Scheduling and Resource Management in Wireless Networks with Bidirectional Relaying Links

SCHEDULING AND RESOURCE MANAGEMENT IN WIRELESS NETWORKS WITH BIDIRECTIONAL RELAYING LINKS

BY

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This thesis is dedicated to my dear parents.

Abstract

In this thesis we study transmission scheduling and resource allocations for wireless networks with bidirectional relaying links (WNBRL). Each link has two end nodes, which communicate through a relay node that can use network coding (NC) to forward packets between them.

We first study an ad hoc WNBRL (Chapter 2), where a single frequency channel is shared by all the transmissions, and therefore co-channel interference is a main problem that requires a scheduling solution to carefully coordinate the transmitting nodes and control their transmission power. Power distributions and time slot allocations are jointly considered, and the objective is to maximize the system throughput. Both digital NC and analog NC are considered. An optimization problem is first formulated, followed by distributed scheduling schemes.

Next, we study a WNBRL with multiple frequency channels, where the emphasis is to jointly allocate frequency channels and time slots for the transmissions of individual nodes. Two objectives are considered, one is to maximize the long-term transmission throughput of the system (Chapter 3), and another is to provide proportional fairness of the average throughput among all the links in the system (Chapter 4). For each objective, both optimization formulation is provided and heuristic solutions are proposed.

We then consider a WNBRL that allows the relay nodes to opportunistically use NC and pure one-way relaying, and study the scheduling and resource allocation with an objective to maximize the total transmission throughput (Chapter 5). Both centralized and distributed topologies are considered. Optimum scheduling is solved, together with different heuristic solutions.

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Abbreviations

ANC	analog network coding
BER	bit error rate
BS	base station
CDMA	code division multiple access
CNSCA	concurrent node selection and channel assignment
DCPC	distributed constrained power control
DNC	digital network coding
GN	graph node
LTE-A	long term evolution advanced
MAC	media access control
MANETs	mobile adhoc networks
MILP	mixed integer linear programming
NC	network coding
OFDMA	orthogonal frequency-division multiple access
PF	proportional fairness
PNC	physical layer network coding
R-node	relay node

SINR	signal to interference plus noise ratio
SNSCA	sequential node selection and channel assignment
TDMA	time division multiple access
UWB	ultra wide-band
WiMAX	worldwide interoperability for microwave access
WNBRL	wireless networks with bidirectional relaying links
WNC	wireless network coding
WSNs	wireless sensor networks
XOR	exclusive or

Notations

M	number of links
s	S-node
d	D-node
r	R-node
T	number of time slots
$A_{x_m,t}$	denoting that node x of link m transmits at time slot t or not
$P_{x_m,t}$	transmission power of node x of link m at time slot t
$G_{x_m,y_n,t}$	link gain between node x of link m and node y of link n at time slot t
k_s	packet that S-node transmits
k_d	packet that D-node transmits
γ	minimum SINR for successful decoding
P_n	power of the background noise
$I_{y_m,t}$	co-channel interference that the node y of link m experiences at time t
C_m	number of packets successfully transmitted in each direction of the link m
$\mathcal{A}_t$	set of the nodes that are allowed to transmit at time slot t
$P_{\max}$	maximum transmission power
Y_m	number of time slots that the Y-node of link m have successfully transmitted

$\beta_{m,t}$	amplification factor of R-node of link m at time slot t for ANC
w_1	distance between the R-node and the S-node of the same link in grid topology
w_2	distance between the S-nodes of two neighboring links in grid topology
α	path loss exponent
X	log-normally distributed shadowing part
d_{x_m,y_n}	distance between node x of link m and node y of link n
$V_{r_m,\tau_{mt}}$	total power received at the R-node of link m at time slot τ_{mt}
$U_{x_m,r_m,\tau_{mt}}$	signal power at the R-node of link m received from node x at time τ_{mt}
$A_{xy,m,t}$	node x of link m transmits to the node y at time slot t or not for pure relaying
$P_{xy,m,t}$	transmission power of the node x to the node y of link m at time t for pure relaying
$C_{sd,m}$	number of packets received by the D-node from the S-node for pure relaying
$C_{ds,m}$	number of packets received by the S-node from the D-node for pure relaying
a	simulation area in random topology
K	number of frequency channels
$B_{\max}$	maximum buffer size
P_x	transmission power of node x
$G^{xy}_{m,k,t}$	link gain (normalized to background noise power) between nodes x and y of link m at channel k and time slot t
$U^{xy}_{m,k,t}$	transmission rate between nodes x and y of link m at channel k and time slot t
$X_{m,k,t}$	denoting frequency channel k is assigned to the S-node of link m at time slot t
$Y_{m,k,t}$	denoting frequency channel k is assigned to the D-node of link m at time slot t
$Z_{m,k,t}$	denoting frequency channel k is assigned to the R-node of link m at time slot t
$C_{x,m,t}$	transmission rate of node x of link m at time slot t

