THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Coordinated MultiPoint Transmission with Incomplete Information

Precoding and scheduling algorithms for efficient backhauling in cellular networks

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Doktorsavhandlingar vid Chalmers Tekniska Högskola
ISBN 978-91-7597-257-2
Series No. 3938
ISSN 0346-718X

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Front Cover: The cover page represents the precoding algorithms such as particle swarm optimization, successive second order cone programming being executed in a Cloud-based Radio Access Network where centralization and virtualization would be possible in future cooperative networks. These algorithms also achieve efficient backhauling as depicted with the "0" in the aggregated channel matrix **H** and being able to have the corresponding "0" in the precoding matrix **W**.

This thesis has been prepared using LyX.
Printed by Chalmers Reproservice
Gothenburg, Sweden, October 2015.

To *<Your Name Here>*

Abstract

The demand for higher data rates and efficient use of various resources has been an unquenchable thirst across different generations of cellular systems, and it continues to be so. Aggressive reuse of frequency resources in cellular systems gives rise to intercell interference which severely affects the data rate of users at the cell-edge. In this regard, coordinated multipoint (CoMP) is one of the ways to mitigate interference for these cell-edge users. In the downlink, joint transmission (JT) CoMP involves the cooperation of two or more geographically separated base stations to jointly transmit to these users by treating the interfering signal as useful signal.

To realize the gains of JT-CoMP in a frequency division duplex system, the users need to feedback the channel state information (CSI) to its serving base station. This needs to be aggregated at the central coordination node for mitigating interference via precoding. However, the process of aggregation poses tremendous burden on the backhaul. One of the ways to reduce this burden is to use relative thresholding, where the users feed back the CSI of only those links that fall within a threshold relative to the strongest base station. The side effect of thresholding results in limited or incomplete CSI for precoding. Efficient backhauling is achieved when the quantity of CSI available for certain links at the central coordination node be correspondingly equivalent to the quantity of precoding weights generated for the same links. The incomplete CSI poses problems for the simple zero-forcing precoder to mitigate interference and also achieve efficient backhauling.

In this thesis, the main problem of simultaneously mitigating interference and achieving efficient backhauling is addressed with a layered approach. Our physical (PHY) layer precoding approach solves the problem and allowes the medium access control (MAC) layer scheduler to be simple. The PHY layer precoding algorithms such as successive second order cone programming are proposed using convex optimization in [**Paper A**], and particle swarm optimization based on stochastic optimization is proposed in [**Paper B**]. Also, we exploit the use of long term channel statistics for the incomplete CSI and characterize the promising performance of the proposed precoder using numerical bounds. Based on our results, we observed that the swarm algorithm struggles with the increase in the problem size. The MAC layer approach exploits scheduling to solve the problem keeping a simple PHY layer zero-forcing precoder [**Paper C**]. Our proposed constrained scheduling approach provides the best tradeoff in terms of average sum rate per backhaul use compared to other MAC layer techniques. These results can be applied to a variant of the *baseband hotel*, a centralized architecture.

In a distributed architecture, the CSI is exchanged periodically between the base stations over the backhaul for JT-CoMP. Any CSI feedback update from the user must be immediately exchanged over the backhaul to preserve the gains of JT-CoMP. We propose an improved decentralized local precoder design where the base station with new local CSI can design the local precoding weights in between the CSI exchange between base stations [**Paper D**]. With our approach some of the gains of JT-CoMP can still be preserved without the need to burden the backhaul.

Keywords: backhauling, centralized, coordinated multipoint, convex optimization, decentralized, efficient backhauling, joint transmission, particle swarm optimization, precoding, scheduling, stochastic optimization

List of included publications

This PhD thesis is based on the following papers. They are:

[A] T.R. Lakshmana, A. Tölli, R. Devassy, and T. Svensson, "Precoder Design with Incomplete Feedback for Joint Transmission," *accepted in IEEE Transactions on Wireless Communications,* Oct. 2015.

[B] T.R. Lakshmana, C. Botella, and T. Svensson, "Partial Joint Processing with Efficient Backhauling using Particle Swarm Optimization," *EURASIP Journal of Wireless Communications and Networking.*, vol. 2012, 2012.

[C] T.R. Lakshmana, J. Li, C. Botella, A. Papadogiannis and T. Svensson, "Scheduling for Backhaul Load Reduction in CoMP," in *proc. IEEE Wireless Communications and Networking Conference* (WCNC), Apr. 2013.

[D] T.R. Lakshmana, A. Tölli, and T. Svensson, "Improved Local Precoder Design for JT-CoMP with Periodical Backhaul CSI Exchange," *resubmitted to IEEE Communications Letters,* Oct. 2015.

List of additional related publications

[a] O. Aydin, Z. Ren, M. Bostov, T.R. Lakshmana, et al., EU FP7 INFSO-ICT-317669 METIS, "D4.2 Final report on trade-off investigations", Aug. 2014.

[b] T. R. Lakshmana, Rikke Apelfröjd, T. Svensson, and M. Sternad, "Particle swarm optimization based precoder in CoMP with measurement data," *5th Nordic Workshop Syst. and Netw. Optimization for Wireless (SNOW)*, Apr. 2014.

[c] R. Fantini, A. Santos, E. de Carvalho, N. Rajatheva, P. Popovski, P. Baracca, D. Aziz, J. Hoydis, F. Boccardi, T. Svensson, J. Li, T.R. Lakshmana, et al., EU FP7 INFSO-ICT-317669 METIS, "D3.2 First performance results for multi-node/multi-antenna transmission technologies", Apr. 2014.

[d] T.R. Lakshmana, B. Makki, and T. Svensson, "Frequency Allocation in Non-Coherent Joint Transmission CoMP Networks," in *proc. IEEE Intl. Conf. Commun.*, pp. 610–615, Jun. 2014.

[e] O. Aydin, S. Valentin, Z. Ren, T.R. Lakshmana, et al., EU FP7 INFSO-ICT-317669 METIS, "D 4.1 Summary on preliminary trade-off investigations and first set of potential network-level solutions", Jul. 2013.

[f] E. de Carvalho, P. Popovski, H. Thomsen, F. Boccardi, R. Fantini, N. Rajatheva, P. Baracca, J. Hoydis, D. Aziz, T. Svensson, A. Papadogiannis, J. Li, T.R. Lakshmana, et. al. EU FP7 INFSO-ICT-317669 METIS, "D3.1 Positioning of multi-node/multi-antenna technologies", Apr. 2013.

[g] V. D'Amico, B. Melis, H. Halbauer, S. Saur, N. Gresset, M. Khanfouci, W. Zirwas, D. Gesbert, P. de Kerret, M. Sternad, R. Apelfröjd, M.L. Pablo, R. Fritzsche, H. Khanfir, S.B. Halima, T. Svensson, T.R. Lakshmana, et al., EU FP7 INFSO-ICT-247223 ARTIST4G, "D1.4 Interference Avoidance Techniques and System Design", Jul. 2012.

[h] T. R. Lakshmana, A. Papadogiannis, J. Li, and T. Svensson, "On the Potential of Broadcast CSI for Opportunistic Coordinated MultiPoint Transmission," in *proc. IEEE Intl. Symposium Pers., Indoor and Mobile Radio Commun.*, Sep. 2012.

[i] T.R. Lakshmana, C. Botella, and T. Svensson, "Partial Joint Processing with Efficient Backhauling in Coordinated MultiPoint Networks," in *proc. IEEE Veh. Technol. Conf.*, Jun. 2012.

[j] C. Botella, L. Brunel, C. Ciochina, L. Cottatellucci, V. D'Amico, P. de Kerret, D. Gesbert, J. Giese, N. Gresset, J. Guillet, H. Halbauer, X. Jiang, H. Khanfir, T.R. Lakshmana, et al., EU FP7 INFSO-ICT-247223 ARTIST4G, "D1.3 Innovative scheduling and cross-layer design techniques for interference avoidance", Mar. 2011.

[k] V. D'Amico, H. Halbauer, D. Aronsson, C. Botella, S. Brueck, C. Ciochina, T. Eriksson, R. Fritzsche, D. Gesbert, J. Giese, N. Gresset, T.R. Lakshmana, et al., EU FP7 INFSO-ICT-247223 ARTIST4G, D1.2 Innovative advanced signal processing algorithms for interference avoidance", Dec. 2010.

[l] T.R. Lakshmana, C. Botella, T. Svensson, X. Xu, J. Li, X. Chen, "Partial Joint Processing for Frequency Selective Channels". in *proc. IEEE Veh. Technol. Conf.*, Sep. 2010.

[m] A.T. Toyserkani, T.R. Lakshmana, E.G. Ström, A. Svensson, "A Low-Complexity Semi-Analytical Approximation to the Block Error Rate in Nakagami-m Block Fading Channels", in *proc. IEEE Veh. Technol. Conf.*, Sep. 2010

Preface

> There are two kinds of truth: the truth that lights the way and the truth that warms the heart. The first of these is science, and the second is art. Neither is independent of the other or more important than the other. Without art science would be as useless as a pair of high forceps in the hands of a plumber. Without science art would become a crude mess of folklore and emotional quackery. The truth of art keeps science from becoming inhuman, and the truth of science keeps art from becoming ridiculous.
>
> — Raymond Thornton Chandler
> writer (23 Jul. 1888-1959)

It gives me immense pleasure to present this doctoral thesis. This thesis has been organized in three parts. In the first part, coordinated multipoint (CoMP) transmission is introduced in the backdrop of 5G in chapter 1. This part leads into the problem addressed in this thesis, enveloping the OSI model for efficient backhauling in chapter 2. In chapter 3, the tools used to achieve efficient backhauling are discussed. Finally, this part concludes with the challenges in realizing CoMP in practice and some visions for future work. In the second part of the thesis, the papers that form this thesis are appended. The final part is the Appendix that complements the material covered in this work.

In light of "Sita sings the blues" and using the tax payers money to fund this work, I have chosen to make this thesis available under **CC0** [1]. I hope you enjoy reading this thesis as much as I have enjoyed writing it.

Thanks to the following bodies: the Swedish Governmental Agency for Innovation Systems (VINNOVA), the Swedish Research Council (VR), the Seventh Framework Program (EU FP7-ARTIST4G), and EU FP7 project ICT-317669 METIS for supporting my work. Some computations were performed on the resources at Chalmers Centre for Computational Science and Engineering, C^3SE, provided by the Swedish National Infrastructure for Computing.

Acknowledgments

I would like to thank each one of you who have helped me in any way during my doctoral studies. My special thanks goes out to:

- Tommy Svensson, my supervisor/examiner and my guide, you took an extra step for me in times when I needed you, especially when I needed that extra push. I have learnt a lot from you. Thank you for this wonderful experience. Giuseppe Durisi, my co-supervisor, oddly I feel that I have underutilized your guidance. However, I learned a few things from you. Thanks.

- Erik Ström for providing me an opportunity to be part of the ComSys group, and being a teaching assistant for your course on wireless communications.

- Carmen Botella, your kindness and your guidance is all I can remember, if not for introducing me to the world of cooperative communications with CoMP. Agisilaos Papadogiannis, your ideas never ceases to amaze me.

- Mikael Sternard, Rikke Apelfröjd, Anna Brunström, Annika Klockar, my sincere thanks for being part of the VR project meetings, where I could discuss my research results, freewheeling beyond those planned hours of research discussions.

- Antti Tölli, I have enjoyed every aspect of our interaction. Thank you for the carefree discussions on nearly unbounded topics.

- Jingya Li, apart from sharing the office space, a complete meal with chopsticks would never have been possible without your help. Yutao Sui, my endless questions related to 3GPP, your awesome gadgets and your never-saying-no for any help request, has taken an humble effect on me. Thanks!

- My colleagues at ComSys group for pushing the (cell) edge users, and for all the timely help. Here is my chance to thank you all.

- The former colleagues at S2, in particular Arash with whom I got started with the ComSys group. To Guillermo and Stelios for the lovely speech and speakers. I miss you guys.

- S2, CWC, ARTIST4G and METIS colleagues, lunch breaks, coffee breaks, research during breaks have shaped me in so many ways that I heartily feel just as Bob Dylan: “so much older then, I am younger than that now”.

- Agneta Kinnander, Zita Bolteus, Karin Hallin, Madeleine Persson, Natasha Adler for your help with the whole new world of administration, human resources, various letters for renewing my visa every year.

- Lars, Martin and Martin for supervising my choice of music, concerts and aiding to be a music maniac.

- The family of St. Andrews.
- To my Cathedral High School teachers, especially Ms Chopde, Sharma, Newton and Santiago for your enthusiasm in teaching Physics, Maths, Geography and Martial Arts–to learn–the art of fighting without fighting.
- Thanks to the Harmony group and all the collapsing new people, to take art where no science has gone before.
- Thanks to the fox hunting[1] enthusiasts, who provided a platform to feel the traveling salesman problem, experience premature convergence, quadratic convergence, and experience the fantastic nature while exploring the topology of finding a fox.
- Friends and colleagues around the world, and especially in Sweden and Finland, Thanks! Tack! Tack! Kiitos! Cheers! Skål! Kippis!
- A friend in need is a friend in deed. Thank you Kasyab, Emma, Prakash, Martin, Kannan and Lakshmi for being there for me.
- Thank you Brita for all the tea, coffee, muffins, birthday parties, and inspirations brimming with Swedish lessons, Totoro, Kalle och Hobbe, Zits and Moomins.
- William Blake may arise when he hears my Göteborg humour reprise:

  Thanks to Johanna–
        the C major scale of my life,
  she keeps me on my toes to B#,
        otherwise, the world would still B♭.

