Multi-Antenna Multi-Group Multi-Way Relaying

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"*Soli Deo Gloria*"

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Kurzfassung

In dieser Arbeit betrachten wir ein drahtloses Relaisnetzwerk, bei dem eine Halbduplex-Mehrantennen-Relaisstation (RS) mehrere Kommunikationsgruppen unterstützt. Jede Kommunikationsgruppe besteht aus mehreren Halbduplexknoten, die untereinander Nachrichten austauschen. Jeder Knoten hat eine Nachricht und will die Nachrichten der anderen Knoten in seiner Gruppe dekodieren. In solch einem Multi-Way-Relaiskanal kann die Kommunikation nur mit Hilfe einer Relaisstation durchgeführt werden, da angenommen wird, dass es keine direkten Verbindungen zwischen den kommunizierenden Knoten gibt.

Auf Grund der Halbduplexeinschränkung wird eine höhere Anzahl von Zeit-Frequenz Kommunikationsressourcen benötigt im Vergleich zum Fall, wenn Vollduplexknoten ihre Nachrichten mit Hilfe einer Vollduplex-RS austauschen. Daher schlagen wir ein spektral effizientes Kommunikationsprotokoll für Mehr-Gruppen Multi-Way (MGMW) Kommunikation vor, das eine Halbduplex-Mehrantennen RS verwendet. Die erforderliche Anzahl von Kommunikationsphasen wird durch die maximale Anzahl von Knoten innerhalb der Gruppen bestimmt. In der ersten Kommunikationsphase, der sogenannten Vielfachzugriffsphase (Multiple Access - MAC), senden alle Knoten ihre Datenströme gleichzeitig zur RS. Nachdem die RS die entsprechende Signalverarbeitung durchgeführt hat, sendet die RS in den verbleibenden Kommunikationsphasen, den sogenannten Broadcast (BC) Phasen, die Datenströme an die Knoten, wobei sichergestellt wird, dass jeder Knoten den für ihn vorgesehenden Datenstrom von seinen Kommunikationsgruppenmitgliedern empfängt.

In dieser Arbeit werden drei BC Strategien entworfen: die Unicasting Strategie, die hybride Uni/multicasting Strategie und die Multicasting Strategie, wobei jede dieser Strategien gewährleistet, dass die MGMW Kommunikation innerhalb der gegebenen Zahl der Kommunikationsphasen durchgeführt wird. Bei der Unicasting Strategie sendet die RS in jeder BC Phase unterschiedliche Datenströme zu den unterschiedlichen Knoten. Jeder Datenstrom ist nur für einen Empfangsknoten vorgesehen. Bei der hybriden Uni/multicasting Strategie sendet die RS zu jeder bedienten Gruppe zwei Datenströme. Ein Datenstrom wird ausschliesslich nur zu einem Knoten gesendet, während der andere Datenstrom zu den anderen Knoten der Gruppe gesendet wird. Bei der Multicasting Strategie sendet die RS zu jeder bedienten Gruppe einen Datenstrom für alle Knoten in der Gruppe. Hierbei wird Netzwerkcodierung angewendet, um die Anzahl der Kommunikationsphasen im Vergleich zu den anderen BC Strategien beizubehalten. Die angewandte Netzwerkcodierung kann als eine Form von drahtloser Kooperation zwischen der RS und den Knoten angesehen werden. Für jede Gruppe

führt die RS in jeder BC Phase eine lineare Operation mit zwei ausgewählten Datenströmen zweier Mitgliederknoten der Gruppe durch und sendet das Ergebnis an alle Gruppenmitgliederknoten. Die ausgewählten Datenströme werden in jeder BC Phase so gewählt, dass der Datenstrom jedes Knotens mindestens einmal berücksichtigt wird. Folglich muss jeder Knoten bezüglich jedes Datenstroms, den der Knoten empfangen hat, Selbstinterferenz- und bekannte Interferenzunterdrückung durchführen. Dazu wird als verfügbare Seiteninformation sein eigener gesendeter Datenstrom oder ein Datenstrom, der in einer vorherigen BC Phase dekodiert worden ist, verwendet.

Weiterhin betrachten wir sowohl eine nicht-regenerative als auch eine regenerative RS für MGMW Relaisverfahren. Eine nicht-regenerative RS wendet ein Transceive (Sende- und Empfängs-) Beamforming auf die empfangenen Signale gemäss der gewählten BC Strategie an und sendet das Ergebnis zu den Knoten weiter. Hierzu entwerfen wir ein vereinheitlichtes Systemmodell für nicht-regenerative MGMW Relaisverfahren, das gültig für alle BC Strategien ist, und leiten Ausdrücke für die Summenrate nicht-regenerativer MGMW Relaisverfahren für zwei Fälle her: asymmetrischer und symmetrischer Datenverkehr. Wir erarbeiten Transceive Beamforming Verfahren, die die Summenrate nicht-regenerativer MGMW Relaisverfahren maximieren. Auf Grund der hohen Komplexität, das optimale Transceive Beamforming zu finden, das die Summenrate maximiert, entwerfen wir allgemeingültige Transceive Beamforming-Algorithmen mit geringer Komplexität für alle BC Strategien unter der Berücksichtigung von drei verschiedenen Optimierungskriterien: Matched Filter (MF), Zero Forcing (ZF) und Minimierung des mittleren quadratischen Fehlers (Minimisation of Mean Square Error - MMSE). Desweiteren führen wir ein sich der BC-Strategie bewusstes (BC-Strategy-aware - BCSA) Transceive Beamforming ein. Das BCSA Transceive Beamforming wird entweder basierend auf Block-Diagonalisation (BD) oder auf regularised BD entworfen. Wir zeigen, dass die Summenratenperformanz nicht-regenerativer MGMW Relaisverfahren von der gewählten BC Strategie und dem angewandten Transceive Beamforming abhängt. Verwendet man MF, ZF oder MMSE, führt die hybride Uni/multicasting Strategie zu den besten Ergebnissen, gefolgt von der Unicasting Strategie und der Multicasting Strategie. Verwendet man BCSA Transceive Beamforming, so ist Multicasting die beste Strategie gefolgt von der hybriden Uni/multicasting Strategie und der Unicasting Strategie. BCSA transceive Beamforming kann sowohl die Performanz der hybrid Uni/multicasting Strategie als auch der Multicasting Strategie auf Grund der besseren Verarbeitung von Störungen im Netz verbessern.

Eine regenerative RS dekodiert in der MAC Phase alle empfangenen Datenströme aller Knoten. Wir verwenden MMSE mit sukzessiver Interferenzunterdrückung zum Dekodieren der Datenströme aller Knoten an der RS. Nachdem die Informationsbits dekodiert worden sind, kodiert die RS die dekodierten Bits wieder und sendet die erneut kodierten Datenströme an die Knoten gemäss der gewählten BC Strategie. Bezüglich der Multicasting Strategie werden zwei lineare Operationen berücksichtigt: ein modifizierter Superpositions-Code (mSPC) und ein Exclusives-Oder (exclusive-or - XOR). Hierzu entwerfen wir ein vereinheitlichtes Systemmodell für regenerative MGMW Relaisverfahren, das für alle BC Strategien gültig ist, und leiten Ausdrücke für die Summenraten regenerativer MGMW Relaisverfahren für zwei Fälle her: asymmetrischer und symmetrischer Datenverkehr. Wir schlagen weiterhin Sendebeamforming-Verfahren vor, die die Sendeleistung der RS minimieren und gleichzeitig sicherstellen, dass in der BC Phase jeder Empfangsknoten die Daten mit der gleichen Rate empfängt, mit der die RS in der MAC Phase den entsprechenden Datenstrom empfangen hat. Auf Grund der Komplexität, ein optimales Sendebeamforming zu finden, das die Sendeleistung der RS minimiert, und da in manchen Fällen die verfügbare Sendeleistung der RS begrenzt ist, entwerfen wir allgemeingültige Sendebeamforming Verfahren für alle BC Strategien unter der Berücksichtigung von drei verschiedene Optimierungskriterien: MF, ZF und MMSE. Desweiteren entwerfen wir allgemeingültige BCSA Sendebeamforming-Verfahren. Es zeigt sich, dass die Multicasting-XOR Strategie im Vergleich zu den anderen BC Strategien die niedrigste Sendeleistung an der RS benötigt. Die Summenratenperformanz der regenerativen MGMW Relaisverfahren hängt im allgemeinen von der gewählten BC Strategie und dem angewandten Sendebeamforming ab. Auf Grund der besseren Verarbeitung von Störungen im Netz führt das BCSA Sendebeamforming zu einer Verbesserung der Summenratenperformanz regenerativer MGMW Relaisverfahren. Weiterhin zeigt sich, dass die Multicasting-XOR Strategie zu den besten Resultaten führt, gefolgt von der hybriden Uni/multicasting Strategie und der Unicasting Strategie. Ferner übertrifft die Multicasting-XOR Strategie die Multicasting-mSPC Strategie.

Abstract

In this thesis, we consider a wireless relay network where a half-duplex multi-antenna relay station (RS) assists multiple communication groups. Each communication group consists of multiple half-duplex nodes who exchange messages. Each node has a message and wants to decode the messages from all other nodes in its group. In such a multi-way relay channel, the communication can only be performed through the RS since it is assumed that there are no direct links between the communicating nodes.

Due to the half-duplex constraint, there is a higher number of time-frequency communication resources needed compared to the case when full-duplex nodes exchange messages through a full-duplex RS. Therefore, we propose spectrally efficient communication protocols to perform multi-group multi-way (MGMW) communication using a half-duplex multi-antenna RS. The required number of communication phases is defined by the maximum number of nodes among the groups. In the first communication phase, the multiple access (MAC) phase, all nodes transmit their data streams simultaneously to the RS. After performing signal processing, in the remaining communication phases, the broadcast (BC) phases, the RS transmits to the nodes by ensuring that each node receives the intended data streams from its communication group members.

Three BC strategies are designed, namely, unicasting, hybrid uni/multicasting and multicasting, where each of these strategies ensures that the MGMW communication is completed within the given number of communication phases. Using unicasting strategy, in each BC phase, the RS transmits different data streams to different nodes. Each data stream is intended only for one receiving node. Using hybrid uni/multicasting, for each served group, the RS sends two data streams. One data stream is sent exclusively to only one node and the other data stream is sent to the other remaining nodes in the group. Using multicasting strategy, for each served group, the RS transmits one data stream for all nodes in the group. Considering multicasting strategy, network coding is applied to maintain the number of communication phases the same as for the other BC strategies. The applied network coding can be seen as a form of wireless cooperation between the RS and the nodes. For each group, in each BC phase, the RS performs a linear operation on two chosen data streams of two member nodes in the group and transmits the output to all group member nodes. The chosen data streams are changed in each BC phase such that the data stream of each node is selected at least once. Consequently, each node needs to perform self- and known-interference cancellation to each received data stream using the available side information, namely, its own transmitted data stream or a data stream which has been decoded in one of the previous BC phases.

We consider both non-regenerative RS and regenerative RS for MGMW relaying. A non-regenerative RS performs transceive (transmit and receive) beamforming to the received signals according to the chosen BC strategy and transmits the output to the nodes. We design a unified system model for non-regenerative MGMW relaying valid for all BC strategies and derive the sum rate expression of non-regenerative MGMW relaying for two cases, namely, asymmetric and symmetric traffic. We address transceive beamforming maximising the sum rate of non-regenerative MGMW relaying. Due to the high complexity of finding the optimum transceive beamforming maximising the sum rate, we design generalised low-complexity transceive beamforming algorithms for all BC strategies with three different optimisation criteria, namely, matched filter (MF), zero forcing (ZF) and minimisation of mean square error (MMSE). Also, we introduce BC-Strategy-aware (BCSA) transceive beamforming. BCSA transceive beamforming is designed based on either block diagonalisation (BD) or regularised BD (RBD). It is shown that the sum rate performance of non-regenerative MGMW relaying depends on the chosen BC strategy and the applied transceive beamforming. Using MF, ZF and MMSE, hybrid uni/multicasting performs best followed by unicasting and multicasting strategies. Using BCSA transceive beamforming, multicasting strategy performs best followed by hybrid uni/multicasting and unicasting strategies. BCSA transceive beamforming is able to improve the performance of both hybrid uni/multicasting and multicasting strategies due to the better approach of handling the interference in the network.

A regenerative RS decodes all the received data streams from all nodes in the MAC phase. We consider MMSE with successive interference cancellation for decoding the data streams of all nodes at the RS. After having the information bits, the RS re-encodes the decoded bits and transmits to the nodes according to the chosen BC strategy. Regarding the multicasting strategy, two linear operations are considered, namely, modified superposition coding (mSPC) and exclusive-or (XOR). We design a unified system model for regenerative MGMW relaying valid for all BC strategies and derive the sum rate expression of regenerative MGMW relaying for two cases, namely, asymmetric and symmetric traffic. We propose transmit beamforming minimising the RS's transmit power while ensuring that each receiving node receives with a rate equal to the rate received at the RS in the MAC phase for each particular data stream. Due to the complexity of finding the optimum transmit beamforming minimising the RS's transmit power and since in some cases the available RS transmit power is limited, we design generalised transmit beamforming algorithms for all BC strategies with three different optimisation criteria, namely, MF, ZF and MMSE. Also, we design generalised BCSA transmit beamforming. It is shown that multicasting-XOR strategy requires the lowest transmit power at the RS compared to the other strategies. In general, the sum rate performance of regenerative MGMW relaying depends on the chosen BC strategy and the applied transmit beamforming. Due to its better approach of handling the interference in the network, BCSA transmit beamforming is able to improve the performance of regenerative MGMW relaying. In general, multicasting-XOR strategy performs best followed by hybrid uni/multicasting and unicasting strategies. Furthermore, multicasting-XOR outperforms multicasting-mSPC.

Contents

Chapter 1

Introduction

1.1 Relaying and Multi-Group Communication

Communication, *a transmission of information from one point to another* [1], is part of our daily life. We need communication to receive and to send information from and to other people. While in the early days, far distance communication was performed through wired communication networks, nowadays, wireless communication networks are more preferable since they can provide high mobility to the users. Radio and television broadcasting, wireless telephony, wireless internet and many other wireless communication services provide us more flexibility in communication while we are on the move.

Current and future wireless applications such as video on demand or television on demand require high communication data rates. Therefore, in Fourth Generation (4G) wireless communications it is envisioned to have high data rate communications within wide coverage area, and to use higher carrier frequency compared to that currently used in Third Generation (3G) wireless communications [2]. In practice, however, the data rate depends on the ratio of the received useful signal power to the sum of the receiver noise power and the unwanted interference signal power. The received useful signal power is defined by several factors, such as the distance between the source and the destination, and the carrier frequency of the transmitted signal [3]. The larger the coverage area, the farther the possible communication distance between the source and the destination. The farther the communication distance and/or the higher the carrier frequency of the transmitted signal, the higher the signal attenuation. This leads to a lower received useful signal power at the destination and, thus, leads to a lower communication data rate.

One direct approach to improve the received useful signal power is to increase the transmitted signal power. However, there are constraints, such as equipment and other practical constraints, which limit the transmitted signal power [4]. Another approach is to introduce an intermediate node between the source and the destination, which is called repeater [4]. The function of the repeater is to counteract the signal attenuation and to relay the information from the source to the destination. If the received useful signal power on the direct link between source and destination is too low, or even when there is no direct link between the source and the destination, the repeater allows a proper communication between the source and the destination. A satellite is one kind of repeater which enables communication between several earth stations since there is no direct link between the earth stations. For example, Telstar I Satellite was used in 1962 to relay the TV signals between Europe and the United States [5]. Repeaters work by simply amplifying the received signal (analog repeater) or by decoding and re-encoding the received signal and retransmitting the regenerated data streams to the destination (regenerative repeater) [4].

Since a repeater is able to counteract the signal attenuation, not only the received useful signal power at the destination is improved but also the coverage area is increased. These are two of the reasons why the use of repeaters, which are called relays, is foreseen for future wireless and mobile broadband radio [2]. The use of relays is already being considered in the WINNER project [6] for 4G wireless communication systems and it has been included in IEEE 802.16j standardisation activity [7]. In cellular communication with metropolitan area test scenario, it was shown in [8] that by adding relays, the coverage area is improved by about 6% compared to only deploying base stations (BSs) for the same cost. Moreover, there is a 7% coverage improvement in indoor area under the test scenario [8]. Regarding the capacity improvement, it was shown in [9] that the downlink capacity is improved by about 6% with the introduction of relays compared to only using BSs. Improvement in both coverage area and capacity due to the implementation of relays was also shown in [10].

Figure 1.1 shows an illustration of a communication between one BS and multiple nodes. The BS can directly communicate with node S1 since there is direct link between them. Such communication is called direct, single-hop or point-to-point communication [11]. Due to the shadowed link caused by the building between BS and node S2 and due to the strongly attenuated link between the BS and node S3, the communication between the BS and both nodes S2 and S3 can be performed only via a relay station (RS). The BS sends the information first to the RS and the RS forwards the corresponding information to nodes S2 and S3. Since the communication needs to be performed within two hops, it is called two-hop communication [11].

If one source sends its information to one or more destinations, we have a one-way communication. Such one-way communication mostly takes place in broadcasting scenarios, for example, broadcast radio and television. However, communication usually involves an exchange of information between the communicating nodes. This means that one source node is also one particular destination node seen by the other communicating source node. The exchange of information in two-way communication between two communicating nodes is termed duplexing [12].

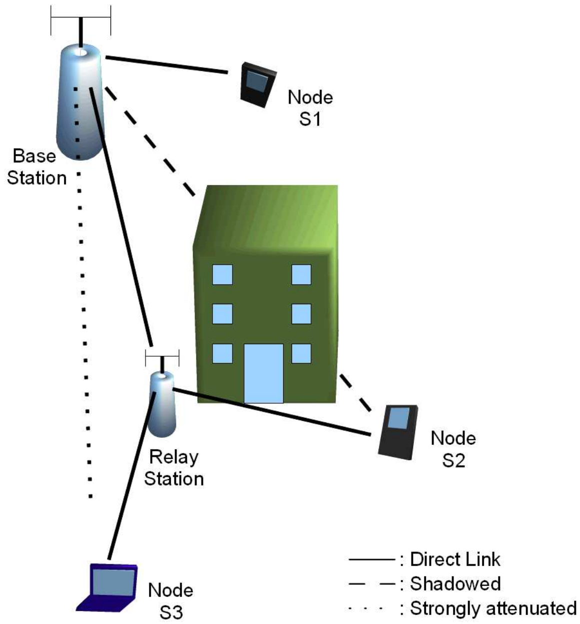
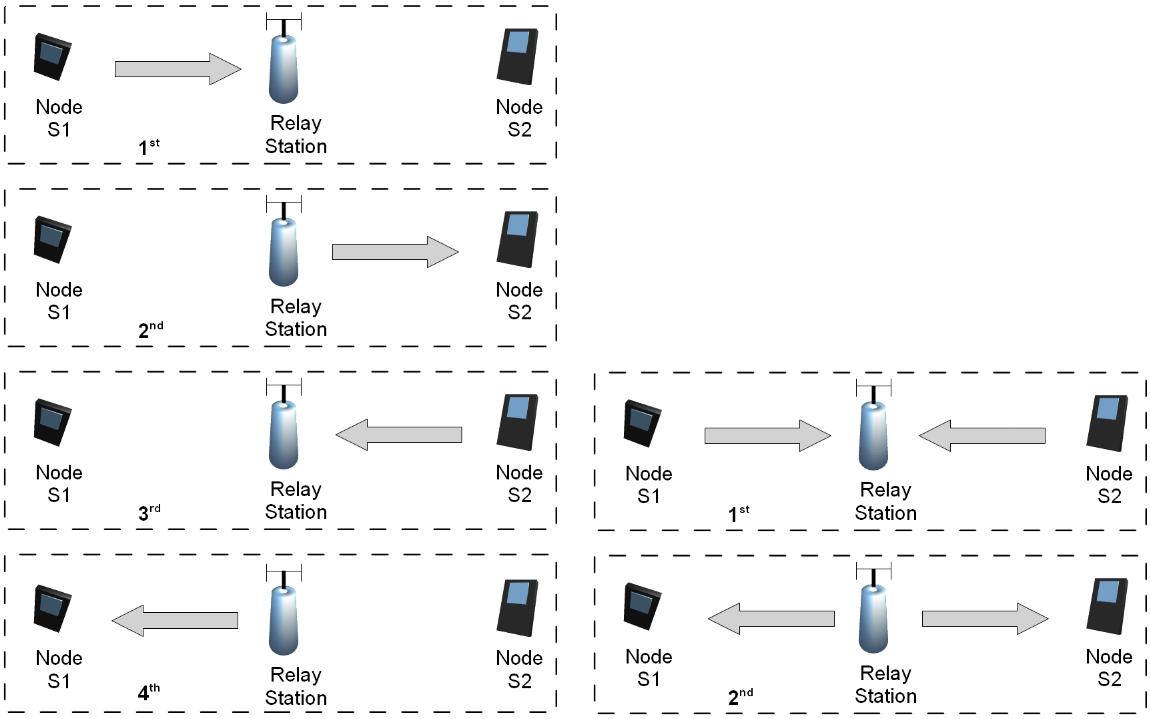


Figure 1.1. Illustration of the use of a relay station to support communication between a base station and multiple nodes

When two communicating nodes can transmit and receive at the same time, they are communicating in full-duplex, and when two communicating nodes can only either transmit or receive at any given time, they are communicating in half-duplex [13]. From practical point of view, however, it is difficult to implement full-duplex devices which can transmit and receive at the same time [14]. Each full-duplex device needs perfect echo cancellation to cancel its transmitted signal which is received back by its receive chain [15]. The large difference in the signal power of the transmitted and the received signal drives the device's analog amplifiers in its receive chain into saturation [14] and causes a severe drop in signal to interference and noise (SINR) ratio [16]. Moreover, the bulk of ferroelectric components like circulators makes full-duplex devices not considered practical [15].

In two-way communication, when two half-duplex nodes S1 and S2 communicate with each other, two time slots are needed. The first time slot is used for S1 to transmit to S2 and the second time slot is used for S2 to transmit to S1. If there is no direct link between the two communicating nodes, the communication can be performed with the assistance of a half-duplex RS. Despite of the advantages of using an RS, due to the half-duplex constraint there is a drawback, which is a higher need of communication resources.

Conventionally, the two-way communication via an RS is performed in two separate one-way communications. In the first one-way communication, which is from S1 to S2,



(a) One-Way Relaying (b) Two-Way Relaying

Figure 1.2. Two-way communication via a relay station

S1 sends its data stream to the RS and, afterwards, the RS forwards to S2. In the second one-way communication, which is from S2 to S1, S2 sends its data stream to the RS and, afterwards, the RS forwards to S1. Since each transmission requires one time slot, in total four time slots are needed which are twice as much compared to direct two-way communication without an RS. Figure 1.2(a) shows the two-way communication via an RS using two separate one-way communications, where 1^{st}, 2^{nd}, 3^{rd} and 4^{th} refer to the first, the second, the third, and the fourth time slot, respectively. Such relaying protocol is called one-way relaying for bidirectional communication [14, 17] or uncoded bidirectional relaying [18].

In order to avoid the doubling of the number of time slots, a spectrally efficient communication protocols for two-way communication using an RS was proposed in [14], which is called two-way relaying [14] or bidirectional relaying [19]. In two-way relaying, the two communicating nodes S1 and S2 send their data streams simultaneously to the RS in the first time slot. In the second time slot, the RS forwards the superposition of both nodes' data streams simultaneously to the nodes. Therefore, the required number of time slots is only two. Figure 1.2(b) shows the two-way communication via an RS using two-way relaying. Two-way relaying needs only two time slots since it takes into account that both nodes are able to perform self-interference cancellation.

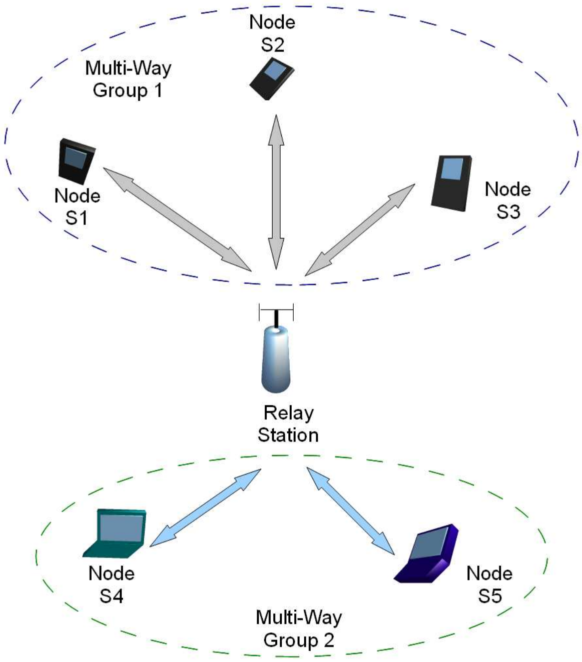


Figure 1.3. Illustration of multi-group multi-way relaying: Two multi-way communication groups have to share a relay station

Self-interference refers to each node's own transmitted data stream which is received back in part in the superposed data stream transmitted from the RS. Since each node knows its own transmitted data stream, it cancels out this self-interference by subtracting its transmitted data stream from its received one. Since two-way relaying needs less time slots than one-way relaying, it outperforms one-way relaying in terms of sum rate performance as shown in [14, 17].

In our daily life, communication involving multiple parties is gaining importance. Recently, we have seen the emergence of many communication applications which involve multiple parties. Voice conference, video conference and multi-player gaming are examples of those applications. In such multi-way communication, each communicating node has its own message and wants to decode the messages of the other nodes. If there are no direct links among the nodes, they can communicate with each other with the assistance of an RS. It may happen that the RS has to serve more than one multi-way group. Such a scenario has recently been investigated from information theory point of view in [20], and has been termed multi-way relay channel. Figure 1.3 shows an illustration of two multi-way groups that have to perform multi-way communication using the same RS. The first group consists of three nodes S1, S2 and S3, and the second group consists of nodes S4 and S5.

The work in [20] considers a full-duplex communication between full-duplex nodes through a full-duplex RS. The groups are separated in time, that is, the groups are served separately in group-specific time slots. Since half-duplex is more into practical consideration, it is an open interesting problem how to perform such multi-group multi-way (MGMW) communication through a half-duplex RS. It is the aim of this thesis to propose solutions for the problem when multiple multi-way communication groups, each consisting of half-duplex nodes, perform MGMW communication with the assistance of a half-duplex RS. Moreover, instead of separating the multi-way groups in time, we separate them in space by applying a multi-antenna RS.

In the remaining of this chapter, we first provide the state of the art from related works. Afterwards, we provide open problems whose solutions are proposed in this thesis. Finally, the overview of the contributions and the outline of this thesis close this chapter.

1.2 State of the Art

The relay channel where one relay assists one-way communication between one source node and one destination node was considered in [21]. In [21], the upper and lower bounds of the capacity of a relay channel were given. This work was extended in [22] by providing capacity bounds of a relay channel with Additive White Gaussian Noise (AWGN). The relay channel under consideration was with both direct link between the source node and the destination node and two-hop link, that is, from source node to relay and from relay to destination node.

In wireless communication, however, it is not only AWGN which affects the communication, but also the channel impairments due to multipath propagation of the transmitted signal from the source to the destination. As a result, the received signal power fluctuates or fades. To mitigate the signal fading, diversity through either frequency, time, or space is needed [4]. The use of a relay to provide space diversity was first briefly explained in [23] and was comprehensively explained in [24,25]. In these works, an uplink scenario was considered where multiple nodes send to a BS. The relay itself is indeed one of the other nodes, that is, each node has a partner node which acts as a relay. It is shown that such cooperation strategy, where one node becomes a relay to assist the communication of the other node to the BS, increases the capacity and the robustness of the overall system in wireless fading channels. Several efficient cooperative diversity protocols were proposed in [26] where it was shown that the proposed protocols achieve full diversity. While the early works consider full-duplex nodes, for practical consideration, [26] already considered half-duplex nodes.

Regarding two-way communication, the early work was started by [27]. Two-way communication between two half-duplex nodes via a half-duplex relay using one-way relaying protocol when there is no direct link between the nodes was studied in [14, 17]. The number of communication phases is four such that the number of required time-frequency resources is also four, which is two times higher than when the two communicating nodes communicate directly. A more efficient communication protocol was considered in [28–32] where three-phase communication is performed for two-way communication with a relay. It is shown in [30] that three-phase coded bidirectional relaying enhanced the throughput by 33% compared to four-phase one-way relaying.

A more efficient communication protocol is proposed in [14,33], which requires only two communication phases and is called two-way relaying. Since, by nature, communication involves exchanging of information and since two-way relaying is spectrally efficient, many recent works made contributions to two-way relaying from different aspects, for example, the achievable rate regions [34–36], the sum rate performance [37,38] and the power allocation methods [39, 40].

It is shown in [41] that in low signal to noise ratio (SNR) region, two-way relaying may not be an appropriate strategy compared to one-way relaying. In cellular communications, where there are interference signals coming to the RS, the BS and the nodes, in [42], two-way relaying was shown to have a better performance compared to one-way relaying only when the MS is close to the RS, that is, when the SINR is high. However, it is already mentioned in [14] that in low SNR region, to become power efficient is more important than being spectrally efficient. In other words, a spectrally efficient communication system is more preferable in high SNR region since the spectral efficiency loss is more significant in high SNR region [14].

The spectrally efficient two-way relaying basically exploits the broadcast nature of wireless communication and the use of network coding. The idea of network coding was introduced in [43] for a wired network, where it was shown that if the intermediate node is allowed to perform operations to the received data streams, instead of only routing them, the capacity of the network is improved. An explanation in a tutorial manner on network coding is given in [44] and the applications of network coding in wireless communication are described in [45].

Another technique which promises an improvement in spectral efficiency and reliability of the communication system is the use of multiple receive antennas and/or multiple transmit antennas, which is known as multi-antenna or smart antennas communication [46]. It has been shown in many references, for example, in [46–53], that the spectral efficiency, the overall capacity and/or the reliability of the communication system is improved by the use of multiple antennas. In some recent works on two-way relaying, applying a single multi-antenna RS or multiple single antenna RSs to assist the two-way communication has been extensively investigated. Multiple single-antenna RSs act as a distributed antenna or a virtual antenna array [54]. Two-way relaying with multiple single-antenna RSs was considered, for example, in [55–57], while two-way relaying with a single multi-antenna RS was considered, for example, in [17, 58–63].

An extension to two-way relaying is a scenario when the RS serves more than one two-way pair, which is called multi-user two-way relaying. In [64–66], the two-way pairs are separated in code domain, that is, using Code Division Multiple Access. Each pair has its own code which is different from the other pairs' code. In [66, 67], the pairs are separated in frequency and time, that is, using Frequency/Time Division Multiple Access. If the RS is equipped with multiple antennas, the pairs can be separated in space, that is, using Space Division Multiple Access. The works in [68–73] considered a multi-antenna RS for multi-user two-way relaying.

A different communication scenario which appears in daily communication is when more than two nodes want to exchange messages. Each node has a message and wants to decode the other messages from the other nodes. Such a scenario is called multi-way channel [74, 75], where the two-way channel [27] is a special case when the number of communicating nodes is two. If there are no direct links among the nodes and the nodes exchange messages via an RS, we have a multi-way relay channel [20]. In [20], there are multiple communication groups which have to be served by the RS. Each communication group consists of two or more nodes. A full-duplex communication with full-duplex RS and full-duplex nodes is assumed and the groups are separated in time. Single-group full-duplex multi-way relaying when N nodes communicate with each other was considered in [76] for the binary multi-way relay channel, and in [77] for the Gaussian multi-way relay channel. Single-group half-duplex multi-way relay channel was considered in [78–80]. The work in [79, 80] consider a special case, that is, when the number of nodes is equal to three and, in [80], in addition to the links via the RS it is assumed that direct links among the nodes are available.

Until this point, we provided related works in relay communication in general without specifically mentioning the signal processing at the RS. As for a repeater, there are two classes of signal processing at the RS, namely, regenerative and non-regenerative. Examples of regenerative signal processing at the RS are decode-and-forward or digital relaying, while examples of non-regenerative signal processing at the RS are amplify-and-forward or analog relaying [81]. Another type of signal processing at the RS is compress-and-forward. While in [16, 81], compress-and-forward is classified as regenerative or digital relaying, in [82, 83] it is classified as non-regenerative relaying. In this thesis, in line with the term regenerative repeater in [4], a regenerative RS decodes and re-encodes the received data streams from the nodes. If the RS does not decode and re-encode the received data streams, we use the term non-regenerative RS. Therefore, compress-and-forward is classified as non-regenerative in this thesis.

Regarding a multi-antenna RS, how to design the transceive (transmit-receive) beamforming at the RS is considered for a non-regenerative RS, for example, for one way relaying in [17, 81], for two-way relaying in [58–60] and for multi-user two-way relaying in [71–73]. For a multi-antenna regenerative RS, after decoding the received data streams, how the RS performs transmit beamforming is considered, for example, for one-way relaying in [70, 84], for two-way relaying in [10, 61–63] and for multi-user two-way relaying in [68–70].

1.3 Problems under Consideration

This thesis deals with multi-antenna MGMW relaying. A multi-antenna half-duplex RS assists multiple communication groups. In each communication group, half-duplex single-antenna nodes exchange messages. Due to the half-duplex constraint, the number of communication phases is higher than in full-duplex communication. The open problems under consideration in this thesis are summarised as follows:

- **P1.** How to design an efficient communication protocol which requires a low number of communication phases?
- **P2.** How to design transmission strategies which ensure that the MGMW communication is performed correctly, that is, that each node receives the data streams of the other nodes in its multi-way communication group within the considered number of communication phases?
- **P3.** How to perform MGMW relaying with a multi-antenna non-regenerative RS?
- **P4.** How to perform MGMW relaying with a multi-antenna regenerative RS?
- **P5.** How to design a unified system model for the considered transmission strategies?
- **P6.** How to measure the performance, that is, what kind of performance metric should be used?
- **P7.** How to design optimum signal processing at the RS?

P8. How to design low complexity signal processing at the RS?

P9. How to compare the performance of MGMW relaying with different signal processing and different transmission strategies?

1.4 Contributions and Organisation of the Thesis

The contributions of this thesis for the problems under consideration in Subsection 1.3 can be summarised as follows.

C1. We propose a spectrally efficient communication protocol for half-duplex MGMW relaying (**P1**). The number of communication phases is defined by the maximum number of nodes among the groups. There is only one multiple access (MAC) phase, where all nodes transmit simultaneously to the RS. The remaining communication phases are the broadcast (BC) phases, where the RS transmits to the nodes.

C2. We propose transmission strategies for half-duplex MGMW relaying (**P2**). Three BC strategies, namely, unicasting, hybrid uni/multicasting and multicasting, are proposed to ensure that MGMW relaying is completed within the given number of communication phases. Regarding multicasting strategy, network coding is applied in order to maintain the number of communication phases the same as for the other strategies.

C3. We consider a multi-antenna non-regenerative RS to support MGMW relaying (**P3**). We design a unified system model for non-regenerative MGMW relaying suitable for the proposed BC strategies (**P5**). The sum rate is chosen as a performance metric since it allows us to assess the spectral efficiency of MGMW relaying (**P6**). The sum rate expression of non-regenerative MGMW relaying is derived for both asymmetric traffic and symmetric traffic. Asymmetric traffic refers to the fact that each node in each group can transmit with different rate, while symmetric traffic refers to the fact that all nodes in each group transmit with equal rate.

C4. We address the transceive beamforming maximising the sum rate of non-regenerative MGMW relaying (**P7**). Since finding the optimum transceive beamforming maximising the sum rate requires high computational complexity, we design low complexity generalised transceive beamforming algorithms for all BC strategies with three different optimisation criteria, namely, matched filter (MF), zero forcing (ZF) and minimisation of mean square error (MMSE) (**P8**). Also, we propose generalised BC-Strategy-aware (BCSA) transceive beamforming for all BC strategies (**P8**). We specially design network coding approach for non-regenerative MGMW relaying, namely, beamforming-based physical layer network coding. We perform Monte-Carlo simulations to investigate the sum rate performance of non-regenerative MGMW relaying (**P9**).

C5. We also consider multi-antenna regenerative RS to support MGMW relaying (**P4**). We design a unified system model for regenerative MGMW relaying suitable for the proposed BC strategies (**P5**). The sum rate expression of regenerative MGMW relaying is derived for both asymmetric and symmetric traffic (**P6**).

C6. We design transmit beamforming minimising the RS's transmit power while ensuring that each receiving node in each BC phase receives the corresponding data stream with a rate equal to the rate which is received at the RS in the MAC phase (**P7**). As finding the optimum transmit beamforming minimising the RS's transmit power requires high computational complexity and there are cases where the transmit power at the RS is fixed, we design low complexity generalised transmit beamforming algorithms for all BC strategies with three different optimisation criteria, namely, MF, ZF and MMSE (**P8**). Also, generalised BSCA transmit beamforming is designed for all BC strategies (**P8**). We consider two network coding approaches for regenerative MGMW relaying, namely, modified superposition coding (mSPC) and exclusive-or (XOR). We perform Monte-Carlo simulations to investigate the sum rate performance of non-regenerative MGMW relaying (**P9**).

The organisation of this thesis is structured as follows:

Chapter 2 explains the motivation of multi-antenna MGMW relaying. Since we consider a multi-antenna RS, a brief explanation of multi-antenna communication is provided. Afterwards, multi-antenna MGMW relaying is described in more detail.

Chapter 3 explains the protocol and the BC strategies for MGMW relaying. The description of the protocol for MGMW relaying opens this chapter followed by the explanation of the proposed BC strategies, namely, unicasting, hybrid uni/multicasting and multicasting strategies. Afterwards, the wireless cooperative network coding for the multicasting strategy and the considerations on the case when the number of nodes is not equal in all groups are explained.

Chapter 4 explains non-regenerative MGMW relaying. A unified system model for non-regenerative MGMW relaying valid for all BC strategies is given, followed by the derivation of the sum rate expression of non-regenerative MGMW relaying. Transceive beamforming maximising the sum rate is addressed followed by the the designs of low complexity transceive beamforming algorithms. This chapter is closed with the simulation results for single-group multi-way relaying and two-group multi-way relaying cases.

Chapter 5 explains regenerative MGMW relaying. We explain first the unified system model for regenerative MGMW relaying and, afterwards, the derivation of the sum rate of regenerative MGMW relaying is given. The optimum transmit beamforming minimising the RS's transmit power is explained. The designs of low complexity transmit beamforming algorithms are described afterwards. The simulation results for single-group multi-way relaying and two-group multi-way relaying cases close this chapter.

Chapter 6 provides the summary of the thesis and some outlooks for future work in MGMW relaying.

