$$= \mathbb{E}\left\{\mathbb{E}\left\{\frac{\sum_{i=1}^{M} R_i(1 - \text{O}_{i,T_{\max}})}{M + \alpha T_{\text{used}}}\middle|\mathbf{H}_{\text{dir}}\right\}\right\}, \tag{3.13}$$
$$= \mathbb{E}\left\{\rho^{\text{FLA}}\right\}.$$

We propose a novel rate allocation strategy $P = P_{\text{new}}$ (coined FLA with partial CSI) which does not depend on $\mathbf{H}_{\text{ind}}$ but changes for each $\mathbf{H}_{\text{dir}}$ realization. Thus, the rate R_i allocated per source does not change within the conditional expectation on $\mathbf{H}_{\text{dir}}$. It is clear that in order to maximize the ASE per frame, the destination should select the rates (i.e., $R_i, i \in \{1, \ldots, M\}$) per frame (that is why it is a FLA) based on the knowledge of $\mathbf{H}_{\text{dir}}$ in a way that maximizes ρ^{FLA}. This is the main advantage of our technique compared to the state of the art FLA: the destination does not need the CSI (i.e., does not need knowledge of H_{ind}) of the indirect links but only the CDI.

The spectral efficiency per frame based on the partial CSI knowledge is a multivariable equation, function of all source rates as well as the node chosen at each time slot in the retransmission phase. We recall that we distinguish here $\widehat{R}_i$, the rate of source i after the optimization, and R_i, one possible value of $\widehat{R}_i$ taken from the set of possible

Algorithm 4 Best-Response algorithm for FLA with Partial CSI.

1: $t \leftarrow 0$. ▷ Counter of iterations.
2: Set the candidate rates: $\widetilde{\mathbb{R}} = \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$.
3: Rate initialization under GA (or other) assumption: $[\widehat{R}_1(0), \ldots, \widehat{R}_M(0)] \leftarrow [R_1^{\text{GA}}, \ldots, R_M^{\text{GA}}]$.
4: $\widehat{R}_i(-1) \leftarrow 0$ for all $i \in \{1, \ldots, M\}$ ▷ To force loop to start
5: **while** $(|\widehat{R}_i(t) - \widehat{R}_i(t-1)| > 0)$, for some $i \in \{1, \ldots, M\}$ **do**
6: $\quad t \leftarrow t + 1$.
7: $\quad$ **for** $i \leftarrow 1$ **to** M **do** ▷ for all sources, choose:
8: $\quad\quad \widehat{R}_i(t) \leftarrow \text{argmax}_{R_i \in \widetilde{\mathbb{R}}}\, \rho^{\text{FLA}} \left(\widehat{R}_1(t), \ldots \widehat{R}_{i-1}(t), R_i, \widehat{R}_{i+1}(t-1), \ldots, \widehat{R}_M(t-1)\right)$
▷ the rate which maximizes ρ^{FLA}.
9: $\quad$ **end for**
10: **end while**

rates $\widetilde{\mathbb{R}}$. Accordingly, our multi-variable optimization problem can be written as:

$$(\widehat{R}_1, \ldots, \widehat{R}_M) = \underset{\{R_1, \ldots, R_M\} \in \widetilde{\mathbb{R}}^M}{\text{argmax}} \; \mathbb{E}\left\{ \frac{\sum_{i=1}^{M} R_i (1 - \text{O}_{i,T_{\max}})}{M + \alpha T_{\text{used}}} \middle| \mathbf{H}_{\text{dir}} \right\} \tag{3.14}$$

where $\widetilde{\mathbb{R}} = \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$ is a predefined finite set of rates of a cardinality that is equal to the number of available MCS (n_{MCS}). Note that we omit including a QoS constraint in the optimization problem. The reason behind this is that we want to compare FLA, SLA, and FLA with partial CSI (the proposal of this section). Since a zero rate is included in the set of possible rates, the FLA strategy with full CSI can avoid any outage. Thus, and to make the comparison possible with FLA, we omit including a QoS constraint. Nevertheless, a QoS constraint can be easily introduced by defining, for example, a minimum rate allowed and/or an outage probability limit in the case of SLA or FLA with partial CSI.

One simplification of the problem is to consider that the CDI of the indirect links is a Dirac distribution around their average SNR (AWGN approximation of the unknown links with the same SNR) assuming a noise variance of 1. Since the optimal solution (the exhaustive search approach) for the optimization problem in (3.14) costs a high complexity and is inefficient in practice, we retain again for the BRD algorithm, where instead of solving the problem jointly, the solution is given to each user iteratively. The detailed algorithm of the BRD approach is presented in Algo. 4.

3.5.3 Numerical result

We present here the results of our MC simulations that validate the effectiveness of the proposed LA scheme. Particularly, we compare the performance of four different LA strategies: FLA, SLA, FLA Partial CSI (our proposed strategy), and FLA Partial CSI Dirac (our approximation strategy described at the end of the previous subsection. To this end, we consider a (3,3,1)-MAMRN scenario, and we set $T_{\max} = 4$ and $\alpha = 2$. The allocated rates are chosen from a discrete MCS family of rates $\widetilde{\mathbb{R}} = \{0,0.5,1,1.5,2,2.5,3,3.5\}$

[bits per channel use]. We further assume that the channel inputs are independent and Gaussian distributed with zero mean and unit variance, while noting that other channel inputs might be considered without changing the conclusions of this work. Finally, we consider the following asymmetric link configuration: first, the average SNR of each link is set to γ; second, the average SNR of each link that includes source 2 is set to $\gamma - 4$dB and which includes source 3 is set to $\gamma - 7$dB; lastly, the average SNR of the link between the sources 2 and 3 is set to $\gamma - 5$dB. Thus we have purposefully set the source 1 to be in the best propagation conditions, while the source 3 is in the worst conditions.

The results are presented in figure 3.11, where it is noticed that for the whole interval of $\gamma \in [-5, 20]$dB, the proposed scheme is approaching the upper bound FLA strategy with insignificant loss. This approach outperforms the SLA approach with a significant improvement, up to 6dB gain for a high SNR regime. Moreover, we see that the Dirac approximation of the proposed algorithm performs in a similar manner with a slight reduction in the gain. That is, using the Dirac approximation of the CDI (i.e., the average SNR) rather than doing MC simulations, can gain up to 4dB compared to SLA strategy, with less than 2dB loss compared to the upper bound FLA approach. In conclusion, the performance of the proposed FLA with partial CSI approaches that of FLA while incurring significantly less control overhead, as it does not require frequent CSI updates from the indirect links.

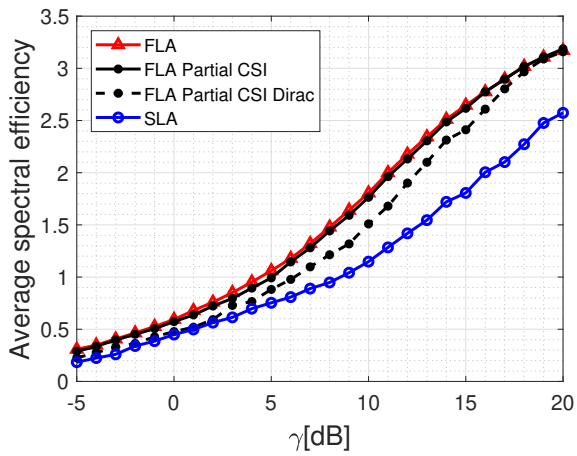


Figure 3.11: ASE that corresponds to the different link adaptation strategies.

3.6 Conclusion

In this chapter, we investigated different LA algorithms for orthogonal MAMRN conditioned on the available channel information at the destination. Furthermore, we proposed a new degree of freedom by adapting the time slot duration of each source during the transmission phase. Both SLA and FLA are investigated, as well as MU encoding and the SU encoding sub-case. Finally, FLA with partial CSI is proposed as an intermediate algorithm that approaches the FLA strategy while incurring less control

overhead similar to the way seen in SLA. MC simulations show the significant impact of user cooperation on the spectral efficiency (up to 4 dB shift) as well as the importance of exploring the degree of freedom of the time slot duration associated with each source during the first transmission phase (up to 6dB shift). This gain is seen to be increasing with the size of the system (number of relaying nodes) and is limited to the maximum possible rate value. Furthermore, the numerical results validate the proposed BRD strategies (including a GA initial point determination), which tackle the complexity issue of the LA utility metric optimization. We see that the efficiency of the proposed algorithms holds in both cases: SLA and FLA, and in both encoding strategies: MU and SU encoding. We also see the practicality of the proposed solution being robust to the number of MC samples and facing a low number of BRD iterations.

Chapter 4

Centralized Scheduling and Relaying Nodes Selection Algorithms

4.1 Chapter summary

In this chapter, we target the problem of scheduling in the retransmission phase. In the first section, we tackle the degree of freedom seen in PR. In PR, we exploit all the possible relaying nodes available in the network. Rather than activating a single relaying node at each retransmission time slot, we propose activating multiple relaying nodes to send a better redundancy version of the message of a source node chosen to be helped. In the second section of this chapter, we further investigate the effect of the control exchange process in each of the scheduling strategies presented. Then, a novel selection strategy is proposed based on the estimation of the number of time slots needed to decode a given source message. The latter strategy uses PR but simultaneously reduces the control exchange process needed in the traditional selection strategies. The numerical results validate the gain of using PR compared to SR. In addition, they show the importance of reducing overhead by tackling the control exchange process performed at the retransmission phase.

4.2 Parallel retransmission

4.2.1 Framework

In the previous chapter, we investigated both MU and SU retransmission. To our interest, SU is a simplified orthogonal MAMRN protocol which is based on existing LDPC and Turbo codes which are used in the 3GPP LTE and NR standards. The protocol allows a retransmission of the IR per source, that is, transmitting bits of different parities on the basis of a single coding with a very low rate. In this chapter, we build on this protocol and we propose exploiting the diversity of activating several relays at a given retransmission to help a selected source node. We propose an improved node selection strategy which takes advantage of the multi-path diversity of the relaying nodes. The idea is based on the fact that each relaying node has its own power budget, and

accordingly, several relaying nodes can be activated at the same time.

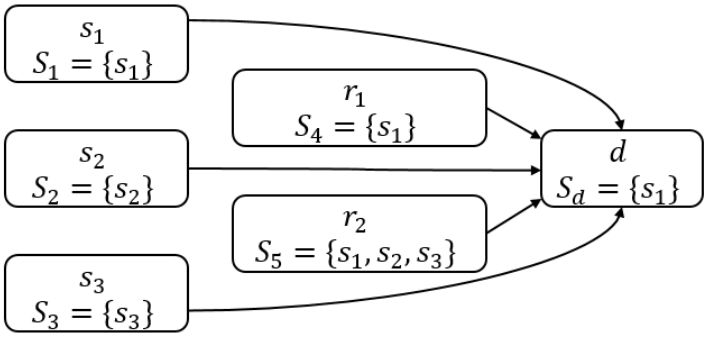
In the previous chapter, for each retransmission, the destination chooses the unique active node which has the best connection to the destination and which can assist the destination. We say that a node can assist when its decoding set includes some source nodes which are not decoded at the destination yet. The scheduling decisions are based on the CSI of the direct links which is assumed to be available at the destination. We recall that the direct links are the S-D links, and the R-D links. The CSI of the indirect links is assumed not available at the destination due to the costly acquisition process needed and the overhead included in this process. We recall that the indirect links are the links of S-S, S-R, and R-R. Finally, we recall that we assume a slow fading scenario where the radio links between the nodes do not change within a frame transmission. Additionally, the channel realization is assumed independent from frame to frame, which simplifies the analysis and is sufficient to capture the performance of practical systems assuming ergodicity of the underlying random processes.

4.2.2 A Toy example

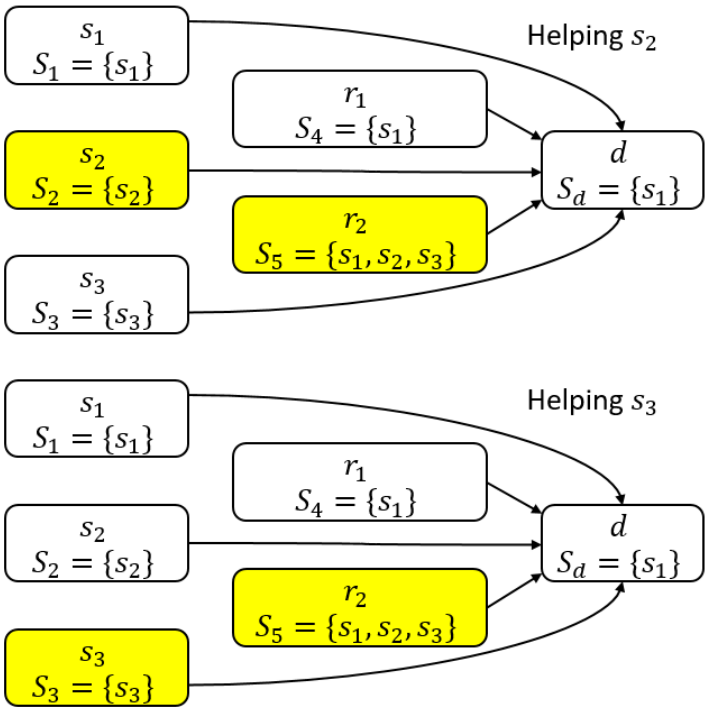
The proposed selection strategy is quite different than the one used in the prior art and in the previous chapter. Rather than selecting a single relaying node to help one source node at a given retransmission time slot, we propose allocating one source to be helped by multiple relaying nodes. In such a way, we make use of the multi-path diversity of the different relaying nodes and we exploit the available power budget at each relaying node. We present a toy example that describes how our proposal works (recheck the toy example presented in chapter 2, Fig. 2.3). Next, we present the control exchange process in the novel selection strategy, followed by the algorithm of how the destination will choose the source node that will be helped by multiple relaying nodes.

We present in Fig. 4.1 a toy example that shows how the selection strategy of our proposal works. We used the same parameters used in chapter 2 to make it easier to compare between our proposal and the prior art. Accordingly, in Fig. 4.1a, we consider a $(3, 2, 1)$-MAMRN. At the considered time slot (any time slot in the retransmission phase), the decoding sets of all the nodes are presented. We see that the destination decoded the message of source s_1, the source did not decode any source message (but their own message), and that the relays r_1 and r_2 decoded respectively the set of sources $\{s_1\}$ and $\{s_1, s_2, s_3\}$. In [43], the candidate relaying nodes to be selected are the nodes that can help at least one source which is not decoded by the destination. Here, on the contrary, the destination does not look for candidate relaying nodes, but looks for candidate source nodes. In other words, in our proposal, the destination first set the candidate sources to be helped by multiple relaying nodes.

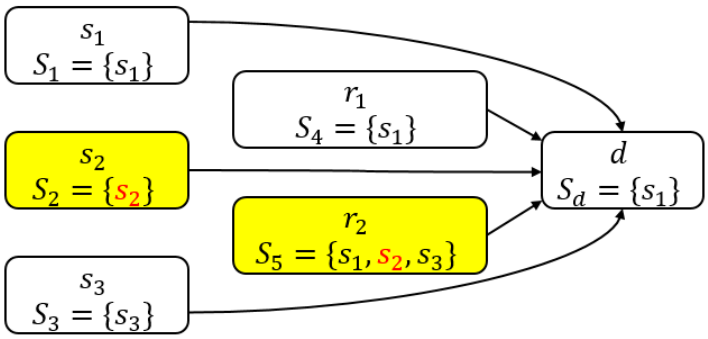
As the destination decoded source s_1, the candidate source nodes (in this example) are the sources s_2 and s_3. In Fig. 4.1b, we see that for each candidate source, a set of relaying nodes can be activated to help this source. For example, if source s_2 is selected, both nodes s_2 and r_2 can be activated. Similarly, if s_3 is selected, both nodes s_3 and r_2 can be activated. After fixing the set of candidate source nodes, as well as the set of relaying nodes that can be activated with each of the source nodes, the destination chooses the source node with the highest equivalent mutual information.



(a) (3,2,1)-MAMRN with the decoding sets



(b) Candidate source nodes in this example



(c) Selected source and relaying nodes in this example

Figure 4.1: A toy example describing the process of the selection strategy proposed in this chapter.

In other words, the destination checks the equivalent channel that will help sources s_2 (equivalent channel of the PR of nodes s_2 and r_2 together) and s_3 (equivalent channel of the PR of nodes s_3 and r_2 together). The source which has a better equivalent channel will be selected. Then, all the relaying nodes that decoded this source message will be activated to send the same redundancy of the message of the selected source. In Fig. 4.1c, we see that the destination chooses to help source s_2, and accordingly, the relaying nodes s_2 and r_2 are going to be activated. This process is repeated at the beginning of each retransmission time slot while using the updated decoding sets of the nodes. The control exchange process of the mentioned strategy, as well as the method of calculating the equivalent channel of multiple relaying nodes are presented next.

4.2.3 Control exchange process and algorithm

First, the destination sends an ACK/NACK bit, then the relaying nodes send their decoding sets. The ACK bit indicates that all the sources have been decoded correctly, and the NACK indicates the contrary. The selection is performed after that. The destination calculates for each source $i \in \{1, ..., M\}$ the SNR_i associated with the transmission of the redundancy version of the source i. This is calculated on the basis of the number of relaying nodes that were able to decode this source, as well as their channel with the destination (check the three cases described below). The channel from each relaying node $j \in \{1, ..., M + L\}$ to the destination is denoted $h_{j,d}$ and the set of relaying nodes j which can help the source i is denoted Help_i. Accordingly, the destination selects the source $\widehat{s}_t$ with the best equivalent channel (highest equivalent SNR), and then, all the relaying nodes which decoded the chosen source $\widehat{s}_t$ retransmit redundancies. We consider three cases for estimating the SNR_i:

- **Case 1:** each relaying node $j \in \{1, ..., M + L\}$ does not know the channel $h_{j,d}$

$$\mathrm{SNR}_i = \mathcal{P} \left| \sum_{j \in \mathrm{Help}_i} h_{j,d} \right|^2 / N_0, \tag{4.1}$$

  where $\mathcal{P}$ is the transmission power of each node, N_0 is the noise spectral density, and $h_{j,d}$ is the channel whose power is normalized to 1.

- **Case 2 "Equal Gain Combining (EGC)":** each node $j \in \{1, ..., M+L\}$ knows the phase Φ_j of its channel toward the destination $e^{-\mathrm{i}\Phi_j} = h^*_{j,d}/|h_{j,d}|$ with $\mathrm{i}^2 = -1$

$$\mathrm{SNR}_i = \mathcal{P} \left(\sum_{j \in \mathrm{Help}_i} |h_{j,d}| \right)^2 / N_0. \tag{4.2}$$

- **Case 3:** Assuming that the subset $\mathrm{Help}_i = \mathrm{Help1}_i \bigcup \mathrm{Help2}_i$ breaks down into a subset $\mathrm{Help1}_i$ of nodes knowing their phase with the destination (sent by the

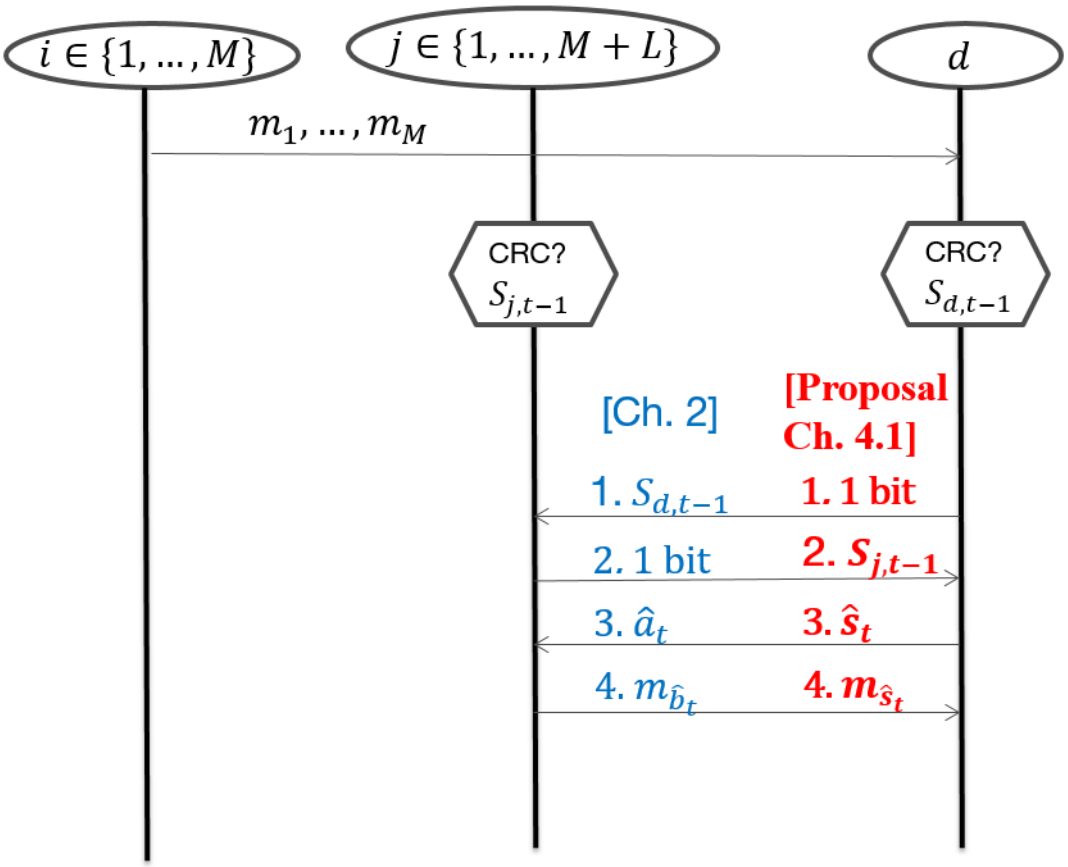


Figure 4.2: Control exchange process corresponding to: the prior art (in blue) and the current proposal (in bold red).

destination) and Help2$_i$ not knowing it, in this case, SNR$_i$ for $i \in \{1, ..., M\}$ is written as:

$$\mathrm{SNR}_i = \mathcal{P} \left| \sum_{j \in \mathrm{Help1}_i} |h_{j,d}| + \sum_{j \in \mathrm{Help2}_i} h_{j,d} \right|^2 / N_0. \tag{4.3}$$

If the node i is selected, the transmission of each node belonging to Help1$_i$ will be multiplied by $e^{-\mathrm{i}\Phi_j}$(coherent reception for the nodes belonging to Help1$_i$).

In Fig. 4.2, we present the control exchange process in each of the prior art (in blue) and the proposed (in bold red) selection strategies. For the prior art, it is similar to the one presented in chapter 2, with the only difference being that here we are using SU retransmission. This means that at the last step, the selected relaying node $\widehat{a}_t$ is going to help one source node $\widehat{b}_t$ from its decoding set and which is not decoded at the destination yet.