- To my parents, Cirla and Lakshmana, your support and kindness goes a long way that I find it hard to contain them in this section. To my sister, Rashmi, and my niece, Trishel, growing up would have been very boring without you around. To my grandma, Rita, I miss your fish curry and keema kurma.

And to <*your name here*> who is reading this thesis. Thanks!

Carpe Diem!

Tilak Rajesh Lakshmana
Gothenburg, October 2015

ps: "Please excuse my rottn' english you see moomins go to school only as long as it amuses them" –Moominmamma, from Finn Family Moomintroll by Tove Jansson

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[1] http://en.wikipedia.org/wiki/Amateur_radio_direction_finding

List of Abbreviations

3GPP	3rd Generation Partnership Project
5G	Fifth Generation
BS	Base Stations
CCN	Central Coordination Node
CDMA	Code Division Multiple Access
CoMP	Coordinated MultiPoint
CQI	Channel Quality Indicator
CSI	Channel State Information
CSIT	CSI at the Transmitter
DAS	Distributed Antenna Systems
DPS	Dynamic Point Selection
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
GSM	Global System for Mobile Communication, Groupe Spéciale Mobile
ICIC	InterCell Interference Coordination
IE	Information Element
IoT	Internet of Things
JT	Joint Transmission
LPD	Local Precoder Design
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output

mmW	millimeter Waves
MOO	MultiObjective Optimization
MU	Multi-User
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PHY	PHYsical Layer
PSO	Particle Swarm Optimization
RAN	Radio Access Network
RF	Radio Frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RRHs	Remote Radio Heads
SCA	Successive Convex Approximations
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SOC	Second Order Cone
SOCP	Second Order Cone Program
SSOCP	Successive Second Order Cone Programming
SVD	Singular Value Decomposition
TD	Time Division
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
WCDMA	Wideband Code Division Multiple Access
WIM	Weighted Interference Minimization
ZF	Zero Forcing

Contents

Part I.

Introduction

You become responsible, forever, for what you have tamed.

— Antoine de Saint-Exupéry
Aviator, Writer (29 Jun. 1900-1944)
An extract from The Little Prince (1943)

1. Potential 5G technologies, the 1000x hype

> The growth of this last area has in the last fifty years been even faster than that of the other two.
>
> — Claude Shannon
> Mathematician, Engineer, Cryptographer (30 Apr. 1916-2001)
> Kyoto Prize acceptance speech in Mathematics (1985)

The hype so far in wireless communications has been branded with paradigm-shifting, ubiquitous, revolutionary technology and many more [2]. The trend has continued with the fifth generation (5G) of communication systems with ultra dense, ultra lean, ultra high reliability, massive machine type communications, etc. The hype also transitions from cellular systems to all type of systems that require communications that can be aided by cellular systems. The ambitious goal of having 1000x higher mobile data volume per area [3] compared to existing technologies is punctuated with services being offered anywhere, anytime for anyone for anything [4].

Based on a Federal Communications Commission (FCC) report, there has been an exponential growth of mobile data traffic leading to 300 MHz of spectrum deficit. This is even without considering the internet of things (IoT), where everything is connected [5]. Cisco® reported with quantitative evidence that the wireless data explosion is for real and this trend will continue [6]. Martin Cooper, the father of the cell phone, noted that the throughput had doubled every 30 months over a period of 104 years. In [7], this is translated to a million-fold increase since 1957, and provide a breakup for this increase. Major gains are expected from reduced cell sizes, due to an increase in the reuse of spectrum across a geographical area, thereby relaxing the constraint on resource allocation. The existing cellular systems are mostly macrocellular in nature, and the small cells would be deployed under the umbrella of a macrocell.

The need for higher data rates has been the driving force for a new generation of communication systems, this is accelerated due to the transition from circuit switched to packet switched connections. Apart from the need for very high data rates everywhere, some of the requirements driving 5G are massive system capacity with lower energy consumption per bit. Learning from history, one of the most expensive part in a cellular network is the front end (power amplifier) that triggers a large electricity bill for the operators. With global warming, the objective to have lower energy per bit could be the prime motivation. The new generation of communication systems also need to satisfy very low latency requirement, ultra-high reliability and availability [3][4]. However, these requirements could oppose each other's objective. For example, for ultra-high reliability there could be a number of transmissions bombarded across the air interface, however such systems might not meet the objective of being energy efficient and having very low latency, even though they are very reliable. This makes the design of 5G systems all the more challenging. Multiobjective optimization (MOO) could be a key in addressing these goals [8].

These 5G requirements drive the need for new technologies, such as massive deployment of multiple antennas, higher throughput, densification, and even operating with new frequencies such as those in the millimeter range [6]. This list is not exhaustive, however, these exciting technologies will enable a better world for all. In this thesis, coordinated multipoint (CoMP) transmission is considered that could address one of the 5G requirements of achieving higher throughput via network coordination.

1.1. Cooperation and its use to mitigate interference

In traditional time division multiple access (TDMA) cellular system such as Global System for Mobile Communication (GSM), a user equipment (UE) moving from one cell to another results in a hard-handover. This is brought about with the event of *break-before-make*. In conventional code division multiple access (CDMA) and wideband CDMA (WCDMA) systems such as universal mobile telecommunications system (UMTS), the UEs are served on the same frequency-time resource. When a UE moves from one cell to another during an active call, a soft-handover is performed, where the UE can communicate simultaneously with many base stations (BSs) with the notion of *make-before-break*. Based on the quality of the received bits, the core network can decide the BS to which the UE can be connected. This leads to a concept called macrodiversity, where independent paths are setup to ensure that the probability of both paths simultaneously being affected with fading is lowered [9, 10].

Multiple-input multiple-output (MIMO) systems promise high capacity [11, 12, 13]. Spectral efficiency is significantly increased when channel state information (CSI) is available at the transmitter (CSIT). In this regard, consider the singular value decomposition (SVD) of a point to point MIMO channel $\mathbf{H}\left(\in \mathbb{C}^{R\times T}\right) = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$, where $\mathbf{U}^H$ can be used for receiver shaping while $\mathbf{V}$ can be used at the transmitter for exploiting diversity via preprocessing or precoding. Here R denotes the number of receiving points and T is the number of transmitting points. With precoding and receiver shaping, the MIMO channel is parallelized into its Eigenmodes [13]. At low signal to noise ratio (SNR), one or few of the strongest Eigenmodes can be used. When the strongest mode alone is used then this leads to MIMO beamforming. At high SNR, all the Eigenmodes could be used. In the absence of CSI at the transmitter space-time coding can be performed [14]. With CSI at the receiver, Bell Laboratories layered space-time (BLAST) can be performed [15], while signal processing at the transmitter side with CSIT leads to precoding. With single user (SU) MIMO with T transmit antennas and R receive antennas, more data to one UE is delivered over the same bandwidth to increase the spectral efficiency, while in the case of multi-user (MU) MIMO, R single antenna UEs are multiplexed over the same bandwidth to increase the system capacity. With multi-layered MU-MIMO, R UEs each have multiple antennas which gives rise to multiple streams (layers) being delivered to the same UE [16].

Theoretical investigations on improving the downlink cellular capacity based on cooperation between the BSs was studied in [17] and potential gains of network coordination for spectrally efficient systems with high-speed backhaul was shown in [18]. The promising gains of cooperation with multiple antennas triggered immense research with multicell MU-MIMO [19, 20], network MIMO [9], multicell processing [10] and distributed antenna systems [21]. High spectral efficiency could be achieved with advanced interference mitigation techniques for 5G systems [22].

Backhaul could be loosely called the backbone of the cellular network, where it forms the interconnection between different nodes or BSs. The medium for backhauling has been wired links such as copper or optical fiber cables, and wirelessly this has been with microwaves links. With the advent of small cells deployments, where wired links can be impractical or expensive, millimeter waves (mmW) based wireless backhauling could be effective [23].

1.2. Nitty-gritties of CoMP and its classification in 3GPP

In 3rd Generation Partnership Project (3GPP), long term evolution (LTE) systems are spectrally efficient systems with frequency reuse factor of one between the cells. However, this comes at the price that such systems are prone to intercell interference. Traditionally, with careful radio frequency (RF) planning the intercell interference was minimized by tweaking the antenna being selected and adjusting the antenna patterns. The new line of thinking with CoMP is to mitigate intercell interference via cooperating BSs, basically treat interference as useful signal [17]. In Fig. 1.1 (a), the UEs using the same frequency-time resource at the cell-edge are prone to intercell interference. In Fig. 1.1 (b), the interfering signal is treated as useful signal. This leads to the basic idea of joint transmission CoMP [17, 24, 25]. The term joint transmission was first proposed in the context of time division (TD)-CDMA systems [26]. Another way to look at CoMP is that the BSs take an active role in interference mitigation for the spatially distributed non-cooperating UEs. It could be said that the CDMA systems did have a primitive version of CoMP, however, note that in [27] it is argued that soft handoff or handover does not aim to overcome interference. The common aspect of CoMP and soft handover is that they both aim to improve signal to interference plus noise ratio (SINR) by sending the same data from different

BSs. In this thesis, the main focus will be on interference mitigation in downlink CoMP joint transmission.

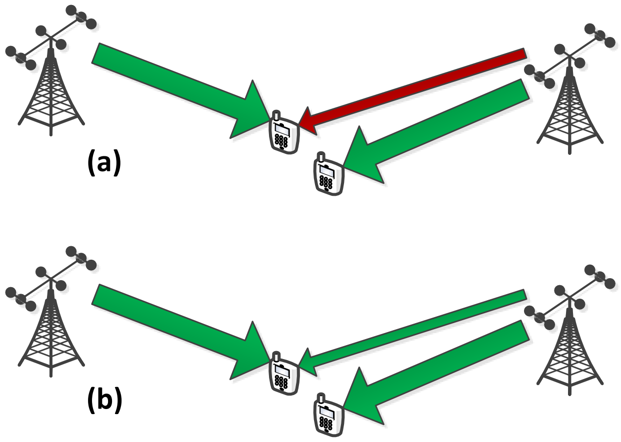

Figure 1.1.: Spectrally efficient cellular systems can be achieved with frequency reuse factor of one. This leads to (a) interference limited system where the cell-edge UEs are prone to interference from the other cell. In (b), treat interference as useful signal, a basic idea of CoMP joint transmission.

Intercell interference coordination (ICIC) and enhanced ICIC was available in Release 8 and Release 10 of the 3GPP specifications, to avoid intercell interference in the frequency domain and time domain, respectively [28]. In particular, enhanced ICIC primarily address interference mitigation in heterogeneous networks between macrocells and small cells. In 3GPP LTE Release 11, CoMP is addressed as a work item [29], and in this subsection, the nitty-gritties of CoMP is presented via its classification in 3GPP.

Downlink CoMP transmission

In the downlink, CoMP can be classified based on how many transmitting points are involved in serving the UEs. With *coordinated scheduling* (CS) and *coordinated beamforming* (CB), only one of the BSs is involved in serving the UE, typically the serving BS. The other BSs are involved in coordinating with this serving BS, so that interference can be mitigated. CS/CB can be seen as an evolution of the ICIC where much lower latency can be expected for coordination. For example, coordinated scheduling over multiple cells allows ICIC on a time scale of individual scheduling decisions [28]. To realize these gains, the CSI can be coarse for CS/CB and the UE data needs to be available at only one serving cell. However, some control signaling is needed over the backhaul to coordinate with other BSs, with reasonable synchronization between the BSs with oscillator accuracy of 0.05 ppm and 3 μs timing accuracy [28, Table 13.5]. The periodicity of CoMP Information Element (IE) exchange over the backhaul X2 interface connecting the BSs is recommended to be $\{5, 10, 20, 40, 80\}$ ms from Radio Access Network (RAN) work group 1 to RAN3 [30]. These numbers are currently under investigation in 3GPP. Bandwidth, latency and maximum possible distance for a given link would prove to be crucial for realizing the new technologies.

In the case of *joint processing* CoMP, the non-serving BSs are also involved in transmission towards a UE. This approach is further divided into *dynamic point selection* (DPS) where only one cell is involved in transmitting to a UE, and *joint transmission* (JT), where a group of BSs coherently transmit data to the UEs. To realize the gains with dynamic point selection, the UE data needs to be available at all the cooperating BSs which increases the load on the backhaul. However, the data transmission occurs from one of the chosen transmitting points. The CSI and the synchronization requirements for DPS are similar to that of CS/CB [28]. Note that CoMP allows independent selection of transmission points in the downlink cell selection, and uplink reception points which is useful in heterogeneous networks. To realize the gains with JT-CoMP, the CSI needs to be accurate and the UE data needs to be available at all the cooperating BSs. This poses heavy load on the backhauling with more tighter requirement on the oscillator accuracy of 0.02 ppm and 0.5 μs timing accuracy [28]. JT-CoMP promises to provide the highest throughput compared to other techniques. However, this is not yet mature for realistic deployment.

