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ΤΕΧΝΙΚΕΣ RATE SPLITTING ΓΙΑ ΤΟΝ ΠΕΡΙΟΡΙΣΜΟ ΤΗΣ ΠΑΡΕΜΒΟΛΗΣ ΣΕ NETWORK MIMO ΣΥΣΤΗΜΑΤΑ

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Περίληψη

Η ενιαία επαναχρησιμοποίηση συχνοτήτων (single frequency reuse) χρησιμοποιείται ευρέως στα πιο εξελιγμένα σύγχρονα ασύρματα συστήματα, όπως το Long Term Evolution Advanced (LTE-A) [1], για την αντιμετώπιση του μέσου αυξανόμενου throughput των κυψελών, χωρίς επέκταση του εύρους ζώνης. Όμως, αν σε αυτά τα συστήματα απουσιάζουν οι τεχνικές περιορισμού παρεμβολής, οι cell-edge user equipments (UEs) θα υποφέρουν από ισχυρή παρεμβολή γειτονικών κυψελών, που υποβαθμίζει το UE throughput. Με σκοπό να βελτιωθεί το μέσο throughput των κυψελών καθώς και το cell-edge UE throughput, μία ισχυρή τεχνική περιορισμού της παρεμβολής αποτελεί αναπόφευκτο κομμάτι των ασύρματων συστημάτων.

Διαφορετικές τεχνικές περιορισμού των παρεμβολών έχουν προταθεί πρόσφατα. Η πρώτη κατηγορία χρησιμοποιεί fractional frequency reuse [2], τεχνική που ευρέως μελετάται στα Long Term Evolution Advanced (LTE) συστήματα. Η βασική ιδέα είναι να ανατεθεί μόνο ένα μέρος του εύρους ζώνης σε cell-edge UEs για να μειωθεί η παρεμβολή και να βελτιωθεί το cell-edge UE throughput. Όμως η μέθοδος ανάθεσης μειωμένης ισχύος μετάδοσης σε μερικές υποζώνες θυσιάζει το μέσο cell throughput γειτονικών τομέων [3].Η δεύτερη κατηγορία υιοθετεί coordinated beamforming [4], τεχνική γνωστή ως coordinated multi-point μετάδοση (CoMP) [5] στο LTE-A σύστημα. Η βασική ιδέα των σύγχρονων CoMP σχημάτων είναι να επιτρέπουν στους σταθμούς βάσης (BSs) να συντονίζουν το beamforming, προκειμένου να μειωθεί η inter-cell interference. Όμως ο συντονισμός απαιτεί τεράστιο overhead στην ασύρματη διασύνδεση και στο backhaul εξαιτίας του ότι η πλήρης channel state information (CSI) πρέπει να διαμοιραστεί μεταξύ των BSs. Η τρίτη κατηγορία αφορά στον περιορισμό της παρεμβολής με τη τεχνική rate splitting [6], [7]. Σύμφωνα με αυτήν την τεχνική, οι προς μετάδοση ροές δεδομένων χωρίζονται σε δύο μέρη: στην common data stream που αποκωδικοποιείται και στους δύο UEs, και στην private data stream που αποκωδικοποιείται μόνο στους προκαθορισμένους UEs. Αποκωδικοποιώντας την common data stream από την παρεμβολή, μέρος αυτής απορρίπτεται και συνεπώς το UE throughput βελτιώνεται.

Μελέτες της πληροφορίας έχουν δείξει, ότι ο περιορισμός της παρεμβολής με την τεχνική rate splitting, είναι μία πολλά υποσχόμενη τεχνική στο κανάλι παρεμβολής. Στο [6], οι Han and Kobayashi εξήγαγαν το πιο γνωστό επιτεύξιμο rate bound για ένα Gaussian κανάλι παρεμβολής βασισμένο σε rate splitting σχήμα. Ο Etkin et al. [7] έδειξαν ότι ένα απλό rate splitting σχήμα μπορεί να επιτύχει rates μέσα σε ένα bit επιτεύξιμου rate bound σε ένα Gaussian κανάλι παρεμβολής δύο χρηστών και ότι το rate splitting σχήμα απαιτεί μόνο την ανταλλαγή πληροφορίας για τον λόγο σήματος προς θόρυβο (SNR) και παρεμβολής προς θόρυβο (INR), μειώνοντας έτσι καθυστέρηση και overhead στην ανατροφοδότηση και στο backhaul.

Πρόσφατα, έρευνες εστιάζουν στην υιοθέτηση του rate splitting για πρακτικές εφαρμογές. Στα [8] και [9], οι προς μετάδοση ροές δεδομένων χωρίζονται σε δύο μέρη, αλλά οι μέθοδοι που εφαρμόζονται προκειμένου να αποφασίσουν το ποσοστό διαίρεσης ισχύος, είναι διαφορετικοί. Στο [8], ο λόγος διαχωρισμού ισχύος βασίζεται σε heuristic τιμές. Ο λόγος για την επιλογή αυτών των τιμών δεν εξηγείται. Στο [9], ο λόγος διαχωρισμού ισχύος αποφασίζεται από τη διασφάλιση επίτευξης της ποιότητας εξυπηρέτησης της συσκευής. Η μέθοδος αυτή χωρίζει μόνο μία προς μετάδοση ροή δεδομένων σε δύο μέρη, έτσι επιτυγχάνει περιορισμένη βελτίωση όταν και οι δύο UEs υποφέρουν από ισχυρή παρεμβολή. Στο [10], προτείνεται ένα νέο πρακτικό σχήμα ονομαζόμενο multi-layer rate-splitting (MLRS). Αυτό το σχήμα διαχωρίζει τις προς μετάδοση ροές δεδομένων σε πολλαπλά μέρη και η κατανομή ισχύος μεταξύ των πολλαπλών τμημάτων υπολογίζεται από έναν αλγόριθμο κατανεμημένης ανάθεσης ισχύος. Τα αποτελέσματα της προσομοίωσης δείχνουν ότι το multi-layer rate-splitting σχήμα μπορεί να προσεγγίσει το επιτεύξιμο rate bound σε ένα κανάλι παρεμβολής δύο χρηστών. Όμως ένα σημαντικό χάσμα υπάρχει μεταξύ του rate ενός πρακτικού συστήματος και της Gaussian χωρητικότητας εισόδου του συστήματος. Για να περιοριστεί αυτό το κενό, στο [11] προτείνεται ένα αποτελεσματικό και πρακτικό multi-layer rate-splitting σχήμα. Συνδυάζει το multi-layer rate-splitting σχήμα με διαμόρφωση και μέθοδο προσαρμοζόμενης κωδικοποίησης. Τα αποτελέσματα της προσομοίωσης δείχνουν ότι το προτεινόμενο multi-layer rate-splitting σχήμα με προσαρμογή MCS, βελτιώνει σημαντικά την απόδοση της cell-edge UE σε ένα ρεαλιστικό δίκτυο και επιτυγχάνει περισσότερη «δικαιοσύνη» μεταξύ και των δύο UEs .

Στους παραδοσιακούς σχεδιασμούς κάθε σταθμός βάσης αποκτά από το δίκτυο κορμού τα δεδομένα που προορίζονται για τους χρήστες της περιοχής κάλυψης του: τα δεδομένα δεν είναι διαθέσιμα σε πολλούς σταθμούς βάσης (Interference channel). Πρόσφατη έρευνα βασισμένη στη θεωρία MIMO, πρότεινε τα οφέλη της χαλάρωσης αυτού του περιορισμού, επιτρέποντας έτσι δεδομένα να μοιράζονται σε πολλαπλούς πομπούς. Σε ένα τέτοιο σενάριο, πραγματοποιείται πολύ-κυψελική επεξεργασία με τη μορφή της κοινής προ- κωδικοποίησης: το σύστημα αυτό αναφέρεται ως network MIMO. Ένα μειονέκτημα της κατερχόμενης ζεύξης network MIMO είναι η απαίτηση μιας μεγάλης υποδομής backhaul, που μπορεί να αμβλυνθεί μέσω της εξυπηρέτησης μόνο υποσυνόλων από UEs με κοινή μετάδοση [12], διαιρώντας ένα κυψελοειδές δίκτυο σε μικρά υποσυστήματα, όπου τα συστήματα αυτά μπορούν να εφαρμοστούν σε τοπικό επίπεδο [13], ή χρησιμοποιώντας ορισμένα σχήματα BS cooperation που μπορούν να βελτιώσουν περαιτέρω το trade off μεταξύ των rates και του απαιτούμενου backhaul [14].

Ορισμένοι συγγραφείς έχουν αντιμετωπίσει το πρόβλημα της κοινής μετάδοσης όταν οι backhaul συνδέσεις μεταξύ της κεντρικής μονάδας και των πομπών (the base stations), ή μεταξύ του τελευταίου, είναι πεπερασμένες. Σε μια τέτοια περίπτωση το προκύπτον πολύ-κυψελικό κανάλι δεν αντιστοιχεί ούτε σε ένα MIMO broadcast channel, ούτε σε ένα interference channel . Μεταξύ άλλων, στο [15] και [16], η από κοινού κωδικοποίηση για την κατερχόμενη ζεύξη ενός κυψελωτού συστήματος μελετάται υπό την παραδοχή ότι οι σταθμοί βάσης συνδέονται σε μία κεντρική μονάδα μέσω συνδέσεων πεπερασμένης χωρητικότητας. Οι συγγραφείς ερευνούν διαφορετικά σχήματα μετάδοσης και τρόπους χρήσης της backhaul χωρητικότητας στο πλαίσιο μιας τροποποιημένης έκδοσης του Wyner's channel model.

Σε αυτήν την εργασία, στο κεφάλαιο 2, παρουσιάζεται η συνεργασία σε ένα πολύ-κυψελικό περιβάλλον όπου οι σταθμοί βάσης (BSs) επιθυμούν από κοινού να εξυπηρετήσουν πολλούς χρήστες, κάτω από ένα περιορισμένης- χωρητικότητας backhaul. Για περιορισμένη backhaul χωρητικότητα αναδύεται ένα trade-off μεταξύ της διαμοίρασης δεδομένων, (πλήρης MIMO cooperation), και της μη εφαρμογής αυτής, (που περιορίζει τη διάταξη σε ένα Interference channel αλλά επίσης απαιτεί λιγότερο overhead). Τα αποτελέσματα της προσομοίωσης δείχνουν πως η backhaul χωρητικότητα καθορίζει πόσα από τα δεδομένα αξίζει να μοιραστούν σε πολλούς

BSs . Στο επόμενο κεφάλαιο παρουσιάζονται ένας user equipment pair selection αλγόριθμος και ένας cooperative proportional fair scheduling αλγόριθμος. Το coordinated multi-point πλαίσιο μετάδοσης βασισμένο στο cooperative rate splitting σχήμα προτείνεται στο LTE-A σύστημα και θεωρείται ότι βελτιώνει την απόδοση του cell-edge UE αποκωδικοποιώντας μέρος της παρεμβολής. Η εργασία αυτή όπως οι περισσότερες δημοσιεύσεις, αγνοεί το κύριο μειονέκτημα των συστημάτων αυτών, δηλαδή την ανάγκη για επιπρόσθετο backhaul. Για να περιορίσουμε αυτό το μειονέκτημα ένα πιο ρεαλιστικό σχήμα προτείνεται στο κεφάλαιο 4, το οποίο οργανώνεται ως εξής: Στο τμήμα I παρουσιάζονται το μοντέλο του συστήματος και το προτεινόμενο σχήμα μετάδοσης του CoMP via Cooperative Rate Splitting and Scheduling scheme under backhaul restriction . Στο τμήμα II, εισάγονται οι εφικτές περιοχές rate των πέντε περιπτώσεων. Η μελέτη ολοκληρώνεται με την παρουσίαση και συζήτηση των αποτελεσμάτων προσομοίωσης στο τμήμα III. Τέλος, ορισμένα συμπεράσματα παρουσιάζονται στο κεφάλαιο 5.

1. Introduction

Single frequency reuse is widely used in current state-of-the-art wireless systems, such as Long Term Evolution Advanced (LTE-A) [1], to deal with the increasing average cell throughput without bandwidth expansion. However, if interference mitigation techniques are absent in these systems, the cell-edge user equipments (UEs) will suffer from strong interference from adjacent cells which degrades the UE throughput. In order to improve the average cell throughput as well as the cell-edge UE throughput, a powerful interference mitigation technique is an inevitable part of wireless systems.

Different interference mitigation techniques have been proposed recently. The first category uses fractional frequency reuse [2], which is widely discussed in the Long Term Evolution (LTE) systems. The main idea is to assign only a part of the bandwidth to cell-edge UEs to reduce the interference and improve the cell-edge UE throughput. However, the method allocating reduced transmission power on some subbands sacrifices the average cell throughput of adjacent sector [3]. The second category adopts coordinated beamforming [4], also known as coordinated multi-point transmission (CoMP) [5] in the LTE-A system. The essence of the current CoMP schemes is to let base stations (BSs) coordinate the beamforming in order to reduce the inter-cell interference. But the coordination requires enormous overhead on the air interface and over the backhaul since complete channel state information (CSI) needs to be shared among BSs. The third category applies the rate-splitting-based interference mitigation [6], [7]. Under this technique, transmitted data streams are split into two parts: the common data stream that is decoded at both UEs, and the private data stream that is decoded only at intended UEs. By decoding the common data stream of the interference, part of the interference is cancelled, and consequently the UE throughput can be improved.

Theoretic Information studies have shown that the rate-splitting-based interference mitigation is a very promising technique in the interference channel. In [6], Han and Kobayashi derived the best known achievable rate bound for a Gaussian interference channel based on a rate splitting scheme. Etkin et al. [7] show that a simple rate splitting scheme can achieve rates within one bit of the achievable rate bound in a two-user Gaussian interference channel and the rate splitting scheme only requires the exchange of the signal-to-noise ratio (SNR) and interference-to-noise ratio (INR) information, thereby reducing delay and overhead in feedback and backhaul.

Recently, some researches focus on adapting the rate splitting scheme for practical applications. In [8], [9], transmitted data streams are both split into two parts, but the methods applied in order to decide the power split ratio are different. In [8], the power split ratio is based on some heuristic values. The reason for selecting these values is not explained. In [9], the power split ratio is decided by guaranteeing the UE achieving target Quality-of-Service. This method splits only one transmitted data stream into two parts, thus it achieves the limited improvement when both UEs suffer strong interference. In [10], a new practical scheme called multi-layer rate splitting (MLRS) is proposed. This scheme split the transmitted data streams into multiple parts and the power distribution among the multiple parts is calculated by a distributed power allocation algorithm. Simulation results show that this multi-layer rate splitting scheme can approach the achievable rate bound of a two-user interference channel. But a significant gap exists between the rate of a practical system and its Gaussian input capacity. To narrow this gap, in [11] an effective and practical multi-layer rate splitting scheme is proposed. This scheme combines the multi-layer rate splitting scheme with modulation and coding adaptation method. Simulation results show that the proposed multi-layer rate splitting scheme with MCS adaptation substantially improves the performance of the cell edge UE in a realistic network and achieves better fairness between both UEs.

In traditional designs, each base station obtains from the backbone the data intended for users in its coverage area; data for users is not available at multiple base stations (Interference channel). Recent research rooted in MIMO theory has suggested the benefits of relaxing this constraint, thereby allowing for data to be shared at multiple transmitters. In such a scenario, multicell processing in the form of joint precoding is realized: this scheme is referred to as network MIMO. A downside of downlink network MIMO is the requirement of a large backhaul infrastructure, which can be alleviated through serving only subsets of UEs with joint transmission

[12], partitioning a cellular network into small subsystems where these schemes can be applied locally [13], or using certain BS cooperation schemes that can further improve the trade off between rates and required backhaul [14].

Some authors have tackled the problem of joint transmission when the backhaul links between a central unit and the transmitters (the base stations), or amongst the latter, are finite, in which case the resulting multicell channel no longer corresponds to a MIMO broadcast channel, nor does it correspond to the so-called interference channel. Among others, in [15] and [16], joint encoding for the downlink of a cellular system is studied under the assumption that the base stations are connected to a central unit via finite capacity links. The authors investigate different transmission schemes and ways of using the backhaul capacity in the context of a modified version of Wyner's channel model.

In this study, in chapter 2, the cooperation in a multicell environment where base stations (BSs) wish to jointly serve multiple users, under a constrained-capacity backhaul is presented. For finite backhaul capacity a trade-off between sharing user data, which allows for full MIMO cooperation, and not doing so, which reduces the setup to an interference channel but also requires less overhead, emerges. Simulation results illustrate how the capacity of the backhaul determines how much of the user data is worth sharing across multiple BSs. In the following chapter, one user equipment pair selection algorithm and a cooperative proportional fair scheduling algorithm are presented. The coordinated multi-point transmission framework based on the cooperative rate splitting scheme is proposed in the Long Term Evolution Advanced system and can be considered to improve the cell-edge UE performance by decoding part of the interference. This work, as the most publications in this field, neglects the main downside of such systems, namely, the need for an additional network backhaul. To erase this downside a more realistic scheme is proposed in chapter 4 which is organized as follows. In Section I, the system model and proposed transmission scheme of the CoMP via Cooperative Rate Splitting and Scheduling scheme under backhaul restriction, are presented. In Section II, the five cases achievable rate regions are introduced. The study is completed with a presentation and discussion of simulation results in Section III. Finally, some conclusions are presented in chapter 5.

2. Optimized data sharing in multicell MIMO with finite backhaul capacity [17]

A major issue in several types of wireless networks is that of the interference. This problem is especially acute in cellular networks with full reuse of the spectrum across all base stations. In traditional designs, each base station obtains from the backbone the data intended for users in its coverage area, data for users is not available at multiple base stations (Interference channel). Recent research rooted in MIMO theory has suggested the benefits of relaxing this constraint, thereby allowing for data to be shared at multiple transmitters so that a giant broadcast MIMO channel results. In such a scenario, multicell processing in the form of joint precoding is realized: this scheme is referred to as network MIMO.

Full data sharing subsumes very high capacity backhaul links, which may not be feasible, or even simply desirable, in certain applications. In fact, under limited backhaul rate constraints, data sharing consumes a precious fraction of the backhaul capacity which otherwise could be used to carry more data to the users: this overhead should thus be compensated by the capacity gain induced by the network MIMO channel over the classical IC.