T_w	time window size
$\tilde{C}_{x,m,k}$	possible transmission rate of the node x of link m at frequency channel k
$b_{sr,m}$	amounts of data buffered at the R-node from the S-node of link m
$b_{dr,m}$	amounts of data buffered at the R-node from the D-node of link m
$\mathcal{M}$	set of all the links that have not been scheduled
$\mathcal{K}$	set of all the channels that have not been used
$\tilde{C}_{m,k}$	instantaneous rate for a pair of channel k and selected node of link m
$\tilde{G}^{xy}_{m,k,t}$	link gain between nodes x and y of link m at channel k and time slot t
$\overline{C}_m$	long-term average throughput of link m
$\overline{A}_m(t)$	weighed average rate for link m up to time t
γ	parameter to balance the past and current transmission rates
$\hat{C}_{x_m,k}$	maximum transmission rate of the node x of link m at frequency channel k
$\mathcal{S}$	set of all S-nodes that have not been scheduled to transmit or receive
$\mathcal{D}$	set of all D-nodes that have not been scheduled to transmit or receive
$\mathcal{R}$	set of all the transmitters of the R-node that both their S- and D-nodes have not been scheduled to transmit or both of them have not been scheduled to receive
$\mathcal{X}$	set of all nodes that have not been scheduled to transmit or receive
$\mathcal{M}_r$	set of all the links whose R-nodes have been scheduled to transmit
$\tilde{A}_{x_m,k}$	utility function of the node x of link m at frequency channel k
w_{1min}	radii of the inner circle in star topology
w_{1max}	radii of the outer circle in star topology
N	number of links that their end nodes are within the inner circle in star topology
L	number of radios at the R-node in centralized topology
$V_{m,k,t}$	denoting frequency channel k is assigned to the R-node for transmitting to

	the S-node of link m at time slot t
$W_{m,k,t}$	denoting frequency channel k is assigned to the R-node for transmitting to the D-node of link m at time slot t
$C_{rs,m,t}$	transmission rate of R-node to S-node of link m at time slot t
$C_{rd,m,t}$	transmission rate of R-node to D-node of link m at time slot t
X_{mk}	denoting frequency channel k is assigned to the S-node of link m at current time slot
Y_{mk}	denoting frequency channel k is assigned to the D-node of link m at current time slot
Z_{mk}	denoting frequency channel k is assigned to the R-node of link m at current time slot
V_{mk}	denoting frequency channel k is assigned to the R-node for transmitting to the S-node of link m at current time slot
W_{mk}	denoting frequency channel k is assigned to the R-node for transmitting to the D-node of link m at current time slot
$\tilde{L}$	represents the number of radios at the R-node that have not been scheduled to transmit or receive for the centralized topology
$\mathcal{R}^s$	set of all the transmitters of the R-node that their S-nodes have not been scheduled to transmit or receive
$\mathcal{R}^d$	set of all the transmitters of the R-node that their D-nodes have not been scheduled to transmit or receive
d_0	reference distance
A	path loss at the reference distance d_0

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Chapter 1

Introduction

In this chapter, we first introduce the basic concept of network coding and its applications in wireless communication networks, then discuss issues related to radio resource management and quality-of-service provisioning in wireless networks using network coding, and finally give the motivations and summarize the main contributions of this thesis.

1.1 Network Coding in Wireless Networks

The notion of network coding (NC) was first introduced in [1] in the context of wired multicast networks. It is a technique for intermediate nodes to combine the received packets from multiple upstream links and forward to subsequent nodes. Using NC can reduce the number of transmissions needed to transmit a given amount of data, thereby increasing transmission efficiency.

NC has been used in wireless networks by exploiting the broadcast nature of the wireless channel, spatial diversity in wireless networks, and data redundancy in data transmissions. Redundant information becomes available in data transmissions either because a packet should travel through different nodes and its content is known to these nodes, or a packet is delivered not only to the intended receiver but also to other nearby nodes because of the broadcast nature of wireless channel. Such redundant information can be used to code packets and improve the data transmission performance. Based on whether messages are decoded at the relay nodes, wireless network coding (WNC) can be implemented in two basic ways. In the conventional WNC, multiple signals received at a relay node should be first decoded and then mixed together before being forwarded to subsequent nodes. This is referred to as digital network coding (DNC). Alternatively, the relay node does not decode the received signals, but treats the superimposed waveforms from multiple upstream nodes as a natural way of implementing NC. This type of WNC is usually called physical layer network coding (PNC) [2] or analog network coding (ANC) [3]. Hereafter, we use the term NC or WNC to refer DNC unless explicitly indicated otherwise. Fig. 1.1 shows three different methods for information exchange between two end nodes A and C through a relay node B. Suppose the channel time is divided into time slots, and the transmission of each packet takes one time slot. As shown in Fig. 1.1 (a), in order for nodes A and C to exchange one pair of packets (i.e., one packet from A to C and another packet from C to A), traditional relaying takes four time slots, DNC takes three time slots (Fig. 1.1 (b)), and ANC takes only two time slots (Fig. 1.1 (c)).