Uplink CoMP joint reception

As the uplink CoMP reception does not affect the standards on the UE side, they can be directly applied for Release 8 compliant UEs. However, on the network side, the uplink UE data received at the geographically separated antennas needs to be collected at a central receiver, where the UE data can be combined and more faithfully reproduced. One of the limiting factors is transporting the UE data in backhaul for the detection process.

CoMP and DAS

Distributed antenna systems (DAS) could resemble a CoMP scenario with the antennas or remote radio heads (RRHs) being geographically distributed. However, the important aspect to note in DAS is that with distributed antennas, the propagation distance is reduced. Therefore, the distributed antennas can be operated with lower transmit power.

In 3GPP, DAS was classified as intra-site CoMP in Release 10, where the coordinated BSs share the same site. While for inter-site CoMP, the coordination occurs over the backhaul with BSs located at different sites [21]. Hence, DAS is a competing technology compared to fixed relays and small cells. Unlike CoMP the primary goal of DAS is to achieve coverage and then throughput. While in the case of CoMP, the coverage is available, however the throughput is limited due to interference and CoMP enables to overcome this interference.

Centralized and distributed architectures

JT-CoMP is more suited for a centralized architecture where a central coordination node (CCN) acts as a controller of BSs or RRHs. With ultra-lean design of LTE in future networks, the notion of *baseband hotel* can be realized. It consists of the

RRHs being connected over high speed fiber to the baseband pool (or CCN) where the protocol stack resides (see Sec. 2.2) and it is connected to the packet core [28].

This approach maps to CoMP scenario 2 in 3GPP and it could prove very useful for JT-CoMP. In this approach, the link between the baseband hotel and the "unintelligent" RF head is called the fronthaul. The baseband hotel can be in the Cloud-RAN. However, unlike cloud computing the requirements on Cloud-RAN will be a lot more aggressive in terms of data rate and latency. Recently, Ericsson demonstrated a microwave fronthaul solution in China [31]. The fronthaul can be regarded as the backhaul if the protocol stack is considered to be residing in the "intelligent" RF head and the CCN is a logical entity that could reside at any one of the BSs. Nevertheless, fronthaul or backhaul in the case of JT-CoMP need to support tremendous capacity with very low latency [28].

In the case of distributed architecture, the protocol stack or the baseband resides at each RF head, and there is no CCN. Thereby, the centralized approach could be performed in a distributed manner [32]. In the case of decentralized approach, each BS has its own version of the data or a subset of the data, for example the CSI available at different BSs could be different [33].

Backhaul the bottleneck

When voice was still the killer application, wireless network operators such as Sprint did not pursue having a split backhaul for voice and data separately [34]. With current trends of exponential growth in mobile data traffic, and increasing operating expenses due to energy consumption, operators can rely on heterogeneous solutions with low-power BSs in addition to the macrocell. In [35], it is found that backhaul could account for 50% of the power consumption, and that having a hybrid backhaul architecture, such as those of microwave and fiber backhauling could be very useful in ultra dense networks. The backhaul traffic can be minimized by jointly designing the precoder and the UE data allocation at the BSs given a quality of service [36].

1.3. Signaling overhead: Channel state information

The cellular network was optimized for laptop type of traffic by keeping the connection active for better user experience [37]. However, with the advent of the smart phone, there was a tremendous increase in the applications in the app market that started to show catastrophic effects on the life of the battery. The handset manufacturers improved the battery life where the data connection was active only when the download was needed and then the connection was torn down immediately thereafter. This improved the battery life, however it also triggered excessive signaling for the network. This behavior is called fast dormancy [37]. Apart from the signaling overhead generated from applications, there is a need to have efficient signaling which indirectly addresses the need for energy efficient systems.

Focusing on the signaling overhead in downlink JT-CoMP, the CSI needs to be available at the transmitter. This was first studied in this pay-walled article [38], where the capacity of the channel was found when the transmitter has causal side information. In a frequency division duplex (FDD) system, the UEs need to feedback the channel to the transmitter. An overview of limited feedback in wireless systems is presented in [39]. In particular, the channel information can be instantaneous or statistical [14, 16]. Distributed strategies to harness the gains of CoMP using instantaneous and statistical CSI is presented in [40] using novel distributed virtual SINR framework. Statistical channel knowledge can be in the form of the channel covariance information and channel mean information. Henceforth, the instantaneous channel information can be referred to as CSI, while the statistical channel information can be seen as the received signal strength indicator (RSSI). The RSSI feedback from the UEs already exist in the current cellular standards while feeding back the CSI is yet to be incorporated.

To realize the gains of JT-CoMP, the CSI is required for interference mitigation via precoding. In a centralized approach, as discussed in the previous section, if all the UEs participating in JT-CoMP were to feedback the CSI over the air to its strongest BS then forwarding them to the CCN for precoding could pose a heavy burden on the backhaul traffic. As the precoding weights designed at the CCN needs to be available at the cooperating BSs along with the UEs' data, this could further overwhelm the backhaul.

The important factors of a given backhaul technology is the latency, throughput and its availability at a certain geographical location. Fiber access could provide a latency as small as 2 ms and a throughput as high as 10 Gbps, while digital subscriber line access could provide a latency of 15 ms supporting 100 Mbps. In places where cabled access is not possible, wireless backhaul could prove to be useful with one-way latency as small as 5 ms supporting 100 Mbps. These values are obtained from [41, Table II]. Nevertheless, non-ideal backhauling has finite limits as to how much data they can carry, and combined with IoT, backhaul could as well be the bottleneck.

CoMP with constrained backhaul would require backhaul-efficient cooperation techniques [42, 43] such as imperfect CSI at the BS and UE [44], with achievable tradeoff between throughput/backhaul use. Stochastic precoding is performed under imperfect CSI with RSSI in [45]. Rate splitting approach is considered in [46] for shared and non-shared user data, thereby optimizing data sharing under finite capacity backhaul. Preclustering based on the backhaul could help [47], where a large network is divided into a number of disjoint cluster of BSs. With limited overlapping clusters soft interference nulling (SIN) linear precoder can be applied when complete CSI is available [48].

A suitable reduction in the quantity and quality of the CSI could aid in the reduction of the signaling overhead, leading to an efficient routing of UE data in the backhaul. The long term channel statistics can also be used for making routing decisions for the UE in the backhaul [49]. Keeping the quality of feedback to be perfect, the quantity of the CSI feedback can be lowered with absolute or relative thresholding. More details on how to reduce the feedback and the corresponding effect on having an efficient backhaul is captured in Sec. 2.1.1 and Sec. 2.1.2, respectively. Keeping the quantity of CSI to be complete, the quality of the CSI being affected by prediction and quantization errors in the case of centralized precoding is captured in App. A. In [50], substantial throughput increment is achieved via JT-CoMP with very limited number of feedback bits per BS. Imperfect CSI require robust precoding be it centralized [51, 52] or decentralized [53]. In [54, 55], “who needs to know what” indirectly addresses the quantity and quality of CSI required at different BSs in a distributed setup. In this thesis, a homogeneous network of macrocellular cell-edge UEs are considered at the cluster center for JT-CoMP (see Chap. 2). In a centralized architecture (see Fig. 2.1), this closely maps to the 3GPP CoMP scenario 2 where the high transmission power RRHs can be seen as another macrocell with backhaul communications over the optical fiber. This leads to inter-site JT-CoMP. To alleviate the backhaul traffic, relative thresholding is considered which maps closely to dynamic point selection with JT. This reduces the quantity of CSI being fed back by the UEs. However, this poses problems for mitigating interference in the system. Nevertheless, there is a trade-off as to how much of the CSI can be incomplete and still be able to mitigate interference in the system. This leads to the notion of efficient backhauling (see Sec. 2.1.2).

1.4. CoMP in the umbrella of 5G technologies

In the previous sections, an FDD system was mainly considered. Here a brief note on FDD and time division duplex (TDD) is presented. This is followed with the prospective use of CoMP in 5G, as to when and where to use CoMP.

1.4.1. To FDD or to TDD?

In simplest terms, an FDD system has the uplink and the downlink separated in frequency, whereas in a TDD system, the uplink and the downlink are on the same frequency, however the uplink and downlink transmissions are separated in time. Consider a typical web browsing experience, where clicking on a hyperlink fetches the data and displays it on the UE terminal, and the user spends some time reading/consuming that information. A similar experience could be with downloading some file/attachment. The traffic is bursty and asymmetric (more downlink than uplink), the act of fetching or downloading requires a larger bandwidth or data pipe to serve the user in the downlink (assuming latency driven applications). While the uplink resources are mainly for acknowledgments and to inform the need for retransmissions. In this use case, the TDD approach could be better than an FDD approach, as the downlink duration can be extended, resulting in squeezing the uplink resource in that time-slot. However, in the case of FDD, the complete uplink channel is mostly idle, if not for the occasional acknowledgments. Therefore, the spectrum can be better utilized in the case of TDD. However, in a homogeneous TDD system, the uplink and downlink flexibility could pose very strict constraints to cooperate/synchronize the change in uplink/downlink duration with the neighboring cells. Note that the bursty traffic causes discontinuous transmission wherein this could degrade the performance of the power amplifier.

Channel reciprocity could be utilized in TDD, for example, the downlink channel can be learnt from the uplink pilots or training sequence. However, this is difficult to realize in practice [14], as the different frequency transfer characteristics in RF chains at the transmitter and receiver becomes part of the channel measurements. Hence, the transmitter and receiver chains require calibration. In the case of FDD, the channel characteristics are different on different frequencies, therefore explicit pilots would be required to learn both the channels.

Given a fixed transmit power, a TDD system would have reduced coverage, as the uplink resources are used part of the time in TDD, while it is used continuously in FDD. A TDD system with 50% duty cycle would have a reduced average transmit SNR or link budget by ~3 dB [56]. Therefore, in [56], it is envisioned that TDD could be used within the cell to meet the asymmetric data usage for dynamic uplink and downlink duration, while FDD is envisioned to be used to cover larger area with the same transmit power as that of a TDD system. Hence, FDD devices can achieve better cell-edge data rates. Also, in the case of TDD, the guard time used to separate the uplink and downlink transmission would need to be increased if the cell size increases. Therefore, some latency critical applications might suffer from this [57]. Hence, TDD is more suited for small cells. A TDD small cell could be under the umbrella of an FDD cell. This design leads to using TDD for small cells while the macro cell could be more suitable to exploit FDD.

To FDD is when we have a macro cell aiming for more coverage when continuous data traffic is expected, and to TDD is when we have small cells and higher frequencies, with bursty data traffic. Thus, the best of both worlds could be exploited. In this regard, 3GPP [58] is looking at the co-existence of both FDD and TDD, and Qualcomm also envisions the deployment of both modes [56] with their array of chipsets. In this thesis, CoMP downlink transmission is considered in an FDD system.

1.4.2. When and where to use CoMP

Spatial diversity with CoMP appears to work against one of the important goals of 5G that the energy per bit needs to lowered. Hierarchically speaking, the requirements for 5G communication system could be firstly to have basic service, such as reliable communication to improve the data rate of the cell-edge UEs. However, this should not be at the expense of higher energy consumption per bit. To improve the data rate of the cell-edge UEs, with CoMP, redundant data is sent to the UE from multiple transmission points. However, this needs to be weighed with the fact that the cell-edge UEs are normally sparse, assuming operators typically have deployed a BS where there is high user activity. On the contrary, a scheduler at a given BS could be serving more of cell-center users as their reported channel is much better than that of the cell-edge user. With aggressive frequency reuse, cell-edge UEs are bound to be interference limited and this is where CoMP will be useful to improve the data rates of the cell-edge UEs.

A possible use case of CoMP in 5G network

A TDD small cell could be deployed under an FDD macrocell for the bursty traffic in dense urban environment. Lean control signaling could be used in the existing microwave range of frequencies, while mmW could be used for user plane data transfer in the TDD cell. The mmW can provide thin-focused beams with high data rates, and that interference is less important in mmW. With continued aggressive frequency reuse, the throughput of the cell-edge UEs will still be affected by intercell interference. Massive MIMO is seen as an alternative to JT-CoMP where significant beamforming gains can be achieved such that intercell interference can be kept low [22]. Moreover, in [22, 23], it is envisioned that there would be large deployment of small cells, and advanced interference mitigation based on JT-CoMP, massive MIMO and 2D-array antenna would be used. In particular, JT-CoMP could be used where the UEs share the same frequency-time resource. Moreover, CoMP could be applicable for operators where massive MIMO might not be a possible option for deployment. The work performed in this thesis, could very well suit this possible 5G network deployment.