In our proposal, the destination returns the source index $\widehat{s}_t$ which has the best SNR. Following the receipt of the source index $\widehat{s}_t$ broadcast by the destination, the nodes having decoded $\widehat{s}_t$ simultaneously transmit the same version of the modulated message

Algorithm 5 Parallel retransmissions selection strategy.

```
1: MAX = 0                                          ▷ Initialize MAX to zero
2: for all i in S̄_{d,t−1} do                        ▷ For every non-decoded source node
3:     Help_i ← φ                                   ▷ Initialize Help_i to empty set
4:     for all j in {1, ..., M + L} do              ▷ for all relaying nodes
5:         if i ∈ S_{j,t−1} then                    ▷ If node j can help source i
6:             Help_i ← Help_i ∪ {j}                ▷ get the set of helping relaying nodes for source i
7:         end if
8:     end for
9:     Calculate SNR_i                              ▷ using one of the three equations above
10:    if SNR_i > MAX then
11:        MAX ← SNR_i                              ▷ Update the value of MAX
12:        ŝ_t ← i                                  ▷ Update the selected source
13:    end if
14: end for
```

of source $\widehat{s}_t$, i.e., $m_{\widehat{s}_t}$ (Fig. 4.2). In the case where each node $j \in \text{Help}_{\widehat{s}_t}$ knows the phase Φ_j of its channel towards the destination, the modulated transmission of $m_{\widehat{s}_t}$ is multiplied by $e^{-\mathrm{i}\Phi_j}$ (the conjugate of the channel divided by its norm) to obtain a coherent combination at the destination (case 2). The phase Φ_j is quantized in practice (e.g., 2 bits are sufficient), and the quantized phase relating to each node can be sent from the destination to the nodes during the initialization phase or just after the first transmission phase. Finally, Algo. 5 presents the pseudo-code of the proposed selection strategy using PR at a given retransmission time slot t. Note that in step 8, and if we were in case 1 (no EGC), the calculation of the highest SNR_i needs to pass through all subsets of Help_i due to the possible destructive retransmissions of the relaying nodes which are out of phase. In other words, and in such a case, the optimal selection would choose a subset of relaying nodes to be active rather than the whole set Help_i. Accordingly, the destination should send the selected source node to be helped, as well as the selected relaying nodes to send redundancies.

4.2.4 Numerical results

In this subsection, we validate the proposed selection strategy using MC simulations. We consider a (3,6,1)-MAMRN scenario, and we set α to 0.25 and $T_{\max}$ to 4. The channel inputs are assumed independent and Gaussian distributed with zero mean and unit variance. Note that other channel inputs might be considered without changing the conclusions of this work. We further assume that the rate of each source is allocated using the BRD algorithm presented in the previous chapter. We consider two link configuration scenarios: symmetric and asymmetric. In the symmetric link configuration (Fig. 4.3), all the links are considered the same (the average SNR of each link is set to γ). On the other hand, in the asymmetric link configuration (Fig. 4.4), we design a scenario where the direct links between the source nodes and the destination are bad. Such a scenario helps in showing the importance of the relaying nodes and the gain of the proposed retransmission strategy. Particularly, the links are set as follows: first, the average SNR

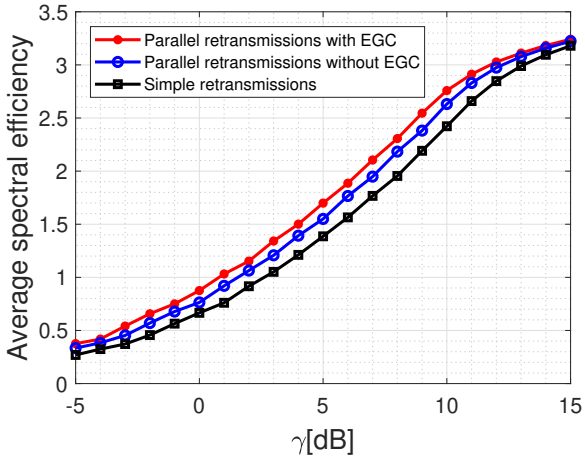


Figure 4.3: ASE with symmetric configuration for SR and PR.

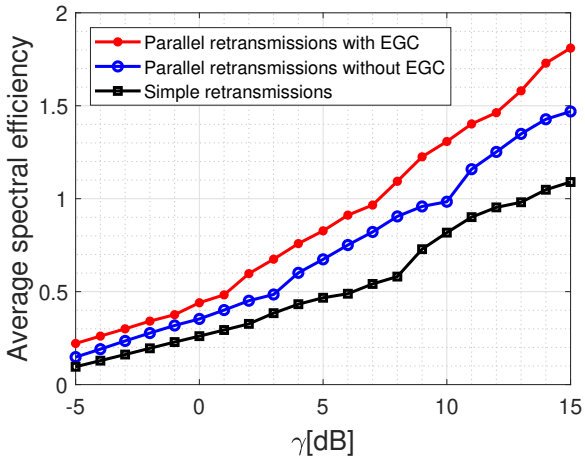


Figure 4.4: ASE with asymmetric configuration for SR and PR.

of each link is set to γ; second, the average SNR of each direct link between the source nodes and the destination is set to $\gamma - 100$dB. In both scenarios, each source is given a rate using the BRD algorithm presented in the previous chapter from the set of possible rates $\{0.75, 1, 1.25, 1.5\}$ bits per channel use, and thus, rates are optimized based on γ.

Three different curves are seen in the two figures 4.3 and 4.4. The first curve corresponds to the proposed selection strategy with PR in the case of EGC. The second curve corresponds to the same strategy, assuming no available information concerning the phase shift at the relaying nodes (no EGC). Finally, the third curve corresponds to simple retransmissions (i.e., SR), as proposed in the prior art. In Fig. 4.3, we see that for the symmetric scenario, and for the considered SNR range (-5dB to 15dB), the proposed strategy outperforms the prior art in both cases, with EGC ($\sim$ 1.5dB) or without EGC ($\sim$ 1dB). In Fig. 4.4, we encounter a significantly higher gain in the asymmetric scenario over the same SNR range, where the proposed strategy outperforms the prior art in both scenarios: with EGC (up to 7dB) or without EGC (up to 4dB).

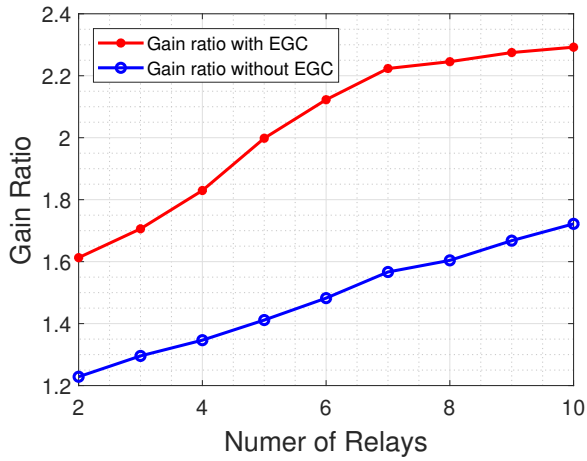


Figure 4.5: Gain ratio with asymmetric configuration with respect to the number of relays in the network.

Finally, in Fig. 4.5, we investigate the effect of the size of the system on the gain of the proposed strategy. Specifically, we fix γ to 0, and we vary the number of relays available in the system from 2 relays to 10 relays. The other parameters are the same as those of Fig. 4.4 (i.e., the asymmetric link configuration, the number of sources $M = 3$, the set of possible rates, $\alpha = 0.25$, and $T_{\max} = 3$). We present in Fig. 4.5 the gain ratio of the proposal with and without EGC. In other words, we present the ratio: (the ASE of PR) / (the ASE of SR). The figure validates that as the number of relays increases, the gain of PR compared to SR increases. This can be justified by the fact that when extra relays are available, the gain of exploiting the multi-path diversity would be more significant.

We summarize our findings below:

1. The gain of the proposed selection strategy is significant in scenarios where direct links are not available.

2. The gain is seen for different values of γ, even for high values (this can be explained by the fact that even if we are in a high SNR regime, the rate allocation will allocate higher rates corresponding to γ leading to better performance).

3. As the number of relays L increases, the gain of the proposed strategy. increases.

4.2.5 Energy-Efficient (EE)

We mentioned that in case of no EGC, the optimal allocation might be to select a subset of relaying nodes to be activated (rather than all the relaying nodes). Following this notion of choosing a subset of relaying nodes rather than the whole set Help_i to help a given source i, we present next the EE strategy which tries to avoid unnecessary activation of relaying nodes. The intuition of the proposed PR strategy is to exploit the multi-path diversity and the power budget available at the relaying nodes. Although this

is optimal in terms of performance and spectral efficiency, it is not energy-efficient. In other words, we would be able to reach the same efficiency without activating the whole set of relaying nodes. Recalling that the outage depends on the mutual information between the relaying nodes and the destination, we propose an EE selection strategy, which allocates the source node to be helped as well as the subset of active relaying nodes as follows:

$$(\widehat{s}_t, \widehat{A}_t) \in \underset{(i,A_i)\in(\overline{S}_{d,t-1})\times \mathrm{Pow}(\mathrm{Help}_i)}{\mathrm{argmax}} \mathcal{U}_{\mathrm{EE}}(\mathrm{SNR}_{A_i}, |A_i|) \tag{4.4}$$

where:

- $i \in \overline{S}_{d,t-1}$ is one possible source node to be selected.
- $A_i \in \mathrm{Pow}(\mathrm{Help}_i)$ is one possible subset of relaying nodes selected to help source i. $\mathrm{Pow}(\mathrm{Help}_i)$ thus represents the power set of Help_i including all the possible subsets of relaying nodes which can help source i.
- $\mathcal{U}_{\mathrm{EE}}(\mathrm{SNR}_{A_i}, |A_i|)$ represent an EE utility metric. It depends on the equivalent SNR (the performance perspective) and the number of activated relays (energy consumption).

In our work, we use $\mathcal{U}_{\mathrm{EE}} = \frac{I_{A_i}(\mathrm{SNR}_{A_i})}{|A_i|^\beta}$ with β a control factor which can be optimized. As we will see in the numerical section, β controls the level of performance we need compared to the energy reduction we save. We omit presenting the algorithm of EE parallel retransmission. Simply, it is similar to Algo. 5 with the difference of using $\mathcal{U}_{\mathrm{EE}}$ while considering all the subsets of Help_i. Also, the control exchange using the EE strategy is similar to the one presented in Fig. 4.2, with the only difference in step 3, where the destination not only shares the selected source $\widehat{s}_t$, but also the selected subset of relaying nodes $\widehat{A}_t$.

Here, we validate the proposed EE selection strategy using MC simulations. We consider a (3,9,1)-MAMRN scenario, and we set α to 0.25 and $T_{\max}$ to 3. We consider an asymmetric link configuration scenario. Specifically, we design a scenario where the direct links of the source nodes and some relay nodes with the destination are bad. Such a scenario helps in showing the importance of the relaying nodes and the gain of the proposed retransmission scheme. Particularly, the links are set as follows: first, the average SNR of each link is set to γ; second, the average SNR of each direct link between the source nodes and the last four relay nodes with the destination is set to $\gamma - 100$dB. The rate allocation of each source is given using the BRD algorithm presented in the previous chapter from the set of possible rates $\{0.75, 1, 1.25, 1.5\}$ bits per channel use, and thus, rates are optimized based on γ.

Five different curves are seen in Fig. 4.6. The first curve corresponds to the PR strategy. The following three curves correspond to three EE strategies with different β values (0.1, 0.3, and 0.5). Finally, the fifth curve corresponds to the prior art which uses simple retransmissions (several prior art strategies can be presented as a lower bound benchmark but we adopt the one used in [43] as it was shown to be optimal for simple retransmissions). We see that the EE strategies are performing intermediately compared

to optimal PR and SR. Also, we notice that the performance is dependent on the value of β.

To further investigate, we present in Fig. 4.7, the percentage of energy reduction corresponding to the three β values used in the EE strategy. This percentage is calculated as: (energy consumed using PR - energy consumed using EE) / (energy consumed using PR). We see that our intuition is correct. Using EE strategies can lead to a high percentage of energy saving as a small cost in the performance. Thus, EE strategies are seen as a good trade-off between optimality and energy consumption. In these two figures, we see that with $\beta = 0.1$ we can converge to the optimal solution while saving more than half of the energy consumption.

Figures 3 and 4 validate our proposal by showing that:

1. The gain of the proposed PR selection strategy is significant in scenarios where direct links are not available.

2. The gain is seen for different values of γ, even for high values (this can be explained by the fact that the rate allocation will allocate higher rates corresponding to γ leading to better performance).

3. The EE strategy is a promising strategy which makes the trade-off between performance and energy consumption.

4. Choosing β plays a significant role in tuning the EE strategy and should be done wisely, i.e., with $\beta = 0.1$, we converged to the PR strategy while saving 60% of the power budget.

5. As the number of relays L and/or the maximum number of possible retransmissions $T_{\max}$ increase, the gain of the two proposed strategies increases.

6. The previous findings hold in symmetric link configuration and hold in the case of no EGC (the corresponding curves of results 5,6 are omitted for brevity).

To sum up this section, we proposed a novel selection strategy for orthogonal MAMRN. Rather than selecting a single relaying node to send redundancies at a given retransmission time slot, the PR strategy allows several relaying nodes to send redundancies for a common source node selected to be helped. The proposed strategy outperforms the prior art (i.e., SR) by making use of the power budget available at each relaying node included in the system. The numerical results show that the gain is seen with and without EGC, whereas in the case of EGC, the system encounters a higher gain. Also, the gain is seen with symmetric and asymmetric scenarios, where in the latter, the gain is higher. Finally, we presented a modified version of the PR strategy which is EE. This strategy not only selects the source node to be helped, but also selects the set of relaying nodes to be activated aiming to avoid any unnecessary energy consumption.

4.3 Optimized control exchange process

In the prior art (e.g., [38, 39, 40, 41, 42, 43, 117], as well as in my previous chapter), the authors first design a control exchange strategy to give the destination useful information

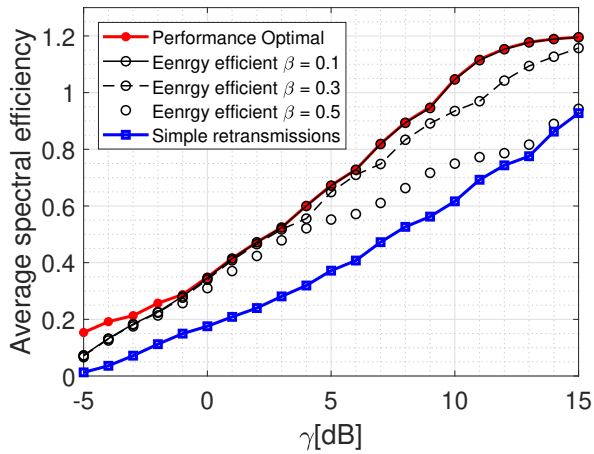


Figure 4.6: ASE with asymmetric configuration with EGC.

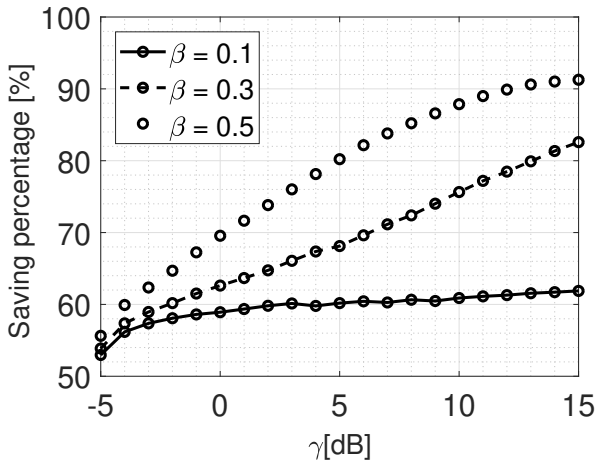


Figure 4.7: Average energy reduction when using the proposed EE strategy for different β values.

about the state of the relaying nodes (and their decoding sets: a decoding set is a set which includes the source nodes which a relaying node decoded correctly at a given time instant). Then, they present some relaying nodes selection strategies. The drawback in the prior art is that the control exchange design is heavy (leads to a heavy overhead). There, at each selection, a control exchange process is performed (even if it was not needed at all). In this section, we tackle the relaying node selection problem, aiming at maximizing the ASE while optimizing the control exchange design in the system. Our intuition is that, upon wisely using the available information at the scheduler, a lighter control exchange design can be used while maintaining good performance. More precisely, and based on the analytical expression of the outage events, we derive an upper bound to the number of retransmissions needed for each source to be decoded successively at the destination. Then, we use this information to propose a selection strategy that can be used when no control exchange process is available between the destination and the relaying nodes.

Now, in order to capture the effect of the overhead of the control exchange process seen in the different selection strategies, we define the effective spectral efficiency per frame as:

$$\begin{aligned}\eta_{\text{eff}}^{\text{frame}}(\mathbf{H}, P) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} K_i(1-\mathrm{O}_{i,T_{\text{used}}})}{MU + QT_{\text{used}} + \Gamma/C} \\ &= \frac{\sum_{i=1}^{M} R_i(1-\mathrm{O}_{i,T_{\text{used}}})}{M + \alpha T_{\text{used}} + \Gamma/(C\cdot U)},\end{aligned} \tag{4.5}$$

where Γ/C represents the overhead of the control exchange process with Γ denoting the number of bits needed for control exchange and C denoting the capacity of the control exchange channel. The metric Γ depends on the selection strategy being used and is analyzed in the following subsection. In the prior art [43, 117], we see no consideration of the overhead included by the control exchange process (i.e., Γ is assumed negligible). This follows the assumption of infinite frame length (K, U, and Q are assumed large enough). For short packet lengths, however, and in realistic scenarios, the control channel overhead cannot be neglected.

Analytically, and following the PR strategy, the individual outage event of a source $i \in S$ after a retransmission time slot $t \in \{0, ..., T_{\max}\}$ ($t = 0$ corresponds to the end of the transmission phase) can be written as:

$$\mathcal{O}_{i,t}^{\text{PR}}(\mathbf{H}, P) = \Big\{R_i > I_{i,d} + \alpha \sum_{l=1}^{t} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_l = i\}}\Big\}, \tag{4.6}$$

where

- $I_{i,d}$ represents the mutual information between the source i and the destination d. The mutual information is defined based on the channel inputs.
- $\widehat{s}_l$ represents the chosen node to be helped at the retransmission time slot l.

- $J_{i,d}(l)$ represents the mutual information between the equivalent channel (all the active relaying nodes) with the destination if the source node i is chosen to be helped at a retransmission time slot l.

- $\mathbf{1}_{\{\widehat{s}_l=i\}}$ is the indicator function which takes the value 1 when the destination chooses to help the source i at the retransmission time slot l (i.e., if $\widehat{s}_l = i$) and zero otherwise.

Note that the difference between this equation and the one presented in chapter 2 (check equation (2.6)) is that here, the selection strategy is PR rather than SR. Also note that $J_{i,d}(l)$ is a function of time, as the equivalent channel might be different from one time slot to another (due to the update in the relaying nodes decoding sets). As a decoding set can not decrease in size (a relaying node might decode more sources at each transmission/retransmission time slot), $J_{i,d}(l)$ is an increasing function of time. As seen in the previous section, $J_{i,d}(l)$ depends on the channel state of all the active relaying nodes helping the source node i.

4.3.1 Novel selection strategy

4.3.1.1 Definitions

At a given retransmission time slot t, we recall the definition of the decoding set of the destination and the that of a given relaying node $j \in \{1, \cdots, M+L\}$ as $S_{d,t-1}$ and $S_{j,t-1}$, respectively ($S_{d,0}$ and $S_{j,0}$ correspond to the decoding sets at the end of the transmission phase). In order to reduce the control exchange overhead, the relaying nodes will only send their decoding sets when the destination asks for. So, rather than running a control exchange process at each retransmission time slot, we assume that the destination may ask for a decoding set update before any retransmission time slot t. At a given retransmission time slot $t > 1$, we define $X(t)$ as the number of retransmission time slots passed without asking for a decoding set update. Due to the fact that we do not know the decoding sets of the relaying nodes in all the time slots, the prior art strategies are not applicable. Accordingly, we propose a new selection strategy, with an optimized control exchange process, that exploits the limited information available at the destination (e.g., rates, $T_{\max}$, etc.). The intuition of our proposal is based on analyzing the individual outage events and trying to propose some estimation of the number of time slots needed to decode the non-decoded source messages. Using this estimation, we try to avoid unnecessary control exchange processes. Let $\lceil q \rceil$ represent the ceiling function which takes the least integer greater than or equal to q, e.g., $\lceil 2.3 \rceil = 3$. Recalling the outage event equation (4.6), and at a given retransmission time slot $t > 0$, we define $x_i(t)$ for a non-decoded source node $i \in \overline{S}_{d,t-1}$ as:

$$x_i(t) = \begin{cases} x_i^b(t) = \lceil y_i^b(t) \rceil & \text{before the decoding set update} \\ x_i^a(t) = \lceil y_i^a(t) \rceil & \text{after the decoding set update} \end{cases} \tag{4.7}$$

where

$$y_i(t) = \begin{cases} y_i^b(t) = \frac{y_i^a(t-X(t))(\alpha J_{i,d}(t-X(t)))-\alpha\sum_{l=t-X(t)}^{t-1} J_{i,d}(t-X(t))\mathbf{1}_{\{\hat{s}_t=i\}}}{\alpha J_{i,d}(t-X(t))} \\ y_i^a(t) = \frac{y_i^a(t-X(t))(\alpha J_{i,d}(t-X(t)))-\alpha\sum_{l=t-X(t)}^{t-1} J_{i,d}(t-X(t))\mathbf{1}_{\{\hat{s}_t=i\}}}{\alpha J_{i,d}(t)} \end{cases} \tag{4.8}$$

with

$$y_i(1) = \begin{cases} y_i^b(1) = \frac{R_i-I_{i,d}}{\alpha I_{i,d}} \\ y_i^a(1) = \frac{R_i-I_{i,d}}{\alpha J_{i,d}(1)} \end{cases} \tag{4.9}$$

Note that in the case when no control exchange is done at all, x_i^a and y_i^a are undefined (due to the lack of the knowledge of $J_{i,d}(t)$, and thus $x_i = x_i^b(1)$). In the case when there are one or more control exchange requests, we assume that the initial request is done at the beginning of the retransmission phase (check the initialization in equation 4.9).

Theorem 4.3.1. *At a given retransmission time slot $t > 0$, for a given non-decoded source node $i \in \overline{S}_{d,t-1}$, if the destination chooses to help the source i for $x_i(t)$ time slots, the destination guarantees the correct decoding of source i. In other words, $x_i(t)$ is an upper bound to the number of time slots needed to guarantee decoding the message of source i.*

Proof. Check appendix A. □

Theorem 4.3.1 means that if the destination chooses to help source i for x_i time slots, it guarantees that this source will be decoded correctly. Note that $x_i(t)$ is defined based on the available information at the destination, and accordingly, we define two forms of $x_i(t)$, one before the control exchange process and one after it (before and after updating the relaying nodes decoding sets). Additionally, the value of $y_i^a(t)$ in the second line depends on $J_{i,d}(t)$ which means that the destination needs to know the decoding sets of the relaying nodes to get $x_i(t)$. In fact, the difference between $x_i^b(t)$ and $x_i^a(t)$ is that the latter is a better estimator (i.e., a tighter upper bound) of the number of needed time slots to decode source i. This is due to the fact that after running the control exchange process and updating the decoding sets of the relaying nodes, $J_{i,d}(t)$ is used to help estimate the correct number of needed time slots.