In general NC can be applied to packets from a single stream, referred to as intra-flow network coding, e.g. [4–7], or from different flows, referred to as inter-flow network coding, e.g. COPE [8]. The use of NC in wireless networks is closely related to radio resource management, routing, scheduling, and other issues, which can greatly

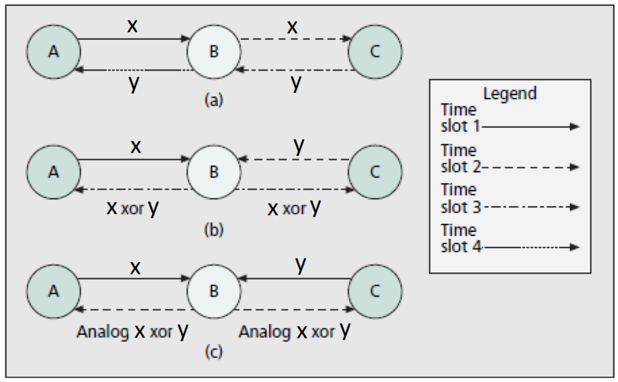

Figure 1.1: Diagram of different transmission methods: a) traditional relaying; b) DNC; c) ANC.

affect the network performance [9]. Potential benefits for using WNC may include increasing network throughput [10, 11], saving transmission power [12], improving network reliability, achieving better fairness, and enhancing routing efficiency [13–15], and a brief summary is given in the rest of this section.

Using NC can reduce number of transmissions and improve the data transmission efficiency. This feature can be used to improve the efficiency for recovering lost packets from a base station (BS) to multiple receivers [16], reduce the overhead of probabilistic routing in delay tolerant networks [17], save both the bandwidth and energy consumption in wireless sensor networks (WSNs) [18]. By using inter-flow network coding, multiple packets from different flows can be delivered to different neighbors in a single transmission, which improves the transmission efficiency and the overall system throughput. This opportunity of NC can be applied to different applications such as content distribution. In wireless networks, nodes may randomly overhear each other's transmissions depending on link conditions, mobility patterns, transmission power, and other network conditions. When more packets are overheard, they have better opportunities to be network-coded, which can potentially increase the transmission efficiency and throughput. Furthermore, transmission rate adaptation can increase the range over which packets are overheard, and enable additional opportunities for coding and throughput improvement. This feature is studied in [19] for wireless ad hoc and mesh networks, where a star topology with a single relay node is considered, and joint optimal rate vector and optimal network coding group is achieved by proposed heuristics. User mobility can also create opportunities for nodes to overhear each other's transmissions and use NC. It is shown in [20] that using NC can provide significant improvement on mobile ad hoc networks (MANETs) performance under different mobility patterns. A lot of work has been done to analyze the transmission efficiency using NC, which shows that using NC can improve transmission throughput [21–25]. On the other hand the throughput improvement of using NC may depend on various network and traffic conditions, such as saturated or possibly emptying queues, scheduled or random access MAC layer, multicast or broadcast communications [24], and latency requirements of the traffic [20].

By reducing number of packet retransmissions, using NC can achieve more reliable multicasting in lossy wireless networks [26]. The overheard information helps nodes to decode packets and achieve higher coding gain, as it is used in [27], where reliable multicast is achieved by using random linear network coding. Alternatively, intra-flow NC can code packets heading to the same destination, so that all the coded packets contain the same information about all the packets in the original file. As the transmitter does not need to know which particular packet is lost in order to retransmit it, bandwidth can be saved for communicating the feedback reliably. The transmitter should only be notified whenever the destination has received enough packets to decode the original file.

Using NC in broadcasting can naturally smooth the rates that receivers experience over a short period of time. A simple example in [28] shows that using NC can lead to the same aggregate throughput, but more evenly divided among the receivers.

1.2 Coding Techniques

There are different ways to combine packets using NC. In a linear network coding [29], each node generates new packets which are linear combinations of earlier received packets. The coefficients of the combination are, by definition, selected from a finite field. XOR-ing can be considered as a special case of linear network coding. The coding operation is to bit-wise XOR two packets to form a new packet. In random network coding [30], nodes transmit random linear combinations of the packets they receive, with coefficients chosen from a finite field. If the field size is sufficiently large, the probability that the receivers will obtain linearly independent combinations (and therefore obtain innovative information) approaches 1. Random NC allows close to optimal throughput using a decentralized algorithm.

As mentioned in the previous section, WNC can be implemented as DNC or ANC. For ANC, by using proper modulation and demodulation methods at the relay nodes, additions of electromagnetic (EM) waves can be equivalent to additions of digital bit streams. The relay amplifies and forwards the received mixed signal to the downstream links without any processing. Compared to DNC, ANC is simple to implement at the relay node. On the other hand, amplifying interference and noise together with the desired signals can deteriorate the transmission quality.

1.3 Specific Applications of WNC

Significant efforts have been put to design different strategies for applying NC in wireless networks [4, 8, 31–34]. Reference [35] provides a survey on applications of NC in different types of wireless networks. Among all the works in the literature, COPE [8] is the first practical implementation of NC for unicast traffic in wireless mesh networks. It allows intermediate nodes along a path to XOR multiple packets, provided the intended next hop node has enough information to decode them.

As an extension of COPE at the MAC layer, BEND [36, 37] allows any nodes to code and forward a packet, even when the node is not the intended MAC receiver of the packet, if the node believes that in doing so it can lead the packet to its ultimate destination (opportunistic forwarding). In both protocols, overhearing condition is critically important to effective NC. In [38], a coding-aware routing was proposed which considers network coding opportunities for routing, as opposed to COPE. Routing flows "close to each other" can better utilize coding opportunities while "away from each other" can avoid wireless interference.