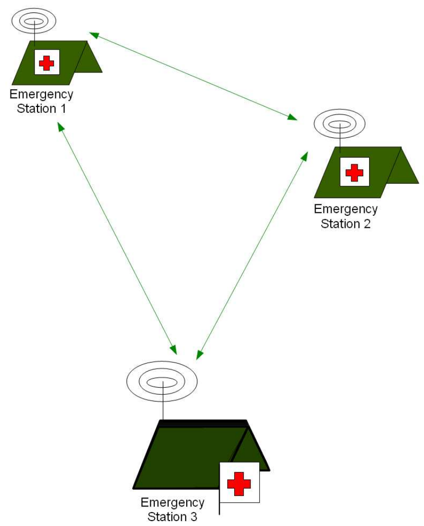
Chapter 2
Motivation of Multi-Antenna Multi-Group Multi-Way Relaying

2.1 Introduction

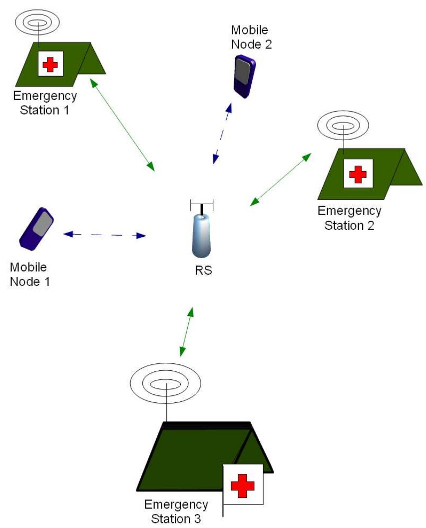
In emergency locations, such as in disaster sites where an earth quake or a volcanic eruption just happened, the communication infrastructures, both wired and wireless networks, may not function properly or may even be totally down. However, if there are wireless communication devices which are able to exchange messages in an *ad-hoc* manner, a conferencing wireless multi-way communication between several parties may be performed. For example, a wireless multi-way communication between several emergency staff members who are on the road or a wireless multi-way communication between several red-cross members who are working in different emergency stations will enable good coordination to provide first aid to the victims. Figure 2.1(a) shows an illustration where three red-cross emergency stations which are equipped with wireless communication devices exchange messages in an emergency location. The emergency staff members in three different emergency stations may perform voice, video or web conference to communicate with each other. They may work cooperatively from distance, for example, to help the emergency staff members in one emergency station to perform emergency operations to the victims.

Due to the impairments of wireless channels, such as signal attenuation and multipath propagation, direct multi-way communication between the communicating nodes may not be possible. One way to enable conferencing multi-way communication when there are no direct links among the nodes is by having an intermediate node, that is, an RS, to assist the nodes to exchange messages. Figure 2.1(b) shows an example of one RS assisting two multi-way groups. One multi-way group consists of three nodes, namely, Emergency Station 1, Emergency Station 2 and Emergency Station 3, and one multi-way conferencing group consists of two nodes, namely, Mobile Node 1 and Mobile Node 2. Each group performs multi-way communication exclusively, that is, each node in each group exchanges messages with the nodes in its group but not with other nodes in the other multi-way group. Both multi-way groups may perform multi-way communication only via an RS.

This thesis deals with such scenarios where multiple conferencing multi-way groups perform per-group multi-way communication via an RS. We consider a multi-antenna



(a) With direct links



(b) Without direct links, using an RS

Figure 2.1. Illustration of multi-way communication in an emergency location

RS to enable spatial processing to spatially separate each group from the other groups and/or each node from the other nodes, that is, we apply space division multiple access (SDMA). The reason for considering a multi-antenna RS is because multi-antenna communication brings performance improvement and has been considered for future wireless systems and, therefore, its features need to be considered early in the design phase of future systems [85]. Otherwise, it is difficult to apply SDMA to systems for which SDMA was not originally foreseen [86].

In the following, in Section 2.2 we provide an explanation of multi-antenna communications. In Section 2.3, we explain multi-antenna MGMW relaying which is considered in this thesis.

2.2 Multi-Antenna Communications

2.2.1 Gains in Multi-Antenna Communications

The use of multiple antennas at the transmitter (multiple-input single-output (MISO)) or at the receiver (single-input multiple-output (SIMO)) or at both (multiple-input multiple-output (MIMO)) offers the exploitation of the spatial dimension to improve the reliability and/or to increase the spectral efficiency of wireless systems. There are four significant performance gains that multiple antennas may bring [46, 53]:

- *Array (or beamforming) gain* is the increase of average received SNR due to coherent combining at the receiver through spatial processing at the receive antenna array or through spatial pre-processing at the transmit antenna array or both.
- *Diversity gain* is obtained as the receiver receives multiple copies of the transmitted signal where each of the copies is experiencing independent fading.
- *Interference reduction (or avoidance) gain* is obtained by suppressing (or avoiding) co-channel interferers (nodes who share the same time-frequency resources).
- *Spatial multiplexing gain* is an increase in the transmission rate (or capacity) even without any additional power and bandwidth expenditure.

The main applications of multiple antennas in wireless communications can be classified into four applications, namely, beamforming, spatial diversity, spatial multiplexing and SDMA [87]. In the following, each of the main applications is briefly explained.

2.2.2 Beamforming

Multi-antenna communication is also termed smart antennas since the transmitter or the receiver has the ability to produce beams in such a way that the useful received signal at the receiver is improved while the unwanted interference signal is reduced. The beams are generated by multiplying each input (for transmit processing) or each output (for receive processing) of each antenna element by a complex weight. There are two methods to implement smart antennas, namely, switched-beam array and adaptive array [88, 89].

Switched-beam array systems generate several fixed beams to cover the coverage area of interest and choose one beam which leads to a maximum signal strength of the intended node [89]. It is an extension of cell sectoring in cellular systems [90]. In cellular systems, the cells are usually divided into three sectors, each covers a 120° angle. Using switched-beam array, there are about four to eight beams per sector [91]. Switched-beam array offers an array gain which can be traded for coverage extension where the gain is $10 \log M$ with M the number of antennas at the BS [91]. It also offers M-fold increase in capacity if the number of beams is also M [92]. The drawbacks of switched-beam array are the higher number of hand-offs from one beam to another [92] and losses in beam selection and in path diversity [91]. Moreover, although it may also reduce co-channel interference, since the beam is fixed, interference cancellation is only possible if the intended user and the interferers are in different beams [91].

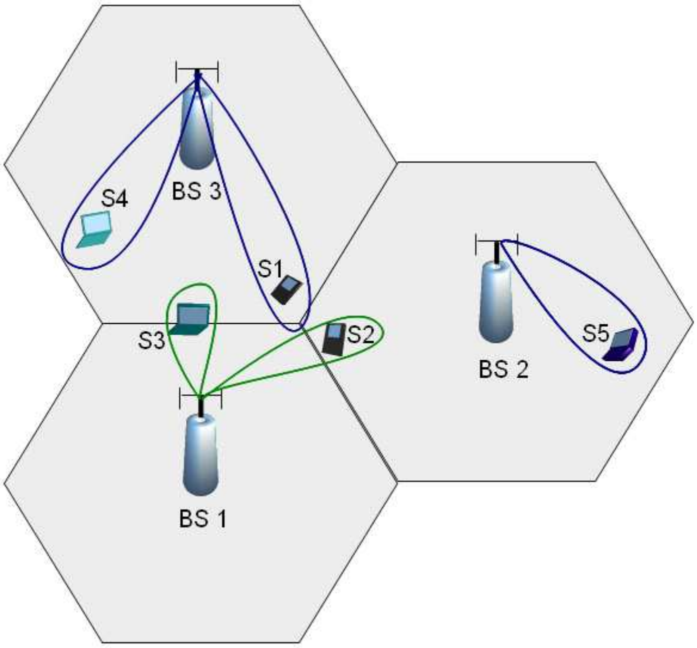


Figure 2.2. Illustration of adaptive beamforming in cellular systems

While the beams in switched-beam array systems are fixed, in adaptive array systems the beams are changed adaptively. The adaptive generation of beams (beamforming) is aiming at tracking the intended signal while reducing or canceling the unintended interference signals. In cellular systems, the use of adaptive arrays provides several benefits, namely, transmit power reduction or an increase in cell radius, battery life extension, channel delay-spread reduction, and co-channel interference reduction in both uplink (nodes to a BS) and downlink (BSs to a node) [86]. Moreover, security is improved, since unwanted jammers or eavesdroppers have to be in the same direction as the intended node, and location-specific services can be applied [88]. Beamforming uses typically $\lambda/2$-spaced antenna elements for reducing co-channel interference and providing beamforming gain, with λ the wavelength [87]. This $\lambda/2$-spaced antenna elements can be seen as the spacing required for fulfilling Nyquist rate criteria, that is, the spacing should be $\leq \lambda/2$, for avoiding grating lobes, that is, the spacing should be $\leq \lambda$, and for dealing with fading, that is, the spacing should be $\geq \lambda/2$ [88].

Figure 2.2 shows an illustration of the use of adaptive beamforming in cellular systems where three multi-antenna BSs serve three cells. Using transmit beamforming, BS 3 serves nodes S1 and S4 with two independent beams while minimising the interference towards node S3 which lies in the cell border and is served by BS 1. Being able to perform beamforming which results in a range extension, BS 1 is able to serve node S3 which lies at the cell border and to serve node S2 which lies outside its cell. Since BS 3 is able to minimise the interference towards node S3, the SINR at node S3 is improved.

On the other hand, BS 2 serves node S5 while minimising the interference at node S2.

2.2.3 Spatial Diversity

In wireless communications, diversity may be exploited in time, frequency or space domain, since the fading may take place in time, frequency and space [93]. In frequency selective channels, frequency diversity, for example, through spread spectrum techniques results in performance improvements [94]. In time selective channels, channel coding and interleaving provide time diversity to improve the performance at the expense of delays [94]. Different to frequency and time diversity, spatial diversity exploits the use of multiple antennas without loss in time or bandwidth [93].

Multiple antennas provide different paths which can be exploited by sending copies of signals. At the receiver, each received signal from a different path tends to face different fades and after combining, a diversity gain is obtained. The diversity gain can be seen from the speed of the decay of the error probability of a maximum-likelihood (ML) detector as the SNR increases [95]. The diversity gain δ can be expressed as

$$\lim_{\rho \to \infty} \frac{\log\ P_{\mathrm{e}}(\rho)}{\log\ \rho} \leq -\delta \tag{2.1}$$

[93,95], with P_{e} the average bit error rate (BER) and ρ the single-branch SNR. Equation (2.1) can be written as [95,96]

$$P_{\mathrm{e}}(\rho) = \rho^{-\delta} \tag{2.2}$$

which shows that the decay of the average error probability depends on δ. Compared to a single antenna with ρ^{-1}, the decay is now faster since $\delta > 1$ when spatial diversity can be exploited. MIMO point-to-point systems with M_{T} transmit antennas and M_{R} receive antennas provide $M_{\mathrm{T}}M_{\mathrm{R}}$ random fading coefficients to be averaged with maximum diversity gain $M_{\mathrm{T}}M_{\mathrm{R}}$ [95]. Spatial diversity, in contrast to $\lambda/2$-spacing for beamforming, needs to spatially separate the antenna elements as far as possible [87]. By having a large spacing between the antenna elements, it is possible to have independent fading of the transmitted signal at different antenna elements. This produces maximum diversity gain [87].

2.2.4 Spatial Multiplexing

Spatial diversity has the objective to counteract fading. However, in MIMO communication, fading can be beneficial through the increase of degrees of freedom available for communication [49, 95]. The channel matrix is well conditioned with high probability when paths between each transmit and receive antenna pair fade independently and, thus, provide multiple parallel spatial channels [95]. The exploitation of these spatial channels by sending independent data streams to increase capacity is called spatial multiplexing [95]. The ergodic capacity in bits per second per Hertz (b/s/Hz) depends linearly on the degrees of freedom, that is, $\min(M_{\mathrm{T}}, M_{\mathrm{R}})$ and logarithmically on ρ [95, 96]. The spatial multiplexing gain is defined (asymptotically - at high ρ) by

$$\xi \triangleq \lim_{\rho \to \infty} \frac{R(\rho)}{\log_2 \rho} \tag{2.3}$$

[93], where $R(\rho)$ is the transmission rate.

The spatial diversity gain in (2.1) and the spatial multiplexing gain in (2.3) represent the extremities of the diversity-multiplexing trade off for MIMO channels [53]. An increase in SNR is exploited either to provide an exponential reduction in bit error rate while keeping the data rate fixed, cf. (2.1), or to provide a linear increase in transmission rate while having fixed bit error rate, cf. (2.3). The optimal diversity gain given a fixed multiplexing gain is defined by

$$\delta(\xi) = (M_{\mathrm{T}} - \xi)(M_{\mathrm{R}} - \xi), \tag{2.4}$$

cf. [53].

2.2.5 Space Division Multiple Access

Multi-user MIMO (MU-MIMO) systems are seen as an important research topic for next generation wireless systems [97]. MU-MIMO systems have a number of users, each with one or more antennas, who communicate with a receiver (Base Station-BS) which is equipped with more than one antenna. MU-MIMO might be seen as a MIMO point-to-point communication (Single-User (SU)-MIMO) except that the signals sent out at the transmit antennas cannot be coordinated [52].

In MU-MIMO, the spatial separation is possible since geographically each user has a different position. The BS sees a different attenuation and direction of arrival of each user's signal which manifest itself in different spatial signatures [98]. The BS uses the uniqueness of the spatial signature of each user to differentiate the users, which allows the multiple users to access the same resources [87], and that is SDMA. SDMA is operated at the BS or access point or RS so that it does not affect the mobile terminal [99]. Figure 2.3 shows the SDMA algorithm in a simple form for both uplink

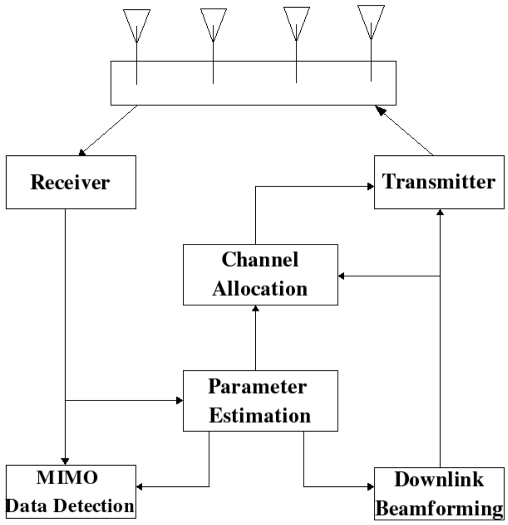
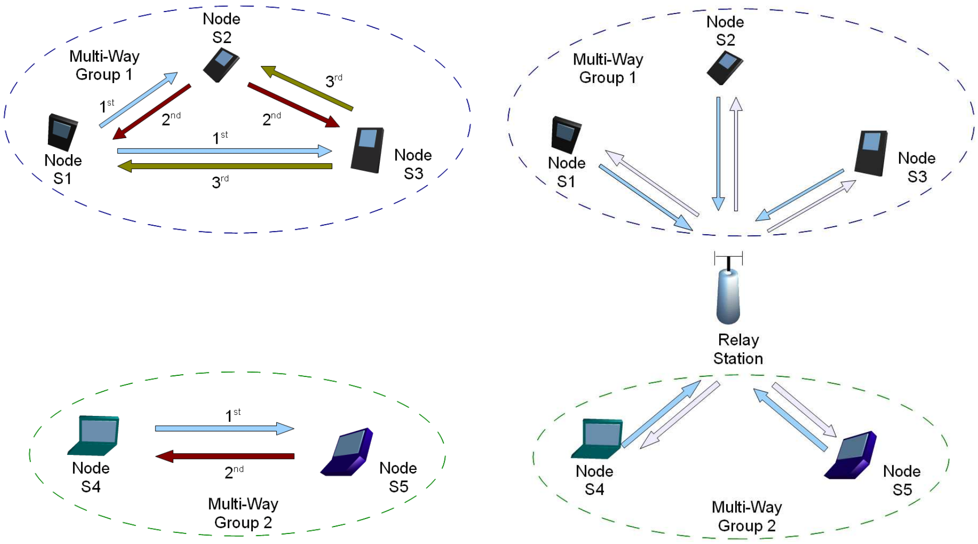


Figure 2.3. Algorithm for SDMA at base station [98]

(UL) and downlink (DL) transmission.

In UL transmission, the operation at the BS is MU-MIMO data detection. MU-MIMO data detection needs the knowledge of channel state information (CSI) of all available paths between each of the nodes' antennas and each of the BS's antennas. If M is the number of BS antennas and N is the number of users who are equipped with a single antenna, then all the available MN paths need to be estimated at the BS. Using this estimation, MU-MIMO data detection is performed at the BS [98].

In DL transmission, the knowledge of CSI is used to perform transmit beamforming and channel allocation. The channel allocation is performed for grouping the nodes such that nodes with low spatial correlations are grouped together to minimise the interference among them. Different to UL where the channel estimation is performed at the BS and directly used for data detection, in DL the channel estimation is performed at the nodes. As a consequence, there is a time delay for the process of sending the estimated channel from the nodes to the BS [98]. Moreover, this requires the use of feedback channels that reduces the data rate. If the channel is time variant, then the feedback of the estimated channel needs to be performed within a time interval shorter than the coherence time of the channel. The shorter the coherence time, the higher the frequency of the feedback transmissions which lowers the spectral efficiency.



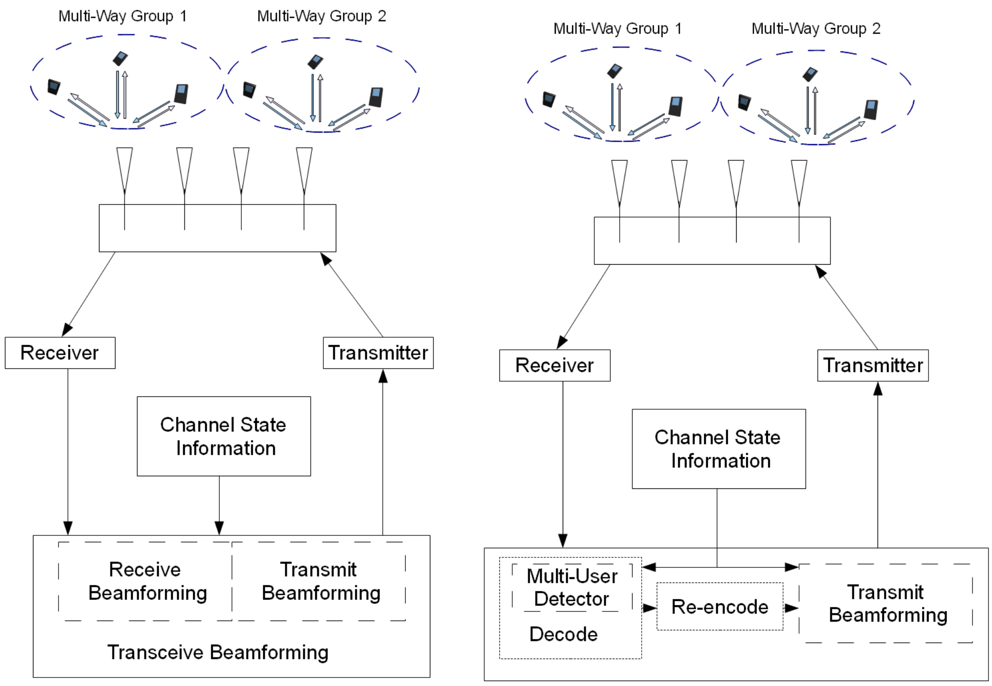
(a) With direct links (b) Without direct links, using an RS

Figure 2.4. Multi-group multi-way communication

2.3 Multi-Antenna Multi-Group Multi-Way Relaying

In this subsection, we briefly explain the motivation for multi-antenna MGMW relaying. When half-duplex nodes perform multi-way communication with direct links between them, the required number of communication phases is equal to the number of nodes. Due to the half-duplex constraint, each node has to transmit sequentially. While one node transmits, the other nodes listen. Figure 2.4(a) shows an illustration of multi-way communication. Multi-way group 1 consists of nodes S1, S2 and S3 while multi-way group 2 consists of nodes S4 and S5. For multi-way group 1, in the first time slot, node S1 sends to nodes S2 and node S3. In the second time slot, node S2 sends to nodes S1 and S3. In the third time slot, node S3 sends to nodes S1 and S2. Multi-way group 2 needs only two time slots to perform multi-way communication.

If both MGMW groups perform multi-way communication via an RS, as depicted in Figure 2.4(b), the required number of communication phases may be higher than the number of nodes in the group, for example, if we use conventional one-way relaying. For multi-way group 1, 6 time slots are needed while for multi-way group 2, 4 time slots are needed. Hence, if both groups are separated in time, in total 10 time slots are needed. Therefore, in this thesis, we propose efficient communication protocol for MGMW relaying and consider a multi-antenna RS in order to separate the groups in space instead of in time. The communication protocol and the transmission strategies are explained in detail in Chapter 3.



(a) Non-Regenerative RS (b) Regenerative RS

Figure 2.5. Signal processing at the RS for MGMW relaying

We consider both multi-antenna non-regenerative RS and multi-antenna regenerative RS. Having multiple antennas, the non-regenerative RS does not simply amplify-and-forward the received signal. The RS performs transceive beamforming in order to exploit the advantages of having multiple antennas. Our first consideration is to have a transceive beamforming which maximises the sum rate of non-regenerative MGMW relaying. However, since finding optimum beamforming maximising the sum rate requires high computational complexity, the design of low complexity transceive beamforming is needed. Moreover, to make it more tractable, the transceive beamforming is decoupled into receive beamforming and transmit bemforming. In this thesis, we assume that perfect CSI is available at the RS. Non-regenerative MGMW relaying is explained in detail in Chapter 4. Figure 2.5(a) shows the block diagram of a multi-antenna non-regenerative RS which supports MGMW relaying.

In case of regenerative RS, after receiving the data streams from all nodes, the RS first decodes all data streams of all nodes. Afterwards, it re-encodes the data streams and performs transmit beamforming to transmit the corresponding re-encoded data streams to the corresponding nodes. We assume perfect CSI at the RS in order to perform multi-user detection and transmit beamforming. The first consideration is to consider optimum multi-user detection. Afterwards, we design transmit beamforming which ensures the transmission with the achievable rate at the RS while minimising the transmit power at the RS. Due to the high complexity of the optimum transmit beamforming and since in many cases the transmit power at the RS is fixed, we design low complexity transmit beamforming subject to a RS power constraint. Regenerative MGMW relaying is explained in more detail in Chapter 5. Figure 2.5(b) shows the block diagram of a multi-antenna non-regenerative RS which supports MGMW relaying.

Chapter 3

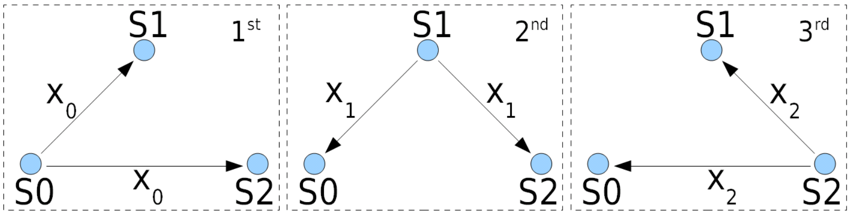
Protocols and Broadcast Strategies for Multi-Group Multi-Way Relaying

3.1 Introduction

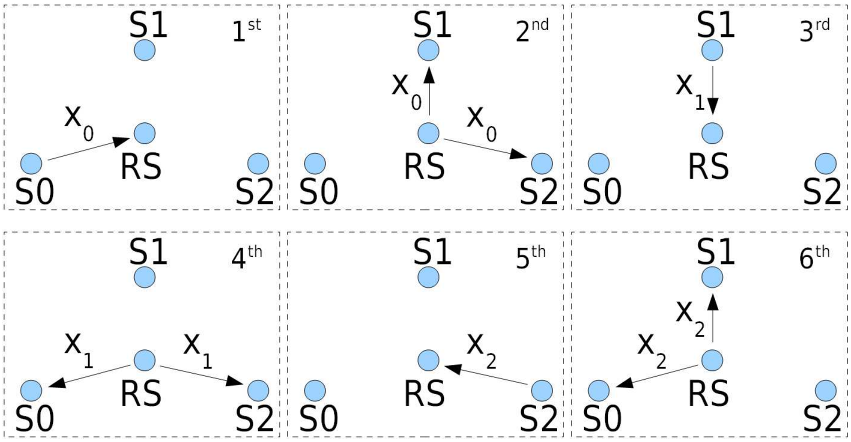
In conferencing multi-way communication, several nodes exchange messages such that each node sends its message and receives the messages from the other nodes. If the nodes are half-duplex nodes and there are direct links among them, they have to send their messages subsequently. Since each node cannot transmit and receive simultaneously, there is only one node that may transmit at one time, and the remaining nodes receive the transmitted data stream. Figure 3.1(a) shows an example when there are three half-duplex nodes in one multi-way group exchanging messages. In the first phase, node S0 transmits its data stream x_0 to both nodes S1 and S2. In the second phase, node S1 transmits x_1 to both nodes S0 and S2. In the third phase, node S2 transmits x_2 to both nodes S0 and S1. After three phases, the multi-way communication is completed. In general, for one multi-way group consisting of N half-duplex nodes, if there are direct links among the nodes, the required number of communication phases is equal to N.

In case of no direct links among the nodes, the nodes can exchange messages with the help of an RS. Using the conventional one way relaying, the number of communication phases is equal to two times the number of nodes. Figure 3.1(b) shows the multi-way communication using one-way relaying. In the first phase, node S0 transmits x_0 to the RS, and in the second phase, the RS transmits x_0 to nodes S1 and S2. In the third phase, node S1 transmits x_1 to the RS, and in the fourth phase, the RS transmits x_1 to nodes S0 and S2. In the fifth phase, node S2 transmits x_2 to the RS, and in the sixth phase, the RS transmits x_2 to nodes S0 and S1. After six phases, the multi-way communication is completed.

In recent works on multi-way relaying, [79,80] consider single-group regenerative multi-way relaying with three half-duplex nodes. In [79], three protocols were considered. The first one is the conventional one-way relaying, which needs six communication phases. The second one is a five-phase communication, where the first three phases are used for the three nodes to transmit their data streams subsequently to the RS and the remaining two phases are used for the RS to transmit to the three nodes. The



(a) With direct links



(b) Without direct links and using one-way relaying

Figure 3.1. Multi-way conferencing of three nodes

most efficient protocol in [79] is the four-phase protocol where in the first three phases the nodes transmit to the RS and, afterwards, the RS transmits to the nodes in one remaining phase. Similarly, [80] considers a four-phase communication protocol for three nodes for single-group multi-way relaying. Using such a protocol, if the number of nodes is only two, that is, a two-way communication using an RS, we require three communication phases as in [28–30]. Since there is only one phase for the RS to transmit to the nodes, complex re-encoding schemes at the RS and, consequently, complex decoding schemes at the nodes are needed, since only by receiving one data stream from the RS, the nodes have to decode $N-1$ messages from the other $N-1$ nodes. For two-way communication and three-way communication using an RS, the approaches in [79, 80] is tractable. However, one may not clearly see the extension to the case when the number of nodes is higher than three and when there are multiple multi-way groups. Moreover, such protocol is more suitable for a regenerative RS, since the RS may decode each received data stream without interference.

In this thesis, we propose a spectrally efficient communication protocol which can be applied for both non-regenerative and regenerative MGMW relaying. The communication protocol is designed in such a way that the required number of communication phases is the same as for direct communication when there are direct links among the

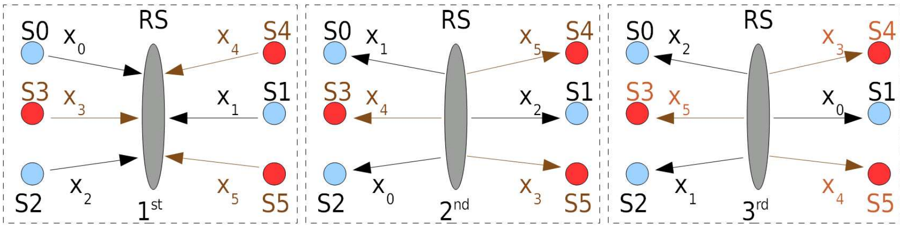
Figure 3.2. Communication protocol for MGMW relaying

nodes. For single-group multi-way relaying, the number P of communication phases is maintained to be equal to N. For MGMW relaying, P is equal to the maximum number of nodes among the groups. In the following, for simplicity of notations, we consider the same number of nodes among all groups, in such a way that P is defined by the number of nodes in each group. However, the extension to different numbers of nodes in each group is straight forward and we provide this extension at the end of this chapter.

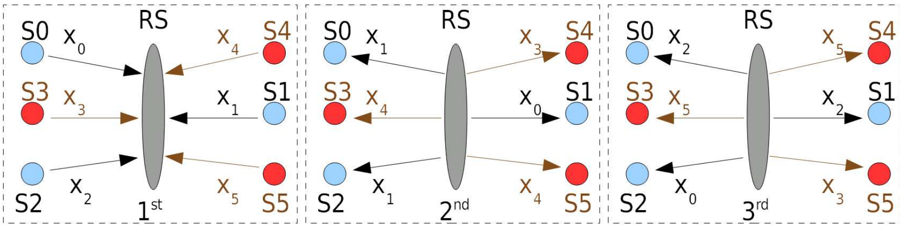
Figure 3.2 shows the proposed communication protocol for MGMW relaying. Within P communication phases, there is only one MAC phase where all nodes transmit simultaneously to the RS. In the remaining $P-1$ BC phases, the RS transmits to the nodes. Since P is equal to the number of nodes in case of a single multi-way group and equal to the number of nodes in each group, if the number of nodes is equal in all groups, the proposed MGMW relaying protocol is a generalisation of two-way relaying in, e.g., [14, 17, 19] and multi-user two-way relaying in, e.g., [64, 68, 71].

Since there is only one MAC phase, the RS has to be able to separate the received data streams. The use of a multi-antenna RS aims at having the ability to separate the data streams at the RS. One of the challenge of having such spectrally efficient communication protocol is that the RS has to ensure that all nodes receive the messages from all other nodes in their group in the remaining BC phases. Therefore, we propose three BC strategies, namely, unicasting, hybrid uni/multicasting and multicasting, which ensure that the MGMW communication is completed within $P-1$ BC phases. Regarding the multicasting strategy, wireless cooperative network coding (WCNC) is needed to maintain the number of communication the same as for the other strategies.

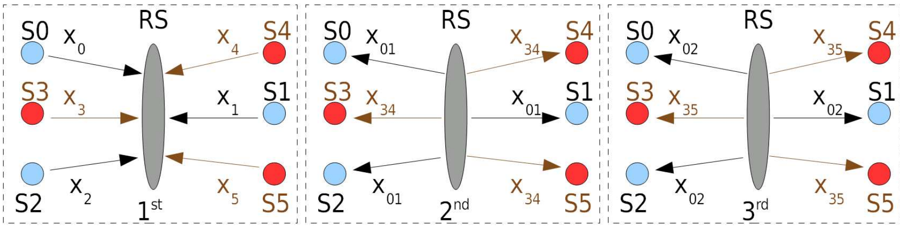
In the remainder of this chapter, we explain the BC strategies in Section 3.2, the WCNC in Section 3.3 and the extension of MGMW relaying for the case when the number of nodes is not equal in all groups in Section 3.4.



(a) Unicasting



(b) Hybrid uni/multicasting



(c) Multicasting

Figure 3.3. MGMW relaying for the case of two-group multi-way with three nodes in each multi-way group.

3.2 Broadcast Strategies

3.2.1 Introduction

Having $P-1$ BC phases, the RS has to ensure that each node receives the data streams of its group member nodes. In the following, we explain three BC strategies for MGMW relaying which aim at ensuring the MGMW communication. We first explain the unicasting strategy in Section 3.2.2 followed by hybrid uni/multicasting strategy in Section 3.2.3 and multicasting strategy in Section 3.2.4.

3.2.2 Unicasting

In case of the unicasting protocol, in each BC phase, the RS sends several data streams simultaneously to the nodes, and each data stream is intended exclusively only for one receiving node. Figure 3.3(a) shows the unicasting strategy for two-group multi-way where each group consists of three nodes. In the second phase, the RS sends x_1 to S0, x_2 to S1, x_0 to S2, x_4 to S3, x_5 to S4 and x_3 to S5. In the third phase, the RS sends x_2 to S0, x_0 to S1, x_1 to S2, x_5 to S3, x_3 to S4 and x_4 to S5. After three phases, all nodes obtain the data streams from all other nodes in their group.

From the example in Figure 3.3(a), one may see that in each BC phase the RS sends six different data streams simultaneously. Since in each BC phase each node is intended to receive only one data stream out of six data streams, due to the broadcast nature of wireless communication, it sees the other five data streams as interference. The interference consists of two parts, namely, other-group-inter-stream interference and same-group-inter-stream interference. Other-group-inter-stream interference refers to interference received at each node which comes from other nodes in other multi-way groups. This interference appears in MGMW relaying, when multiple multi-way groups share the same RS and they are separated in space. Same-group-inter-stream interference refers to the interference received at each node which comes from unintended data streams from the nodes in its group. For example, node S0 is intended to receive x_1 in the second phase. It decodes the received signal in the second phase to obtain only x_1. Therefore, data streams x_0 and x_2 contribute to same-group-inter-stream interference and data streams x_3, x_4 and x_5 contribute to other-group-inter-stream interference seen by node S0 in the second phase.

3.2.3 Hybrid Uni/Multicasting

The term hybrid uni/multicasting refers to the fact that the RS applies unicast and multicast transmissions simultaneously when serving each group. For each served group, one data stream is transmitted to one node exclusively (unicast transmission) and one data stream is transmitted simultaneously to the other group member nodes (multicast transmission). In each BC phase, the unicasted data stream is fixed and is transmitted to a different node in the group. Consequently, the multicasted data stream has to be changed in each BC phase to ensure that each node in each group receives all data streams of the other nodes in its group within the BC phases. In case of one pair two-way relaying and multi-user two-way relaying, the hybrid uni/multicasting protocol is the same as the unicasting protocol.

Figure 3.3(b) shows the hybrid uni/multicasting strategy for two-group multi-way relaying where each group consists of three nodes. In the second phase, the data stream x_0 is unicasted only to node S1 and the data stream x_1 is multicasted to nodes S0 and

S2. Similarly, x_3 is unicasted only to node S4 and the data stream x_4 is multicasted to nodes S3 and S5. In the third phase, x_0 is unicasted to node S2 and the data stream x_2 is multicasted to nodes S0 and S1, and x_3 is unicasted to node S5 and x_5 is multicasted to nodes S3 and S4. Thus, after three phases the communication is completed.

Using hybrid uni/multicasting strategy, there is less interference seen by each node compared to the unicasting strategy. For example, from Figure 3.3(b), node S0 in the second phase is intended to decode data stream x_1. Data stream x_0 contributes to same-group-inter-stream interference and data streams x_3 and x_4 contribute to other-group-inter-stream interference.

3.2.4 Multicasting

Another way to reduce the interference is to allow the RS to transmit only one data stream per group in each BC phase. Using such approach, there is no same-group-inter-stream interference. The interference comes only from the data streams which are intended for other groups. Figure 3.4 shows MGMW relaying without same-group-inter-stream interference. In the second phase, the RS sends x_0 to nodes S1 and S2 and x_3 to nodes S4 and S5. In the third phase, the RS sends x_1 to nodes S0 and S2 and x_4 to nodes S3 and S5. Finally, in the fourth phase, the RS sends x_2 to nodes S0 and S1 and x_5 to nodes S3 and S4.

As a penalty of having no same-group-inter-stream interference, the number of communication phases is higher than for unicasting and hybrid uni/multicasting, since the RS needs one more phase in order to ensure that each node receives the messages of its group members. In this thesis, we propose a BC strategy which is called multicasting strategy. It also does not allow any same-group-inter-stream interference but needs only the same number of communication phases as for unicasting strategy and hybrid uni/multicasting strategy.

Using multicasting strategy, the RS transmits only one data stream to all nodes in each group. The transmitted data stream from the RS is an output of a linear operation on two data streams of two nodes in each group. Since the RS is not only routing the received data streams, but is allowed to perform operations on the received data streams, the multicasting strategy applies network coding [43].

Figure 3.3(c) shows multicasting strategy with network coding for two-group multi-way relaying where each group consists of three nodes.. Let $x_{v_l w_l}$ denote the network coded

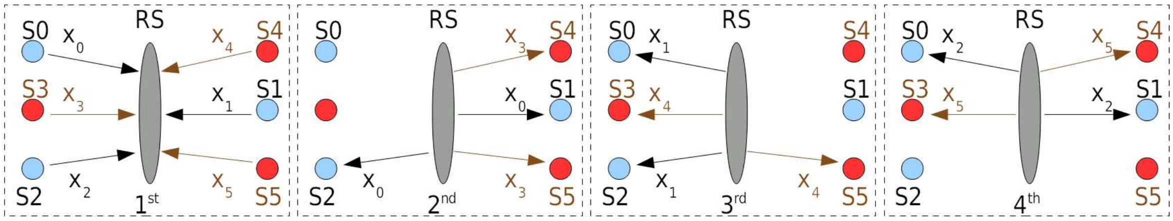


Figure 3.4. Multi-group multi-way relaying without same-group-inter-stream interference for the case of two-group multi-way with three nodes in each multi-way group: Four communication phases are needed.

data streams of two nodes in group $l, l = \{1, 2\}$, namely, Sv_l and Sw_l. In the second phase, the RS sends x_{01} to all nodes in the first group and x_{34} to all nodes in the second group. In the first group, both S0 and S1 perform self-interference cancellation by canceling their transmitted data stream from x_{01} to obtain their partner's data stream. Hence, S0 obtains x_1 and S1 obtains x_0. Node S2 cannot yet perform self-interference cancellation, since x_{01} does not contain its own data stream. In the second group, S3 and S4 perform self-interference cancellation but node S5 cannot yet perform self-interference cancellation. In the third phase, the RS transmits x_{02} to all nodes in the first group and x_{35} to all nodes in the second group. In the first group, both nodes S0 and S2 perform self-interference cancellation so that S0 obtains x_2 and S2 obtains x_0. Since S1 knows x_0 from the second phase, it performs known-interference cancellation to obtain x_2. Since S2 knows x_0 from the third phase, it obtains x_1 by performing known-interference cancellation to the received data stream in the second phase, namely x_{01}. A similar process is performed at the nodes in the second group. Thus, node S2 in the first group and node S5 in the second group need to wait until they receive the data stream containing their own data stream. After performing self-interference cancellation, they perform known-interference cancellation to obtain the other data stream. After three phases, all nodes obtain the data streams from all other nodes in their group.