A number of recent interesting research efforts have considered networks with finite-capacity backhaul. A recent study which deals with a Wyner-like channel model is [18], which has taken an information-theoretic look at the problem of partial message exchange between neighbouring BSs and derived the corresponding asymptotic multiplexing gain per-user as the number of users (and BSs) goes to infinity.

This chapter presents the way of using a given backhaul to serve the users in the system. The authors propose a transmission scheme whereby superposition coding is used to transmit signals to each user: each user's data is in fact split into two types; 'private' data sent by a single BS and 'shared' data transmitted via multiple bases. Such an approach should be useful, as it allows tuning how much data is shared as a function of the backhaul constraints. Moreover, by their assumptions and equation forms, this chapter -using simulation- illustrates the rates achieved for different values of backhaul capacity.

2.1 System model and proposed transmission scheme

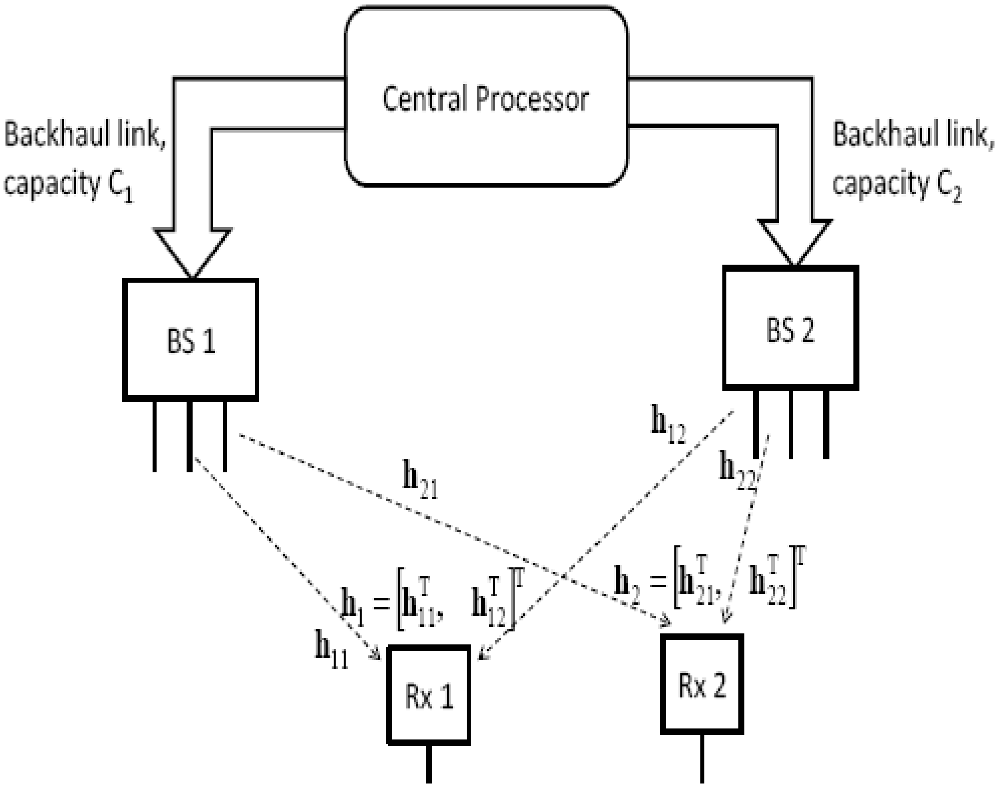

Figure 1: System model

Constrained backhaul setup. The rates of the messages carried by each backhaul link are represented. The central processor is assumed to collect all downlink traffic then route it to individual (non shared traffic) or both (shared traffic) transmitters.

This study focuses on a two transmitter two receiver setup. It emphasizes the problem of precoding at the transmitter side, the receivers are assumed to have a single antenna while the transmitters have Nt ≥1 antennas each:

h_{ij} is the N_t - dimensional complex vector corresponding to the channel between transmitter j and user i,

h_i represents user i's whole channel state vector.

$$h_i = [\, h^T_{i1}, h^T_{i2} \,]^T$$

$$h_1 = [\, h^T_{11}, h^T_{12} \,]^T \qquad h_2 = [\, h^T_{21}, h^T_{22} \,]^T$$

-considers that the signal received at user i will be given by

$$y_i = \sum_{j=1}^{2} h_{ij}^T x_j + z_i ,$$

Where $x_j \in \mathbb{C}^{N_t}$ denotes BS j's transmit signal and $z_i \sim \mathcal{C}(0, \sigma^2)$ is the receiver noise.

x_j is subject to power constraint P_j so that

$$E\|x_j\|^2 \leq P_j , \quad j=1,2$$

-assumes a backhaul link of capacity Cj [bits/sec/Hz] between the central processor (CP), which collects all downlink traffic then routes it to individual (non shared traffic) or both (shared traffic) transmitters, or the backbone network and transmitter j, for j = 1, 2

-in an attempt to bridge the IC situation (where the transmitters do not share user data) and the multi-cell MIMO scenario (where they do), proposes to split the user traffic content across two types of messages:

- private messages which are sent from the CP to only one of the transmitters, and
- shared messages, which are sent from the CP to both transmitters, and are consequently jointly transmitted.

Thus, the total information rate for user i, r_i, will be split across $r_{i1,p}$, $r_{i2,p}$ and $r_{i,c}$, where $r_{i,c}$ refers to the rate of the shared message for that user, and $r_{ij,p}$ refer to the rate of the private message for user i reaching it from BS j:

$$r_i = \sum_{j=1}^{2} r_{ij,p} + r_{i,c} \qquad (1)$$

$$r_1 = r_{11,p} + r_{12,p} + r_{1,c} \qquad r_2 = r_{21,p} + r_{22,p} + r_{2,c}$$

2.1.1 Assumptions

The main assumptions used in this study are the following:

- each receiver does single user detection (SUD), in the sense that any source of interference is treated as noise.
- the study examines the costs and benefits of sharing user data, not that of sharing the channel state information (CSI), hence full global CSIT is assumed at each transmitter.

2.1.2 Examined Cases

The transmission scheme proposed covers the two particular cases of:

-an IC, obtained by forcing $r_{ii,p} \equiv r_i$, r_i, $i = 1, 2$, and

-a network MIMO channel, obtained by forcing $r_{ij,p} \equiv 0$, $i = 1, 2$, $j = 1, 2$.

2.1.3 Backhaul constraints

Backhaul link j with finite capacity C_j serves to carry both private (from BS j) and shared messages for both users, so that the following constraint applies:

$$C_j \geq \sum_{i=1}^{2} r_{ij,p} + \sum_{i=1}^{2} r_{i,c}, \qquad j=1,2$$

Using (1), this constraint can be rewritten as:

$$C_j \geq \sum_{i=1}^{2} r_i - \sum_{i=1}^{2} r_{i\bar{j},p}, \qquad j=1, 2$$

Finally, the sum rate $r = r_1 + r_2$ cannot exceed the total backhaul capacity, so that

$$r \leq C_1 + C_2$$

2.1.4 Over-the-air transmission

The channel between the two transmitters and user i, $h_{i,}$ can be viewed as a MAC with a common message [19]. The overall channel can be regarded as the superposition of two such channels, which interfere with each other so that the receiver noise at user i is enhanced by the interference due to the signals carrying user $\bar{i}$'s data, the total interference plus noise power at user i will be denoted by σ^2_i.

The transmit signal of BS j as a superposition of two signals, x_{ij}, i = 1, 2, one intended for each user:

$$x_j = \sum_{i=1}^{2} x_{ij}$$

$$x_1 = x_{11} + x_{21} \qquad x_2 = x_{12} + x_{22}$$

Restricting the transmission model to beamforming, xij can be generated as:

$$x_{ij} = w_{ij,c}\, s_{i,c} + w_{ij,p}\, s_{ij,p} \qquad (2)$$

$$x_{11} = w_{11,c}\, s_{1,c} + w_{11,p} s_{11,p} \qquad x_{21} = w_{21,c}\, s_{2,c} + w_{21,p}\, s_{21,p}$$

$$x_{12} = w_{12,c}\, s_{1,c} + w_{12,p}\, s_{12,p} \qquad x_{22} = w_{22,c}\, s_{2,c} + w_{22,p}\, s_{22,p}$$

Where

$s_{i,c}$ and $s_{ij,p}$ are independent $\mathcal{CN}$ (0, 1) random variables

$w_{i,c} = [w^T_{i1,c}\, w^T_{i2,c}]^T \in \mathbb{C}^{2N}{}_t$, is the beamforming vector carrying symbols $s_{i,c}$ and

$w_{ij,p} \in \mathbb{C}^N{}_t$ is the beamforming vector carrying symbols $s_{ij,p}$.

According to the authors the following rate region Rair is achievable by transmit signals of the form given in (2) on the over-the-air segment

[Using the Shannon capacity formula: $R_i = \log_2(1+ \text{SINR})$

SINR_i = received power of UE_i / the total interference plus noise power at user i]

$$r_{ij,p} \le \log_2\left(1 + \frac{|h_{ij}{}^T w_{ij,p}|^2}{\sigma_i{}^2}\right) \qquad j=1,2, \quad i=1,2$$

$$\sum_{j=1}^{2} r_{ij,p} \le \log_2\left(1 + \frac{\sum_{j=1}^{2}\left|h_{ij}{}^T w_{ij,p}\right|^2}{\sigma_i{}^2}\right) \qquad i=1,2$$

$$r_i \le \log_2\left(1 + \frac{\left|h_i{}^T w_{i,c}\right|^2 + \sum_{j=1}^{2}\left|h_{ij}{}^T w_{ij,p}\right|^2}{\sigma_i{}^2}\right) \qquad i=1,2$$

where

$$\sigma_i^2 = \sigma^2 + \sum_{j=1}^{2} |h_{ij}{}^T w_{\bar{i}j,p}|^2 + |h_i{}^T w_{\bar{i},c}|^2$$

and the beamforming vectors are subject to power constraint

$$\sum_{i=1}^{2} (\|w_{ij,c}\|^2 + \|w_{ij,p}\|^2) \le P_j \qquad j=1, 2$$

$$\|w_{11,c}\|^2 + \|w_{11,p}\|^2 + \|w_{21,c}\|^2 + \|w_{21,p}\|^2 \le P_1$$

$$\|w_{12,c}\|^2 + \|w_{12,p}\|^2 + \|w_{22,c}\|^2 + \|w_{22,p}\|^2 \le P_2$$

2.2 Achievable Rate Region

The authors under the assumption that the set of rate-tuples (r_1, $r_{11,p}$, $r_{12,p}$, r_2, $r_{21,p}$, $r_{22,p}$) that belong to R_{air} and also satisfy the specified backhaul constraints defines an achievable rate region R, investigate its boundary and beamforming strategies to achieve points on this boundary.

By the assumption that points on the rate region boundary are thus obtained by solving the following problem for $\propto$ discretized over [0, 1], where $\propto$ denotes the proportion of the total sum rate intended for user 1's data:

$$\begin{aligned} &\max. \ r \\ &\text{s.t.} \quad r_1 = \propto r, \quad r_2 = (1-\propto)\, r \\ &\qquad\quad r_i \geq 0, \quad r_{ij,p} \geq 0, \quad i=1,2, \ \ j=1,2 \\ &\qquad\quad \sum_{j=1}^{2} r_{ij,p} \leq r_i \quad i=1,2 \\ &\qquad\quad \sum_{i=1}^{2} r_i - \sum_{i=1}^{2} r_{i\bar{j},p} \leq C_j, \quad j=1,2 \\ &\qquad\quad (r_1, r_{11,p}, r_{12,p}, r_2, r_{21,p}, r_{22,p}) \in R_{air} \end{aligned}$$

This problem may be solved using a bisection method over r, which requires testing the feasibility of any chosen sum rate r.

2.2.1 Establishing feasibility of a given rate pair (r_1, r_2)

It is assumed that sum rate r and $\propto$ to be fixed. Thus, $r_1 = \propto r$, $r2 = (1 - \propto)\, r$. The authors consider that a rate pair (r_1, r_2) is achievable, if and only if a rate-tuple (r_1, $r_{11,p}$, $r_{12,p}$, r_2, $r_{21,p}$, $r_{22,p}$) such that

$$\sum_{i=1}^{2} r_{ij,p} = \max\left(0, r_1 + r_2 - C_{\bar{j}}\right) \equiv c_j, \qquad j=1,2,$$

can be supported on the over-the-air segment.

Taking into above consideration, the feasibility of a rate pair (r_1, r_2) may be checked by solving the following power minimization:

$$P_{\min}: \ \min. \sum_{i=1}^{2} \sum_{j=1}^{2} \left(\|w_{ij,c}\|^2 + \| w_{ij,p} \|^2 \right)$$

$$\text{s.t.} \quad 0 \le r_{1j,p} \le c_j, \quad j=1,2$$

$$c_1 + c_2 - r_2 \le r_{11,p} + r_{12,p} \le r_1$$

$$(r_1, r_{11,p}, r_{12,p}, r_2, c_1 - r_{11,p}, c_2 - r_{12,p}) \in \mathcal{R}_{air}$$

which is an optimization over both the private rates, and the beamforming vectors.

2.2.2 Solving Pmin

Fixing the rates i.e. a *rate pair* (r_1, r_2), which is part of the achievable rate region $\mathcal{R}_{air}$ and also satisfy the specified backhaul constraints, the remaining power minimization problem can be shown to be equivalent to a convex optimization, and can be solved efficiently thus finding beamforming vectors. It is not of the scope of this thesis to present the solution of this convex optimization problem.

2.2.3 Extension to N > 2 base stations

The approach can be extended to N > 2 cells. For N cooperating BSs, messages for a certain user may be shared by k = 2,…., N BSs, and for each k, there will be $\binom{N}{k}$ possible BS combinations. Thus, some simplification would be required. This may not be too restrictive since in general, a user in a cellular network is most sensitive to the signals reaching it from its 3 closest BSs, and would benefit most by receiving messages from these alone.

2.3 Numerical results

2.3.1 Rate Regions Comparison

This presented analysis verifies the Rate Region for the proposed rate splitting scheme and also, the rates achieved for network MIMO and IC for 10dB SNR.

The given channel instance is:

$h^T_{11} = [0.2939 – 1.1488i – 1.5260 – 0.3861i]$,

$h^T_{12} = [0.3963 –0.2679i \quad 0.8306 + 0.6110i]$,

$h^T_{21} = [-0.7201 – 0.3025i – 0.9658 – 0.1754i]$,

$h^T_{22} = [0.1952 – 0.0026i \quad 1.7096 + 0.4040i]$,

By the assumptions and equation forms:

Hybrid IC/MIMO proposed scheme

The total information rate for user i, r_i, will be split across $r_{i1,p}$, $r_{i2,p}$ and $r_{i,c}$, where $r_{i,c}$ refers to the rate of the shared message for that user, and $r_{ij,p}$ refer to the rate of the private message for user i reaching it from BS j:

$$r_i = \sum_{j=1}^{2} r_{ij,p} + r_{i,c}$$

Backhaul usage

Backhaul link j with finite capacity C_j serves to carry both private (from BS j) and shared messages for both users, so that the following constraint applies:

$$C_j \geq \sum_{i=1}^{2} r_i - \sum_{i=1}^{2} r_{i\bar{j},p} \qquad j=1,2$$

Finally, the sum rate $r = r_1 + r_2$ cannot exceed the total backhaul capacity, so that

$$r_1 + r_2 \leq C_1 + C_2$$

Establishing feasibility of a given rate pair

Rate pair (r_1, r_2) is achievable, if and only if a rate-tuple (r_1, $r_{11,p}$, $r_{12,p}$, r_2, $r_{21,p}$, $r_{22,p}$)

such that $$\sum_{i=1}^{2} r_{ij,p} = \max(0, r_1 + r_2 - C_{\bar{j}}) = c_j, \qquad j=1,2$$

$$\text{s.t.} \quad 0 \le r_{1j,p} \le c_j, \quad j=1,2$$

$$c_1+c_2 - r_2 \le r_{11,p} + r_{12,p} \le r_1$$

A. For $C_1=C_2= C=1$bits/sec/Hz

- The proposed rate splitting scheme, which we label FRS (for Full Rate Splitting)

$$r_2 = C_1 + C_2 - r_1$$

- The rate splitting scheme studied in [20], where private rates originate from only one of the two BSs ($r_{ij,p} = 0$, for $i \neq j$), which we label ARS (for Asymmetric Rate Splitting),

$$r_1 = C_1 \qquad \text{and} \qquad r_2 = C_2$$

-Particular Case

Beamforming on the interference channel ($r_{ii,p} = r_i$, $i =1,2$), labelled IC, $r_{ij,p} = 0$ for $i \neq j$, $r_{i,c} = 0$ $i=1,2$

$$r_1 = C_1 \quad \text{and} \quad r_2 = C_2$$

-Particular Case

Network MIMO beamforming ($r_{i,c} = r_{i,}$), labelled NM, $r_{ij,p}=0$ i=1,2 j=1,2

$$r_2 = C2 - r_1$$

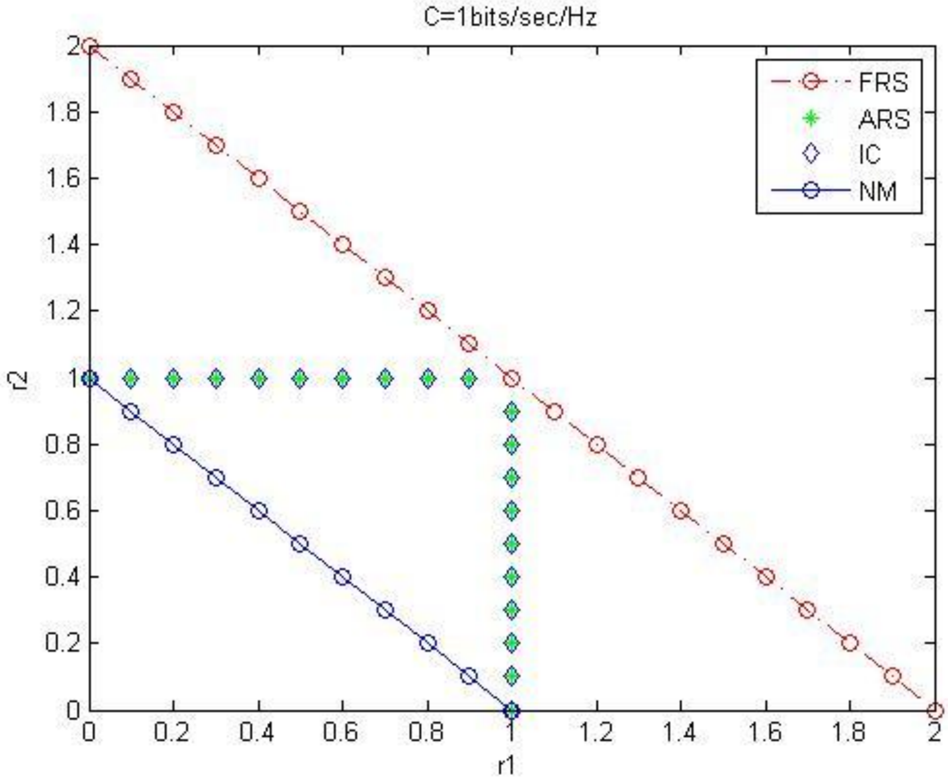

Figure 2: (C =C1 =C2=1bit/sec/Hz) One can note that if C is relatively low the system is backhaul-limited. The proposed rate splitting scheme, which we label FRS (for Full Rate Splitting)

As can be seen, depending on C, the FRS scheme may achieve a total sum rate of up to 2C, which is the maximum possible. One can also note that if C is relatively low, one may be better off giving up on a network MIMO approach, especially if the backhaul is used to forward the messages themselves.