4.3.1.2 Selection strategy

Assume that at a given retransmission time slot t, there are T_{av} available time slots in the retransmission phase. One advantage of knowing $x_i(t)$ is that in case $T_{\text{av}} \geq \sum_{i\in\overline{S}_{d,t-1}} x_i(t)$, the solution of the selection strategy problem would be easy. Simply, the destination chooses the non-decoded source nodes successively and randomly. On the contrary, if $T_{\text{av}} < \sum_{i\in\overline{S}_{d,t-1}} x_i(t)$, the problem becomes non-trivial. In this section, we propose the following: at the end of the transmission phase, the destination calculates $x_i(1)$ using equation (4.7) (before the decoding set update). In case $T_{\max} \geq \sum_{i\in\overline{S}_{d,0}} x_i(1)$, then no control exchange is needed. The destination simply allocates in each round any non-decoded source node to be helped. In case $T_{\max} < \sum_{i\in\overline{S}_{d,0}} x_i(1)$, an optimized control exchange process is performed (to be presented below), and the destination asks for

an update of the relaying nodes decoding sets. Then, the $x_i(1)$ values are recalculated using equation (4.7) (after the decoding set update). During the following retransmission time slots, the relaying nodes do not perform any control exchange process. The destination then performs a novel selection strategy based on the available information ($x_i(1), R_i, T_{\max}$, and its decoding set) (to be presented below). At a given retransmission time slot t during which the destination chooses to send a decoding set update request, the previous two steps of calculating x_i are repeated using the available retransmission time slots calculated as: $T_{\text{av}} = T_{\max} - t + 1$. For such an event, we propose a selection strategy which takes into consideration the rates of the sources, and can be written as:

$$\begin{aligned} \widehat{A} \in & \underset{A \in \text{Pow}(\overline{S}_{d,t-1})}{\text{argmax}} \sum_{i \in A} R_i \\ \text{such that} & \sum_{i \in A} x_i(t) \leq T_{\text{av}} \end{aligned} \tag{4.10}$$

where:

- $\text{Pow}(\overline{S}_{d,t-1})$ represents the power set of $\overline{S}_{d,t-1}$ (set of all possible subsets).
- A represents one possible subset of the source nodes taken from all possible subsets: $A \in \text{Pow}(\overline{S}_{d,t-1})$.
- $\widehat{A}$ represents the selected subset of source nodes after the maximization process.

The intuition of the above utility is quite simple: we select a subset of sources $\widehat{A}$ having the highest sum-rate, while guaranteeing all the source nodes in the selected set to be decoded. After choosing the subset $\widehat{A}$, the destination allocates all the source nodes $i \in \widehat{A}$ successively, source by source, until they are decoded (or until it asks for a decoding sets update request). For example, if we have three source nodes: $S = \{1, 2, 3\}$, and the selected subset of nodes is: $\widehat{A} = \{1, 3\}$, then, the destination will select source 1 until it is decoded then source 3 until it is decoded. The order between the source nodes included in $\widehat{A}$ does not matter, as we ensure that each source node $i \in \widehat{A}$ will be allocated enough rounds till it gets decoded (following the constraint $\sum_{i \in A} x_i(t) \leq T_{\text{av}}$).

4.3.1.3 Proposed control exchange

We distinguish here between our proposal and the different strategies used in the prior art (check Fig. 4.8). In [117], the destination chooses the relaying node which minimizes the common outage probability. In order to be able to do this selection, the destination first sends an ACK/NACK bit, then the relaying nodes send their decoding sets. The ACK bit indicates that all the sources have been decoded correctly, and the NACK indicates the contrary. The selection is performed after that. In [43] (and in the previous chapter), the selection strategy is based on choosing the relaying node with the highest mutual information. Thus, the destination only needs to know which nodes can help some non-decoded source nodes at the destination. Thus, the destination first shares its decoding set with the relaying nodes, then the relaying nodes which are able to help

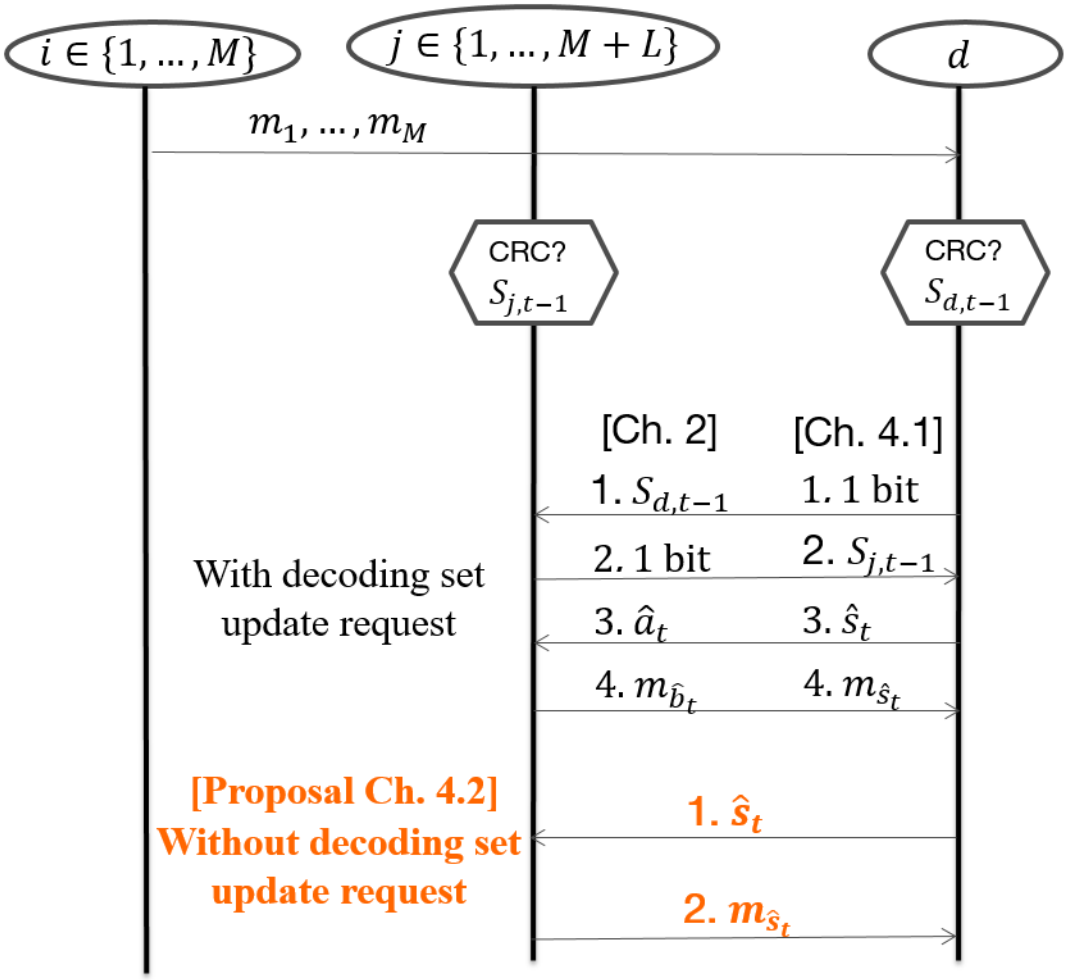


Figure 4.8: Control exchange process in the proposed selection strategy: in black, we see the steps upon a decoding set update request; and in bold orange, we see the reduced steps when there is no decoding set update request.

some non-decoded source messages at the destination send a notifying bit. This update in the control exchange will reduce the overhead in the strategy of [43] compared to that of [117]. Finally, in PR (proposed in the previous section), we go back to the control exchange in [117] as we again need to know the decoding sets of the relaying nodes to choose the source node which will be selected to be helped by all the relaying nodes which decoded it. The control exchange processes of the prior art are seen in the first part of Fig. 4.8 (in non-bold black). Note that in step 3, for reference [117], $\widehat{s}_t$ represents the selected relaying node activated while in reference [6] (previous section), it represents the selected source node to be helped by multiple relaying nodes. $m_{\widehat{s}_t}$ represents the redundancy version shared by either a single activated relaying node (as in [117]) or by multiple relaying nodes (as in [6]).

To our interest, we want to reduce the control exchange overhead by reducing the number of requests done in the retransmission phase. As described before, we will run a

control exchange process only when the destination asks for one. Thus, in our proposal, and as we use PR, the control exchange process will be as the ones of [6] and [117] when there is a control exchange request, and nothing when there is no request. In the first part (in black), we see the control exchange process when we have a decoding set update request (as in [6, 117]). As described above, the destination sends 1 ACK/NACK bit. Then, all the relaying nodes transmit their decoding sets. After that, the destination calculates $x_i(t) = x_i^a(t)$ and performs the proposed strategy to get the subset $\widehat{A}$. Finally, the destination selects a source node from the selected subset $\widehat{A}$, and the relaying nodes which decoded this source send redundancies. In the second part (in bold orange), we see the optimized control exchange process in the retransmission time slots when no control exchange process is done from the relaying nodes side. Simply, the destination allocates source nodes from the previously obtained set $\widehat{A}$, and the relaying nodes which decoded the selected source node send redundancies. Following this scheme, Γ in eq. (4.5) can be written as: $\Gamma_{\text{n req}} = n(1 + M(M + L)) + T_{\text{used}}\lceil \log_2 M \rceil$ if there were n control exchange requests. Concerning the prior art, and since we have a control exchange request at each retransmission time slot, we write: for [6] and [117], $\Gamma_{[6,\ 117]} = (1 + M(M + L) + \lceil \log_2 M \rceil)T_{\text{used}}$, and for [43]: $\Gamma_{[43]} = (M + 1(M + L) + \lceil \log_2 M + L \rceil)T_{\text{used}}$.

4.3.1.4 Proposed algorithm

$x_i(t)$ represents the sufficient number (i.e., upper bound) of retransmission selections so that i is decoded correctly. Nevertheless, the real needed number of selections might be less than $x_i(t)$. This is due to the fact that the destination does not know the updates of the decoding sets at the relaying nodes. In case the estimator x_i is not the exact needed number, the proposed strategy is still valid. We simply have some extra retransmission time slots. Thus, we propose to repeat the selection of the subset $\widehat{A}$ when such an event occurs (i.e., when extra retransmission time slots are available).

Finally, we answer below two possible questions:

1. When should we select or reselect the subset $\widehat{A}$?

2. When should the destination send a request for an update in the relaying nodes decoding sets?

To answer the first question, we clarify that we can reselect the subset $\widehat{A}$ each time a source node is decoded before $x_i(t)$. Simply, some extra time slots are available and it might give a better sum-rate if we select a new subset. To answer the second question, we build on our proposed selection strategy mentioned above (the selection of $\widehat{A}$). In fact, our selection strategy is suitable to reduce the control exchange to a single control exchange at the beginning of the retransmission phase. We propose that at the beginning of the retransmission phase, if $T_{\max} \leq \sum_{i \in \overline{S}_{d,0}} x_i^b(1)$, the destination makes a control exchange process with the relaying nodes and gets $x_i^a(1)$. After that, no request is needed. The idea is based on the analysis of the selection strategy. In our proposal, the destination is allocating sources successively from the subset $\widehat{A}$. This means that when we update $x_i(t)$ (after a possible decoding sets update request), we might have three types of source nodes i: some decoded source nodes (no need for an estimator for

those nodes), some non-decoded source nodes which were not selected in the previous rounds (no change in their estimators), at most one non-decoded source node which was selected but not decoded yet. Thus, at most one $x_i(t)$ might be updated. Nevertheless, this update in this $x_i(t)$ is not interesting, as following the definition of $x_i(t)$, it is a decreasing function, and the update in this $x_i(t)$ will be decreasing it. The intuition is, as the source i was previously selected with a bigger $x_i(t)$ it will be selected again with this decreased $x_i(t)$. Thus, the changes in the selection strategy will only be included in $\widehat{A} \setminus i$).

In the case when the chosen subset $\widehat{A}$ is empty (i.e., no subset is guaranteed to be decoded successively), we can either stop the transmission to avoid wasting the channel resources, or we can select the source node with the least x_i. The latter case (which we use in our numerical analysis next) is an optimistic method for which the choice is based on the possibility that the real number of needed retransmissions is less than x_i. In addition, this case aligns with the method used in all the thesis where the frame transmission terminates when reaching $T_{\max}$ (or when decoding all the source messages). This also explains the utility metric we used when choosing the subset $\widehat{A}$; we focused on the sum-rate rather than the spectral efficiency. In other words, since we know that the sources we are selecting are going to be decoded (no outage in the numerator of the spectral efficiency), and that the frame will not terminate before $T_{\max}$ (the denominator of the spectral efficiency is independent of $\widehat{A}$), choosing the sum-rate as an utility metric will lead to the optimal spectral efficiency. Algo. 6 presents the steps of the proposed selection strategy with the optimized control exchange process.

4.3.2 Numerical results

In this subsection, we validate the proposed selection strategy using MC simulations. We consider an orthogonal (6,6,1)-MAMRN scenario, with $T_{\max} = 6$ and $\alpha = 0.25$. The channel inputs are assumed independent and Gaussian distributed with zero mean and unit variance with $I_{a,b} = \log_2(1 + |h_{a,b}|^2)$ being the mutual information between the transmitting node a and the receiving node b. As relaying nodes use PR with EGC [6], the mutual information of the equivalent channel with the destination is written as $J_{i,d} = \log_2(1 + \sum_{a \in \text{Help}_i} |h_{a,d}|^2)$ where Help_i represents the set of all the relays which will help the source i. We consider a symmetric rate and link configuration scenario, i.e., all the links are considered the same (the average SNR of each link is set to γ), and all the rates are fixed to 1 [bits per channel use]. We present and compare five strategies: Our proposal with no control exchange, our proposal with a single control exchange (as in Algo. 5), and the strategies of references [6, 43, 117]. Note that the strategies used in [118] and [119] are the same as the ones used (and presented) by [43] and [6] respectively. In Fig. 4.9 and Fig. 4.10, we present the ASE as a function of γ for two benchmark scenarios: $\Gamma = 0$ (overhead is negligible as seen in the prior art), and $\Gamma \neq 0$ (overhead is considered). For the latter case, we set $U = 512$ channel uses in the transmission phase, and $C = 0.1$ [bits per channel use] as the capacity in the control exchange channel.

For the case of no overhead consideration (i.e., Fig. 4.9), we observe that our proposals (with 1 or 0 request) converge to the PR proposed in [6] (as well as the first section

Algorithm 6 The proposed selection strategy with optimized control exchange process.

```
t ← 0, T_av ← T_max, and Â = φ                                   ▷ Initialization
Calculate x_i: x_i ← x_i^b(1) for all i ∈ S̄_{d,t}
if (T_av < Σ_{i∈S̄_{d,t}} x_i) then                               ▷ if no enough time slots
    Relaying nodes send their updated decoding sets
    x_i ← x_i^a(1) for all i ∈ S̄_{d,t} after decoding set update
end if
Compute Â using equation (4.10)
while (t < T_max and Â ≠ φ) do
    Select source i ← argmin_{i∈Â} x_i
    while (i ∉ S_{d,t}) do                  ▷ destination tries to decode i until it is decoded
        Destination requests that the relaying nodes help source i
        t ← t + 1, T_av ← T_av − 1, x_i ← x_i − 1                    ▷ update counters
        if (i ∈ S_{d,t}) then                          ▷ if i is decoded at the end ofround t
            Â ← Â \ {i}                                              ▷ remove i from Â
            if (x_i > 0 and Â ≠ S̄_{d,t}) then                ▷ If a new computation is needed
                Compute Â using equation (4.10)                       ▷ recompute Â
            end if
        end if
    end while
end while
```

of this chapter) while outperforming the strategies of SR [43, 117]. The strategy used in [43] (and in the previous chapter of this manuscript) outperforms the strategy used in [117] which verifies the results deduced in [43]. Now, when overhead is considered (i.e., Fig. 4.10), the proposed strategies outperform the prior art strategies, and the proposal with zero requests outperforms the proposal with 1 request. Additionally, we see again that the strategy in [43] outperforms that of [117]. Interestingly, we notice that when we consider the overhead, the PR is not optimal. As it is seen in Fig. 4.10, the strategy of [6] gives an intermediate result between the SR strategies used in [43] and [117].

Following these observations, we deduce that:

1. The proposal with zero requests is robust and optimal, as it achieves the upper bound in the case of no overhead consideration, and outperforms all the other strategies when we take into consideration the overhead.

2. The strategy of [43] outperforms that of [117] which confirms that when using SR, it is better to choose the relaying node having the highest mutual information, rather than minimizing the common outage probability.

3. Although PR [6] outperforms the other strategies (i.e., strategies of [43, 117]), it acts poorly when considering the overhead of its control exchange process. The third conclusion can be justified by the fact that, although PR is a promising strategy, it acquires a heavier control exchange process which degrades its performance.

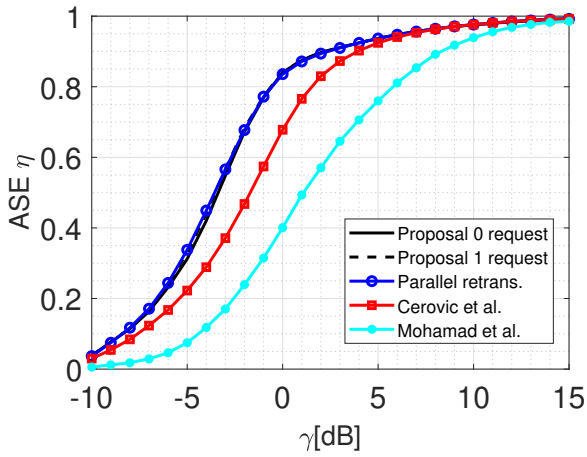


Figure 4.9: ASE with symmetric link and rate configuration with $\Gamma = 0$.

This highlights the importance of our proposal, being optimal in both scenarios: with and without overhead consideration.

4. Note that similar results are seen in asymmetric rate and link configuration but are not presented for brevity.

Finally, in our analysis, it is seen that when we consider the overhead, as the size of the network increases (the number of relaying nodes), the gain of the proposed strategies increase (due to the increase of the effect of the overhead of the control exchange process). Thus, we present in Fig. 4.11 the ratio of the ASE of the upper bound (the proposal with 0 request) to that of the different strategies. The x-axis represents the number of sources and relays and γ is set to 0dB. Thus, we are in an $(x, x, 1)$-MAMRN, where x represents the different points of the x-axis from (2,2,1)-MAMRN to (10,10,1)-MAMRN. The other parameters are kept the same as in the case of the scenario of Fig. 4.10. In Fig. 4.11, it is seen that as the system size increases, the gain of the proposal increases. We observe that the gain compared to [6] and [117] gets significant faster than that of [43]. This verifies again the importance of the reduced control exchange process seen in [43] compared to that of [6] and [117]. It further validates our proposals, as we see that the difference between zero requests and 1 request is small even for (10,10,1) MAMRN.

To sum up, we presented in this section a TDM-based orthogonal MAMRN. Using a two-phase system, we tackled the scheduling problem with a centralized strategy. Using estimation of the number of retransmissions needed for every source to be correctly decoded, we proposed a low-complexity low-overhead selection strategy which is applicable without a heavy control exchange process. The proposed algorithm outperforms the strategies of the prior art as it reduces the overhead of the control exchange process.

4.4 Conclusion

In this chapter, a novel selection strategy is proposed. We first presented PR followed by the control exchange process when using it. Then, the calculation of the equivalent

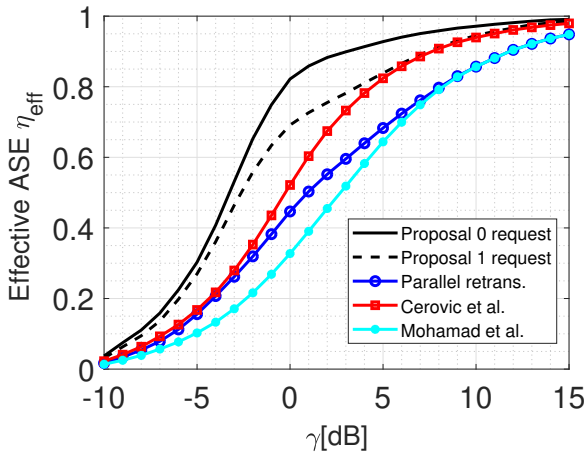


Figure 4.10: ASE with symmetric link and rate configuration with $\Gamma \neq 0$.

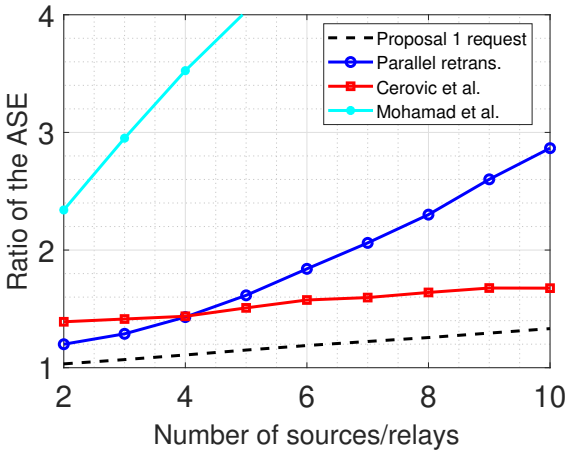


Figure 4.11: The ratio of the effective ASE of proposal with 0 requests and the effective ASE of the different benchmark selection strategies.

SNR is derived for the different cases. Then, an EE method is further proposed to reduce the power consumption when we avoid activating the whole set of relaying nodes. In the second part of this chapter, the overhead problem is tackled. Using estimation, we reduced the number for control exchanges by proposing a novel selection strategy that can be applied without the need of a control exchange. Numerical results show the gain of using PR as compared to SR. In addition, it validate the significant effect of the control exchange on the performance.

Chapter 5

Joint Rate and Relaying Nodes Allocation

5.1 Chapter summary

In chapter 3, we tackled the rate allocation problem, and the solution presented consists in a sequential BRD allocation. The rate allocation strategy assumes that there is a certain relaying node scheduling in the retransmission phase, and thus, the rate allocation depends on the scheduling process used in the retransmission phase. In chapter 4, on the other hand, we tackled the scheduling problem in the retransmission phase, and the solution presented chooses to help a set of sources which can be guaranteed to be decoded before the end of the frame (parallel retransmission). As the selection depends on the rates, we see that the selection strategy depends on the rate allocation problem. We notice that when solving any of these two problems (rate allocation or the relaying node scheduling), the second problem is considered fixed and a given solution is adopted. In other words, when solving problem 1, problem 2 is not considered, and similarly, when solving problem 2, problem 1 is not considered.

In this chapter, we propose an optimal joint rate and relaying nodes allocation strategy. The proposal determines jointly the rates of the sources and the sources that will be helped in the retransmission phase. In the first section, we present the different steps leading to the optimal solution. First, we present the possible allocations in the retransmission phase. Then, we give the optimal rate allocation for a given scheduling in the retransmission phase. Finally, we present two joint allocations: optimal joint allocation and sequential joint allocation. In the second section, we present the MC simulations that validate our proposal. It is seen that using the joint allocation can lead to better performance compared to the non-joint allocations previously seen (in the prior art and in the previous chapters).

5.2 Optimal rate and scheduling allocation

To our interest, we aim in this chapter to solve the two problems jointly. Rather than assuming a given relaying node strategy when doing the rate allocation (as in chapter

3), and rather than doing the scheduling in the retransmission phase assuming a pre-allocated rates (as in chapter 4), we propose an optimal solution which performs rate allocation and selection scheduling jointly. The idea tackles the sub-optimality of solving the two problems sequentially, and aims to reach an optimal joint allocation that leads to the highest spectral efficiency. Note that the outage event definition depends on both the rates of the sources and on the activated relaying nodes in the retransmission phase and the selected sources for help. Thus, in order to optimize the spectral efficiency which depends on the outage of the sources, we need to optimize the rate and the scheduling process jointly.

Furthermore, another motivation for the joint allocation is one limitation seen in the BRD algorithm presented. This limitation comes from the fact that the allocation follows a finite discrete set of rates $\widetilde{\mathbb{R}} = \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$. Upon following a discrete set of possible rates, the performance optimization is limited to the possible choices available, and the best performance is limited by the highest rate in the discrete set. One way to reduce this limitation is to increase the size of the set of possible rates $\widetilde{\mathbb{R}}$. Nevertheless, the complexity of the BRD and its convergence speed depend on the size of the network and the size of the discrete set (on M and $|\widetilde{\mathbb{R}}|$)). So, we encounter a typical trade-off of practicality and performance. When we try to improve the performance of the BRD algorithm, we face a problem of practicality. In this chapter, we tackle the mentioned issues, by proposing a joint rate and scheduling algorithm where there is no need for an exhaustive search over the discrete set of possible rates, instead, the rates are chosen following the channel realization and the optimal scheduling in the retransmission phase. In other words, in our proposal, increasing the size of the set $\widetilde{\mathbb{R}}$ does not increase (linearly) the complexity of the proposed allocation.