1.4 Challenges in Radio Resource Management

While WNC has a great potential to improve the performance of wireless networks, applying WNC increases the complexity in managing the radio resources. In particular, transmission scheduling at a given node in the network is dependent on not only the conditions of the multiple upstream links, but also that of the multiple downstream links. Packets received from some upstream links may have to be buffered in order to wait for more packets to arrive from other upstream links. This increases the average data transmission delay, and may negatively affect the network throughput performance. Furthermore, transmission power allocations become different after NC is used, as one transmission often needs to reach multiple destinations. In order for a NCed packet to reach all the destinations, the transmission power of the relay station should be based on the worst link condition. This can increase the interference level and reduce the network performance [39, 40]. The advantage of using network coding, such as throughput improvement, can be reduced significantly in a fading channel [41]. This happens because the worst link gain can be very small, which either requires very high transmission power in order to keep a reasonably high transmission rate, or results in very low transmission rate for the same transmission power. The problem of power management using WNC becomes particularly challenging in networks with co-channel interference, where coding packets and allocating transmission power are closely coupled.

Packet transmission scheduling

Network coding is closely related to packet transmission scheduling, which is important in order to coordinate the resource allocations and optimize the network performance. Different scheduling schemes have been proposed for wireless networks using network coding. Some works allow links to adaptively switch between direct transmissions and relay-assisted network coding, e.g. [42] and [43]. Other works take advantage of the random channel conditions, so that packets mixed in the same transmission have similar channel conditions to their respective destinations, thereby saving the transmission power or maximizing the transmission rate. For example, the opportunistic scheduling in [44] tries to find an optimum number of destinations for the NC operation that results in a maximum throughput at each instant. In [45] and [46] the performance of the opportunistic wireless NC in [44] is evaluated by assuming that the relay node always has an infinite amount of data to transmit to both end nodes.

The interaction between NC and the physical and MAC layer implementations can be very important because of special properties of wireless networks such as omnidirectional transmissions, co-channel interference, and the physical channel conditions. When multiple sessions share the same relay node, appropriately assigning the transmission rate and power of the relay node can be important to improve the throughput of all the sessions [47]. Adaptive modulation and coding adjusts the transmission rate based on the channel conditions to destination nodes, and can be applied in NCed packet transmissions as in [48] to improve the data transmission efficiency. In [49], linear network coding is applied to optimize performance metrics such as throughput and energy costs by first constructing conflict-free network realizations in MAC layer and then assigning time-varying network codes.

There has been a considerable interest in applying NC in multi-channel wireless networks, where effective scheduling is important to decide which node should send at which frequency channel in order to take advantage of both the link and channel diversities. As both the transmission and overhearing conditions can vary at different channels, NC and channel assignment are often jointly considered as in [50], and further combined with routing decisions [9, 51] in multihop networks or transmission power allocation. The work in [52] takes the advantage of network coding at the symbol level to maximize the throughput in multi-channel wireless networks with presence of transmission errors. In [53] the scheduling problem is studied jointly with channel and power allocations for broadcast traffic in an OFDMA-based WiMAX network using random network coding, where all nodes work in the full-duplex mode and are equipped with multiple radios, which support concurrent communication with multiple nodes in both downlink and uplink via separate sub-channels.

1.5 Two-way Relay Channels

Among various scenarios for applying NC and PNC, the two-way relaying channel that uses simple XOR operation at the relay node has attracted a lot of research attention. This coding operation requires very low overhead, but can still bring a lot of benefits of NC. In a two-way relaying channel, two nodes communicate with each other via a relay node because of transmission range limitation. This model plays an important role in studying WNC since it can be considered as a basic unit in the implementation of NC in wireless multihop transmissions. In [54], a network with two end nodes and one relay node is studied, where the relay node can choose either to transmit to a single end node using traditional relaying mode (i.e., one-way relay) or to both end nodes simultaneously using NC (i.e., two-way relay). The link gain distribution is used to find a fraction of channel transmission time for each node. A similar two-way relay link is considered in [55], where the problem is how to use the link gain information to minimize the total time span for sending a certain amount of data. The work in [56] considers the scheduling of both the relay node and the end nodes with finite buffers, and the objective is to maximize the long term transmission throughput. In [57], an opportunistic scheduling algorithm is proposed that considers the buffer status, channel conditions, and random packet arrival processes, where it shows that much lower average delay can be achieved for packet transmissions when using NC. In [58], transmission power and rate are jointly controlled based on current channel conditions for a set of nodes that communicate through a relay node using NC. The link gain information is used to select the best relay station in [59]. The transmission rate of different PNC schemes is studied in [60, 61] for the two-way relay channels. The average BER of the information exchanged between the two nodes using PNC is analyzed in [62]. Based on the derived BER, a power control scheme is proposed for the two end nodes in order to minimize the instantaneous BER.