B. For C_1=C_2= C=5bits/sec/Hz

- The proposed rate splitting scheme, which we label FRS (for Full Rate Splitting)

$$r_2 \leq 2(C_2 + C_1) / 3 - r_1 \qquad r_2 = (2C_2 + C_1)/2 - r_1$$

-The rate splitting scheme studied in [20], where private rates originate from only one of the two BSs ($r_{ij,p} = 0$, for $i \neq j$), which we label ARS (for Asymmetric Rate Splitting),

$$r_1 = C_1 \quad \text{and} \quad r_2 = C_2 \qquad r_2 = (2C_2 + C_1)/2 - r_1$$

-Particular Case

Beamforming on the interference channel ($r_{ii,p} = r_i$, $i = 1, 2$), labelled IC, and $r_{ij,p} = 0$ for $i \neq j$ and $r_{i,c} = 0$ $i=1,2$

$$r_1 = C_1 \quad \text{and} \quad r_2 = C_2 \qquad r_2 \leq (2C_2 + C_1)/2$$

–Particular Case

Network MIMO beamforming ($r_{i,c} = r_i$), labelled NM, and $r_{ij,p} = 0$ $i=1,2$ $j=1,2$

$$r_2 = C_2 - r_1$$

As the backhaul capacity increases, the NM approach increases in appeal. The FRS and ARS approaches outperform it as C increases until the point where both achieve the same rate region: when this happens, the system is no longer backhaul-limited and becomes limited by the achievable rate region over the air interface.

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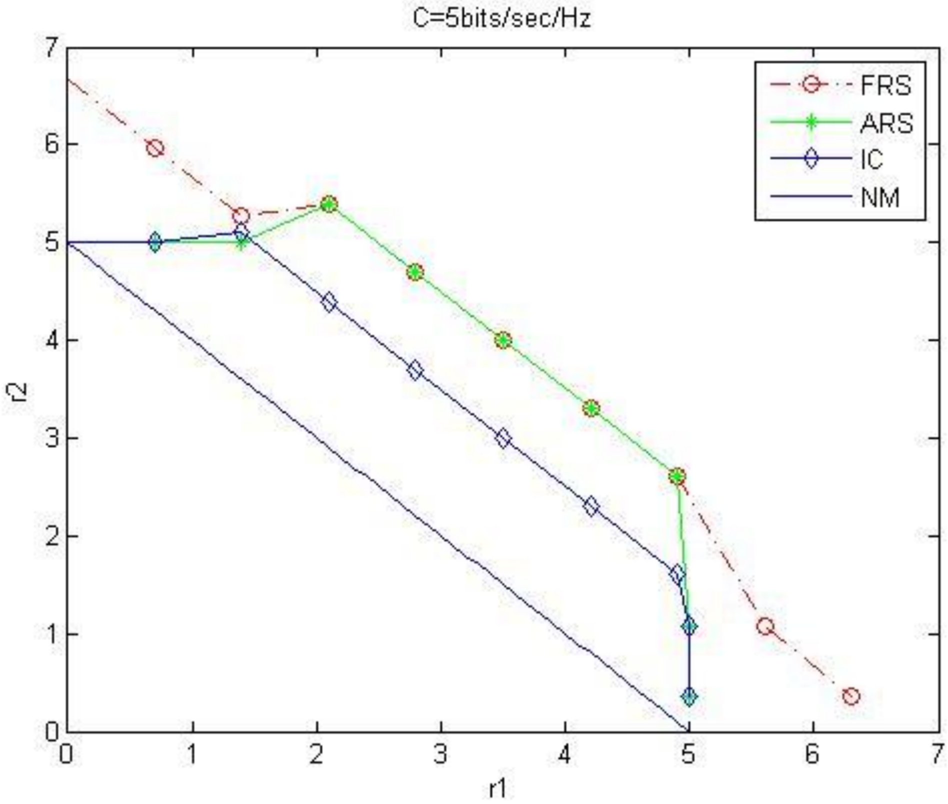

Figure 3: (C = C1 = C2 = 5bits/sec/Hz) One can note that as C increases the system is no longer backhaul-limited and becomes limited by the achievable rate region over the air interface. The proposed rate splitting scheme, which we label FRS (for Full Rate Splitting)

2.3.2 Average maximum sum rate versus SNR

This presented analysis illustrates the sum rate and the rate per user versus SNR for the proposed rate splitting scheme (FRS) and also, how much of the total data rate comes from private messages. (The figure also shows how much of the rates achieved correspond to private messages alone).

By the assumptions and equation forms:

Backhaul usage

The sum rate $r = r_1 + r_2$ cannot exceed the total backhaul capacity, so that

$$r_1 + r_2 \quad \leq C_1 + C_2$$

Achievable rate region Rair on the over-the-air segment

$$\sum_{j=1}^{2} r_{ij,p} \le \log_2\left(1 + \frac{\sum_{j=1}^{2}\left|h_{ij}^{T} w_{ij,p}\right|^2}{\sigma_i^2}\right), \quad i=1,2$$

$$r_i \le \log_2\left(1 + \frac{\left|h_i^{T} w_{i,c}\right|^2 + \sum_{j=1}^{2}\left|h_{ij}^{T} w_{ij,p}\right|^2}{\sigma_i^2}\right) \quad i=1,2$$

Where $$\sigma_i^2 = \sigma^2 + \sum_{j=1}^{2} |h_{ij}^T w_{\bar{i}\,j,\,p}|^2 + |h_i^T w_{\bar{i},\,c}|^2$$

Because it is not of the scope of this thesis to find the beamforming vectors:

- it is assumed that w11p, w12p are equal to 0.5, w22p, w21p are equal to 0.1, w11c , w12c are equal to 1, and w22c, w21c are equal to 0.5, for $C_1 = C_2 =$ C=1bits/sec/Hz (FRS)

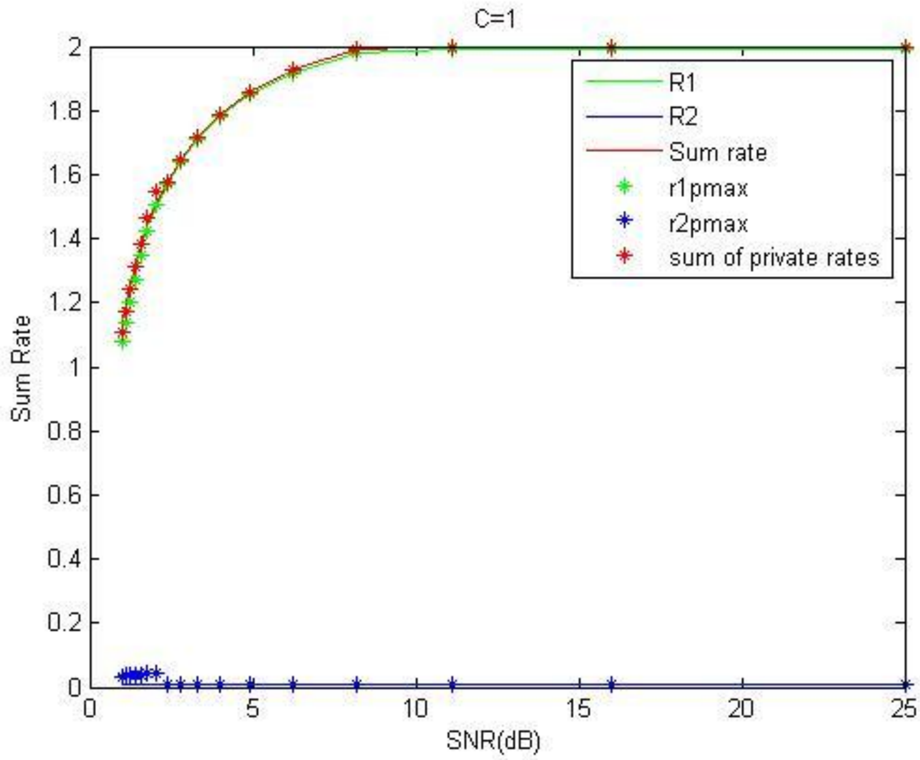

Figure 4: Rates Vs SNR for $C_1 = C_2 =$ C=1bits/sec/Hz

- It is assumed that w11p is equal to 1 w12, w22p, w21p are equal to 0.1, w11c , w12c are equal to1, w22c, w21c are equal to 0.5, for $C_1 = C_2 = C=5$ bits/sec/Hz (FRS)

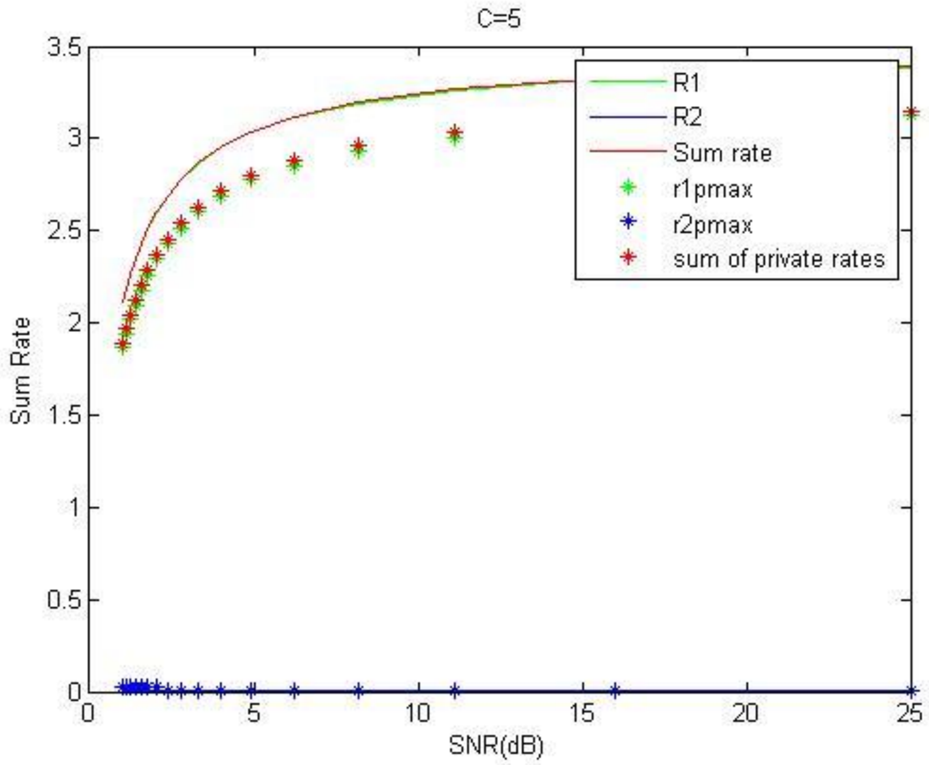

Figure 5: Rates Vs SNR for C1 = C_2 = C=5bits/sec/Hz

Simulation results illustrate, how the capacity of the backhaul determines how much of the user data is worth sharing across multiple BSs. For quite low C all of the data will be in the form of private messages, the proposed scheme and the IC's performance are quite close. As C increases, the IC rate region corresponds to a larger portion of the network MIMO region, the achieved rates correspond to more shared than private messages, the proposed scheme approach the NM. If the backhaul is too constrictive, it may be better to simply have each user served by a single base station rather have both messages routed to both base stations. This is because, although data sharing allows to convert the interference channel into a MIMO broadcast channel with higher capacity, data sharing occupies the resources that could otherwise be used to send fresh (non shared) data. Consequently for finite backhaul capacity a trade off between sharing user data and not doing so is present.

3. Inter-cell Interference Coordination via Cooperative Rate Splitting and Scheduling [21]

In a multi-cell wireless network, an efficient interference mitigation technique is an inevitable part of the current state-of-the-art wireless system. As opposed to conventional interference mitigation techniques which treat the interference as noise, a coordinated multi-point transmission framework based on the cooperative rate splitting scheme can be considered to improve the performance by decoding part of the interference.

Current state-of-the-art wireless systems, such as Long Term Evolution Advanced (LTE-A) [1], aim at using a single frequency reuse to deal with the increasing average cell throughput without bandwidth expansion. However, in these wireless systems, cell-edge user equipments (UEs) inevitably suffer from strong interference from adjacent cells which leads to the UE throughput decrease if interference mitigation techniques are not employed. Major challenges of wireless systems are to increase not only the average cell throughput, but also the cell-edge UE throughput. Therefore, in the LTE-A system, one of the main concepts of the current CoMP schemes is that transmissions are coordinated so to avoid the interference. But, these CoMP schemes require enormous overhead on the air interface and over the backhaul based on the data and the channel state information (CSI) sharing scenarios. Consequently, it is state of the art to investigate CoMP schemes to achieve a good trade-off between the performance and the coordination cost. The rate splitting scheme is a promising method which balances the performance and cost in CoMP schemes. Rate-splitting-based interference mitigation schemes [6]–[8] have attracted many researchers recently.

This chapter presents the effort made to deal with the interference problem for cell-edge user equipments (UEs) without penalty, as well as to improve the average performance in certain scenarios. The authors propose a CoMP scheme based on the cooperative rate splitting where a user equipment pair selection algorithm and a cooperative proportional fair scheduling algorithm are developed. Also, by their assumptions and equation forms, this chapter -using simulation- indicates the performance of the CoMP scheme.

3.1 System model

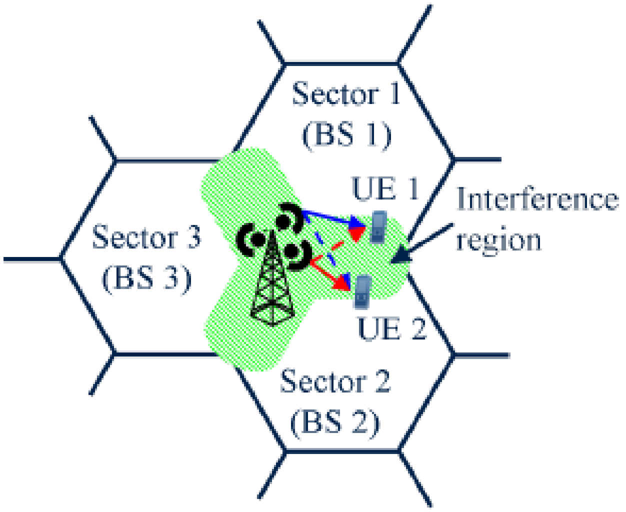

Figure 6: Hexagonal cell structure with 120° sector antenna

This study considers a downlink OFDMA system where three sectors in one BS site share the same carrier frequency and assumes each BS use one transmit antenna to serve a sector. Also, considers the coordination between only two BSs and a total of N_{UE} UEs, equipped with one receive antenna, served by each BS.

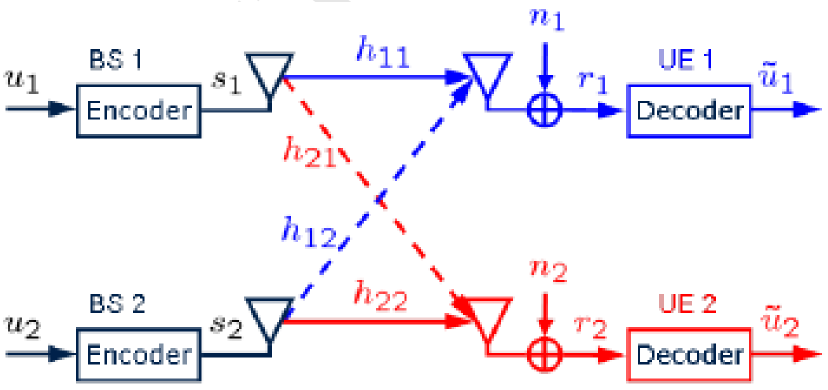

Figure 7: Two-user interference channel model

Focusing on a two-user interference channel model the authors consider both UE1 (served by BS1) and UE2 (served by BS2) are cell-edge users and they are geometrically close to each other. Accordingly, UE1 and UE2 receive interference from one another and the received signals, r_1 and r_2, of UE1 and UE2 can be expressed as

$$r_1 = h_{11}s_1 + h_{12}s_2 + n_1 \qquad r_2 = h_{21}s_1 + h_{22}s_2 + n_2$$

Where hij denotes the independent Rayleigh fading channel gain from transmitter j to receiver i. h11, h22, h12 and h21 are independent identically distributed (i.i.d.) zero-mean complex Gaussian random variables with variances σ^2_{11}, σ^2_{22}, σ^2_{12} and σ^2_{21} respectively

where σ^2_{ij} reflects the channel propagation loss from transmitter j to receiver i. si is the transmitted symbol with covariance $\sigma^2_{s,i} = \mathcal{E}[|s_i|^2] = P_{s,i}$ at transmitter i. η_i and w_i are the interference caused by other transmitters and i.i.d additive white Gaussian noise (AWGN) samples, respectively. Here, ηi is treated as noise, thus the covariance of the noise ni(ηi +wi) is given by

$$\Phi_{nn,i} = \mathcal{E}[|n_i|^2] = \mathcal{E}[|\eta_i|^2] + \mathcal{E}[|w_i|^2] = \sigma^2_{n,i}$$

-For each UE, BSs can be divided into 3 types: serving, cooperative and uncooperative BS.

a. the serving BS, the UE chooses the BS with the strongest signal as the serving BS, determines the UE's power allocation policy and transmits data to the UE, while the UE feeds back the power level of the interference to its serving BS(CSI).

b. the cooperative BS cooperates with the serving BS. The UE suffers the strongest interference from the cooperative BS.

c. the uncooperative BS. The UE treats the interference from the uncooperative BSs as noise (SUD).