In this chapter, we propose a FLA joint solution. As the channel state might be different from one frame to another, the best allocation would be done dynamically per frame following any possible update in the channel state. Such allocation (i.e., FLA), assumes the presence of the full CSI of all the links of the network at the destination side (the central node). Such an assumption limits our contributions to the scenarios with slow-changing radio conditions (e.g., low mobility cases). The generalization to the case where the CSI is not known by the destination is left for future work and is not included in this manuscript.

Now, in order to solve the two problems jointly, we recall the assumptions followed in this chapter:

1. The destination knows the full CSI.

2. The rates and the relaying nodes scheduling are performed per frame (FLA) and jointly.

3. The SU encoding method with PR is used in the retransmission phase (at each time slot in the retransmission phase, a selected source node is helped by multiple relaying nodes).

4. The retransmission phase is limited to $T_{\max}$ time slots and the frame terminates if it exceeds $T_{\max}$.

5.2.1 The possible source allocation in the retransmission phase

The proposed joint allocation follows the above assumptions. To start, and following assumptions 3 and 4, we see that there is a finite possible selections in the retransmission phase. First, the destination needs to determine how many retransmission time slots it would need, i.e., it needs to select $T_{\text{used}} \in \{0, \ldots, T_{\max}\}$. Then, it needs to select which source node to be helped in each time slot within the T_{used} time slots. Note that the order is not important, but the number of selections for each source node is what really matters. To make it clear, here is an example:

Assume $T_{\max} = 2$, and there are two sources in the network, then, the possible selections are:

- $T_{\text{used}} = 0$.
- $T_{\text{used}} = 1$, and then there are two possibilities: choose source 1 or source 2.
- $T_{\text{used}} = 2$, and then there are three possibilities: choose source 1 twice or choose source 2 twice, or choose source 1 one time and source 2 one time.

Note that in case the destination chooses to help source 1 one time and source 2 one time, it is not important which one goes first and which one goes second. In other words, if we select to help source 1 then source 2, it will give the same performance if we select to help source 2 then source 1. The reason we are mentioning this comment is that it would decrease the possibilities of possible selections, and thus, reduces the complexity of the strategy we would propose next.

Since rates are not allocated, going exhaustively over all selections in the retransmission phase would not help to determine the scheduling that gives the highest spectral efficiency. Thus, we propose next, for a given selection (assuming it is already selected), how to allocate the source rates optimally. The idea is to give for any possible scheduling in the second phase, the highest possible rate allocation, and then we determine which selection would give the highest spectral efficiency.

5.2.2 The optimal rate allocation for a given allocation in the retransmission phase

Assume the destination chooses to use $T_{\text{used}} \in \{0, \ldots, T_{\max}\}$ time slots in the retransmission phase, and to help a vector of sources $\widehat{\boldsymbol{A}}$ of size T_{used} where each source $[\widehat{\boldsymbol{A}}]_i$ in the vector $\widehat{\boldsymbol{A}}$ is helped at the ith retransmission time slot. We define the vector $\widehat{\boldsymbol{N}}$ of size M representing the number of times each source will be helped in the T_{used} time slots. Obviously, the vector $\widehat{\boldsymbol{N}}$ can be deduced from the vector $\widehat{\boldsymbol{A}}$. Going back to the previous example, and assuming that $T_{\text{used}} = T_{\max} = 2$, then, there are three possibilities: choose source 1 twice or choose source 2 twice, or choose source 1 one time and source 2 one time. The three possibilities can be written as:

- If source 1 is chosen twice, then: $\widehat{\boldsymbol{A}} = [1, 1]^T$ and $\widehat{\boldsymbol{N}} = [2, 0]^T$.
- If source 2 is chosen twice, then: $\widehat{\boldsymbol{A}} = [2, 2]^T$ and $\widehat{\boldsymbol{N}} = [0, 2]^T$.

- If both sources 1 and 2 are chosen each, then: $\widehat{\boldsymbol{A}} = [1, 2]^T$ and $\widehat{\boldsymbol{N}} = [1, 1]^T$

The last case would also be written as: $\widehat{\boldsymbol{A}} = [2, 1]^T$ and $\widehat{\boldsymbol{N}} = [1, 1]^T$ with no change in the performance.

Here, in this subsection, we aim to determine the optimal rate allocation for any selection of $\boldsymbol{A}$. We say, for a selected vector $\boldsymbol{A}$, the outage event of a given source i is written as:

$$\mathcal{O}^{\mathrm{PR}}_{i,T_{\mathrm{used}}}(\boldsymbol{A}) = \left\{ R_i > I_{i,d} + \alpha \sum_{l=1}^{[\boldsymbol{N}]_i} \overline{J}_{i,d}(l) \right\}, \tag{5.1}$$

where $\overline{J}_{i,d}(l)$ is defined as the mutual information between the message of source i and the destination through the equivalent channel (all the active relaying nodes) towards the destination after the lth selection of source i where $l \in \{1, \ldots, [\widehat{\boldsymbol{N}}]_i\}$. Note that here the index l refers to the number of retransmissions of a given source and not the retransmission time slot l as it was the case for not $J_{i,d}(l)$ seen in the outage event in the previous chapter (we also omitted the dependency on the channel gains $\mathbf{H}$ for brevity). So, in order to calculate $\overline{J}_{i,d}(l)$ for $l \in \{1, \ldots, [\widehat{\boldsymbol{N}}]_i\}$, it is first needed to compute the set of relaying nodes that have decoded source i at the end of the $l-1$ retransmissions. To get whether a relaying node j can decode source i at the end of the lth retransmission, a similar outage event computation is performed taking node j as the destination, i.e., all the relaying nodes having decoded source i at the end of retransmission $l-1$ transmit the message of source i which defines an equivalent channel towards node j or the mutual information $\overline{J}_{i,d}(l)$. Node j cannot decode source i at the end of the $[\widehat{\boldsymbol{N}}]_i^{\mathrm{th}}$ retransmissions if and only if $\{R_i > I_{i,j} + \alpha \sum_{l=1}^{[\widehat{\boldsymbol{N}}]_i} \overline{J}_{i,j}(l)\}$.

We define $\overline{J}^*_{i,d}$ as the maximum possible equivalent mutual information which can be reached when all the relaying nodes decoded a given source message. $\overline{J}^*_{i,d}$ is needed next to limit the possible choices of a rate allocation. Now, we see that an optimal rate allocation would be the highest rate allocation which can be decoded before the end of the frame transmission. Specifically, and following the outage event, the optimal rate allocation for a given selection $\boldsymbol{A}$, would be the highest rate that guarantees that the outage event is not declared, or in other words,

$$\begin{aligned} R_i(\boldsymbol{A}) &= \underset{R_i \in \mathbb{R}}{\operatorname{argmax}}\, R_i \\ &\text{such that}: \mathrm{O}_{i,T_{\mathrm{used}}}(\boldsymbol{A}) = 0. \end{aligned} \tag{5.2}$$

In order to analyze the above "argmax", we note that:

- $\overline{J}_{i,d}(l)$ depends on R_i. The decoding set of a given relaying node depends on the channel state and on the rate allocated. Accordingly, the equivalent mutual information $\overline{J}_{i,d}(l)$ depends on the selected rate R_i.

- Although the possible rate belongs to the real numbers set ($R_i \in \mathbb{R}$), the selection strategy is not that "exhaustive" as it looks (check more details below).

Following the above notes, we say that the optimal rate value for a given source i can be limited following the decoding sets of the relaying nodes. More specifically, the rate value of a given source is limited between: $I_{i,d}+\alpha[\boldsymbol{N}]_i I_{i,d}$ as a lower bound, if no relaying node is activated to help this source (for example if the links with this source are very bad and no relaying node decoded the message of this source after the transmission and the different retransmissions). $I_{i,d}+\alpha[\boldsymbol{N}]_i \overline{J}^*_{i,d}$ as an upper bound, if all relaying nodes are activated to help this source (for example if the links with this source are very good and all relaying nodes decoded the message of this source after the transmission phase). Thus, the "argmax" is rewritten as:

$$\begin{aligned} R_i(\boldsymbol{A}) = & \underset{R_i \in [I_{i,d}+\alpha[\boldsymbol{N}]_i I_{i,d}, I_{i,d}+\alpha[\boldsymbol{N}]_i \overline{J}^*_{i,d}]}{\operatorname{argmax}} R_i \\ & \text{such that : } \mathrm{O}_{i,T_{\text{used}}}(\boldsymbol{A}) = 0. \end{aligned} \tag{5.3}$$

The rate value window is reduced to: $[I_{i,d}+\alpha[\boldsymbol{N}]_i I_{i,d}, I_{i,d}+\alpha[\boldsymbol{N}]_i \overline{J}^*_{i,d}]$. In other words, the size of the window is only: $\alpha[\boldsymbol{N}]_i(\overline{J}^*_{i,d} - I_{i,d})$. As the window size is limited now, different approaches can be used to reach the optimal rate.

One practical proposal to solve the above "argmax" is to use binary search algorithm. Since we aim to choose the highest source rate which can be decoded, and since we know the structure of the outage event, the search would be very simple, and the binary search algorithm becomes intuitive. When we say "structure" of the outage event, we mean the fact that when we encounter an outage with a given rate R_i, we will encounter an outage with all rates $R_j \geq R_i$. Similarly, when we encounter no outage with a given rate R_i, we will encounter no outage with all rates $R_j \leq R_i$. Such structure makes the search easy and gives the intuition to use the binary search algorithm.

The algorithm is quite simple: we choose the intermediate value between the lower and the upper bound. If there is no outage, the lower bound is updated to the intermediate value just checked. If there is an outage, the upper bound is updated to the intermediate value. Check Algo. 7 for the steps of the binary search algorithm. The only issue we should mention is that the stopping condition for this search (since it belongs to real values which are infinite), is simply when the difference between the lower and the upper bounds is smaller than a given constant ϵ. In other words, when the search window is small enough (following a system parameter ϵ), the algorithm terminates.

5.2.3 The optimal joint allocation of source rates and relaying nodes scheduling

To this end, we have proposed for a given selection strategy in the retransmission phase, the optimal source allocation. Recalling again that the possible selections are finite, the optimal joint allocation would be to check for all possible selections in the retransmission phase, the optimal rate allocation strategy. Thus, the optimal joint allocation would be the selection which leads to the highest possible spectral efficiency. This strategy can be written as:

$$\widehat{\boldsymbol{A}} = \underset{\boldsymbol{A} \in \{1,\ldots,M\}^{T_{\text{used}}} : T_{\text{used}} \in \{0,\ldots,T_{\max}\}}{\operatorname{argmax}} \eta^{\text{frame}}(\boldsymbol{R}(\boldsymbol{A}), \boldsymbol{A}), \tag{5.4}$$

Algorithm 7 Binary search to get the optimal rate for a given selection $\boldsymbol{A}$ and ϵ.

Fix ϵ, Left $\leftarrow I_{i,d} + \alpha \cdot [\boldsymbol{N}]_i \cdot I_{i,d}$, Right $\leftarrow I_{i,d} + \alpha \cdot [\boldsymbol{N}]_i \cdot \overline{J}^*_{i,d}$. ▷ Initialize the boundaries.
while (Right − Left $> \epsilon$) **do** ▷ While the window size $> \epsilon$
  $R_i \leftarrow$ (Right − Left)/2. ▷ Set the candidate rate
  if ($\mathrm{O}_{i,T_{\text{used}}}(\boldsymbol{A}) = 0$) **then** ▷ If there is no outage
    Left $\leftarrow R_i$ ▷ Shift the lower bound
  else ▷ If there is outage
    Right $\leftarrow R_i$ ▷ Shift the upper bound
  end if
end while
$R_i \leftarrow$ Left ▷ Select R_i as lower bound to ensure its correctly decoded

Algorithm 8 Binary search to get the optimal rate for a given $\widetilde{\mathbb{R}}$ and $\boldsymbol{A}$.

1: $\epsilon \leftarrow \min_{i \in \{1,\ldots,n_{\text{MCS}}-1\}}(\widetilde{R}_{i+1} - \widetilde{R}_i)$
Left $\leftarrow \min(\widetilde{R}_{n_{\text{MCS}}}, I_{i,d} + \alpha \cdot [\boldsymbol{N}]_i \cdot I_{i,d})$,
Right $\leftarrow \min(\widetilde{R}_{n_{\text{MCS}}}, I_{i,d} + \alpha \cdot [\boldsymbol{N}]_i \cdot \overline{J}^*_{i,d})$. ▷ Initialize the boundaries.
2: **while** (Right − Left $> \epsilon$) **do** ▷ While the window size $> \epsilon$
3: $R_i \leftarrow$ (Right − Left)/2. ▷ Set the candidate rate
4: **if** ($\mathrm{O}_{i,T_{\text{used}}}(\boldsymbol{A}) = 0$) **then** ▷ If there is no outage
5: Left $\leftarrow R_i$ ▷ Shift the lower bound
6: **else** ▷ If there is outage
7: Right $\leftarrow R_i$ ▷ Shift the upper bound
8: **end if**
9: **end while**
10: $R_i \leftarrow \operatorname{argmin}_{\widetilde{r} \in \widetilde{R} \text{ such that: } \widetilde{r} \leq \text{Left}}(\text{Left} - \widetilde{r})$ ▷ Select R_i as the closest rate to Left in the set $\widetilde{\mathbb{R}}$

where $\boldsymbol{R}(\boldsymbol{A})$ is a vector of size M of allocated rates for the M sources, with the elements $R_i(\boldsymbol{A})$ computed as seen in equation (5.3).

In practice (e.g., [91, 129]), there is always a MCS family where possible rate values are predefined. In other words, although the optimal rates in our proposal do not depend on a predefined set of rates, we note that our proposal can be used in realistic scenarios where a predefined set of rates is adopted. But here, there is no need to search through all the values to reach the optimal rate value. Simply, the binary search algorithm can be adopted to follow the available set of possible rates. Thus, we conclude that our proposal can be used in realistic scenarios where a predefined set of rates is presented, while avoiding the complexity of searching through all of the set as done in the prior art. The modifications needed in the binary search algorithm are presented in Algo. 8 (mainly check step 1 where the bounds are initialized and step 10 where the rate is selected). Finally, a complete algorithm, for the proposed joint scheduling and rate allocation strategy is presented in the in Algo. 9.

Algorithm 9 Proposed joint allocation.

```
MAX ← 0                                                    ▷ Initialize the MAX value
for T_used = 0 till T_used = T_max do                      ▷ For all frame sizes
    for all A such that: A ∈ S^{T_used} do                 ▷ For any possible selection
        Compute R(A) : (R_i(A) for all i ∈ S)              ▷ Compute the highest rates for A
        if (MAX < η^frame(R(A), A)) then                   ▷ If we encounter a better selection
            Â ← A                                          ▷ Update the chosen set
            MAX ← η^frame(R(A), A)                         ▷ Update MAX
        end if
    end for
end for
Compute R(Â) : (R_i(Â) for all i ∈ S)                      ▷ Choose the highest rate for selected Â
```

Algorithm 10 Proposed sequential joint allocation.

```
A ← φ, MAX ← η^frame(R(φ), φ)                              ▷ Initialization
for t = 1 till t = T_max do                                ▷ For all frame sizes
    b̂_t ← argmax_{b_t∈S} η^frame(R(B), B = [b̂_1, ..., b̂_{t-1}, b_t]^T)   ▷ Select the t^th source
    if (MAX < η^frame(R(B̂), B̂)) then                       ▷ If we encounter a better selection
        Â ← B̂                                              ▷ Update the chosen set
        MAX ← η^frame(R(Â), Â)                             ▷ Update MAX
    end if
end for
Compute R(Â) : (R_i(Â) for all i ∈ S)                      ▷ Choose the highest rate for selected Â
```

The proposed algorithm faces a complexity issue following the exponential number of possible allocations $\boldsymbol{A} \in S^{T_{\text{used}}}$. For a given T_{used}, the number of possible vectors $\boldsymbol{A}$ is T_{used}^{M}. Recalling again that the order of the sources does not matter, and we only care about the number of allocations of each source, the number of possible vectors $\boldsymbol{A}$ is reduced to:

$$C_{T_{\text{used}}}^{M+T_{\text{used}}-1} = \frac{(M + T_{\text{used}} - 1)!}{T_{\text{used}}!(M-1)!}. \tag{5.5}$$

Although such a reduction is quite interesting, we might still face a practicality issue when using the proposed algorithm. To solve this issue, a sequential allocation strategy might be used. Specifically, when allocating the vector $\boldsymbol{A}$, we allocate sequentially the sources $[\boldsymbol{A}]_t$ leading to a practical allocation where no need for an exponential search over the vectors $\boldsymbol{A}$. Note that in such a case, and when we are calculating the optimal rate corresponding to the set $\boldsymbol{A}$, only one rate would be updated; that is the rate of source $[\boldsymbol{A}]_t : R_{i=[\boldsymbol{A}]_t}$. The complete algorithm for the sequential joint scheduling and rate allocation strategy is presented in Algo. 10.

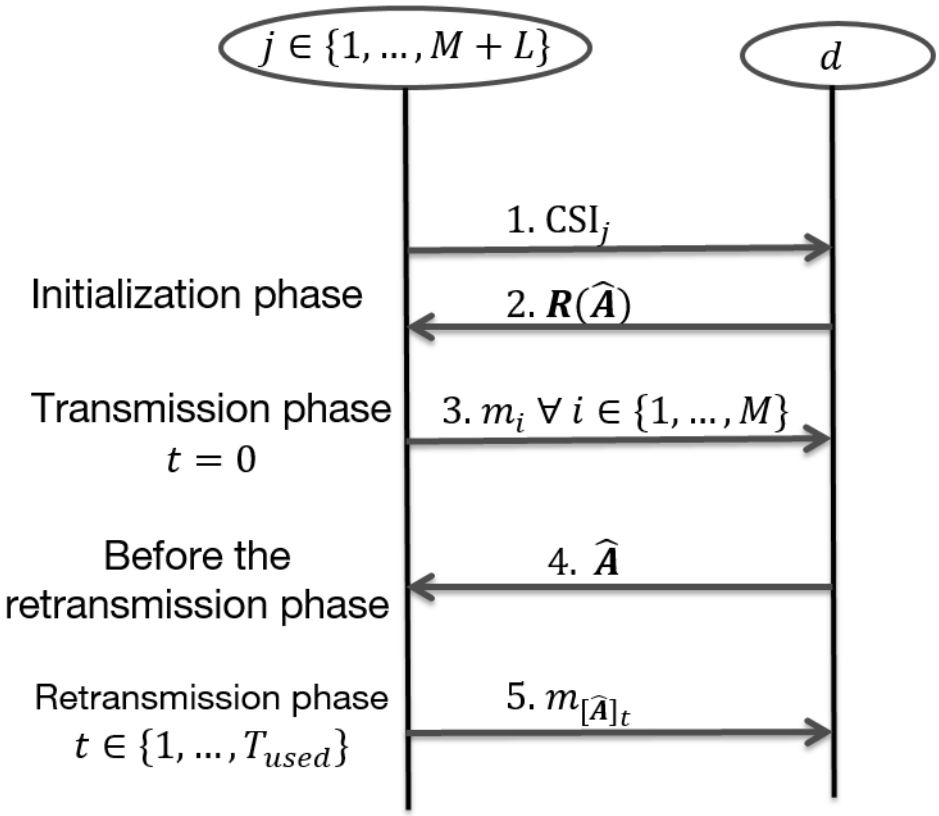


Figure 5.1: Control exchange process in the proposed joint allocation.

5.2.4 The control exchange process in the proposed joint strategy

Finally, the control exchange process between the relaying nodes and the destination is presented in Fig. 5.1. First, the relaying nodes share their CSI with the destination. Using the full CSI, the destination determines the optimal rates and the optimal selected sources for help $(\widehat{\boldsymbol{A}}, \boldsymbol{R}(\widehat{\boldsymbol{A}}))$. It then broadcasts the allocated rates with the relaying nodes. Then, each source transmits successively each on its time slot in the transmission phase following its allocated rate. After that, the destination broadcasts the selected vector of source nodes to be helped at the retransmission phase. Finally, at each time slot $t \in \{1, \dots, T_{\text{used}}\}$ in the retransmission phase, all the relaying nodes which decoded the selected source $[\widehat{\boldsymbol{A}}]_t$ send redundancies. Note that $[\widehat{\boldsymbol{A}}]_t$ is the tth element in the vector $\widehat{\boldsymbol{A}}$. Following our proposal in this chapter, the scheme of transmission of a frame can be presented as seen in Fig. 5.2. We see that in this figure (as compared to 2.2), both the rate allocation and the scheduling are done in the initialization phase. In other words, we see the selected vector of sources to be helped $\widehat{\boldsymbol{A}}$ and the set of optimal rates $\boldsymbol{R}(\widehat{\boldsymbol{A}})$ are both allocated before the transmission of the frame. Also, we see that in the retransmission phase, there is no presence of a control exchange process, and the allocated sources $[\widehat{\boldsymbol{A}}]_t$ are the elements of the allocated vector $\widehat{\boldsymbol{A}}$.

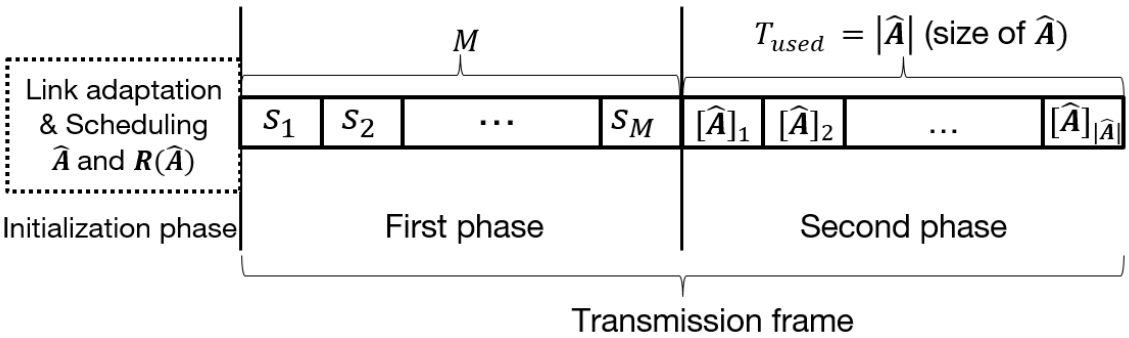


Figure 5.2: Transmission of a frame following the proposed joint allocation.

5.2.5 The reason behind using a full CSI acquisition

The full CSI acquisition means that the destination will know at each frame the state of the different direct and indirect links of the network. For the direct links (S-D, and R-D links), the CSI acquisition is quite simple. The relays and the sources send to the destination some pilot symbols (which can be included within their message), then, the destination performs pilot-based channel estimation messages to know the state of each of the direct links. On the other hand, for the indirect links (S-S, R-R, and S-R links) it is quite heavier. Since these links are not direct to the destination, the relaying nodes themselves should send the CSI to the destination. In other words, the relaying nodes will first receive some pilot symbols from their respective direct links messages to know the state of these links and then it will share this information with the destination.

The CSI knowledge is essential in our proposal and is seen in the equations/algorithms next. As we presented, our proposal determines for each possible scheduling, an optimal rate allocation. The latter is based on the knowledge of the outage events of each source. And as we are following PR where all relaying nodes that decoded a given source are activated to help, the knowledge of the CSI is essential to know the decoding sets of the relaying nodes and then to know which relaying nodes are activated and what is the equivalent channel for a given selection. In other words, following every different selection, a different equivalent channel is produced at each retransmission time slot. These channels are needed to calculate the equivalent mutual information and thus needed to know the outage events. For this reason, the full CSI acquisition is essential in our proposal.