3.3 Wireless Cooperative Network Coding

3.3.1 Introduction

Multicasting strategy with network coding is a form of cooperation between the RS and the nodes in managing the interference in the network. The RS suppresses interference that cannot be suppressed at the nodes, namely, the other-group-inter-stream interference. It also performs a linear operation on two data streams of each group, since the nodes can perform self- and known-interference cancellation by using the available side information, namely, its own transmitted data stream or a data stream which has been decoded in the previous BC phases. In order to ensure the completion of MGMW communication, there is a general rule on selecting the two data streams to be linearly operated in each BC phase. The RS has to ensure that the data stream of each node is used at least once within the $P-1$ BC phases. In this section, we explain the principle of WCNC for non-regenerative MGMW relaying in Section 3.3.2 followed by the principle for regenerative MGMW relaying in Section 3.3.3.

3.3.2 WCNC for Non-Regenerative MGMW Relaying

Since a non-regenerative RS does not decode and re-encode the received data streams, the WCNC for non-regenerative MGMW relaying is performed at signal level. The first step is to separate the two data streams which are going to be superposed by the RS from the other received data streams. Afterwards, the RS has to separate the groups and it sends each corresponding superposed data stream to all corresponding group members. Having multiple antennas at the RS, we can make the separation spatially.

Figure 3.5 shows an illustration of WCNC for non-regenerative MGMW relaying for the second phase and third phase. Let, in the following, $\mathbf{h}_i$ and x_i denote the channel vector between node Si and the RS and the transmit symbol of node Si, respectively. Regarding multi-way group 1, in the second phase, the RS separates the superposition of two data streams of nodes S0 and S1, namely, $(\mathbf{h}_0 x_0 + \mathbf{h}_1 x_1)$, from the other received signal and sends it to all nodes in multi-way group 1. In the third phase, the RS separates the superposition of two data streams of nodes S0 and S2, namely, $(\mathbf{h}_0 x_0 + \mathbf{h}_2 x_2)$, from the other received data streams and sends it to all nodes in multi-way group 1. Each node in multi-way group 1 performs self- and known-interference cancellation by using the available side information. For example, in the second phase, node S0 performs self-interference cancellation $(\mathbf{h}_0 x_0 + \mathbf{h}_2 x_2) - \mathbf{h}_0 x_0 = \mathbf{h}_2 x_2$. Similar process is performed at the RS for multi-way group 2 and at the nodes in multi-way group 2.

3.3.3 WCNC for Regenerative MGMW Relaying

In case of regenerative MGMW relaying, after decoding the data streams of all nodes, the RS knows the bit sequences of all nodes. In this thesis, we consider two approaches on performing network coding for regenerative MGMW relaying. The first one is

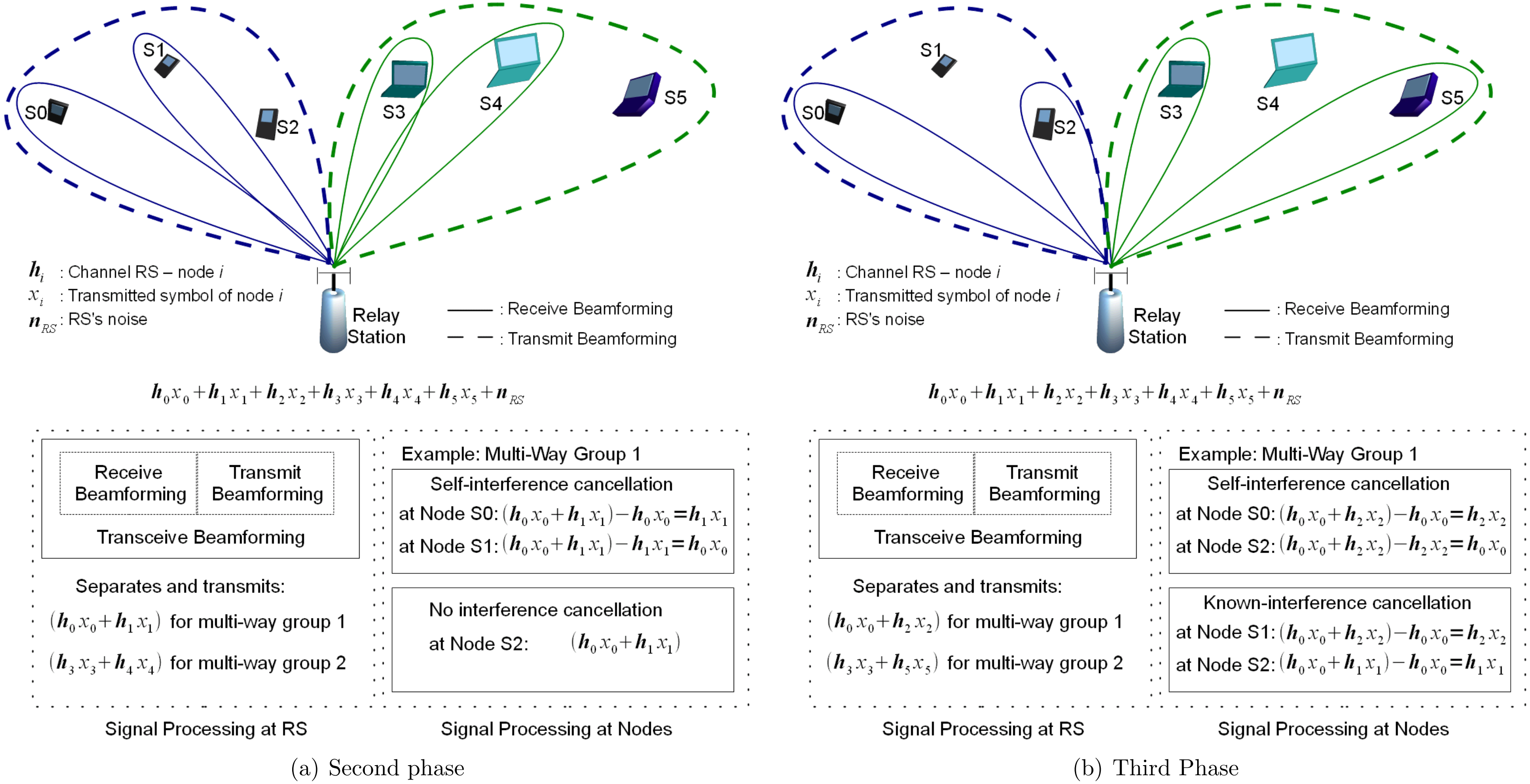


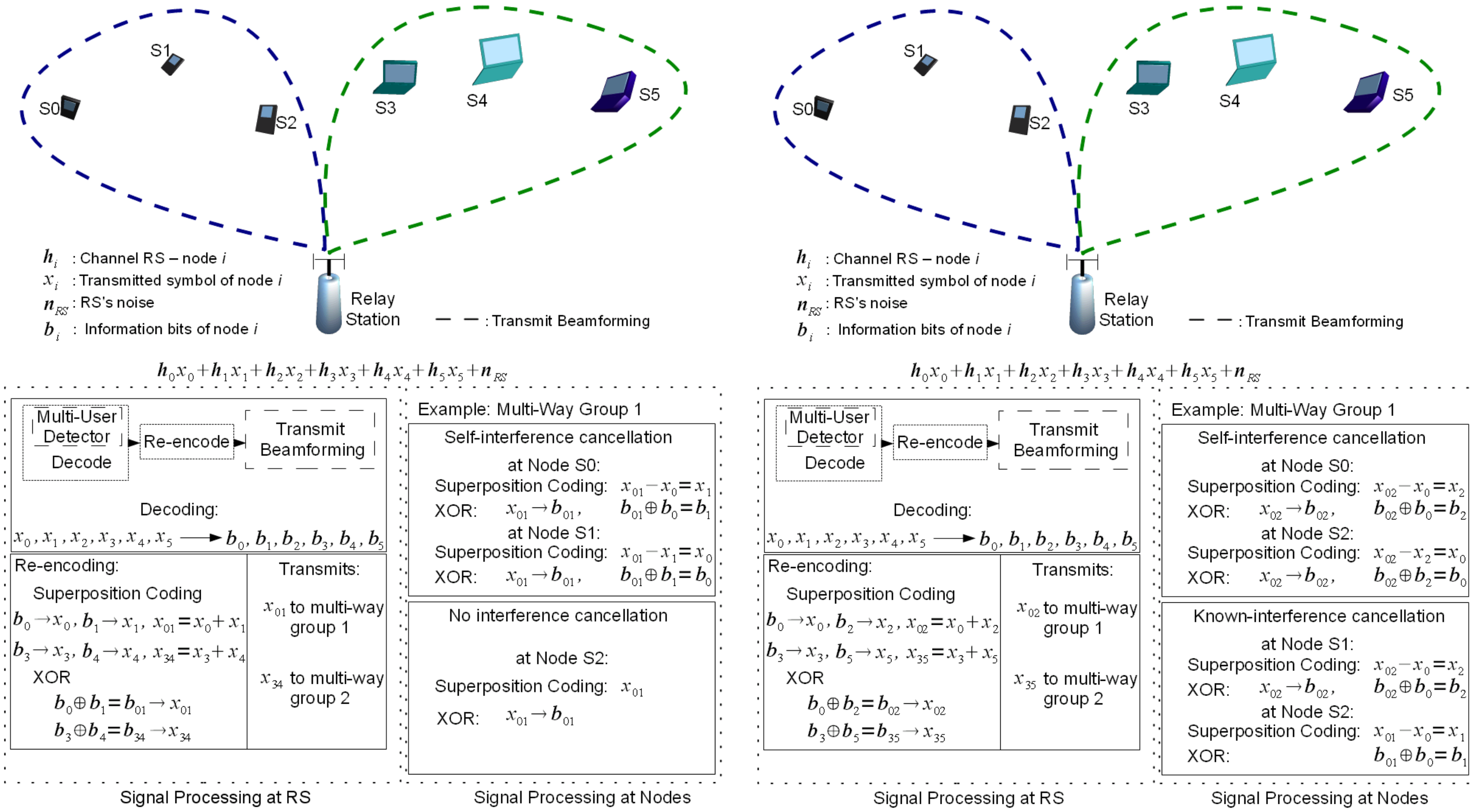
Figure 3.5. Illustration of WCNC for non-regenerative MGMW relaying: Nodes S0, S1 and S2 in multi-way group 1, and nodes S3, S4 and S5 in multi-way group 2

modified superposition coding (mSPC) and the second one is exclusive-OR (XOR). mSPC is a modification of superposition coding for two-way relaying in [14] or for multi-user two-way relaying in [70], where the modification is needed to suit multicasting strategy for MGMW relaying. For SPC as in [14, 70], after decoding the data streams, the RS re-encodes each decoded bit sequence of each node into a transmit symbol. Afterwards, each transmit symbol is weighted differently and two weighted symbols of two nodes in each two-way pair are added. Using mSPC, the RS re-encodes each of the decoded bit sequences of each nodes and it superposes two symbols of two nodes in each group. Afterwards, the output is weighted. Thus, both symbols are equally weighted. We consider also XOR network coding since it provides low complexity solutions in three different aspects [70]: implementation, encoding/decoding and the required information for self-interference cancellation. Moreover, the practicality of XOR network coding in wireless network has been shown in [28]. Using XOR, the RS first performs XOR operation on two bit sequences of two nodes in each group. The XOR-ed bit sequence is then re-encoded into one transmit symbol.

Figure 3.6 shows an illustration of WCNC for regenerative MGMW relaying for the second and third phase. Let, in the following, $\mathbf{b}_i$ denote the bit sequence of node Si. Regarding multi-way group 1, in the second phase, if the RS applies mSPC, it re-encodes $\mathbf{b}_0$ into x_0 and $\mathbf{b}_1$ into x_1 and performs $x_0 + x_1 = x_{01}$ operation and sends x_{01} to all nodes in multi-way group 1. In the third phase, it re-encodes $\mathbf{b}_0$ into x_0 and $\mathbf{b}_2$ into x_2 and performs $x_0 + x_2 = x_{02}$ operation and sends x_{02} to all nodes in group 1. Using XOR, in the second phase the RS performs XOR operation $\mathbf{b}_0 \oplus \mathbf{b}_1 = \mathbf{b}_{01}$ and re-encodes $\mathbf{b}_{01}$ into x_{01} and transmits x_{01} to all nodes in multi-way group 1. In the third phase, the RS performs XOR operation $\mathbf{b}_0 \oplus \mathbf{b}_2 = \mathbf{b}_{02}$ and re-encodes $\mathbf{b}_{02}$ into x_{02} and transmits x_{02} to all nodes in multi-way group 1. Each node has to perform self- and known-interference cancellation. For example, in the second phase at node S0, if the RS applies mSPC, after receiving x_{01}, it subtracts its transmitted symbol x_0 from x_{01} and, if the RS applies XOR, it first decodes x_{01} to obtain the bit sequence $\mathbf{b}_{01}$ and, afterwards, it performs $\mathbf{b}_{01} \oplus \mathbf{b}_0$ to obtain $\mathbf{b}_1$. A similar network coding process is performed at the RS for multi-way group 2 and a similar self- and known-interference cancellation is performed at each node in multi-way group 2.

3.4 Different Numbers of Nodes in the Groups

In the previous section, we have explained three BC strategies for MGMW relaying for the case when the number of nodes is equal in all groups. In this section, we explain the extension to the case when the numbers of nodes are not the same in all groups.



(a) Second phase (b) Third Phase

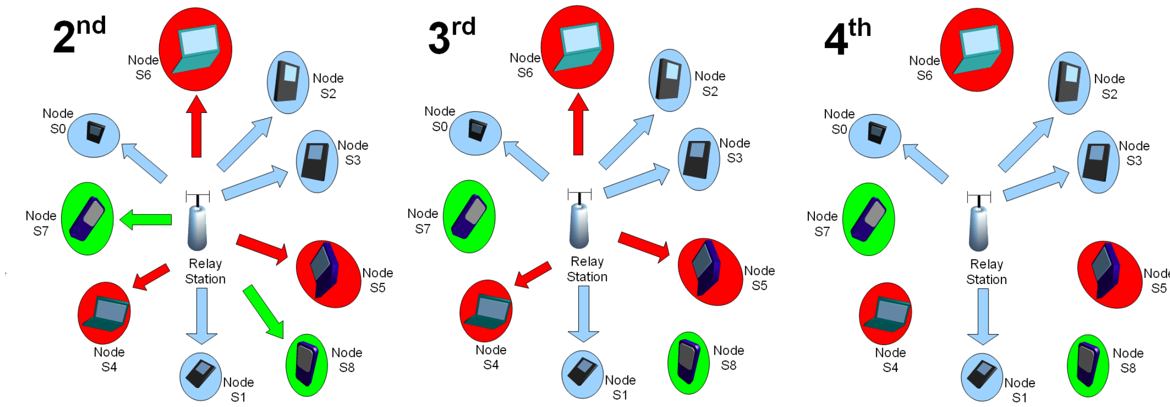
Figure 3.6. Illustration of WCNC for regenerative MGMW Relaying: Nodes S0, S1 and S2 in multi-way group 1, and nodes S3, S4 and S5 in multi-way group 2

When the numbers of nodes are not the same in all groups, the required number of communication phases is defined by the maximum number of nodes among the groups. There are three exemplary considerations considering the extension to different numbers of nodes in the groups. The first one is regarding communication latency. Many communication applications, such as voice telephony, are requiring low latency. In such applications, it is important to transmit to the corresponding nodes as soon as possible to avoid long delay in communication. In MGMW relaying with different numbers of nodes in the groups, a latency-wise approach as shown in Figure 3.7(a) is designed to avoid long delay in transmission from the RS to the nodes. There are three multi-way groups. Multi-way group 1 consists of four nodes, namely, S0, S1, S2 and S3, multi-way group 2 consists of three nodes, namely, S4, S5 and S6, and multi-way group 3 consists of two nodes, namely, S7 and S8. All groups are served by the RS simultaneously in the second phase. Since multi-way group 3 has completed its communication in the second phase, in the third phase, the RS only serves multi-way groups 1 and 2. Finally, in the fourth phase, as multi-way groups 2 and 3 have completed their MGMW communication, the RS only serves multi-way group 1.

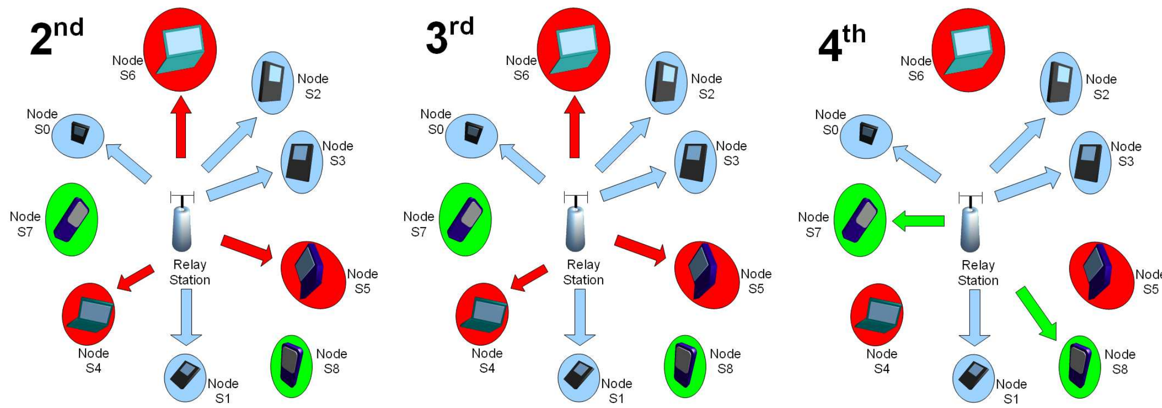
The second consideration is to divide the number of groups to be served by the RS as equally as possible within the $P - 1$ BC phases. This reduces the number of other-group-interstream-inteference among the groups. A group-wise approach which aims at equally dividing the number of groups to be served by the RS is shown in Figure 3.7(b). In the second phase and in the third phase, the RS only serves multi-way groups 1 and 2. After the multi-way communication in group 2 is completed, in the fourth phase, the RS only serves multi-way groups 1 and 3.

The third consideration is to separate the data streams of one or more groups into several BC phases while still ensuring the completion of MGMW relaying. Figure 3.7(c) shows a stream-wise approach where the RS splits the data streams to be transmitted for group 2 into two BC phases. In the second phase, the RS sends to all nodes in groups 1 and 2, and also to node S7 in group 3. In the third phase, the RS sends to all nodes in groups 1 and 2, and also to node S8 in group 3 while node S7 does not receive a data stream in this phase. In the fourth phase, since groups 2 and 3 have completed their communication, the RS only serves group 1.

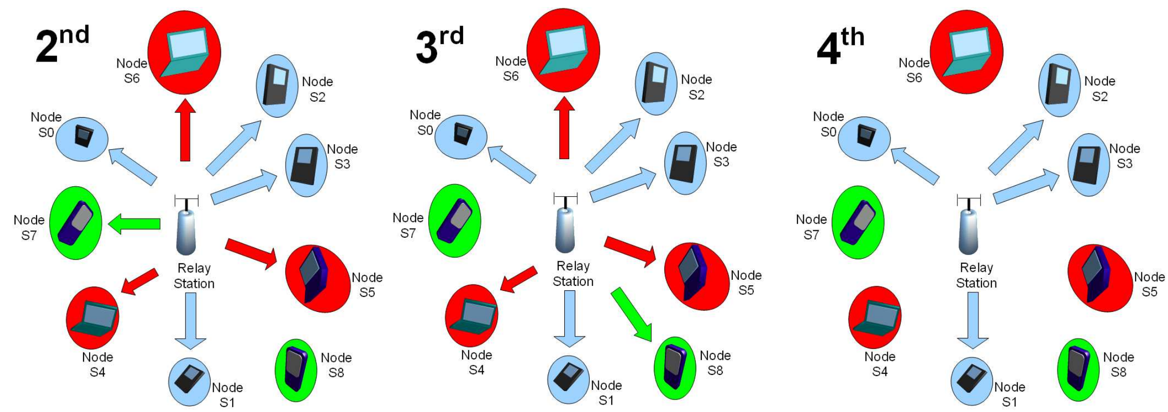
Having different numbers of nodes in the groups, the RS may optimise the scheduling transmission for the groups and chooses the best approach based on the objective function which shall be optimised. In this work, in the following, for simplicity of notations, we consider the same number of nodes in all groups. However, the extension to different numbers of nodes in the groups with all the above mentioned consideration is straight forward. The mathematical form of the BC strategies which are derived in



(a) Latency-wise



(b) Group-wise



(c) Stream-wise

Figure 3.7. Illustration of BC strategies for different numbers of nodes in the groups. Multi-way group 1: nodes S0, S1, S2 and S3, multi-way group 2: Nodes S4, S5 and S6, multi-way group 3: nodes S7 and S8.

Chapter 4 and Chapter 5 is designed also for different numbers of nodes with latency-wise approach. Therefore, if the number of nodes is not equal, this thesis considers an approach to reduce the delay of MGMW communication in the groups which is suitable for low-latency communication application.

Chapter 4

Non-Regenerative Multi-Antenna Multi-Group Multi-Way Relaying

4.1 Introduction

In this chapter, we explain non-regenerative MGMW relaying. Non-regenerative, compared to regenerative, has three advantages: no decoding error propagation, no delay due to decoding and deinterleaving, and transparency to the modulation and coding schemes that are used at the nodes [17].

It is shown in [73] for multi-user two-way relaying, that if the multi-antenna RS only amplifies its received signal and forwards the amplified signal to the nodes, the sum rate performance is much lower compared to the case if the RS performs transceive beamforming. Hence, in this thesis, the multi-antenna non-regenerative RS performs transceive beamforming to serve the groups and to improve the performance of the MGMW communication.

Several works have considered multi-antenna non-regenerative RS and their contributions were mostly on the design of the transceive beamforming. For two-way relaying, [17, 58] assume multi-antenna nodes and [59, 60] assume single antenna nodes. Their works consider optimal transceive beamforming at the RS maximising the sum rate as well as linear transceive beamforming based on Zero Forcing (ZF) [17, 58–60], Minimisation of Mean Square Error (MMSE) [17, 58, 59], and Maximisation of Signal to Noise Ratio (MSNR) [17] or Matched Filter (MF) criteria [59, 60].

In case of multi-user two-way relaying, where the RS serves multiple two-way pairs, [71, 73] proposed low complexity transceive beamforming. In [71], ZF and MMSE transceive beamforming for multi-user non-regenerative two-way relaying is designed to separate the nodes. In [73], block-diagonalisation-singular-value-decomposition (BD-SVD) transceive beamforming is designed for separating the two-way pairs by extending BD-SVD transmit beamforming for the multi-user downlink problem proposed in [100].

In this thesis, we design generalised transceive beamforming algorithms for MGMW relaying for all BC strategies. We use the term generalised to emphasize that each beamforming algorithm is derived in a general way, such that it is valid for all BC strategies. We address optimum transceive beamforming maximising the sum rate of non-regenerative MGMW relaying. Due to the high complexity of finding the optimum transceive beamforming maximising the sum rate, we design generalised low complexity transceive beamforming algorithms for all BC strategies, namely, MF, ZF and MMSE. Also, BC-strategy-aware (BCSA) transceive beamforming algorithms are introduced.

In the remainder of this chapter, we first derive a unified system model of non-regenerative MGMW relaying for all BC strategies in Section 4.2. Afterwards, we derive the sum rate expression of non-regenerative MGMW relaying in Section 4.3. The design of the generalised transceive beamforming algorithms for all BC strategies is given in Section 4.4. The simulation results showing the performance of single-group and two-group multi-way relaying are given in Section 4.5.

Notations: Boldface lower and upper case letters denote vectors and matrices, respectively, while normal letters denote scalar values. The superscripts $(\cdot)^{\mathrm{T}}$, $(\cdot)^{*}$ and $(\cdot)^{\mathrm{H}}$ stand for matrix or vector transpose, complex conjugate, and complex conjugate transpose, respectively. The operators $\mathrm{mod}_N(x)$, $\mathrm{E}\{\mathbf{X}\}$ and $\mathrm{tr}\{\mathbf{X}\}$ denote the modulo N of x, the expectation and the trace of $\mathbf{X}$, respectively, and $\mathcal{CN}(0,\sigma^2)$ denotes the circularly symmetric zero-mean complex normal distribution with variance σ^2.

4.2 Unified System Model and Broadcast Strategy Parameterisation

4.2.1 Unified System Model

We consider L multi-way communication groups. It is assumed that there are no direct links among the nodes in each group. The MGMW communication can only be performed with the assistance of a half-duplex multi-antenna RS with M antenna elements. In the l-th group, $l \in \mathcal{L}, \mathcal{L} = \{1, \cdots, L\}$, there are N_l nodes which exchange messages through an RS. For simplicity of the notations, we consider the same number of nodes in all groups, i.e., $N_l = N_{\mathrm{mw}}, \forall l \in \mathcal{L}$. The total number N of nodes in the network is $N = \sum_{l\in\mathcal{L}} N_l = LN_{\mathrm{mw}}$.

Assuming that the RS already knows which nodes belong to which communication group, the RS makes the indexing of all nodes according to their group membership. Nodes in group 1 are indexed within the set $\{0, \cdots, N_1 - 1\}$, nodes in group 2 are indexed within the set $\{N_1, \cdots, (N_1 + N_2) - 1\}$, and so on. In general, it can be given as follows: The l-th group consists of nodes $\mathrm{S}i_l, i_l \in \mathcal{I}_l$, where $\mathcal{I}_l$ is the set of node indices given by

$$\mathcal{I}_l = \{a_l, \cdots, b_l\}, \text{ with } a_l = (l-1)N_{\text{mw}} \text{ and } b_l = lN_{\text{mw}} - 1. \tag{4.1}$$

Each node only exchanges messages with the other nodes in its group and each node belongs only to one multi-way group, i.e., $\mathcal{I}_l \cap \mathcal{I}_k = \emptyset, \forall l \neq k$ and $\mathcal{I} = \bigcup_{l=1}^{L} \mathcal{I}_l = \{0, \cdots, N-1\}$.

The number P of communication phases to perform MGMW communication is given by the maximum number of nodes among all groups, i.e., $P = \max_l N_l = N_{\text{mw}}$. In the first phase, the MAC phase, all nodes transmit simultaneously to the RS. In the following $P-1$ BC phases, the RS transmits to the nodes. Let p, $p \in \mathcal{P}, \mathcal{P} = \{2, \cdots, P\}$, denote the index of the BC phase. In p-th phase, in group l, a receiving node $r_l \in \mathcal{I}_l$ is intended to receive the data stream of a transmitting node $t_l \in \mathcal{I}_l \setminus \{r_l\}$ according to the chosen BC strategy.

In the following, we derive the unified discrete-time baseband system model for non-regenerative MGMW relaying. We assume flat fading channels. The overall channel matrix from the nodes to the RS is given by

$$\mathbf{H} = [\mathbf{h}_0, \cdots, \mathbf{h}_{N-1}] \in \mathbb{C}^{M \times N}, \tag{4.2}$$

with

$$\mathbf{h}_i = (h_{i,1}, \cdots, h_{i,M})^{\mathrm{T}} \in \mathbb{C}^{M \times 1}, i \in \mathcal{I}, \tag{4.3}$$

the channel vector between node $\mathrm{S}i$ and the RS. The channel coefficient $h_{i,m}, m \in \mathcal{M}, \mathcal{M} = \{1, \cdots, M\}$, follows $\mathcal{CN}(0, \sigma_h^2)$. The vector

$$\mathbf{x} = (x_0, \cdots, x_{N-1})^{\mathrm{T}} \in \mathbb{C}^{N \times 1} \tag{4.4}$$

denotes the transmit vector with x_i the transmit signal of node $\mathrm{S}i$ that follows $\mathcal{CN}(0, \sigma_x^2)$. The AWGN noise vector at the RS is denoted as

$$\mathbf{z}_{\text{RS}} = (z_{\text{RS}1}, \cdots, z_{\text{RS}M})^{\mathrm{T}} \in \mathbb{C}^{M \times 1}, \tag{4.5}$$

with $z_{\text{RS}m}$ following $\mathcal{CN}(0, \sigma_{z_{\text{RS}}}^2)$. In this work, we assume that all nodes transmit with fixed and equal transmit power.

In the first phase, all nodes transmit simultaneously to the RS and the received signal at the RS is given by

$$\mathbf{y}_{\text{RS}} = \mathbf{H}\mathbf{x} + \mathbf{z}_{\text{RS}}. \tag{4.6}$$

Assuming reciprocal and time-invariant channels in P phases, the downlink channel from the RS to the nodes is simply the transpose of the uplink channel $\mathbf{H}$. In the p-th phase, the RS performs transceive beamforming, denoted by matrix $\mathbf{G}^p$, to the received signals and transmits to the nodes. Therefore, $\mathbf{G}^p$ has to be designed to ensure that the MGMW relaying is performed according to the chosen BC strategy. It is assumed that there is a transmit power constraint at the RS. The received signal vector of all nodes in the p-th phase can be written as

$$\mathbf{y}^p_{\text{nodes}} = \mathbf{H}^{\mathrm{T}}\mathbf{G}^p(\mathbf{H}\mathbf{x} + \mathbf{z}_{\text{RS}}) + \mathbf{z}^p_{\text{nodes}}, \tag{4.7}$$

where

$$\mathbf{z}^p_{\text{nodes}} = \left(z^p_0, \cdots, z^p_{N-1}\right)^{\mathrm{T}}, \tag{4.8}$$

with $z^p_{r_l}$ the noise at receiving node r_l which follows $\mathcal{CN}(0, \sigma^2_{z_{\text{node}}})$. Accordingly, the received signal at node $\mathrm{S}r_l, r_l \in \mathcal{I}_l$, while receiving the data stream from node $\mathrm{S}t_l, t_l \in \mathcal{I}_l \setminus \{r_l\}$, in the p-th phase is given by

$$y^p_{r_l,t_l} = \underbrace{\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_{t_l}x_{t_l}}_{\text{useful signal}} + \underbrace{\sum_{\substack{j=0\\ j\neq t_l}}^{N-1} \mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_j x_j}_{\text{interference signals}} + \underbrace{\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{z}_{\text{RS}}}_{\text{RS's propagated noise}} + \underbrace{z^p_{r_l}}_{\text{node } r_l\text{'s noise}}. \tag{4.9}$$

In this subsection, we explain the unified system model for non-regenerative MGMW relaying which is valid for all BC strategies. In order to have non-regenerative MGMW relaying with a specific BC strategy, in the following subsection, we describe the relationship of p, r_l and t_l, which has to be set appropriately according to the applied BC strategy.

4.2.2 Broadcast Strategy Parameterisation

4.2.2.1 Unicasting Strategy

Using unicasting strategy, in each BC phase, the RS transmits different data streams to different nodes. Each data stream is intended only for one receiving node. Consequently, each node sees the other data streams transmitted by the RS to the other nodes as interference.

The relationship of the parameters p, r_l and t_l is given by

$$t_l = a_l + \operatorname{mod}_{N_l}(r_l + p - a_l - 1). \tag{4.10}$$

Using such strategy, assuming each node knows its index and all other nodes' indices in its group, there is no signalling required in the network. The proposed unicasting strategy is a generalisation of the work in [17, 59] for $L = 1$ and $N_1 = 2$, and in [71] for $L > 1$ and $N_l = 2, \forall l$.

4.2.2.2 Hybrid Uni/Multicasting Strategy

For each served group, one data stream is transmitted to one node exclusively (unicast transmission) and one data stream is transmitted to the other $N_l - 1$ nodes (multicast transmission). In each BC phase, the unicasted data stream is fixed and is transmitted to a different node in the group. Consequently, the multicasted data stream has to be changed in each BC phase to ensure that each node in each group receives all data streams of the other nodes in its group within P phases. Compared to the unicasting strategy, same-group-inter-stream interference in each BC phase is reduced since only two data streams are transmitted simultaneously.

In the l-th group, given the index $t_{l_\mathrm{u}} \in \mathcal{I}_l$ of the transmit node whose data stream is unicasted by the RS and the index $t_{l_\mathrm{m}} \in \mathcal{I}_{l_\mathrm{M}}, \mathcal{I}_{l_\mathrm{M}} = \mathcal{I}_l \setminus \{t_{l_\mathrm{u}}\}$, of the transmit node whose data stream is multicasted, the relationship between r_l, t_l and p is defined by

$$t_l = \begin{cases} t_{l_\mathrm{u}}, & \text{if } r_l = t_{l_\mathrm{m}} \\ t_{l_\mathrm{m}}, & \text{otherwise,} \end{cases} \tag{4.11}$$

where

$$t_{l_\mathrm{m}} = \begin{cases} (p + a_l) - 1, & \text{if } \ (p + a_l) \geq t_{l_\mathrm{u}} + 2, \\ (p + a_l) - 2, & \text{if } \ (p + a_l) \leq t_{l_\mathrm{u}} + 1. \end{cases} \tag{4.12}$$

The relationships in (4.11) and (4.12) are defined after choosing the data stream to be unicasted for group l, t_{l_u}, which remains the same in all $N_l - 1$ BC phases. In the p-th phase, node $r_l = t_{l_\mathrm{m}}$, whose data stream is multicasted by the RS, receives the unicasted data stream from t_{l_u}. The other nodes $r_l, r_l \in \mathcal{I}_l \setminus \{t_{l_\mathrm{m}}\}$, receive the data stream from node t_{l_m} which is multicasted by the RS to these $N_l - 1$ nodes. The multicasted data stream is changed in every BC phase as defined in Eq. (4.12).

Using hybrid uni/multicasting strategy, the nodes need to know which data stream is unicasted and which data stream is multicasted by the RS in the p-th phase. However, given (4.11) and (4.12), and by choosing the unicasted data stream from the node with the lowest index, that is, $t_{l_\mathrm{u}} = a_l$, there is no signaling effort needed. The RS is then multicasting the data streams in the $P - 1$ BC phases starting from the lowest index in the set $\mathcal{I}_l \setminus \{t_{l_\mathrm{u}} = a_l\}$. In case of one pair two-way relaying and multi-user two-way relaying, the hybrid uni/multicasting strategy is the same as the unicasting strategy. The hybrid uni/multicasting strategy is a generalisation of the work in [17,59] for $L = 1$ and $N_1 = 2$, and in [71] for $L > 1$ and $N_l = 2, \forall l$.

4.2.2.3 Multicasting Strategy

Using multicasting strategy, the non-regenerative RS transmits only one data stream for each served group in each BC phase. The RS transmits $\hat{x}_{v_l w_l}$, that is, the noisy superposition of the data streams of nodes $\mathrm{S}v_l, v_l \in \mathcal{I}_l$, and $\mathrm{S}w_l, w_l \in \mathcal{I}_l \setminus \{v_l\}$, in the l-th group, to all N_l nodes in group l. Prior to detection, each node has to cancel the self- and known-interference from each of the received data streams using the available side information. The side information can be its own transmitted data stream or a data stream which has been decoded in one of the previous BC phases.

Given the general rule, we may have several options to define the superposed data streams. However, each option will lead to different signaling requirement, since the RS has to inform the nodes about the indices v_l and w_l in each BC phase. In this work, we are interested in an option that does not need any signalling. We always choose $v_l = a_l$, and, consequently, w_l is changed in each BC phase and is selected successively based on the relationship defined by

$$w_l = v_l + p - 1. \tag{4.13}$$

The relationship between r_l, t_l and p can be written as

$$t_l = \begin{cases} a_l, & \text{if } r_l = (p + a_l) - 1, \\ (p + a_l) - 1, & \text{otherwise.} \end{cases} \tag{4.14}$$

Using the relationship in (4.14), node $\mathrm{S}r_l = a_l$ always performs self-interference cancellation, that is, $x_{v_l w_l} - x_{v_l = a_l}$, to obtain all $N_l - 1$ data streams from other nodes $t_l = w_l, \forall w_l \in \mathcal{I}_l \setminus \{a_l\}$. Regarding the other nodes $r_l \in \mathcal{I}_l \setminus \{a_l\}$, they have to be able to decode x_{a_l} and, afterwards, use x_{a_l} to perform known-interference cancellation. Each node $r_l \in \mathcal{I}_l \setminus \{a_l\}$ has to wait until its own data stream is superposed with $x_{v_l = a_l}$, that is in the p-th phase which leads to $r_l = (p + a_l) - 1$. In this corresponding p-th phase, node $r_l = (p + a_l) - 1$ performs self-interference cancellation, that is, $x_{v_l w_l} - x_{w_l = (p + a_l) - 1}$ to obtain $x_{v_l = a_l}$. Afterwards, using $x_{v_l = a_l}$, it performs known-interference cancellation $x_{v_l w_l} - x_{v_l = a_l}$ to obtain the other data streams from other nodes $t_l = w_l, \forall w_l \in \mathcal{I}_l \setminus \{a_l, r_l\}$ received in the other BC phases. The proposed multicasting strategy is a generalisation of the work in [14, 101, 102] for $L = 1$ and $N_1 = 2$ and in [73] for $L > 1$ and $N_l = 2, \forall l$.

Note that all the relationships of parameters which are described in this subsection can be directly applied to the case when the number of nodes are not equal in all groups. If the number of nodes is not equal in all groups, in each p-th phase, the RS serves only the groups with $N_l \geq p$, that is, with latency-wise consideration, cf. Section 3.4.

4.3 Sum Rate Expression

4.3.1 Introduction

In this section, we derive the achievable sum rate expression of non-regenerative MGMW relaying. The achievable sum rate is the sum of the rates received at all nodes. We start by defining the signal to interference and noise ratio (SINR) for the BC strategies in Section 4.3.2. The achievable sum rate of MGMW relaying for both asymmetric and symmetric traffic are explained afterwards in Section 4.3.3 and in Section 4.3.4, respectively.