- Four received signal strength ratios of UE i are defined and are given by

signal-to-interference-plus-noise ratio	$SINR_i = \sigma^2_{\gamma,i} / (\sigma^2_{\mu,i} + \sigma^2_{n,i})$
signal-to-noise ratio	$SNR_i = \sigma^2_{\gamma,i} / \sigma^2_{n,i}$
interference-to-noise ratio	$INR_i = \sigma^2_{\mu,i} / \sigma^2_{n,i}$
signal-to-interference ratio	$SIR_i = \sigma^2_{\gamma,i} / \sigma^2_{\mu,i}$

where

$\sigma^2_{\gamma,i} = \sigma^2_{ii}\sigma^2_{s,i}$, $\sigma^2_{\mu,i} = \sigma^2_{ij}\sigma^2_{s,j}$ with $(i \neq j)$ are the received power of UE i from its serving BS i and from its cooperative BS j respectively

3.2 Cooperative Rate Splitting Scheme

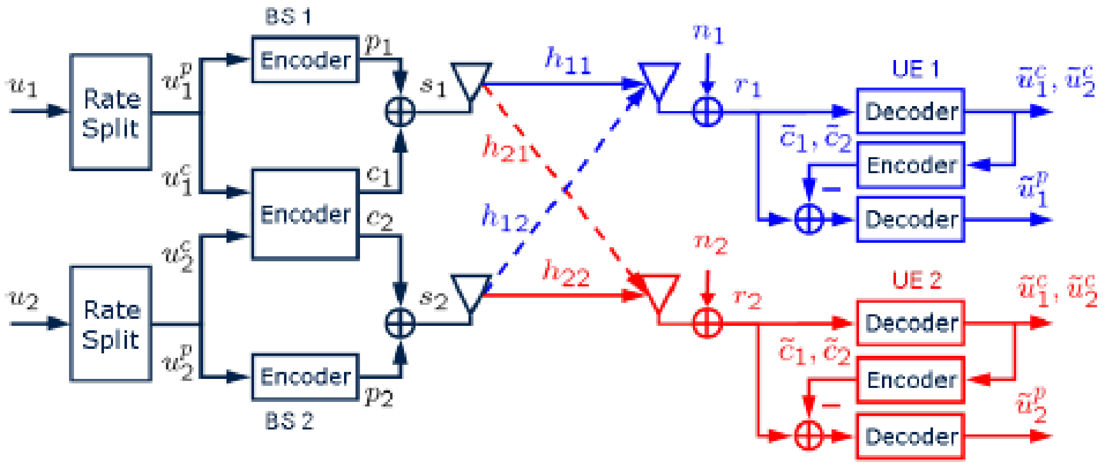

Figure 8: The cooperative rate splitting model (two-user case)

The proposed cooperative rate splitting scheme is introduced for a two user case. The key idea of this system is the cooperatively common information encoding :

-BS i splits its data u_i into two parts: $u_i^{\mathbf{c}}$ and $u_i^{\mathbf{p}}$ (where ‘c’ stands for the common information and ‘p’ for the private information).

– encode the common information u_1^c and u_2^c cooperatively, in particular, the c_1 and c_2 are generated due to the joint encoding of u_1^c and u_2^c

-u_i^p are encoded into p_i

-c_i and p_i are superimposed with the power allocation policy

$$\sigma^2_{s,i} = \sigma^2_{c,i} + \sigma^2_{p,i}$$

where

$\sigma^2_{c,i}$, $\sigma^2_{p,i}$ denote the covariance of the common signal c_i and of the private signal p_i respectively

at the receiving end

-at the first stage, both UEs jointly decode u_1^c and u_2^c and simultaneously subtract off c_1 and c_2 from the received signal, while

-at the second stage u_1^p and u_2^p are only decoded by the intended UE

One of their main conclusions is that the fully- cooperative MAC is equivalent to a single user channel. Thus a single user code is used instead of multiuser codes, which will reduce the decoding complexity of the common signals. But this scheme needs to share the common information between BSs thereby increasing the effort at the transmitting end.

The authors consider the two-user sum rate of the cooperative rate splitting scheme is contained in the following region [22]

$$R_1 \leq \log 2\left(1+\frac{g_{11}\sigma^2_{p,1}}{\sigma^2_{n,1}+g_{12}\sigma^2_{p,2}}\right) + \min\left\{\log 2\left(1+\frac{g_{11}\sigma^2_{c,1}}{\sigma^2_{n,1}+g_{11}\sigma^2_{p,1}+g_{12}\sigma^2_{p,2}}\right), \log 2\left(1+\frac{g_{21}\sigma^2_{c,1}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}+g_{22}\sigma^2_{p,2}}\right)\right\},$$

$$R_2 \leq \log_2 \left(1+\frac{g_{22}\sigma^{2}_{p,2}}{\sigma^{2}_{n,2}+g_{21}\sigma^{2}_{p,1}}\right) + \min \left\{\log2 \left(1 + \frac{g_{12}\sigma^{2}_{c,2}}{\sigma^{2}_{n,1}+ g_{11}\sigma^{2}_{p,1}+ g_{12}\sigma^{2}_{p,2}}\right), \log2 \left(1 + \frac{g_{22}\sigma^{2}_{c,2}}{\sigma^{2}_{n,2}+ g_{21}\sigma^{2}_{p,1}+ g_{22}\sigma^{2}_{p,2}}\right)\right\},$$

$$R_1 + R_2 \leq \log_2 \left(1+\frac{g_{11}\sigma^{2}_{p,1}}{\sigma^{2}_{n,1}+g_{12}\sigma^{2}_{p,2}}\right) + \log_2 \left(1+\frac{g_{22}\sigma^{2}_{p,2}}{\sigma^{2}_{n,2}+g_{21}\sigma^{2}_{p,1}}\right) + \min \left\{\log2 \left(1 + \frac{g_{11}\sigma^{2}_{c,1}+g_{12}\sigma^{2}_{c,2}}{\sigma^{2}_{n,1}+g_{11}\sigma^{2}_{p,1}+g_{12}\sigma^{2}_{p,2}}\right), \log2 \left(1 + \frac{g_{21}\sigma^{2}_{c,1}+g_{22}\sigma^{2}_{c,2}}{\sigma^{2}_{n,2}+g_{21}\sigma^{2}_{p,1}+g_{22}\sigma^{2}_{p,2}}\right)\right\}, \quad (3)$$

Where

g_{ij} is the channel gain from BS j to UE i

R_i denotes the rate of UE i.

- the optimal power allocation solution can be obtained by solving the following overall optimization problem

$\sigma^{2,*}_{p,1}$, $\sigma^{2,*}_{p,2}$ = $\arg_{\sigma^2_{p,1},\, \sigma^2_{p,2}} \max$ eq. (3)

s.t: $\sigma^2_{s,1} = \sigma^2_{c,1} + \sigma^2_{p,1}$, $\sigma^2_{s,2} = \sigma^2_{c,2} + \sigma^2_{p,2}$

Moreover they distinguish the following five cases:

In case 1,

$\sigma^2_{p,1} = \sigma^2_{s,1}$ and $\sigma^2_{p,2} = \sigma^2_{s,2}$ ($\sigma^2_{c,1} = 0$ and $\sigma^2_{c,2} = 0$)

The maximum sum rate in (3) is

$$(R_1 + R_2)_{\max} = \log2 \left(1+\frac{g_{11}\sigma^{2}_{s,1}}{\sigma^{2}_{n,1}+ g_{12}\sigma^{2}_{s,2}}\right) + \log_2 \left(1+\frac{g_{22}\sigma^{2}_{s,2}}{\sigma^{2}_{n,2}+ g_{21}\sigma^{2}_{s,1}}\right),$$

if $$\frac{g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,1}} + \frac{g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,1}} \times \frac{g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}} \leq \frac{g_{22}\sigma^{2}_{s,2}}{\sigma^{2}_{n,2}}$$

$$\frac{g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}} + \frac{g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}} \times \frac{g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,1}} \leq \frac{g_{11}\sigma^{2}_{s,1}}{\sigma^{2}_{n,1}}$$

The sum rate is achieved by sending only private information (respective with particular case IC)

In case 2,

$\sigma^2_{p,1} = 0$ and $\sigma^2_{p,2} = 0$ ($\sigma^2_{s,1} = \sigma^2_{c,1}$ and $\sigma^2_{s,2} = \sigma^2_{c,2}$)

When $\frac{g_{11}\sigma^{2}_{s,1}}{\sigma^{2}_{n,1}} \leq \frac{g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}}$ and $\frac{g_{22}\sigma^{2}_{s,2}}{\sigma^{2}_{n,2}} \leq \frac{g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,1}}$

The maximum sum rate is

$$(R_1+R_2)_{max} = \min\{\log 2\,(1 + \frac{g_{11}\sigma^{2}_{s,1} + g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,1}}), \log 2\,(1 + \frac{g_{22}\sigma^{2}_{s,2} + g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}})\}$$

The sum rate is achieved by sending only common information (respective with particular case NM, 1o paper).

In case 3,

$\sigma^2_{p,1} = \sigma^2_{s,1}$ and $\sigma^2_{p,2} = 0$ ($\sigma^2_{c,1} = 0$ and $\sigma^2_{s,2} = \sigma^2_{c,2}$)

The maximum sum rate is

$$(R_1 + R_2)_{max} = \log 2\,(1 + \frac{g_{11}\sigma^{2}_{s,1}}{\sigma^{2}_{n,1}}) + \log_2 (1 + \frac{g_{22}\sigma^{2}_{s,2}}{\sigma^{2}_{n,2} + g_{21}\sigma^{2}_{s,1}}),$$

if $$\frac{g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}} < \frac{g_{11}\sigma^{2}_{s,1}}{\sigma^{2}_{n,1}}$$

The maximum sum rate is

$$(R_1 + R_2)_{\max} = \log_2 \left(1 + \frac{g_{11}\sigma^2_{s,1} + g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}}\right),$$

$$\text{if} \quad \frac{g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}} + \frac{g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}} \times \frac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} < \frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2}}$$

UE 1 only sends private information and UE 2 only sends common information.

In case 4,

$\sigma^2_{p,1} = 0$ and $\sigma^2_{p,2} = \sigma^2_{s,2}$ ($\sigma^2_{s,1} = \sigma^2_{c,1}$ and $\sigma^2_{c,2} = 0$)

The maximum sum rate is

$$(R_1 + R_2)_{\max} = \log2 \left(1 + \frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2}}\right) + \log_2 \left(1 + \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1} + g_{12}\sigma^2_{s,2}}\right)$$

$$\text{If} \quad \frac{g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}} < \frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2}}$$

The maximum sum rate is

$$(R_1 + R_2)_{\max} = \log_2 \left(1 + \frac{g_{22}\sigma^2_{s,2} + g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}}\right)$$

$$\text{if} \quad \frac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} + \frac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} \times \frac{g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}} < \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1}}$$

UE 1 only sends common information and UE 2 only sends private information.

In case 5,

They define

$$\kappa = \frac{\sigma^{2}_{n,1} + g_{11}\sigma^{2}_{p,1} + g_{12}\sigma^{2}_{p,2}}{\sigma^{2}_{n,2} + g_{21}\sigma^{2}_{p,1} + g_{22}\sigma^{2}_{p,2}} = \frac{\sigma^{2}_{n,1} + g_{11}\sigma^{2}_{s,1} + g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,2} + g_{21}\sigma^{2}_{s,1} + g_{22}\sigma^{2}_{s,2}} \qquad (4)$$

Without loss of generality, they assume $\kappa \le 1$ (otherwise swap the numerator and the denominator of Eq. (4)).The optimal power allocation is given by

$$\sigma^{2}_{p,1} = \min\left\{\frac{-ABC + \sqrt{ABC(C-AB+1)}}{AC(C+1)}, \sigma^{2}_{s,1}\right\}$$

$$\sigma^{2}_{p,2} = \sigma^{2}_{p,1}\,\frac{g_{11} - \kappa g_{21}}{\kappa g_{22} - g_{12}} + \frac{\sigma^{2}_{n,1} - \kappa\sigma^{2}_{n,2}}{\kappa g_{22} - g_{12}},$$

where

$$A = \frac{g_{21}}{\sigma^{2}_{n,2}}, \qquad B = \frac{\kappa}{g_{11}} \times \frac{g_{12}\sigma^{2}_{n,2} - g_{22}\sigma^{2}_{n,1}}{g_{12} - \kappa g_{22}}, \qquad C = \frac{g_{12}}{g_{11}} \times \frac{\kappa g_{21} - g_{11}}{g_{12} - \kappa g_{22}}$$

$$\sigma^{2}_{c,1} = \sigma^{2}_{s,1} - \sigma^{2}_{p,1}, \qquad \sigma^{2}_{c,2} = \sigma^{2}_{s,2} - \sigma^{2}_{p,2}$$

The maximum sum rate is

$$(R_1 + R_2)_{\max} = \log_2\left(1+\frac{g_{11}\sigma^{2}_{p,1}}{\sigma^{2}_{n,1} + g_{12}\sigma^{2}_{p,2}}\right) + \log_2\left(1+\frac{g_{22}\sigma^{2}_{p,2}}{\sigma^{2}_{n,2} + g_{21}\sigma^{2}_{p,1}}\right) + \min\left\{\log_2\left(1 + \frac{g_{11}\sigma^{2}_{c,1} + g_{12}\sigma^{2}_{c,2}}{\sigma^{2}_{n,1} + g_{11}\sigma^{2}_{p,1} + g_{12}\sigma^{2}_{p,2}}\right), \log_2\left(1 + \frac{g_{21}\sigma^{2}_{c,1} + g_{22}\sigma^{2}_{c,2}}{\sigma^{2}_{n,2} + g_{21}\sigma^{2}_{p,1} + g_{22}\sigma^{2}_{p,2}}\right)\right\},$$

And the power region is

$$\frac{g_{12}\sigma^{2}_{s,2}}{\sigma^{2}_{n,1}} < \frac{g_{22}\sigma^{2}_{s,2}}{\sigma^{2}_{n,2}} \quad \text{and} \quad \frac{g_{21}\sigma^{2}_{s,1}}{\sigma^{2}_{n,2}} < \frac{g_{11}\sigma^{2}_{s,1}}{\sigma^{2}_{n,1}}$$

3.3 Proposed CoMP Scheme

In the context of cooperative rate splitting scheme the authors focus on the fact that BSs can maximize a system utility, i.e., sum rate where the utility of UEs has to be taken into consideration. Hereby they propose a new CoMP scheme based on the cooperative rate splitting to increase cell-edge UE performance **(**at the interference dominant cell-edge region).

When RBs (of serving BS and cooperative BS which are synchronized) are allocated to different UEs, each RB pair can be viewed as a UE pair. The proposed CoMP scheme is comprised of 3 steps:

1) cell-edge UE pair identification

2) RB allocation for cell-edge UE pair

3) UE scheduling.

3.3.1 Cell-edge UE pair identification

Serving BSs send UE interference reports to a centralized radio resource management (CRRM) unit which collects the interference measurements of UEs and then starts identifying cell-edge UE pairs. This method will choose the cell-edge UE pairs (in *the* interference dominant cell-edge region) which benefit from the cooperative rate splitting scheme contained in Ω_{c1} and $\Omega_{c2.}$ In addition, the UEs which get no benefit from the cooperative rate splitting scheme (in the noise dominant cell-edge region) are considered as the single-cell transmission UEs (treat the interference as noise) contained in Ω_{s1} or $\Omega_{s2.}$ The paper evaluates the performance improvement by taking the geometric mean of the UE rates which provides UE rates fairness compared to the sum rate.

Therefore, a set containing all selected cell-edge UE pairs is given by

$$\Omega_c := \{ (i_1, j_2) \in \Omega : i_1 \in \Omega_{c1}, \; j_2 \in \Omega_{c2}, \; R^c_{i1} R^c_{j2} > R^s_{i1} R^s_{j2} \},$$

Where

Ω_{c1}, Ω_{c2} denote the sets that contain all cell-edge UEs served by BS1and BS2 respectively

R^c_{i1}, R^c_{j2} are the rates of the cooperative rate splitting scheme for UE i served by BS1 and UE j served by BS2 respectively

R^s_{i1} R^s_{j2} are single-cell transmission rates that treat the interference as noise for UE i served by BS1 and UE j served by BS2 respecively

By the Shannon capacity formula:

$$R^s_{i1} = \log_2(1+ \mathrm{SINR}_{i1}) = \log_2\left(1 + \frac{g_{i1}\sigma^2_{s,1}}{\sigma^2_{n,1} + \sigma^2_{i2}\sigma^2_{s,2}}\right)$$

$$R^s_{j2} = \log_2(1+ \mathrm{SINR}_{j2}) = \log_2\left(1 + \frac{g_{j2}\sigma^2_{s,2}}{\sigma^2_{n,2} + \sigma^2_{j1}\sigma^2_{s,1}}\right)$$

Based on the above criterion, UEs are evaluated by long-term channel gains which are characterized by the path loss and log-normal shadow fading.

3.3.2 RB(C-RBs) allocation for cell-edge UE pair

Since only cell-edge UEs need the cooperation of BSs while the other UEs can work alone, the authors propose RB division into two groups. One group C-RBs is exclusively reserved for cooperative rate splitting and the other group S-RBs is used only for single-cell transmission without cooperation.