Overall, more in-depth research work is required for wireless networks with bidirectional relaying links (WNBRL) in order to provide more comprehensive understanding regarding the relationship between available radio resources such as transmission power, frequency channels, and time slots and network resources such as transmission throughput and service fairness in a more general scenario. Because of the two-way and two-hop transmissions, resource allocations at different time slots are correlated, which complicates the objective of optimizing the network performance.

1.6 Contributions and Overview of the Thesis

In Chapter 2 we study time and power allocations for a WNBRL, where a single frequency channel is shared by all the transmissions, and therefore co-channel interference is a main problem that requires carefully controlling transmission power of the nodes. Power distributions and time slot allocations are jointly considered in order to maximize the transmission throughput of the system. Both DNC and ANC are considered. An optimization problem is first formulated and solved for the network using DNC, followed by a heuristic scheme for power distributions and time slot allocations. When using ANC, an optimization problem is formulated, which helps design of a heuristic scheme for power distributions and time slot allocations. Although the considered network is ad hoc and all links involve two-hop transmissions, the proposed heuristic scheduling schemes are fully distributed, and do not require a centralized controller or interactions among nodes in different links. By comparing throughput performance of the system using DNC, ANC, and traditional pure relaying, it is concluded that each of these techniques can outperform the other ones under some conditions in terms of maximizing total transmission throughput.

In Chapters 3-5 we switch to consider WNBRL with multiple frequency channels, where the emphasis is to allocate frequency channels and time slots to individual nodes. The objective in Chapter 3 is to maximize the long-term transmission throughput of the system, where the optimum scheduling is solved and two heuristic schemes with different complexity are proposed. In Chapter 4, the objective is to provide proportional fairness of the average throughput among all the links in the system. A sub-optimum solution is achieved and a heuristic scheme is proposed. In Chapter 5 the relay nodes are allowed to opportunistically use NC and pure one-way relaying, and the objective is to maximize the total transmission throughput. Both centralized and distributed topologies are considered. Optimum scheduling is solved, together with different heuristic solutions. The work provides some interesting insights about throughput performance of using different relaying techniques and scheduling rules.

Chapter 2

Power Distributions and Time Allocations in a WNBRL

In this chapter we study time and power allocations for a network using network coding and suffering from co-channel interference. Both DNC and ANC are considered. All the transmissions in the network share the same frequency channel, and simultaneous transmissions interfere with each other. For the network using DNC, an optimization problem is first formulated and solved by assuming that a central station is available to collect all the link gain information and make the scheduling decisions. Distributed schemes are proposed for both networks using DNC and ANC. The scheduling is to decide the transmission time and power for each node in order to maximize the overall throughput of all the links. Some preliminary results have been published in [63], where centralized scheduling schemes have been proposed, which are not included in this thesis. This work has been published in [64]. The remainder of the chapter is organized as follows. In Section 2.1 we describe the system that this work is based on. The scheduling problem for a network using DNC is studied in Section 2.2, and the scheduling problem for a network using ANC is studied in Section 2.3. For comparison, an optimum scheduling problem is formulated and solved in Section 2.4 for a network using pure relaying. Numerical results are shown in Section 2.5 to demonstrate the performance of the scheduling schemes. Section 2.6 summarizes the chapter.

2.1 System Description

We consider a network with M bidirectional links, indexed by $m = 1, 2, \ldots, M$. For each link, there are two end nodes, referred to as S-node and D-node, respectively. We consider a scenario where the direct link between the S- and D-nodes does not exist, e.g., due to object blocking, and a relay node (R-node) is used to forward data packets between them. Each link is equipped with a separated relay node. We consider that the nodes are relatively static and mobility is not a problem. Channel time is divided into equal length time slots, one of which is for one packet transmission, including all the overhead, such as acknowledgement frames, inter-frame spaces and signaling exchanges between the transmitter and the receiver in order to perform transmission power control (details will be given later on). A single frequency channel is shared by all the transmissions, and therefore simultaneous transmissions interfere with each other. At any given time slot, the scheduling problem is to decide which nodes can transmit and find their transmission power, so that high throughput can be achieved for the network over a certain period.

We use $x = s, d, r$ to represent the type of the nodes with s for the S-nodes, d for the D-nodes, and r for the R-nodes, and use $t = 1, 2, \ldots, T$ to represent the time slots, where T is the number of time slots over which the throughput performance is considered. Define a set of binary variables $A_{x_m,t}$'s with $A_{x_m,t} = 1$ denoting that node x of link m transmits at time slot t, and $A_{x_m,t} = 0$ denoting that the same node does not transmit at the time slot. Let $P_{x_m,t}$ represent the transmission power of node x of link m at time slot t, and $G_{x_m,y_n,t}$ represent the link gain between node x of link m and node y of link n at time slot t.

We consider a saturated case, where the S- and D-nodes always have data to transmit. When using DNC, we consider that the R-node should correctly decode all packets from S- and D-nodes. Three time slots are needed for the S-node and D-node of a given link to exchange one pair of packets using DNC, i.e., one packet is transmitted from the S-node to the D-node and one is transmitted from the D-node to the S-node. In the first two time slots, the S-node transmits packet k_s to the R-node, and the D-node transmits packet k_d to the R-node, each taking one time slot. The two packets are decoded at the R-node, which combines the decoded packets and transmits $k_d \oplus k_s$ to both the S-node and D-node in the third time slot, where $\oplus$ is the bit-wise XOR operation. After correctly decoding the combined signal from the R-node, the S-node recovers k_d and the D-node recovers k_s.