Example:

Assume we are in an orthogonal $(2, 2, 1)$-MAMRN. The set of sources is $\mathcal{S} = \{1, 2\}$, and the set of relays is $\mathcal{R} = \{3, 4\}$ and the destination is d. Assume after the transmission phase, the decoding sets of the relaying nodes and the destination are:

$$S_{1,0} = \{1\}, S_{2,0} = \{1\}, S_{3,0} = \{1\}, S_{4,0} = \{2\}, S_{d,0} = \phi.$$

If the destination chooses to help source 1 at the first retransmission time slot, we see that the first three relaying nodes are going to be activated. Then we have an equivalent channel corresponding to these relaying nodes. Such an equivalent channel will result in an equivalent mutual information. For Gaussian inputs with EGC, the equivalent

mutual information can be written as:

$$\overline{J}_{1,d} = \log_2 \left(1 + \sum_{i=1}^{3} |h_{i,d}|^2 \right)$$

where $h_{i,d}$ represents the channel gain within the link between the relaying node i and the destination. We see that the destination needed the decoding sets of the relaying nodes to calculate $\overline{J}_{1,d}$ (in order to know which relaying nodes to include in the summation due to the equivalent channel). Here comes the need for the CSI of the indirect links. In order to know which nodes are active in the first retransmission, the destination needs to calculate the decoding sets of each relaying node after the transmission phase (following the equations $\{R_1 > I_{1,j}\}$). So, we need to calculate $I_{1,j}$ which is a function of the channel gain of the indirect link $h_{i,j}$ (for Gaussian inputs, $I_{1,j} = \log_2(1 + |h_{i,d}|^2)$. A similar procedure is needed in the following retransmission time slots. To sum up, in our proposal, the destination needs:

- To calculate the outage events given a fixed selection.
- In order to calculate the outage events, the destination needs the mutual information of the equivalent channels.
- In order to know what the equivalent channel is, the destination needs to know the decoding sets of the relaying nodes.
- To know the decoding sets of the relaying nodes, the destination needs to know the states of the links between the relaying nodes.

Thus, the destination needs the full CSI of the network.

5.2.6 Complexity analysis

The BRD is used to reduce the complexity of the exhaustive search approach. In fact, the BRD reduces the complexity from n_{MCS}^M (in the exhaustive search approach) into Mn_{MCS} multiplied by the number of BRD iterations needed (which is limited due to the limited set considered). Nevertheless, we see that the complexity is still linear with the number of possible rates. In other words, the complexity is linear with n_{MCS}. Our proposal, on the other hand, and following the complexity of the binary search algorithm, reduces the complexity to $M \log(n_{\text{MCS}})$.

5.3 Numerical results

In this subsection, we validate the proposed joint allocation strategy using MC simulations. We consider an orthogonal (3,6,1)-MAMRN scenario, with $T_{\max} = 4$ and $\alpha = 0.25$. The channel inputs are assumed independent and Gaussian distributed with zero mean and unit variance with $I_{a,b} = \log_2(1 + |h_{a,b}|^2)$ being the mutual information between the transmitting node a and the receiving node b. As relaying nodes use PR with EGC

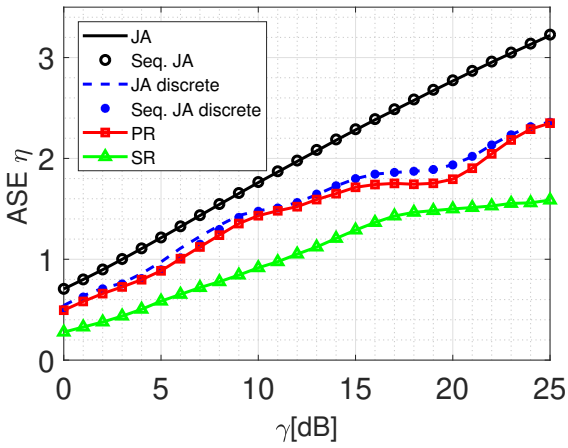


Figure 5.3: ASE that corresponds to the proposed joint allocation and the BRD allocation with symmetric link configuration.

[6], the mutual information of the equivalent channel with the destination is written as $J_{i,d} = \log_2(1 + \sum_{a \in \text{Help}_i} |h_{a,d}|^2)$ where Help_i represents the set of all the relays which will help the source i. We consider a symmetric link configuration scenario, i.e., all the links are considered the same (the average SNR of each link is set to γ). The set of possible rates is fixed to: $\widetilde{\mathbb{R}} = \{0, 0.75, 1.5, 2.25, 3\}$ [bits per channel use]. We present and compare six strategies:

- The joint allocation (denoted in figures by JA)
- The sequential joint allocation (denoted in figures by Seq. JA)
- The joint allocation following the discrete set $\widetilde{\mathbb{R}}$
- The sequential joint allocation following the discrete set $\widetilde{\mathbb{R}}$
- BRD with optimal PR allocation (as proposed in chapter 4 section 1 and [6])
- BRD with optimal SR allocation (as proposed in chapter 2 and [43])

The first four strategies are the proposal of this chapter. The first one is the upper bound, when the optimal rates are taken from the real numbers set (as seen in the first algorithm) with the best allocation of vector $\widehat{\boldsymbol{A}}$. The second one is the sequential version of the first strategy, where the allocation is considered as described in the last algorithm. The third and the fourth strategies are the same as the first two strategies, respectively, with the constraint of taking the rate values from the discrete set $\widetilde{\mathbb{R}}$ (as seen in the second algorithm). The last two strategies are the strategies of the previous two chapters. Specifically, strategy five is the strategy of chapter 4, and strategy six is the strategy of chapter 3.

In Fig. 5.3, we present the ASE as a function of γ. First, we see that the PR strategy is outperforming the strategy of SR. Second, we observe that our proposals (in both cases: with or without the discrete set) outperform the non-joint allocation

presented in the previous chapters (both SR and PR). As the gain is seen significant when the rates are allocated from the real numbers set, this gain is quite insignificant when the discrete set of rates $\widetilde{\mathbb{R}}$ is considered. Finally, we notice that the sequential joint strategies coincide with the optimal joint allocation strategies (in both cases: with or without the discrete set $\widetilde{\mathbb{R}}$). Note that similar results are seen in asymmetric rate and link configuration but are not presented for brevity. Accordingly:

- We ensure that the performance of the PR strategy presented in the previous is good as it approaches the optimal allocation seen in the joint allocation strategy and outperforms the SR strategy.
- Although the PR strategy is performing well, the proposed joint allocation is seen interesting as it can be reached with no need of an exhaustive search over the discrete set of rates $\widetilde{\mathbb{R}}$.
- The gain of using the joint allocation strategy from the real set numbers is very significant, which ensures the dependency of the performance on the discrete set values.
- The sequential strategies are seen as practical alternatives as they achieve the performance of the joint allocations while facing a reduced complexity.

Following the last two findings, we further investigate:

1. The effect of the discrete set of rates on the performance of the joint allocation strategy.
2. The effect of the size of the network on the performance of the sequential strategy.

Thus, we present in Fig. 5.4 the ASE of the joint allocation strategies with respect to γ for different discrete sets of rates. The investigated sets are:

- $\widetilde{\mathbb{R}} = \{0, 2, 4, 6, 8\}$
- $\widetilde{\mathbb{R}} = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$
- $\widetilde{\mathbb{R}} = \{0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9\}$
- $\widetilde{\mathbb{R}} = \{0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75, 4, 4.25, 4.5, 4.75, 5, 5.25, 5.5, 5.75, 6, 6.25, 6.5, 6.75, 7, 7.25, 7.5, 7.75, 8, 8.25, 8.5, 8.75, 9\}$

We see that as the size of the shift between the possible rates decreases, the joint allocation performance increases and approaches the upper bound. Specifically, it is seen that for the size shift = 0.25 [bits per channel use], the difference is seen insignificant. This validates the importance of our proposal (compared to PR seen in the previous chapter). As BRD needs to pass through all the values of the discrete set $\widetilde{\mathbb{R}}$, it faces a complexity problem when the size of $\widetilde{\mathbb{R}}$ gets bigger. On the contrary, using a binary search algorithm, the complexity of the search is not linear with the increase of the size of the discrete set. Thus, we conclude that our joint allocation proposal can approach

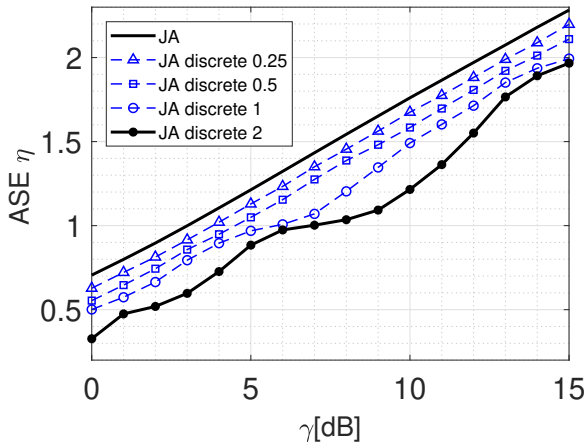


Figure 5.4: ASE that corresponds to the proposed joint allocation with symmetric link configuration for different discrete sets of rates.

the upper bound with an acceptable complexity by using a discrete set with a small shift between the rates. This is done by using the binary search algorithm presented above.

Finally, we present in Fig. 5.5 the ASE of the joint allocation strategies (both: with and without the discrete set $\widetilde{\mathbb{R}}$; and both exact and sequential) for $\gamma = 12$dB with respect to the network size. Specifically, the x-axis represents the number of sources and relays of the network. Thus, we are in an $(x, x, 1)$-MAMRN, where x represents the different points of the x-axis from (2,2,1)-MAMRN to (10,10,1)-MAMRN. The other parameters are kept the same as in the case of the scenario of Fig. 5.4. In Fig. 5.5, it is seen that as the system size changes, the performance of the sequential strategies is always approaching the joint allocation strategies. This validates again the performance of the sequential strategies as a practical alternative of the joint allocation strategy. We note that the decrease in the ASE with respect to the increase of the network size is due to the fact that $T_{\max}$ is fixed to 4. This means that the needed number of retransmission to decode the source nodes of the network (which increases with the x-axis) is higher than the available time slots. Accordingly, we add to our previous findings:

- Our proposal is more practical than the previous proposal as it can achieve the upper bound when using a larger set of possible rates. This increase does not make the proposal impractical due to the help of the binary search algorithm being used.
- The performance of the sequential strategies is robust to the size of the network which ensures its practicality as an alternative to the joint allocation strategies.

5.4 Conclusion

To sum up, we proposed in this chapter a FLA joint strategy for the rate and the relaying nodes allocation. The proposed strategy leads to the highest possible spectral efficiency. It first passes through all the possible relaying nodes allocation, and then, for

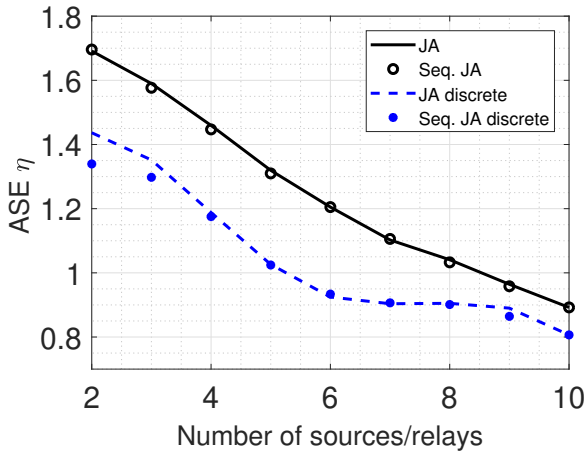


Figure 5.5: ASE of the proposal joint allocation (optimal and sequential) with respect to the size of the network.

each allocation, it determines the highest rate allocation for the sources in the network. This strategy makes it possible to choose the joint allocation which gives the highest spectral efficiency. The proposal solves two main issues seen in the prior art:

1. It removes the sub-optimality of solving the two problems separately (the rate allocation problem and the selection strategy problem).

2. It removes the need for an exhaustive search over a discrete finite set of possible rates that used to limit the practicality of the BRD proposed in the previous chapters.

Chapter 6

Future Work: different directions and open challenges

6.1 Chapter summary

In this manuscript, we presented different approaches to tackle two main open problems of the considered orthogonal MAMRN: 1- the rate allocation problem, and 2- the relaying node scheduling problem. For the first problem, we presented several strategies concerning the different radio scenarios (FLA, SLA, FLA with partial CSI), and different encoding schemes (SU and MU). In the second problem, we proposed solutions concerning the optimality of the relaying nodes scheduling as well as the optimality of the control exchange process included. Finally, we proposed a FLA joint allocation strategy that outperforms the sequential allocation. To this end, in all the presented work, two assumptions were considered: 1- a certain knowledge of the network (CSI or CDI), and 2- TDM frame transmission.

In this chapter, we present some other directions and some generalizations of our work. First, we present one solution for the rate allocation problem when no knowledge is assumed at the destination side. This solution is a learning solution, which bases its strategy on the MAB framework. Second, we present a generalization of our work in the FDM framework. Finally, we mention some open challenges and some future works which might be tackled for the considered systems.

6.2 Rate allocation via learning algorithms

In this section, we consider the problem of LA of orthogonal MAMRN using the MAB online learning framework. We assume that we have no knowledge of neither the CSI nor the CDI. Accordingly, rate allocation must be learned online following a sequential learning algorithm. We aim to solve the LA problem using a different perspective. First, we aim to use an algorithm which is not heuristic, and where the regret is bounded and tractable. Next, we want to solve the problem when no information is given at the destination. In other words, we aim to perform rate allocation using a learning algorithm, where the probability of transmission success at a certain rate is unknown

(since the channel state is unknown) and rather needed to be learned. We adopt the well known framework called MAB, where it addresses the exploration-exploitation dilemma. Here, we started with the same assumptions presented in chapter 2 (MU encoding, SR method, etc.,), and the further contributions presented in chapter 4 (SU encoding, PR method) are seen as interesting future work to investigate.

First, we recall the main issue which MAB framework tackles, i.e., the exploration-exploitation dilemma. In scenarios where multiple choices are possible (multiple arms), each with an unknown average reward, MAB algorithms give sequential steps to decide whether we need to learn more (exploration), or to stay with the option that gave the best rewards in the past (exploitation). There are different types of MAB problems, each based on the assumptions of the problem. In the survey [96], three different fundamental types of MAB problems were mentioned, stochastic, adversarial, and Markovian. In this section, we are interested in the stochastic MAB problem, as it aligns with the case of the rate allocation problem (the reward is stochastic). From a historical point of view, Lai and Robbins [97] introduced the first analysis of stochastic bandits with asymptotic analysis of regret. There, the principle of *optimism in the face of uncertainty* (to be optimistic while thinking about the not well explored choices) was used and the UCB algorithm was proposed. This concept is widely used in most of the MAB literature.

In our framework, there is a fixed set of MCS representing the available set of rates. These rates represent the possible choices of the MAB problem. Since we are considering MAMRN framework, at each frame transmission, the destination will allocate a rate for each given source. In other words, rather than selecting a single arm of the MAB, we need to select multiple arms, each corresponding to each of the multiple source nodes. Such kind of MAB problems is given under the name of CMAB, where a subset of arms is selected at each step, forming a *Super Arm*. In the literature, CMAB was investigated in several applications [106, 107, 108]. Check section 1.2.2 for more literature review.

6.2.1 MAB problem formulation

In the MAB framework, a unique utility metric is considered when evaluating the performance of a considered arm. Here, the utility function used is the spectral efficiency per frame. We recall the definition of the spectral efficiency per frame:

$$\begin{aligned}\eta^{\text{frame}}(\mathbf{H}, P) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} K_i(1 - \mathrm{O}_{i,T_{\text{used}}})}{MU + QT_{\text{used}}} \\ &= \frac{\sum_{i=1}^{M} R_i(1 - \mathrm{O}_{i,T_{\text{used}}})}{M + \alpha T_{\text{used}}}. \end{aligned} \tag{6.1}$$

After defining the utility metric, we can now formulate the considered rate adaptation problem as a MAB problem. We consider a finite set of possible arms of size n_{MCS} (i.e., $\widetilde{\mathbb{R}} = \{\widetilde{R}_1, \ldots, \widetilde{R}_{n_{\text{MCS}}}\}$). We define the RL round as the procedure of: i) the destination selects and broadcasts a super arm, ii) the sources follow the rates allocated by the selected super arm for the RL round t during the transmission of a frame, iii) the

destination computes the updated cumulative reward. At each RL round, a *super arm* of size M is selected for the M source nodes included. This leads us to an equivalent CMAB of arms size n_{MCS}^{M}. The reward of each arm is a stochastic random variable, with an unknown distribution and unknown average. We define the random variable $\text{Rew}_i(t)$ as the reward given when we select the *super arm* i at the tth RL round. The reward was defined before as the spectral efficiency per frame, and the randomness is within the variables T_{used} which varies between zero and $T_{\max}$, and the outage event indications of each source node. We define the expected value of the reward of the *super arm* i as $\theta_i = \mathbb{E}[\text{Rew}_i(t)]$.

For a given online sequential algorithm π, where at each frame j, a decision $\text{Dec}(t)$ of a *super arm* i is selected ($\text{Dec}(t) = i$), we define the regret as the difference between the rewards of the optimal algorithm (Oracle algorithm selecting the optimal arm each RL round) and the given algorithm. The regret of algorithm π up to RL round t can be written as:

$$\text{Reg}^{\pi}(t) = \theta^* t - \sum_{i=1}^{n_{\text{MCS}}^{M}} \theta_i \mathbb{E}[\text{nb}_i^{\pi}(t)], \tag{6.2}$$

where θ^* represents the expected value of the optimal reward (i.e., the reward of the optimal *super arm* i^*), and $\mathbb{E}[\text{nb}_i^{\pi}(t)]$ represents the expected value of the number of times arm i was selected after t RL rounds when using algorithm π. We aim to propose a rate allocation algorithm which performs exploration and exploitation in a way that minimizes this regret.

6.2.2 Algorithm

We retain here a well-known algorithm in the literature, specifically, a UCB-like algorithm. Several types of UCB algorithms are seen in the prior art, each depending on the problem considered, the reward type, and the way we choose the upper bound. In our proposal, we use the UCB1 algorithm [130], where it is known that it achieves a logarithmic regret uniformly over t and without any preliminary knowledge about the reward distributions. The only condition is to assume that the rewards are bounded in [0, 1], and this normalization can be assumed easily with no loss of generality. The sketch of the algorithm is presented in **Algorithm 11**, where $\overline{\text{Rew}}_i(t) = \frac{\sum_{l=1}^{t-1} \text{Rew}_{i,l}}{\text{nb}_i(t)}$, and:

- $\begin{cases} \text{Rew}_{i,l} = 0 \text{ if } \text{Dec}(l) \neq i. \\ \text{Rew}_{i,l} = \frac{\sum_{j=1}^{M} R_{i,j}(1-\text{O}_{j,T_{\text{used}}})}{M+\alpha T_{\text{used}}} \text{ if } \text{Dec}(l) = i. \end{cases}$
- $i \in \{1, \ldots, n_{\text{MCS}}^{M}\}$ super arms
- $\text{nb}_i(t)$ is the number of times super arm i was chosen until RL round t.
- $\boldsymbol{R}_i$ is the rate vector allocated if super arm i is selected (i.e., $\text{Dec}(l) = i$).

After the initialization step, where each arm is explored once, we start choosing the next arms based on the information collected. We see next that the choice is based

Algorithm 11 UCB1.

1: **Initialization:** For $t = 1, \ldots, n^M_{\text{MCS}}$, for the tth RL round, select the super arm t (play each super arm once).
2: **UCB:** For $t \geq n^M_{\text{MCS}}+1$, for the tth RL round, select the super arm i which maximizes $\overline{\text{Rew}}_i(t) + \sqrt{\frac{2 \ln t}{\text{nb}_i(t)}}$.

on two terms summed together, $\overline{\text{Rew}}_i(t)$ representing the average reward obtained from *super arm* i up to RL round t, and the upper confidence term represented by $\sqrt{\frac{2 \ln t}{\text{nb}_i(t)}}$, where $\text{nb}_i(t)$ represents the number of times *super arm* i was selected up to RL round t. The first term, i.e., $\overline{\text{Rew}}_i(t)$, gives the exploitation term, where the history rewards of the arms are taken into consideration. On the other hand, the second term, i.e., $\sqrt{\frac{2 \ln t}{\text{nb}_i(t)}}$, gives the exploration term. The ratio can be understood as, when a given arm i is not selected for enough time, compared to other arms, the fraction increases, and then the index of this arm composed of the sum of the two terms increases. In this way, we tend to compromise between the history of the rewards of each arm and the number of times this arm was selected. One final comment, about the logarithmic in the expression: In UCB1, we try to decrease the exploration coefficient as time increases, trying to set a limit to the exploration phase when enough information is collected through previously selected arms. The mathematical aspect of this result is based on Hoeffding's Inequality, a theorem applicable to any bounded distribution. In theorem 1, the expected regret of the UCB1 algorithm when played t times is presented.

Theorem 6.2.1. *For all $n^M_{\text{MCS}} > 1$, if policy UCB1 is run on n^M_{MCS} machines having arbitrary reward distributions $Pr_1, \ldots, Pr_{n^M_{\text{MCS}}}$ with support in $[0, 1]$, then its expected regret after any number t of plays is at most:*

$$8 \sum_{i:\theta_i<\theta^*} \left(\frac{\ln t}{\Delta_i}\right) + \left(1 + \frac{\pi^2}{3}\right) \left(\sum_{j=1}^{n^M_{\text{MCS}}} \Delta_j\right),$$

where $\theta_1, \ldots, \theta_{n^M_{\text{MCS}}}$ are the expected values of $Pr_1, \ldots, Pr_{n^M_{\text{MCS}}}$, and Δ_i is defined as:

$$\Delta_i = \theta^* - \theta_i.$$

Proof. Check appendix B. □

In practice, the proposed algorithm suffers mainly from the exponential growth of arms. Specifically, the initialization phase (pure exploration phase) will take too much time before reaching the exploitation-exploration phase. Thus, we propose an Approximated UCB1 (AUCB1) algorithm, which reduces the complexity of the initialization phase.

The goal of the initialization phase is to explore each *super arm* once, and to set its index, we call index the sum $\overline{\text{Rew}}_i(t)+\sqrt{\frac{2 \ln t}{\text{nb}_i(t)}}$. We propose here setting an approximated

Algorithm 12 AUCB1

1: For $t = 0, \ldots, n_{\text{MCS}} \times (M-1)$, for the $(t+1)^{th}$ RL round, select successively a single arm for each source $\{1, \ldots, M\}$ an arm $\{1, \ldots, n_{\text{MCS}}\}$ (play for each single source, all possible arms once).

2: Set the index of all super arms based on the average of the indices of the included arms. For $t \geq n_{\text{MCS}} \times M$, for the $(t+1)^{th}$ RL round, select the super arm i which maximizes $\overline{\text{Rew}}_i + \sqrt{\frac{2 \ln t}{\text{nb}_i}}$.

initial index in order to decrease the complexity of the initialization phase. One way in doing so is by removing the exponential relationship between the sources forming the *super arm*. In other words, rather than taking *super arms* initially, we take each arm by itself (each possible rate), and we test this arm with all the possible sources. In this case, when a source is sending with a given rate, other sources send nothing. We repeat this process for a given arm with all the given sources. Finally, we average for this arm the number of transmitted bits (Rate $\times$ success or failure), and we save the highest T_{used} needed with all the sources. We repeat this process for all arms (rates). Finally, for each *super arm* composed of M subset of arms, we calculate the reward (index) as the average of transmitted bits divided by the number of channel uses while using the highest T_{used} of the considered subset of arms (rates). Following these steps, we approximate the reward (recall equation 6.1). The complexity of the initialization phase is reduced from $O(n_{\text{MCS}}^M)$ to $O(n_{\text{MCS}} \times M)$. The sketch of the algorithm is presented in **Algorithm 12**.