They also define

K the total number of RBs in the OFDMA frequency bandwidth
K_c, K_s the numbers of C-RBs and S-RBs respectively
P RBs the period of C-RBs whose locations can be uniformly distributed over the whole frequency bandwidth

$$K_c = \left\lfloor \frac{K}{P} \right\rfloor \quad \text{and} \quad K_s = K - K_c$$

Supposing that RBs are equally assigned to each UE belonging to the same BS (this assumption is compatible for both round robin and proportional fair scheduler):

$K_{cue} = \frac{K_c}{|\Omega_{ci}|}$ denotes the C-RBs can be allocated to each cell-edge UE served by BS i

$K_{sue} = \frac{K_s}{|\Omega_{si}|}$ denotes the S-RBs can be allocated to each single-cell transmission UE served by BS i

In an attempt to determine the set containing all selected cell-edge UE pairs (Ω_c), the authors also have in mind the following system throughput maximization:

$$\max_{\Omega c} \left\{ \sum_{i_1 \in \Omega_{c1}} \ln(K_{cue} R^{c}{}_{i1}) + \sum_{i_2 \in \Omega_{c2}} \ln(K_{cue} R^{c}{}_{i2}) + \sum_{j_1 \in \Omega_{s1}} \ln(K_{sue} R^{s}{}_{j1}) + \sum_{j_2 \in \Omega_{s2}} \ln(K_{sue} R^{s}{}_{j2}) \right\}, \qquad (5)$$

Where

$R^{c}{}_{i1}$, $R^{c}{}_{i2}$ are the rates of UE i1 and UE i2 respectively which can be obtained by using the cooperativere rate splitting

$R^{s}{}_{j1}$, $R^{s}{}_{j2}$ are the rates of UE j1 and UE j2 respectively which can be obtained by the scheme which treats interference as noise (single-cell transmission rate).

In this paper, these rates are calculated by the long-term channel gains.

Under the assumption that an exhaustive search over all cell-edge UE pair combinations is obviously infeasible in a practical implementation the authors propose an efficient algorithm to handle this situation more wisely.

3.3.2.1 The proposed UE pair selection algorithm

1. Calculate and sort the corresponding Δ for each cell-edge UE pair

They calculate the performance improvement between two schemes (cooperative rate splitting and single-cell transmission rate) for all cell-edge UE pairs which are identified in the first step

$$\Delta_i = \frac{R^{c}_{i1,1} R^{c}_{i2,2}}{R^{s}_{i1,\,1} R^{s}_{i2,2}}$$

The performance improvement is ranked in a non-increasing order:

$$\Delta 1 \geq \Delta 2 \geq \ldots \geq \Delta\left|\Omega_c\right| \qquad \text{and} \qquad \Omega_c(i) = (i_1, i_2) \in \Omega_c$$

2. Set i=1

3. Select the top i rank UE pairs and consider them as candidates in Ωc. If UE appears more than once, remove the low rank UE pair as a candidate in Ωc and go to step 5, else go to step 4.

4. Evaluate the metric of the problem (5).

5. Increment i.

If $i \leq \left|\Omega_c\right|$, go to step 3, else go to step 6.

6. Select the top i rank UE pairs to obtain the maximum metric of the problem (5).

7. *The top i rank UE pairs will constitute* Ω_c *and the corresponding sets* Ω_{c1} *and* Ω_{c2}*, then the rest UEs will be included in the sets* Ω_{s1} *or* Ω_{s2}*.*

3.3.3 UE scheduling

After the cell-edge UE pairs are determined, the CRRM unit allocates CRBs to serve cell-edge UEs and informs the size and location of this allocation to all BSs.

Each BS schedules its own single-cell transmission UEs over the allocated S-RBs with no coordination with other BSs, which can adopt any scheduling algorithm.

In this paper, two common scheduling algorithms, round robin and proportional fair schedulers, will be employed to allocate C-RBs to cell-edge UEs.

Round robin scheduler: A round robin scheduler is one of the simplest scheduling algorithms for users in a wireless system. RBs are allocated equally to all UEs in a certain BS during one frame, which provides a great fairness among the UEs.

Proportional fair scheduler: A proportional fair scheduler is considered to achieve a balance between the throughput gain and the fairness at the same time.

For the single-cell transmission, the scheduler (considers the case with only one BS) allocates S-RB i to UE m with the largest ratio, which is given by

$$m^*(i) = \text{argmax} \ \frac{R^s_{m,i}}{\overline{R}^s_m} ,$$

Where

$R^s_{m,i}$ denotes the instantaneous UE rate and

$\overline{R}^s m$ denotes the average UE rate

For the cooperative rate splitting scheme, the proportional fair scheduler is required to serve UEs concurrently with more than one BSs. In this paper, we are going to propose a cooperative proportional fair algorithm, which is still absent in the literature. In this cooperative proportional fair algorithm, we aim to maximize the sum-log utility function Λ which can be expressed as

$$\Lambda = \sum_{(i_1,\, i_2) \in \Omega_c} (\log \overline{R}^c_{i1} + \log \overline{R}^c_{i2})$$

Where

$\overline{R}^c_{i1}$, $\overline{R}^c_{i2}$ denote the average rate of UE i_1 and UE i_2 respectively using the cooperative rate splitting scheme

Finally the cooperative proportional fair scheduler assigns C-RB i to the UE pair m which satisfies

$$m^*(i) = \text{argmax}\left(\frac{R^c{}_{m1,i}}{\overline{R^c{}_{m1}}} + \frac{R^c{}_{m2,i}}{\overline{R^c{}_{m2}}}\right)$$

where

$R^c_{m1,i}$, $R^c_{m2,i}$ denote the instantaneous rates of the cooperative rate splitting scheme of UE (served by BS1) and UE (served by BS2) respectively

$\overline{R}^c_{m1}$, $\overline{R}^c_{m2}$ denote the average rates of the cooperative rate splitting scheme of UE (served by BS1) and UE (served by BS2) respectively

3.4 Simulation Results

By the assumptions and the equation forms, this section indicates the performance of the CoMP scheme based on the cooperative rate splitting.

The following figures illustrate the achieved max sum rate and rate per user as well as the covariance of the private signals respectively at each case.

It is shown in the graphs that the sum rate is progressively increasing from the first case to the last. The lower value is observed in the 1st case. Each BS obtains from the backhaul the data intended for users in its coverage area alone. This results in the so-called interference channel (IC) and is treated for the MISO case. In the 2nd case the sum rate is higher than the previous case. The user messages are shared at multiple transmitters. This scheme is referred to as network MIMO.

The higher value is achieved in the 5th case, the proposed CoMP via Cooperative Rate Splitting and Scheduling scheme.

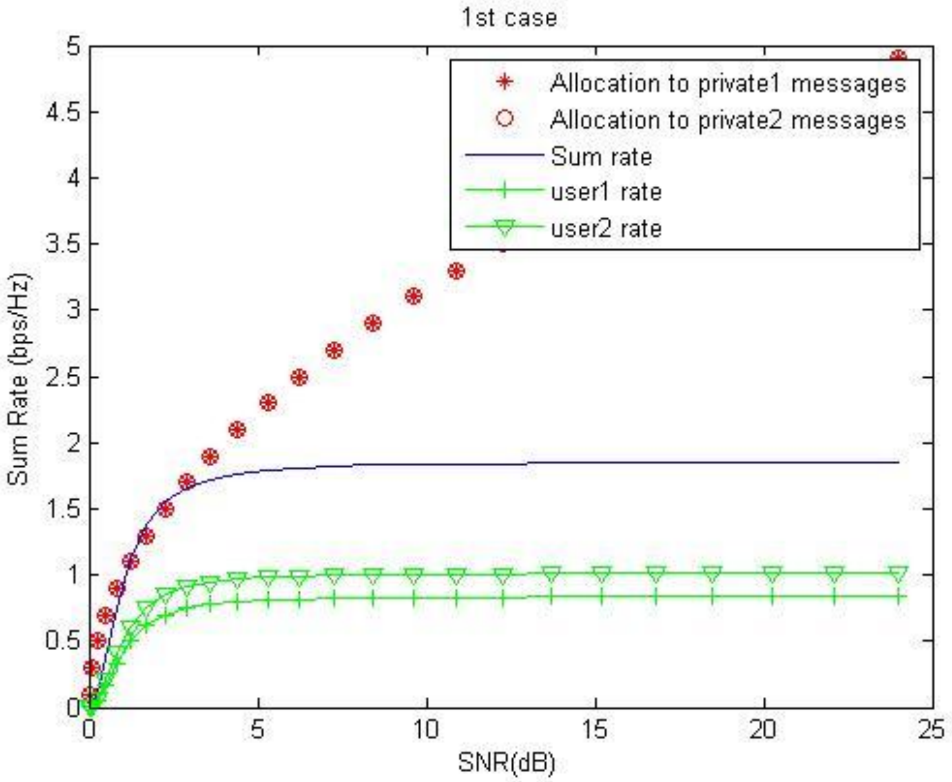

Figure 9: Rate allocation, 1st case

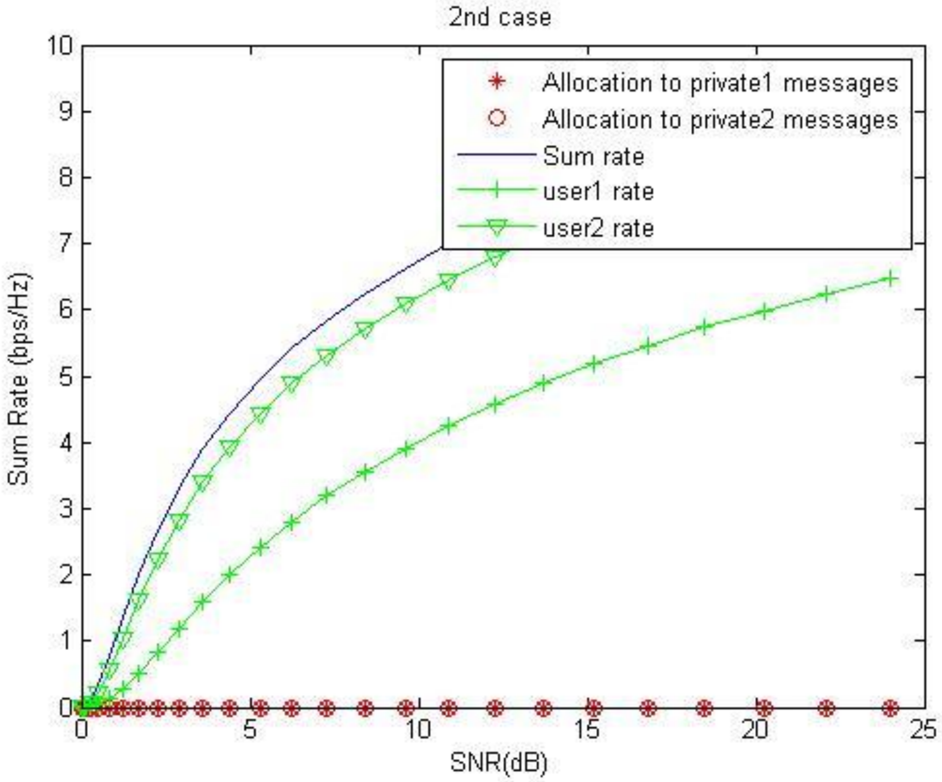

Figure 10: Rate allocation, 2nd case

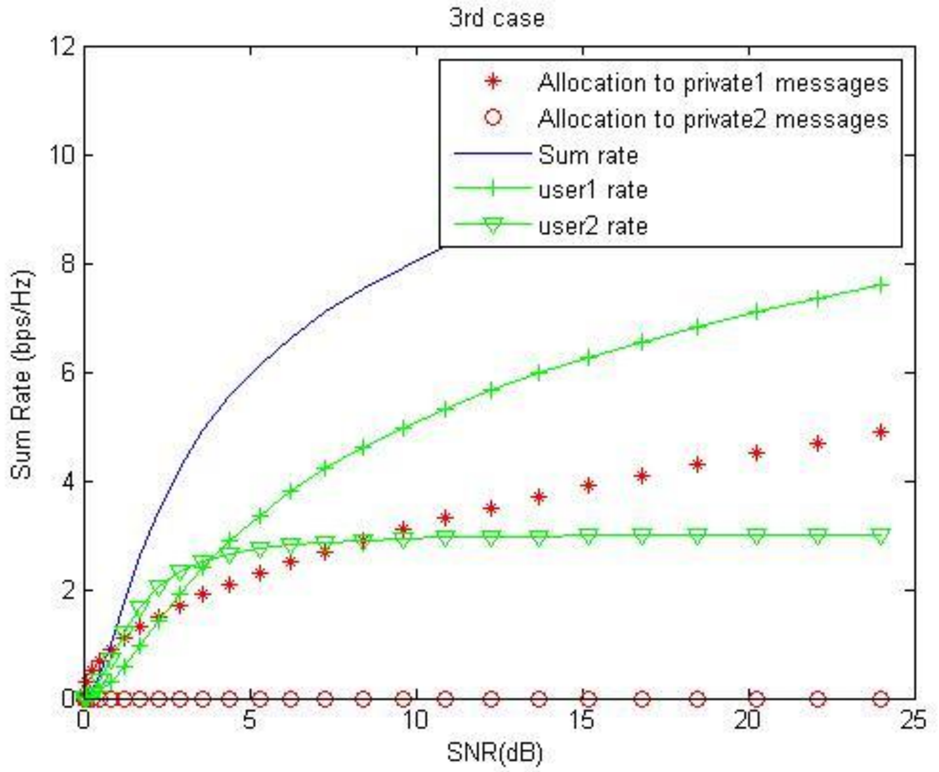

Figure11: Rate allocation, 3rd case

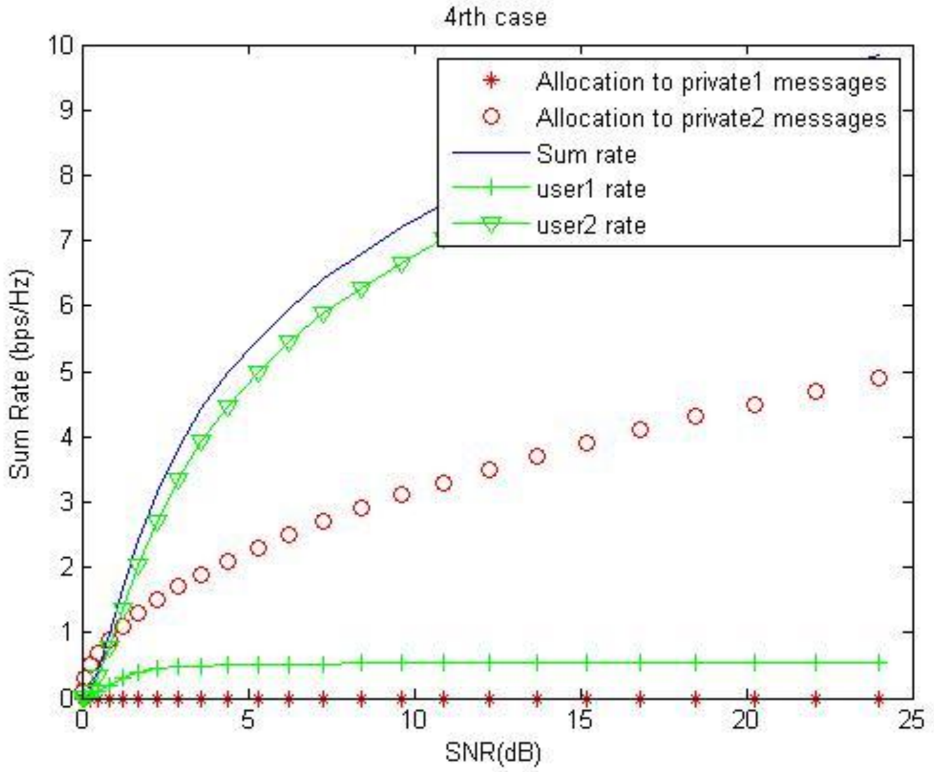

Figure 12: Rate allocation, 4rth case

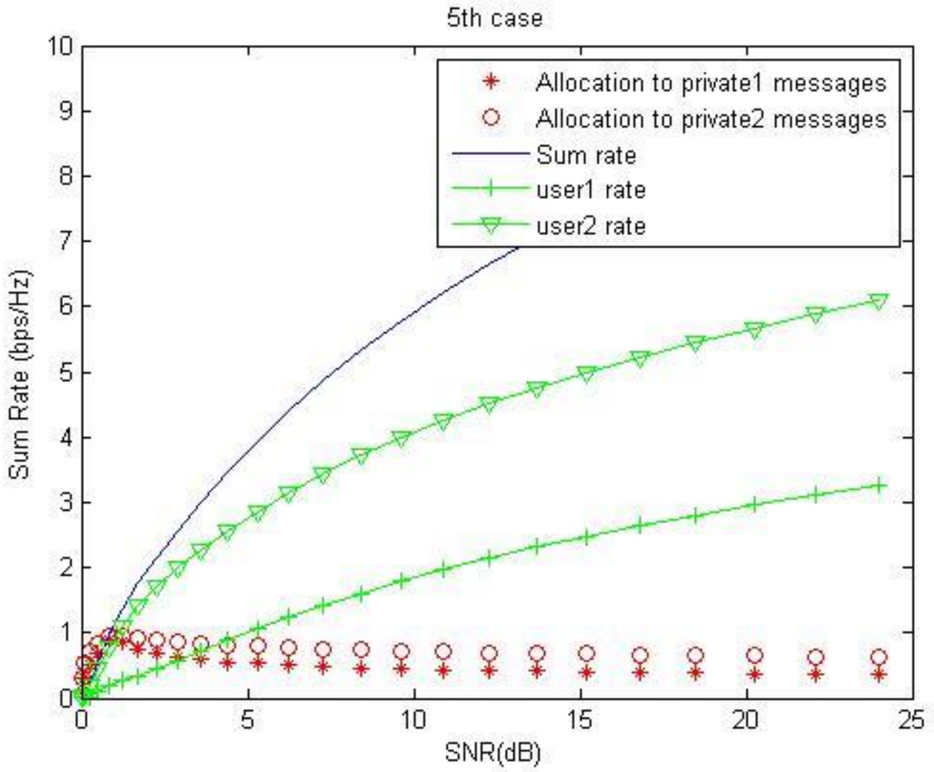

Figure13: Rate allocation, 5th case

The sum rate at the first case is not following the increment of SNR. On the contrary the sum rate at the rest of cases is increasing proportionally to SNR. This has the negative effect of increasing the systems backhaul capacity demands. In fact, this scheme subsumes high capacity backhaul links, which may not always be available, or even simply desirable. Hence this procedure provides a major disadvantage because of the requirement of a large capacity backhaul. This proposition evaluates the performance gains of the CoMP based on the cooperative rate splitting scheme in non realistic cellular systems.