When using ANC, it takes two time slots for the S-node and D-node of a given link to exchange one pair of packets. In the first time slot, the S-node transmits packet k_s and the D-node transmits packet k_d simultaneously to the R-node. The R-node does not decode the packets, but amplifies the mixed analog signals and forwards to both the S-node and D-node in the second time slot. Upon receiving the forwarded signal, the S-node recovers k_d and the D-node recovers k_s.

Since multiple links in the network share the same frequency channel, co-channel interference exists, which makes both power control and slot scheduling important to improve the network throughput. In order to save power, all the nodes should transmit at the minimum power. We consider that data packets are transmitted at a fixed rate. The transmission power should achieve a minimum signal-to-interference-plus-noise ratio (SINR) at the receiver, denoted as γ, in order for the receiver to correctly decode the desired signal. This type of scheduling is referred to as "adaptive power" systems, which have been studied extensively in the literature for different types of wireless networks, such as in [65–68]. In contrast, another scheduling option is to fix the transmission power of the nodes, and adjust the transmission rate of each node based on the link gain and interference conditions. This type of scheduling is referred to as "adaptive rate". In [69, 70], the theoretical upper bounds of the achievable transmission rates of the systems using bidirectional relaying are derived based on information theory. Compared to adaptive rate scheduling, adaptive power scheduling has several advantages: i) the transceiver design can be simple as it does not require adjusting the modulation/demodulation and coding/decoding schemes; and ii) the maximum required buffer size at the receivers can be easily calculated so that buffer overflow can be avoided. In addition, the fixed transmission rate requires a minimum SINR to be achieved at the receiver. This can effectively prevent the nodes from wasting power resource when the link and interference conditions are poor, in which case the transmissions can only deliver very low rate, even the sender transmits at the peak power.

For DNC, all the transmissions should meet the SINR target. For ANC, only the transmissions from the R-node should meet the SINR target. For both DNC and ANC, we consider that the scheduling process tries to reduce the data transmission delay caused by buffering packets in the R-nodes. A simple criterion is that when the R-node receives a packet from one of the end nodes, it tries to have the earliest chance to receive another packet from the other end node (for DNC only); and after the R-node receives one packet from each of the end nodes, it tries to have the earliest chance in order to multicast the combined signal to the two end nodes (for both DNC and ANC). We consider that the R-node of a given link does not receive from the end nodes until it has successfully forwarded all previously received packets. Based on this, at any given time slot, the R-node buffers at most one packet from each of the end nodes. Below we analyze the power and time allocations in the network.

2.2 Scheduling for a Network Using DNC

For DNC, correctly decoding the received packets is required for each hop of the transmissions. Consider a typical bidirectional link m. If the S-node or D-node transmit at time slot t, the transmission power should satisfy the following condition in order for the R-node to correctly decode the packet:

$$\frac{P_{x_m,t}G_{x_m,r_m,t}}{I_{r_m,t}+P_n} \geq \gamma, \tag{2.1}$$

where $x = s$ or d, P_n is the power of the background noise, and $I_{r_m,t}$ is the co-channel interference that the R-node experiences from all other transmissions at time slot t and is given by

$$I_{r_m,t} = \sum_{\text{all } z_n \neq x_m} A_{z_n,t}P_{z_n,t}G_{z_n,r_m,t}. \tag{2.2}$$

If the R-node transmits at time slot t, its transmission power should satisfy the following condition in order for both the S-node and the D-node to correctly decode the XORed packet:

$$\min\left\{\frac{P_{r_m,t}G_{r_m,s_m,t}}{I_{s_m,t}+P_n}, \frac{P_{r_m,t}G_{r_m,d_m,t}}{I_{d_m,t}+P_n}\right\} \geq \gamma, \tag{2.3}$$

where $I_{s_m,t}$ and $I_{d_m,t}$, respectively, represent the co-channel interference that the S-node and D-node experience from all other transmissions at time t, and their expressions can be obtained as

$$I_{y_m,t} = \sum_{\text{all } z_n \neq r_m} A_{z_n,t}P_{z_n,t}G_{z_n,y_m,t}, \tag{2.4}$$

where $y = s$ and d.

In addition to transmission power, transmission time of the nodes for the same link should also be constrained. For each link, at most one node can transmit at any given time. That is,

$$A_{s_m,t} + A_{r_m,t} + A_{d_m,t} \leq 1. \tag{2.5}$$

Furthermore, since the R-node does not cumulate more than one packet from each of the end nodes, the following condition should be true for all $t > 0$,

$$0 \leq \sum_{\tau=1}^{t} A_{x_m,\tau} - \sum_{\tau=1}^{t} A_{r_m,\tau} \leq 1, \tag{2.6}$$

where $x = s$ or d. In (2.6), the first summation is the total number of packets that the R-node has received from the S-node (if $x = s$) or D-node (if $x = d$) up to time slot t, and the second summation is the total number of packets that the R-node has successfully transmitted up to time slot t. The left-hand side inequality in (2.6) specifies that at any given time slot t, the total number of packets transmitted from the S- or D-node of one link is no less than that transmitted from the R-node of the same link, and the right-hand side inequality specifies that the R-node stores at most one packet from each of the end nodes at any given time slot.