In SUCB1, the idea is to generalize the AUCB1 algorithm for all iterations rather than only the initialization step. After setting the indices of each arm using AUCB1, SUCB1 chooses each *super arms* successively, arm by arm. In other words, instead of choosing the *super arm* directly, we choose for each source of the M sources the arm with the highest index. After each selection, we update the indices' counter. Finally, we update the indices based on the cumulative reward, each based on decoding the signal of the related source. In SUCB1, we have n_{MCS} arms, rather than n_{MCS}^M arms, and this reduction will decrease the regret as we will see in the numerical results section. The sketch of the algorithm is presented in **Algorithm 13**, where $\overline{Y}_i(t) = \frac{\sum_{l=1}^{t-1} \sum_{j=1}^{M} Y_{i,l,j}}{\text{nb}_i(t)}$, and:

- $\begin{cases} Y_{i,l,j} = 0 \text{ if } \text{Dec}(l,j) \neq i. \\ Y_{i,l,j} = \frac{R_{i,j}(1-\text{O}_{j,T_{used}})}{M+\alpha T_{\text{used}}} \text{ if } \text{Dec}(l,j) = i. \end{cases}$
- $i \in \{1, \ldots, n_{\text{MCS}}\}$ simple arms, $n_i(t)$ is the number of times arm i was chosen until RL round t.
- $\text{Dec}(l,j)$ represents the index of the selected simple arm at RL round l for source j.
- $R_{i,j}$ is the rate allocated for source j if arm i is selected (i.e., $\text{Dec}(l,j) = i$).

Algorithm 13 SUCB1.

1: **Initialization:** For $t = 1, \ldots, n_{\text{MCS}} \times M$, for the tth RL round, initialize the arms indices following the reward of each source independently, i.e., a single source transmits during a frame (the other sources becomes relays).

2: **SUCB:** For $t \geq n_{\text{MCS}} \times M + 1$, for the tth RL round, select the super arm successively, arm by arm, for each of the M sources as:

for $j = 1$ **till** M

Allocate source j with the rate of arm i which maximizes $\overline{Y}_i(t) + \sqrt{\frac{2 \ln t}{\text{nb}_i(t)}}$.

Update $\text{nb}_i(t)$

end for

6.2.3 Numerical results

In this section, we validate the learning algorithms with an orthogonal (3,3,1)-MAMRN, while using 4 possible retransmissions in the second phase ($T_{\max} = 4$) and $\alpha = 0.5$. We assume independent Gaussian distributed channel inputs (with zero mean and unit variance), with $I_{a,b} = \log_2(1 + |h_{a,b}|^2)$. Note that some other formulas could be also used for calculating $I_{a,b}$ but they would not have any impact on the basic concepts of this work. There are many factors to investigate: links configuration, SNR levels, and different MCS families.

Due to brevity, and after carefully checking different possible scenarios, we present the results of symmetric link configuration (SNR of all channel links is symmetric). Three different levels of SNR will be considered, specifically, SNR = $\{-4, 6, 21\}$dB. The importance of choosing the different SNR links, is that the optimal rate allocation (the Oracle allocation) is different at each SNR level. Following the discrete MCS family whose rates belong to the set {0.5,1,1.5,2,2.5,3,3.5} [bits per channel use], the Oracle rate allocation of sources $\{s_1, s_2, s_3\}$ will be $\{1, 1, 1\}$, $\{3, 3, 2.5\}$, and $\{3.5, 3.5, 3.5\}$ respectively to the SNR set investigated.

In figures 6.1, 6.2, and 6.3, we see the regret analysis of the three different SNR levels. For clarity of the results, we present the regret in the form of a percentage loss with respect to the optimal efficiency. In other words, we compare the efficiency of the algorithms as a ratio of the rewards of the algorithms and the Oracle. In Fig. 6.1, for SNR = -4dB, we see that the three algorithms are featuring a close regret level (up to 25% loss after 1000 samples). Next, in Fig. 6.2, for SNR = 6dB, we see a great improvement with using SUCB1 (reaching 90% of the optimal reward), as compared to UCB1 and AUCB1 which act closely as in the case when $\gamma = -4$dB. In Fig. 6.3, the same result is seen for SNR = 21dB, where SUCB1 is outperforms other algorithms, while AUCB1 is slightly better than UCB1. Finally, in Fig. 6.4, we present the ASE, for the different SNR levels between -5 and 15dB after 500 samples (larger numbers of samples were investigated and gave the same results). We see that the proposed SUCB1 algorithm approaches the upper bound (the Oracle) while outperforming UCB1 and AUCB1.

To sum up, we investigated in this section the LA of OMAMRN using an online learning framework, MAB. First, we formulate the system model as a MAB problem.

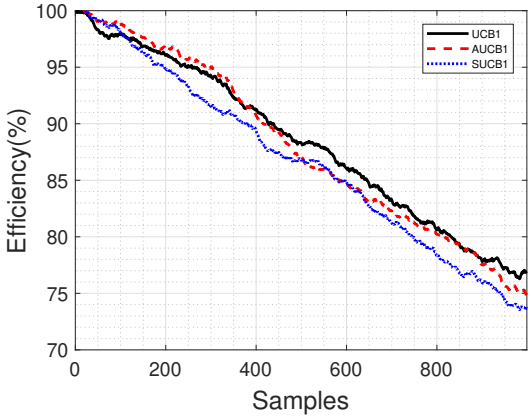


Figure 6.1: Efficiency of the different MAB algorithms for $\gamma = -4$dB.

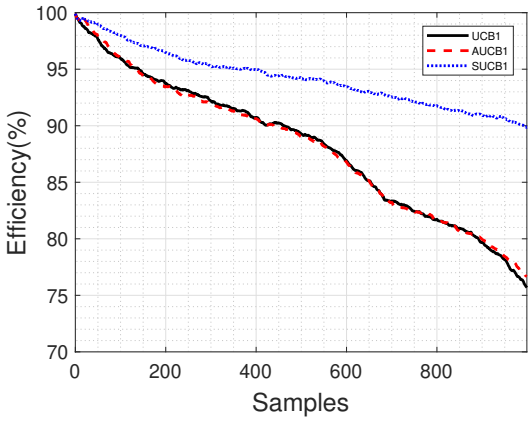


Figure 6.2: Efficiency of the different MAB algorithms for $\gamma = 6$dB.

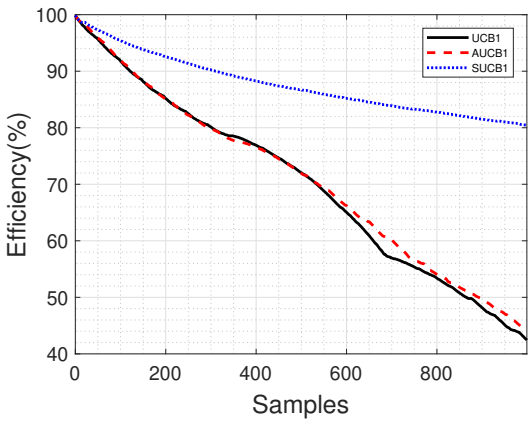


Figure 6.3: Efficiency of the different MAB algorithms for $\gamma = 21$dB.

Then, we adopt the UCB-type family, specifically the UCB1 algorithm. In order to solve the problem of complexity of the exponential number of arms included in the

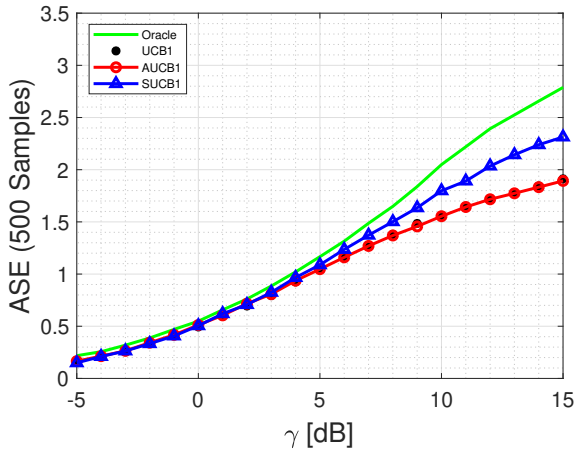


Figure 6.4: ASE vs γ after 500 Samples.

MAMRN system, a sequential algorithm SUCB1 is proposed. Within SUCB1, we use an approximated initialization phase AUCB1, then, we choose arms sequentially for the considered set of sources. The numerical results show that the proposed algorithm outperforms the traditional UCB1 algorithm in terms of regret and ASE.

Several interesting directions can be further investigated. One important issue would be the regret analysis of the proposed algorithms. Unfortunately, we could not reach an upper bound to the regret of the presented SUCB1. We tried to use the structure seen in the utility metric, but since MU encoding case was used, it was still complex. As mentioned in [91], the structure stems from inherent properties of the achieved throughput as a function of the selected rates. In the MAB framework, a structure of the utility metric is used to speed up the exploration process. This means that while looking through the different arms, we take into consideration the different properties. For example, in our considered problem, the rewards associated with the various rates on a given channel are stochastically correlated, i.e., the outcomes of transmissions at different rates are not independent: for example, if a transmission at a high rate is successful, it would be also successful at lower rates. In addition, the average efficiency achieved at various rates exhibits natural structural properties. For a given channel, the throughput is an unimodal function of the selected rate. We are interested in revisiting these notions (regret upper bound analysis, exploiting system structure) when the SU encoding case is used.

6.3 Generalization to FDM domain

In all the previous chapters, TDM was adopted. All the presented LA and scheduling algorithms were TDM-type strategies. In this section, we give some insights into generalizing the contributions to FDM regime. Concerning the LA strategies using BRD methods, no change is seen upon adopting the FDM regime. Concerning the scheduling strategies, on the other hand, the strategies proposed in the prior art become inapplicable.

Since FDM is used for orthogonality, different nodes are allocated at each sub-band of the transmission and retransmission phases. In this section, we present the system model of the considered orthogonal MAMRN when the FDM mechanism is adopted, while including the analytical derivations of the utility metrics (spectral efficiency and outage events). Then, two centralized node selection strategies are proposed to generalize the methods used in chapter 3 (and in the prior art). The presented algorithm uses SR with SU encoding. The generalization to PR could be seen in the following section. Moreover, we present the control information exchange process between the destination and the different nodes. The proposed strategies allocate for each sub-band the node that will transmit (or retransmit) with the goal of maximizing the spectral efficiency.

Upon adopting the FDM mechanism, we encounter a new DoF represented by the several sub-bands at each transmission or retransmission time slots. To exploit this DoF, the relaying nodes must be able to transmit on a given sub-band while listening to the others, i.e., the relaying nodes are capable of full duplex communication. Guard bands between sub-bands can be inserted to simplify the implementation of duplexer filters.

6.3.1 Proposed selection strategies

6.3.1.1 Utility metric

In the proposed FDM-based orthogonal MAMRN, each time slot is composed of several frequency sub-bands, and each sub-band is made of a time-frequency grid corresponding to F resource elements made of consecutive Orthogonal Frequency Division Multiplexing (OFDM) symbols and consecutive subcarriers set per OFDM symbols. We fix the number of sub-bands to B, and thus, the first $\lceil M/B \rceil$ time slots are reserved for transmission (first phase), while the other $T_{\max}$ time slots are dedicated for retransmissions (second phase). We recall that $\lceil q \rceil$ represents the ceiling function which gives the first integer greater than or equal to q. In each time slot, the number of channel uses is defined as: $N = B \times F$ resource elements. In the first phase, a scheduler at the destination decides which source node will be allocated to each different sub-band, with the constraint that at least one sub-band is allocated for each source. At a given time slot in the second phase, the scheduler decides which subset of relaying nodes will be active in the retransmission phase. The scheduler also allocates the partition of sub-bands given for each element of this active subset of nodes.

We define the B-dimensional vector of selected nodes in the transmission and retransmission phase at a certain time slot t as $\boldsymbol{a}_t \in (\mathcal{S} \cup \mathcal{R})^B$. The ith element $[\boldsymbol{a}_t]_i$, of vector $\boldsymbol{a}_t$ refers to the ith sub-band and the selected node active during this time slot in sub-band i. Similarly, we define the vector of number of allocated sub-bands for each node at a certain time slot t as the $(M+L)$-dimensional vector $\boldsymbol{n}_t \in \{0, 1, \ldots, B\}^{M+L}$. The ith element $[\boldsymbol{n}_t]_i$ of vector $\boldsymbol{n}_t$ refers to the number of sub-bands allocated for the node $i \in \mathcal{N}$ at time slot t. An example is given in Fig. 6.5, where $M = 3$, $L = 2$, and $B = 5$. Following this example, the vector $\boldsymbol{a}_t$ is written as: $\boldsymbol{a}_0 = [s_1, s_1, s_2, s_3, s_1]^T$, $\boldsymbol{a}_1 = [s_3, r_2, r_2, r_2, s_2]^T$, and $\boldsymbol{a}_2 = [r_1, r_1, s_1, s_1, r_1]^T$; and the vector $\boldsymbol{n}_t$ is written as: $\boldsymbol{n}_0 = [3, 1, 1, 0, 0]^T$, $\boldsymbol{n}_1 = [0, 1, 1, 0, 3]^T$, and $\boldsymbol{n}_2 = [2, 0, 0, 3, 0]^T$. It can be seen that $\boldsymbol{n}_t$ can be directly deduced from $\boldsymbol{a}_t$.

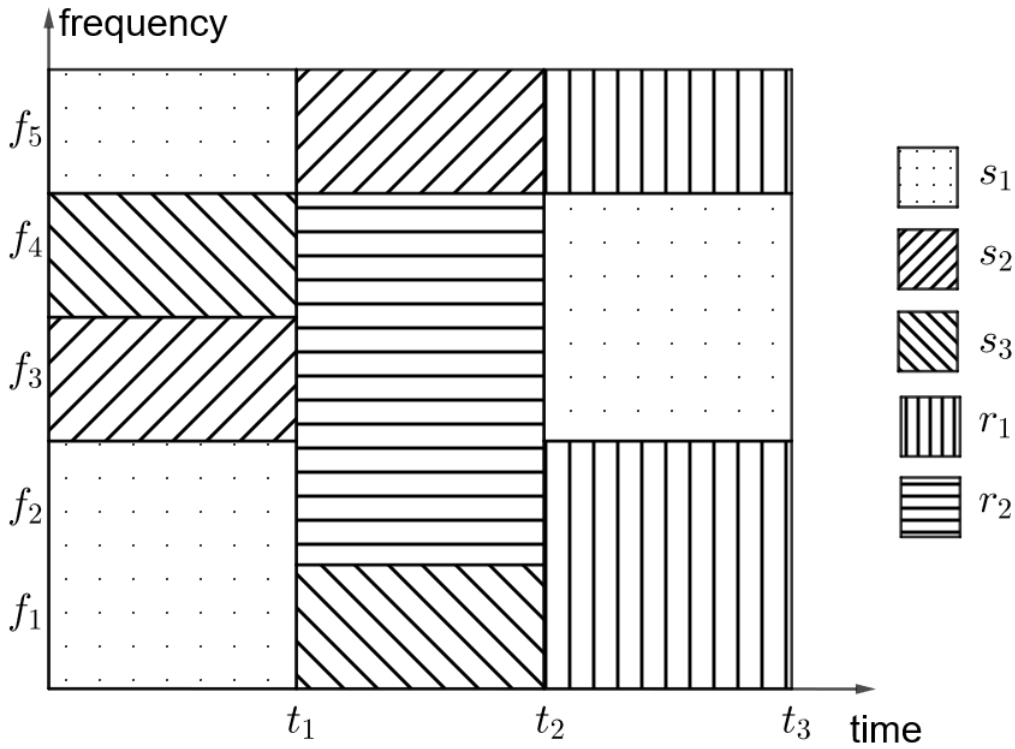


Figure 6.5: Allocation of the resources between the sources and the relays in the transmission and the retransmission phases.

The goal is to maximize the ASE (utility metric), which is the expectation of the spectral efficiency per frame $\eta_{\text{FDM}}^{\text{frame}}$. The metric $\eta_{\text{FDM}}^{\text{frame}}$ depends on the channel realization $\mathbf{H}$, and the selection strategy used P. In the FDM regime, $\mathbf{H}$ contains the channel gains per sub-band of all the links $h_{f,a,b}$ where f is the sub-band, a a source or a relay, and b a source or a relay or the destination. The channel gains $h_{f,a,b}$ are independent and follow a zero-mean circularly symmetric complex Gaussian distribution with variance $\gamma_{a,b}$. Also, $\eta_{\text{FDM}}^{\text{frame}}$ depends on the RP used, LA considered (how rates are allocated based on the channel information, e.g., SLA), and the parameters of the system (e.g., $M, L, T_{\max}$). For simplicity, we only include within the following equations the dependency on the channel and the selection strategy. Now, $\eta_{\text{FDM}}^{\text{frame}}$ can be defined as:

$$\begin{aligned}\eta_{\text{FDM}}^{\text{frame}}(\mathbf{H}, P) &= \frac{\text{nb bits successfully received}}{\text{nb channel uses}} \\ &= \frac{\sum_{i=1}^{M} R_i(1 - \text{O}_{i,T_{\text{used}}})}{\lceil M/B \rceil + T_{\text{used}}} \end{aligned} \tag{6.3}$$

where $R_i = K_i/N$ is the rate of a source i, with K_i being the number of bits that can be transmitted by source i given N channel uses. R_i is allocated based on the SLA process.

6.3.1.2 Outage events

The individual outage event $\mathcal{O}_{s,t}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}|\mathbf{h}_{\text{dir}}, \mathcal{L}_{t-1})$, of a source s after time slot t, depends on the selected vector of nodes $\boldsymbol{a}_t$, the vector of number of allocated sub-bands $\boldsymbol{n}_t$, and the associated decoding sets $S_{\boldsymbol{a}_t,t-1}$ (i.e., the set containing the sets of successfully decoded source messages in the previous time slots at the nodes selected to transmit redundancies at different sub-bands at time slot t). It is conditional on the knowledge of the channel realization of the direct links $\mathbf{h}_{\text{dir}}$ and on $\mathcal{L}_{t-1}$ which denotes the set collecting the vectors $\boldsymbol{a}_k$ and $\boldsymbol{n}_k$ that were selected in time slots $k \in \{1, \ldots, t-1\}$ prior to time slot t together with their associated decoding sets $S_{\boldsymbol{a}_k,k-1}$, and the decoding set of the destination $S_{d,t-1}$ ($\boldsymbol{a}_0$ is the selected vector of source nodes allocated in the transmission phase; $\boldsymbol{n}_0$ is the selected vector of number of sub-bands allocated for each source node in the transmission phase; and $S_{d,0}$ is the destination's decoding set after the first phase). Here again, we notice that in order to simplify the notation, the dependency on $\mathbf{h}_{\text{dir}}$ and $\mathcal{L}_{t-1}$ is omitted. Analytically, and following the SU encoding case, where a selected relaying node $[\boldsymbol{a}_l]_f$ only helps a random source node chosen from its decoding set which is not decoded yet at the destination (called $b_{l,f}$ such that $b_{l,f} \in S_{[\boldsymbol{a}_l]_f,l-1} \cap \overline{S}_{d,l-1}$), the individual outage using SU encoding of a source s can be written as:

$$\mathcal{O}_{s,t}^{\text{SU-FDM}}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}) = \left\{ BR_s > \overline{\ell}_0^{(s)} + \sum_{l=1}^{t-1} \overline{\ell}_l^{(s)} + \overline{\ell}_t^{(s)} \right\}, \tag{6.4}$$

where

- Index l is for the retransmission time slot with the convention that $l = 0$ corresponds to the end of the transmission phase; $l \in \{1, \ldots, T_{\max}\}$.
- $\overline{\ell}_l^{(s)}$ corresponds to the block fading mutual information from the nodes of $\boldsymbol{a}_t$ to the destination d allocated at time l over the whole sub-bands:

$$\overline{\ell}_l^{(s)} = \sum_{f=1}^{B} I_{l,f,[\boldsymbol{a}_l]_f,d} \left[s = b_{l,f} \right] \tag{6.5}$$

  where $b_{l,f} \in S_{[\boldsymbol{a}_l]_f,l-1} \cap \overline{S}_{d,l-1}$ is the selected source among the decoding set of node $[\boldsymbol{a}_l]_f$, and $[q]$ represents the Iverson bracket which gives 1 if the event q is satisfied, and 0 otherwise.

For the common outage event, in the SU encoding sub-case, it is simply the union of the individual outage events of all the sources included in the considered subset $\mathcal{B}$, and can be written as:

$$\mathcal{E}_{t,\mathcal{B}}^{\text{SU-FDM}}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}) = \bigcup_{s \in \mathcal{B}} \mathcal{O}_{s,t}^{\text{SU-FDM}}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}). \tag{6.6}$$

$I_{l,f,[\boldsymbol{a}_l]_f,d}$ is the mutual information between node $[\boldsymbol{a}_l]_f$ allocated to sub-band f at time slot l and the destination, and which is defined based on the channel inputs (check section 6.3.2 for the Gaussian inputs example). The mutual information depends on the

transmit power on sub-band f which is $\frac{\mathcal{P}_T}{[\boldsymbol{n}_l]_{[\boldsymbol{a}_l]_f}}$ and the channel between $[\boldsymbol{a}_l]_f$ and d, where $\mathcal{P}_T$ is the total power given for each node.

Although we use the SU encoding in our numerical results to be presented next, we present for completeness the outage events in case of the MU encoding case. The reason behind using SU case follows the results seen in chapter 3, which states the practicality of the SU case. Now, in the case of MU encoding, the outage events can be written as:

$$\mathcal{E}_{t,\mathcal{B}}^{\text{FDM}}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}) = \bigcup_{\mathcal{U}\subseteq\mathcal{B}} \Big\{ \sum_{s\in\mathcal{U}} BR_i > \sum_{i\in\mathcal{U}} \overline{\ell}_0^{(i)} + \sum_{l=1}^{t-1} \overline{\ell}_l^{(\mathcal{U})} + \sum_{i\in\mathcal{U}} \overline{\ell}_t^{(\mathcal{U})} \Big\}, \tag{6.7}$$

$$\begin{aligned} \mathcal{O}_{s,t}^{\text{FDM}}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}) &= \bigcap_{\mathcal{I}\subset\overline{S}_{d,t-1},\mathcal{B}=\overline{\mathcal{I}},s\in\mathcal{B}} \mathcal{E}_{t,\mathcal{B}}(\boldsymbol{a}_t, S_{\boldsymbol{a}_t,t-1}) \\ &= \bigcap_{\mathcal{I}\subset\overline{S}_{d,t-1}} \bigcup_{\mathcal{U}\subseteq\overline{\mathcal{I}}:s\in\mathcal{U}} \Big\{ \sum_{i\in\mathcal{U}} BR_i > \sum_{i\in\mathcal{U}} \overline{\ell}_0^{(i)} + \sum_{l=1}^{t-1} \overline{\ell}_l^{(\mathcal{U})} + \sum_{i\in\mathcal{U}} \overline{\ell}_t^{(\mathcal{U})} \Big\}, \end{aligned} \tag{6.8}$$

where

$$\overline{\ell}_l^{(\mathcal{U})} = \sum_{f=1}^{B} I_{l,f,[\boldsymbol{a}_l]_f,d} \Big[(S_{[\boldsymbol{a}_l]_f,l-1} \cap \mathcal{U} \neq \emptyset) \wedge (S_{[\boldsymbol{a}_l]_f,l-1} \cap \mathcal{I} = \emptyset) \Big]. \tag{6.9}$$

6.3.1.3 Selection strategies

Here, rather than choosing a unique node to transmit/retransmit, a subset of nodes are chosen simultaneously. Due to the power distribution over the allocated sub-bands of each node, an optimal selection strategy needs to allocate the sub-bands jointly. In fact, in an exhaustive search strategy (optimal strategy), one can simply check all the possible combinations of vector allocations at all time slots. Conditional on the knowledge of the CSI of all the links in the network (the matrix $\mathbf{H}$), we can find the optimal activation sequence of vectors with respect to the considered utility metric. Since there are $T_{\max}$ retransmission time slots and $\lceil M/B \rceil$ transmission time slot, the complexity of this strategy is $(M+L)^{B(\lceil M/B \rceil + T_{\max})}$. Clearly, this strategy is computationally very expensive. In addition, we should stress that the knowledge of the CSI of all the links (the matrix $\mathbf{H}$) would cost extremely large feedback overhead. Thus, this strategy is practically infeasible and is only considered as an upper bound to the proposed algorithms.