2. The motivation and the problem formulation

> The idea is to try to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another.
>
> — Richard Feynman
> Physicist (11 May 1918-1988)
> From a Caltech commencement address (1974)

In this chapter, the need for efficient control signaling in the backhaul is emphasized with the introduction to the system model. In particular, how this can be achieved in the physical (PHY) layer and the medium access control (MAC) layer of the protocol stack while mitigating interference.

Recall that spectrally efficient systems are limited by interference. In this regard, consider a homogeneous network as shown in Fig. 2.1. The darker shaded hexagonal structure in the middle is defined as the cluster area where the BSs are allowed to cooperatively serve the UEs in this area. Modern cellular systems are spectrally efficient, as the same frequency-time resource is used in a given cluster area. This gives rises to intracluster interference. If one were to visualize Fig. 2.1 being replicated around itself, then the interference from the other clusters could be seen as intercluster interference. The UEs at the cluster edge are prone to intercluster interference that can potentially degrade the system performance. To overcome this problem, the clusters also need to be coordinated. However, full coordination is practically impossible. In [59], limited intercluster coordination is performed for the disjoint clusters, and in [60], frequency reuse schemes are proposed to mitigate the intercluster interference. In [61], interference floor shaping is considered with the notion of *tortoise* concept, where the beamforming is combined with power distribution per cluster area defined by cell specific antenna tilting. The cluster center beams has low tilt of 7° with strong power of 46 dBm, while the outbound beams from the cluster area have strong tilt of 15° with low power of 40 dBm. The main focus of this thesis is on the UEs at the cell-edge in the cluster center, as illustrated in Fig. 2.1. Hence, we assume that the intercluster inference is already taken care of by such means as in [60, 61]. In [62], it was shown that when a large network is clustered together, the spectral efficiency saturates as it becomes independent of power. This is due to the intercluster interference dominating the system giving rise to cluster-edge effects. Hence, it is highly important that the small cluster of BSs are well protected from intercluster interference.

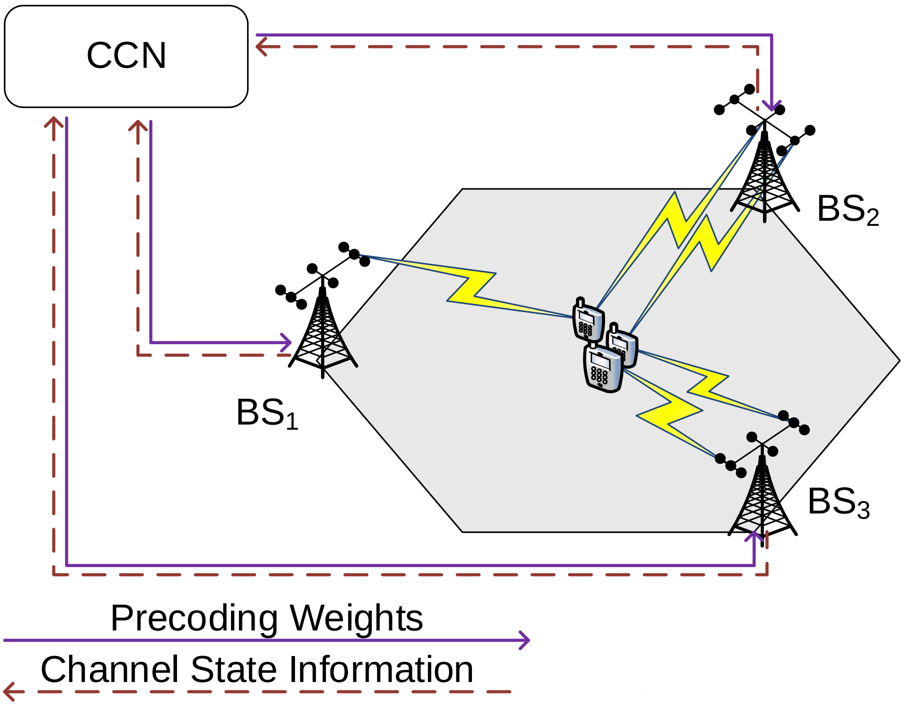

Figure 2.1.: A centralized network architecture for JT-CoMP. The shaded hexagon is the cluster area with the UEs located near the cluster center.

In the case of downlink CoMP in an FDD system, the K transmitting points or the BSs are geographically distributed while the M receiving points or the UEs are from a group requiring service. For simplicity, single antennas can be assumed at the BSs and the UEs. For precoding in a CoMP setup, the UEs need to feed back the CSI, so that the BSs can cooperatively design the precoder. For transmit beamforming, the overhead of learning the channel can be avoided if we have data associated pilots, where the pilots are beam-formed along with the data [14]. Fig. 2.2 abstracts the main aspects of realizing centralized JT-CoMP. As step (1), the BSs send pilots in the downlink so that the UEs can acquire the CSI for this link. In [63], it was shown that it is difficult to estimate the channel if the difference with respect to the strongest BS is greater than 15 dB. In step (2), the UEs feedback the CSI to their serving BS, typically its strongest BS. In step (3), the CSI acquired at the BSs is forwarded to a CCN to form the precoding weights to mitigate interference. In step (4), the UE data is routed to the cooperating BSs based on the precoding weights for JT-CoMP. Finally, in step (5), the UEs are served. The transmission in steps (1), (2) and (5) are wireless, while the transmissions in step (3) and (4) could be via an optical fiber link or wireless backhauling. Recall that the backhaul constitutes all the connections and network entities used to interconnect the BSs.

In Fig. 2.1, this would constitute the connections between the BSs and the CCN. The focus of the thesis is mainly on the backhaul traffic, consisting of the CSI and the precoding weights. In the case of TDD, the channel reciprocity would help the BS to acquire the CSI knowledge at transmitter/CCN.

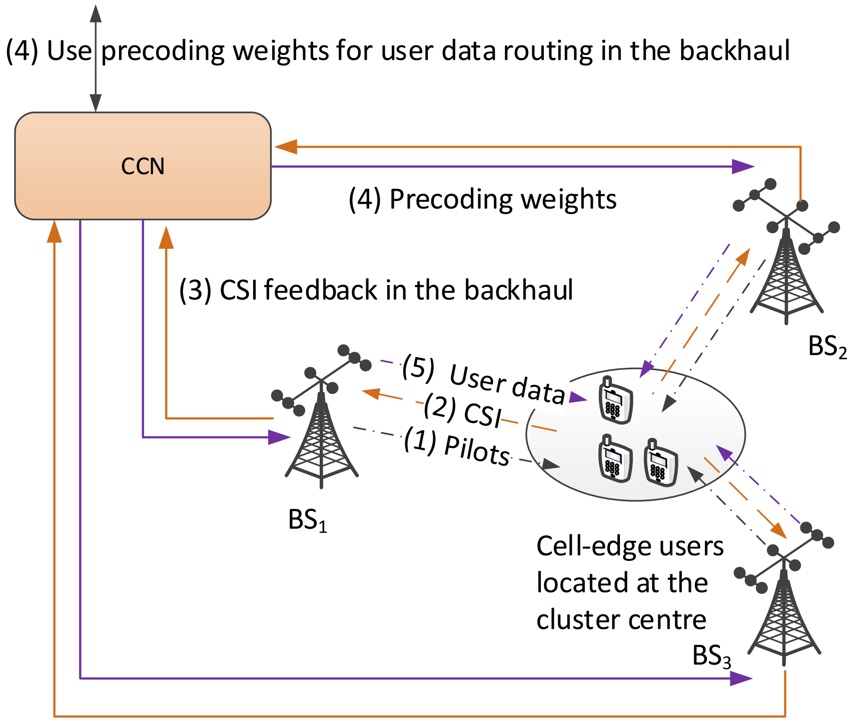

Figure 2.2.: An abstract representation of CoMP in an FDD system where step (1) shows the downlink pilots from the BSs to the UEs, step (2) shows the CSI being fed back by the UEs to the serving BSs, typically the strongest BS, step (3) CSI transported from the BS to the CCN, step (4) where the UE data is transported to the corresponding BSs based on the precoding weights, and finally step (5) where the actual UE data is transmitted to a cluster of UEs at the cell-edge.

2.1. System model

Consider a homogeneous network cluster consisting of $|\mathcal{B}|$ BSs, each with N_T antennas, where $\mathcal{B}$ is the set of BSs involved in cooperation. The BSs are coordinated to serve $|\mathcal{U}|$ single antenna cell-edge UEs. The signal received by the uth UE is y_u, and it consists of the desired signal and intracluster interference

$$y_u = \sum_{b\in\mathcal{B}_u} \mathbf{h}_{b,u}\mathbf{w}_{b,u}x_u + \sum_{i\neq u}\sum_{b\in\mathcal{B}_i} \mathbf{h}_{b,u}\mathbf{w}_{b,i}x_i + n_u, \tag{2.1}$$

where $\mathcal{B}_u$ is the set of BSs from which the uth UE is served. In this model, the intercluster interference is made negligible for the cell-edge UEs located at the cluster center, with suitable intercluster interference coordination scheme such as the tortoise concept [61], or fractional frequency reuse [60]. Therefore it is not accounted for in (2.1). The channel experienced by the uth UE from bth BS with N_{T} antennas is $\mathbf{h}_{b,u} \in \mathbb{C}^{1\times N_{\mathrm{T}}}$. The precoding weight for the uth UE with normalized data x_u from the bth BS with N_{T} antennas is $\mathbf{w}_{b,u} \in \mathbb{C}^{N_{\mathrm{T}}\times 1}$, such that $\mathbf{w}_{b,u} = [w_{b,u}^{(1)}, w_{b,u}^{(2)}, \ldots, w_{b,u}^{(k)}, \ldots, w_{b,u}^{(N_{\mathrm{T}})}]^T$ where $w_{b,u}^{(k)}$ is the precoding weight on the kth antenna of the bth BS for the uth UE, and n_u is the receiver noise at uth UE with power N_0.

Treating interference as noise, consider the SINR evaluated at the CCN for the uth UE as

$$\begin{aligned}\gamma_u &= \frac{\left|\sum\limits_{b\in\mathcal{B}_u} \mathbf{h}_{b,u}\mathbf{w}_{b,u}\right|^2}{\sum\limits_{i\neq u}\left|\sum\limits_{b\in\mathcal{B}_i} \mathbf{h}_{b,u}\mathbf{w}_{b,i}\right|^2 + N_0} \\ &= \frac{\left|\sum\limits_{b\in\mathcal{B}_u} \mathbf{h}_{b,u}\mathbf{w}_{b,u}\right|^2}{\sum\limits_{i\neq u}\left\{\left|\sum\limits_{b\in\mathcal{B}_i\cap\mathcal{B}_u} \mathbf{h}_{b,u}\mathbf{w}_{b,i} + \sum\limits_{b\in\mathcal{B}_i\setminus\mathcal{B}_u} \overline{\mathbf{h}}_{b,u}\mathbf{w}_{b,i}\right|^2\right\} + N_0},\end{aligned} \tag{2.2}$$

where the interference terms in the denominator of (2.2) are split based on relative thresholding in terms of CSI known and unknown at the CCN. That is, the set $\mathcal{B}_i \cap \mathcal{B}_u$ denotes the set of BSs that are involved in serving both the uth and the ith UE, as the CSI $\mathbf{h}_{b,u}$ falls within the relative threshold window. However, those links that fall outside this threshold constitute the term $\overline{\mathbf{h}}_{b,u}$ where $\mathcal{B}_i\setminus\mathcal{B}_u$ is the set of BSs serving the ith UE but not the uth UE. The given set $\mathcal{B}_u$ is defined by the relative thresholding algorithm as described in the next subsection. Finally, the weighted sum rate of $|\mathcal{U}|$ UEs while designing the precoder is evaluated as

$$R_{\text{tot}} = \sum_u \alpha_u \log_2\left(1+\gamma_u\right) \text{[bps/Hz]}, \tag{2.3}$$

where α_u is a non-negative weight of the uth UE.

2.1.1. Reduced feedback overhead

Ultra-lean design is the future of wireless access networks [4], where the design goal is to minimize any traffic not related to the delivery of UE data. With such a design philosophy, a practical scenario could be that the UE data constitutes a major portion of the backhaul traffic. In a centralized network architecture, the UE data could be routed based on the precoding weights. Thus, the focus is more on the control signaling part of the backhaul traffic. As mentioned earlier, to coordinate all the BSs in the network would be impractical, and hence, clusters of BSs are formed [64]. A predefined set of BSs forming a cluster that does not change with time is referred to as static clustering [59]. Likewise, dynamic clusters of BSs can be formed depending on the channel conditions [64]. Moreover, depending on where the clustering decisions are performed, it can be classified as network centric or UE centric clustering. Various combinations of the clustering can be performed. In our work, particularly in papers A/B/C, a *dynamic UE centric clustering* is performed, where the UE dynamically chooses the set of BSs from which it would like to be served [65, 66]. To alleviate the problems of the CSI feedback overhead within a cluster area, absolute thresholding and relative thresholding can be considered [65, 67]. In the case of absolute thresholding, the UEs are instructed to feed back the CSI of links that are above a certain value, while in the case of relative thresholding, the UEs are instructed to feed back links that fall within a window relative to the best link. Relative thresholding based on long term channel statistics is captured in Alg. 2.1 [Paper A] or based on the instantaneous CSI as in [Paper B]. This could avoid feeding back the poor channels. In [54, 55], CSI sharing strategies with different cooperating BSs are proposed where performance close to the full CSIT can be achieved. We consider a dynamic UE centric clustering based on relative thresholding, due to which CSI feedback load over the air and over the backhaul can be reduced.