For a given link, the throughput in both directions (from the S-node to the D-node or from the D-node to the S-node) is the same because of the use of network coding. Therefore, below we consider the throughput in one direction for each link. Let C_m represent the total number of successfully transmitted packets for link m in one direction up to time slot T. We have $C_m = \sum_{t=1}^{T} A_{r_m,t}$. Define C_m/T as the average throughput in number of packets per time slot for link m. Our objective is to maximize $\sum_{m=1}^{M} C_m/T$.

2.2.1 Optimum scheduling

Based on the above analysis, we can formulate an optimization problem as follows:

$$\text{P1:} \quad \max_{\{A_{x_m,t}\},\{P_{x_m,t}\}} \sum_{m=1}^{M} C_m/T \tag{2.7}$$

$$\text{s.t.} \quad \frac{A_{x_m,t}P_{x_m,t}G_{x_m,y_m,t}}{I_{y_m,t}+P_n} \geq \gamma A_{x_m,t}, \text{ for all } m, x, \text{ and } t \tag{2.8}$$

$$I_{y_m,t} = \sum_{\text{all } z_n \neq x_m} A_{z_n,t}P_{z_n,t}G_{z_n,y_m,t}, \text{ for all } m, y, \text{ and } t \tag{2.9}$$

$$C_m = \sum_{t=1}^{T} A_{r_m,t}, \text{ for all } m \tag{2.10}$$

$$A_{s_m,t} + A_{r_m,t} + A_{d_m,t} \leq 1, \text{ for all } m \text{ and } t \tag{2.11}$$

$$0 \leq \sum_{\tau=1}^{t} A_{x_m,\tau} - \sum_{\tau=1}^{t} A_{r_m,\tau} \leq 1, \ x \in \{s,d\}, \text{ for all } m \text{ and } t \tag{2.12}$$

$$A_{x_m,t} \in \{0,1\}, \text{ for all } m, x, \text{ and } t \tag{2.13}$$

$$0 \leq P_{x_m,t} \leq P_{\max}, \text{ for all } m, x, \text{ and } t. \tag{2.14}$$

When $A_{x_m,t} = 1$, the constraint in (2.8) gives the SINR conditions defined in (2.1) when the S- or D-nodes transmit (i.e., $x = s$ or d) and in (2.3) when the R-node transmits (i.e., $x = r$). The constraint defined in (2.9) gives the interference levels at the receiver defined in (2.2) when the S- or D-nodes transmit (i.e., $x = s$ or d) and in (2.4) when the R-node transmits (i.e., $x = r$). The problem is a non-linear mixed-integer problem and cannot be solved efficiently using commercial software available. Below we convert the problem to a linear problem.

Define $\tilde{P}_{x_m,t}$'s for all x, m, and t to satisfy the two constraints as follows

$$0 \leq \tilde{P}_{x_m,t} \leq P_{x_m,t}, \text{ and} \tag{2.15}$$

$$P_{x_m,t} - 1000(1 - A_{x_m,t}) \leq \tilde{P}_{x_m,t} \leq 1000A_{x_m,t}, \tag{2.16}$$

where the value 1000 can be replaced by any other value that is much greater than $P_{\max}$. Then $\tilde{P}_{x_m,t}$ can be used to replace $A_{x_m,t}P_{x_m,t}$ in both (2.8) and (2.9). If $A_{x_m,t} = 0$, $\tilde{P}_{x_m,t} = 0$; and if $A_{x_m,t} = 1$, $\tilde{P}_{x_m,t} = P_{x_m,t}$. In addition, by removing $A_{x_m,t}$ on the right-hand side of (2.8) and adding an extra term to the numerator on the left-hand side of the constraint, we have

$$\frac{\tilde{P}_{x_m,t}G_{x_m,y_m,t} + 1000(1 - A_{x_m,t})}{I_{y_m,t} + P_n} \geq \gamma, \tag{2.17}$$

where the value 1000 can be replaced by any other value that is big enough. When $A_{x_m,t} = 1$, the extra term that we added is zero, which makes the constraint as expected. When $A_{x_m,t} = 0$, the extra term is much larger than the denominator, and the constraint is always satisfied. Therefore, (2.17) is equivalent to (2.8).

The original optimization problem P1 can then be rewritten as

$$\text{P1a:} \quad \max_{\{P_{x_m,t}\},\{A_{x_m,t}\},\{\tilde{P}_{x_m,t}\}} \sum_{m=1}^{M} C_m/T \tag{2.18}$$

$$\text{s.t.} \quad \frac{\tilde{P}_{x_m,t} G_{x_m,y_m,t} + 1000(1 - A_{x_m,t})}{I_{y_m,t} + P_n} \geq \gamma, \text{ for all } x, y, m, \text{ and } t \tag{2.19}$$

$$I_{y_m,t} = \sum_{\text{all } z_n \neq x_m} \tilde{P}_{z_n,t} G_{z_n,y_m,t}, \text{ for all } x, y, m, \text{ and } t \tag{2.20}$$