As the optimal solution costs a high complexity and heavy overhead, we propose a lower-complexity algorithm which does not need the full CSI of the channel. In strategy 1, we allocate the vector which maximizes the mutual information with the destination at each time slot. The idea of this strategy is to go through all the vector selection alternatives and find the one with the highest mutual information with the destination. In other words, we try all the possible values of the vector $\boldsymbol{a}_t$, and we select the one with the highest $\overline{\ell}_t$ where $\overline{\ell}_t = \sum_{f=1}^{B} I_{t,f,[\boldsymbol{a}_l]_f,d}$. Note that we do not take into consideration the nodes which cannot help any non-decoded source node, i.e., we only consider the nodes i satisfying $\overline{S}_{d,t-1} \cap S_{i,t-1} \neq \emptyset$, for $i \in \{1, \ldots, M+L\}$. Finally, the selection

Algorithm 14 Selection process of strategy 1: highest mutual information.

```
Help ← ∅                                                  ▷ Empty set of candidate nodes
for all i in (S ∪ R) do                                   ▷ For every candidate node
    if S̄_{d,t−1} ∩ S_{i,t−1} ≠ ∅ then                      ▷ If node i can help
        Help ← Help ∪ {i}
    end if
end for
â_t ← argmax_{a_t ∈ Help^B_{S_{d,t−1}}} { Σ_{f=1}^{B} I_{t,f,[a_t]_f,d} }
```

criterion at a time t has the following form:

$$\widehat{\boldsymbol{a}}_t \in \underset{\boldsymbol{a}_t \in \mathrm{Help}^B_{S_{d,t-1}}}{\mathrm{argmax}} \left\{ \sum_{f=1}^{B} I_{t,f,[\boldsymbol{a}_t]_f,d} \right\} \tag{6.10}$$

where $\mathrm{Help}_{S_{d,t-1}}$ is the set of nodes that can help at time slot t. Note that for $t = 0$, the only candidate nodes are the source nodes, where their decoding sets are exactly themselves. Other relay nodes have empty decoding sets. Algo. 14 presents strategy 1, which as we can see faces a complexity issue, as the destination needs to exhaustively search all the allocation vectors belonging to $\mathrm{Help}_{S_{d,t-1}}$. Since the cardinality of $\mathrm{Help}_{S_{d,t-1}}$ is lower or equal to $L + M$, the complexity is upper bounded by $(M + L)^B$ operations, each operation being the sum of B mutual information terms.

As a lower complexity approach, we propose selection strategy 2. Here, rather than considering exhaustively all possible allocation vectors, we perform a sequential allocation per sub-band conditional on the increasing order of sub-bands. The active node selection for a given sub-band b is based on the computation of the cumulative mutual information up to that sub-band ($f = 1, \cdots, b$). Indeed, the transmit power per sub-band depends on the number of sub-bands each node (source or relay) occupies. As a result, the mutual information of each previously allocated sub-bands needs to be re-evaluated if the power constraint is modified. Then, after each sub-band selection, the number is incremented for the allocated node. Strategy 2 can be implemented at a given time t and sub-band b as:

$$[\widehat{\boldsymbol{a}}_t]_b \in \underset{i \in \mathrm{Help}_{S_{d,t-1}}}{\mathrm{argmax}} \left\{ \sum_{f=1}^{b-1} I_{t,f,[\widehat{\boldsymbol{a}}_t]_f,d} + I_{t,b,i,d} \right\} \tag{6.11}$$

where $\mathrm{Help}_{S_{d,t-1}}$ is defined above. Strategy 2 is presented in Algo. 15. This algorithm reduces the complexity of Algo. 14 by removing partially the inter-dependency of sub-band allocations. The number of needed operations is upper bounded by $B(M + L)$ where each operation corresponds to an accumulated mutual information computation which has a lower or equal complexity than the sum of B mutual information terms.

Note that the presented algorithms are applicable in the transmission and the re-transmission time slots. The only difference in the transmission phase is the presence of an additional constraint, that each source will be allocated at least 1 sub-band. Since relays' decoding sets are empty in the transmission phase, we only pass through all possible combinations of source nodes giving the highest mutual information.

Algorithm 15 Selection process of strategy 2: highest cumulative mutual information per sub-band.

1: $\text{Help}_{S_{d,t-1}} \leftarrow \emptyset$ ▷ Empty set of candidate nodes
2: **for all** i in $(\mathcal{S} \cup \mathcal{R})$ **do** ▷ For every candidate node
3: **if** $\overline{S}_{d,t-1} \cap S_{i,t-1} \neq \emptyset$ **then** ▷ If node i can help
4: $\text{Help}_{S_{d,t-1}} \leftarrow \text{Help}_{S_{d,t-1}} \cup \{i\}$
5: **end if**
6: **end for**
7: $n_{t,i} = 1$ for all $i \in \text{Help}_{S_{d,t-1}}$ ▷ fix n_t to 1 for all candidate nodes
8: **for** $b = 1$ to B **do** ▷ At each sub-band
9: $[\widehat{\boldsymbol{a}}_t]_b \leftarrow \text{argmax}_{i \in \text{Help}_{S_{d,t-1}}} \left\{ \sum_{f=1}^{b-1} I_{t,f,[\widehat{\boldsymbol{a}}_t]_f,d} + I_{t,b,i,d} \right\}$
10: $[\widehat{\boldsymbol{n}}_t]_i = [\widehat{\boldsymbol{n}}_t]_i + 1$ ▷ Increment the number of allocated sub-bands for the node $i = \widehat{a}_{t,b}$
11: **end for**

6.3.1.4 Control information exchange

Fig. 6.6 describes the control information exchange process between the destination and the relay nodes. During the first phase, each source transmits its message at its dedicated sub-band(s) following the vector $\widehat{\boldsymbol{a}}_0$. Since the relays and sources are full-duplex, all nodes will be able to listen to the different messages. During the second phase, at the retransmission time slot t, the following control information exchange procedure occurs:

1. The destination broadcasts its decoding set $S_{d,t-1}$ after the time slot $t-1$ over the feedback broadcast control channel. M bits are broadcasted in this step. If all the sources are included in the set $S_{d,t-1}$ (i.e., the CRC succeeds), the process terminates, and a new frame transmission is initiated. Otherwise, the procedure continues through steps 2-4.

2. Each node which was able to decode at least one source message that is not included in the decoding set of the destination $S_{d,t-1}$ sends one bit on a dedicated unicast forward coordination control channel.

3. The destination allocates the node vector $\widehat{\boldsymbol{a}}_t$ which has the highest mutual information with the destination following the strategy mentioned in the previous subsection. Only the nodes described in step 2 are candidates at this step.

4. Each element $[\widehat{\boldsymbol{a}}_t]_f \in \widehat{\boldsymbol{a}}_t$ retransmits on its dedicated sub-band f. Each node performs SU encoding and chooses to help one source node from its decoding set. We call the vector of chosen nodes to be helped $\widehat{\boldsymbol{b}}_t$.

In the following section, we compare the proposed strategies with three benchmark strategies: the exhaustive search strategy, and the strategies used in [43] and [117]. In [117], the selection strategy is based on minimizing the probability of the common outage event after each retransmission time slot. A common outage event is the event that at least one source node is in outage. Although the individual outage probability is lowered

in this strategy (since $\Pr(\mathcal{O}_{s,T_{\max}}) \leq \Pr(\text{common outage})$), it is not minimized. In [43], the selection strategy is based on choosing the relaying node having the best channel with the destination at each time slot. Here (i.e., in the FDM regime), as we have several sub-bands, the selection using the strategy of [43] is repeated at each different sub-band. The drawback of this method is that it ignores the fact that one sub-band allocation may affect other sub-bands allocations.

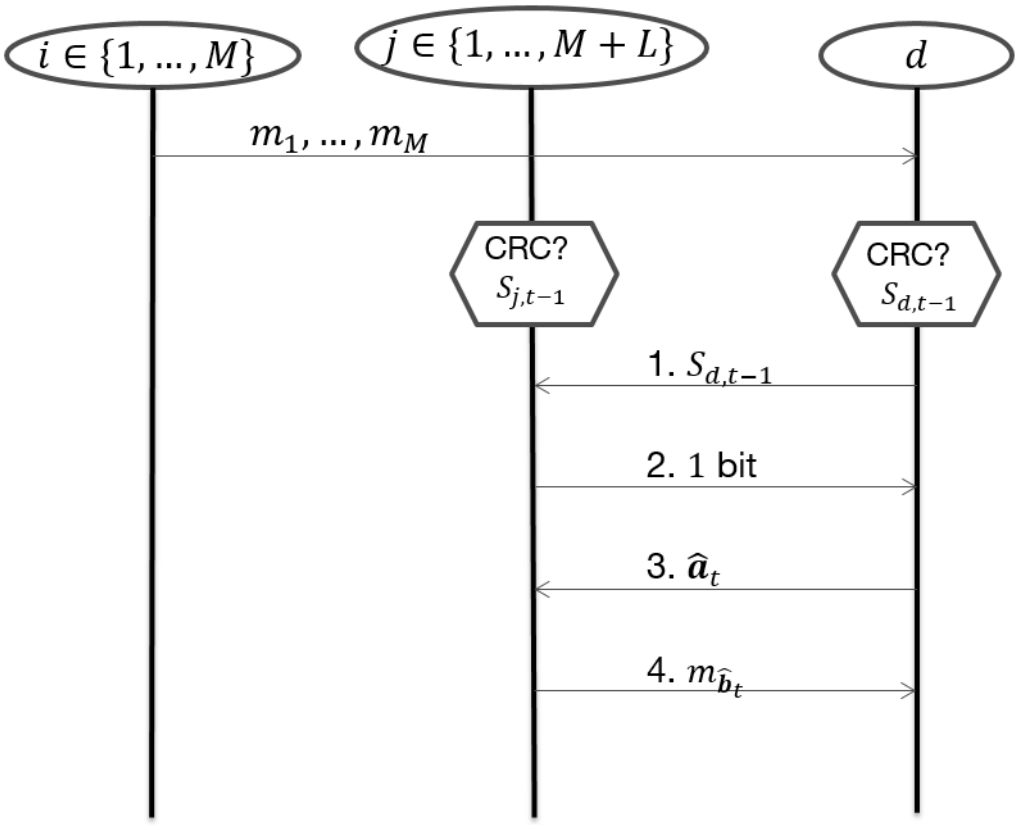


Figure 6.6: Control information exchange for the proposed selection strategies in the FDM orthogonal MAMRN.

6.3.2 Numerical results

In this section, we validate the proposed selection strategies using MC simulations. We consider a (3,3,1)-MAMRN scenario, with 3 sub-bands per time slot. We set $T_{\max}$ to 1 following the goal of reducing the latency, although the results are similar with higher $T_{\max}$. The channel inputs are assumed independent and Gaussian distributed with zero mean and unit variance with $I_{t,f,a,b} = \log_2(1 + \frac{|h_{f,a,b}|^2}{[\boldsymbol{n}_t]_a})$ being the mutual information between the transmitting node a and the receiving node b at a given sub-band f, where $[\boldsymbol{n}_t]_a$ is the number of allocated sub-bands for the transmitting node a at time slot t. Note that other channel inputs might be considered without changing the conclusions of this work. We consider two link configuration scenarios: symmetric and asymmetric.

In the symmetric link configuration (Fig. 6.7), all the links are considered the same (the average SNR of each link is set to γ), and all the rates are fixed to 0.5 [bits per channel use]. On the other hand, in the asymmetric link configuration (Fig. 6.8), we design a scenario where source 1 is in the best radio conditions and source 3 is in the worst radio conditions. Particularly, the links are set as follows: first, the average SNR of each link is set to γ; second, the average SNR of each link that includes source 2 is set to $\gamma - 1$dB and which includes source 3 is set to $\gamma - 1.5$dB; lastly, the average SNR of the link between the sources 2 and 3 is set to $\gamma - 2$dB. Here, the rate allocation of each source is given using the SLA algorithm presented in [43] from the set of possible rates $\{0.75, 1, 1.25, 1.5\}$ [bits per channel use], and thus, the rates are optimized based on the value of γ.

In Fig. 6.7, we see the results of the five strategies in the symmetric link and rate scenario. For the considered SNR range (-5dB to 15dB), strategy 1 is approaching the upper bound with a shift less than 2dB. Similarly, strategy 2 is approaching strategy 1 with approximately the same shift. Both proposed strategies (1 and 2) outperform the strategy used in [43] for all the SNR range with a significant shift. Finally, the strategy of reference [117] outperforms that of reference [43], but still faces a significant shift at low SNR values. In Fig. 6.8, a similar performance is seen over the same SNR range (-5dB till 15dB) for the asymmetric link and rate scenario. The strategy of reference [117] is left out of the simulations as it is only considered for symmetric scenarios. For other strategies, we encounter a similar performance as in the symmetric scenario, where strategies 1 and 2 approach the upper bound and perform similarly, outperforming the strategy used in [43].

We summarize our findings as follows: 1- The selection strategies used in the prior art are not effective in the FDM-based orthogonal MAMRN. 2- The proposed strategy 1 achieves a performance that is close to that of the exhaustive search approach, while including no overhead for full CSI acquisition and reducing the complexity. 3- The sub-optimal strategy 2 represents a good trade-off between complexity/optimality, and can be practically used to reduce the complexity included in strategy 1. 4- the previous findings are valid with symmetric/asymmetric channel realizations and with fixed or optimally allocated rates.

In this section, we presented an FDM-based orthogonal MAMRN. Using a two-phase system, we reduce latency trying to reach the requirements of URLLC. We defined the error events and the spectral efficiency utility metric, and proposed two low-complexity low-overhead selection strategies that aim at maximizing this metric. Then, we presented the control information exchange procedure. The proposed algorithms outperform the strategies used in the prior art and achieve a spectral efficiency that is close to the upper bound while incurring no overhead for the full CSI acquisition and lowering the complexity. In future work, we might investigate the effect of PR of relaying nodes and work on reducing the control exchange process between the destination and the different nodes.

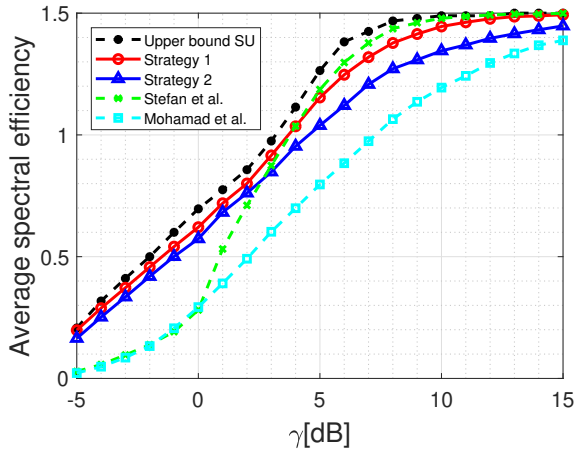


Figure 6.7: ASE with symmetric link and rate configuration for different FDM allocation strategies.

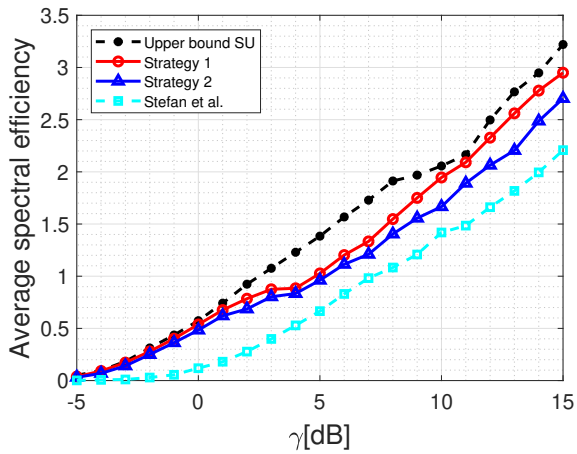


Figure 6.8: ASE with asymmetric link and rate configuration for different FDM allocation strategies.

6.4 Open challenges

Several problems related to the tackled MAMRN remain open challenges that can be tackled in future work. In this section, we shed the light on some of these problems.

6.4.1 PR in FDM domain

In the previous section, we proposed selection strategies that can be used in the FDM orthogonal MAMRN. Nevertheless, the proposal uses SR. To our interest, and following the results of chapter 4 that ensure the significant gain of using PR, one further proposal is to use PR in the FDM regime. In the previous section, the selection strategies proposed aim to maximize the mutual information at the destination. In other words, the destination chooses the vector of relaying nodes which maximizes the mutual infor-

mation. Here, upon using PR, rather than selecting a vector of relaying nodes to help (to send redundancies), we select a vector of source nodes to be helped (by multiple relaying nodes).

The algorithm of selecting the vector of source nodes to be helped at each different sub-bands depends on the channel realization of the different nodes included in the considered network. In addition, the vector of source nodes which gives the highest mutual information depends on the equivalent channel of all relaying nodes helping all sources in the vector of selected source nodes to be helped. Accordingly, we present first the equivalent channel (similar to the way we did in chapter 4 section 1), followed by two selection strategies which select a vector of source nodes which gives the highest equivalent mutual information at the destination.

We denote the channel from each relaying node $j \in \{1, ..., M+L\}$ to the destination at a given t and a given b as denoted $h_{j,d,b}$ and the set of relaying nodes j which can help the source i is denoted Help_i. Accordingly, the destination selects the vector of sources $\widehat{\boldsymbol{s}}_t$ of size B (corresponding to the available B sub-bands) with the best equivalent channel (highest equivalent SNR) to be helped at each sub-band. Then, at each sub-band $f \in B$, all the relaying nodes which decoded the chosen source $[\widehat{\boldsymbol{s}}_t]_f$ retransmit redundancies accordingly. At a given retransmission time slot t, at a given sub-band b, and for a given set of helping relaying nodes Help_i, the equivalent SNR for helping the source i can be written as:

- **Case 1:** each relaying node $j \in \{1, ..., M+L\}$ does not know the channel $h_{j,d,b}$

$$\text{SNR}_{i,t,b} = \mathcal{P} \left| \sum_{j \in \text{Help}_i} \frac{h_{j,d,b}}{\sqrt{[\boldsymbol{n}_t]_j}} \right|^2 / N_0, \tag{6.12}$$

  where $\mathcal{P}$ is the transmission power of each node, N_0 is the noise spectral density, and $h_{j,d,b}$ is the channel whose power is normalized to 1. We recall that $[\boldsymbol{n}_t]_j$ refers to the number of sub-bands allocated for the node $j \in \mathcal{N}$ at time slot t.

- **Case 2 "Equal Gain Combining (EGC)":** each node $j \in \{1, ..., M+L\}$ knows the phase Φ_j of its channel toward the destination $e^{-\mathrm{i}\Phi_j} = h^*_{j,d,b}/|h_{j,d,b}|$ with $\mathrm{i}^2 = -1$

$$\text{SNR}_{i,t,b} = \mathcal{P} \left(\sum_{j \in \text{Help}_{i,t,b}} \left| \frac{h_{j,d,b}}{\sqrt{[\boldsymbol{n}_t]_j}} \right| \right)^2 / N_0. \tag{6.13}$$

- **Case 3:** Assuming that the subset $\text{Help}_i = \text{Help1}_i \bigcup \text{Help2}_i$ breaks down into a subset Help1_i of nodes knowing their phase with the destination (sent by the destination) and Help2_i not knowing it, in this case, SNR_i for $i \in \{1, ..., M\}$ is written as:

$$\text{SNR}_{i,t,b} = \mathcal{P} \left| \sum_{j \in \text{Help1}_i} \left| \frac{h_{j,d,b}}{\sqrt{[\boldsymbol{n}_t]_j}} \right| + \sum_{j \in \text{Help2}_i} \frac{h_{j,d,b}}{\sqrt{[\boldsymbol{n}_t]_j}} \right|^2 / N_0. \tag{6.14}$$

If the node i is selected, the transmission of each node belonging to Help1_i will be multiplied by $e^{-\mathrm{i}\Phi_j}$(coherent reception for the nodes belonging to Help1_i).

Now, at a given time slot t, the destination selects the vector $\boldsymbol{s}_t \in \{1, \ldots, M\}^B$ following:

$$\widehat{\boldsymbol{s}}_t \in \underset{\boldsymbol{s}_t \in \{\overline{S}_{d,t-1}\}^B}{\operatorname{argmax}} \left\{ \sum_{f=1}^{B} I_{t,f,[\boldsymbol{s}_t]_f,d} \right\}. \tag{6.15}$$

In the proposed strategy, the destination passes through all the possible vectors of sources of size B taken from the non-decoded source messages. One drawback of the proposed strategy is that the number of vectors might be huge with a high number of sources and/or sub-bands (for big M and/or B). Accordingly, a lower-complexity choice would be to select the vector of sources sequentially, sub-band by sub-band. At a given time slot t, at each sub-band b, we choose the source $s_{t,b}$ following:

$$[\widehat{\boldsymbol{s}}_t]_f \in \underset{s \in \{\overline{S}_{d,t-1}\}}{\operatorname{argmax}} \left\{ \sum_{f=1}^{b-1} I_{t,f,[\widehat{\boldsymbol{s}}_t]_f,d} + I_{t,b,s,d} \right\}. \tag{6.16}$$

Note that $I_{t,f,[\boldsymbol{s}_t]_f,d}$ with $i \in \{1, \ldots, M\}, f \in \{1, \ldots, B\}$, and $t \in \{0, \ldots, T_{\max}\}$ depends on the number of sub-bands $[n_t]_j$ allocated to each node j belonging to Help_i (having decoded source i) since the power per node is shared in frequency and cannot exceed the maximum power $\mathcal{P}$. As a result, it needs to be recomputed if one of these numbers changes. The complete algorithms can be written as in the following two algorithms.

As a comparison with SR in FDM (the previous section), we notice that the generalization to PR was quite simple. Comparing the equations (6.15, 6.16) with the equations (6.10, 6.11), we see that the difference is only in choosing a vector of sources to be helped rather than a vector of relaying nodes to help. In other words, the difference is seen in the way we calculate the equivalent mutual information, wherein the proposal with PR, we aim to exploit the DoF of all the available relaying nodes. Similarly, the algorithms of the two proposed strategies are quite similar to Algorithms 14 and 15, and the control exchange process is quite similar to the exchange process presented in 6.3.1.4 and in Fig. 6.6 (omitted for brevity).

Unfortunately, we did not yet prepare any numerical analysis for PR in the FDM regime. We assume that similar to the TDM case, the PR method will introduce a significant gain compared to the SR method. Also, we hope that using PR would reduce the gap between the upper bound and the two SR proposed strategies in the FDM regime. This analysis is to be investigated in the near future. Another direction would be to investigate PR with MU encoding case. Although the intuition of PR followed the SU encoding case, an interesting problem would be the generalization of PR with MU encoding case. That case is more complicated than PR in SR method and is also left as a future work.