Algorithm 2.1 Relative thresholding performed at the UE based on the long term channel statistics (pathloss and shadow fading)

```
Set the feedback threshold, $T$ (= 3 dB, for example)
for $\forall u \in \mathcal{U}$ do
    Perform channel measurements of the BSs, $\mathcal{B}$
    $c = \max_{b \in \mathcal{B}} \left( E\left[ ||\mathbf{h}_{b,u}||_2^2 \right] \right)$
    for $\forall b \in \mathcal{B}$ do
        if $\left( c_{\mathrm{dB}} - \left[ E\left[ ||\mathbf{h}_{b,u}||_2^2 \right] \right]_{\mathrm{dB}} \right) \leq T$ then
            Include $b$ in the set $\mathcal{B}_u$
        end if
    end for
    The $u$th UE feeds back the CSI of the set of BSs in $\mathcal{B}_u$
end for
```

Based on relative thresholding, consider the following channel matrix aggregated at the CCN as shown in Table 2.1, where UE_1 feeds back the CSI of BS_1 and BS_2 while CSI of BS_3 is not fed back as it falls outside the relative threshold window. Likewise, other UEs also feed back the CSI that falls above the threshold. Modeling of CSI that is not available at the CCN as zeros may not be the best way to go about it. However, intuitively it makes sense to treat them as zeros [67, 68, 69]. These zeroes denote the feedback reduction obtained with relative thresholding. We define the feedback load reduction, f_{LR} as the number of zeros in a sparse aggregated channel matrix $\widetilde{\mathbf{H}} \in \mathbb{C}^{|\mathcal{U}| \times N_{\mathrm{T}}|\mathcal{B}|}$ i.e., the cardinality of set $\mathcal{S}_{\mathrm{FB}} = \left\{ \widetilde{\mathbf{H}}_{i,j} = 0, \, \forall i, j \in \mathbb{N}^{+}, i \leq |\mathcal{U}|, j \leq N_{\mathrm{T}}|\mathcal{B}| \right\}$. The feedback load reduction is calculated as

$$f_{\mathrm{LR}} = |\mathcal{S}_{\mathrm{FB}}|. \tag{2.4}$$

To overcome the signaling overhead, one could broadcast the CSI [33, 70, 71], such that all the cooperating BSs can obtain the CSI without the need for a CCN. The UEs estimating the channel is one aspect of obtaining the CSI. The inherent delays due to the control loop emphasizes the other important aspect of estimating and predicting the channel well in advance. The prediction horizon defines the duration of time for which the channel is predicted. A short prediction horizon will indirectly limit the UE velocity and it imposes a fast backhauling network with very low latency, in the order of milliseconds. The predicted CSI is quantized and fed back to the anchor BS. Quantization by itself gives rise to quantization errors and the process of feeding back the CSI also occupies the uplink resources. These practical aspects are considered in the precoder design and the results are presented in App. A.

Table 2.1.: Aggregated Channel Matrix at the CCN

$\widetilde{\mathbf{H}}$	BS_1	BS_2	BS_3
UE_1	h_{11}	h_{12}	0
UE_2	0	h_{22}	h_{23}
UE_3	0	0	h_{33}

2.1.2. Efficient backhauling and the limitation

Efficient backhauling is one of the main aspects being addressed in this thesis. Consider the CSI obtained at the CCN is error free. The question that one would like to ask is, if an equivalent backhaul reduction be obtained in terms of the precoding weights as shown in Table 2.2 in comparison to Table 2.1. That is, can the quantity of CSI coefficients for certain BSs-UEs available at the CCN be correspondingly equivalent to the quantity of precoding weights for the same BSs-UEs? More importantly, this is a desired property for the precoding matrix. The main reason for this is that the UE data is routed based on the precoding weights designed at the CCN. In the case of a centralized architecture aiming towards ultra-lean radio access, the UE data is several orders of magnitude greater than the control information (precoding weights). This desired property will alleviate the burden on the backhaul, and the need for the UE data to be present at all the cooperating BSs is reduced.

Table 2.2.: Desired precoding matrix based on $\widetilde{\mathbf{H}}$ from Table 2.1.

$\widetilde{\mathbf{W}}$	UE_1	UE_2	UE_3
BS_1	w_{11}	0	0
BS_2	w_{21}	w_{22}	0
BS_3	0	w_{32}	w_{33}

We define the sparse precoding matrix as $\widetilde{\mathbf{W}} \in \mathbb{C}^{N_{\mathrm{T}}|\mathcal{B}| \times |\mathcal{U}|}$ where the backhaul load reduction is the cardinality of set $\mathcal{S}_{\mathrm{BH}} = \left\{\widetilde{\mathbf{W}}_{j,i} = 0, \forall i, j \in \mathbb{N}^{+}, i \leq |\mathcal{U}|, j \leq N_{\mathrm{T}}|\mathcal{B}|\right\}$, i.e.,

$$b_{\mathrm{LR}} = |\mathcal{S}_{\mathrm{BH}}|. \tag{2.5}$$

For equivalent backhauling,

$$if\, \widetilde{\mathbf{H}}_{i,j} = 0 \Rightarrow \widetilde{\mathbf{W}}_{j,i} = 0, \forall i,j \in \mathbb{N}^{+}, i \leq |\mathcal{U}|, j \leq N_{\mathrm{T}}|\mathcal{B}|, \tag{2.6}$$

and this results in $f_{\mathrm{LR}} = b_{\mathrm{LR}}$. Fig. 2.3 illustrates the CSI, precoding weights and the user data in the network. Linear zero forcing (ZF) precoder can be obtained with incomplete CSI due to relative thresholding. However, they are not aimed for efficient backhauling [72]. In the following sections, a brief explanation of how this can be solved is presented.

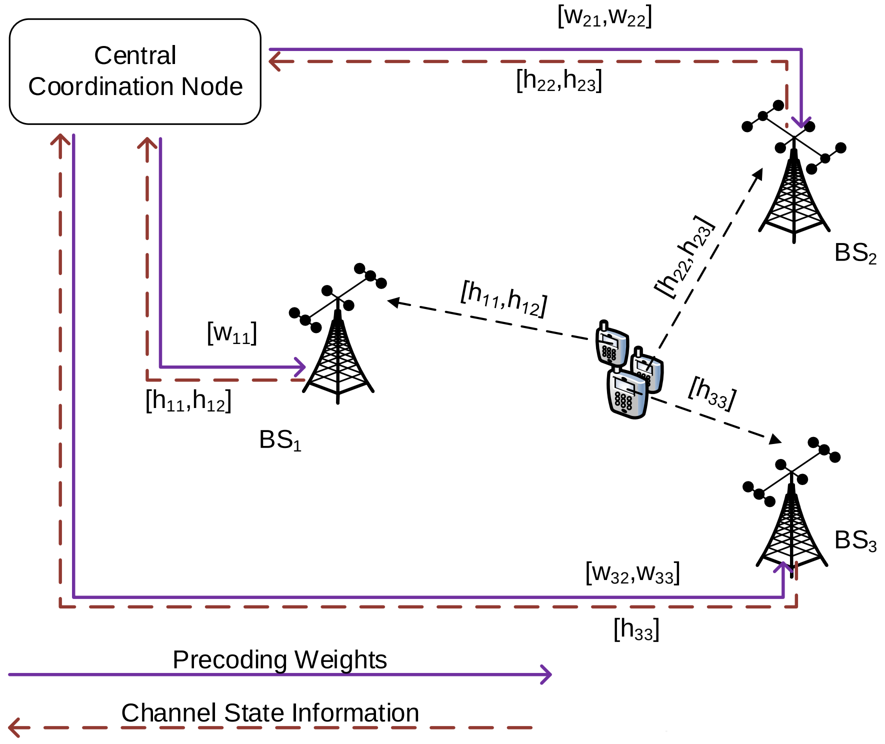

Figure 2.3.: An illustration of the equal number of CSI coefficients and the precoding weights. The uneven distribution of the CSI coefficients and the precoding weights is also captured in the backhauling links. Moreover, the UE data is routed based on the precoding weights.

2.2. The OSI model and the protocol stack

The notion of backhaul savings is partly inspired from [68] based on the layered approach of the open systems interconnection (OSI) model. To understand the subsequent sections better, a brief description of the OSI model is presented. The OSI model is depicted along with the protocol stack of the UE and the BS in Fig. 2.4. The layered structure of the communication software makes it easier to realize complex systems. Every layer of the OSI model performs a dedicated task. This provides an opportunity to design and test the layers in parallel. The lowest layer is called the PHY layer or Layer1. It is mostly concerned with channel coding and modulation. The second layer is the data link layer. In the protocol stack of the UE, this corresponds to the radio link control (RLC) and MAC. The RLC performs the segmentation of the data packets obtained from Layer3 which is the radio resource control (RRC), and reassembly of data packets obtained from the PHY layer. The MAC layer performs the scheduling as to when the PHY layer should transmit a given data block. In this thesis, the focus is mostly on the control plane aspects related to the PHY layer and MAC layer. More details about the functions of various protocol stack layers can be found in [73]. Interference mitigation could be considered at various layers in the protocol stack, along the lines of the OSI model of the protocol stack in cellular communications where segmentation and reassembly of packets is performed at various layers. Here we only focus on the PHY and the MAC layer for interference mitigation.

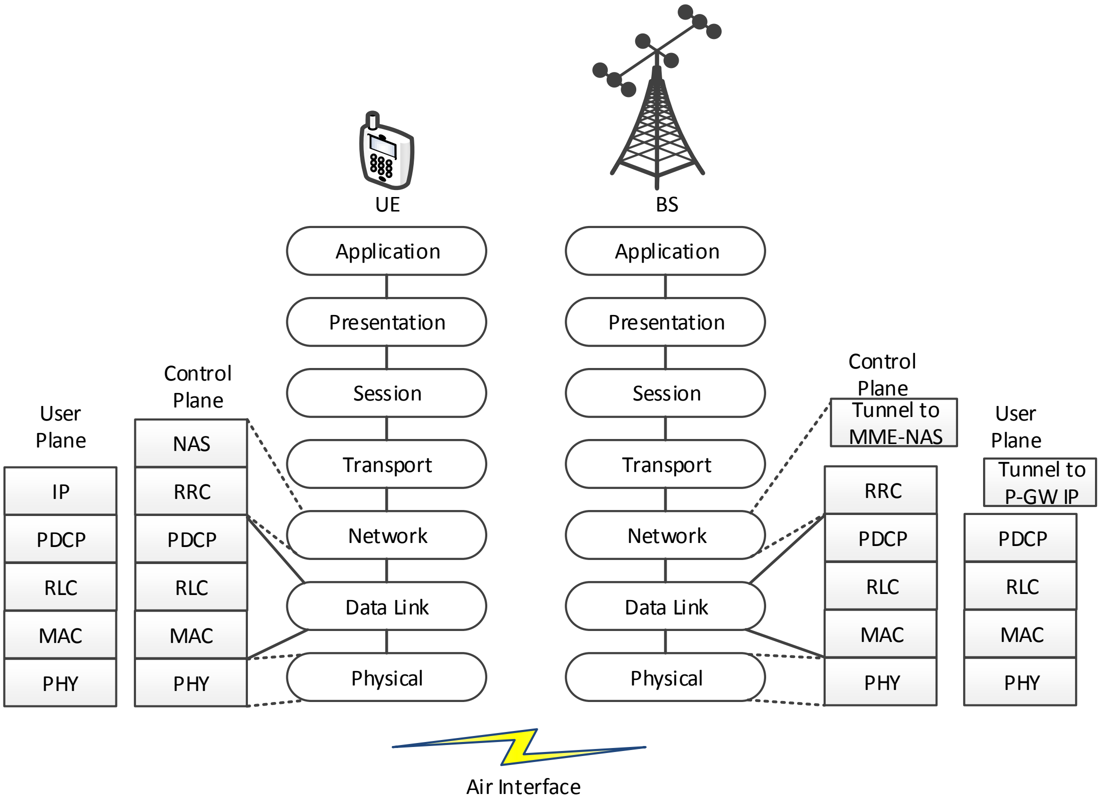

Figure 2.4.: An illustrative mapping of the OSI model that maps to the protocol stack of the UE and BS highlighted in rectangular blocks.