4.3.2 Signal to Interference and Noise Ratio

It is assumed that $x_i, \forall i$, $z_{\mathrm{RS}_m}, \forall m$, and $z_i, \forall i$, are all statistically independent. Therefore, given the received signal in (4.9), the SINR for the link between receiving node Sr_l and transmitting node St_l is given by

$$\gamma_{r_l,t_l}^{p} = \frac{S_{r_l}}{I_{r_l} + Z_{\mathrm{RS}_{r_l}} + Z_{r_l}}, \tag{4.15}$$

with the useful signal power at node Sr_l

$$S_{r_l} = \mathrm{E}\{|\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_{t_l} x_{t_l}|^2\} = |\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_{t_l}|^2 \sigma_x^2, \tag{4.16}$$

the RS's propagated noise power which appear at node Sr_l

$$Z_{\mathrm{RS}_{r_l}} = \mathrm{E}\{|\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{z}_{\mathrm{RS}}|^2\} = |\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p|^2 \sigma_{z_{\mathrm{RS}}}^2 \tag{4.17}$$

and the node Sr_l's noise power

$$Z_{r_l} = \mathrm{E}\{|z_{r_l}|^2\} = \sigma_{z_{\mathrm{node}}}^2. \tag{4.18}$$

The interference power at receiving node Sr_l, is given by

$$I_{r_l} = I_{\mathrm{sg}_{r_l}} + I_{\mathrm{og}_{r_l}}, \tag{4.19}$$

with $I_{\mathrm{sg}_{r_l}}$ the same-group-inter-stream interference power and $I_{\mathrm{og}_{r_l}}$ the other-group-inter-stream interference power. While $I_{\mathrm{sg}_{r_l}}$ depends on the applied BC strategy, $I_{\mathrm{og}_{r_l}}$ does not depend on the BC strategy and it is given by

$$I_{\mathrm{og}_{r_l}} = \sum_{d \notin \mathcal{I}_l} \mathrm{E}\{|\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_d x_d|^2\} = \sum_{d \notin \mathcal{I}_l} |\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_d|^2 \sigma_x^2. \tag{4.20}$$

At each receiving node $\mathrm{S}r_l$, $I_{\mathrm{sg}_{r_l}}$ includes the interference power caused by its own data stream and other data streams that have been decoded in the previous BC phases. These a priori known data streams can be canceled by each receiving node prior to detection by performing self- and known-interference cancellation. If self- and known-interference cancellation is performed, the remaining interference power which is not canceled by the receiving node, $I_{\mathrm{not-canc}_{r_l}}$, is given by

$$I_{\mathrm{not-canc}_{r_l}} = I_{\mathrm{sg}_{r_l}} - I_{\mathrm{canc}_{r_l}} \tag{4.21}$$

with $I_{\mathrm{canc}_{r_l}}$ the interference power caused by the data streams which are a priori known by the receiving node $\mathrm{S}r_l$ and is canceled. With interference cancellation, the interference power in (4.19) can be rewritten as

$$I_{r_l} = I_{\mathrm{not-canc}_{r_l}} + I_{\mathrm{og}_{r_l}}. \tag{4.22}$$

In the following, we explain the same-group-inter-stream interference power of each BC strategy.

Same-group-inter-stream interference power of unicasting strategy

The same-group-inter-stream interference power is given by

$$I_{\mathrm{sg}_{r_l}}^{\mathrm{u}} = \sum_{\substack{j=a_l \\ j \neq t_l}}^{b_l} \mathrm{E}\{|\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_j x_j|^2\} = \sum_{\substack{j=a_l \\ j \neq t_l}}^{b_l} |\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_j|^2 \sigma_x^2. \tag{4.23}$$

In every p-th phase, node $\mathrm{S}r_l$ may perform interference cancellation. It subtracts the a priori known self-interference as well as the a priori known same-group other-stream interference from the previous BC phases. Once the nodes have decoded the other nodes' data streams in the previous BC phases, they may use them to perform known-interference cancellation in a similar fashion to self-interference cancellation. Using interference cancellation, $I_{\mathrm{not-canc}_{r_l}}$ for unicasting strategy is given by

$$I_{\mathrm{not-canc}_{r_l}}^{\mathrm{u}} = \sum_{\substack{j=a_l \\ j \neq \{r_l, t_l\} \\ j \notin \mathcal{B}_{r_l}}}^{b_l} |\mathbf{h}_{r_l}^{\mathrm{T}} \mathbf{G}^p \mathbf{h}_j|^2 \sigma_x^2 \tag{4.24}$$

with $\mathcal{B}_{r_l}$ the set of the nodes' indices whose data streams have been decoded by receiving node r_l in the previous BC phases.

Same-group-inter-stream interference power of hybrid uni/multicasting strategy

The same-group-inter-stream interference power can be decoupled into two parts. The first part is the interference caused by the unicasted or the multicasted data stream, denoted by $I_{\mathrm{u/m}_{r_l}}$. The second part is the interference caused by other data streams which can only appear at the receiving node r_l if the transceive beamforming applied at the RS cannot fully suppress it. The same group interference power is given by

$$I^{\mathrm{u/m}}_{\mathrm{sg}_{r_l}} = I_{\mathrm{u/m}_{r_l}} + \sum_{\substack{j=a_l \\ j\neq\{t_{l_\mathrm{u}},t_{l_\mathrm{m}}\}}}^{b_l} |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_j|^2\sigma_x^2, \tag{4.25}$$

with t_{l_u} the index of the transmitting node whose data stream is unicasted by the RS, t_{l_m} the index of the transmitting node whose data stream is multicasted by the RS, and

$$I_{\mathrm{u/m}_{r_l}} = \begin{cases} \mathrm{E}\{|\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_{r_l}x_{r_l}|^2\} = |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_{r_l}|^2\sigma_x^2, \text{if } r_l = t_{l_\mathrm{m}}, \\ \mathrm{E}\{|\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_{t_{l_\mathrm{u}}}x_{t_{l_\mathrm{u}}}|^2\} = |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_{t_{l_\mathrm{u}}}|^2\sigma_x^2, \text{otherwise}, \end{cases} \tag{4.26}$$

the interference at the nodes which only can be either from the unicasted data stream (at $N_l - 1$ nodes which are intended to receive the multicasted data stream) or from the multicasted data stream (at the node which receives the unicasted data stream). Similar to the unicasting strategy, interference cancellation at the nodes can also be applied. For hybrid uni/multicasting transmission, $I_{\mathrm{not-canc}_{r_l}}$ is defined by

$$I^{\mathrm{u/m}}_{\mathrm{not-canc}_{r_l}} = I_{\mathrm{u}_l} + \sum_{\substack{j=a_l \\ j\neq\{r_l,t_{l_\mathrm{m}}\} \\ j\notin\mathcal{B}_l}}^{b_l} |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_j|^2\sigma_x^2, \tag{4.27}$$

with $\mathcal{B}_l$ the sets of nodes' indices whose data streams have been multicasted by the RS in the previous BC phases and

$$I_{\mathrm{u}_l} = \begin{cases} |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^{p}\mathbf{h}_{t_{l_\mathrm{u}}}|^2\sigma_x^2, & \text{if } r_l \neq t_{l_\mathrm{u}} \text{ and } r_l \notin \mathcal{B}_l \\ 0, & \text{otherwise.} \end{cases} \tag{4.28}$$

Same-group-inter-stream interference power of multicasting strategy

The same-group-inter-stream interference power can be decoupled into two parts. The first part is the inherent interference within the superposed data stream which can only be either self- or known-interference, denoted by $I_{\mathrm{s|k}}$. The second part is the interference caused by other data streams which can only appear at the receiving node

r_l if the transceive beamforming applied at the RS cannot fully suppress it. The same-group-inter-stream interference power is given by

$$I^{\mathrm{m}}_{\mathrm{sg}_{r_l}} = I_{\mathrm{s|k}_{r_l}} + \sum_{\substack{j=a_l \\ j\neq\{v_l,w_l\}}}^{b_l} |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_j|^2\sigma_x^2, \tag{4.29}$$

with $\{v_l, w_l\}$ the indices of the two nodes in group l whose data streams are superposed by the RS in the p-th phase. $I_{\mathrm{s|k}_{r_l}}$ is the self- or known-interference power, which can only be either self-interference power at nodes $r_l = w_l$ and $r_l = v_l$ given by

$$I_{\mathrm{s|k}_{r_l}} = I_{\mathrm{s}_{r_l}} = \mathrm{E}\{|\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_{r_l}x_{r_l}|^2\} = |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_{r_l}|^2\sigma_x^2, \tag{4.30}$$

or known-interference power at nodes $r_l \neq w_l \neq v_l$ given by

$$I_{\mathrm{s|k}_{r_l}} = I_{\mathrm{k}_{r_l}} = \mathrm{E}\{|\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_{\tilde{vw}_l}x_{\tilde{vw}_l}|^2\} = |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_{\tilde{vw}_l}|^2\sigma_x^2, \tag{4.31}$$

with $\tilde{vw}_l$ the index of the known-interference which can only be either w_l or v_l. As explained in Section 4.2.2.3, $I_{\mathrm{s|k}_{r_l}}$ can be cancelled and, thus, $I_{\mathrm{s|k}_{r_l}} = 0$. Moreover, once the nodes have decoded other nodes' data streams from the previous BC phases, they may use them to reduce the amount of interference in the second summand in (4.29). For the multicasting strategy, $I_{\mathrm{not-canc}_{r_l}}$ is defined by

$$I^{\mathrm{m}}_{\mathrm{not-canc}_{r_l}} = \sum_{\substack{j=a_l \\ j\neq\{v_l,w_l\} \\ j\notin\mathcal{B}_{r_l}}}^{b_l} |\mathbf{h}^{\mathrm{T}}_{r_l}\mathbf{G}^p\mathbf{h}_j|^2\sigma_x^2 \tag{4.32}$$

with $\mathcal{B}_{r_l}$ the set of the nodes' indices whose data streams have been decoded by receiving node r_l in the previous BC phases.

4.3.3 Sum Rate for Asymmetric Traffic

Asymmetric traffic refers to the situation where we allow all nodes in the group to transmit with different rates. Each node transmits with a rate that ensures that in the following $N_l - 1$ consecutive BC phases, all $N_l - 1$ nodes in its group can decode its data stream correctly. Given the SINR as introduced in the previous subsection, the information rate at receiving node r_l when it receives from transmitting node t_l in the p-th phase is given by

$$R_{r_l,t_l} = \log_2(1 + \gamma^p_{r_l,t_l}). \tag{4.33}$$

Since in MGMW relaying there is only one MAC phase, the transmitting node t_l has to ensure that its data stream can be decoded correctly by all $N_l - 1$ intended receiving nodes. Consequently, we have

$$R_{t_l} = \min_{r_l \in \mathcal{I}_l \setminus \{t_l\}} \left(R_{r_l, t_l} \right), \tag{4.34}$$

which is the minimum rate among all receiving nodes r_l in group l when they receive the data stream from a certain transmitting node t_l. The achievable sum rate for asymmetric traffic of non-regenerative MGMW relaying is given by

$$SR_{\text{asym}} = \frac{1}{P} \sum_{l=1}^{L} \left((N_l - 1) \sum_{t_l \in \mathcal{I}_l} R_{t_l} \right). \tag{4.35}$$

The factor $N_l - 1$ is since in group l there are $N_l - 1$ nodes that receive the same data stream from a certain transmitting node t_l. The scaling factor $\frac{1}{P}$ is due to P channel uses for MGMW relaying.

One important note regarding (4.34) is that by taking the minimum, we ensure that each node Si transmits x_i with the rate that can be decoded correctly by all other nodes in its group. Thus, knowing x_i, all other nodes in the group can use it to perform known-interference cancellation in a similar fashion to their self-interference cancellation.

4.3.4 Sum Rate for Symmetric Traffic

In certain scenarios, there may be a requirement to have a symmetric traffic between all nodes in group l. Symmetric traffic is when all nodes in group l have to transmit simultaneously with the same rate that is defined by the lowest rate among all possible link combinations of receive and transmit node (r_l, t_l) in group l. The achievable sum rate for symmetric traffic for all BC strategies is given by

$$SR_{\text{symm}} = \frac{1}{P} \sum_{l=1}^{L} (N_l - 1) N_l \left(\min_{t_l \in \mathcal{I}_l} R_{t_l} \right). \tag{4.36}$$

4.4 Transceive Beamforming

4.4.1 Introduction

In this section, we explain the design of the generalised transceive beamforming for non-regenerative MGMW relaying. It is assumed that perfect channel state information is available at the RS. Moreover, since we consider low complexity transceive beamforming, the number of antennas at the RS has to be higher than or equal to the total number of the nodes, that is, $M \geq N$. We provide reasoning for transceive beamforming in Section 4.4.2. We address the optimum transceive beamforming maximising the sum rate of non-regenerative MGMW relaying in Section 4.4.3. The design of linear low complexity transceive beamforming is explained in Section 4.4.4. We introduce BCSA transceive beamforming in Section 4.4.5.

4.4.2 Reasoning for Transceive Beamforming

In this thesis, we address transceive beamforming maximising the sum rate of non-regenerative MGMW relaying. The aim is to provide a sum rate performance bound for non-regenerative MGMW relaying. However, finding the optimum transceive beamforming requires high computational complexity. Therefore, we design generalised low complexity linear transceive beamforming for non-regenerative MGMW relaying with three different optimisation criteria, namely, MF, ZF and MMSE. Also, we design BCSA transceive beamforming for non-regenerative MGMW relaying.

MF is aiming at maximising the signal to noise ratio. It is suitable when there is no or low interference. ZF is aiming at suppressing interference and, thus, is suitable for interference-limited networks. Despite of its ability to suppress interference, ZF leads to a noise enhancement. MMSE is designed to find a trade-off between the interference suppression and the noise enhancement. BCSA transceive beamforming is designed based on BD [100] or regularised BD [103]. The idea is to make the data stream separation both in receive and transmit beamforming according to the chosen BC strategy by exploiting the null-space of the unintended node or nodes.

4.4.3 Sum Rate Maximisation

In order to maximise the sum rate of non-regenerative MGMW relaying, we have to consider asymmetric traffic, since asymmetric traffic leads to a higher sum rate compared to symmetric traffic. The optimisation problem of finding the optimum transceive beamforming maximising the sum rate of non-regenerative MGMW relaying with asymmetric traffic can be written as

$$\begin{aligned} \max_{\mathbf{G}^p} \ & \sum_{i} \sum_{f(i,p)} R_{f(i,p),i} \\ \text{s.t. } & \operatorname{tr}\{\mathbf{G}^p(\mathbf{H}\mathbf{R}_{\mathbf{x}}\mathbf{H}^{\mathrm{H}} + \mathbf{R}_{\mathbf{z}_{\mathrm{RS}}})\mathbf{G}^{p\mathrm{H}}\} = E_{\mathrm{RS}}, \end{aligned} \tag{4.37}$$

with $f(i,p)$ the receiving node index, which is a function of transmitting index i and BC phase index p, and depends on the applied BC strategy, E_{RS} the RS transmit power constraint,

$$\mathbf{R}_{\mathbf{x}} = \mathrm{E}\{\|\mathbf{x}\mathbf{x}^{\mathrm{H}}\|_2^2\} \tag{4.38}$$

and

$$\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}} = \mathrm{E}\{\|\mathbf{z}_{\mathrm{RS}}\mathbf{z}_{\mathrm{RS}}^{\mathrm{H}}\|_2^2\}. \tag{4.39}$$

In this work, we assume that the transmit powers at the nodes are fixed and equal. In order to improve the sum rate, one could have the transmit powers at the nodes as variables to be optimised subject to a power constraint at each node. However, since there is only one MAC phase, one has to find the optimum transmit power at each node and, simulateneously, the transceive beamforming for all BC phases, i.e., $\mathbf{G}^p, \forall p, p \in \mathcal{P}$. This joint optimisation problem would further increase the computational effort.

The optimisation problem in (4.37) is non-convex and it requires high computational complexity to find the global optimum solution which is too complex for practical applications. In this work, we solve (4.37) using fmincon from MATLAB. However, due to the non-convexity of (4.37), we can only obtain local optimum which depends on the initial value. In the following, we propose generalised low complexity transceive beamforming algorithms for all proposed BC strategies.

4.4.4 Linear Transceive Beamforming

4.4.4.1 Introduction

As mentioned in Section 4.2.1 and as seen in (4.37), the transceive beamforming $\mathbf{G}^p$ depends on the BC strategy applied at the RS. In the following, we explain the design of generalised transceive beamforming for MGMW relaying with three different optimisation criteria, namely, MF, ZF and MMSE. In order to design generalised transceive beamforming for all BC strategies and to make the problem more tractable, we decouple $\mathbf{G}^p$ into transmit beamforming $\mathbf{G}_{\mathrm{T}}^p$, BC-strategy-defining permutation matrix $\mathbf{\Pi}^p$ and receive beamforming $\mathbf{G}_{\mathrm{R}}^p$, such that

$$\mathbf{G}^p = \mathbf{G}_{\mathrm{T}}^p \mathbf{\Pi}^p \mathbf{G}_{\mathrm{R}}^p. \tag{4.40}$$

Since we have only one MAC phase, the receive beamforming is computed only once, that is, $\mathbf{G}_{\mathrm{R}}^p = \mathbf{G}_{\mathrm{R}}, \forall p \in \mathcal{P}$. The BC-strategy-defining permutation matrix $\mathbf{\Pi}^p$ defines

Table 4.1. BC-strategy-defining permutation matrices for example in Figure 3.3 with $L = 2, N_1 = N_2 = 3$

	$\mathbf{\Pi}^2$	$\mathbf{\Pi}^3$
Unicasting	$\begin{pmatrix} 0&1&0&0&0&0\\ 0&0&1&0&0&0\\ 1&0&0&0&0&0\\ 0&0&0&0&1&0\\ 0&0&0&0&0&1\\ 0&0&0&1&0&0 \end{pmatrix}$	$\begin{pmatrix} 0&0&1&0&0&0\\ 1&0&0&0&0&0\\ 0&1&0&0&0&0\\ 0&0&0&0&0&1\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0 \end{pmatrix}$
Uni/Multicasting	$\begin{pmatrix} 0&1&0&0&0&0\\ 1&0&0&0&0&0\\ 0&1&0&0&0&0\\ 0&0&0&0&1&0\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0 \end{pmatrix}$	$\begin{pmatrix} 0&0&1&0&0&0\\ 0&0&1&0&0&0\\ 1&0&0&0&0&0\\ 0&0&0&0&0&1\\ 0&0&0&0&0&1\\ 0&0&0&1&0&0 \end{pmatrix}$
Multicasting	$\begin{pmatrix} 1&1&0&0&0&0\\ 1&1&0&0&0&0\\ 1&1&0&0&0&0\\ 0&0&0&1&1&0\\ 0&0&0&1&1&0\\ 0&0&0&1&1&0 \end{pmatrix}$	$\begin{pmatrix} 1&0&1&0&0&0\\ 1&0&1&0&0&0\\ 1&0&1&0&0&0\\ 0&0&0&1&0&1\\ 0&0&0&1&0&1\\ 0&0&0&1&0&1 \end{pmatrix}$

the transmission from the RS according to the BC strategies. Table 4.1 shows $\mathbf{\Pi}^p$ for the example in Figure 3.3 for MF, ZF and MMSE for all BC strategies. One important note is that, even though the derivation for the MF, ZF and MMSE generalised transceive beamforming appears to be similar with the three-step transceive beamforming for two-way relaying in [58], however, our generalised transceive beamforming algorithms have a different approach and are based on different motivation. In [58], the downlink (from the RS to the nodes) channel matrix is a permuted matrix of the uplink (from the nodes to the RS) channel matrix. Therefore, $\mathbf{\Pi}^p$ in [58] is a diagonal matrix with weighting factors in each of its diagonal elements. Such approach as in [58] is only suitable for unicasting strategy. Hence, our generalised transceive beamforming is a generalisation of the three-step transceive beamforming for two-way relaying in [58].

4.4.4.2 Matched Filter

Given the received signal at the RS as in (4.6), the output of the receive filtering is given by

$$\hat{\mathbf{x}}_{\mathrm{RS}} = \mathbf{G}_{\mathrm{R}}\mathbf{y}_{\mathrm{RS}} = \mathbf{G}_{\mathrm{R}}(\mathbf{H}\mathbf{x} + \mathbf{z}_{\mathrm{RS}}). \tag{4.41}$$

In [104], an MF optimisation problem is formulated using a different expression of signal to noise ratio (SNR) compared to the well known SNR of the standard MF optimisation. The equivalence of both SNR formulations is proven in Appendix A6 of [104]. In this work, we use the formulation of SNR as in [104]. The MF optimisation problem for receive beamforming can be written as

$$\mathbf{G}_{\mathrm{R_{MF}}} = \underset{\mathbf{G}_{\mathrm{R}}}{\mathrm{argmax}} \frac{|\mathrm{E}\{\mathbf{x}^{\mathrm{H}}\hat{\mathbf{x}}_{\mathrm{RS}}\}|^2}{\mathrm{E}\{\|\mathbf{x}\|_2^2\}\ \mathrm{E}\{\|\mathbf{G}_{\mathrm{R}}\mathbf{z}_{\mathrm{RS}}\|_2^2\}}. \tag{4.42}$$

The objective function in (4.42) can be written as

$$\frac{|\mathrm{E}\{\mathbf{x}^{\mathrm{H}}\hat{\mathbf{x}}_{\mathrm{RS}}\}|^2}{\mathrm{E}\{\|\mathbf{x}\|_2^2\}\ \mathrm{E}\{\|\mathbf{G}_{\mathrm{R}}\mathbf{z}_{\mathrm{RS}}\|_2^2\}} = \frac{|\mathrm{tr}\,(\mathbf{G}_{\mathrm{R}}\mathbf{H}\mathbf{R}_{\mathbf{x}})|^2}{\mathrm{tr}\,(\mathbf{R}_{\mathbf{x}})\,\mathrm{tr}\,(\mathbf{G}_{\mathrm{R}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}\mathbf{G}_{\mathrm{R}}^{\mathrm{H}})}. \tag{4.43}$$

By taking the derivative of (4.43) with respect to $\mathbf{G}_{\mathrm{R}}$ and setting it equal to zero, we have [see, e.g, [104, 105]]

$$\mathbf{G}_{\mathrm{R_{MF}}} = \mathbf{R}_{\mathbf{x}}\mathbf{H}^{\mathrm{H}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}^{-1}. \tag{4.44}$$

The received signal at the nodes in (4.7) can now be rewritten as

$$\mathbf{y}_{\mathrm{nodes}}^{p} = \mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p}\mathbf{\Pi}^{p}\hat{\mathbf{x}}_{\mathrm{RS}} + \mathbf{z}_{\mathrm{nodes}}^{p} = \mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p}\tilde{\mathbf{x}}_{\mathrm{RS}}^{p} + \mathbf{z}_{\mathrm{nodes}}^{p}, \tag{4.45}$$

with

$$\tilde{\mathbf{x}}_{\mathrm{RS}}^{p} = \mathbf{\Pi}^{p}\hat{\mathbf{x}}_{\mathrm{RS}} \tag{4.46}$$

the transmitted signals from the RS in the p-th phase. The MF optimisation problem for transmit beamforming can be written as

$$\begin{gathered}\{\mathbf{G}_{\mathrm{T_{MF}}}^{p}\} = \underset{\mathbf{G}_{\mathrm{T}}^{p}}{\mathrm{argmax}} \frac{|\mathrm{E}\{\tilde{\mathbf{x}}_{\mathrm{RS}}^{p\mathrm{H}}\mathbf{y}_{\mathrm{nodes}}^{p}\}|^2}{\mathrm{E}\{\|\tilde{\mathbf{x}}_{\mathrm{RS}}^{p}\|_2^2\}\ \mathrm{E}\{\|\mathbf{z}_{\mathrm{nodes}}^{p}\|_2^2\}} \\ \text{s.t. } \mathrm{tr}\{\|\mathbf{G}_{\mathrm{T}}^{p}\tilde{\mathbf{x}}_{\mathrm{RS}}^{p}\|^2\} = E_{\mathrm{RS}}.\end{gathered} \tag{4.47}$$

With

$$\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p} = \mathrm{E}\{\|\tilde{\mathbf{x}}_{\mathrm{RS}}^{p}\tilde{\mathbf{x}}_{\mathrm{RS}}^{p\mathrm{H}}\|_2^2\} \tag{4.48}$$

and

$$\mathbf{R}_{\mathbf{z}_{\mathrm{nodes}}}^{p} = \mathrm{E}\{\|\mathbf{z}_{\mathrm{nodes}}^{p}\mathbf{z}_{\mathrm{nodes}}^{p\mathrm{H}}\|_2^2\}, \tag{4.49}$$

the Lagrangian function can be written as

$$L(\mathbf{G}_{\mathrm{T}}^{p}, \lambda^{p}) = \frac{|\mathrm{tr}\left(\mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\right)|^2}{\mathrm{tr}\left(\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\right)\mathrm{tr}\left(\mathbf{R}_{\mathbf{z}_{\mathrm{nodes}}}^{p}\right)} + \lambda^{p}(\mathrm{tr}(\mathbf{G}_{\mathrm{T}}^{p}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\mathbf{G}_{\mathrm{T}}^{p\mathrm{H}}) - E_{\mathrm{RS}}), \tag{4.50}$$

with $\lambda^{p} \in \mathbb{R}_{+}$ the Lagrange multiplier. Using the same steps as in [104] by deriving and solving the Karush-Kuhn-Tucker (KKT) conditions, we have

$$\mathbf{G}_{\mathrm{T_{MF}}}^{p} = \beta_{\mathrm{MF}}^{p}\mathbf{H}^{*}, \tag{4.51}$$

where $\beta_{\mathrm{MF}}^{p} \in \mathbb{R}_{+}$ is needed to fulfill the power constraint and is given by

$$\beta_{\mathrm{MF}}^{p} = \sqrt{\frac{E_{\mathrm{RS}}}{\mathrm{tr}\left(\mathbf{H}^{*}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\mathbf{H}^{\mathrm{T}}\right)}}. \tag{4.52}$$

4.4.4.3 Zero Forcing

Given (4.41), the MMSE optimisation problem with ZF constraint for receive beamforming can be written as

$$\begin{aligned} \mathbf{G}_{\mathrm{R_{ZF}}} &= \underset{\mathbf{G}_{\mathrm{R}}}{\mathrm{argmin}}\ \mathrm{E}\{\|\mathbf{x} - \hat{\mathbf{x}}_{\mathrm{RS}}\|_2^2\} \\ &\text{s.t. } \hat{\mathbf{x}}_{\mathrm{RS}} = \mathbf{x}|_{\mathbf{z}_{\mathrm{RS}}=0}. \end{aligned} \tag{4.53}$$

where $\hat{\mathbf{x}}_{\mathrm{RS}} = \mathbf{x}|_{\mathbf{z}_{\mathrm{RS}}=0}$ is the ZF constraint which implies that

$$\mathbf{G}_{\mathrm{R}}\mathbf{H} = \mathbf{I}_{M}. \tag{4.54}$$

Due to the ZF constraint, the objective function in (4.53) can be written as

$$\mathrm{E}\{\|\mathbf{x} - \hat{\mathbf{x}}_{\mathrm{RS}}\|_2^2\} = \mathrm{tr}\left(\mathbf{G}_{\mathrm{R}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}\mathbf{G}_{\mathrm{R}}^{\mathrm{H}}\right). \tag{4.55}$$

The Lagrangian function can be written as

$$L(\mathbf{G}_{\mathrm{R}}, \mathbf{\Lambda}^{p}) = \mathrm{tr}\left(\mathbf{G}_{\mathrm{R}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}\mathbf{G}_{\mathrm{R}}^{\mathrm{H}}\right) - 2\mathbb{R}\left(\mathrm{tr}(\mathbf{\Lambda}^{p}(\mathbf{G}_{\mathrm{R}}\mathbf{H} - \mathbf{I}_{M}))\right), \tag{4.56}$$

with $\mathbf{\Lambda}^{p} \in \mathbb{C}^{M\times M}$ the Lagrange multiplier.

Using the same steps as in [104] by deriving and solving the KKT conditions, we have [see, e.g., [105]]

$$\mathbf{G}_{\mathrm{R_{ZF}}} = \left(\mathbf{H}^{\mathrm{H}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}^{-1}\mathbf{H}\right)^{-1}\mathbf{H}^{\mathrm{H}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}^{-1}. \tag{4.57}$$

Given (4.45), the MMSE optimisation problem with ZF constraint for transmit beamforming can be written as

$$\begin{aligned} \{\mathbf{G}_{\mathrm{T_{ZF}}}^{p}\} &= \underset{\mathbf{G}_{\mathrm{T}}^{p}}{\mathrm{argmin}}\ \mathrm{E}\{\|\tilde{\mathbf{x}}_{\mathrm{RS}}^{p} - \mathbf{y}_{\mathrm{nodes}}^{p}\|_2^2\} \\ &\text{s.t. } \mathrm{tr}\{\|\mathbf{G}_{\mathrm{T}}^{p}\tilde{\mathbf{x}}_{\mathrm{RS}}^{p}\|^2\} = E_{\mathrm{RS}}, \\ &\mathbf{y}_{\mathrm{nodes}}^{p} = \tilde{\mathbf{x}}_{\mathrm{RS}}|_{\mathbf{z}_{\mathrm{nodes}}=0}. \end{aligned} \tag{4.58}$$

where $\mathbf{y}_{\mathrm{nodes}}^{p} = \tilde{\mathbf{x}}_{\mathrm{RS}}|_{\mathbf{z}_{\mathrm{nodes}}=0}$ is the ZF constraint which implies that $\mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p} = \mathbf{I}_{N}$. Due to the ZF constraint, the objective function in (4.58) can be written as

$$\mathrm{E}\{\|\tilde{\mathbf{x}}_{\mathrm{RS}}^{p} - \mathbf{y}_{\mathrm{nodes}}^{p}\|_2^2\} = \mathrm{tr}\left(\mathbf{R}_{\mathbf{z}_{\mathrm{nodes}}}^{p}\right). \tag{4.59}$$

The Lagrangian function can be written as

$$L(\mathbf{G}_{\mathrm{T}}^{p}, \mathbf{\Lambda}^{p}, \mu^{p}) = \mathrm{tr}\left(\mathbf{R}_{\mathbf{z}_{\mathrm{nodes}}}^{p}\right) - 2\mathbb{R}\left(\mathrm{tr}\left(\mathbf{\Lambda}^{p}\left(\mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p} - \mathbf{I}_{M}\right)\right)\right) + \mu^{p}(\mathrm{tr}(\mathbf{G}_{\mathrm{T}}^{p}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\mathbf{G}_{\mathrm{T}}^{p\mathrm{H}}) - E_{\mathrm{RS}}), \tag{4.60}$$

with $\mu^{p} \in \mathbb{R}_{+}$ the Lagrange multiplier. Using the same steps as in [104] by deriving and solving the KKT conditions, we have

$$\mathbf{G}_{\mathrm{T}_{\mathrm{ZF}}}^{p} = \beta_{\mathrm{ZF}}^{p}\mathbf{H}^{*}\left(\mathbf{H}^{\mathrm{T}}\mathbf{H}^{*}\right)^{-1}, \tag{4.61}$$

where $\beta_{\mathrm{ZF}}^{p} \in \mathbb{R}_{+}$ is needed to fulfill the power constraint and is given by

$$\beta_{\mathrm{ZF}}^{p} = \sqrt{\frac{E_{\mathrm{RS}}}{\mathrm{tr}\left(\left(\mathbf{H}^{*}\mathbf{H}^{\mathrm{T}}\right)^{-1}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\right)}}. \tag{4.62}$$

4.4.4.4 Minimisation of Mean Square Error

Given (4.41), the MMSE optimisation problem for receive beamforming can be written as

$$\mathbf{G}_{\mathrm{R}_{\mathrm{MMSE}}} = \underset{\mathbf{G}_{\mathrm{R}}}{\mathrm{argmin}}\ \mathrm{E}\{\|\mathbf{x} - \hat{\mathbf{x}}_{\mathrm{RS}}\|_{2}^{2}\}. \tag{4.63}$$

The objective function in (4.63) can be written as

$$\mathrm{E}\{\|\mathbf{x} - \hat{\mathbf{x}}_{\mathrm{RS}}\|_{2}^{2}\} = \mathrm{tr}\left(\mathbf{R}_{\mathbf{x}} - 2\mathbb{R}(\mathbf{G}_{\mathrm{R}}\mathbf{H}\mathbf{R}_{\mathbf{x}}) + \mathbf{G}_{\mathrm{R}}\mathbf{H}\mathbf{R}_{\mathbf{x}}\mathbf{H}^{\mathrm{H}}\mathbf{G}_{\mathrm{R}}^{\mathrm{H}} + \mathbf{G}_{\mathrm{R}}\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}\mathbf{G}_{\mathrm{R}}^{\mathrm{H}}\right). \tag{4.64}$$

By taking the derivative of (4.64) with respect to $\mathbf{G}_{\mathrm{R}}$ and setting it equal to zero, we have [see, e.g., [104, 105]]

$$\mathbf{G}_{\mathrm{R}_{\mathrm{MMSE}}} = \mathbf{R}_{\mathbf{x}}\mathbf{H}^{\mathrm{H}}\left(\mathbf{H}\mathbf{R}_{\mathbf{x}}\mathbf{H}^{\mathrm{H}} + \mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}\right)^{-1}. \tag{4.65}$$

Given (4.45), the MMSE optimisation problem for transmit beamforming can be written as

$$\begin{aligned}\{\mathbf{G}_{\mathrm{T}_{\mathrm{MMSE}}}^{p}, \beta_{\mathrm{MMSE}}^{p}\} &= \underset{\mathbf{G}_{\mathrm{T}}^{p}, \beta^{p}}{\mathrm{argmin}}\mathrm{E}\{\|\tilde{\mathbf{x}}_{\mathrm{RS}}^{p} - \frac{1}{\beta^{p}}\mathbf{y}_{\mathrm{nodes}}^{p}\|_{2}^{2}\} \\ &\mathrm{s.t.}\ \mathrm{tr}\{\|\mathbf{G}_{\mathrm{T}}^{p}\tilde{\mathbf{x}}_{\mathrm{RS}}^{p}\|^{2}\} = E_{\mathrm{RS}}.\end{aligned} \tag{4.66}$$

where $1/\beta^{p}$ is introduced to modify the mean square error as in [106, 107]. The Lagrangian function can be written as

$$\begin{aligned}L(\mathbf{G}_{\mathrm{T}}^{p}, \beta^{p}, \lambda^{p}) = \mathrm{tr}(\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p} - 2\frac{1}{\beta^{p}}\mathbb{R}\left(\mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\right) + \left(\frac{1}{\beta^{p}}\right)^{2}(\mathbf{H}^{\mathrm{T}}\mathbf{G}_{\mathrm{T}}^{p}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\mathbf{G}_{\mathrm{T}}^{p^{\mathrm{H}}}\mathbf{H}^{*} + \mathbf{R}_{\mathbf{z}_{\mathrm{nodes}}}^{p})) \\ +\lambda^{p}(\mathrm{tr}(\mathbf{G}_{\mathrm{T}}^{p}\mathbf{R}_{\tilde{\mathbf{x}}_{\mathrm{RS}}}^{p}\mathbf{G}_{\mathrm{T}}^{p^{\mathrm{H}}}) - E_{\mathrm{RS}})\end{aligned} \tag{4.67}$$

Using the same steps as in [107] by deriving and solving the KKT conditions, we have

$$\mathbf{G}^p_{\mathrm{T}_{\mathrm{MMSE}}} = \beta^p_{\mathrm{MMSE}} \left(\mathbf{H}^* \mathbf{H}^{\mathrm{T}} + \frac{\mathrm{tr}\left(\mathbf{R}^p_{\mathbf{z}_{\mathrm{nodes}}}\right)}{E_{\mathrm{RS}}} \mathbf{I}_M \right)^{-1} \mathbf{H}^*, \tag{4.68}$$

where $\beta^p_{\mathrm{MMSE}} \in \mathbb{R}_+$ is needed to fulfill the power constraint and is given by

$$\beta^p_{\mathrm{MMSE}} = \sqrt{\frac{E_{\mathrm{RS}}}{\mathrm{tr}\left(\left(\mathbf{H}^* \mathbf{H}^{\mathrm{T}} + \frac{\mathrm{tr}\left(\mathbf{R}^p_{\mathbf{z}_{\mathrm{nodes}}}\right)}{E_{\mathrm{RS}}} \mathbf{I}_M \right)^{-2} \mathbf{H}^* \mathbf{R}^p_{\tilde{\mathbf{x}}_{\mathrm{RS}}} \mathbf{H}^{\mathrm{T}} \right)}}. \tag{4.69}$$

The p-th Phase Linear Transceive Beamforming

Finally, for MF, ZF and MMSE the transceive beamforming is given by

$$\mathbf{G}^p = \mathbf{G}^p_{\mathrm{T}_{\mathrm{algorithm}}} \mathbf{\Pi}^p \mathbf{G}^p_{\mathrm{R}_{\mathrm{algorithm}}}, \tag{4.70}$$

where the subscript $(\cdot)_{\mathrm{algorithm}}$ refers to either MF, ZF or MMSE.

4.4.5 Broadcast-Strategy-Aware Transceive Beamforming

4.4.5.1 Introduction

In the following, we explain the design of BCSA transceive beamforming. Based on the chosen BC strategy, the RS separates the data streams which are going to be transmitted in the BC phase and transmits to the correponding node or nodes. For unicasting strategy, the RS separates all data streams and transmits each data stream to each corresponding receiving node. For hybrid uni/multicasting, for each group, the RS separates the unicasted data stream from the other data streams and transmits it to the corresponding node whose data stream is multicasted. The RS also separates the multicasted data stream from the other data streams and transmits it to the remaining nodes in the corresponding group. For multicasting strategy, the RS separates the superposition of two data streams from the others and transmits the superposed data stream to all nodes in the group.

In order to compute the transceive beamforming, we first compute the equivalent channels for receive beamforming and transmit beamforming. The equivalent channels are needed to ensure that the inter-stream interference received at receiving node or nodes is supressed or minimised. In order to compute the equivalent channel, BD as proposed in [100] can be applied. Several works have considered BD for separation of data streams, for example, [73, 108, 109]. In this work, we consider also regularised BD (RBD) as proposed in [103]. RBD avoids the drawbacks of BD which has a quite poor performance if the subspaces of the users channel matrices overlap significantly [103].

After having the equivalent channel, we compute the precoding for the equivalent channel. Since the equivalent channel is free of interference (if it is obtained using BD) or has low interference but more robust to noise enhancement (if it is obtained using RBD), we consider precoding techniques which have good performance in environments with low interference or without interference, namely, MF, SVD and Semidefinite Relaxation (SDR) of maximising minimum SNR.

In the following, we first explain the steps to obtain the equivalent channel using BD or RBD in Section 4.4.5.2. Afterwards, the explanation of the precoding techniques for the equivalent channel is given in Section 4.4.5.3.

4.4.5.2 Equivalent Channel

Without loss of generality, in the following we omit the BC phase index p. Let $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} \in \mathbb{C}^{\eta_{\mathrm{i_n}} \times M}$ and $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} \in \mathbb{C}^{(N-\eta_{\mathrm{i_n}}) \times M}$ denote the channel matrix of the intended nodes and the channel matrix of the other unintended nodes, respectively, with $\eta_{\mathrm{i_n}}$ the number of intended nodes. Both channel matrices are parts of the overall channel matrix, that is, $\mathbf{H}^{\mathrm{T}} = \mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} \bigcup \tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$. Since the steps of computing the equivalent channel for receive beamforming and transmit beamforming are similar, we generally explain the methods for finding the equivalent channel using $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}$ and $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$. In order to relate them with the receive beamforming and transmit beamforming for the BC strategies, we have to set $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}$ and $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$ accordingly. Table 4.2 shows the corresponding $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}$ and $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$ for all BC strategies. Given the singular value decomposition (SVD) of the unintended nodes' channels as

$$\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \tilde{\mathbf{U}}_{\mathrm{u_n}} \tilde{\boldsymbol{\Sigma}}_{\mathrm{u_n}} \underbrace{[\tilde{\mathbf{V}}_{\mathrm{u_n}}^{(1)}, \tilde{\mathbf{V}}_{\mathrm{u_n}}^{(0)}]}_{\tilde{\mathbf{V}}_{\mathrm{u_n}}}, \tag{4.71}$$

we compute the equivalent channel for the intended nodes $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}}$. The equivalent channel is given by

$$\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}} = \mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} \mathbf{F}_{\mathrm{null}}, \tag{4.72}$$

where $\mathbf{F}_{\mathrm{null}}$ is the null-space matrix which can be computed either using BD or RBD.