Further generalizations of our work to the FDM regime are possible. One interesting problem to investigate in the FDM orthogonal MAMRN is the cost of the control exchange process. Similarly to the work presented in chapter 4 section 2, future work

would be how to propose a similar method in the FDM regime with the aim of reducing the overhead of the control exchange process. Another future work would be proposing a joint allocation that can be applied in FDM orthogonal MAMRN. In fact, the generalization of the contributions of chapter 5 to FDM is straight forward. Nevertheless, in FDM, the dimension of the selected vector is higher (due to the B sub-bands available). This leads to a critical complexity problem that needs novel and different proposals to avoid. In a similar manner, and as mentioned in chapter 5, an important future work is to propose a joint allocation that does not depend on the full CSI acquisition. In fact, and due to the need for the full CSI, the contributions of chapter 5 are limited to slow-changing radio conditions scenarios (e.g., low mobility cases), and thus, interesting work is to propose a CDI-dependent joint allocation.

6.4.2 Selection strategies for multiple antennas receivers

6.4.2.1 Control exchange

In chapter 3, we used the selection strategy proposed in the prior art [43]. In chapter 4, we proposed some novel selection strategies based on PR. All these strategies assume that the destination has only 1 receiving antenna. In particular, when using PR with EGC, the relaying nodes multiply its redundancy version by $e^{-\mathrm{i}\Phi_j}$ (the conjugate of the channel divided by its norm). Upon the presence of multiple antennas at the receiver, EGC becomes inapplicable, and novel strategies are needed.

In a given orthogonal MAMRN configuration, the destination which is a base station can be possibly equipped with Ant > 1 receive antennas. In this configuration, the co-phasing or the technique of EGC allows the coherent addition of the channels only for a single reception antenna among the Ant antennas. Thus, the technique of EGC does not make it possible to maximize the global SNR resulting from the reception from the Ant antennas.

From a control information exchange point of view between the destination and the nodes, the first two steps of the control exchange seen in section 1 of chapter 4 remain the same (check Fig. 4.2). First, the destination broadcasts an ACK/NACK bit to all the relaying nodes. Then each node transmits to the destination, the clues of the sources that they can help. On this basis, the destination chooses the source to be helped for the current retransmission $\widehat{s}_i$ then sends the vector $\mathbf{v}_i \in \mathbb{C}^{|\mathrm{Help}_i|}$, a vector of complex coefficients containing the coefficients to be applied for each node having decoded $\widehat{s}_i$ in order to maximize the SNR at the destination (MRT) and the vector $\mathbf{w}_i \in \mathrm{Help}_i^{|\mathrm{Help}_i|}$, where $|\mathrm{Help}_i|$ is the cardinality of the set Help_i, which establishes the correspondence between the nodes of Help_i and the coefficients to apply of $\mathbf{v}_i$. Thus, the node $[\mathbf{w}_i]_j \in \mathrm{Help}_i$ applies the complex coefficient $\mathbf{v}_{i,j}$ for all $j \in \{1, \ldots, |\mathrm{Help}_i|\}$ to its transmission based on the receipt of $\mathbf{w}_i$ and Help_i.

Example: Suppose that the nodes $\mathrm{Help}_i = \{1, 4, 5\}$ have decoded $\widehat{s}_i$, then $\mathbf{w}_i = [1, 4, 5]^T$ with $[\mathbf{w}_i]_1 = 1, [\mathbf{w}_i]_2 = 4$, and $[\mathbf{w}_i]_3 = 5$. The destination transmits the vector $\mathbf{v}_i$ and $\mathbf{w}_i$, and based on the reception of these vectors, the node $[\mathbf{w}_i]_j$ transmits $m_{\widehat{s}_i}$ applying the coefficient $v_{i,j}$ for all $j \in \{1, 2, 3\}$, i.e.,:
node 1: $m_{\widehat{s}_i} \times v_{i,1}$

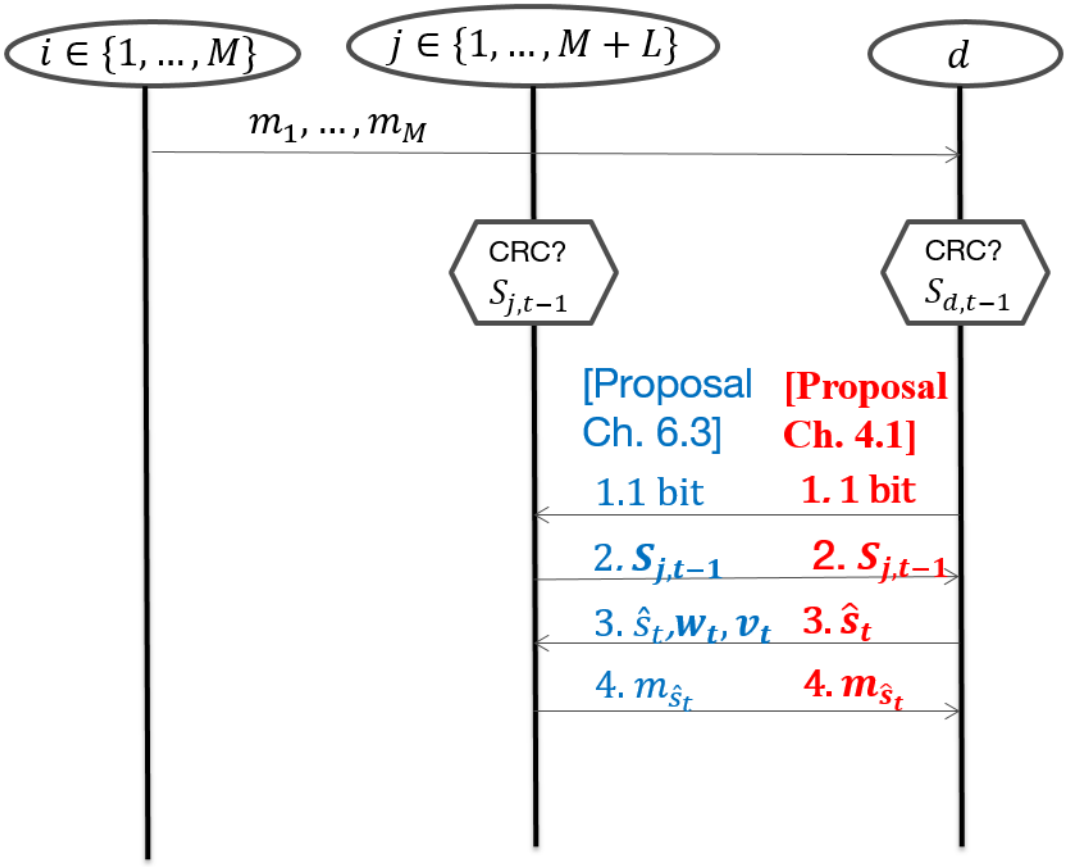


Figure 6.9: Control exchange process corresponding to: multiple antennas (in blue) and the single antenna (in bold red).

node 4: $m_{\widehat{s}_i} \times v_{i,4}$
node 5: $m_{\widehat{s}_i} \times v_{i,5}$.

6.4.2.2 Selection strategy: Maximum Ratio Transmission (MRT)

As a reminder, the LA corresponds to the allocation per source of a bit rate (rate) defined by a modulation and a coding rate. Each retransmission associated with a source uses the modulation assigned during LA. On the basis of the reception of the vectors $\mathbf{w}_i$ and $\mathbf{v}_i$, each node $[\mathbf{w}_i]_j$ transmits the symbol $[\mathbf{v}_i]_j m_{s_i}$ for the considered round. It turns out that the model received at the destination can be written

$$\mathbf{y} = \mathbf{H}_i \mathbf{v}_i m_{s_i} + \mathbf{z}_i \tag{6.17}$$

where:

- $\mathbf{y} \in \mathbb{C}^F$ represents the vector of Ant samples received by the Ant antennas.
- $\mathbf{H}_i \in \mathbb{C}^{F \times \mathrm{Help}_i}$ is the MIMO channel connecting the Help_i nodes with the Ant antennas with $[\mathbf{H}_i]_{r,j}$ representing the channel connecting the node $[\boldsymbol{w}_i]_j$ and the antenna r of the destination denoted thereafter $h_{r,[\boldsymbol{w}_i]_j}$.
- $\mathbf{z}_i$ is a vector of noise plus interference samples whose covariance is Cov_i.

It is well known by the prior art [131] that the vector $\mathbf{v}_i$ which maximizes the SNR is the eigenvector of $\mathbf{H}_i^T \mathrm{Cov}_i^{-1} \mathbf{H}_i$ is associated with the maximum eigenvalue $\lambda_i = \lambda_{\max}(\mathbf{H}_i^T \mathrm{Cov}_i^{-1} \mathbf{H}_i)$, i.e., $\mathbf{H}_i^T \mathrm{Cov}_i^{-1} \mathbf{H}_i \mathbf{v}_i = \lambda_i \mathbf{v}_i$ where λ_i is the maximum eigenvalue. The associated SNR is then maximized $\mathrm{SNR} = |\lambda_i|^2$. Then, the base station knowing for all the sources $s_l : l \in \{1, \ldots, M\}$, the nodes having decoded this source Help_i and the channels $h_{r,n_{l,j}}$ for all $j \in \{1, \ldots, |\mathrm{Help}_l|\}$, chooses the source s_i to be helped for a given retransmission following:

$$i = \underset{j \in \{1,\ldots,M\}}{\operatorname{argmax}} \ \lambda_{\max}(\mathbf{H}_i^T \mathrm{Cov}_i^{-1} \mathbf{H}_i) \tag{6.18}$$

and then sends the vectors $\boldsymbol{w}_i$ and $\mathbf{v}_i$. Note that for complexity reasons, the covariance Cov_i can be approximated by a multiple matrices of the identity. Moreover, the complex vector $\mathbf{v}_i$ must in practice be quantized over a finite number of bits.

The presented proposal is not yet investigated numerically. In addition, the generalization to FDM orthogonal MAMRN is not yet proposed and considered as a near future work. Further interesting idea is to target the case of multiple antennas at the transmitter side and not only at the receiver side.

6.4.3 Reconfigurable intelligent surface

One interesting method to improve the communication is to use Reconfigurable Intelligent Surface (RIS) elements. The RIS topic is widely investigated [132, 133] and is seen as a hot topic in wireless communication nowadays [134, 135]. Citing [136], an RIS is an artificial surface, made of electromagnetic material, that is capable of customizing

the propagation of the radio waves impinging upon it. The reason that we mention RIS here is that it shares some of the concepts and notions of relaying. In fact, several works compared relaying and RIS networks, shedding light on the limitations and the advantages of each of the cooperative networks. In [136], we see an interesting survey that compares the usage of RIS and relaying. The authors present the similarities and differences between the two notions of cooperative communication, following the different factors such as hardware complexity, spectral efficiency, power budget, and noise. The takeaway message of this work is that the RIS-aided transmission may outperform the relay-aided transmission if the size of the RIS is sufficiently large.

Thus, following this reference, as well as other references (check for example [137, 138, 139, 140]), we see that going to the RIS domain would be interesting, and we believe that several contributions proposed in this manuscript could be applicable to RIS networks. In addition, we see that the use of RIS with relaying networks is a DoF that would lead to significant improvements.

Finally, and besides the mentioned perspectives, we mention here some directions that we could further investigate. First, NOMA cooperative network is seen as interesting due to its theoretical gains in capacity. Second, investigating non-centralized networks is another direction that would be analyzed with the aim of reducing the different control exchanges between the different networks. In addition, analyzing the orthogonal MAMRN with non-perfect feedback and its effect on the performance is also interesting.

Chapter 7

Conclusion

Cooperative communication is seen as an innovative concept that allows the enhancement of efficiency of multi-terminal wireless networks. The focus of this thesis is set on two main important aspects of the TDM orthogonal MAMRN: the design of LA algorithms that are applicable in slow and fast changing radio channel conditions, as well as the design of relaying nodes scheduling algorithms that exploit the multi-path diversity of the relaying nodes. As compared to the prior art, these algorithms outperform the performance of the previous works by improving the practicality, reducing the complexity, increasing the efficiency, and reducing the overhead.

In chapter 3, LA algorithms based on the BRD methods are proposed. The algorithms presented tackle both the rate and the channel use allocation. In addition, they are applicable in both MU and SU encoding schemes. In order to reduce the complexity of the proposed algorithms, the rate and the channel use ratio of each source are first determined by using the "Genie-Aided" assumption which consists in considering for a given source that all the other ones are known to the relaying nodes and the destination. In a second step, an iterative correction step is applied. The resulting LA allocations offer a tractable complexity for the different scenarios investigated. In addition, it is shown that there is a significant impact of user cooperation on the spectral efficiency as well as exploring the DoF of the time slot duration associated with each source during the first transmission phase. The performance of MU and SU encoding are seen alike, and thus, it ensures the importance of SU being a practical low-complexity method. In the last section of this chapter, an intermediate LA strategy is proposed. The idea of this strategy is to outperform the SLA strategy by using a FLA with partial CSI. The strategy builds its selection by exploiting the knowledge of the CSI of the direct with the destination. Using this method, it is seen that the performance outperforms the SLA strategy and approaches the FLA with no need for a heavy overhead.

In chapter 4, a novel selection strategy for orthogonal MAMRN is proposed. Rather than selecting a single relaying node to send redundancies at a given retransmission time slot, the PR strategy allows several relaying nodes to send redundancies for a common source node selected to be helped. The proposed strategy outperforms the prior art (i.e., SR) by making use of the power budget available at each relaying node included in the system. Furthermore, the overhead of the control exchange process is tackled. Using estimation of the number of retransmissions needed for every source to be

correctly decoded, a low-complexity low-overhead selection strategy which is applicable without a heavy control exchange process is presented. It is seen using MC simulations that the proposed algorithms outperform the performance of the prior art. Specifically, the PR strategy outperforms the SR strategy. In addition, using the low-overhead selection strategy significantly improves the performance by avoiding unnecessary control exchange processes.

In chapter 5, a FLA joint strategy for the rate and the relaying nodes allocation is studied. The proposed strategy leads to the highest possible spectral efficiency. It first passes through all the possible relaying nodes allocation, and then, for each allocation, it determines the highest rate allocation for the sources in the network. This strategy makes it possible to choose the joint allocation which gives the highest spectral efficiency. The proposal solves two main issues seen in the prior art: 1- it removes the sub-optimality of solving the two problems separately (the rate allocation problem and the selection strategy problem), and 2-, it removes the need of an exhaustive search over a discrete finite set of possible rates that used to limit the practicality of the BRD proposed in the prior art.

Finally, in chapter 6, future directions and open challenges are presented. In learning framework, the MAB framework is seen as a possible direction to solve the rate allocation problem when no CDI information is available at the scheduler. In addition, the SUCB1 algorithm is seen as an interesting solution to the exploration-exploitation problem of an online learning problem. On the other hand, the FDM-based orthogonal MAMRN is presented with the needed outage and utility metric events. Two novel preliminary algorithms for relaying nodes scheduling are presented and seen to have a good performance.

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Appendix

Appendix A: Proof of theorem 4.3.1 (proof of the derived upper bound)

First, since $x_i^a(t) \leq x_i^b(t)$ for every t, then, it is sufficient to prove the theorem for $x_i^a(t)$. Second, we define $\overline{y}_i^a(t)$ as:

$$\overline{y}_i^a(t) = \frac{\overline{y}_i^a(t - X(t))(\alpha J_{i,d}(t - X(t))) - \alpha \sum_{l=t-X(t)}^{t-1} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_t = i\}}}{\alpha J_{i,d}(t)} \tag{1}$$

The only difference between $y_i^a(t)$ and $\overline{y}_i^a(t)$ is that we are subtracting $J_{i,d}(l)$ instead of $J_{i,d}(t - X(t))$. As we know that $J_{i,d}(l) \geq J_{i,d}(l - X(t))$ for all $l \in \{t - X(t), \ldots, t-1\}$, we deduce that $y_i^a(t) \geq \overline{y}_i^a(t)$. Now, $\overline{y}_i^a(t)$ can be rewritten as:

$$\overline{y}_i^a(t) = \frac{R_i - I_{i,d} - \alpha \sum_{l=1}^{t-1} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_t = i\}}}{\alpha J_{i,d}(t)} \tag{2}$$

In order to be sure that we have no outage for source i, we know from the outage event (equation (4.6)) that the following inequality should be satisfied:

$$R_i \leq I_{i,d} + \alpha \sum_{l=1}^{T_{\max}} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_l = i\}} \tag{3}$$

Thus, at a given retransmission time slot t, if a source node is selected in the following time slots $x_i(t)$ times, we can write:

$$\sum_{l=t}^{T_{\max}} \mathbf{1}_{\{\widehat{s}_l = i\}} = x_i^a(t) \geq y_i^a(t) \tag{4}$$

$$\sum_{l=t}^{T_{\max}} \mathbf{1}_{\{\widehat{s}_l = i\}} \geq \overline{y}_i^a(t) = \frac{R_i - I_{i,d} - \alpha \sum_{l=1}^{t-1} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_t = i\}}}{\alpha J_{i,d}(t)} \tag{5}$$

$$R_i \leq I_{i,d} + \alpha \sum_{l=1}^{t-1} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_l = i\}} + \alpha J_{i,d}(t) \sum_{l=t}^{T_{\max}} \mathbf{1}_{\{\widehat{s}_l = i\}} \tag{6}$$

$$R_i \leq I_{i,d} + \alpha \sum_{l=1}^{t-1} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_l = i\}} + \alpha \sum_{l=t}^{T_{\max}} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_l = i\}} \tag{7}$$

$$R_i \leq I_{i,d} + \alpha \sum_{l=1}^{T_{\max}} J_{i,d}(l)\mathbf{1}_{\{\widehat{s}_l = i\}} \tag{8}$$

Equation (4) is obtained using the definition of the ceiling function. Equation (5) follows using the fact that $y_i^a(t) \geq \overline{y}_i^a(t)$ and using the definition of $\overline{y}_i^a(t)$. Equation (6) is obtained after a simple reorganization. Equation (7) is obtained using the fact that $J_{i,d}(l) \geq J_{i,d}(t)$ for all $t \leq l$. Equation (8) is obtained by making the two summations one big summation, and leads us to the needed inequality. Finally, we recall that as we proved the theorem for $x_i^a(t)$, we directly deduce that the result holds for $x_i^b(t)$.

Appendix B: Proof of theorem 6.2.1 (proof of the expected regret of the UCB1 algorithm)

The proof to be presented can be found in [130] and is presented here for completeness. We start by recalling the Chernoff-Hoeffding inequality. Let $X_1, \ldots, X_j$ be i.i.d random variables which are all bounded by the interval [0, 1]. The sample mean is $\overline{X}_j = \frac{1}{j}\sum_{q=1}^{j} X_q$, then for $a > 0$, we have

$$\Pr\left(\mathbb{E}(X) > \overline{X}_j + a\right) \leq e^{-2ja^2},$$

$$\Pr\left(\mathbb{E}(X) < \overline{X}_j - a\right) \leq e^{-2ja^2}.$$

Now, for a given *super arm* i, we set the target as $a(i,j) = \sqrt{2\ln j/\mathrm{nb}_i}$ where nb_i is the number of times *super arm* i is selected and j is the total number of plays till now. As a result, we reach

$$\Pr(\overline{X}_j > \mathbb{E}(X) + a) \leq j^{-4},$$
$$\Pr(\overline{X}_j < \mathbb{E}(X) - a) \leq j^{-4}.$$

Next, we upper bound nb_i. Recall that the random variable $\mathrm{Dec}(j)$ has as its value the index of the *super arm* selected and $[\mathrm{Dec}(j) = i]$ is the indication function which gives 1 when the selected arm at RL round j is the *super arm* i (and zero otherwise). Now,

$$\mathrm{nb}_i(t) = 1 + \sum_{j=n^M_{\mathrm{MCS}}}^{t} [\mathrm{Dec}(j) = i]$$

$$\leq m + \sum_{j=n^M_{\mathrm{MCS}}}^{t} [\mathrm{Dec}(j) = i \text{ and } \mathrm{nb}_i(j-1) \geq m]$$

$$\leq m + \sum_{j=n^M_{\mathrm{MCS}}}^{t} \big[\overline{X}_i + a(i,j-1) \geq \overline{X}^*_i + a(i^*, j-1)$$
$$\text{and } \mathrm{nb}_i(j-1) \geq m]$$

$$\leq m + \sum_{j=n^M_{\mathrm{MCS}}}^{t} \big[\max_{m \leq s < j} \overline{X}_{i,s} + a(s, j-1)$$
$$\geq \min_{0 < s' < j} \overline{X}^*_{s'} + a(s', j-1)]$$

$$\leq m + \sum_{j=1}^{+\infty}\sum_{s=m}^{j-1}\sum_{s'=1}^{j-1} \left[\overline{X}_{i,s} + a(s,j) \geq \overline{X}^*_{s'} + a(s',j)\right]$$

where the second line means that we are picking *super arm* i in RL round j and we have already played this arm at least m times. The third line comes from the fact that saying that we have picked *super arm* i in RL round j means that the upper bound for *super arm* i exceeds the upper bound for every other *super arms*. In particular, this means its

upper bound exceeds the upper bound of the best *super arm* (and j might coincide with the best action, but that's fine). The fourth line comes from the following fact. If the upper bound of *super arm* i exceeds that of the optimal choice, it is also the case that the maximum upper bound for action i we have seen after the first m trials exceeds the minimum upper bound we have seen on the optimal *super arm* ever. But, on RL round j we do not know how many times we have played the optimal *super arm*, nor do we even know how many times we have played *super arm* i (except that it's more than m). So we try all possibilities and look at the minimum and the maximum. We denote by $\overline{X}_{i,s}$ the random variable for the empirical mean after playing action i a total of s times, and $\overline{X}^*_s$ the corresponding quantity for the optimal *super arm*. Realizing everything in notation, the final line holds due to the following: at each j for which the max is greater than the min, there will be at least one pair s, s' for which the values of the quantities inside the max/min will satisfy the inequality. And so, even worse, we can just count the number of pairs s, s' for which it happens. That is, we can expand the event above into the double sum which is at least as large. For the first summation, we increase the sum to go from $j = 1$ to ∞. This means that we can replace $j - 1$ with j and thus the final line is reached.
Now, when the event $\overline{X}_{i,s} + a(s, j) \geq \overline{X}^*_{s'} + a(s', j)$ is actually happened, one of the following must hold:

$$(1) : \overline{X}^*_{s'} \leq \theta^* - a(s', j)$$

$$(2) : \overline{X}_{i,s} \geq \theta_i + a(s, j)$$

$$(3) : \theta^* < \theta_i + 2a(s, j)$$

where θ^* and θ_i are the average reward of the optimal *super arm* and the *super arm* i. Using union bound, bounding (1) and (2) by j^{-4}, and making (3) always false by choosing $s \geq m > 8 \ln t/\Delta_i^2$, we reach:

$$\mathbb{E}[\mathrm{nb}_i(t)] \leq \left\lceil \frac{8 \ln t}{\Delta_i^2} \right\rceil + \sum_{j=1}^{+\infty} \sum_{s=m}^{j} \sum_{s'=1}^{j} 2j^{-4}$$

$$\leq \frac{8 \ln t}{\Delta_i^2} + 1 + \sum_{j=1}^{+\infty} \sum_{s=1}^{j} \sum_{s'=1}^{j} 2j^{-4}$$

$$= \frac{8 \ln t}{\Delta_i^2} + 1 + 2 \sum_{j=1}^{+\infty} j^{-2} = \frac{8 \ln t}{\Delta_i^2} + 1 + \frac{\pi^2}{3}$$

where the last equality uses the classic solution to Basel's problem, and the proof is reached by bounding the total regret using

$$\sum_{j:\theta_j < \theta^*} \Delta_j \mathbb{E}[\mathrm{nb}_j(t)].$$