2.2.1. Precoding, a PHY layer approach

In the case of CoMP systems, the transmitter is distributed at multiple geographically separated BSs, and in a centralized architecture, the precoder design resides in the CCN. Now consider an aggregated channel matrix formulated at the CCN as shown in Table 2.1. In this approach, the MAC layer scheduler is made simple and the complexity is pushed to the PHY layer precoder for interference mitigation and also to achieve backhaul savings with incomplete CSI feedback. In this regard, stochastic and convex optimization algorithms such as particle swarm optimization (PSO), and successive second order cone programming (SSOCP) are proposed, respectively, where individual precoding weights can be tweaked by maximizing a nonconvex objective such as the weighted sum rate. The performance of SSOCP is validated using the branch and bound technique [74]. Minimizing the weighted sum mean square error was shown to be equivalent to maximizing the weighted sum rate in [75, 76]. In this regard, an MSE approach was also derived to obtain efficient backhauling. The performance in terms of the throughput can be improved when using the long term channel statistics such as RSSI as part of modeling the statistical interference when designing the precoder. In Chap. 3, PHY layer precoding for efficient backhauling with these optimization tools are presented.

2.2.2. Scheduling, a MAC layer approach

Alternately, for a given frequency-time resource, the goal of interference mitigation and backhaul savings comparable to the incomplete CSI feedback can be achieved with a MAC layer approach. In this regard, a simple precoder such as ZF is considered. The ZF beamforming is asymptotically optimal to completely remove the interference [77]. The simplicity of this linear precoding approach is very much preferred from an implementation point of view. This means that the complexity needs to be handled by the scheduler, residing at the CCN. In [78], reducing the backhaul requirements with limited clusters of BSs was carried out via MAC layer coordination at the CCN. In [79, 80], utility functions of internet applications is used as a method for user selection in CoMP systems with limited backhaul. Their approach also reduces the overhead in the CSI feedback with the preselection of users.

In our MAC layer approach, the backhaul usage could result in the total number of precoding weights being less than or equal to the total number of CSI coefficients. This is primarily due to the scheduling constraint where a given set of UEs that feed back the CSI coefficients is not guaranteed to be served. Hence, to faithfully compare the MAC layer approach with the PHY layer approach, one has to consider what goes into the precoder in terms of the CSI that results in the precoding weights for the actual transmission. Thus, efficient backhauling can still be achieved with the MAC layer approach. On the contrary, with limited set of UEs, it can be argued that the MAC layer approach as a whole does not achieve efficient backhauling.

3. Precoding with optimization tools for efficient backhauling

> “What day is it,?” asked Pooh.
>
> “It’s today,” squeaked Piglet.
>
> “My favorite day,” said Pooh,
>
> — A. A. Milne
> Novelist, Playwright, Poet (18 Jan. 1882 - 1956)
> An extract from Winnie the Pooh (1924)

In this chapter, the focus is more on the optimization tools used for PHY layer precoding to achieve efficient backhauling. In this regard, a stochastic optimization algorithm such as PSO is used to design the precoding weights that leads to efficient backhauling. Even though PSO provides a stable equilibrium solution, it does not guarantee to provide a global optimum. However, different objectives can be quickly explored. Alternatively, convex optimization tool can also be applied for precoder design keeping efficient backhauling in mind. Transforming a non-convex problem into a convex problem could be regarded as an art in itself [81, 82, App. A]. Once the problem is made convex then it can be solved very efficiently. The chapter begins with a brief review of stochastic and convex optimization for precoder design that is considered in this thesis, taking PSO and SSOCP as an example. The chapter concludes with the pros and cons of using these different tools.

3.1. Precoding via stochastic optimization

Nature provides a lot of inspiration to gain insights into the working forces around us. An interesting part is how evolution has brought forth optimization as one of its core elements. Evolutionary algorithms are stochastic algorithms whose driving force is optimization. There are various evolutionary algorithms, such as ant colony optimization based on the movement of ants, PSO inspired from the swarming of birds, and genetic algorithms derived from the mutation of chromosomes over many generations [83].

Stochastic algorithms are used in designing hardware. For example, PSO is used for designing chipsets for lowering the heat dissipation or the run length of wires in a given circuitry. It is also used for designing antennas with a desired side-lobe level or the antenna element positions in a nonuniform array [84]. A comprehensive analysis of the publications on the applications of PSO is presented in [85]. PSO has been proposed to be used in some parts of a communication system. Limiting ourselves to the scope of this thesis, PSO has been proposed to find the optimal precoding vector that maximizes the throughput in a MU-MIMO system [86]. It is also used for optimizing the scheduling in the downlink for a MU-MIMO system [87]. Apart from [85], PSO was also proposed in a MIMO-orthogonal frequency-division multiplexing (OFDM) receiver for the initialization of channel estimates in iterative receiver structures that jointly perform channel estimation and decoding [88].

A flock of birds or a shoal of fish or a swarm of bees tend to move together as a group. The fish tend to avoid the shark by moving in a group without an apparent leader in the swarm. Thus making it harder for the predator to catch its prey. The birds move together looking for food, as more eyes can increase the chances of finding food. Scientists simulating the coherent movement of these birds based on the social interactions with their neighbors discovered that the birds were performing optimization [89]. In Fig. 3.1, a flock of birds can be seen flying together. This helps in reducing the drag and the effort needed for flying. PSO is viewed as a paradigm within the field of swarm intelligence and its differences with other evolutionary algorithms is captured in [90].

Figure 3.1.: Birds flying together to minimize the drag. This picture is taken by Peter M. Prehn, a Flickr user, and it is used here under CC BY-NC-ND license.

In the remaining of this subsection, the basic understanding of how the PSO works in finding the best possible precoding weights is presented. Each bird in a swarm carries the real and imaginary parts of the non-zero elements of the BF matrix, i.e., the ith member of the swarm is the ith *particle* that carries all the ($n = 2N_{\mathrm{T}}|\mathcal{B}||\mathcal{U}|$) BF coefficients. The '2' is due to PSO treating the real and the imaginary part of the complex BF coefficients as another dimension to the search space. Hence, the particle having the best n values needs to be found for a given objective function. For example, an infinite threshold would yield $n = 2N_{\mathrm{T}}|\mathcal{B}||\mathcal{U}|$ non-zero CSI coefficients in the aggregated channel matrix of size $[|\mathcal{U}| \times N_T|\mathcal{B}|]$. With an active set threshold of 0 dB then only the best link (or reference link) would be fed back by each UE yielding $n = 2 \cdot 1 \cdot N_T|\mathcal{U}|$. The real and the imaginary parts of the non-zero BF matrix, $\widetilde{\mathbf{W}}$, are mapped to a particle. This mapping, during initialization, is only for illustrating how the BF is translated to a particle. These steps can be omitted in the actual implementation. The position, $\mathbf{X}(i,j)$, and the velocity, $\mathbf{V}(i,j)$, of the ith particle with the jth BF coefficient are stochastically initialized as $\mathbf{X}(i,j) = x_{\min} + r \cdot (x_{\max} - x_{\min})$ and $\mathbf{V}(i,j) = \frac{1}{\Delta t}\left(-\frac{(x_{\max}-x_{\min})}{2} + s \cdot (x_{\max} - x_{\min})\right)$, respectively. Here r and s are random numbers picked from a uniform distribution in the interval $[0,1]$, and $x_{\max}$ is the maximum value that a BF coefficient is initialized with. This does not mean that the position of the particle will not exceed this value, i.e., the particles in the PSO can actually go beyond these limits. The same holds for the velocity of the particle, but it is restricted by a maximum velocity, $v_{\max}$, so that the particle does not diverge. The time step length is Δt, and the total number of particles is Q. Recall that each particle is indexed using the variable i, where each particle is carrying n BF coefficients. These coefficients are indexed using the variable j.

A given objective function is evaluated for every particle i carrying the BF coefficients, and it is demapped to form the BF matrix as $\widetilde{\mathbf{W}}(l,m) \leftarrow \{\mathbf{X}(i,j)\} + \mathrm{i} \cdot \{\mathbf{X}(i,j+1)\}, l \in \{1,\ldots,N_{\mathrm{T}}|\mathcal{B}|\}, m \in \{1,\ldots,|\mathcal{U}|\}$. The ith particle keeps a record of its best BF as $\mathbf{X}^{pb}(i,:)$, and the best BF achieved by any of the particles in the swarm is stored as $\mathbf{x}^{sb}$. The equations governing the update of the velocity and the position of a particle are:

$$\mathbf{V}(i,j) \leftarrow \psi \cdot \mathbf{V}(i,j) + c_1 \cdot p \cdot \left(\frac{\mathbf{X}^{pb}(i,j) - \mathbf{X}(i,j)}{\Delta t}\right) + c_2 \cdot q \cdot \frac{\mathbf{x}^{sb}(j) - \mathbf{X}(i,j)}{\Delta t}, \quad (3.1)$$

$$\mathbf{X}(i,j) \leftarrow \mathbf{X}(i,j) + \mathbf{V}(i,j) \cdot \Delta t. \quad (3.2)$$

The variables p and q are random numbers drawn from a uniform distribution in the interval $[0,1]$. The terms involving c_1 and c_2 are called the *cognitive* component and the *social* component, respectively. The cognitive component tells how much a given particle should rely on itself or believe in its previous memory, while the social component tells how much a given particle should rely on its neighbors. The cognitive and social constant factors, c_1 and c_2, are equal to 2, as highlighted in [89]. An *inertia weight*, ψ, is used to bias the current velocity based on its previous value, such that when the inertia weight is initially being greater than 1 the particles are biased to explore the search space. When the inertia weight decays to a value less than 1, the cognitive and social components are given more attention [91]. The decaying of the inertia weight is governed by a non-zero constant decay factor β, such that $\psi \leftarrow \beta\psi$ and ψ is confined within a limit.

The pseudocode of PSO described above is summarized in Alg. 3.1, and more details are presented in [Paper B].

Algorithm 3.1 Pseudocode for obtaining the precoding weights via PSO.

```
Initialization:
Determine the number of non-zero coefficients $n$ needed in the BF matrix, $\widetilde{\mathbf{W}}$
Map the BF to the $i$th particle:
  $\mathbf{X}(i,j) \leftarrow \Re\left\{\widetilde{\mathbf{W}}(l,m)\right\}, l \in \{1,\ldots,N_{\mathrm{T}}|\mathcal{B}|\}, m \in \{1,\ldots,|\mathcal{U}|\}$
  $\mathbf{X}(i,j+1) \leftarrow \Im\left\{\widetilde{\mathbf{W}}(l,m)\right\}$
Stochastically initialize particles with BF coefficients:
  $x_{\max} = 1/\max|\widetilde{\mathbf{H}}(i,j)|$
  $x_{\min} = -x_{\max}$
  Position: $\mathbf{X}(i,j) = x_{\min} + r \cdot (x_{\max} - x_{\min})$
  Velocity: $\mathbf{V}(i,j) = \frac{1}{\Delta t}\left(-\frac{(x_{\max}-x_{\min})}{2} + s \cdot (x_{\max} - x_{\min})\right)$
while Termination Criterion do
    for the $i$th particle in the swarm do
        Demap the variables in a particle to form the BF matrix
        $\widetilde{\mathbf{W}}(l,m) \leftarrow \{\mathbf{X}(i,j)\} + \mathrm{i} \cdot \{\mathbf{X}(i,j+1)\}$
        Evaluate the objective function $f(\mathbf{X}(i,:))$
        Store:
        if $f(\mathbf{X}(i,:)) < f(\mathbf{X}^{pb}(i,:))$ then
            Particles' Best: $\mathbf{X}^{pb}(i,:) \leftarrow \mathbf{X}(i,:)$
        end if
        if $f(\mathbf{X}(i,:)) < f(\mathbf{X}^{sb}(i,:))$ then
            Swarm's Best: $\mathbf{x}^{sb} \leftarrow \mathbf{X}(i,:)$
            $\widetilde{\mathbf{W}}^{\mathbf{sb}}(l,m) \leftarrow \left\{\mathbf{x}^{sb}(j)\right\} + \mathrm{i} \cdot \left\{\mathbf{x}^{sb}(j+1)\right\}$
        end if
    end for
    for Each particle in the swarm with BF coefficients do
        Update:
        Velocity: $\mathbf{V}(i,j) \leftarrow \psi \cdot \mathbf{V}(i,j) + c_1 \cdot p \cdot \left(\frac{\mathbf{X}^{pb}(i,j)-\mathbf{X}(i,j)}{\Delta t}\right) + c_2 \cdot q \cdot \frac{\mathbf{x}^{sb}(j)-\mathbf{X}(i,j)}{\Delta t}$
        Restrict velocity: $|\mathbf{V}(i,j)| < v_{\max}$
        Position: $\mathbf{X}(i,j) \leftarrow \mathbf{X}(i,j) + \mathbf{V}(i,j) \cdot \Delta t$
    end for
    $\psi \leftarrow \beta\psi$
end while
return BF Weight Matrix, $\widetilde{\mathbf{W}}^{\mathbf{sb}}$
```

3.2. Precoding via convex optimization

Convex problems can be solved either in closed form or numerically [92, 93]. In reality, most engineering problems are not convex, such as the weighted sum rate maximization which is also NP-hard [94, 95]. An optimization problem in the standard form can be written as

$$\begin{aligned} \underset{\mathbf{x}}{\text{minimize}} \quad & f_0(\mathbf{x}) \\ \text{subject to} \quad & f_i(\mathbf{x}) \leq 0, 1 \leq i \leq P, \\ & h_i(\mathbf{x}) = 0, 1 \leq i \leq Q. \end{aligned} \tag{3.3}$$

The problem is said to be convex if the objective, f_0 and the inequality constraints functions f_i are convex, and the equality constraints functions h_i are affine, where $\mathbf{x} \in \mathbb{R}^N$ is the optimization variable. A function is said to be convex i.e., $f(\alpha\mathbf{x}+\beta\mathbf{y}) \leq \alpha f(\mathbf{x})+\beta f(\mathbf{y})$, for all $\mathbf{x}, \mathbf{y} \in \mathbb{R}^N$ and $\alpha, \beta \in \mathbb{R}$ with $\alpha+\beta = 1$, $\alpha, \beta \geq 0$. For convex problems, any locally optimal point is globally optimal. Transforming the primal problem (3.3) to a dual problem using the Lagrange duality theory could be simpler to solve the problem. The optimal value obtained from the dual problem serves as the lower bound for the primal optimal value. The Karush–Kuhn–Tucker optimality conditions could be exploited in most cases to obtain a closed-form solution. There are different classes of convex problems depending on the form taken by f_i and h_i. When f_0 is quadratic and the constraints are affine, this results in a quadratic program. A second order cone program (SOCP) includes constraints of the form

$$||\mathbf{A}\mathbf{x} + \mathbf{b}||_2 \leq \mathbf{c}^T\mathbf{x} + d, \tag{3.4}$$

where $\mathbf{A} \in \mathbb{R}^{K\times N}$, $\mathbf{b} \in \mathbb{R}^K$, $\mathbf{c} \in \mathbb{R}^N$ and $d \in \mathbb{R}$ are given.