Table 4.2. Corresponding $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}$ and $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$ for all BC strategies

	Receive Beamforming	Transmit Beamforming
UC	$\forall\ t_l$: $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{t_l}^{\mathrm{T}} \in \mathbb{C}^{1\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{t_l\}}^{\mathrm{T}} \in \mathbb{C}^{(N-1)\times M}$	$\forall r_l$: $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{r_l}^{\mathrm{T}} \in \mathbb{C}^{1\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{r_l\}}^{\mathrm{T}} \in \mathbb{C}^{(N-1)\times M}$
U/MC	For t_{l_u} : $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{t_{l_\mathrm{u}}}^{\mathrm{T}} \in \mathbb{C}^{1\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{t_{l_\mathrm{u}}\}}^{\mathrm{T}} \in \mathbb{C}^{(N-1)\times M}$ For t_{l_m} : $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{t_{l_\mathrm{m}}}^{\mathrm{T}} \in \mathbb{C}^{1\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{t_{l_\mathrm{m}}\}}^{\mathrm{T}} \in \mathbb{C}^{(N-1)\times M}$	For $r_l = t_{l_\mathrm{m}}$: $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{r_l}^{\mathrm{T}} \in \mathbb{C}^{1\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{r_l=t_{l_\mathrm{m}}\}}^{\mathrm{T}} \in \mathbb{C}^{(N-1)\times M}$ $\forall r_l, r_l \in \mathcal{I}_l \setminus t_{l_\mathrm{m}}$: $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{r_l=t_{l_\mathrm{m}}\}}^{\mathrm{T}} \in \mathbb{C}^{(N_l-1)\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{t_{l_\mathrm{m}}\}}^{\mathrm{T}} \in \mathbb{C}^{(N-(N_l-1))\times M}$
MC	$\forall l$: $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{v_l w_l}^{\mathrm{T}} \in \mathbb{C}^{2\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l\setminus\{v_l w_l\}}^{\mathrm{T}} \in \mathbb{C}^{(N-2)\times M}$	$\forall l$: $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}_l}^{\mathrm{T}} \in \mathbb{C}^{N_l\times M}$ $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}} = \mathbf{H}_{\mathcal{I}\setminus\mathcal{I}_l}^{\mathrm{T}} \in \mathbb{C}^{(N-N_l)\times M}$
UC: Unicasting, U/MC: Hybrid uni/multicasting, MC: Multicasting t_{l_u}: index of transmitting node whose data stream is unicasted, $t_{l_\mathrm{u}} \in \mathcal{I}_l$ t_{l_m}: index of transmitting node whose data stream is multicasted, $t_{l_\mathrm{m}} \in \mathcal{I}_l \setminus \{t_{l_\mathrm{u}}\}$		

Using BD,

$$\mathbf{F}_{\mathrm{null}} = \tilde{\mathbf{V}}_{\mathrm{u_n}}^{(0)} \in \mathbb{C}^{M\times(N-\tilde{r}_{\mathrm{u_n}})} \tag{4.73}$$

with $\tilde{r}_{\mathrm{u_n}}$ denoting the rank of matrix $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$. The BD approach can be used directly for receive and transmit beamforming, since it only deals with the channels without considering the noise. Using RBD, however, the equivalent channels for receive and transmit beamforming need to be computed differently. RBD for transmit beamforming has been derived in [103] and in this work, we provide the derivation of RBD for receive beamforming in the Appendix. Using RBD,

$$\mathbf{F}_{\mathrm{null}} = \tilde{\mathbf{V}}_{\mathrm{u_n}} \left(\tilde{\mathbf{\Sigma}}_{\mathrm{u_n}}^{\mathrm{T}} \tilde{\mathbf{\Sigma}}_{\mathrm{u_n}} + \kappa \mathbf{I}_M \right)^{-1/2} \in \mathbb{C}^{M\times M}. \tag{4.74}$$

κ is different for transmit and receive beamforming, that is,

$$\kappa_{\mathrm{T}} = \frac{N\sigma_{\mathrm{node}}^2}{E_{\mathrm{RS}}} \tag{4.75}$$

for transmit beamforming [103] and

$$\kappa_{\mathrm{R}} = \frac{\sigma_{z_{\mathrm{RS}}}^2}{\sigma_x^2} \tag{4.76}$$

for receive beamforming, see Appendix.

4.4.5.3 Precoding for Equivalent Channel

Having $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}}$, we can now compute the receive beamforming and transmit beamforming. In the following, when computing the receive beamforming and transmit beamforming, $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}}$ and $\eta_{\mathrm{i_n}}$ relate to $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}$ and $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$ as defined in Table 4.2 for receive beamforming and transmit beamforming, respectively.

Since the interference in $\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}}$ is already minimised, we consider signal processing algorithms which do not deal with interference namely, MF, SVD and semidefinite relaxation (SDR) of maximising the minimum SNR. MF and SVD for single-pair two-way relaying have been investigated in [17, 59]. BD-SVD has been designed in [73] only for multi-user two-way relaying with multicasting strategy.

In this work, BSCA transceive beamforming is designed for non-regenerative MGMW relaying for all proposed BC strategies. Due to the requirement to make generalised BCSA transceive beamforming also suitable for non-regenerative MGMW relaying with multicasting strategy, it has a slight difference to [17, 59, 73]. Using BCSA for multicasting strategy, for each group l, the RS has to transmit one data stream, which is a superposition of two data streams, to N_l nodes in the group where N_l can be any number higher than two. For that reason, in the design of receive beamforming using MF and SVD, we have to do a superposition of two data streams. This makes the proposed BCSA not a direct generalisation of [17, 59, 73]. However, for cases of single-pair two-way relaying and multi-user two-way relaying, if the superposition is not performed, BCSA is a generalisation of [17, 59, 73].

Matched Filter

The receive beamforming vector is given by

$$\mathbf{m} = \Gamma_{\mathrm{i_n}} \underbrace{\mathbf{1}_{\eta_{\mathrm{i_n}}}^{\mathrm{T}} \mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}*} \mathbf{F}_{\mathrm{null}}^{\mathrm{T}}}_{\tilde{\mathbf{m}}}, \tag{4.77}$$

where $\mathbf{1}_{\eta_{\mathrm{i_n}}}$ is a vector of ones of length $\eta_{\mathrm{i_n}}$ and

$$\Gamma_{\mathrm{i_n}} = \mathrm{mean}(|\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}} \tilde{\mathbf{m}}^{\mathrm{T}}|) \tag{4.78}$$

can be seen as the receive power loading where the modulus operator $|\cdot|$ is assumed to be applied element-wise and the mean function returns the mean of a vector. For multicasting strategy, $\mathbf{1}_{\eta_{\mathrm{i_n}}}$ superposes (adds) two-data streams from two nodes in each group.

The transmit beamforming vector is given by

$$\mathbf{m}_{\mathrm{DL}} = \underbrace{\mathbf{F}_{\mathrm{null}}\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}\,\mathrm{H}}\mathbf{1}_{\eta_{\mathrm{i_n}}}}_{\tilde{\mathbf{m}}_{\mathrm{DL}}}\Gamma_{\mathrm{i_n DL}}, \tag{4.79}$$

with

$$\Gamma_{\mathrm{i_n DL}} = \mathrm{mean}(|\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}\tilde{\mathbf{m}}_{\mathrm{DL}}|) \tag{4.80}$$

the transmit power loading. For multicasting strategy, $\mathbf{1}_{\eta_{\mathrm{i_n}}}$ replicates the superposed data stream $\eta_{\mathrm{i_n}}$ times.

Singular Value Decomposition

Let the SVD of the equivalent channel be given by

$$\mathbf{H}_{\mathrm{i_n}}^{\mathrm{eq}} = \mathbf{U}_{\mathrm{i_n}}^{\mathrm{eq}}\mathbf{\Sigma}_{\mathrm{i_n}}^{\mathrm{eq}}[\mathbf{V}_{\mathrm{i_n}}^{\mathrm{eq}(1)}, \mathbf{V}_{\mathrm{i_n}}^{\mathrm{eq}(0)}]. \tag{4.81}$$

The receive beamforming vector is given by

$$\mathbf{m} = \Gamma_{\mathrm{i_n}}\underbrace{\mathbf{1}_{\eta_{\mathrm{i_n}}}^{\mathrm{T}}\mathbf{V}_{\mathrm{i_n}}^{\mathrm{eq}(1)^{\mathrm{T}}}\mathbf{F}_{\mathrm{null}}^{\mathrm{T}}}_{\overline{\mathbf{m}}}, \tag{4.82}$$

with

$$\Gamma_{\mathrm{i_n}} = \mathrm{mean}(|\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}\overline{\mathbf{m}}^{\mathrm{T}}|) \tag{4.83}$$

the receive power loading.

The transmit beamforming vector is given by

$$\mathbf{m}_{\mathrm{DL}} = \underbrace{\mathbf{F}_{\mathrm{null}}\mathbf{V}_{\mathrm{i_n}}^{\mathrm{eq}(1)}\mathbf{1}_{\eta_{\mathrm{i_n}}}}_{\overline{\mathbf{m}}_{\mathrm{DL}}}\Gamma_{\mathrm{i_n DL}}, \tag{4.84}$$

with

$$\Gamma_{\mathrm{i_n DL}} = \mathrm{mean}(|\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}\overline{\mathbf{m}}_{\mathrm{DL}}|) \tag{4.85}$$

the transmit power loading.

Semidefinite Relaxation

Since in MGMW relaying all member nodes in each group exchange messages, we are also interested in a fair beamforming algorithm which aims at balancing the SNRs at the RS as well as at the receiving nodes.

The SNR balancing problem for receive beamforming can be written as

$$\mathbf{m}_{\text{sdr}} = \underset{\mathbf{m}}{\text{argmax}} \min_{i_{\text{in}} \in \mathcal{I}_{\text{in}}} \left| \frac{\mathbf{m}\mathbf{h}^{\text{eq}}_{i_{\text{in}}}}{\sigma^2_{z_{\text{RS}}}} \right|^2, \quad \text{s.t. } \|\mathbf{m}\|_2^2 \leq 1 \tag{4.86}$$

with $\mathcal{I}_{\text{in}}$ the set of nodes, with its cardinality equal to η_{in}. i_{in} is the index of a member node in $\mathcal{I}_{\text{in}}$ and $\mathbf{h}^{\text{eq}}_{i_{\text{in}}} \in \mathbf{H}^{\text{eq}}_{\text{in}}$. The receive beamforming is given by

$$\mathbf{m} = \Gamma_{\text{in}} \underbrace{\mathbf{m}^{\text{T}}_{\text{sdr}} \mathbf{F}^{\text{T}}_{\text{Null}}}_{\tilde{\mathbf{m}}_{\text{sdr}}}, \tag{4.87}$$

with

$$\Gamma_{\text{in}} = \text{mean}(|\mathbf{H}^{\text{T}}_{\text{in}} \tilde{\mathbf{m}}^{\text{T}}_{\text{sdr}}|) \tag{4.88}$$

the receive power loading.

Equation (4.86) is a non-convex quadratically constrained quadratic program. A similar optimisation is also considered in [110]. It is proven to be NP-hard in [110]. Nonetheless, it can be approximately solved using SDR techniques [110, 111]. Therefore, we rewrite the problem into a semidefinite program. Having

$$\mathbf{X} = \mathbf{m}^{\text{H}} \mathbf{m}, \tag{4.89}$$

$$\mathbf{Q}_i = \mathbf{h}^{\text{eq}}_{i_{\text{in}}} \mathbf{h}^{\text{eq H}}_{i_{\text{in}}} / \sigma^2_{z_{\text{RS}}}, \tag{4.90}$$

and using relaxation by dropping the rank one constraint, we can rewrite (4.86) after introducing variable t, into

$$\begin{aligned} &\max_{\mathbf{X}, t \in \mathcal{R}} \ t \\ \text{s.t.} \quad &\text{tr}\{(\mathbf{X}\mathbf{Q}_i)\} \geq t, \forall i \in \mathcal{I}_{\text{in}}, \\ &\text{tr}\{\mathbf{X}\} = 1, \\ &\mathbf{X} \succeq \mathbf{0}. \end{aligned} \tag{4.91}$$

By introducing slack variables, we can further rewrite the problem in (4.91) in order to solve it using a solver such as SEDUMI [112]. Since the solution might be higher rank due to the relaxation, an approximate solution is obtained using randomisation techniques [110]. Bounds on the approximation error of the SDR techniques have been developed in [113], which was motivated by the work in [110].

The SNR balancing problem for transmit beamforming can be written as

$$\mathbf{m}_{\text{sdrDL}} = \underset{\mathbf{m}}{\text{argmax}} \min_{i_{\text{in}} \in \mathcal{I}_l} \left| \frac{\mathbf{m}\mathbf{h}^{\text{eq}}_{i_{\text{in}}}}{\sigma^2_{z_{\text{node}}}} \right|^2 \quad \text{s.t. } \|\mathbf{m}_{\text{DL}}\|_2^2 \leq 1, \tag{4.92}$$

with $\mathbf{h}_{i_{\text{in}}}^{\text{eq}} \in \mathbf{H}_{\text{i}_\text{n}}^{\text{eq}}$. The transmit beamforming is given by

$$\mathbf{m}_{\text{DL}} = \underbrace{\mathbf{F}_{\text{Null}}\mathbf{m}_{\text{sdr DL}}}_{\tilde{\mathbf{m}}_{\text{sdr}_{\text{DL}}}}\Gamma_{\text{i}_\text{n}\text{DL}}, \tag{4.93}$$

with

$$\Gamma_{\text{i}_\text{n}\text{DL}} = \text{mean}(|\mathbf{H}_{\text{i}_\text{n}}^{\text{T}}\tilde{\mathbf{m}}_{\text{sdr}_{\text{DL}}}|) \tag{4.94}$$

the transmit power loading. Note that to compute the transmit beamforming with SDR, we assume that the information of the noise power at the nodes is available at the RS. Similar to (4.86), (4.92) can be approximately solved with semidefinite relaxation techniques using a solver such as SEDUMI [112].

The p-th Phase BCSA Transceive Beamforming

In the following, we use again the BC phase index p to describe the BCSA transceive beamforming. For unicasting strategy, the receive beamforming matrix is given by

$$\mathbf{G}_{\text{R}}^{p} = [\mathbf{m}_1^p, \cdots, \mathbf{m}_N^p], \tag{4.95}$$

where $\mathbf{m}_{t_l}^p, \forall t_l \in \mathcal{I}$, is the receive beamforming as in (4.77), (4.82) or (4.87) given the equivalent channel of node t_l. The transmit beamforming matrix is given by

$$\mathbf{G}_{\text{T}}^{p} = \left[\mathbf{m}_{\text{DL}_1}^p, \cdots, \mathbf{m}_{\text{DL}_N}^p\right], \tag{4.96}$$

where $\mathbf{m}_{\text{DL}_{r_l}}^p, \forall r_l \in \mathcal{I}$, is the transmit beamforming as in (4.79), (4.84) or (4.93) given the equivalent channel of node r_l.

For hybrid uni/multicasting strategy, the receive beamforming matrix is given by

$$\mathbf{G}_{\text{R}}^{p} = \left[\mathbf{m}_{t_{1_\text{u}}}^p, \mathbf{m}_{t_{1_\text{m}}}^p, \cdots, \mathbf{m}_{t_{L_\text{u}}}^p, \mathbf{m}_{t_{L_\text{m}}}^p\right], \tag{4.97}$$

where $\mathbf{m}_{t_{l_\text{u}}}^p, \forall l \in \mathcal{L}$, and $\mathbf{m}_{t_{l_\text{m}}}^p, \forall l \in \mathcal{L}$, are the receive beamforming as in (4.77), (4.82) or (4.87) given the equivalent channels of nodes t_{l_u} and t_{l_m}, respectively. The transmit beamforming matrix is given by

$$\mathbf{G}_{\text{T}}^{p} = \left[\mathbf{m}_{\text{DL}_{r_1=t_{1_\text{m}}}}^p, \mathbf{m}_{\text{DL}_{\mathcal{I}_1\setminus\{t_{1_\text{m}}\}}}^p, \cdots, \mathbf{m}_{\text{DL}_{r_L=t_{L_\text{m}}}}^p, \mathbf{m}_{\text{DL}_{\mathcal{I}_L\setminus\{t_{L_\text{m}}\}}}^p\right], \tag{4.98}$$

where $\mathbf{m}_{\text{DL}_{r_l=t_{l_\text{m}}}}^p, \forall l \in \mathcal{L}$, and $\mathbf{m}_{\text{DL}_{\mathcal{I}_l\setminus\{t_{l_\text{m}}\}}}^p, \forall l \in \mathcal{L}$, are the transmit beamforming as in (4.79), (4.84) or (4.93) given the equivalent channel of node $r_l = t_{l_\text{m}}$ and the equivalent channel of all other nodes in group l, $\forall r_l \in \mathcal{I}_l \setminus \{t_{l_\text{m}}\}$, respectively.

For multicasting strategy, the receive beamforming matrix is given by

$$\mathbf{G}_{\mathrm{R}}^{p} = \left[\mathbf{m}_{l}^{p}, \cdots, \mathbf{m}_{L}^{p}\right], \tag{4.99}$$

where $\mathbf{m}_{l}^{p}, \forall l \in \mathcal{L}$, is the receive beamforming as in (4.77), (4.82) or (4.87) given the equivalent channels of two nodes v_l and w_l whose data streams are superposed. The transmit beamforming matrix is given by

$$\mathbf{G}_{\mathrm{T}}^{p} = \left[\mathbf{m}_{\mathrm{DL}_1}^{p}, \cdots, \mathbf{m}_{\mathrm{DL}_L}^{p}\right], \tag{4.100}$$

where $\mathbf{m}_{\mathrm{DL}_l}^{p}, \forall l \in \mathcal{L}$, is the transmit beamforming as in (4.79), (4.84) or (4.93) given the equivalent channels of all nodes in group l.

Finally, BCSA transceive beamforming is given by

$$\mathbf{G}^{p} = \beta^{p}\mathbf{G}_{\mathrm{T}}^{p}\mathbf{\Pi}^{p}\mathbf{G}_{\mathrm{R}}^{p}. \tag{4.101}$$

where β^p is needed in order to satisfy the transmit power constraint at the RS, with

$$\beta^{p} = \sqrt{\frac{E_{\mathrm{RS}}}{\mathrm{tr}\left\{\mathbf{G}_{\mathrm{T}}^{p}\mathbf{\Pi}^{p}\mathbf{G}_{\mathrm{R}}^{p}(\sigma_x^2\mathbf{H}\mathbf{H}^{\mathrm{H}} + \sigma_{\mathrm{RS}}^2\mathbf{I})\mathbf{G}_{\mathrm{R}}^{p^{\mathrm{H}}}\mathbf{\Pi}^{p^{\mathrm{H}}}\mathbf{G}_{\mathrm{T}}^{p^{\mathrm{H}}}\right\}}}. \tag{4.102}$$

Note that $\mathbf{\Pi}^p$ is not the same for all BC strategies. For unicasting strategy, $\mathbf{\Pi}^p$ is the same as for MF, ZF and MMSE, where an example for $L = 2, N_1 = N_1 = 3$ is given in Table 4.1. For hybrid uni/multicasting strategy, $\mathbf{\Pi}^p = \mathbf{I}_{2L}$ and for multicasting strategy, $\mathbf{\Pi}^p = \mathbf{I}_L$.

4.5 Simulation Results

4.5.1 Introduction

In this section, the sum rate performance is analysed based on simulation results. We set $\sigma_{z_{\mathrm{RS}}}^2 = \sigma_{z_{\mathrm{node}}}^2 = 1, \sigma_x^2 = 1$, and $E_{\mathrm{RS}} = 1$. The channel coefficients are i.i.d. $\mathcal{CN}(0, \sigma_h^2)$, i.e., Rayleigh fading. Hence, the SNR value is given by $\frac{\sigma_x^2}{\sigma_{z_{\mathrm{node}}}^2}|h_{i,m}|^2 = \frac{\sigma_x^2}{\sigma_{z_{\mathrm{RS}}}^2}|h_{i,m}|^2$. In the following, we analyse the sum rate performance of non-regenerative MGMW relaying for single-group in Section 4.5.2 and for multi-group in Section 4.5.3. The following acronyms are used in the figures, namely, UC for unicasting, U/MC for hybrid uni/multicasting and MC for Multicasting.

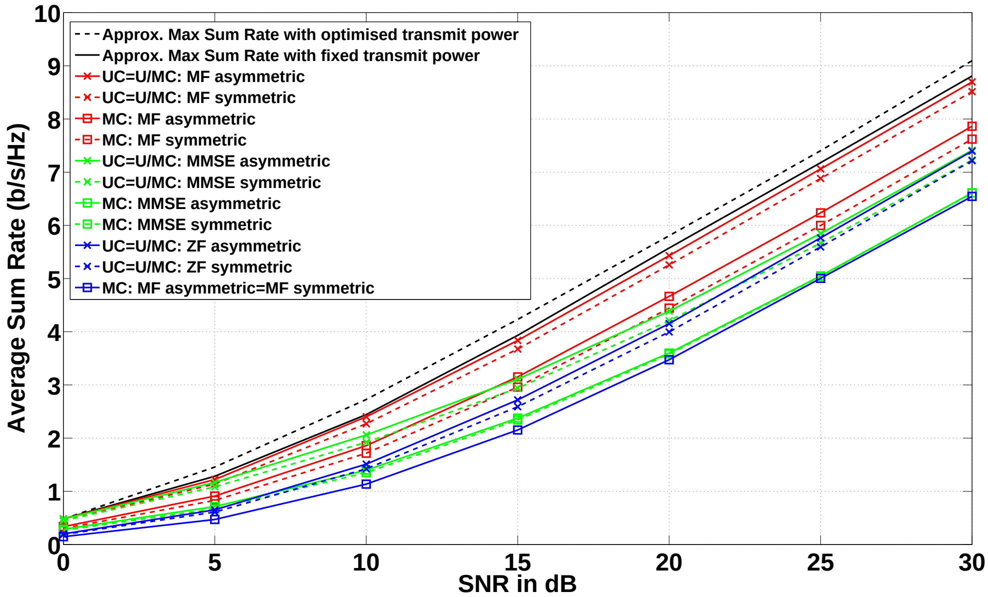


Figure 4.1. Sum rate performance of first single-group scenario with MF, ZF and MMSE

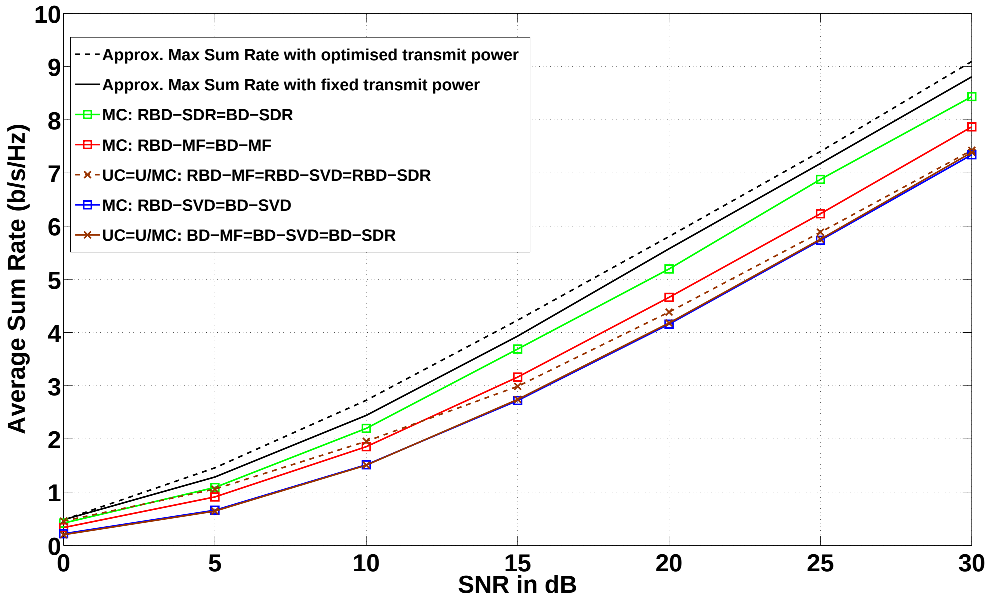


Figure 4.2. Sum rate performance of first single-group scenario with BCSA

4.5.2 Single-Group Multi-Way Relaying

First Single-Group Scenario: $L = 1$ and $N_1 = 2$

In single-pair two-way relaying, unicasting and hybrid uni/multicasting are the same. Figure 4.1 shows the sum rate performance of single-pair two-way relaying with MF, ZF and MMSE transceive beamforming for both asymmetric traffic and symmetric traffic. The approximation of maximum sum rate is also provided for two cases, that is, with optimised and with fixed transmit powers at the nodes. The solution for both cases were computed using fmincon from MATLAB to provide performance bounds for single-pair two-way relaying. We use the value of MMSE transceive beamforming as the initial value. In general, using MF, ZF and MMSE transceive beamforming, unicasting and hybrid uni/multicasting outperform multicasting strategy. A direct superposition of the outputs of receive beamforming for multicasting strategy doubles the amount of the RS's filtered noise. Moreover, the RS transmit power is distributed within the superposed data stream and after self-interference cancellation, each node only receives half of the power. Since each node performs self-interference cancellation, no interference appears at the nodes, and thus, for all BC strategies MF outperforms MMSE and ZF. At low SNR, MMSE converges to MF and in high SNR, ZF converges to MMSE. In this work, we assume fixed transmit power at all nodes and the performance of unicasting and hybrid uni/multicasting with MF is close to the approximation of maximum sum rate with fixed transmit power. If the nodes can optimise their transmit power, the sum rate is improved with a penalty of having higher computational complexity. It can also be seen that asymmetric traffic leads to a higher rate compared to symmetric traffic since the rate for symmetric traffic is defined by the weakest link among all available links. Therefore, in the following, we only consider asymmetric traffic.

Figure 4.2 shows the sum rate performance of two-way relaying with BCSA transceive beamforming for the first single-group scenario with $L = 1$ and $N_1 = 2$. For multicasting strategy, since there is no separation needed both for receive beamforming and transmit beamforming, BD and RBD are the same. For unicasting and hybrid uni/multicasting strategies, BD-MF, BD-SVD and BD-SDR perform the same and they have similar performance to multicasting strategy with SVD. Different to multicasting strategy, for unicasting and hybrid uni/multicasting, since there is a stream separation both in receive beamforming and transmit beamforming, RBD improves the performance in low SNR region. In high SNR region, BD converges to RBD. For unicasting and hybrid uni/multicasting strategies, since the equivalent channels (which are free from interference) always correspond only to one intended node for both receive beamforming and transmit beamforming, MF, SVD and SDR will always have

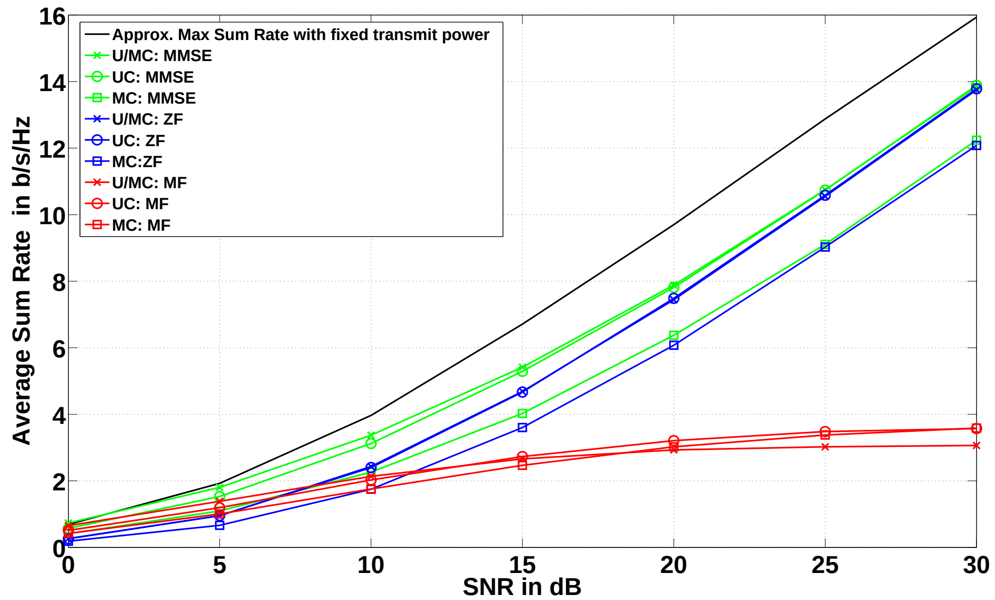


Figure 4.3. Sum rate performance of second single-group scenario with MF, ZF and MMSE

the same performance. It can be seen that multicasting strategy with SDR performs best. Hence, having a suitable transceive beamforming, one can exploit the benefit of beamforming-based physical layer network coding.

Comparing Figures 4.1 and 4.2, unicasting and hybrid uni/multicasting strategies with BD-MF, BD-SVD and BD-SDR performs the same as ZF, while with RBD-MF, RBD-SVD and RBD-SDR performs the same as MMSE. Since in single-pair two-way relaying there is no other-group interference and each node performs self-interference cancellation, multicasting strategy with BD-MF or RBD-MF performs similar to MF.

Second Single-Group Scenario: $L = 1$ and $N_1 = 3$

Figure 4.3 shows the sum rate performance of single-group three-way relaying with MF, ZF and MMSE for the second single-group scenario with $L = 1$ and $N_1 = 3$. In this scenario, regardless of the BC strategy, MF performs worse than the others while MMSE performs best. Different to the first scenario for two-way relaying, in three-way relaying there is same-group-inter-stream interference. The MF does not cancel this interference and, thus, its performance is worse than that of MMSE and ZF. For high SNR, ZF converges to MMSE and for low SNR, MF converges to MMSE. The approximation of maximisation of sum rate for fixed nodes' transmit powers is solved using fmincon

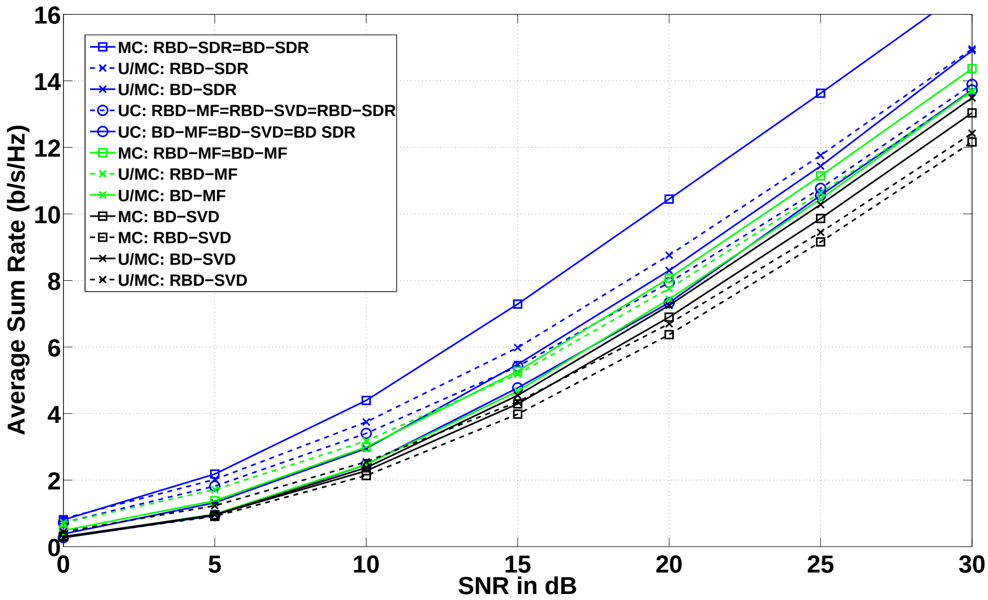


Figure 4.4. Sum rate performance of second single-group scenario with BCSA

from MATLAB to provide a sum rate performance bound for three-way relaying with unicasting strategy and the MMSE solution as the initial value. For three-way relaying with MF, ZF and MMSE transceive beamforming, hybrid uni/multicasting with MMSE performs best due to its less number of transmitted data streams. Even though multicasting strategy has the least number of transmitted data stream, however, it is a superposition of two different data streams and, thus, the power is distributed to the two data streams. Each node decodes only one intended data stream and, thus, it receives only halves the power. Since MF does not cancel the same-group-inter-stream interference, multicasting strategy with MF performs worse than the other strategies.

Figure 4.4 shows the sum rate performance of single-group three-way relaying with BCSA transceive beamforming for the second single-group scenario with $L = 1$ and $N_1 = 3$. For unicasting strategy, RBD with MF, SVD and SDR perform the same and they outperform BD with MF, SVD and SDR in low SNR region. As expected, BD converges to RBD in high SNR region. For hybrid uni/multicasting, RBD-SDR performs best followed RBD-MF and in high SNR region, BD-SDR converges to RBD-SDR and BD-MF converges to RBD-MF. Using SVD, both for hybrid uni/multicasting and multicasting strategy, RBD performs worse than BD. For multicasting strategy, RBD-SDR performs similar to BD-SDR and RBD-MF performs similar to BD-MF. Using BCSA, multicasting strategy with BD-SDR and RBD-SDR performs best, followed by hybrid uni/multicasting with RBD-SDR.

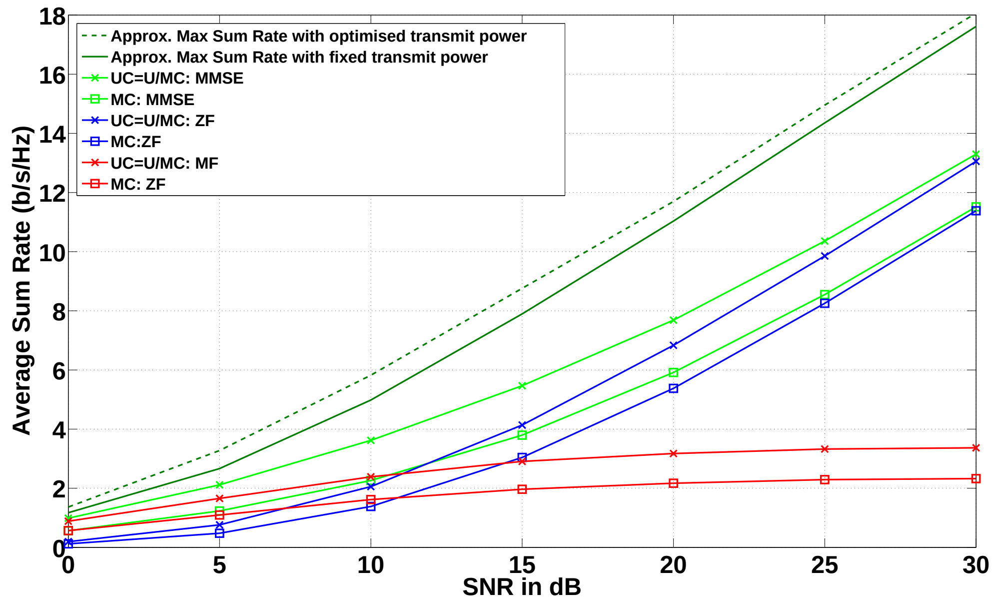


Figure 4.5. Sum rate performance of first multi-group scenario with MF, ZF and MMSE

Comparing Figures 4.3 and 4.4, multicasting strategy with RBD-SDR and BD-SDR performs best and outperforms other strategies with any transceive beamforming. If appropriate transceive beamforming is applied for multicasting strategy such as BCSA transceive beamforming, multicasting strategy outperforms the other strategies, especially in high SNR region. In high SNR region, being spectrally-efficient is more important than being power-efficient [14]. Therefore, BC strategy with appropriate transceive beamforming which performs best in high SNR region is more appropriate to be applied. In three-way relaying, multicasting strategy with RBD-SDR or BD-SDR is the most spectrally-efficient strategy.

4.5.3 Multi-Group Multi-Way Relaying

First Multi-Group Scenario: $L = 2$ and $N_1 = N_2 = 2$

Figure 4.5 shows the sum rate performance of multi-user two-way relaying with MF, ZF and MMSE for the first multi-group scenario with $L = 2$ and $N_1 = N_2 = 2$. In this scenario, unicasting and hybrid uni/multicasting are the same and they outperform multicasting strategy. The reason is the same as in the case of single-pair two-way relaying given in Section 4.5.2. Moreover, the direct superposition of the outputs of receive beamforming for multicasting strategy not only increases the amount of the RS's

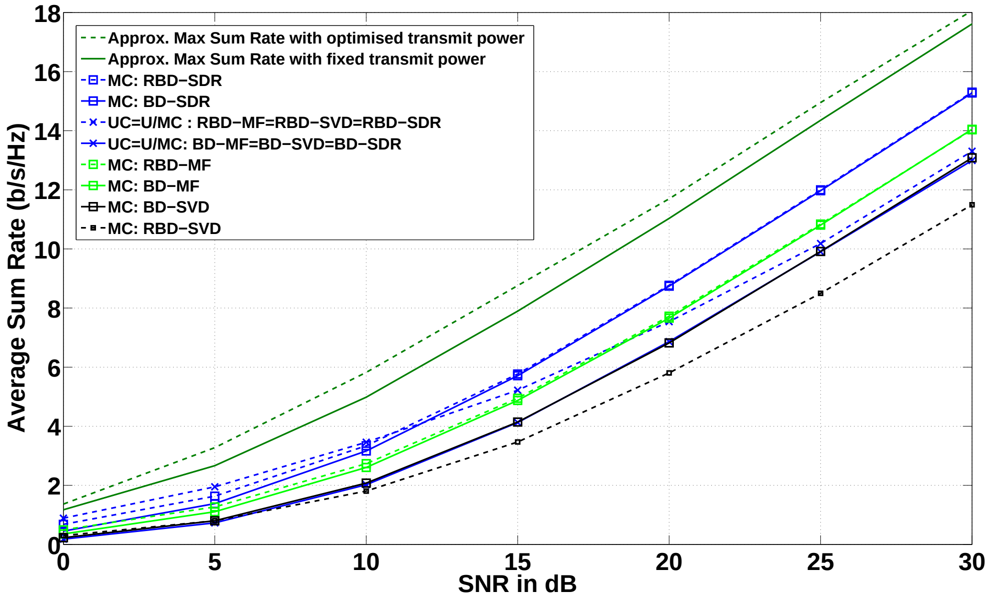


Figure 4.6. Sum rate performance of first multi-group scenario with BCSA

filtered noise, but also increases the unwanted interference at the receiving nodes. For all strategies, MMSE performs best and in high SNR region, ZF converges to MMSE, while in low SNR region, MF converges to MMSE. Different to the case of single-pair two-way relaying, in multi-user two-way relaying MF performs worse since it does not cancel the interference form other pairs which appears at each node. The transceive beamforming maximising the sum rate was computed using fmincon from MATLAB to provide a bound for multi-user two-way relaying. We use the value of MMSE tranceive beamforming as initial value. It can be clearly seen that if the transmit power at the nodes can be optimised, the sum rate can be improved at the expense of computational complexity.