Most publications in this field assume that an infinite amount of information can be exchanged between the cooperating base stations, neglecting the main downside of such systems, namely the need for an additional network backhaul.

4. CoMP via Cooperative Rate Splitting and Scheduling scheme under backhaul restriction.

Motivation

The CoMP via Cooperative Rate Splitting and Scheduling scheme can substantially improve the performance of the cell-edge UE. However, it is not well developed to be implemented in realistic applications. Critical issues of such schemes include, among others, the large extent of backhaul infrastructure required for the information exchange between cooperating base stations, and the availability of channel knowledge at transmitter and receiver. A joint encoding for the downlink of a cellular system is proposed without the assumption that the base stations are connected to a central processor (CP) or a backbone network via finite capacity links. This scheme subsumes very high capacity backhaul which may not be feasible, or even simply desirable, in certain applications. Most publications in this field assume that an infinite amount of information can be exchanged between the cooperating base stations, neglecting the main downside of such systems, namely the need for an additional network backhaul.

Backhaul constraints are seriously taken into consideration in the majority of the existing literatures. The key idea of the Randa Zakhour and David Gesbert in [17] is to use the backhaul capacity to convey different types of messages: private messages transmitted from the serving base station, and common messages jointly transmitted from several base stations. Patrick Marsch and Gerhard Fettweis in [23] showed that, even low-complexity optimization approaches for cellular systems with a strongly constrained backhaul can yield major performance improvements over conventional systems. Moreover in [24] they showed that, a cellular system should adapt between different forms of BS cooperation depending on channel conditions, in order to optimize the rate/backhaul trade-off, confirming results based on suboptimal precoding schemes in [14].

In this chapter the CoMP via Cooperative Rate Splitting and Scheduling scheme is adapted to suit realistic applications, by considering a setup in which a restricted rate backhaul connects the network with each of the BSs. Using simulation, it is shown that this proposed scheme is equally effective and more realistic.

4.1 System Model and Proposed Transmission Scheme

A downlink OFDMA system is considered here, where three sectors of one base station site share the same carrier frequency. For the sake of simplicity, each transmitter is assumed to use one antenna to serve a sector, and there is only one receiver served by each transmitter. We consider only one single subcarrier and assume that each receiver is equipped with one antenna.

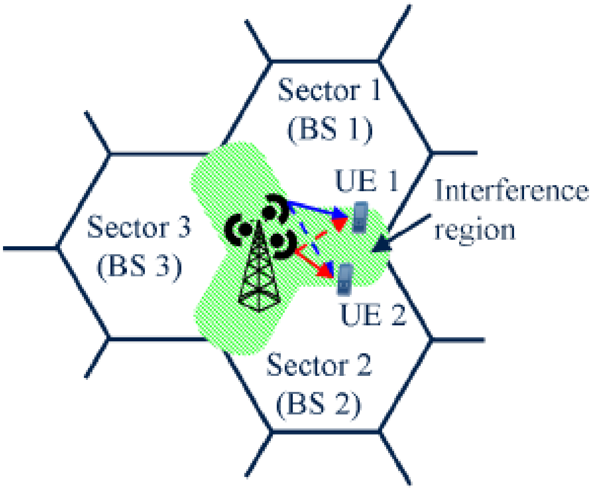

Figure14: Hexagonal cell structure with 120° sector antenna

In this simple system, transmitter1 is the serving transmitter for receiver1 and transmitter2 is the serving transmitter for receiver2. And both receivers are cell-edge users and they are geometrically close to each other. Accordingly, receiver1 and receiver2 receive interference from each other.

To be more specific, the received signals, r1 and r2, of receiver1 and receiver 2 can be written as

$$r_1 = h_{11}s_1 + h_{12}s_2 + \eta_1 + w_1 \qquad r_2 = h_{21}s_1 + h_{22}s_2 + \eta_2 + w_2$$

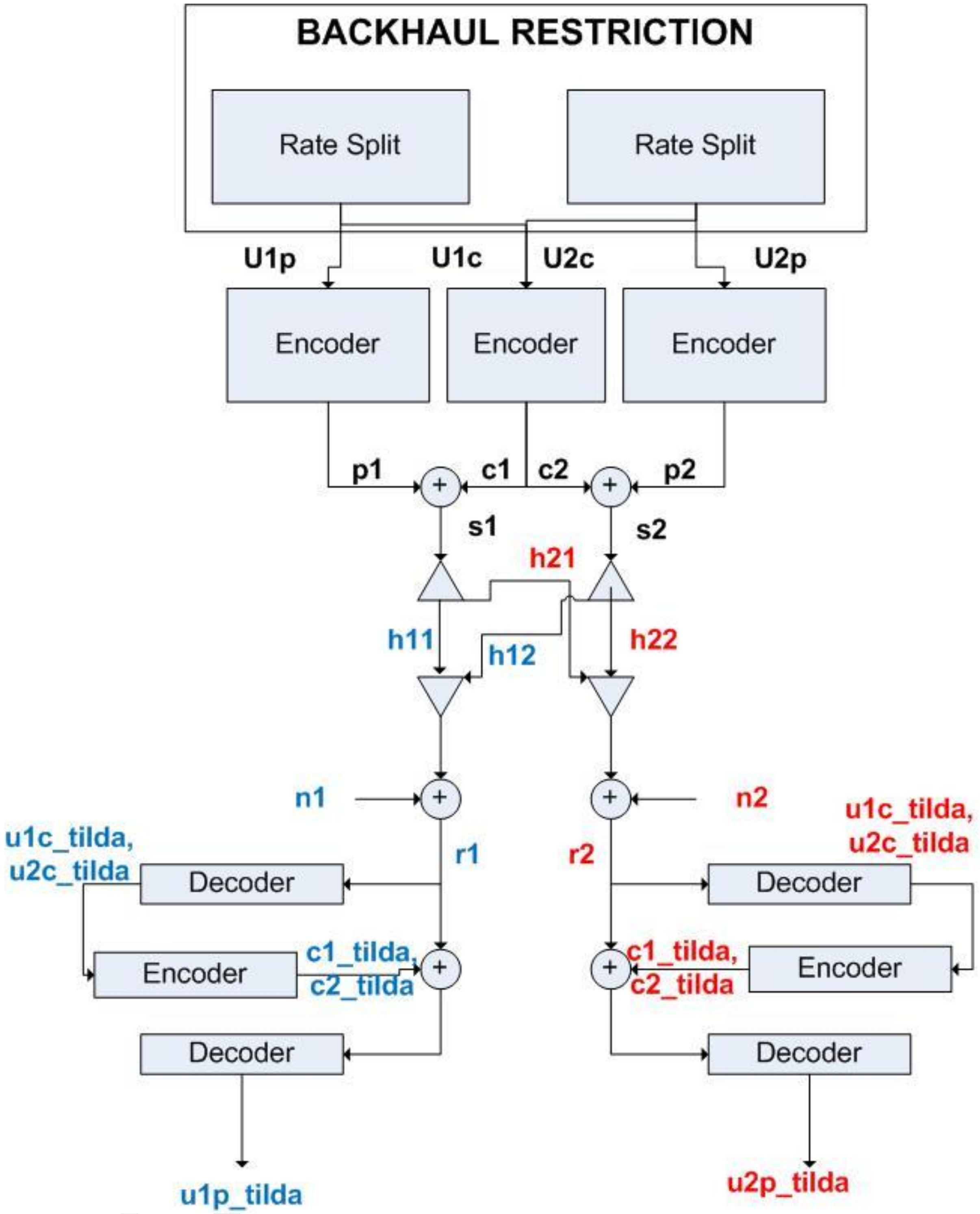

Figure15: The cooperative rate splitting model (two-user case) under backhaul restriction

where hij denotes the independent Rayleigh fading channel gain from transmitter j to receiver i. h11, h22, h12 and h21 are independent identically distributed (i.i.d.) zero-mean complex Gaussian random variables with variances σ^2_{11}, σ^2_{22}, σ^2_{12} and σ^2_{21} respectively,

where σ^2_{ij} reflects the channel propagation loss from transmitter j to receiver i. si is the transmitted symbol with covariance $\sigma^2_{s,i} = \mathcal{E}[|s_i|^2] = P_{s,i}$ at transmitter i. η_i and w_i are the interference caused by other transmitters and i.i.d additive white Gaussian noise (AWGN) samples, respectively. Here, ηi is treated as noise, thus the covariance of the noise ni (ηi + wi) is given by

$\Phi_{nn,i} = \mathcal{E}[|n_i|^2] = \mathcal{E}[|\eta_i|^2] + \mathcal{E}[|w_i|^2] = \sigma^2_{n,i}$

For each receiver, transmitters can be divided into three types: serving transmitter, cooperative transmitter and uncooperative transmitter. The cooperative transmitter cooperates with the serving transmitter. The receiver suffers the strongest interference from the cooperative transmitter. The receiver treats the interference from the uncooperative transmitters as noise. The received power of receiver i from its serving transmitter is $\sigma^2_{\gamma,i}=\sigma^2_{ii}\sigma^2_{s,i}$ and the received power of receiver i from its cooperative transmitter is $\sigma^2_{\mu,i}=\sigma^2_{ij}\sigma^2_{s,j}$ with (i≠j).

Four received signal strength ratios of receiver i are defined: signal-to-interference-plus-noise ratio $SINR_i = \sigma^2_{\gamma,i} / (\sigma^2_{\mu,i} + \sigma^2_{n,i})$, signal-to-noise ratio $SNR_i = \sigma^2_{\gamma,i} / \sigma^2_{n,i}$, interference-to-noise ratio $INR_i = \sigma^2_{\mu,i} / \sigma^2_{n,i}$ and signal-to-interference ratio $SIR_i = \sigma^2_{\gamma,i} / \sigma^2_{\mu,i}$.

In this analysis presented, we adopt the cooperative rate splitting scheme from the second paper: transmitter i splits its data u_i into two parts, $u_i^{\mathbf{c}}$ and u_i^p (where ‘c’ stands for the common information and ‘p’ for the private information). Encode the common information u_1^c and u_2^c cooperatively, in particular, the c_1 and c_2 are generated due to the joint encoding of u_1^c and u_2^c , u_i^p are encoded into p_i, c_i and p_i are superimposed with the power allocation policy

$$\sigma^2_{s,i} = \sigma^2_{c,i} + \sigma^2_{p,i}$$

where

$\sigma^2_{c,i}$ denote the covariance of the common signal c_i

$\sigma^2_{p,i}$ denote the covariance of the private signal p_i

s_i denote the transmitted signal

at the receiving end at the first stage, both receivers jointly decode u_1^c and u_2^c and simultaneously subtract off c_1 and c_2 from the received signal, while at the second stage u_1^p and u_2^p are only decoded by the intended receiver.

The two-user sum rate is contained in the following region:

$$\mathbf{R_1} \le \log_2\left(1+\frac{g_{11}\sigma^2_{p,1}}{\sigma^2_{n,1}+g_{12}\sigma^2_{p,2}}\right) + \min\left\{\mathrm{log2}\left(1+\frac{g_{11}\sigma^2_{c,1}}{\sigma^2_{n,1}+g_{11}\sigma^2_{p,1}+g_{12}\sigma^2_{p,2}}\right), \mathrm{log2}\left(1+\frac{g_{21}\sigma^2_{c,1}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}+g_{22}\sigma^2_{p,2}}\right)\right\},$$

$$\mathbf{R_2} \le \log_2\left(1+\frac{g_{22}\sigma^2_{p,2}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}}\right) + \min\left\{\mathrm{log2}\left(1+\frac{g_{12}\sigma^2_{c,2}}{\sigma^2_{n,1}+g_{11}\sigma^2_{p,1}+g_{12}\sigma^2_{p,2}}\right), \mathrm{log2}\left(1+\frac{g_{22}\sigma^2_{c,2}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}+g_{22}\sigma^2_{p,2}}\right)\right\},$$

$$\mathbf{R_1 + R_2} \le \log_2\left(1+\frac{g_{11}\sigma^2_{p,1}}{\sigma^2_{n,1}+g_{12}\sigma^2_{p,2}}\right) + \log_2\left(1+\frac{g_{22}\sigma^2_{p,2}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}}\right) + \min\left\{\mathrm{log2}\left(1+\frac{g_{11}\sigma^2_{c,1}+g_{12}\sigma^2_{c,2}}{\sigma^2_{n,1}+g_{11}\sigma^2_{p,1}+g_{12}\sigma^2_{p,2}}\right), \log_2\left(1+\frac{g_{21}\sigma^2_{c,1}+g_{22}\sigma^2_{c,2}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}+g_{22}\sigma^2_{p,2}}\right)\right\}, \quad (3)$$

Where

g_{ij} is the channel gain from transmitter j to receiver i

R_i denotes the rate of receiver i.

The **optimal power allocation** solution can be obtained by solving the following overall optimization problem

$$\sigma^{2,*}_{p,1},\ \sigma^{2,*}_{p,2} = \arg_{\sigma^{2}_{p,1},\ \sigma^{2}_{p,2}} \max \quad \text{eq. (3)}$$

$$\text{s.t:} \quad \sigma^{2}_{s,1} = \sigma^{2}_{c,1} + \sigma^{2}_{p,1}, \qquad \sigma^{2}_{s,2} = \sigma^{2}_{c,2} + \sigma^{2}_{p,2}$$

4.1.1 Backhaul restriction

Assuming a backhaul link of capacity Cj [bits/sec/Hz] between the backbone network and transmitter j for j = 1, 2, have to be taken into consideration We introduce the fundamental inequalities imposed by the backhaul restriction which will be helpful in characterizing the achievable rate region for this cooperative rate splitting scheme:

$$R1 + R2 \leq C1 + C2 \Rightarrow R1 + R2 \leq C$$

The sum rate (R1+ R2) cannot exceed the total backhaul capacity and the each user rate:

$$R1 \leq C - R2 \qquad R2 \leq C - R1$$

4.2 Achievable Rate Region

The corresponding rate region is expressed in terms of the backhaul restriction and the power allocation variances used to carry the different signals: finding the boundary of the aforementioned region we also solve the problem of optimal power allocation. This study adopts the fives cases of the second paper and imposes the previous backhaul restriction. The five cases are formulated:

In case 1,

$\sigma^2_{p,1} = \sigma^2_{s,1}$ and $\sigma^2_{p,2} = \sigma^2_{s,2}$ ($\sigma^2_{c,1} = 0$ and $\sigma^2_{c,2} = 0$)

The maximum sum rate in is

$$(R_1 + R_2)_{\max} = \log 2\left(1 + \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1} + g_{12}\sigma^2_{s,2}}\right) + \log_2\left(1 + \frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2} + g_{21}\sigma^2_{s,1}}\right) \leq C$$

the sum rate is achieved by sending only private information and the rate per user

$$R1 \leq C - R2$$

In case 2,

$\sigma^2_{p,1} = 0$ and $\sigma^2_{p,2} = 0$ ($\sigma^2_{s,1} = \sigma^2_{c,1}$ and $\sigma^2_{s,2} = \sigma^2_{c,2}$)

The maximum sum rate in is

$$(R_1 + R_2)_{\max} = \min\left\{\log_2\left(1 + \frac{g_{11}\sigma^2_{s,1} + g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}}\right), \log_2\left(1 + \frac{g_{22}\sigma^2_{s,2} + g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}}\right)\right\} \leq C$$

the sum rate is achieved by sending only common information and the rate per user

$$R1 \leq C - R2$$

In case 3,

$\sigma^2_{p,1} = \sigma^2_{s,1}$ and $\sigma^2_{p,2} = 0$ ($\sigma^2_{c,1} = 0$ and $\sigma^2_{s,2} = \sigma^2_{c,2}$)

The maximum sum rate

if $\dfrac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} < \dfrac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1}}$

$$(R_1 + R_2)_{\max} = \log2\left(1 + \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1}}\right) + \log_2\left(1+\frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2} + g_{21}\sigma^2_{s,1}}\right) \leq \; C$$

$$\text{if} \quad \frac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} < \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1}}$$

$$(R_1 + R_2)_{\max} = \log_2\left(1 + \frac{g_{11}\sigma^2_{s,1} + g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}}\right) \leq \; C$$

UE 1 only sends private information and UE 2 only sends common information. The rate per user

$$R1 \leq C - R2$$

In case 4,

$\sigma^2_{p,1} = 0$ and $\sigma^2_{p,2} = \sigma^2_{s,2}$ $(\sigma^2_{s,1} = \sigma^2_{c,1}$ and $\sigma^2_{c,2} = 0)$

The maximum sum rate

$$\text{If} \quad \frac{g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}} < \frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2}}$$

$$(R_1 + R_2)_{\max} = \log2\left(1 + \frac{g_{22}\sigma^2_{s,2}}{\sigma^2_{n,2}}\right) + \log_2\left(1 + \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1} + g_{12}\sigma^2_{s,2}}\right) \leq \; C$$

$$\text{if} \quad \frac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} + \frac{g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}} \times \frac{g_{12}\sigma^2_{s,2}}{\sigma^2_{n,1}} < \frac{g_{11}\sigma^2_{s,1}}{\sigma^2_{n,1}}$$

$$(R_1 + R_2)_{\max} = \log_2\left(1 + \frac{g_{22}\sigma^2_{s,2} + g_{21}\sigma^2_{s,1}}{\sigma^2_{n,2}}\right) \leq \; C$$

UE 1 only sends common information and UE 2 only sends private information. The rate per user is:

$$R1 \leq C - R2$$

In case 5,

$$\sigma^2_{p,1} = \min\left\{\frac{-ABC + \sqrt{ABC(C-AB+1)}}{AC(C+1)},\ \sigma^2_{s,1}\right\}$$

$$\sigma^2_{p,2} = \sigma^2_{p,1}\,\frac{g_{11}-\kappa g_{21}}{\kappa g_{22}-g_{12}} + \frac{\sigma^2_{n,1}-\kappa\sigma^2_{n,2}}{\kappa g_{22}-g_{12}},$$

$$\sigma^2_{c,1} = \sigma^2_{s,1} - \sigma^2_{p,1}, \qquad \sigma^2_{c,2} = \sigma^2_{s,2} - \sigma^2_{p,2}$$

where

$$\kappa = \frac{\sigma^2_{n,1} + g_{11}\sigma^2_{p,1} + g_{12}\sigma^2_{p,2}}{\sigma^2_{n,2} + g_{21}\sigma^2_{p,1} + g_{22}\sigma^2_{p,2}} = \frac{\sigma^2_{n,1} + g_{11}\sigma^2_{s,1} + g_{12}\sigma^2_{s,2}}{\sigma^2_{n,2} + g_{21}\sigma^2_{s,1} + g_{22}\sigma^2_{s,2}}$$

$$A = \frac{g_{21}}{\sigma^2_{n,2}}, \qquad B = \frac{\kappa}{g_{11}} \times \frac{g_{12}\sigma^2_{n,2} - g_{22}\sigma^2_{n,1}}{g_{12}-\kappa g_{22}}, \qquad C = \frac{g_{12}}{g_{11}} \times \frac{\kappa g_{21} - g_{11}}{g_{12}-\kappa g_{22}}$$

The maximum sum rate is

$$(R_1 + R_2)_{\max} = \log_2\left(1+\frac{g_{11}\sigma^2_{p,1}}{\sigma^2_{n,1}+g_{12}\sigma^2_{p,2}}\right) + \log_2\left(1+\frac{g_{22}\sigma^2_{p,2}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}}\right) + \min\left\{\log_2\left(1+\frac{g_{11}\sigma^2_{c,1}+g_{12}\sigma^2_{c,2}}{\sigma^2_{n,1}+g_{11}\sigma^2_{p,1}+g_{12}\sigma^2_{p,2}}\right),\ \log_2\left(1+\frac{g_{21}\sigma^2_{c,1}+g_{22}\sigma^2_{c,2}}{\sigma^2_{n,2}+g_{21}\sigma^2_{p,1}+g_{22}\sigma^2_{p,2}}\right)\right\} \le \mathbf{C}$$

The rate per user

$$R1 \le C - R2$$

4.3 Simulation results

This chapter adopting the CoMP scheme of the second paper, by the assumptions and the equation forms, indicates the performance of the CoMP scheme based on the cooperative rate splitting under backhaul restriction. In the context of optimal power allocation solution the following figures illustrate the achieved max sum rate and rate per user as well as the covariance of the private signals respectively at each case. Throughout the simulations, $C_1 = C_2$ and C is the total backhaul capacity C=5bits/sec/Hz.