There are many algorithms in the literature that address the nonconvex problem of weighted sum rate maximization under per-antenna power constraints when designing the precoding weights. In this thesis, this problem is studied in [Paper A] under the constraint of incomplete feedback and efficient backhauling. While in [Paper D], a local precoder design is applied when there is new CSI. Some of the techniques applied are linearization of the nonconvex constraint, successive convex approximations (SCA) where the problem that is made convex is iterated until convergence [48, 96, 97], block coordinate descent technique involves sequentially fixing all but one of the optimization variables and iterating between them until convergence [75, 76]. There are various software packages such as CVX [92] that support different solvers such as Gurobi [98], MOSEK [99], SDPT3, SeDuMi, etc.

In this section, precoder design for efficient backhauling is presented based on [Paper A]. Some of the art forms of making the problem convex is considered. SSOCP is based on SCA that can efficiently solve the problem with guaranteed convergence in every iteration. The optimization framework originally proposed in [100] is adopted for linearizing a non-convex constraint that forms a constraint for the useful signal. The techniques in [97, 101] are also adopted for handling the SINR, and reformulate as second order cone (SOC) constraints. The maximization of weighted sum rate R_{tot}, recall (2.3) with per-antenna power constraint and incomplete feedback is formulated as

$$\begin{aligned} \underset{\mathbf{w}_{b,u}}{\text{maximize}} \quad & \prod_{u} (1+\gamma_u)^{\alpha_u} \\ \text{subject to} \quad & \sum_{u \in \mathcal{U}_b} |w_{b,u}^{(k)}|^2 \leq P_{\text{max}}, \forall b \in \mathcal{B}_u, k = 1, \ldots, N_{\text{T}}, \end{aligned} \tag{3.5}$$

where the logarithm being a monotonically non-decreasing function can be removed from the objective, and P_{max} is the maximum transmit power of an antenna of a BS serving a set of $\mathcal{U}_b$ UEs. This can be recast by letting $t_u = (1+\gamma_u)^{\alpha_u}$ where γ_u from (2.2) is manipulated to include the long term channel statistics from [Paper A] and adding a slack variable β_u as

$$\underset{t_u, \beta_u, \mathbf{w}_{b,u}}{\text{maximize}} \quad \prod_{u} t_u \tag{3.6a}$$

$$\text{subject to} \quad \frac{\left| \sum_{b \in \mathcal{B}_u} \mathbf{h}_{b,u} \mathbf{w}_{b,u} \right|^2}{\beta_u} \geq t_u^{1/\alpha_u} - 1, \forall u \in \mathcal{U}, \tag{3.6b}$$

$$\sum_{i \neq u} \left\{ \left| \sum_{b \in \mathcal{B}_i \cap \mathcal{B}_u} \mathbf{h}_{b,u} \mathbf{w}_{b,i} \right|^2 + |\mathcal{B}_i \backslash \mathcal{B}_u| \sum_{b \in \mathcal{B}_i \backslash \mathcal{B}_u} \lambda_{b,u}^2 ||\mathbf{w}_{b,i}||_2^2 \right\} + N_0 \leq \beta_u, \quad \forall u \in \mathcal{U}, \tag{3.6c}$$

$$\sum_{u \in \mathcal{U}_b} |w_{b,u}^{(k)}|^2 \leq P_{\text{max}}, \forall b \in \mathcal{B}_u, k = 1, \ldots, N_{\text{T}}. \tag{3.6d}$$

The LHS of (3.6b) is of the form quadratic over linear, which is a convex function, and t_u^{1/α_u} is convex only when $0 < \alpha_u \leq 1$, and concave when $\alpha_u > 1$. Thus, the constraint is non-convex. A concave approximation of the LHS can be obtained as in [100, (6b)], by defining the following expressions

$$p_u \triangleq \Re \left\{ \sum_{b \in \mathcal{B}_u} \mathbf{h}_{b,u} \mathbf{w}_{b,u} \right\} \quad \text{and} \quad q_u \triangleq \Im \left\{ \sum_{b \in \mathcal{B}_u} \mathbf{h}_{b,u} \mathbf{w}_{b,u} \right\}. \tag{3.7}$$

Applying the first order Taylor expansion for $\frac{(p_u^2 + q_u^2)}{\beta_u}$ around the local point $\left\{ \widetilde{p}_u, \widetilde{q}_u, \widetilde{\beta}_u \right\}, \forall u \in \mathcal{U}$, (3.6b) becomes

$$\frac{2\widetilde{p}_u}{\widetilde{\beta}_u} (p_u - \widetilde{p}_u) + \frac{2\widetilde{q}_u}{\widetilde{\beta}_u} (q_u - \widetilde{q}_u) + \frac{\widetilde{p}_u^2 + \widetilde{q}_u^2}{\widetilde{\beta}_u} \left(1 - \left(\frac{\beta_u - \widetilde{\beta}_u}{\widetilde{\beta}_u} \right) \right) + 1 \quad \geq \quad t_u^{1/\alpha_u}. \tag{3.8}$$

When $\alpha_u > 1$, t_u^{1/α_u} in the RHS of (3.8) is not convex, it needs to be replaced by its upper bound. Doing as in [100]-[101], with the first order approximation at the point $\widetilde{t}_u$, the RHS of (3.8) becomes

$$t_u^{1/\alpha_u} \leq \widetilde{t}_u^{1/\alpha_u} + \frac{1}{\alpha_u} \widetilde{t}_u^{\frac{1}{\alpha_u} - 1} \left(t_u - \widetilde{t}_u \right). \tag{3.9}$$

Otherwise, all the α_u can be scaled such that t_u^{1/α_u} becomes convex $\forall\alpha_u$. Therefore, combining with (3.8) results in

$$\begin{aligned}\frac{2\widetilde{p}_u}{\widetilde{\beta}_u}\left(p_u-\widetilde{p}_u\right)+\frac{2\widetilde{q}_u}{\widetilde{\beta}_u}\left(q_u-\widetilde{q}_u\right)+\frac{\widetilde{p}_u^2+\widetilde{q}_u^2}{\widetilde{\beta}_u}\left(1-\left(\frac{\beta_u-\widetilde{\beta}_u}{\widetilde{\beta}_u}\right)\right)+1&\\ \geq \widetilde{t}_u^{1/\alpha_u}+\frac{1}{\alpha_u}\widetilde{t}_u^{\frac{1}{\alpha_u}-1}\left(t_u-\widetilde{t}_u\right).&\qquad(3.10)\end{aligned}$$

Now consider (3.6c) which can be rewritten as an SOC constraint [101]

$$\begin{aligned}\left(\sum_{i\neq u}\left\{\left|\sum_{b\in\mathcal{B}_i\cap\mathcal{B}_u}\mathbf{h}_{b,u}\mathbf{w}_{b,i}\right|^2+|\mathcal{B}_i\backslash\mathcal{B}_u|\sum_{b\in\mathcal{B}_i\backslash\mathcal{B}_u}\lambda_{b,u}^2||\mathbf{w}_{b,i}||_2^2\right\}+\left(\sqrt{N_0}\right)^2+\frac{1}{4}\left(\beta_u-1\right)^2\right)^{1/2}&\\ \leq\frac{1}{2}\left(\beta_u+1\right),\forall u\in\mathcal{U}.&\qquad(3.11)\end{aligned}$$

Therefore, the reformulated convex problem for precoder design with the objective of maximizing the geometric mean of t_u becomes

$$\begin{aligned}\underset{t_u,\beta_u,\mathbf{w}_{b,u}}{\text{maximize}}\quad&\left(\prod_{u=1}^{|\mathcal{U}|}t_u\right)^{1/|\mathcal{U}|}\\ \text{subject to}\quad&(3.6\text{d}),(3.10)\text{ and }(3.11),\end{aligned}\qquad(3.12)$$

where the geometric mean is concave, and the exponent does not affect the optimal value. This is performed merely to simplify the implementation. Also, the interfering terms can be collected in a vector as

$$\mathbf{r}_i=\begin{bmatrix}\sum\limits_{b\in\mathcal{B}_i\cap\mathcal{B}_u}\mathbf{h}_{b,u}\mathbf{w}_{b,i}\\ \sqrt{|\mathcal{B}_i\backslash\mathcal{B}_u|}\lambda_{b',u}\mathbf{w}_{b',i}\end{bmatrix},b'\in\mathcal{B}_i\backslash\mathcal{B}_u,\forall i\neq u.\qquad(3.13)$$

The SSOCP with the above simplified notation is summarized in Alg. 3.2.

Algorithm 3.2 SSOCP algorithm for precoder design

```
1: To avoid numerical instability, rescale the aggregated channel matrix and the noise power with a factor of the least pathloss such that the SINR is the same.
2: Set $maxRetries$ := MAXRETRIES
3: while $maxRetries$ do
4:     Randomly initialize the non-zero precoding weight, $\mathbf{w}_{b,u}$, from $\mathcal{CN}(0,1)$, apply efficient backhauling, and ensure the power of each antenna is limited to $P_{\max}$.
5:     Calculate $\gamma_u$ as in [Paper A]$\forall u$.
6:     Set $n := 0$
7:     Evaluate $\widetilde{p}_u^{(n)}$ and $\widetilde{q}_u^{(n)}$ from (3.7).
8:     Evaluate $t_u^{(n)} = (1+\gamma_u)^{\alpha_u}$ and $\beta_u^{(n)} = \frac{\left(\widetilde{p}_u^{(n)}\right)^2 + \left(\widetilde{q}_u^{(n)}\right)^2}{t_u^{(n)}-1}$
9:     Set $maxIter$ := MAXITER
10:    while $maxIter$ AND † do
11:        Treat $p_u^{(n)}$ and $q_u^{(n)}$ as expressions in CVX [92] which will be used in (3.10).
12:        Solve the convex problem (3.12) as
               $$\begin{aligned} \underset{t_u, \beta_u, \mathbf{w}_{b,u}}{\textbf{maximize}} \quad & \textbf{geo\_mean}\,(t_u) \\ \text{subject to} \quad & \left\| \begin{matrix} \mathbf{r}_i \\ \sqrt{N_0} \\ \frac{1}{2}(\beta_u - 1) \end{matrix} \right\|_2 \leq \frac{1}{2}(\beta_u + 1)\,, \\ & \forall i \in \mathcal{U}, \\ & (3.6\text{d}), \\ & \text{and}\,(3.10), \forall u \in \mathcal{U}. \end{aligned}$$
13:        Update: $t_u^{(n+1)} := t_u^{(n)}, \beta_u^{(n+1)} := \beta_u^{(n)}$
14:        Update: $p_u^{(n+1)} := p_u^{(n)}, q_u^{(n+1)} := q_u^{(n)}$
15:        Update: $n := n+1$
16:        $maxIter := maxIter - 1$
17:        Evaluate and save the best weighted sum rate achieved so far, as well as the corresponding precoding weights.
18:    end while
19:    $maxRetries := maxRetries - 1$
20: end while
21: return Precoding matrix
```

† The weighted sum rate does not improve within a certain tolerance.

The weighted sum rate maximization is a non-convex problem, and the solution may end up as an inefficient local optimum. In order to further improve the solution, random initialization similar to [102] is introduced, where the best solution is selected out of a number of random initializations. For a given aggregated channel matrix, a small increase in the number of random initializations, as in step 2, increases the probability to find a solution close to the global optimal [102].