Figure 4.6 shows the sum rate performance for the first multi-group scenario with $L = 2, N_1 = N_2 = 2$ with BCSA transceive beamforming. In general, RBD outperforms BD in low SNR region and BD converge to RBD in high SNR. Only for multicasting strategy, BD-SVD outperforms RBD-SVD for all considered SNR values and it has similar performance as unicasting and hybrid uni/multicasting with BD-MF, BD-SVD and BD-SDR. In low SNR region, the gain of RBD compared to BD is obtained most for unicasting and hybrid uni/multicasting strategies, while for multicasting strategy (with MF and SDR), the gain is small. Compared to BD which nullifies the interference, RBD tries to minimise the interference while taking into consideration the noise. The lower the number of the same-group- and other-group-inter-stream interference, the lower the gain of RBD compared to BD. In medium to high SNR region, multicasting strategy with RBD-SDR or BD-SDR perform best. This shows that multicasting strategy with RBD-SDR and BD-SDR is able to manage the interference better and, thus, is spectrally efficient. While for both unicasting and hybrid uni/multicasting strategies, the performance of MF, SVD and SDR are the same, for multicasting strategy SDR always performs best followed by MF and SVD.

Comparing Figures 4.5 and 4.6, once again BCSA transceive beamforming is able to improve the performance of multicasting strategy. Multicasting strategy with RBD-SDR, RBD-MF, BD-SDR and BD-MF perform better than with MF, ZF and MMSE. Multicasting strategy with BD-SVD performs the same with ZF, while with RBD-SVD performs worse than ZF and MMSE, even though still better than MF. Once again, unicasting and hybrid uni/multicasting strategies with BD-MF, BD-SVD and BD-SDR perform the same as with ZF, while with RBD-MF, RBD-SVD and RBD-SDR perform similar to with MMSE.

Second Multi-Group Scenario: $L = 2$ **and** $N_1 = N_2 = 3$

Figure 4.7 shows the sum rate performance of two-group three-way relaying using MF, ZF and MMSE for the second multi-group scenario with $L = 2$ and $N_1 = N_2 = 3$. In general, hybrid uni/multicasting performs best followed by unicasting and multicasting strategies. While hybrid uni/multicasting strategy with MMSE slightly ouperforms unicasting strategy with MMSE, both strategies have similar ZF performance. With MMSE, we find the trade-off between the noise enhancement and the interference suppression. Since, hybrid uni/multicasting has a smaller number of transmit data streams from the RS, it performs better than unicasting strategy both for MMSE and MF. ZF perfectly cancels the interference, and, thus, both unicasting and hybrid uni/multicasting perform similar. In general, for all strategies, ZF converges to MMSE in high SNR region and in low SNR region, MF converges to MMSE. It can be seen that multicasting strategy is outperformed by other strategies since it suffers from the increase of RS's filtered noise and the reduced received power at the nodes. This shows that analog network coding for non-regenerative MGMW relaying obtained by directly adding the outputs of receive beamforming (using MF, ZF and MMSE receive beamforming) is not an efficient strategy and, thus, appropriate transceive beamforming is required.

Figure 4.8 shows the sum rate performance of two-group three-way relaying using BCSA transceive beamforming for the second multi-group scenario with $L = 2$ and $N_1 = N_2 = 3$. In general, RBD outperforms BD, and they converge in high SNR

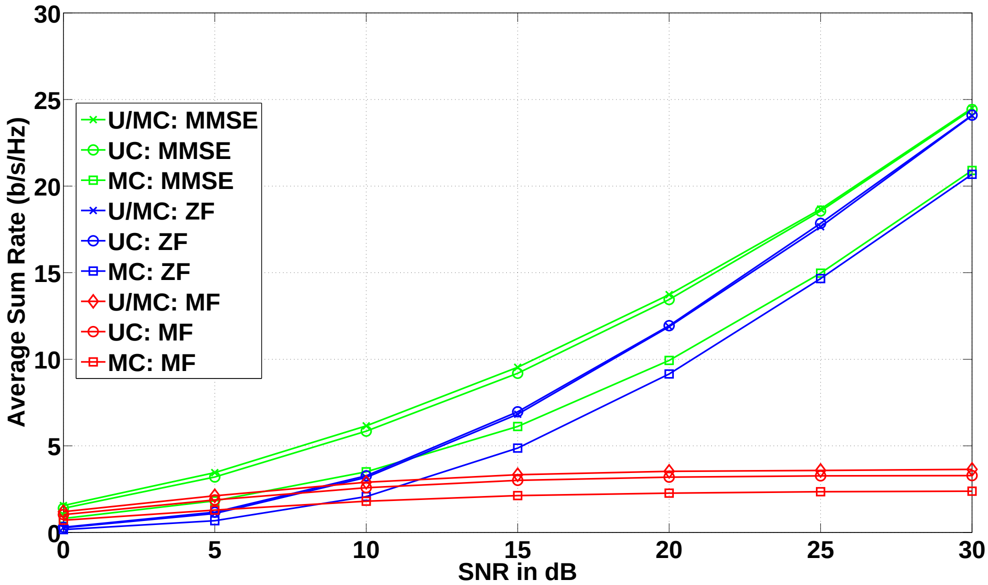


Figure 4.7. Sum rate performance of second multi-group scenario with MF, ZF and MMSE

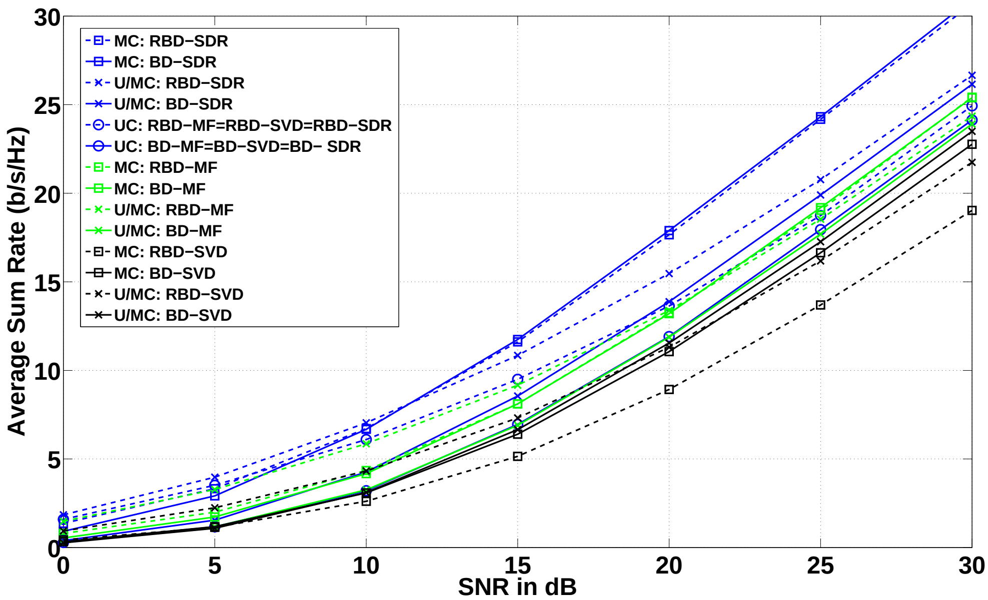


Figure 4.8. Sum rate performance of second multi-group scenario with BCSA

region. Only when using SVD, for both hybrid uni/multicasting and multicasting strategies, RBD-SVD performs worse than BD-SVD and BD-SVD does not converge to RBD-SVD in high SNR region. In medium to high SNR, multicasting strategy outperforms the other strategies when using SDR and MF. However, if SVD is applied, unicasting strategy performs best. For unicasting strategy, MF, SVD and SDR have similar performance.

Comparing Figures 4.7 and 4.8, one can clearly see that BCSA transceive beamforming improves the sum rate performance, especially for multicasting strategy and hybrid uni/multicasting with BD-MF, BD-SDR, RBD-MF and RBD-SDR. The highest sum rate (especially in high SNR region) is obtained by multicasting strategy with SDR. Therefore, provided a suitable transceive beamforming is applied which can exploit analog network coding, the sum rate of non-regenerative MGMW relaying can be improved.

In this section, we have seen the simulation results of non-regenerative MGMW relaying with different BC strategies and different transceive beamforming algorithms. In summary, the sum rate performance of non-regenerative MGMW relaying depends on the chosen BC strategy and the applied transceive beamforming at the RS.

Chapter 5

Regenerative Multi-Antenna Multi-Group Multi-Way Relaying

5.1 Introduction

In Chapter 4, non-regenerative MGMW relaying has been considered. A non-regenerative RS only performs linear signal processing, that is, transceive beamforming, to the received signals and forwards the output to the nodes. As a consequence, the RS noise is propagated to the nodes.

A regenerative RS regenerates (decodes and re-encodes) the received data streams prior to transmission to the nodes. Hence, compared to a non-regenerative RS, a regenerative RS has the advantage that the noise at the RS does not propagate to the nodes. Moreover, each node needs to know only its own channel to the RS for the decoding process.

A regenerative multi-antenna RS which supports one two-way pair using two-way relaying has been considered in [61, 63]. The extension for multi-user two-way relaying has been considered in [69]. Their works consider rate regions of regenerative two-way relaying [61, 63] or multi-user two-way relaying [69]. It is assumed that a perfect detector for the MAC phase is available and, thus, their works are aiming at the design of transmit beamforming for the BC phase.

In this chapter, we consider regenerative MGMW relaying. Regenerative two-way relaying and regenerative multi-user two-way relaying are two special cases of the proposed regenerative MGMW relaying. For multicasting strategy, we consider two linear operations, namely, modified superposition coding (mSPC) and exclusive-or (XOR). mSPC is a modification of superposition coding (SPC) for two-way relaying in [14, 70]. For SPC for two-way relaying as in [14, 70], since each particular symbol will be sent to only one particular node, each symbol is optimally weighted such that each weighting factor can be different. Afterwards, the two optimally weighted symbols are added. For MGMW relaying with multicasting strategy, the output of the linear operation will be sent to all nodes in the group where the number of nodes in the group is arbitrary and is equal or higher than two. Each symbol may be intended to arbitrary number of nodes in the group. Using mSPC, the RS simply adds two symbols from two different nodes in a group and, afterwards, the output is weighted. Thus, both symbols for mSPC are equally weighted where the weighting factor is the multicast transmit beamforming vector of the corresponding group. Hence, mSPC is suboptimum compared to SPC, but it requires lower computational complexity. Moreover, the modification in mSPC suits well with MGMW relaying and it allows us to have a simpler system model for MGMW relaying. We consider also XOR network coding since it provides low complexity solutions in three different aspects [70]: implementation, encoding/decoding and the required information for self-interference cancellation. Moreover, the practicality of XOR network coding in wireless network has been shown in [28].

Assuming perfect channel state information is available at the RS, we propose a generalised transmit beamforming algorithm for all BC strategies minimising the RS's transmit power while ensuring that each node receives with a rate equal to the received rate at the RS for each particular data stream. It is designed by coupling the MAC and BC phases. Since finding the optimum transmit beamforming requires high computational complexity and since there are cases where the RS's transmit power is fixed, we design generalised low complexity transmit beamforming algorithms for all BC strategies with three different optimisation criteria, namely, MF, ZF and MMSE. Also, we introduce BCSA transmit beamforming. In the following, we first explain the unified system model and the BC strategy parameterisation for regenerative MGMW in Section 5.2. Afterwards, we derive the sum rate of regenerative MGMW relaying in Section 5.3. The designs of the transmit beamforming algorithms are explained in Section 5.4. Finally, the simulation results are given in Section 5.5. The same notations as introduced in Section 4.1 are used.

5.2 Unified System Model and Broadcast Strategy Parameterisation

5.2.1 Unified System Model

We consider L multi-way groups where in the l-th group, $l \in \mathcal{L}, \mathcal{L} = \{1, \cdots, L\}$, there are N_l half-duplex single-antenna nodes that communicate to each other. For simplicity of notation, we assume the same number of nodes in each group, i.e., $N_l = N_{\mathrm{mw}}, \forall l \in \mathcal{L}$. However, the extension to different numbers of nodes in each group is straightforward. The total number N of nodes in the network is $N = \sum_{l\in\mathcal{L}} N_l = LN_{\mathrm{mw}}$. It is assumed that the MGMW communication can only be performed with the assistance of a regenerative half-duplex multi-antenna RS with M antenna elements. The set of nodes' indices as introduced in Section 4.2.1 is also used here.

In the following, we derive the unified discrete-time baseband system model for regenerative MGMW relaying. We assume flat fading channels. The overall channel matrix from the nodes to the RS is given by

$$\mathbf{H} = [\mathbf{h}_0, \cdots, \mathbf{h}_{N-1}] \in \mathbb{C}^{M\times N}, \tag{5.1}$$

with

$$\mathbf{h}_i = (h_{i,1}, \cdots, h_{i,M})^{\mathrm{T}} \in \mathbb{C}^{M\times 1}, i \in \mathcal{I}, \tag{5.2}$$

the channel vector between node Si and the RS. The channel coefficient $h_{i,m}, m \in \mathcal{M}, \mathcal{M} = \{1, \cdots, M\}$, follows $\mathcal{CN}(0, \sigma_h^2)$. The information bit sequence of node i, denoted by $\mathbf{b}_i$, is coded into the complex transmit symbol x_i, i.e.,

$$\mathbf{b}_i \to x_i \in \mathbb{C}, \tag{5.3}$$

cf. [70]. The vector

$$\mathbf{x} = (x_0, \cdots, x_{N-1})^{\mathrm{T}} \in \mathbb{C}^{N\times 1} \tag{5.4}$$

denote the transmit vector with x_i the transmit symbol of node Si that follows $\mathcal{CN}(0, \sigma_x^2)$. The additive white Gaussian noise (AWGN) vector at the RS is denoted as

$$\mathbf{z}_{\mathrm{RS}} = (z_{\mathrm{RS}1}, \cdots, z_{\mathrm{RS}M})^{\mathrm{T}} \in \mathbb{C}^{M\times 1} \tag{5.5}$$

with $z_{\mathrm{RS}m}$ following $\mathcal{CN}(0, \sigma_{z_{\mathrm{RS}}}^2)$.

In the first phase, the MAC phase, all nodes transmit their data streams simultaneously to the RS. The received signal at the RS is given by

$$\mathbf{y}_{\mathrm{RS}} = \mathbf{H}\mathbf{x} + \mathbf{z}_{\mathrm{RS}}. \tag{5.6}$$

The RS decodes the received data streams from all nodes. It is assumed that the RS decodes all data streams correctly. Hence, the RS has all the information bit sequences $\mathbf{b}_i$ from all nodes $i \in \mathcal{I}$.

In the following communication phases, the BC phases, the RS transmits to the nodes. Let p, $p \in \mathcal{P}, \mathcal{P} = \{2, \cdots, P\}$, denote the index of the BC phase. Assuming reciprocal and time-invariant channels in P phases, the downlink channel from the RS to the nodes is simply the transpose of the uplink channel $\mathbf{H}$. In the p-th phase, the RS transmits the corresponding data streams to the nodes according to the chosen BC strategy. For that, the RS determines the transmit data vector $\mathbf{x}_{\mathrm{RS}}^p$ and the data permutation matrix $\mathbf{\Pi}_{\mathrm{d}}^p$. Afterwards, the RS computes the transmit beamforming matrix $\mathbf{G}^p$.

Table 5.1. Data Permutation Matrix $\mathbf{\Pi}_{\mathrm{d}}^{p}$ for the example of Figure 3.3

	$\mathbf{\Pi}_{\mathrm{d}}^{2}$	$\mathbf{\Pi}\mathrm{d}^{3}$
Unicasting	$\begin{pmatrix} 0&1&0&0&0&0\\ 0&0&1&0&0&0\\ 1&0&0&0&0&0\\ 0&0&0&0&1&0\\ 0&0&0&0&0&1\\ 0&0&0&1&0&0 \end{pmatrix}$	$\begin{pmatrix} 0&0&1&0&0&0\\ 1&0&0&0&0&0\\ 0&1&0&0&0&0\\ 0&0&0&0&0&1\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0 \end{pmatrix}$
Hybrid uni/multicasting	$\begin{pmatrix} 1&0&0&0&0&0\\ 0&1&0&0&0&0\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0 \end{pmatrix}$	$\begin{pmatrix} 1&0&0&0&0&0\\ 0&0&1&0&0&0\\ 0&0&0&1&0&0\\ 0&0&0&0&0&1 \end{pmatrix}$
Multicasting-mSPC	$\begin{pmatrix} 1&1&0&0&0&0\\ 0&0&0&1&1&0 \end{pmatrix}$	$\begin{pmatrix} 1&0&1&0&0&0\\ 0&0&0&1&0&1 \end{pmatrix}$
Multicasting-XOR	$\begin{pmatrix} 1&0\\ 0&1 \end{pmatrix}$	$\begin{pmatrix} 1&0\\ 0&1 \end{pmatrix}$

$\mathbf{x}_{\mathrm{RS}}^{p}$ is not the same for all BC strategies. For unicasting, hybrid uni/multicasting and multicasting-mSPC (multicasting-mSPC) strategies, the RS re-encodes the bits into a complex transmit signal, i.e.,

$$\mathbf{b}_i \to x_{\mathrm{RS}_i}^{p} \in \mathbb{C}, \forall i \in \mathcal{I}, \tag{5.7}$$

and

$$\mathbf{x}_{\mathrm{RS}}^{p} = (x_{\mathrm{RS}_0}^{p}, \cdots, x_{\mathrm{RS}_{N-1}}^{p})^{\mathrm{T}}, \tag{5.8}$$

with $x_{\mathrm{RS}_i}^{p}$ following $\mathcal{CN}(0, \sigma_x^2)$. For the multicasting-XOR (multicasting-XOR) strategy, the RS first performs a bitwise-XOR operation to the information bits of nodes $\mathrm{S}v_l$ and $\mathrm{S}w_l$, i.e.,

$$\mathbf{b}_{v_l w_l} = \mathbf{b}_{v_l} \oplus \mathbf{b}_{w_l}. \tag{5.9}$$

The RS re-encodes the XOR-ed bits into a complex transmit signal, i.e.,

$$\mathbf{b}_{v_l w_l} \to x_{\mathrm{RS}_{v_l w_l}}^{p} \in \mathbb{C}, \tag{5.10}$$

and

$$\mathbf{x}_{\mathrm{RS}}^{p} = (x_{\mathrm{RS}_{v_1 w_1}}^{p}, \cdots, x_{\mathrm{RS}_{v_L w_L}}^{p})^{\mathrm{T}}, \tag{5.11}$$

with $x_{\mathrm{RS}_{v_l w_l}}^{p}$ following $\mathcal{CN}(0, \sigma_x^2)$.

In the following, let

$$\mathbf{d}_{\mathrm{RS}}^{p} = (d_{\mathrm{RS}_1}^{p}, \cdots, d_{\mathrm{RS}_Q}^{p})^{\mathrm{T}} = \mathbf{\Pi}_{\mathrm{d}}^{p} \mathbf{x}_{\mathrm{RS}}^{p} \tag{5.12}$$

and

$$\mathbf{z}_{\mathrm{nodes}}^{p} = \left(z_0^{p}, \cdots, z_{N-1}^{p}\right)^{\mathrm{T}}, \tag{5.13}$$

with Q the number of the chosen RS's transmitted data streams according to the BC strategy, and $z_{r_l}^p$ be the noise at receiving node r_l which follows $\mathcal{CN}(0, \sigma_{z_{\text{node}}}^2)$. $\mathbf{\Pi}_{\text{d}}^p$ defines the data streams to be transmitted by the RS according to the chosen BC strategy. In Table 5.1, we provide $\mathbf{\Pi}_{\text{d}}^p$ corresponding to the example in Figure 3.3. For unicasting strategy, $\mathbf{\Pi}_{\text{d}}^p$ only permutes $\mathbf{x}_{\text{RS}}^p$ and has a size of $Q \times N = N \times N$. For the hybrid uni/multicasting strategy, $\mathbf{\Pi}_{\text{d}}^p$ chooses the data streams to be unicasted and multicasted in each BC phase and has a size of $Q \times N = 2L \times N$. For example for the first group in Figure 3.3, in the second phase, it chooses $x_{\text{RS}_0}^p$ for unicast transmission and $x_{\text{RS}_1}^p$ for multicast transmission. In the third phase, it chooses again $x_{\text{RS}_0}^p$ for unicast transmission and $x_{\text{RS}_2}^p$ for multicast transmission. As a result, $d_{\text{RS}_q}^p, \forall q = 2l-1, \forall l$, are the unicasted data streams for all groups and $d_{\text{RS}_q}^p, \forall q = 2l, \forall l$, are the multicasted data streams for all groups. Using multicasting strategy, the RS transmits $Q = L$ data streams in each BC phase. For multicasting-XOR, $\mathbf{\Pi}_{\text{d}}^p$ is simply an identity matrix of size $Q \times L = L \times L$. However, for multicasting-mSPC, $\mathbf{\Pi}_{\text{d}}^p$ chooses and adds two data streams for each group and has a size of $Q \times N = L \times N$.

The received signal vector of all nodes in the p-th phase can be written as

$$\mathbf{y}_{\text{nodes}}^p = \mathbf{H}^{\text{T}} \mathbf{G}^p \mathbf{d}_{\text{RS}}^p + \mathbf{z}_{\text{nodes}}^p, \tag{5.14}$$

and, accordingly, the received signal at node $\text{S}r_l, r_l \in \mathcal{I}_l$, when receiving the data stream $d_{\text{RS}_q}^p$ from the RS is given by

$$y_{r_l}^p = \underbrace{\mathbf{h}_{r_l}^{\text{T}} \mathbf{g}_q^p d_{\text{RS}_q}^p}_{\text{useful signal}} + \underbrace{\sum_{\substack{j \in \mathcal{Q} \\ j \neq q}} \mathbf{h}_{r_l}^{\text{T}} \mathbf{g}_j^p d_{\text{RS}_j}^p}_{\text{other stream interference signals}} + \underbrace{z_{r_l}^p}_{\text{node } r_l\text{'s noise}}, \tag{5.15}$$

where $\mathbf{g}_q^p$ is the corresponding transmit beamforming vector for the RS's transmitted data stream $d_{\text{RS}_q}^p$, i.e., the q-th column of $\mathbf{G}^p$, and $\mathcal{Q} = \{1, \cdots, Q\}$ is the set of indices of the RS's transmitted data streams.

Using multicasting-mSPC, for each group, the RS adds two data streams from two different nodes. Therefore, the useful signal in (5.15) contains the intended data stream and the self- and known-interference which has to be canceled. Regarding multicasting-XOR, the process of cancellation is similar to multicasting-mSPC. However, the cancellation is performed at bit level. After each node decodes the received data stream and obtains the bit sequence, it performs self- or known-interference cancellation by XOR-ing the decoded bits with the a priori known own bits or known bits.

In this subsection, we explain the unified system model for regenerative MGMW relaying which is valid for all BC strategies. Therefore, we need to have the relationship between the receiving index r_l, the transmitting index t_l, the RS transmitted data stream index q and the BC phase index p. In the following subsection, we introduce the relationship of the indices which defines the applied BC strategy for regenerative MGMW relaying.

5.2.2 Broadcast Strategy Parameterisation

5.2.2.1 Unicasting Strategy

For the unicasting strategy, the RS transmits $Q = N$ data streams simultaneously to the nodes, one data stream for each intended node. For example in Figure 3.3(a), $Q = 6$. The relationship of the indices for the unicasting strategy is given by

$$\begin{aligned} q &= r_l, \\ t_l &= a_l + \mathrm{mod}_{N_l}\left(r_l + p - a_l - 1\right). \end{aligned} \tag{5.16}$$

The relationship in (5.16) should be read as follows, in the p-th phase, the node with receiving index r_l receives the RS's data stream with index q which corresponds to the data stream of transmitting node t_l. Using such relationship, assuming each node knows its index and all other nodes' indices in its group, there is no signalling required in the network.

5.2.2.2 Hybrid Uni/Multicasting Strategy

Using hybrid uni/multicasting strategy, for each group the RS transmits one unicasted data stream to one node exclusively and one multicasted data stream to the other $N_l - 1$ nodes, i.e., $Q = 2L$. The unicasted data stream is fixed and it is transmitted to a different node in the group in each BC phase. Consequently, the multicasted data stream has to be changed in each BC phase to ensure that each node receives all data streams of the other nodes in its group. For the example in Figure 3.3.(b), the RS transmits $Q = 4$ data streams in each BC phase. The relationship of the indices for the hybrid uni/multicasting strategy is given by

$$\begin{aligned} q &= \begin{cases} 2l - 1, & \text{if } r_l = t_{l_\mathrm{m}}, \\ 2l, & \text{otherwise}, \end{cases} \\ t_l &= \begin{cases} t_{l_\mathrm{u}} = a_l, & \text{if } r_l = t_{l_\mathrm{m}}, \\ t_{l_\mathrm{m}} = (p + a_l) - 1, & \text{otherwise} \end{cases} \end{aligned} \tag{5.17}$$

with $t_{l_\mathrm{u}}, t_{l_\mathrm{u}} \in \mathcal{I}_l$, the index of the transmitting node whose data stream is unicasted by the RS and $t_{l_\mathrm{m}}, t_{l_\mathrm{m}} \in \mathcal{I}_l \setminus \{t_{l_\mathrm{u}}\}$, the index of the transmitting node whose data stream is multicasted by the RS. The relationship in (5.17) should be read as follows, in the p-th phase, the node with receiving index r_l receives the RS's data stream with index q which corresponds to the data stream of transmitting node t_l. Using such relationship, assuming each node knows its index and all other nodes' indices in its group, there is no signalling required in the network.

5.2.2.3 Multicasting Strategy

Using multicasting strategy, the RS transmits only one data stream per group, i.e., $Q = L$. The data stream for each group is an output of a linear operation on two data streams of two nodes in the group. For the example in Figure 3.3.(c), the RS transmits $Q = 2$ data streams in each BC phase. The relationship of the indices for the multicasting strategy is given by

$$
\begin{aligned}
q &= l, \\
v_l = a_l,\ & w_l = (p + a_l) - 1, \\
t_l = &\begin{cases} v_l, & \text{for } r_l = (p + a_l) - 1, \\ w_l, & \text{otherwise} \end{cases}
\end{aligned}
\tag{5.18}
$$

with v_l and w_l the indices of two nodes whose data streams are linearly operated. The relationship in (5.18) should be read as follows, in the p-th phase, the node with receiving index r_l receives the RS's data stream with index q which corresponds to the data stream of transmitting node t_l. Using such relationship, assuming each node knows its index and all other nodes' indices in its group, there is no signalling required in the network.

5.3 Sum Rate Expression

5.3.1 Introduction

In this section, we derive the achievable sum rate expression of regenerative MGMW relaying. The achievable sum rate is the sum of the rates at each receiving node. We first explain the MAC phase rate which is achieved at the RS in Section 5.3.2. It is followed by the BC rate which can be achieved at each receiving node in Section 5.3.3. Finally, the overall achievable sum rate for both asymmetric traffic and symmetric traffic are given in Section 5.3.4.

5.3.2 MAC Phase

Different to previous works in regenerative two-way relaying which consider the achievable rate region, e.g., [61, 63], in this work, we consider the achievable sum rate of regenerative MGMW relaying. Therefore, we propose to apply a practical multi user detector for decoding at the RS which achieves the optimum rate of the MAC phase, i.e., one of the $N!$ rate tuples. Hence, we consider a Minimum Mean Square Error (MMSE) with successive interference cancellation (SIC) multi-user detector since it is information theoretically optimal for the uplink MAC scenario [52].

First, we compute the SINR of each node i, which is given by

$$\gamma_i = \sigma_x^2 \mathbf{h}_i^{\mathrm{H}} \left(\sigma_x^2 \sum_{\substack{j=0 \\ j \neq i}}^{N-1} \mathbf{h}_j \mathbf{h}_j^{\mathrm{H}} + \sigma_{z_{\mathrm{RS}}}^2 \mathbf{I}_M \right)^{-1} \mathbf{h}_i \tag{5.19}$$

cf. [52] and, afterwards, perform the SIC. In this work, we consider only one possible SIC based on the SINR in (5.19). The data stream of the node with the highest SINR is decoded first and subtracted from the received data streams. The data streams of the other nodes with lower SINR are decoded succesively afterwards in a similar way. After SIC, the SINR of node i is given by

$$\gamma_i^{\mathrm{MAC}} = \begin{cases} \gamma_i, \text{ if } i \text{ is decoded first,} \\ \frac{\sigma_x^2 |\mathbf{h}_i|^2}{\sigma_{z_{\mathrm{RS}}}^2}, \text{ if } i \text{ is decoded last,} \\ \sigma_x^2 \mathbf{h}_i^{\mathrm{H}} \left(\sigma_x^2 \sum_{j \in \mathcal{B}_i} \mathbf{h}_j \mathbf{h}_j^{\mathrm{H}} + \sigma_{z_{\mathrm{RS}}}^2 \mathbf{I}_M \right)^{-1} \mathbf{h}_i, \text{ otherwise,} \end{cases} \tag{5.20}$$

with $\mathcal{B}_i$ the set of all nodes whose data streams have not been decoded in the previous SIC stage, excluding node i. The achievable rate of node i at the RS is defined by

$$R_i^{\mathrm{MAC}} = \log_2 \left(1 + \gamma_i^{\mathrm{MAC}} \right) \tag{5.21}$$

and the achievable sum rate for the MAC phase is given by

$$R^{\mathrm{MAC}} = \sum_{i=0}^{N-1} R_i^{\mathrm{MAC}}. \tag{5.22}$$

Different SIC ordering due to certain requirements, such as group priority, etc., can be applied. However, it is beyond the scope of this work.

5.3.3 BC Phase

Given the received signal in (5.15), for unicasting, hybrid uni/multicasting and multicasting-XOR strategies, the SINR of node r_l when receiving data stream $d^p_{\mathrm{RS}_q}$ in the p-th phase is given by

$$\gamma^p_{r_l} = \frac{\sigma_x^2 |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_q|^2}{\sigma_x^2 \sum_{j \in \mathcal{Q} \backslash \{q\}} |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_j|^2 + \sigma^2_{\mathrm{node}}}. \tag{5.23}$$

The SINR for multicasting-mSPC strategy is different, since the RS adds two complex signals for each group and the sum is transmitted to all group members. Therefore, for multicasting-mSPC,

$$\gamma^p_{r_l} = \frac{\sigma_x^2 |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_q|^2}{\underbrace{\sigma_x^2 |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_q|^2}_{\substack{\text{self}- \text{ or known}- \\ \text{interference}}} + 2\sigma_x^2 \sum_{j \in \mathcal{Q} \backslash \{q\}} |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_j|^2 + \sigma^2_{\mathrm{node}}}. \tag{5.24}$$

For multicasting-mSPC strategy, each node has to perform self- or known-interference cancellation. After the self- or known-interference is perfectly cancelled, the SINR is given by

$$\gamma^p_{r_l} = \frac{\sigma_x^2 |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_q|^2}{2\sigma_x^2 \sum_{j \in \mathcal{Q} \backslash \{q\}} |\mathbf{h}^{\mathrm{T}}_{r_l} \mathbf{g}^p_j|^2 + \sigma^2_{\mathrm{node}}}. \tag{5.25}$$

The achievable rate at a receiving node r_l in the p-th phase is given by

$$R^p_{r_l} = \log_2 \left(1 + \gamma^p_{r_l}\right). \tag{5.26}$$

5.3.4 Overall Achievable Sum Rate

In regenerative two-way relaying, the rate at a receiving node r_l is defined by $\min(R^{\mathrm{MAC}}_{t_l}, R^{\mathrm{BC}}_{r_l})$ with $R^{\mathrm{MAC}}_{t_l}$ the MAC rate that is achieved by the RS from node t_l in the MAC phase and $R^{\mathrm{BC}}_{r_l}$ is the possible rate that can be achieved at node r_l from the RS [14]. In the following, we provide the overall achievable rate of MGMW relaying.

Unicasting Strategy

Considering the information flow from one transmitting node t_l to a receiving node r_l in the p-th phase, the information rate is defined by

$$R_{r_l,t_l} = \min\left(R_{t_l}^{\mathrm{MAC}}, R_{r_l}^{p}\right), \tag{5.27}$$

since the RS cannot transmit to node r_l with higher rate than what it received from node t_l in the MAC phase. The sum of the rates received at all $N_l - 1$ receiving nodes $r_l \in \mathcal{I}_l \setminus \{t_l\}$ when they receive from node t_l is defined by

$$R_{t_l} = \sum_{r_l \in \mathcal{I}_l \setminus \{t_l\}} R_{r_l,t_l}. \tag{5.28}$$

In regenerative MGMW relaying, the RS decodes all the received data streams and the data streams of all nodes are available at the RS prior to transmission in the BC phases. It is the task of the RS to transmit the re-encoded data streams to the nodes with a rate that can be correctly decoded by each intended receiving node. Due to the decoding and re-encoding at RS, the MAC phase and the BC phases are decoupled. Therefore, for unicasting strategy, we have (5.27) since in each BC phase, each node receives a different data stream from the RS and for each data stream, the RS cannot transmit with higher rate than what it received in the MAC phase. Hence, since a data stream from node t_l is received by $N_l - 1$ receiving nodes in different BC phases, the sum of the rates received at $N_l - 1$ receiving nodes is given by (5.28).

Hybrid Uni/Multicasting Strategy

For hybrid uni/multicasting strategy, in each BC phase the RS transmits two data streams for each group. One is the unicasted data stream which is fixed in all BC phases and the other one is the multicasted data stream which is different in each BC phase. Therefore, we have two kinds of sums of the rates. One relates to the data stream of a fixed node whose data stream is unicasted, namely $R_{r_l,t_{l_\mathrm{u}}}$, and the other one relates to the data streams of nodes whose data streams are multicasted sequentially in the BC phases, namely $R_{r_l,t_{l_\mathrm{m}}}, t_{l_\mathrm{m}} \in \mathcal{I} \setminus \{t_{l_\mathrm{u}}\}$. In the following, we first explain $R_{r_l,t_{l_\mathrm{u}}}$ and, afterwards, we explain $R_{r_l,t_{l_\mathrm{m}}}$.

Considering the information flow from a transmitting node t_{l_u} whose data stream is always unicasted in all BC phases, to a receiving node r_l in the p-th phase, the information rate is defined by

$$R_{r_l,t_{l_\mathrm{u}}} = \min\left(R_{t_{l_\mathrm{u}}}^{\mathrm{MAC}}, R_{r_l}^{p}\right), \tag{5.29}$$

with $r_l = t_{l_\mathrm{m}}$ since the node whose data stream is multicasted by the RS to $N_l - 1$ nodes in its group receives the unicasted data stream. The sum of the rates received at all nodes $r_l \in \mathcal{I}_l \setminus \{t_{l_\mathrm{u}}\}$ when they receive the data stream of node t_{l_u} is given by

$$R_{t_{l_\mathrm{u}}} = \sum_{r_l \in \mathcal{I}_l \setminus \{t_{l_\mathrm{u}}\}} R_{r_l, t_{l_\mathrm{u}}}. \tag{5.30}$$

Considering the information flow from a transmitting node t_{l_m} whose data stream is multicasted in the p-th phase to $N_l - 1$ receiving nodes r_l, $r_l \neq t_{l_\mathrm{m}}$, the information rate is given by

$$R_{r_l, t_{l_\mathrm{m}}} = \min\left(R_{t_{l_\mathrm{m}}}^{\mathrm{MAC}}, \min_{r_l \in \mathcal{I}_l \setminus \{t_{l_\mathrm{m}}\}} R_{r_l}^{p} \right), \tag{5.31}$$

since the RS has to ensure that all $N_l - 1$ receiving nodes can decode the data stream from node t_{l_m} correctly and that the RS cannot transmit with higher rate than what it received from node t_{l_m} in the MAC phase. The sum of the rates received at all nodes $r_l \in \mathcal{I}_l \setminus \{t_{l_\mathrm{m}}\}$ when they receive from node t_{l_m} is given by

$$R_{t_{l_\mathrm{m}}} = \sum_{r_l \in \mathcal{I}_l \setminus \{t_{l_\mathrm{m}}\}} R_{r_l, t_{l_\mathrm{m}}} = (N_l - 1) R_{r_l, t_{l_\mathrm{m}}}. \tag{5.32}$$

Multicasting-XOR Strategy

The RS performs bitwise XOR operation of two information bits from two nodes Sv_l and Sw_l. The rate received at node r_l when receiving from node t_l is given by

$$R_{r_l, t_l} = \min\left(\min\left(R_{v_l}^{\mathrm{MAC}}, R_{w_l}^{\mathrm{MAC}} \right), \min_{r_l \in \mathcal{I}_l} R_{r_l}^{p} \right). \tag{5.33}$$

The second part in (5.33) is since the RS has to ensure that all N_l receiving nodes are able to decode the multicasted data stream correctly. The first part is since the RS has to perform a bitwise-XOR operation of two information bit sequences. Since both bit sequences can be of different length, the RS needs to take the minimum out of those two. However, if zero padding (ZP) is applied to the shorter bit sequence such that both bit sequences are of the same length, we can perform XOR operation to both sequences without loosing any information bits, cf. [70]. Since there are known zeros that are added to the shorter bit sequence, if node r_l receives from node t_l with the longer bit sequence,

$$R_{r_l, t_l} = \min\left(\max\left(R_{v_l}^{\mathrm{MAC}}, R_{w_l}^{\mathrm{MAC}} \right), \min_{r_l \in \mathcal{I}_l} R_{r_l}^{p} \right), \tag{5.34}$$

and if node r_l receives from node t_l with the shorter bit sequence,

$$R_{r_l, t_l} = \min\left(\min\left(R_{v_l}^{\mathrm{MAC}}, R_{w_l}^{\mathrm{MAC}} \right), \min_{r_l \in \mathcal{I}_l} R_{r_l}^{p} \right). \tag{5.35}$$

The sum of the rates received at all $N_l - 1$ receiving nodes $r_l \in \mathcal{I}_l \setminus \{t_l\}$ when they receive from node t_l is defined by

$$R_{t_l} = \sum_{r_l \in \mathcal{I}_l \setminus \{t_l\}} R_{r_l,t_l}. \tag{5.36}$$

Multicasting-mSPC Strategy

The information rate at node r_l when receiving from node t_l is given by

$$R_{r_l,t_l} = \min\left(R_{t_l}^{\mathrm{MAC}}, \min_{r_l \in \mathcal{I}_l} R_{r_l}^{p}\right), \tag{5.37}$$

where t_l can be either v_l or w_l, with their relationship given in Section 5.2.2.3. Equation (5.37) is valid since the RS has to ensure that all receiving nodes can decode the corresponding data stream from either node v_l or w_l correctly and that the RS cannot transmit with higher rate than what it received from these nodes in the MAC phase. Note that it is important to ensure that all nodes are able to decode the received data streams correctly in each BC phase, since each node needs to perform self- and known-interference cancellation. The sum of the rates received at all $N_l - 1$ receiving nodes $r_l \in \mathcal{I}_l \setminus \{t_l\}$ when they receive from node t_l is defined by

$$R_{t_l} = \sum_{r_l \in \mathcal{I}_l \setminus \{t_l\}} R_{r_l,t_l}. \tag{5.38}$$

5.3.5 Sum Rate for Asymmetric Traffic

In regenerative MGMW relaying, the nodes in each group can communicate with different rate. In such situation, we have asymmetric traffic and the overall achievable sum rate for unicasting and multicasting strategies is given by

$$R_{\mathrm{asymm}} = \frac{1}{P} \sum_{l=1}^{L} \sum_{t_l \in \mathcal{I}_l} R_{t_l}, \tag{5.39}$$

while for hybrid uni/multicasting strategy, it is given by

$$R_{\mathrm{asymm}} = \frac{1}{P} \sum_{l=1}^{L} \left(R_{t_{l_{\mathrm{u}}}} + \sum_{t_{l_{\mathrm{m}}} \in \mathcal{I}_l \setminus t_{l_{\mathrm{u}}}} R_{t_{l_{\mathrm{m}}}} \right). \tag{5.40}$$

The pre-log factor $\frac{1}{P}$ factor is because of the half-duplex constraint which requires P channel uses to perform MGMW relaying.