As can be seen, at the first case the sum rate is significantly lower than the total backhaul capacity. Each BS obtains from the backhaul the data intended for users in its coverage area alone. This results in the so-called interference channel (IC) and is treated for the MISO case. If the backhaul is constrictive, it may be better to simply have each user served by a single base station (1st case) rather have both messages routed to both base stations. This is because, although data sharing allows to convert the interference channel into a MIMO broadcast channel with higher capacity, data sharing occupies the resources that could otherwise be used to send fresh (non shared) data.

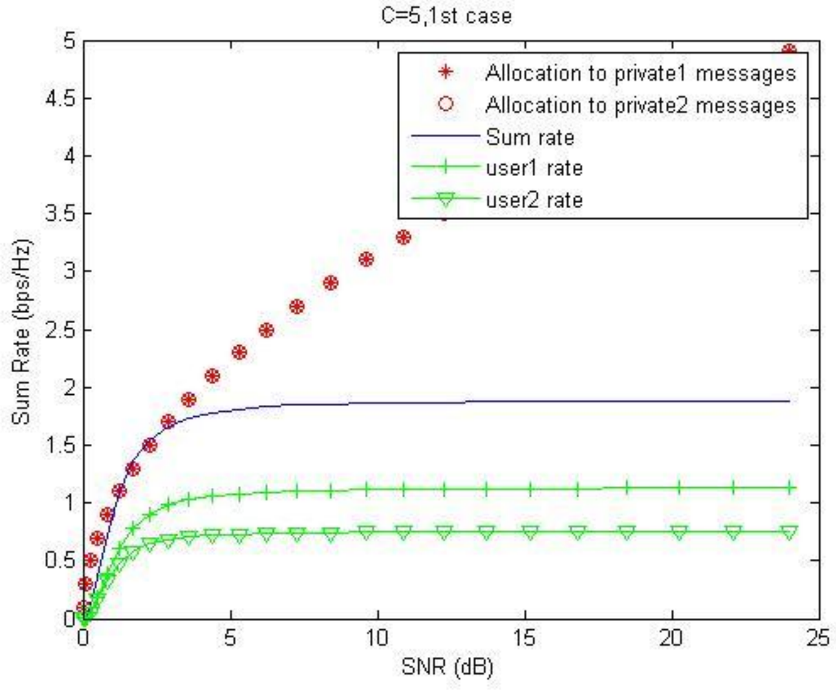

Figure 16: Combining the two schemes, C=5, 1st case

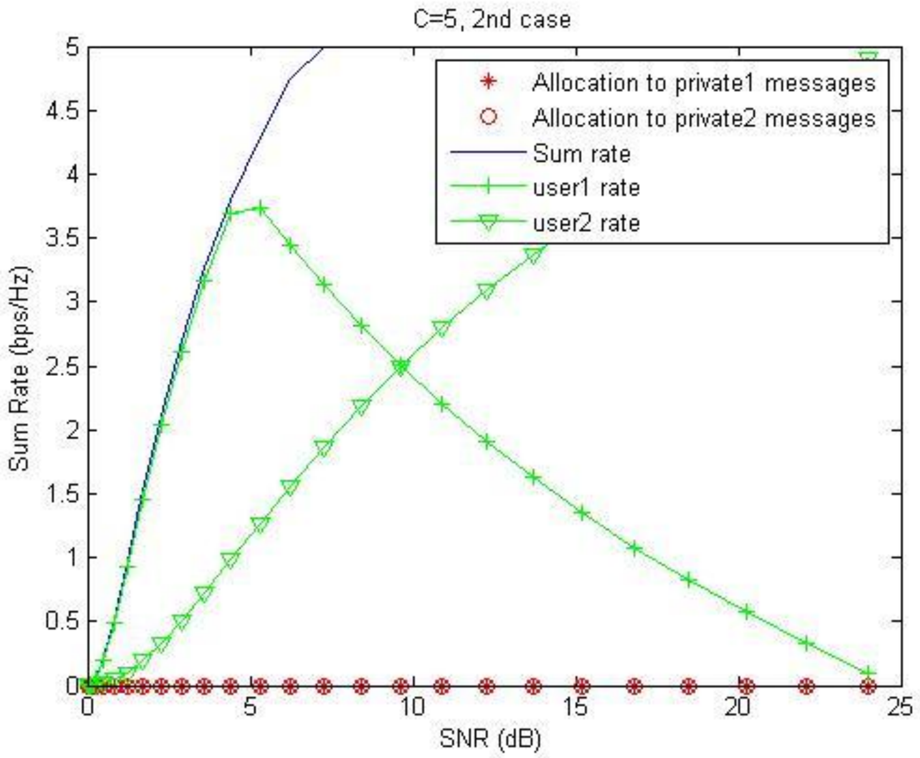

Figure 17: Combining the two schemes, C=5, 2nd case

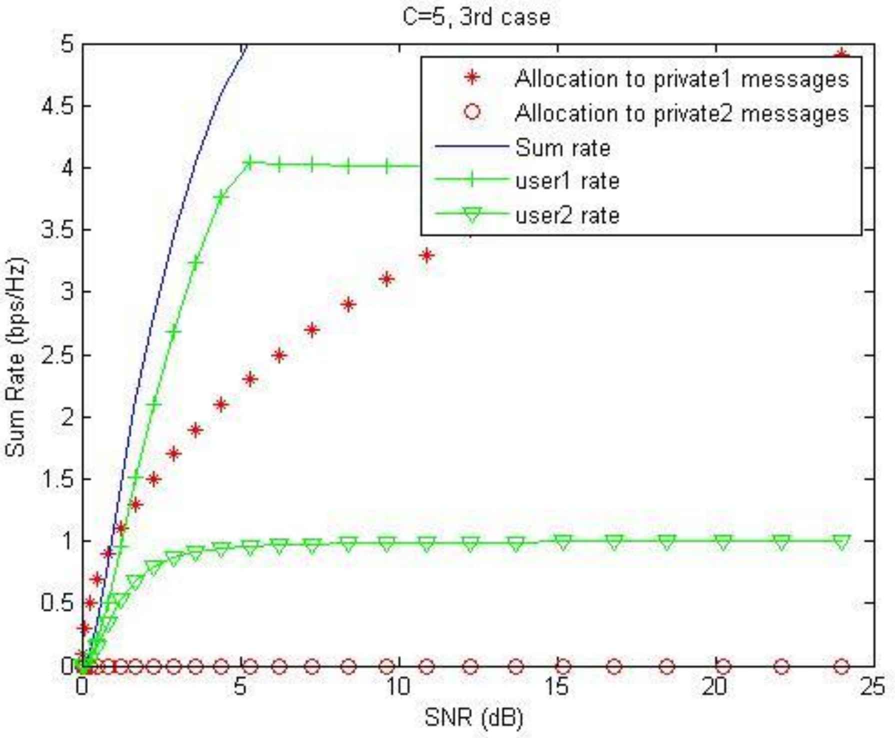

Figure 18: Combining the two schemes, C=5, 3rd case

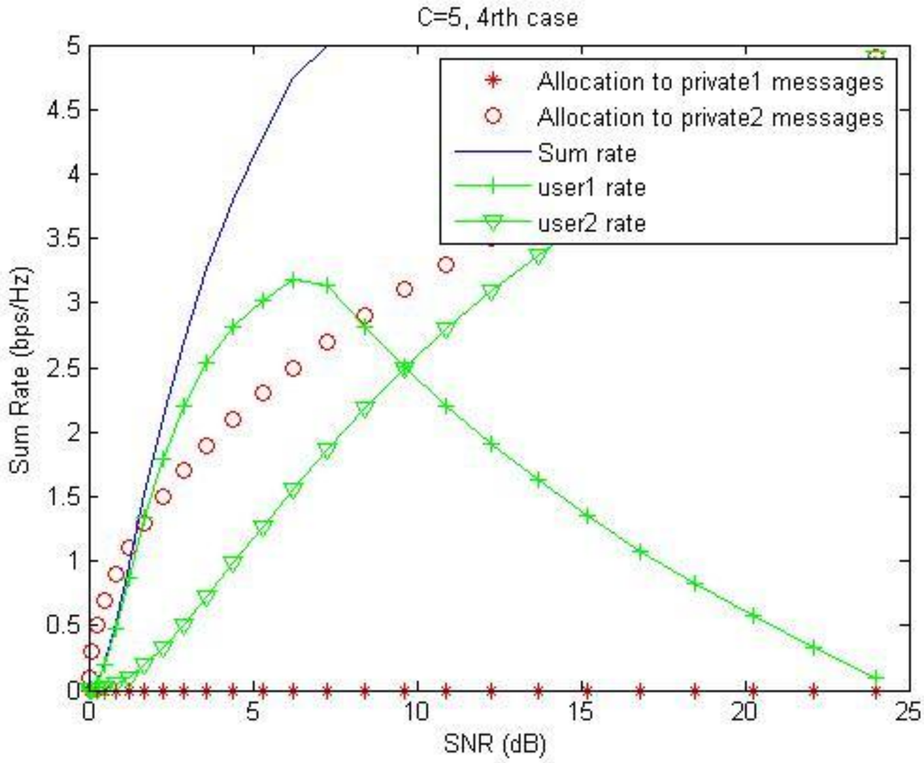

Figure 19: Combining the two schemes, C=5, 4th case

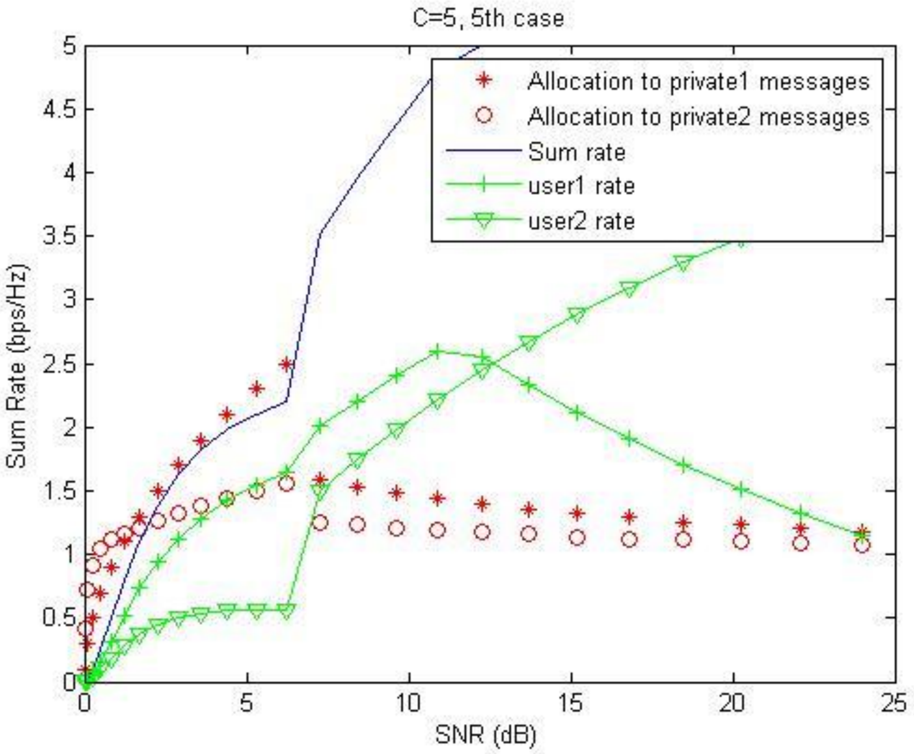

Figure 20 Combining the two schemes, C=2, 5th case

The results in the rest of the cases indicate that the corresponding rate region is defined of the backhaul restriction, necessary to achieve feasibility.

Under the rate splitting scheme, transmitted data streams are split into common and private data stream, by decoding the common data stream of the interference, part of the interference is cancelled, and consequently the UE throughput can be improved. But, this CoMP scheme requires information exchange between involved BSs, thereby requires more overhead in feedback and backhaul. As shown in the fifth case (general case), for low SNR the transmitted data streams are only private data streams: this is the case in Figures 20 and 21. As the SNR increases the effective throughput is improved but the need for more overhead increases which poses the need for an additional network backhaul. Consequently one can note a trade off between effective throughput and rate overhead in this CoMP scheme under constrained backhaul.

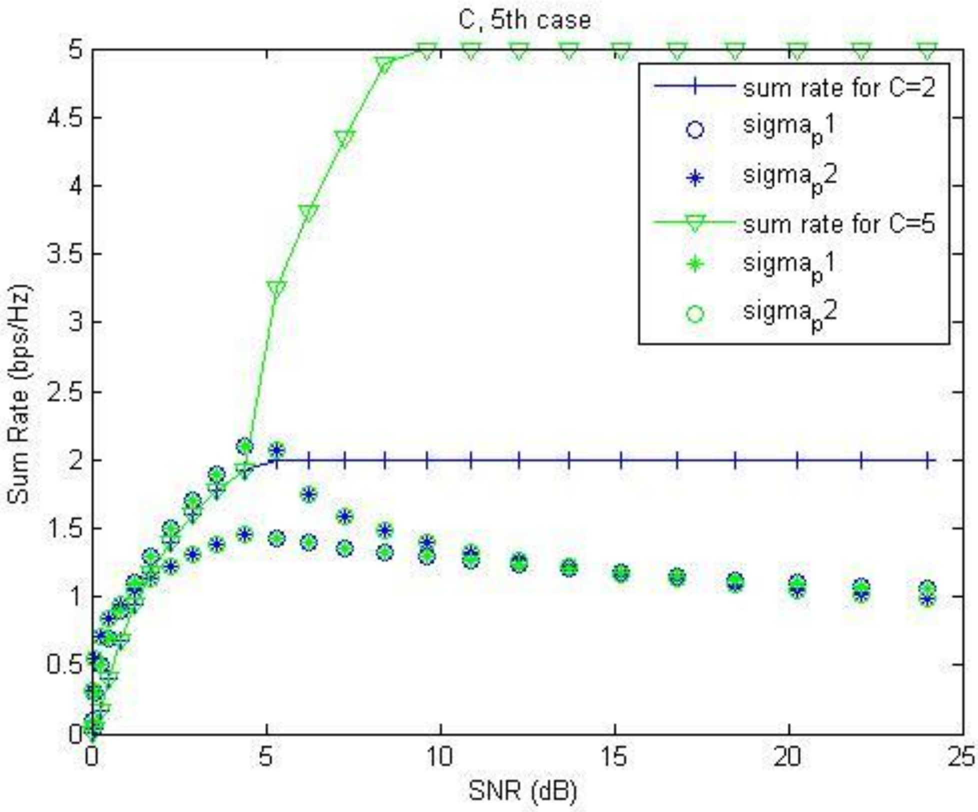

Figure 21: Average maximum sum rate versus SNR for C=2, 5 bits/sec/Hz. The figure also shows how much of the power is in the form of private signals

Figure 21 illustrates the max sum rate, achieved by the 5th case, the proposed CoMP via Cooperative Rate Splitting and Scheduling scheme and the allocation power policy for C= 2bits/sec/Hz and C= 5bits/sec/Hz. Figure 22 shows the max sum rate achieved by the 5th case, the proposed CoMP via Cooperative Rate Splitting and Scheduling scheme for different values of the backhaul (C = 2, 5 and 10 bits/sec/Hz).