3.3. The pros and cons

Some extrapolated results on the optimization tools based on the PHY layer precoder design are captured in Table 3.1. The PSO and SSOCP are taken as examples for stochastic and convex optimization algorithms, respectively. PSO even with multi-start struggles with the problem size when compared to SSOCP, however, stable equilibrium solution can be obtained with PSO even when the objective of the problem is obfuscated. In App. B, weighted interference minimization is explored with PSO and compared with maximizing the minimum SINR of the UE. PSO would require a one-time mapping of the optimization variables to that of the particles and any new objective could easily be applied. While in the case of SSOCP the subproblems are made convex and any change in objective requires reformulation of the problem to make it convex.

Table 3.1.: Comparison of PSO and SSOCP

Characteristics	PSO	SSOCP
Increase in problem size	Poor	Good
Obfuscated nonconvex objective/ constraint	Easy to get a result, problem mapping required	Difficult to get a result, until made convex
	No approximations when mapping the problem	Approximations may be required to make it convex
Hardware implementation	Probably difficult to realize for large problems	Probably difficult due to SCA

4. Conclusions and future challenges

> "How we look for new laws: Guess→ Compute consequences → Compare experiment. If the guess disagrees with the experiment, then it is wrong. That is all there is to it".
>
> — Richard Feynman
> Physicist (11 May 1918-1988)
> The Scientific Method (1964)

This chapter introduces the contributions of this thesis, in particular emphasizing the work performed by the author and coauthors. It concludes with the challenges in realizing CoMP.

4.1. Contributions of the thesis and my roles

The focus of this thesis is to provide solutions to efficiently use the backhaul resources in a CoMP system. An OSI model based approach for interference mitigation in JT-CoMP is applied to achieve efficient backhauling. The papers presented in this work can be categorized based on the following: (a) efficient backhaul based on a PHY layer approach [Paper A/B], (b) efficient backhaul reduction based on a MAC layer approach [Paper C]. The PHY and MAC layer approaches focus on a centralized approach. In [Paper D], the focus transitions to using a decentralized approach for local precoder design (LPD) so that backhaul use can be lowered when there is local CSI updates. The papers can be summarized as depicted in Table 4.1.

Table 4.1.: A high level view of the contributions in this thesis

Layer	CoMP Arch.	Backhaul reduction approaches	Contributions in
PHY	Centralized	SSOCP/PSO based precoding	Paper A/B
MAC	Centralized	Scheduling	Paper C
PHY	Decentralized	LPD based precoding	Paper D

The thesis is mainly based on the following papers aimed towards efficient backhauling, and they are briefly introduced as follows:

- **Paper A**: T.R. Lakshmana, A. Tölli, R. Devassy, and T. Svensson, "Precoder Design with Incomplete CSI for Joint Transmission," *accepted in IEEE Trans. on Wireless Commun.,* Oct. 2015.

In this PHY layer approach, relative thresholding is used to reduce the CSI feedback load. However, this approach presents challenges in designing the precoder due to this incomplete/limited information. For a centralized precoder design, prior works considered the unavailable CSI to be modeled as zeros. In this work, we pessimistically incorporate the large scale fading statistics as part of the statistical interference for the incomplete CSI. The precoder design problem is efficiently solved using a SSOCP capable of achieving efficient backhauling. As an alternative to SSOCP, we derive the precoder based on the weighted MSE criterion. Branch and bound technique is used to show that the proposed SSOCP is very close to the optimal. Also, the performance is compared with a stochastic algorithm such as PSO with the increase in the problem size. It was found that the PSO algorithm scales poorly. Prior to this work in [Paper A], PSO was considered in [Paper B].

- **Paper B**: T.R. Lakshmana, C. Botella, and T. Svensson, "Partial Joint Processing with Efficient Backhauling using Particle Swarm Optimization," *EURASIP Journal of Wireless Commun. and Netw..*, vol. 2012, 2012.

  PSO was one of the first approaches studied to address the problem of interference mitigation with efficient backhauling. This PHY layer approach is an extension of [103], where the PSO is analyzed in greater detail for backhaul load reduction. A simple linear zero-forcing precoder is very attractive. However, they fall short of achieving efficient backhauling. A stochastic algorithm such as PSO is used for precoder design in a CoMP setup that achieves the goal for efficient backhauling. The objective function of sum rate maximization is explored where it can be biased towards UEs with good SINR compared to the low SINR UEs. In the ARTIST4G project, user fairness was heavily stressed. This lead to the proposal of a new metric called *weighted interference minimization* (WIM), where the objective function is to minimize interference and recursively improve the weak SINR UEs. In App. B, the weighted interference minimization is compared with the maximization of the minimum SINR UE, and the benefits of considering weighted interference minimization is highlighted.

  The PSO was used with field measurement data where the statistical uncertainty of CSI or imperfect CSI were considered. Various algorithms from different partners of the ARTIST4G consortium were considered. It was found that the PSO outperformed all the other algorithms in the scenarios considered. Some of the interesting results from [104, 105] are provided in App. A, which complement the work performed on PSO.

- **Paper C**: T.R. Lakshmana, J. Li, C. Botella, A. Papadogiannis and T. Svensson, "Scheduling for Backhaul Load Reduction in CoMP," in *proc. IEEE Wireless Commun. and Netw. Conf.* (WCNC), Apr. 2013.

  In this MAC layer approach, scheduling is explored for efficient backhauling, where a subset of UEs and BSs combinations are considered. Constrained and unconstrained scheduling are proposed. With the constrained scheduling approach, subsets are formed by removing zeros from the aggregated channel matrix, while in the case of unconstrained scheduling approach, the zeros are allowed, however this leads to the zeros showing up in the precoding matrix where it might not be needed. Our results show that the constrained scheduling approach outperforms the state of the art block diagonal approach, in terms of the average sum rate per backhaul use.

- **Paper D**: T.R. Lakshmana, A. Tölli, and T. Svensson, "Improved Local Precoder Design for JT-CoMP with Periodical Backhaul CSI Exchange," *resubmitted to IEEE Commun. Lett.,* Oct. 2015.

  Unlike the other papers in this thesis, a distributed JT-CoMP architecture is considered where the CSI is exchanged between the BSs periodically. Mobility of a UE could trigger a CSI update to its local BS, where this local BS can design the local precoding weights in a decentralized fashion in-between the periodic exchange of CSI between the BSs. The results show that with local decentralized precoding, some of the gains of distributed precoder design can still be preserved.

Other related contributions

In [103], a PHY layer approach precoding approach is investigated for minimizing interference and achieve efficient backhauling. The state of the art precoding algorithm for backhaul reduction in [68] is compared with PSO. This conference article led to work in [Paper B]. In [33], a decentralized network architecture is considered for backhaul load reduction. In this setting, the CSI coefficients broadcasted by the UE undergo a certain probability of error as they are received at different BSs, hence, giving rise to precoding loss and scheduling loss. It is shown that with a minimal exchange of scheduling information, the decentralized architecture can achieve the rates comparable to the centralized approach that makes use of the CCN, thereby reducing the stringent latency constraints in the backhaul. In this work, the phase information of the CSI alone is considered to undergo errors while the amplitude or channel quality indicator (CQI) can be assumed to be error free. Moreover, one could protect the CQI with robust channel codes, whose overhead is not significant. In [106], we investigate how the frequency resources should be allocated to the UEs in the case of non-coherent JT-CoMP with CSI at the receiver only. In this regard, the UEs are served on shared frequency allocation or dedicated or partly shared and partly dedicated. We discovered that it is best to completely share the frequency resource at low/medium SNRs, or completely dedicate the frequency resources at high SNR. As a fallback mechanism a closed loop system with one-bit hybrid automatic repeat request is also considered, resulting in high long term throughput and low outage probability with affordable average delay under slow and fast fading conditions. In [107], we consider a subcluster or an active set of BSs that are dynamically defined by the UE. In a frequency selective channel such as the WINNER II channel model, the active set thresholding can be performed frequency adaptively per resource block or non-adaptively, when the relative thresholding is averaged over all the resource blocks. The advantages and disadvantages of these approaches are studied in [107].

My roles in these contributions

Apart from the interactions with my co-authors, my contributions for the papers included in this thesis are:

- Defining efficient backhauling where the precoding weights is correspondingly equivalent to the CSI coefficients being fed back from the UEs [Paper A/B/C].
- Use PSO to achieve efficient backhauling [Paper B].
- To find the bounds on the sum rate with incomplete CSI and efficient backhauling. As stated in [14], with partial CSIT, we numerically arrive at these bounds [Paper A].
- Derived the use of long term channel statistics, the MSE, branch and bound, with feedback from coauthors [Paper A].
- Introduced the idea of new CSIT and its scope of performing local precoder design without sharing the CSI with other cooperating BSs within the transmission epoch [Paper D].
- Performance of precoders in ARTIST4G were evaluated by my colleagues Rikke Apelfröjd from Uppsala University and Richard Fritzsche from TU Dresden. I was involved in integrating the PSO algorithm in their framework at Uppsala University. These results are captured in App. A.
- Implemented all the algorithms except for the block diagonalization [Paper C] which was performed by Jingya Li.
- Performed all the analytical investigations and simulations in all the papers.

4.2. Challenges for CoMP in practice

In this section, some of the major challenges to realize CoMP in practice are discussed with potential future steps.

4.2.1. CSI uncertainty, clustering, synchronization

From a standardization perspective, one of the main challenges of realizing a centralized JT-CoMP is the high impact on the user plane where the user data is required to be available at all the coordinating BSs. Suitable clustering of BSs exploiting the geometry of deployment and grouping of UEs could alleviate this overhead. Caching in the backhaul would benefit in realizing JT-CoMP, and that the price of memory will be cheaper compared to having low-latency networks [108]. However, the signaling information will still pose as a bottleneck, and efficient backhauling will be necessary. In [28], the authors conclude that downlink CoMP is not a game-changer to meet the growing capacity demands. In light of the recent trends with operators tending towards Cloud-RAN, providing centralization and virtualization [109, 110], there is still hope for JT-CoMP. The gains with centralization could be worsened with the increase in the number of antennas at the cell-sites due to the load on the fronthaul links. However, partial centralization could provide flexible and scalable solutions [111]. The contributions from [Paper A/B/C] could be useful in mitigating interference in this centralized setup and also achieve efficient backhauling.

Apart from this, acquiring the CSI, the need for CSIT and coordinating this information with various BSs is still a challenge [112]. Some promising results are presented in [113, 114] for the predicted CSI. The quantity of CSI feedback can be reduced with relative thresholding, which lowers the signaling overhead in the air as well as the backhaul. However the quality of CSI is prone to quantization errors, where the complex channel coefficient needs to be represented with finite precision. The promising results from [Paper A] needs to be studied under the lens of CSI uncertainty, a joint effort with Uppsala university is planned.

Synchronization is another major aspect that should be addressed to realize CoMP. Here all the cooperating BSs and UEs need to be synchronized for JT-CoMP in a given frequency-time resource. Different local oscillators at different BSs and UEs poses a challenge in having a common time. The exchange of CoMP IE with suitable synchronization information via the X2 interface could help, where these timing offset could be absorbed by the precoder. Cooperating BSs via the proprietary X2 application protocol may not be the optimal path, as sharing the network infrastructure between different operators could reduce the interference in the system. This will result in better use of resources. Hence, one may need to standardize the X2 protocol.

As a last resort, the UE receiver should be capable to suppress interference under favorable conditions while the network has the primary responsibility for interference mitigation for the UEs. Careful network design of various components can realize the gains of JT-CoMP. In particular, MOO [8] could play an important role in integrating CoMP with the requirements of 5G.

4.2.2. Practical tools

As pointed out in [82, 93] from [115]: “In fact the great watershed in optimization isn’t between linearity and nonlinearity, but convexity and nonconvexity. Even for problems that aren’t themselves of convex type, convexity may enter for instance in setting up subproblems as part of an iterative numerical scheme”. A NP-hard problem such as weighted sum rate maximization being nonconvex maybe iteratively solved by making the subproblems convex. With incomplete CSI, equivalent efficient backhauling can be achieved via numerical solutions as envisioned in [14].

Due to the limitations of PSO with increase in problem size, it might not be a candidate to be implemented in the BS/CCN hardware for precoder design. However, with a smaller problem size, PSO performs well when the CSI is imperfect due to prediction errors and quantization errors as observed in App. A. The limitations of PSO should not deter the use of stochastic optimization techniques in understanding the solution space. As the PSO can be applied to any type of problem be it nonlinear or nonconvex, the challenge is in the mapping of a given problem to PSO. As observed with SSOCP, successive convex approximations are used to solve the problem of sum rate maximization recursively. Even though the subproblem solved is optimal, the recursive nature could hinder its deployment. Especially when it comes to IoT where latency and memory requirements are at a premium in these embedded systems. Simple linear approaches such as ZF is very attractive to be used in practice. The complexity of ZF is further reduced using Neumann series based approximations [116]. Even though this is a suboptimal approach, it could be more practical depending on the tradeoff in terms of performance and complexity.

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