5.3.6 Sum Rate for Symmetric Traffic

In certain applications, the nodes in each group should communicate with the same data rate. In such situation, we have symmetric traffic. The overall rate is now defined by the minimum rate among all the links in the group. The achievable sum rate for unicasting and multicasting strategies is given by

$$R_{\text{symm}} = \frac{1}{P} \sum_{l=1}^{L} N_l \left(N_l - 1\right) \min_{\{r_l, t_l\} \in \mathcal{I}_l, r_l \neq t_l} R_{r_l, t_l}, \tag{5.41}$$

while for hybrid uni/multicasting strategy, it is

$$R_{\text{symm}} = \frac{1}{P} \sum_{l=1}^{L} N_l \left(N_l - 1\right) \min \left(\min_{r_l \in \mathcal{I}_l \setminus \{t_{l_\text{u}}\}} R_{r_l, t_{l_\text{u}}}, \min_{t_{l_\text{m}} \in \mathcal{I}_l \setminus \{t_{l_\text{u}}\}, r_l \in \mathcal{I}_l \setminus \{t_{l_\text{m}}\}} R_{r_l, t_{l_\text{m}}} \right). \tag{5.42}$$

5.4 Transmit Beamforming

5.4.1 Introduction

In regenerative MGMW relaying, the RS decodes all the received data streams from the nodes and re-encodes them. In order to transmit the regenerated data streams to the nodes according to the chosen BC strategy, the RS need to apply appropriate transmit beamforming. In the following, we explain the reasoning for transmit beamforming algorithms which are designed in this thesis for regenerative MGMW relaying in Section 5.4.2. The design of transmit beamforming minimising the RS's transmit power is explained in Section 5.4.3. It is followed by the design of low complexity linear transmit beamforming under three different optimisation criteria, namely, MF, ZF and MMSE, in Section 5.4.4. Finally, we introduce BCSA transmit beamforming for regenerative MGMW relaying in Section 5.4.5.

5.4.2 Reasoning for Transmit Beamforming

In this thesis, we first design generalised transmit beamforming algorithm for all BC strategies minimising the RS's transmit power while ensuring that each node receives with a rate equal to the received rate at the RS for each particular data stream. Given any multi-user detector, our designed transmit beamforming will ensure that the MAC rate achieved at the RS is also achieved at the nodes. Afterwards, we design low complexity linear transmit beamforming algorithms, namely, MF, ZF and MMSE. Also, we introduce BCSA transmit beamforming. The reasons for considering MF, ZF, MMSE and BCSA transmit beamforming are the same as the reasons explained in Chapter 4.

5.4.3 Minimisation of RS's Transmit Power

The information rate at node r_l when it receives from node t_l is defined by the minimum between the MAC rate and the BC rate. Since before the transmission in each BC phase, the RS knows already $R_i^{\mathrm{MAC}}, \forall i \in \mathcal{I}$, the optimum transmit strategy at the RS is to ensure that each receiving node r_l receives the data streams from node t_l with the rate equal to $R_{t_l}^{\mathrm{MAC}}$. However, since the transmit power at the RS is a limited resource, we have to minimise the use of it. Therefore, in this work, we propose optimum transmit beamforming which achieves the aim while minimising the transmit power at the RS.

The optimisation problem can be written as

$$\min_{\mathbf{G}} \mathrm{E}\{\|\mathbf{G}\mathbf{\Pi}_{\mathrm{d}}^{p}\mathbf{x}_{\mathrm{RS}}^{p}\|^2\} \quad \text{s.t.} \quad \gamma_{r_l}^{p} \geq \gamma_{t_l}^{\mathrm{MAC}}, \tag{5.43}$$

with $\gamma_{r_l}^{p}$ of (5.23) or (5.25) depending on the chosen BC strategy, and $\gamma_{t_l}^{\mathrm{MAC}}$ given in (5.20). For multicasting strategy, since the RS transmits a common message which is an output of a linear operation of two data streams, x_{v_l} and x_{w_l},

$$\gamma_{t_l}^{\mathrm{MAC}} = \max\left(\gamma_{v_l}^{\mathrm{MAC}}, \gamma_{w_l}^{\mathrm{MAC}}\right) \tag{5.44}$$

has to be used to achieve the MAC rate.

Different to previous works in regenerative (two-way) relaying, which decouple the MAC and BC phase, by (5.43) we couple the MAC and BC phases. The idea comes from the fact that the RS knows already the MAC rate prior to BC transmission, and it can use this information for optimising the transmission in the BC phases. The constraint in (5.43) shows the coupling of MAC and BC phases, where $\gamma_{r_l}^{p}$ and $\gamma_{t_l}^{\mathrm{MAC}}$ are the MAC-BC coupling parameters. This constraint ensures the transmission of rate $R_{t_l}^{\mathrm{MAC}}$ for each corresponding receiving node r_l in each p-th BC phase. Even though in this work we consider MMSE-SIC detector to achieve the optimum MAC rate, our proposal can be used for any multi-user detector.

Asumming mutually uncorrelated symbols in $\mathbf{x}_{\text{RS}}^{p}$ with $\sigma_x^2 = 1$, (5.43) can be written as

$$\min_{\mathbf{g}_q^p \forall q \in \mathcal{Q}} \alpha \cdot \sum_{q \in \mathcal{Q}} \|\mathbf{g}_q^p\|_2^2 \quad \text{s.t.} \quad \gamma_{r_l}^p \geq \gamma_{t_l}^{\text{MAC}}. \tag{5.45}$$

The optimisation problem in (5.45) is valid for all BC strategies when properly relating the index variables r_l, t_l, q and p. The scalar factor α depends on the BC strategy. For unicasting, hybrid uni/multicasting and multicasting-XOR $\alpha = 1$, while for multicasting-mSPC $\alpha = 2$ due to the superposition of two symbols in $\mathbf{x}_{\text{RS}}^{p}$.

Since α is only a scalar factor, it may be omitted from (5.45). Equation (5.45) is similar to the optimisation problem treated in [114] for downlink unicast beamforming with Quality of Service (QoS) constraint, in [110] for single-group multicast beamforming and in [111] for multi-group multicast beamforming with QoS constraint. It can be treated as the problem in [114] if $\mid \mathcal{Q} \mid= N$, i.e., unicasting strategy, or as the problem in [110] if $\mid \mathcal{Q} \mid= 1$, i.e., multicasting strategy with $L = 1$, or as the problem in [111] if $\mid \mathcal{Q} \mid= L$ and $L > 1$, i.e., multicasting strategies with $L > 1$, and if $\mid \mathcal{Q} \mid= 2L$, i.e., hybrid uni/multicasting, with $\mid \cdot \mid$, in this case, the cardinality of a set. Since if we have multicasting strategy with $L = 1$ the problem associates to [110], (5.45) is NP-hard [111].

By defining,

$$\mathbf{X}_q^p = \mathbf{g}_q^p \mathbf{g}_q^{p\text{H}}, \tag{5.46}$$

$$\mathbf{W}_{r_l} = \mathbf{h}_{r_l}^* \mathbf{h}_{r_l}^{\text{T}}, \tag{5.47}$$

and by dropping the rank-one constraint, we can rewrite (5.43) into

$$\begin{aligned} &\min_{\mathbf{X}_q^p \forall q \in \mathcal{Q}} \sum_{q \in \mathcal{Q}} \operatorname{tr}\left(\mathbf{X}_q^p\right) \\ &\text{s.t. } \operatorname{tr}\left(\mathbf{W}_{r_l}\mathbf{X}_q^p\right) - \alpha\gamma_{t_l}^{\text{MAC}} \sum_{j \in \mathcal{Q}\setminus\{q\}} \operatorname{tr}\left(\mathbf{W}_{r_l}\mathbf{X}_j^p\right) \geq \gamma_{t_l}^{\text{MAC}} \sigma_{\text{node}}^2 \\ &\mathbf{X}_q^p \succeq \mathbf{0}. \end{aligned} \tag{5.48}$$

Let us define

$$\varkappa = \left[\operatorname{vec}\left(\mathbf{X}_1\right), \cdots, \operatorname{vec}\left(\mathbf{X}_Q\right)\right] \tag{5.49}$$

with $\operatorname{vec}(\cdot)$ the vectorisation of a matrix, and a $Q \times 1$ vector

$$\mathbf{a}_{r_l} = \left[\left(\alpha\gamma_{t_l}^{\text{MAC}} + 1\right)\mathbf{e}_{r_l} - \alpha\gamma_{t_l}^{\text{MAC}}\mathbf{1}_Q\right] \tag{5.50}$$

where $\mathbf{e}_{r_l}$ is a $Q \times 1$ vector with all zero elements except for its q-th element which has a value of one, and $\mathbf{1}_Q$ is a $Q \times 1$ vector of ones. We can rewrite (5.48) as

$$\begin{aligned} &\min_{\varkappa} \left[\mathbf{1}_Q \otimes \operatorname{vec}\left(\mathbf{I}_M\right)\right]^{\text{T}} \operatorname{vec}\left(\varkappa\right) \\ &\text{s.t. } \left[\mathbf{a}_{r_l} \otimes \operatorname{vec}\left(\mathbf{W}\right)^{\text{T}}\right]^{\text{T}} - s_{r_l} = \gamma_{t_l}^{\text{MAC}} \sigma_{\text{node}}^2, \\ &\mathbf{X}_q^p \succeq \mathbf{0}, \end{aligned} \tag{5.51}$$

with $s_{r_l}, \forall r_l$, slack variables to convert the inequality constraints into equality ones. Equation (5.51) is a semidefinite program which can be solved using SeDuMi solver [112].

Note that for the unicasting case, since the problem associates to the problem in [114], (5.48) is not a relaxation, but indeed equivalent to (5.45). However for hybrid uni/multicasting and multicasting strategies, by dropping the rank-one constraint, the solution may be of higher rank. Therefore, one of the randomisation techniques as given in [110] needs to be performed. After finding the optimum transmit beamforming, the required transmit power at the RS is given by

$$E_{\mathrm{RS}_{\min}} = \mathrm{tr}\left(\mathbf{G}\mathbf{G}^{\mathrm{H}}\right). \tag{5.52}$$

5.4.4 Linear Transmit Beamforming

5.4.4.1 Introduction

Given the system model as in Section 5.2, we intend to design generalised low complexity transmit beamforming algorithms for all BC strategies. Consequently, in this subsection, it is assumed that $M > N$. For the design of transmit beamforming algorithms based on MF, ZF and MMSE, permutation matrix $\mathbf{\Pi}_{\mathrm{G}}^{p}$ is needed. Note that $\mathbf{\Pi}_{\mathrm{G}}^{p}$ consists of $\mathbf{e}_{r_l}^{\mathrm{T}}$ in its r_l-th row. Table 5.2 provides $\mathbf{\Pi}_{\mathrm{G}}^{p}$ for the example given in Figure 3.3.

5.4.4.2 Matched Filter

The MF optimisation problem can be written as

$$\begin{aligned} \mathbf{G}_{\mathrm{MF}}^{p} = \underset{\mathbf{G}^{p}}{\mathrm{argmax}} & \frac{|\mathrm{E}\{\mathbf{s}^{p\mathrm{H}}\mathbf{y}_{\mathrm{nodes}}^{p}\}|^2}{\mathrm{E}\{\|\mathbf{s}^{p}\|^2\}\mathrm{E}\{\|\mathbf{z}_{\mathrm{nodes}}^{p}\|^2\}} \\ \text{s.t. } & \mathrm{E}\{\|\mathbf{G}^{p}\mathbf{s}^{p}\|^2\} \leq E_{\mathrm{RS}}, \end{aligned} \tag{5.53}$$

with E_{RS} the RS transmit power contstraint and

$$\begin{aligned} \mathbf{s}^{p} &= \mathbf{\Pi}_{\mathrm{G}}^{p}\mathbf{d}_{\mathrm{RS}}^{p}, \\ \mathbf{d}_{\mathrm{RS}}^{p} &= \mathbf{\Pi}_{\mathrm{d}}^{p}\mathbf{x}_{\mathrm{RS}}^{p}. \end{aligned} \tag{5.54}$$

Equation (5.53) can be rewritten as

$$\begin{aligned} \mathbf{G}_{\mathrm{MF}}^{p} = \underset{\mathbf{G}^{p}}{\mathrm{argmax}} & \frac{|\mathrm{E}\{\{\mathbf{\Pi}_{\mathrm{G}}^{p}\mathbf{\Pi}_{\mathrm{d}}^{p}\mathbf{x}_{\mathrm{RS}}^{p}\}^{\mathrm{H}}\mathbf{y}_{\mathrm{nodes}}^{p}\}|^2}{\mathrm{E}\{\|\mathbf{\Pi}_{\mathrm{G}}^{p}\mathbf{\Pi}_{\mathrm{d}}^{p}\mathbf{x}_{\mathrm{RS}}^{p}\|^2\}\mathrm{E}\{\|\mathbf{z}_{\mathrm{nodes}}^{p}\|^2\}} \\ \text{s.t. } & \mathrm{E}\{\|\mathbf{G}^{p}\mathbf{\Pi}_{\mathrm{G}}^{p}\mathbf{\Pi}_{\mathrm{d}}^{p}\mathbf{x}_{\mathrm{RS}}^{p}\|^2\} \leq E_{\mathrm{RS}}. \end{aligned} \tag{5.55}$$

Table 5.2. Permutation Matrices $\mathbf{\Pi}_{\mathrm{G}}^{2}$ and $\mathbf{\Pi}_{\mathrm{G}}^{3}$ for the example of Figure 3.3

	$\mathbf{\Pi}_{\mathrm{G}}^{2}$	$\mathbf{\Pi}_{\mathrm{G}}^{3}$
Unicasting	$\begin{pmatrix} 1&0&0&0&0&0\\ 0&1&0&0&0&0\\ 0&0&1&0&0&0\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0\\ 0&0&0&0&0&1 \end{pmatrix}$	$\begin{pmatrix} 1&0&0&0&0&0\\ 0&1&0&0&0&0\\ 0&0&1&0&0&0\\ 0&0&0&1&0&0\\ 0&0&0&0&1&0\\ 0&0&0&0&0&1 \end{pmatrix}$
Uni/Multicasting	$\begin{pmatrix} 0&1&0&0\\ 1&0&0&0\\ 0&1&0&0\\ 0&0&0&1\\ 0&0&1&0\\ 0&0&0&1 \end{pmatrix}$	$\begin{pmatrix} 0&1&0&0\\ 0&1&0&0\\ 1&0&0&0\\ 0&0&0&1\\ 0&0&0&1\\ 0&0&1&0 \end{pmatrix}$
Multicasting	$\begin{pmatrix} 1&0\\ 1&0\\ 1&0\\ 0&1\\ 0&1\\ 0&1 \end{pmatrix}$	$\begin{pmatrix} 1&0\\ 1&0\\ 1&0\\ 0&1\\ 0&1\\ 0&1 \end{pmatrix}$

Using Lagrangian multiplier method, i.e., following the same procedure as in [104,108], we obtain

$$\mathbf{G}_{\mathrm{MF}}^{p} = \beta^{p} \underline{\mathbf{G}}_{\mathrm{MF}}^{p}, \tag{5.56}$$

with

$$\underline{\mathbf{G}}_{\mathrm{MF}}^{p} = \mathbf{H}^{*} \mathbf{\Pi}_{\mathrm{G}}^{p} \tag{5.57}$$

and β^{p} a normalisation factor to fulfill the transmit power constraint at the RS given by

$$\beta^{p} = \sqrt{\frac{E_{\mathrm{RS}}}{\sigma_x^2 \ \mathrm{tr}\left(\underline{\mathbf{G}}_{\mathrm{MF}}^{p} \mathbf{\Pi}_{\mathrm{d}}^{p} \mathbf{\Pi}_{\mathrm{d}}^{p\mathrm{H}} \underline{\mathbf{G}}_{\mathrm{MF}}^{p\mathrm{H}}\right)}}. \tag{5.58}$$

5.4.4.3 Zero Forcing

The optimisation problem of an MMSE with ZF constraint can be written as

$$\begin{aligned} \mathbf{G}_{\mathrm{ZF}}^{p} &= \underset{\mathbf{G}^{p}}{\mathrm{argmin}}\ \mathrm{E}\{\|\hat{\mathbf{s}}^{p} - \mathbf{s}^{p}\|^{2}\} \\ \text{s.t. } & \mathrm{E}\{\|\mathbf{G}^{p} \mathbf{\Pi}_{\mathrm{G}}^{p} \mathbf{\Pi}_{\mathrm{d}}^{p} \mathbf{x}_{\mathrm{RS}}^{p}\|^{2}\} \le E_{\mathrm{RS}}, \\ & \hat{\mathbf{s}}^{p} = \mathbf{s}^{p} \text{ iff } \mathbf{z}_{\mathrm{nodes}}^{p} = 0, \end{aligned} \tag{5.59}$$

where the second constraint is the ZF constraint and $\hat{\mathbf{s}}^p$ is a vector of the corresponding detected symbols at the nodes and $\mathbf{s}^p$ as in (5.54).

The ZF constraint leads to

$$\mathbf{H}^{\mathrm{T}}\mathbf{G}^p\mathbf{\Pi}_{\mathrm{G}}^p\mathbf{\Pi}_{\mathrm{d}}^p\mathbf{x}_{\mathrm{RS}}^p = \mathbf{\Pi}_{\mathrm{G}}^p\mathbf{\Pi}_{\mathrm{d}}^p\mathbf{x}_{\mathrm{RS}}^p \tag{5.60}$$

which requires

$$\mathbf{H}^{\mathrm{T}}\mathbf{G}^p = \mathbf{I}. \tag{5.61}$$

Finally, we obtain

$$\mathbf{G}_{\mathrm{ZF}}^p = \beta^p\underline{\mathbf{G}}_{\mathrm{ZF}}^p, \tag{5.62}$$

where

$$\underline{\mathbf{G}}_{\mathrm{ZF}}^p = \mathbf{H}^*\left(\mathbf{H}^{\mathrm{T}}\mathbf{H}^*\right)^{-1}\mathbf{\Pi}_{\mathrm{G}}^p \tag{5.63}$$

and β^p is solved for the first constraint and is given by (5.58) by replacing $\underline{\mathbf{G}}_{\mathrm{MF}}^p$ with $\underline{\mathbf{G}}_{\mathrm{ZF}}^p$.

5.4.4.4 Minimum Mean Square Error

The MMSE optimisation problem can be written as

$$\begin{aligned} \mathbf{G}_{\mathrm{MMSE}}^p = \underset{\mathbf{G}^p}{\operatorname{argmin}}\ \mathrm{E}\{\|\hat{\mathbf{s}}^p - \mathbf{\Pi}_{\mathrm{G}}^p\mathbf{\Pi}_{\mathrm{d}}^p\mathbf{x}_{\mathrm{RS}}^p\|^2\} \\ \text{s.t. } \mathrm{E}\{\|\mathbf{G}^p\mathbf{\Pi}_{\mathrm{G}}^p\mathbf{\Pi}_{\mathrm{d}}^p\mathbf{x}_{\mathrm{RS}}^p\|^2\} \leq E_{\mathrm{RS}}. \end{aligned} \tag{5.64}$$

Using Lagrangian multiplier method, i.e., following the same procedure as in [104,108], we obtain

$$\mathbf{G}_{\mathrm{MMSE}}^p = \beta^p\underline{\mathbf{G}}_{\mathrm{MMSE}}^p, \tag{5.65}$$

with

$$\underline{\mathbf{G}}_{\mathrm{MMSE}}^p = \mathbf{H}^*\left(\mathbf{H}^{\mathrm{T}}\mathbf{H}^* + \frac{N\sigma_{\mathrm{node}}^2}{P_{\mathrm{RS}}}\mathbf{I}_N\right)^{-1}\mathbf{\Pi}_{\mathrm{G}}^p \tag{5.66}$$

and β^p given by (5.58) by replacing $\underline{\mathbf{G}}_{\mathrm{MF}}^p$ with $\underline{\mathbf{G}}_{\mathrm{MMSE}}^p$.

5.4.5 BCSA Transmit Beamforming

5.4.5.1 Introduction

BCSA transmit beamforming is designed to directly suit the system model. Therefore, permutation matrix $\mathbf{\Pi}_{\mathrm{G}}^p$ is not needed. BCSA transmit beamforming is decomposed into two steps. The first step is to separate the nodes according to the transmitted data streams from the RS. The nodes who are receiving the same data stream from the RS are considered as one stream-group. Therefore, the number of stream-groups is equal to the cardinality of $\mathcal{Q}$. We make stream-group separation by using BD proposed in [100] and RBD proposed in [103]. The results of the first step are the equivalent channels of each stream-group.

In the second step, we compute the precoding vector for each stream-group. In this work, we consider MF and semidefinite relaxation (SDR) of maximisation of minimum SNR. We do not consider SVD since it has been shown in Chapter 4 that for non-regenerative MGMW relaying, SVD performs worse than MF and SDR.

5.4.5.2 Equivalent Channel

Given the channel matrix of a stream-group who receives the data stream $d^p_{\mathrm{RS}_q}$ from the RS as $\mathbf{H}_q^{\mathrm{T}} \in \mathbb{C}^{\eta_q \times M}$, with η_q the number of nodes who receive the data stream $d^p_{\mathrm{RS}_q}$, and the channel matrix of all other nodes in other stream-groups, $\tilde{\mathbf{H}}_q^{\mathrm{T}} \in \mathbb{C}^{(N-\eta_q)\times M}$, we compute the equivalent downlink channel matrix of stream-group q,

$$\mathbf{H}_q^{\mathrm{eq}} = \mathbf{H}_q^{\mathrm{T}} \mathbf{F}_q. \tag{5.67}$$

In order to obtain the null-space matrix $\mathbf{F}_q$ of stream-group q, we perform singular value decomposition of $\tilde{\mathbf{H}}_q^{\mathrm{T}}$ given by

$$\tilde{\mathbf{H}}_q^{\mathrm{T}} = \mathbf{U}_q \boldsymbol{\Sigma}_q \underbrace{[\mathbf{V}_q^1 \mathbf{V}_q^0]}_{\mathbf{V}_q}, \tag{5.68}$$

where $\mathbf{V}_q^0$ holds the last $(M - \tilde{f}_q)$ right singular vectors of $\mathbf{V}_q$ with $\tilde{f}_q$ the rank of $\tilde{\mathbf{H}}_q^{\mathrm{T}}$. For BD,

$$\mathbf{F}_q = \mathbf{V}_q^0, \tag{5.69}$$

cf. [100] and for RBD,

$$\mathbf{F}_q = \mathbf{V}_q \left(\Sigma_q^{\mathrm{T}} \Sigma_q + \frac{N\sigma^2_{\mathrm{node}}}{E_{\mathrm{RS}}} \mathbf{I}_M \right), \tag{5.70}$$

cf. [103].

5.4.5.3 Precoding for Equivalent Channel

After having the equivalent channel of each stream-group, we make the precoding for the equivanet channel. In the following, the MF algorithm is explained followed by the explanation of SDR of maximisation of minimum SNR.

Matched Filter

The transmit beamforming vector of stream-group q is given by

$$\mathbf{m}_q = \mathbf{F}_q \mathbf{H}_q^{\mathrm{eqH}}. \tag{5.71}$$

Semidefinite Relaxation

We consider a fair algorithm for the transmit beamforming. The algorithm aims at balancing the SNRs at the receiving nodes in each group. This is in line with the fact that in MGMW relaying, multiple nodes in each group communicate with each other. Thus, we maximise the minimum SNR among the nodes in stream-group q.

For transmit beamforming of stream-group q, the SNR balancing problem can be written as

$$\begin{aligned} &\underset{\mathbf{m}_{\mathrm{SDR}_q}}{\operatorname{argmax}} \ \min_{i_q \in \Phi_q} \left| \frac{\mathbf{m}_{\mathrm{SDR}_q} \mathbf{h}_{i_q}^{\mathrm{eq}}}{\sigma_{z_{\mathrm{node}}}^2} \right|^2 \\ &\text{s.t. } \|\mathbf{m}_{\mathrm{SDR}_q}\|_2^2 \leq 1, \end{aligned} \tag{5.72}$$

with Φ_q the set of the nodes who are intended to receive the data stream $d_{\mathrm{RS}_q}^p$ and $|\Phi_q| = \eta_q$. Equation (5.72) is a non-convex quadratically constrained quadratic program and is proved to be NP-hard in [110]. Nonetheless, it can be approximately solved using SDR techniques [110, 111]. It can be rewritten into a semidefinite program as in [110] and, thus, it can be solved using SEDUMI [112]. The bounds on the approximation error of the SDR techniques have been developed in [113]. The transmit beamforming vector of stream-group q is given by

$$\mathbf{m}_q = \mathbf{F}_q \mathbf{m}_{\mathrm{SDR}_q}, \tag{5.73}$$

The p-th Phase BCSA Transmit Beamforming

The transmit beamforming matrix $\mathbf{G}_{\mathrm{Tx}}^p$ is given by

$$\mathbf{G}_{\mathrm{Tx}}^p = [\mathbf{m}_1, \cdots, \mathbf{m}_Q]. \tag{5.74}$$

In order to satisfy the transmit power constraint at the RS, a normalisation factor

$$\beta^p = \sqrt{\frac{E_{\mathrm{RS}}}{\sigma_x^2 \mathrm{tr}\left\{\mathbf{G}_{\mathrm{Tx}}^p \mathbf{\Pi}_{\mathrm{d}}^p \mathbf{\Pi}_{\mathrm{d}}^{p\mathrm{H}} \mathbf{G}_{\mathrm{Tx}}^{p\ \mathrm{H}}\right\}}} \tag{5.75}$$

is needed. Finally, the BCSA transmit beamforming $\mathbf{G}^p$ is given by

$$\mathbf{G}^p = \beta^p \mathbf{G}_{\mathrm{Tx}}^p. \tag{5.76}$$

5.5 Simulation Results

5.5.1 Introduction

In this section, we provide the simulation results to analyse the sum rate performance. In the first scenario, we consider single-group multi-way relaying with $L = 1$, $N_1 = 3$ and $M = N_1 = 3$. In the second scenario, we consider MGMW relaying with $L = 2$, $N_1 = N_2 = 3$ and $M = N = N_1 + N_2 = 6$. We only provide one scenario for single-group since in regenerative MGMW relaying both scenarios considered in Section 4.5.2 will have the same trends in performance. We also consider only one scenario for multi-group since in regenerative MGMW relaying both scenarios considered in Section 4.5.3 will have the same trends in performance. We set $\sigma^2_{z_{\text{RS}}} = \sigma^2_{z_{\text{node}}} = 1, \sigma^2_x = 1$. The channel coefficients are i.i.d. $\mathcal{CN}(0, \sigma^2_h)$, i.e., Rayleigh fading, and the SNR is defined by σ^2_h. We analyse the sum rate performance of regenerative MGMW relaying for single-group in Section 5.5.2 and for multi-group in Section 5.5.3. The following acronyms are used in the figures, namely, UC for unicasting, U/MC for hybrid uni/multicasting, MC-XOR for multicasting with XOR, MC-XOR-ZP for multicasting with XOR and zerro padding, and MC-mSPC for multicasting with mSPC.

5.5.2 Single-Group Multi-Way Relaying

Figure 5.1 shows the average minimum required power at the RS using the optimum transmit beamforming minimising the RS's transmit power while guaranteeing that each node receives with a rate equal to the rate received at the RS for different SNR values from 0 dB to 30 dB. The values in y-axis are the averages of 300 channel realisations where RandC as in [110] was used as the randomisation technique. Multicasting-XOR requires the least power followed by the hybrid uni/multicasting, unicasting and multicasting-mSPC strategies. Since with multicasting-XOR the RS transmits only one data stream to all nodes, there is no interference in the network. Moreover, since the linear operation is performed in bit level, there is no loss in power received at the nodes. Multicasting-mSPC performs worse since within the received data stream, each node only receives half portion of the power and, thus, the RS has to spent more power to ensure that each node receives with a rate equal to the rate received at the RS. Hybrid uni/multicasting has lower interference compared to unicasting, and thus it requires less power. The optimum transmit beamforming ensures that the achievable MAC rate is achieved at the nodes, which is denoted as the MAC bound in the following simulation figures.

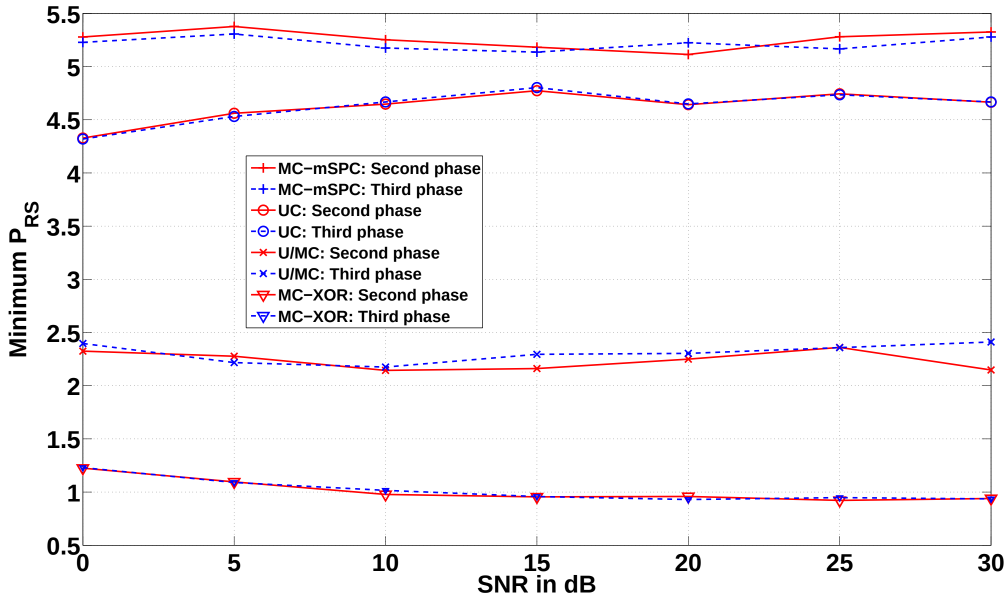


Figure 5.1. Minimum P_{RS} for single-group scenario

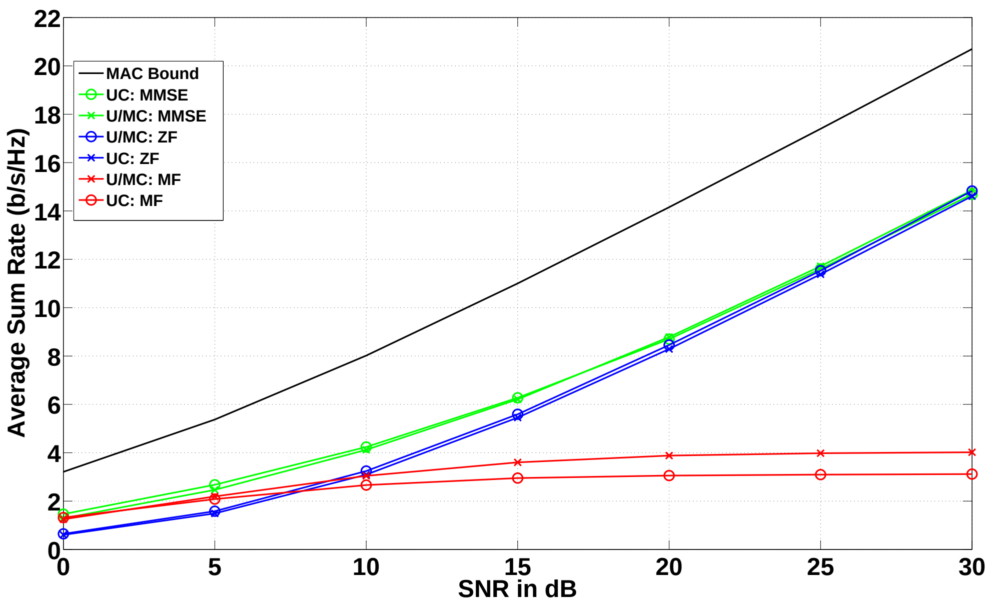


Figure 5.2. Sum rate performance of single-group scenario with MF, ZF and MMSE: Unicasting and hybrid uni/multicasting

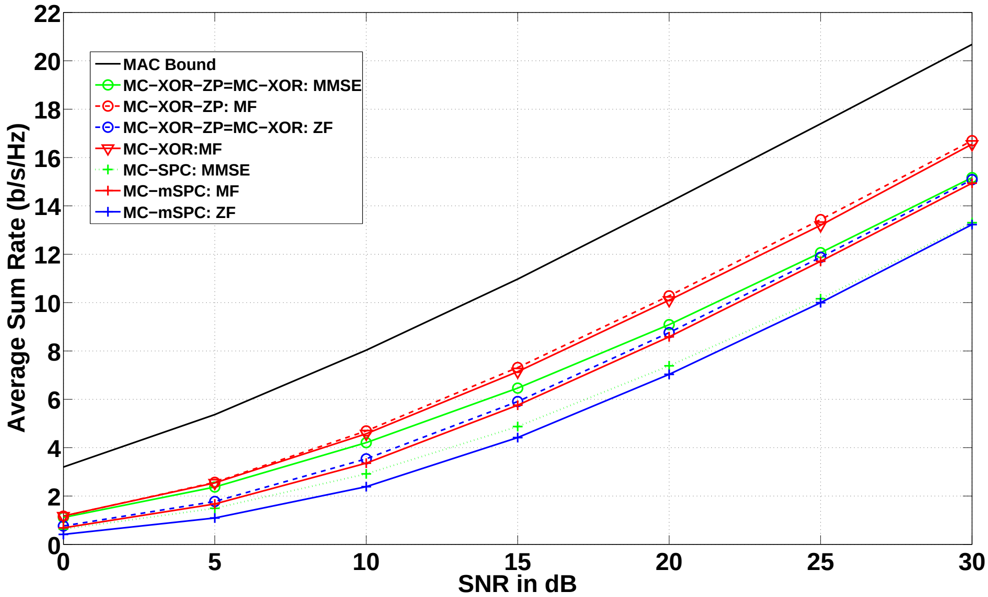


Figure 5.3. Sum rate performance of single-group scenario with MF, ZF and MMSE: Multicasting-XOR with and without zero padding and multicasting-mSPC

In order to assess the BC strategies for MGMW relaying with low complexity transmit beamforming algorithms, we perform 10000 channel realisations and we set $E_{\text{RS}} = 1$. As asymmetric traffic leads to a better sum rate, in the following, we consider only asymmetric traffic.

Figure 5.2 shows the sum rate performance of unicasting and hybrid uni/multicasting strategies with MF, ZF, and MMSE transmit beamforming. For both strategies, MMSE performs best. At high SNR, ZF converges to MMSE and at low SNR, MF converges to MMSE. Using MMSE and ZF, the performance of hybrid uni/multicasting strategy and unicasting strategy is quite similar. Using MF, hybrid uni/multicasting strategy outperforms unicasting strategy since it has lower inter-stream interference. Since MF does not manage the interference, in high SNR region, it performs worse than MMSE and ZF.

Figure 5.3 shows the performance of the multicasting strategy with MF, ZF and MMSE transmit beamforming. In this scenario, since using multicasting strategy there is no interstream interference, MF performs better than MMSE and ZF. This is as expected since in single-group scenario there is no same-group-inter-stream interferences and, thus, MF outperforms MMSE and ZF. As can be clearly seen, multicasting-XOR outperforms multicasting-mSPC. mSPC adds two symbols, consequently, the power is divided to both symbols. Using XOR, there is only one transmitted symbol, since the

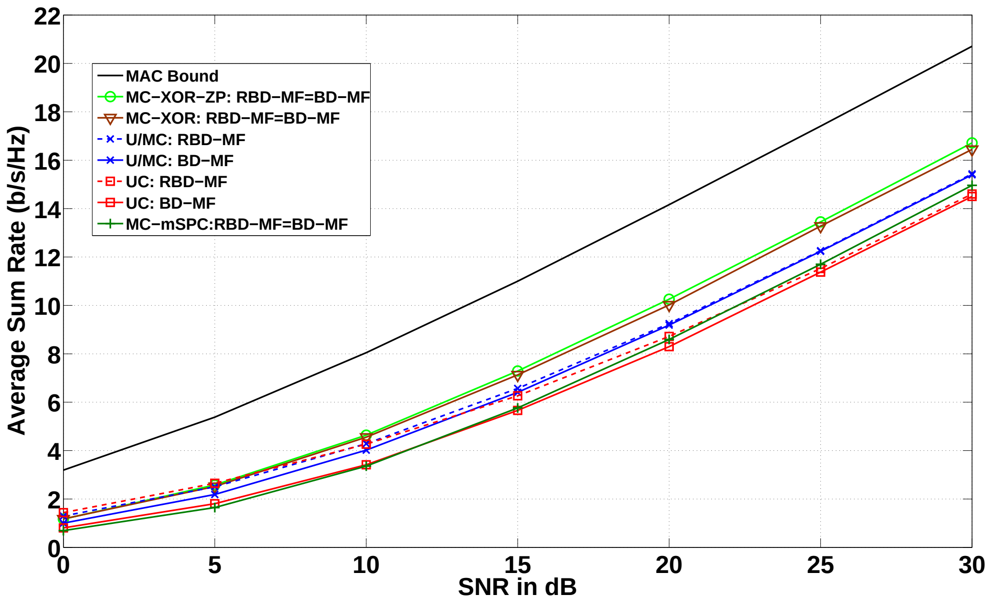


Figure 5.4. Sum rate performance of single-group scenario with BCSA MF

network coding is performed at bit level. For multicasting-XOR strategy, ZP improve the sum rate when MF is used. Using MMSE and ZF there is no performance improvement when ZP is applied. This shows that MF provides higher minimum BC rate compared to MMSE and ZF, which in some channel realisations is higher than the maximum MAC rate of both linearly operated data streams. Comparing both Fig. 5.2 and 5.3, multicasting-XOR outperforms both unicasting and hybrid uni/multicasting. However, multicasting-mSPC performs worse than the others.