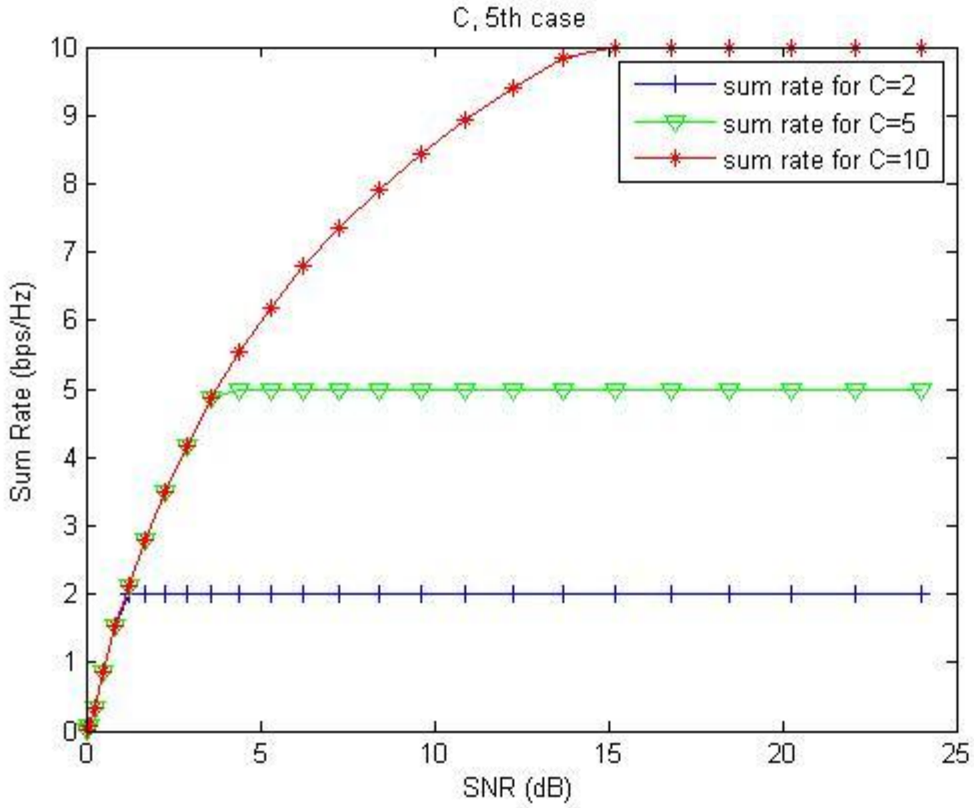

Figure 22: Average maximum sum rate versus SNR for C=2, 5 and 10 bits/sec/Hz

Fig. 21 and 22 indicate that, without the backhaul restriction, the graph line would continue going upwards, thus increasing substantially the rate, required by the application, which may not be available, or even simply desirable. On the contrary, under the backhaul restriction the rate is adjusted each time to the available backhaul capacity but a trade off between rates and required backhaul, because of the overhead, always exists.

Therefore, the proposed approach is equally effective although it utilizes lower rate. Consequently, the proposed approach proves to be more realistic.

5. Conclusions

It is known that inter-cell interference poses the main capacity limitation in future cellular systems, meaning that, the downlink capacity of cellular wireless networks is limited by inter-cell interference which is caused by the neighboring cell transmissions and can sharply degrade the received signal quality. The rate splitting method partially overcomes this problem. However, when it is applied in the CoMP scheme - an process to coordinate the base antenna transmissions so as to minimize the inter-cell interference and hence to increase the downlink system capacity – in order to bring in more benefits to cell-edge UE, the main downside is the major amount of backhaul required for information exchange between involved BSs. Thus a main problem connected to multi-cell signal processing is the additional backhaul traffic required between cooperating base stations. While multicell processing is by now regarded as a key candidate technology for future wireless communication standards, a number of issues remain to be investigated to fully assess its potentiality, most notably the impact of finite-capacity backhaul.

In chapter 3, analysis of the performance of multicell processing has been carried out under the assumption that all the BSs in the network are connected to a central processor via links of unlimited capacity. Since the assumption of unlimited-capacity links to a central processor is quite unrealistic, for large networks, in this study, there has been an attempt to alleviate this condition by considering an alternating model. The alternating model, described in chapter 4, adapts the coordinated multi-point transmission framework based on the cooperative rate splitting scheme under the assumption that the base stations (BSs) are connected to a central processor (CP) via finite capacity links (finite –capacity backhaul).

The study shows that the proposed scheme is equally effective and more realistic. Moreover, the limits of SNR are defined, among which it is possible to achieve this scheme.

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Appendix

The code of the CoMP via Cooperative Rate Splitting and Scheduling scheme under backhaul restriction:

```
clear all;
close all;

sigma_s1 = 0.1:0.2:5;
sigma_s2 = 0.1:0.2:5;
sigma_n1 = ones(1,size(sigma_s1,2));
sigma_n2 = ones(1,size(sigma_s1,2));
SNR1 = (sigma_s1.^2)./(sigma_n1.^2);
SNR2 = (sigma_s2.^2)./(sigma_n2.^2);
hchan = (randn(2,2) + j*randn(2,2))/sqrt(2); % Rayleigh channel
g11 = abs(SNR1.*hchan(1,1));
g12 = abs(SNR1.*hchan(1,2));
g21 = abs(SNR2.*hchan(2,1));
g22 = abs(SNR2.*hchan(2,2));

Capacity = 5;

%% rate splitting scheme, 1st case

sigma_p1_1 = sigma_s1;  % BS 1
sigma_p2_1 = sigma_s2;  % BS 2
```

```
% Max Sum Rate
for i=1:size(sigma_s1,2)
   MaxSumRate1(i) = log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2+g12(i).*sigma_s2(i).^2)) + log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2+g21(i).*sigma_s1(i).^2));

if MaxSumRate1(i) > Capacity
   MaxSumRate1(i) = Capacity;
end

R11(i) = log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2+g12(i).*sigma_s2(i).^2));
R21(i) = log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2+g21(i).*sigma_s1(i).^2));

if (R11(i)+R21(i)) > Capacity
   R11(i) = Capacity - R21(i);
end

end


plot(SNR1,sigma_p1_1,'*r',SNR2,sigma_p2_1,'or');
hold on
plot(SNR1, MaxSumRate1, 'b');
hold on
plot(SNR1, R11, 'g+-', SNR2, R21, 'gv-');
title ('C=5,1st case ');
xlabel('SNR');
```

```
ylabel('Sum Rate - Alocation private messages');

legend('Allocation to private1 messages','Allocation to private2 messages','Sum rate ','user1
rate','user2 rate')




%% rate splitting scheme, 2nd case


sigma_p1_2 = zeros(1,size(sigma_s1,2));

sigma_p2_2 = zeros(1,size(sigma_s1,2));




% Max Sum Rate

for i=1:size(sigma_s1,2)

     if (log2(1+(g11(i).*sigma_s1(i).^2+g12(i).*sigma_s2(i).^2)./sigma_n1(i).^2)) <
(log2(1+(g22(i).*sigma_s2(i).^2+g21(i)*sigma_s1(i).^2)./sigma_n2(i).^2))

        MaxSumRate2(i) = log2(1+(g11(i).*sigma_s1(i).^2+g12(i).*sigma_s2(i).^2)./sigma_n1(i).^2);

    else

        MaxSumRate2(i) = log2(1+(g22(i).*sigma_s2(i).^2+g21(i).*sigma_s1(i).^2)./sigma_n2(i).^2);

    end


if MaxSumRate2(i) > Capacity

    MaxSumRate2(i) = Capacity;

end


    if (log2(1+(g11(i).*sigma_s1(i).^2)./sigma_n1(i).^2)) <
(log2(1+(g21(i).*sigma_s1(i).^2)./sigma_n2(i).^2))

        R12(i) = log2(1+(g11(i).*sigma_s1(i).^2)./sigma_n1(i).^2);

    else

        R12(i) = log2(1+(g21(i).*sigma_s1(i).^2)./sigma_n2(i).^2);
```

```
   end

   if (log2(1+(g12(i).*sigma_s2(i).^2)./sigma_n1(i).^2)) <
(log2(1+(g22(i).*sigma_s2(i).^2)./sigma_n2(i).^2))
      R22(i) = log2(1+(g12(i).*sigma_s2(i).^2)./sigma_n1(i).^2);
   else
      R22(i) = log2(1+(g22(i).*sigma_s2(i).^2)./sigma_n2(i).^2);
   end

   if (R12(i)+R22(i)) > Capacity
   R12(i) = Capacity - R22(i);
end

end

figure;
plot(SNR1,sigma_p1_2,'*r',SNR2,sigma_p2_2,'or');
hold on
plot(SNR1, MaxSumRate2, 'b');
hold on
plot(SNR1, R12, 'g+-', SNR2, R22, 'gv-');
title ('C=5, 2nd case');
xlabel('SNR');
ylabel('Sum Rate - Alocation private messages');
legend('Allocation to private1 messages','Allocation to private2 messages','Sum rate ','user1
rate','user2 rate')
```

```
%% rate splitting scheme, 3rd case


sigma_p1_3 = sigma_s1;

sigma_p2_3 = zeros(1,size(sigma_s1,2));




% Max Sum Rate - Rate per user

for i=1:size(sigma_s1,2)

 if  (g21(i).*sigma_s1(i).^2)./(sigma_n2(i).^2)<(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2)

     MaxSumRate3(i) = log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2)) + 
log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2+g21(i).*sigma_s1(i).^2));

     R13(i) = log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2));

     R23(i) = log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2+g21(i).*sigma_s1(i).^2));


  else

     MaxSumRate3(i) = log2(1+(g11(i).*sigma_s1(i).^2 + g12(i).*sigma_s2(i).^2)./(sigma_n1(i).^2));

     R13(i) = log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2));

     R23(i) = log2(1+(g12(i).*sigma_s2(i).^2)./(sigma_n1(i).^2+g12(i).*sigma_s1(i).^2));


end


 if MaxSumRate3(i) > Capacity

    MaxSumRate3(i) = Capacity;

 end


 if (R13(i)+R23(i)) > Capacity

    R13(i) = Capacity - R23(i);

end
```

```
end



figure;
plot(SNR1,sigma_p1_3,'*r',SNR2,sigma_p2_3,'or');
hold on
plot(SNR1, MaxSumRate3, 'b');
hold on
plot(SNR1, R13, 'g+-', SNR2, R23, 'gv-');
title ('C=5, 3rd case');
xlabel('SNR');
ylabel('Sum Rate - Alocation private messages');
legend('Allocation to private1 messages','Allocation to private2 messages','Sum rate ','user1 rate','user2 rate')



%% rate splitting scheme, 4rth case


sigma_p1_4 = zeros(1,size(sigma_s1,2));
sigma_p2_4 = sigma_s2;



% Max Sum Rate - Rate per user
for i=1:size(sigma_s1,2)


if (g12(i).*sigma_s2(i).^2)./(sigma_n1(i).^2) < (g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2)
```

```
    MaxSumRate4(i) = log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2)) + log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2+g12(i).*sigma_s2(i).^2));

    R14(i) = log2(1+(g11(i).*sigma_s1(i).^2)./(sigma_n1(i).^2+g12(i).*sigma_s2(i).^2));

    R24(i) = log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2));

    else

    MaxSumRate4(i) = log2(1+(g21(i).*sigma_s1(i).^2 + g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2));

    R14(i) = log2(1+(g21(i).*sigma_s1(i).^2)./(sigma_n2(i).^2+g22(i).*sigma_s2(i).^2));

    R24(i) = log2(1+(g22(i).*sigma_s2(i).^2)./(sigma_n2(i).^2));


end

 if MaxSumRate4(i) > Capacity

    MaxSumRate4(i) = Capacity;

 end


   if (R14(i)+R24(i)) > Capacity

    R14(i) = Capacity - R24(i);

  end

end




figure;

plot(SNR1,sigma_p1_4,'*r',SNR2,sigma_p2_4,'or');

hold on

plot(SNR1, MaxSumRate4, 'b');

hold on

plot(SNR1, R14, 'g+-', SNR2, R24, 'gv-');

title ('C=5, 4rth case');

xlabel('SNR');
```

```
ylabel('Sum Rate - Alocation private messages');

legend('Allocation to private1 messages','Allocation to private2 messages','Sum rate ','user1 rate','user2 rate')



%% rate splitting scheme, 5th case


for h=1:size(sigma_s1,2)

k1(h) = (sigma_n1(h).^2 +g11(h)*sigma_s1(h).^2+g12(h).*sigma_s2(h).^2)./(sigma_n2(h).^2 +g21(h).*sigma_s1(h).^2+g22(h).*sigma_s2(h).^2);


if k1(h)>1

    k1(h) = 1./k1(h);

end



A(h) = g21(h)./sigma_n2(h).^2;

B(h) = (k1(h)./g11(h))*(g12(h).*sigma_n2(h).^2 - g22(h).*sigma_n1(h).^2)./(g12(h) - k1(h)*g22(h));

C(h) = (g12(h)./g11(h)).*(k1(h)*g21(h) - g11(h))./(g12(h) - k1(h)*g22(h));


if sqrt((-A(h)*B(h)*C(h)+sqrt(A(h).*B(h).*C(h).*(C(h)-A(h).*B(h)+1)))./(A(h).*C(h).*(C(h)+1)))<sigma_s1(h)

    sigma_p1_5(h)= sqrt(abs(sqrt((-A(h).*B(h).*C(h)+sqrt(A(h).*B(h).*C(h).*(C(h)-A(h).*B(h)+1)))./(A(h).*C(h).*(C(h)+1)))));

else

    sigma_p1_5(h) = sigma_s1(h);

end
```

```
sigma_p2_5(h) = sqrt(abs(sqrt(sigma_p1_5(h).^2.*(g11(h)-k1(h)*g21(h))./(k1(h)*g22(h)-g12(h)) +
(sigma_n1(h).^2 - k1(h)*sigma_n2(h).^2)./(k1(h)*g22(h) - g12(h)))));

end


sigma_p1 = sigma_p1_5;

sigma_p2 = sigma_p2_5;



if (log2(1+(g11.*(sigma_s1.^2-sigma_p1.^2)./(sigma_n1.^2+g11.*sigma_p1.^2+g12.*sigma_p2.^2))))
< (log2(1+(g21.*(sigma_s1.^2-sigma_p1.^2)./(sigma_n2.^2+g21.*sigma_p1.^2+g22.*sigma_p2.^2))))

R1max = log2(1+(g11.*sigma_p1.^2)./(sigma_n1.^2+g12.*sigma_p2.^2)) +
log2(1+(g11.*(sigma_s1.^2-sigma_p1.^2)./(sigma_n1.^2+g11.*sigma_p1.^2+g12.*sigma_p2.^2)));

else

R1max =  log2(1+(g21.*(sigma_s1.^2-
sigma_p1.^2)./(sigma_n2.^2+g21.*sigma_p1.^2+g22.*sigma_p2.^2))) +
log2(1+(g11.*sigma_p1.^2)./(sigma_n1.^2+g12.*sigma_p2.^2));

end


if (log2(1+(g12.*(sigma_s2.^2-sigma_p2.^2)./(sigma_n1.^2+g21.*sigma_p1.^2+g12.*sigma_p2.^2))))
< (log2(1+(g21.*(sigma_s1.^2-sigma_p1.^2)./(sigma_n2.^2+g21.*sigma_p1.^2+g22.*sigma_p2.^2))))

R2max = log2(1+(g22.*sigma_p2.^2)./(sigma_n2.^2+g21.*sigma_p1.^2)) +
log2(1+(g11.*(sigma_s1.^2-sigma_p1.^2)./(sigma_n1.^2+g11.*sigma_p1.^2+g12.*sigma_p2.^2)));

else

R2max =  log2(1+(g21.*(sigma_s1.^2-
sigma_p1.^2)./(sigma_n2.^2+g21.*sigma_p1.^2+g22.*sigma_p2.^2))) +
log2(1+(g22.*sigma_p2.^2)./(sigma_n2.^2+g21.*sigma_p1.^2));

end



for i = 1:size(sigma_s1,2)

 MaxSumRate5(i) = R1max(i)+R2max(i);
```

```
 if MaxSumRate5(i) > Capacity

   MaxSumRate5(i) = Capacity;

 end


  if (R1max(i) + R2max(i)) > Capacity

   R1max(i) = Capacity - R2max(i);

  end


end


figure;

plot(SNR1,sigma_p1_5,'*r',SNR2,sigma_p2_5,'or');

hold on

plot(SNR1, MaxSumRate5, 'b');

hold on

plot(SNR1, R1max, 'g+-', SNR2, R2max, 'gv-');

title ('C=5, 5th case');

xlabel('SNR');

ylabel('Sum Rate - Alocation private messages');

legend('Allocation to private1 messages','Allocation to private2 messages','Sum rate ','user1
rate','user2 rate')


% Algorithm - 1st phase


sigma_12=1;

sigma_11=1;
```

```
sigma_21=1;
sigma_22=1;
R11s = log2(1+(g11.*sigma_s1.^2/(sigma_n1.^2+sigma_12.^2.*sigma_s2.^2)));%
R21s = log2(1+(g21.*sigma_s1.^2/(sigma_n1.^2+sigma_22.^2.*sigma_s2.^2)));%
R12s = log2(1+(g12.*sigma_s2.^2/(sigma_n2.^2+sigma_11.^2.*sigma_s1.^2)));
R22s = log2(1+(g22.*sigma_s2.^2/(sigma_n2.^2+sigma_21.^2.*sigma_s1.^2)));
k=1;
l=1;
users=10;
Omega1=zeros(1,10);
Omega2=zeros(1,10);

for i = 1:users

   R1 =R1max.*rand(1,1);
   R2 =R2max.*rand(1,1);

if R1(10)*R2(10) > R11s*R21s

   Omega1(k) = R1(i);
   Omega2(k) = R2(i);
   k=k+1;

else

   Omega_s1(l)=R1(i);
   Omega_s2(l)=R2(i);
```

```
    l=l+1;

end


end


% Algorithm - 2nd phase


sum1 = 0;

sum2 = 0;

sum3 = 0;

sum4 = 0;

Delta_max = -500;

Omega_c_max = -500;

K =20;

P=3;

Kc = floor(K/P);

Ks = K - Kc;

Kcue = Kc/size(Omega1,2);

Ksue = Ks/size(Omega_s1,2);


for i = 1:size(Omega1,2)

    Delta(i) = Omega1(i)*Omega2(i)/(R11s*R21s);


    if Delta(i) > Delta_max

        Delta_max = Delta(i);

        sum1(i) = log(Kcue*Omega1(i));

        sum2(i) = log(Kcue*Omega2(i));
```

```
        sum3(i) = log(Ksue*Omega_s1(i));
        sum4(i) = log(Ksue*Omega_s2(i));
        Omega_c(i) = sum1(i)+sum2(i)+sum3(i)+sum4(i);
        if Omega_c(i) > Omega_c_max
            Omega_c_max = Omega_c(i);
            Pair = i;
        end
    end


end
```