Figures 5.4 and 5.5 show the BC strategies with BCSA MF and BCSA SDR, respectively. For all BC strategies, the BCSA SDR outperforms BCSA MF and they perform better than MF, ZF and MMSE. In general, multicasting-XOR performs best and the performance improvement using ZP is higher when using BCSA SDR. This is due to the fact that BCSA SDR balances the SNR and, thus, it increases the minimum BC rates among the receiving nodes. This is also the reason why multicasting-mSPC outperforms the other BC strategies. Using BCSA SDR, one can clearly see that multicasting strategy performs best followed by hybrid uni/multicasting and unicasting strategies. Another important analysis is that RBD outperforms BD. The higher the value of Q one strategy has, the higher the gain of RBD against BD. This is also the reason why for multicasting strategy there is no improvement when using RBD, since in this scenario, only one data stream is transmitted to the nodes. Even though there is a performance improvement using RBD, in high SNR, BD converges to RBD. The reason is the same as why ZF converges to MMSE in high SNR region. Both BD and ZF only consider

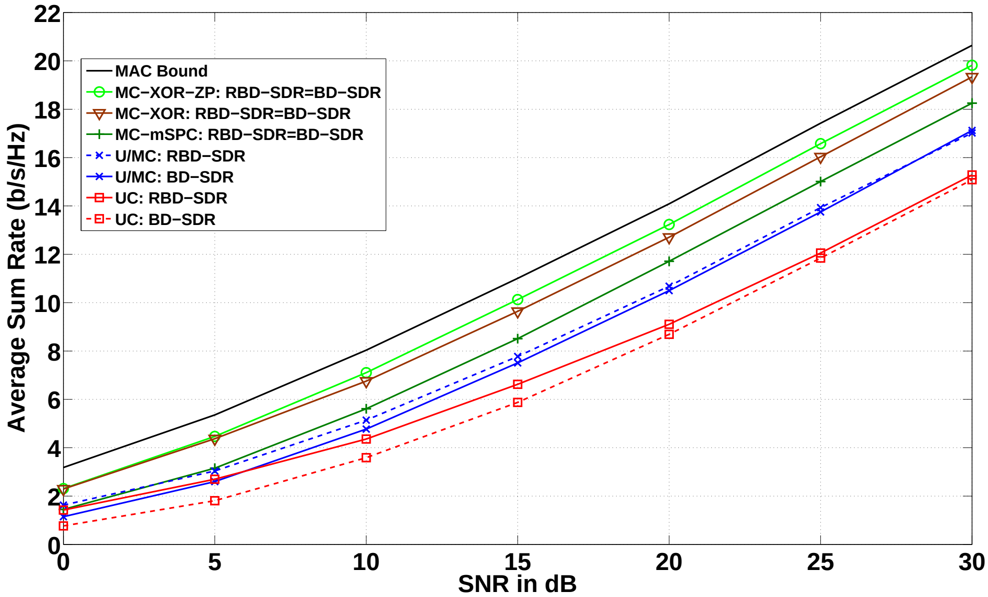


Figure 5.5. Sum rate performance of single-group scenario with BCSA SDR

the interference and try to suppress it at the expense of a noise enhancement. On the other hand, both RBD and MMSE find a trade off between interference suppression and noise enhancement.

5.5.3 Multi-Group Multi-Way Relaying

Figure 5.6 shows the average minimum required power at the RS using the optimum transmit beamforming minimising the RS's transmit power while guaranteeing that each node receives with a rate equal to the rate received at the RS for different SNR values from 0 dB to 30 dB. The values in y-axis are the averages of 300 channel realisations where RandC as in [110] was used as the randomisation technique. Multicasting-XOR requires the least transmit power followed by the hybrid uni/multicasting, unicasting and multicasting-mSPC strategies with the same reasons as explained in Section 5.5.2

Figure 5.7 shows the sum rate performance of the BC strategies using MF, ZF and MMSE for the second scenario. Looking at MF and ZF transmit beamforming, multicasting-XOR performs best followed by hybrid uni/multicasting and unicasting. While in high SNR region, MMSE shows the same performance as ZF, in low SNR region, unicasting performs best followed by hybrid uni/multicasting. The higher the value of Q one BC strategy has, the better the performance in low SNR region when

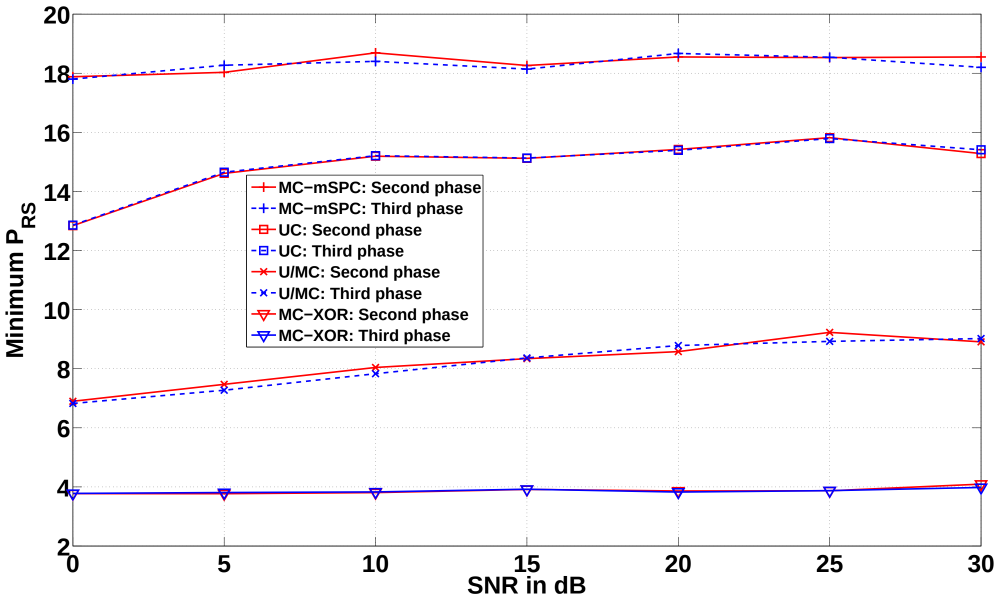


Figure 5.6. Minimum P_{RS} for multi-group scenario

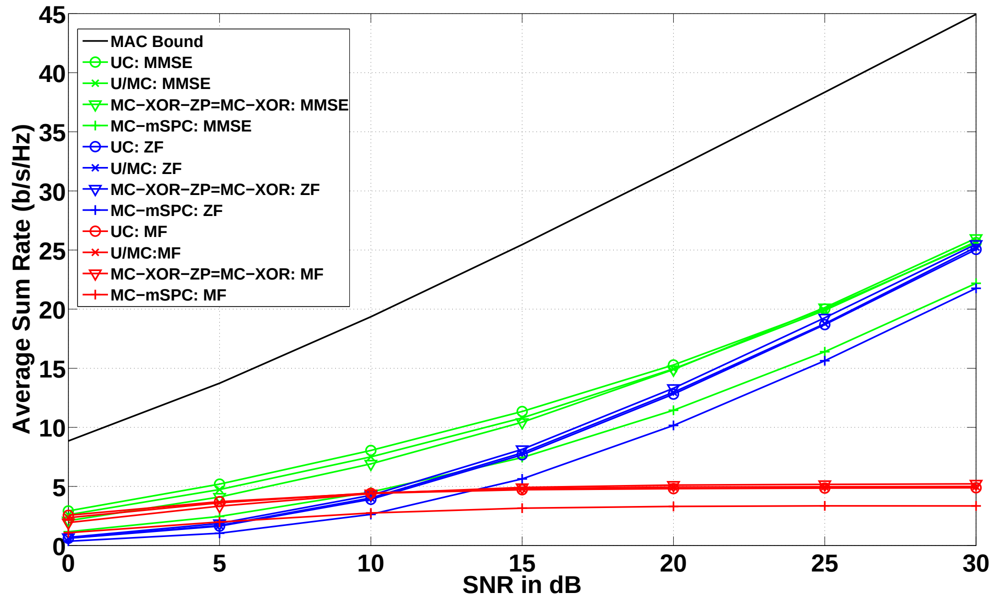


Figure 5.7. Sum rate performance of multi-group scenario with MF, ZF and MMSE

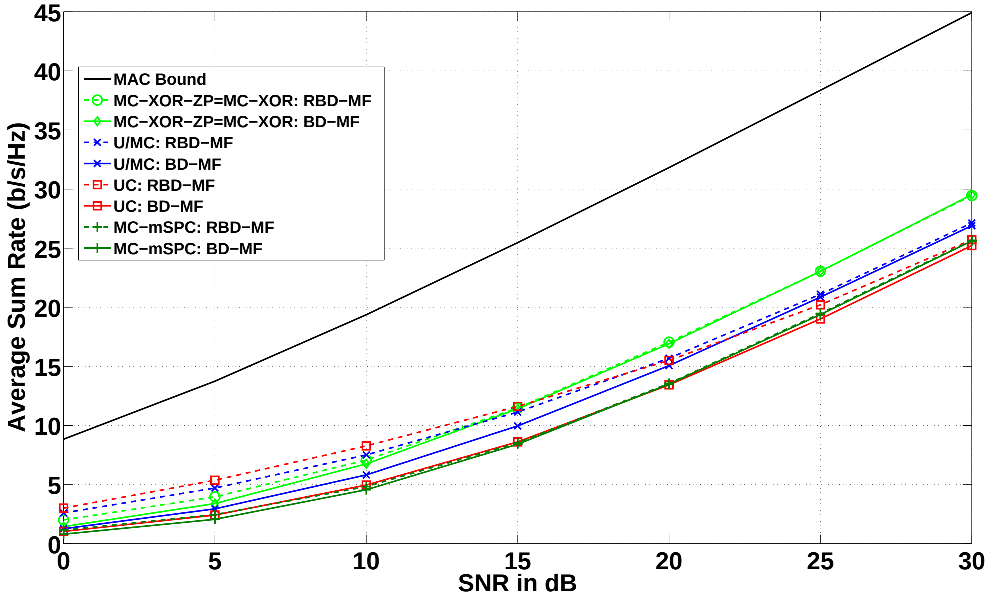


Figure 5.8. Sum rate performance of multi-group scenario with BCSA MF

using MMSE. Once again, multicasting-mSPC performs worst when using MF, ZF and MMSE. For all BC strategies, ZF converges to MMSE in high SNR, and in low SNR, MF converges to MMSE. As can be seen, in high SNR region, MF performs worse than MMSE and ZF. This also applies for multicasting strategy since in this scenario there is other-group-inter-stream interference.

Figures 5.8 and 5.9 show all BC strategies with BCSA MF and BCSA SDR, respectively, for the second scenario. For both BCSA cases, it can be seen that RBD outperforms BD for all BC strategies. In high SNR region, BD converges to RBD. In this scenario, the gain when using RBD is also perceived for the multicasting strategy, since now there are other-group-inter-stream interferences that have to be separated by the RS. The higher the value of Q one BC strategy has, the higher the RBD gain. Using BCSA MF, the superiority of the multicasting strategy only appears when using XOR and it is perceived only in medium to high SNR. Using BCSA SDR, multicasting strategy performs best in all considered value of SNR (0-30 dB). Multicasting-XOR performs best followed by multicasting-mSPC, hybrid uni/multicasting and unicasting. In this scenario, there is no performance improvement when using ZP for multicasting-XOR. This shows that the minimum BC rate is lower than the maximum between the MAC rates of the two linearly operated data streams. In this scenario, we set $E_{\mathrm{RS}} = 1$. If the RS transmits with higher power, such that the minimum BC rate can be improved, we can see again the gain of using ZP.

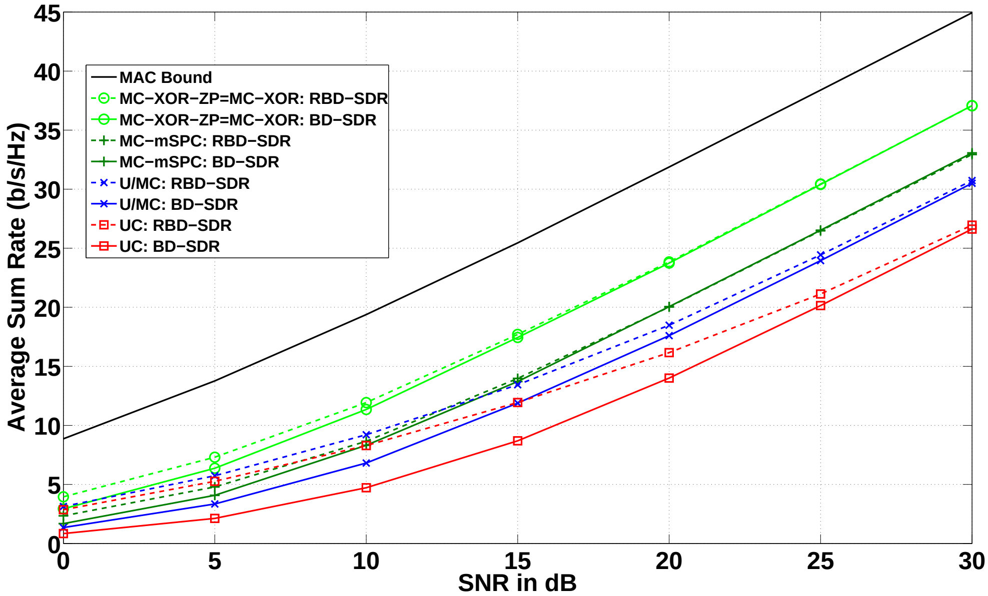


Figure 5.9. Sum rate performance of multi-group scenario with BCSA SDR

In summary, the sum rate performance of the proposed BC strategies depends on the applied transmit beamforming. While in general, multicasting-XOR always shows its superiority compared to the other strategies especially in high SNR, in low SNR, other strategies may perform better depending on the applied transmit beamforming. However, one can conclude that when interference defines the performance more than the noise, i.e., in high SNR region, BC strategies which have smaller values of Q in each BC phase perform better than ones with higher Q.

Chapter 6

Summary and Outlook

6.1 Summary

In this thesis, we consider MGMW relaying. A half-duplex multi-antenna RS assists multiple multi-way communication groups. In each multi-way group, multiple half-duplex single-antenna nodes exchange messages. A spectrally efficient communication protocol is proposed where the number P of communication phases is defined by the maximum number of nodes among all groups. Within P communication phases, the first phase is the MAC phase where all nodes transmit their data streams simultaneously to the RS. In the following $P-1$ BC phases, the RS transmits to the nodes. In order to ensure that the MGMW communication is completed in P phases, three BC strategies are proposed, namely, unicasting, hybrid uni/multicasting and multicasting. Regarding multicasting strategy, wireless cooperative network coding is applied.

We consider both non-regenerative and regenerative relaying. We derive unified system models for both non-regenerative MGMW relaying and regenerative MGMW relaying for all BC strategies. As a performance metric, we derive the sum rate expression of both non-regenerative and regenerative MGMW relaying.

A non-regenerative RS performs transceive beamforming to the received signals and transmits the output to the nodes. Having multiple antennas, the RS may perform transceive beamforming to separate the nodes spatially. In this thesis, we address generalised transmit beamforming maximising the sum rate of MGMW relaying for all BC strategies. Due to the high computational complexity of finding the optimum transceive beamforming maximising the sum rate, we propose generalised low complexity transceive beamforing for all BC strategies, namely, MF, ZF and MMSE. Also, BCSA-aware transceive beamforming is introduced. BCSA transceive beamforming is designed based on BD or RBD to separate the data streams received from and transmitted to all nodes according to the chosen BC strategies. We investigate the sum rate performance of non-regenerative MGMW relaying. It is shown that the sum rate performance depends both on the chosen BC strategy and the applied transceive beamforming algorithm. Using MF, ZF and MMSE, hybrid uni/multicasting performs best followed by unicasting and multicasting strategies, which shows that MF, ZF and MMSE are more suitable for an RS applying BC strategies which treat the data stream individually than for an RS superposing two data streams and transmitting the superposed data stream to all group member nodes. Using BCSA transceive beamforming with BD, multicasting strategy outperforms the other strategies. Since RBD finds a better trade off between interference suppression and noise enhancement, BCSA-RBD transceive beamforming improves the performance of non-regenerative MGMW relaying in low SNR region. In high SNR region, BCSA-BD converges to BCSA-RBD. Using BCSA-RBD, multicasting strategy performs best in high SNR region while the other BC strategies perform better in low SNR region.

A regenerative RS decodes and re-encodes the received data streams and performs transmit beamforming to transmit the corresponding data streams to the corresponding nodes according to the BC strategies. The achievable sum rate for regenerative MGMW relaying is defined by the minimum between the achievable MAC rate at the RS and the achievable BC rate from the RS to the nodes. First, we consider an MMSE-SIC multi-user detector, which is optimum for the uplink MAC, for decoding the data streams of all nodes. Since the RS knows the achievable data rates in the MAC phase prior to BC transmission, we design generalised transmit beamforming for all BC strategies minimising the RS's transmit power while ensuring that each node receives a particular data stream with a rate equal to the rate received at the RS. Since finding the optimum transmit beamforming minimising the transmit power requires high complexity and in some cases the transmit power at the RS is fixed, we design generalised low complexity linear transmit beamforming algorithms for all BC strategies, namely, MF, ZF and MMSE. Also, BCSA transmit beamforming is introduced. It is shown that multicasting-XOR strategy requires least power compared to the other strategies followed by hybrid uni/multicasting, unicasting and multicasting-mSPC. In general, the sum rate performance of regenerative MGMW relaying depends on the chosen BC strategy and the applied transmit beamforming algorithm. Due to its better approach of handling the interference in the network, BCSA transmit beamforming is able to improve the performance of regenerative MGMW relaying. In general, multicasting-XOR strategy performs best followed by hybrid uni/multicasting and unicasting strategies. Furthermore, multicasting-XOR outperforms multicasting-mSPC.

6.2 Outlook

There are other topics that are not covered in this thesis. Some of them are briefly discussed in the following:

- Diversity-multiplexing and performance-complexity trade-off: As briefly explained in Chapter 2, multi-antenna communication provides spatial diversity and spatial multiplexing gains. Maximum (full) gains can not be achieved at the same time, that is, increasing one gain leads to a reduction of the other gain [53]. In this work, we consider sum rate performance of MGMW relaying with three different BC strategies and several beamforming algorithms. A better performance is usually obtained with a higher computational complexity. Therefore, the trade-off between computational complexity and performance and between the diversity-multiplexing gain for both non-regenerative and regenerative MGMW relaying are interesting open problems. Recent work in [115] studied the diversity and multiplexing gains for non-regenerative multi-user two-way relaying, and in [116] the multiplexing gain of multi-user two-way relaying is investigated. In [115], the performance-complexity trade-off is briefly discussed.

- Channel state information: In this thesis, we assume that perfect CSI is available at the RS to perform transceive beamforming in case of non-regenerative MGMW, and multi-user detection and transmit beamforming in case of regenerative MGMW relaying. The nodes are assumed to have the required CSI for the decoding process as well. In reality, the CSI needs to be estimated at the nodes and at the RS. Since we assume time-invariant channels within P communication phases, the estimated uplink CSI at the RS can be used for downlink CSI. Most recent works on channel estimation, to the best of our knowledge, is only for single-pair two-way relaying, for example [117–120]. Channel estimation for MGMW relaying is, thus, another open issue which is important since the availability of the CSI will define the performance of the system. Efficient and robust channel estimation needs to be developed for MGMW relaying.

- Signaling and synchronisation: In this thesis, we have developed BC strategies which require no or very low signaling effort in the network. However, when there is signaling needed, it is assumed that the information transmitted from the RS to the nodes regarding the indexing for the BC strategies can be obtained perfectly at the nodes. In practice, this might not be the case. Therefore, it is also interesting to consider imperfect CSI and imperfect signaling and to model them as close as possible to practice. Moreover, in practice, due to multipath propagation and device impairments, the signals received from and transmitted to the nodes may not be synchronous anymore and, thus, MGMW relaying with asynchrony in time or frequency is an interesting open issue. Asynchronous non-regenerative two-way relaying has been considered recently in [121, 122].

- Group selection: In this thesis, the groups are already defined. In practice, when the number of groups is higher than what the RS can afford, group selection can be performed. If the RS is able to select the groups, a higher sum rate can be achieved, since only groups which are spatially compatible will be served. Several works have considered grouping of users for downlink transmission, for example [123, 124].

- Assessment and resource allocation for MGMW relaying using recent or future communication standards: Since relays have been considered for future generation of wireless systems, it is an interesting issue to assess MGMW relaying using current and future standard. Recently, B-IFDMA and its variants have been assessed and thoroughly investigated in [125]. Compared to OFDMA, B-IFDMA has low PAPR which saves battery life and it leads to a lower computational complexity for sub-carrier allocation. Hence, it is interesting to apply B-IFDMA for MGMW relaying. This assessment should include cross layer optimisation, that is, the resource allocation in terms of time slots and frequency subcarriers should take into account the requirements for network and application layers.

- Multiple relays and relays selection: Another interesting issue is to consider multiple single antenna RSs, instead of a multi-antenna RS. Several possible research directions are, for example, relay selection and distributed antenna array with local CSI. Several recent works have considered relay selection in two-way relaying with network coding, for example in [126, 127], and optimal distributed beamforming for two-way relaying in [55].

Appendix

A.1 Derivation of Regularised Block Diagonalisation for BCSA Receive Beamforming

In this section, RBD for BCSA receive beamforming is derived. For receive beamforming, the RS has to ensure that the interference from other unintended users to the intended users can be minimised while taking into consideration the appearance of noise at the RS. The matrix $\mathbf{F}_{\text{Null}}$ is designed to achieve the aim and, by rewriting the optimisation problem for transmit beamforming in [103] Equation (9), we have the optimisation problem for receive beamforming,

$$\mathbf{F}_{\text{Null}_{i,\forall i}} = \underset{\mathbf{F}_i,\forall i}{\text{argmin}}\ \text{E}\left\{\sum_{i=1}^{N} \|\mathbf{F}_i \tilde{\mathbf{H}}_{i_{\text{un}}}\|^2 + \frac{\|\mathbf{F}_i \mathbf{z}_{\text{RS}}\|^2}{\beta^{-1}}\right\}, \quad \text{s.t. } \beta \text{E}\{\|x_i x_i^{\text{H}}\|\} = P_{\text{nodes}}, \tag{A.1}$$

where β is a scaling factor needed to fulfill the nodes' transmit power constraint. In this work we assume that all nodes transmit with fixed and equal unit power and, thus, the constraint can be written as

$$\beta = \frac{P_{\text{nodes}}}{\text{E}\{\|x_i x_i^{\text{H}}\|\}} = \frac{1}{\sigma_x^2}. \tag{A.2}$$

The objective function in (A.1), $f(\mathbf{F}_i)$, can be written as

$$f(\mathbf{F}_i) = \sum_{i=1}^{N} \left(\text{tr}\left(\mathbf{F}_i \tilde{\mathbf{H}}_{i_{\text{un}}} \tilde{\mathbf{H}}_{i_{\text{un}}}^{\text{H}} \mathbf{F}_i^{\text{H}} \right) + \frac{\sigma_{\text{RS}}^2 \mathbf{I}_M}{\sigma_x^2} \text{tr}\left(\mathbf{F}_i^{\text{H}} \mathbf{F}_i \right) \right). \tag{A.3}$$

Let the SVD of $\tilde{\mathbf{H}}_{i_{\text{un}}}$ be given by

$$\tilde{\mathbf{H}}_{i_{\text{un}}} = \tilde{\mathbf{U}}_{i_{\text{un}}} \tilde{\mathbf{\Sigma}}_{i_{\text{un}}} \tilde{\mathbf{V}}_{i_{\text{un}}}, \tag{A.4}$$

(A.3) can be rewritten as

$$f(\mathbf{F}_i) = \sum_{i=1}^{N} \left(\text{tr}\left(\mathbf{F}_i \tilde{\mathbf{U}}_{i_{\text{un}}} \left(\tilde{\mathbf{\Sigma}}_{i_{\text{un}}} \tilde{\mathbf{\Sigma}}_{i_{\text{un}}}^{\text{T}} + \frac{\sigma_{\text{RS}}^2 \mathbf{I}_M}{\sigma_x^2} \right) \tilde{\mathbf{U}}_{i_{\text{un}}}^{\text{H}} \mathbf{F}_i^{\text{H}} \right) \right). \tag{A.5}$$

Let $\mathbf{F}_i = \mathbf{F}\text{a}_i \mathbf{F}\text{b}_i$ and let $\mathbf{F}\text{b}_i = \tilde{\mathbf{U}}_{i_{\text{un}}}^{\text{H}}$, the optimisation problem reduces to

$$\underset{\mathbf{F}\text{a}_i,\forall i}{\text{argmin}} \sum_{i=1}^{N} \left(\text{tr}\left(\left(\tilde{\mathbf{\Sigma}}_{i_{\text{un}}} \tilde{\mathbf{\Sigma}}_{i_{\text{un}}}^{\text{T}} + \frac{\sigma_{\text{RS}}^2 \mathbf{I}_M}{\sigma_x^2} \right) \mathbf{F}\text{a}_i^2 \right) \right) \tag{A.6}$$

where $\mathbf{F}\mathrm{a}_i$ needs to be positive definite in order to find a nontrivial solution [103]. Using the results from [103, 128], we have

$$\mathbf{F}\mathrm{a}_i = \left(\tilde{\mathbf{\Sigma}}_{i_{\mathrm{un}}} \tilde{\mathbf{\Sigma}}_{i_{\mathrm{un}}}^{\mathrm{T}} + \kappa_{\mathrm{R}} \mathbf{I}_M \right)^{-1/2}, \tag{A.7}$$

with $\kappa_{\mathrm{R}} = \frac{\sigma_{\mathrm{RS}}^2}{\sigma_x^2}$.

List of Acronyms

3G	Third Generation
4G	Fourth Generation
AWGN	Additive White Gaussian Noise
BC	Broadcast
BCSA	BC-Strategy-aware
BD	Block Diagonalisation
BER	Bit Error Rate
BS	Base Station
CSI	Channel State Information
DL	Downlink
KKT	Karush-Kuhn-Tucker
mSPC	modified Superposition Coding
MAC	Multiple Access
MC	Multicasting
MC-mSPC	Multicasting with modified Superposition Coding
MC-XOR	Multicasting with XOR
MC-XOR-ZP	Multicasting with XOR and Zerro Padding
MF	Matched Filter
MGMW	Multi-Group Multi-Way
MISO	Multiple-Input Single-Output
MIMO	Multiple-Input Multiple-Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MU-MIMO	Multi User-MIMO

RBD	Regularised BD
SDMA	Space Division Multiple Access
SDR	Semidefinite Relaxation
SIMO	Single-Input Multiple-Output
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
SU-MIMO	Single-User MIMO
SVD	Singular Value Decomposition
RS	Relay Station
UC	Unicasting
UL	Uplink
U/MC	Hybrid Uni/Multicasting
WCNC	Wireless Cooperative Network Coding
XOR	Exclusive-OR
ZF	Zero Forcing
ZP	Zero Padding

List of Symbols

β	Scalar factor to fulfill RS's transmit power constraint
δ	Diversity gain
$\eta_{\mathrm{i_n}}$	Number of intended nodes
γ_{r_l,t_l}	SINR at node Sr_l when receiving the data stream of node St_l
Γ_{in}	Receive power loading
Γ_{inDL}	Transmit power loading
κ_{T}	Regularised factor of transmit RBD
κ_{R}	Regularised factor of receive RBD
λ	Wavelength
λ^p	Lagrange multiplier
$\mathbf{\Lambda}^p$	Lagrange multiplier
μ^p	Lagrange multiplier
$\mathbf{\Pi}^p$	BC-strategy-defining permutation matrix
$\mathbf{\Pi}^p_{\mathrm{d}}$	Data permutation matrix for regenerative RS
$\mathbf{\Pi}^p_{\mathrm{G}}$	Permutation matrix of regenerative RS with linear transmit beamforming
ρ	Single-branch SNR
σ_x^2	Variance of transmit symbol
σ_h^2	Variance of channel coefficient
$\sigma^2_{z_{\mathrm{node}}}$	Variance of AWGN at the nodes
$\sigma^2_{z_{\mathrm{RS}}}$	Variance of AWGN at RS
$\tilde{\mathbf{\Sigma}}_{\mathrm{u_n}}$	Singular values matrix of $\tilde{\mathbf{H}}^{\mathrm{T}}_{\mathrm{u_n}}$
ξ	Multiplexing gain
a_l	Lowest node index of multi-way group l
b_l	Highest node index of multi-way group l
$\mathbf{b}_i$	Bit sequence of node Si
$\mathbf{b}_{v_l w_l}$	XOR-ed bit sequence of node Sv_l and Sw_l
$\mathcal{B}_l$	Set of nodes indices whose data streams have been multicasted by the RS in the previous BC phases
$\mathcal{B}_{r_l}$	Set of nodes indices whose data streams have been decoded by receiving node r_l in the previous BC phases
$\mathbb{C}$	Set of complex numbers
$\mathcal{CN}(0,\sigma^2)$	Circularly symmetric zero-mean complex normal distribution with variance σ^2

$\mathbf{d}_{\mathrm{RS}}$	RS transmit data vector according to the BC strategy
$\mathrm{E}\{\mathbf{X}\}$	Expectation of $\mathbf{X}$
E_{RS}	Transmit power constraint at RS
$f(i,p)$	Function of transmitting index i and BC phase index p
$\mathbf{F}_{\mathrm{null}}$	Null-space matrix
$\mathbf{G}$	Transmit or transceive beamforming matrix
$\mathbf{G}_{\mathrm{R}}$	Receive beamforming matrix
$\mathbf{G}_{\mathrm{T}}$	Transmit beamforming matrix
$h_{i,m}$	Channel coefficient of node i and RS antenna m
$\mathbf{h}_i$	Vector of channel coefficients between node Si and RS
$\mathbf{h}_{\mathrm{i}}^{(\mathrm{eq})}$	Equivalent channel vector of node Si
$\mathbf{H}$	Matrix of channel coefficients
$\mathbf{H}_{\mathrm{in}}^{(\mathrm{eq})}$	Equivalent channel matrix of the intended nodes
$\mathbf{H}_{\mathrm{i_n}}^{\mathrm{T}}$	Channel matrix of the intended nodes
$\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$	Channel matrix of the unintended nodes
i	Node index
$\mathcal{I}$	Set of all nodes indices
$\mathbf{I}$	Identity matrix
$\mathcal{I}_l$	Set of nodes indices in multi-way group l
$\mathcal{I}_{l_{\mathrm{M}}}$	Set of nodes indices in multi-way group l whose data streams are going to be multicasted
$I_{\mathrm{not-canc}_{r_l}}$	Interference power without self-interference and same-group-inter-stream interference of those data streams that have been decoded in the previous BC phases
$I_{\mathrm{og}_{r_l}}$	Other-group-inter-stream interference power
$I_{\mathrm{sg}_{r_l}}$	Same-group-inter-stream interference power
$I_{\mathrm{s\|k}_{r_l}}$	Inherent interference power within the superposed data stream which can only be either self- or known-interference power
$I_{\mathrm{u/m}_{r_l}}$	Interference power caused by the unicasted or the multicasted data stream
l	Multi-way group index
L	Number of multi-way groups
$\mathcal{L}$	Set of multi-way groups indices
$mod_N(x)$	Modulo N of x
m	RS antenna index
$\mathbf{m}$	Receive beamforming vector

$\mathbf{m}_{\mathrm{DL}}$	Transmit beamforming vector
M	Number of antennas at the RS
$\mathcal{M}$	Set of RS antennas indices
M_{R}	Number of receive antennas for MIMO point-to-point
M_{T}	Number of transmit antennas for MIMO point-to-point
N	Number of nodes
N_l	Number of nodes in multi-way group l
N_{mw}	Number of nodes in all multi-way groups (assuming equal number of nodes in all groups)
p	BC phase index
P	Number of communication phases
$\mathcal{P}$	Set of BC phase indices
P_{e}	Average bit error rate
q	RS transmitted data stream index
Q	Number of transmitted data stream from the RS
$\mathcal{Q}$	Set of RS transmitted data streams indices
r_l	Receiving node index in multi-way group l
R_{r_l,t_l}	Rate at receiving node r_l when it receives from transmitting node t_l
R_{t_l}	For Non-Regenerative MGMW relaying: Minimum rate among all receiving nodes r_l in group l when they receive the data stream from a certain transmitting node t_l
R_{t_l}	For Regenerative MGMW relaying: Sum of the rates at all receiving nodes r_l in group l when they receive the data stream from a certain transmitting node t_l
$\mathbf{R}_{\mathbf{x}}$	Covariance matrix of $\mathbf{x}$
$\mathbf{R}_{\mathbf{z}_{\mathrm{RS}}}$	Covariance matrix of $\mathbf{z}_{\mathrm{RS}}$
$R(\rho)$	Transmission rate as a function of ρ
S	Useful signal power
Si	Node Si
SR_{asym}	Achievable sum rate for asymmetric traffic
SR_{symm}	Achievable sum rate for symmetric traffic
t_l	Transmit node index in multi-way group l
$t_{l_{\mathrm{u}}}$	Node index whose data stream is unicasted
$t_{l_{\mathrm{m}}}$	Node index whose data stream is multicasted
$\mathrm{tr}\{\mathbf{X}\}$	Trace of $\mathbf{X}$
$\tilde{\mathbf{U}}_{\mathrm{u_n}}$	Left eigenvector of $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$

v_l	Node index in group l whose data stream is chosen for network coding
$v\tilde{w}_l$	Index of the known-interference which can only be either w_l or v_l
$\tilde{\mathbf{V}}_{\mathrm{u_n}}$	Right eigenvector of $\tilde{\mathbf{H}}_{\mathrm{u_n}}^{\mathrm{T}}$
w_l	Node index in group l whose data stream is chosen for network coding
x_i	Transmit symbol of node Si
$x_{v_l w_l}$	Linearly operated data stream of two nodes Sv_l and Sw_l
$\hat{x}_{v_l w_l}$	The noisy superposed data stream of two nodes Sv_l and Sw_l
$\mathbf{x}$	Vector of nodes' transmitted data streams
y_{r_l,t_l}	Received signal at node Sr_l when receiving the data stream of node St_l
$\mathbf{y}_{\mathrm{nodes}}$	Received vector at all nodes
$\mathbf{y}_{\mathrm{RS}}$	Received vector at the RS
z_i	AWGN at node Si
$\mathbf{z}_{\mathrm{nodes}}$	Vector of AWGN at all nodes
z_{RS_m}	AWGN at RS antenna m
$\mathbf{z}_{\mathrm{RS}}$	Vector of AWGN at the RS
Z_{r_l}	Node Sr_l noise power
Z_{RS}	RS propagated noise power
$\mathbf{1}$	Vector of ones
$\bigoplus$	Exlusive-OR operator
$(\cdot)^{\mathrm{T}}$	Transpose of a vector or matrix
$(\cdot)^{\mathrm{H}}$	Conjugate transpose of a vector or matrix
$(\cdot)^{*}$	Conjugate of a scalar, vector, or matrix
$(\cdot)^{-1}$	Inverse of a square matrix
$\lvert \cdot \rvert$	Absolute value of a scalar
$\lvert\lvert \cdot \rvert\rvert$	Euclidean norm or 2-norm of a vector

Publications

The following publications have been produced during the period of PhD candidacy.

Internationally Refereed Journal Articles

1. A. U. T. Amah and A. Klein, "Non-Regenerative Multi-Way Relaying: Space-Time Analog Network Coding and Repetition," *submitted to IEEE Communications Letters* (Feb. 2011).

2. A. U. T. Amah and A. Klein, "Regenerative Multi-Group Multi-Way Relaying," *submitted to IEEE Transactions on Vehicular Technology* (Dec. 2010, under second round review).

3. A. U. T. Amah and A. Klein, "Non-Regenerative Multi-Antenna Multi-Group Multi-Way Relaying," *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, (accepted - to appear).

4. A. U. T. Amah and A. Klein, "Beamforming-Based Physical Layer Network Coding for Non-Regenerative Multi-Way Relaying," *EURASIP Journal on Wireless Communications and Networking* (*special issue: Physical Layer Network Coding for Wireless Cooperative Networks*), Vol. 2010 (2010), Article ID 521571, 12 pages.

Internationally Refereed Conference Articles

1. A. U. T. Amah and A. Klein, "Multi-Group Multi-Way Relaying: When Analog Network Coding Finds Its Transceive Beamforming," in *Proc. IEEE Wireless Communications and Networking Conference*, Sydney, Australia, April 2010.

2. A. U. T. Amah and A. Klein, "Pair-Aware Transceive Beamforming for Non-Regenerative Multi-User Two-Way Relaying," in *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing*, Dallas, USA, March 2010.

3. A. U. T. Amah, T. Frank, and A. Klein, "On Combining SDMA and B-IFDMA: Multi-User Detection and Channel Estimation," in *Proc. International IEEE/ITG Workshop on Smart Antennas*, Bremen, Germany, Feb. 2010.

4. A. U. T. Amah and A. Klein, "A Transceive Strategy for Regenerative Multi-Antenna Multi-Way Relaying," in *Proc. IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing*, Aruba, Dec. 2009.

5. A. U. T. Amah and A. Klein, "Non-Regenerative Multi-Way Relaying with Linear Beamforming," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Tokyo, Japan, Sept. 2009.

6. A. U. T. Amah, A. Klein, Y. C. B. Silva, and A. Fernekeß, "Multi-Group Multicast Beamforming for Multi-User Two-Way Relaying," in *Proc. International ITG Workshop on Smart Antennas*, Berlin, Germany, Feb. 2009.

Invited Posters

1. A. U. T. Amah, A. Klein and A. Martin, "Multi-Antenna Multi-Group Multi-Way Relaying," at International Workshop on Multi-Scale Methods in Computational Engineering, Darmstadt, Germany, Dec. 2010.

Invited Talks

1. A. U. T. Amah and A. Klein, "Multi-Way Relaying," at 14. Sitzung ITG-Fachgruppe "Angewandte Informationstheorie", Aachen, Germany, Oct. 2009.

2. A. U. T. Amah and A. Klein, "Multi-Antenna Multi-User Two-Way Relaying," at Department of Discrete Optimisation, TU Darmstadt, Darmstadt, Germany, Sept. 2008.

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Scholarships

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