$$C_m = \sum_{t=1}^{T} A_{r_m,t}, \text{ for all } m \tag{2.21}$$

$$A_{s_m,t} + A_{r_m,t} + A_{d_m,t} \leq 1, \text{ for all } m \text{ and } t \tag{2.22}$$

$$0 \leq \sum_{\tau=1}^{t} A_{x_m,\tau} - \sum_{\tau=1}^{t} A_{r_m,\tau} \leq 1, \text{ for } x \in \{s, d\}, \text{ all } m \text{ and } t \tag{2.23}$$

$$0 \leq \tilde{P}_{x_m,t} \leq P_{x_m,t}, \text{ for all } m \text{ , } x, \text{ and } t \tag{2.24}$$

$$P_{x_m,t} - 1000(1 - A_{x_m,t}) \leq \tilde{P}_{x_m,t} \leq 1000 A_{x_m,t}, \text{ for all } m \text{ , } x, \text{ and } t \tag{2.25}$$

$$A_{x_m,t} \in \{0, 1\}, \text{ for all } m, x, \text{ and } t \tag{2.26}$$

$$0 \leq P_{x_m,t} \leq P_{\max}, \text{ for all } m \text{ , } x, \text{ and } t \tag{2.27}$$

where the objective and the constraints are all linear.

The solutions to this optimization problem can be used as an upper bound for a practical scheduling problem. Implementing the solutions is unlikely, since it jointly optimizes the scheduling decisions at all the time slots, and therefore requires future information of all the link gains. In addition, it requires a central controller that can collect all the link gain information in the network. Below we design a simple distributed scheduling scheme that can be implemented in a practical ad hoc network without a central controller.

2.2.2 Heuristic scheduling

The scheduling scheme is divided into two steps. The first step is to select one eligible node from each link based on the time constraints and put the node into a set $\mathcal{A}_t$, which is empty before making the scheduling decision at each time slot, and the second step is to perform an iterative power control algorithm to find the transmission power of the nodes in $\mathcal{A}_t$, so that as many eligible nodes as possible can transmit subject to the SINR requirements and maximum transmission power limit.

According to the time constraints (2.11)-(2.12), the three nodes of the same link should transmit at three different time slots. We define S_m, D_m and R_m, respectively, as the number of time slots that the S-, D-, and R-nodes of link m have successfully transmitted up to the current time slot. When $t = 0$, $S_m = D_m = R_m = 0$. The value of S_m (D_m or R_m) is increased by 1 after the S-node (D-node or R-node) of link m transmits one packet successfully. For link m, the S-node knows both S_m and R_m, the D-node knows both D_m and R_m, and the R-node knows all S_m, D_m, and R_m. We assume that the S-node can obtain D_m and the D-node can obtain S_m from the R-node, which may piggyback the values to the end nodes when transmitting data packets, and then the values of S_m, D_m, and R_m are known to the three nodes, so that they can make consistent decisions in the first step based on the relative values of S_m, D_m, and R_m. For link m,

- if $S_m = D_m = R_m$, either the S- or the D-node can be scheduled to transmit next. Determining which node has better transmission conditions can be complicated, because this depends on the transmission activity of other links in the network. Here we arbitrarily choose to include the S-node in $\mathcal{A}_t$. Because of this, $S_m \geq D_m$ is always true. A more complicated decision is possible, but will be at a price of increased overhead, which may degrade the network level throughput performance.

- If $S_m = D_m > R_m$, then the R-node of the link should be scheduled to transmit next, and this node is included in $\mathcal{A}_t$.
- If $S_m > D_m$, the D-node is included in $\mathcal{A}_t$.

After one node from each link is selected and put into $\mathcal{A}_t$, the transmission power for the nodes in $\mathcal{A}_t$ should be determined in the second step. Based on (2.8), when node x_m transmits, $A_{x_m,t} = 1$, its transmission power should satisfy the following condition

$$\frac{P_{x_m,t} G_{x_m,y_m,t}}{\sum_{z_n \in \mathcal{A}_t,\ z_n \neq x_m} P_{z_n,t} G_{z_n,y_m,t} + P_n} \geq \gamma, \tag{2.28}$$

for all $x_m \in \mathcal{A}_t$. Since the transmission of each node in $\mathcal{A}_t$ has a target SINR at the respective receiver, the distributed constrained power control (DCPC) algorithm proposed in [71] can be used for the nodes to reach their transmission power iteratively. Details for deriving the iterative power control formulas are given in Appendix A. Although the power control algorithm in [71] was originally proposed for cellular networks without time scheduling, it has been proved later in [72] that the algorithm converges exponentially in single-hop wireless ad hoc networks and can be used in TDMA-based wireless ad hoc networks, which perform joint power control and slot scheduling. In the network considered in this work, each link requires two-hop transmissions. However, after the first step of the scheduling process, power control is reduced to meet the SINR targets for single hop transmissions of the nodes in $\mathcal{A}_t$. As long as the time slot duration is much longer than it is required for the power control algorithm to converge, the time slot scheduling should not affect the convergence of the power control. This is not a problem for relative static channel conditions.

The DCPC power control requires the receivers to feedback the measured SINR values to their respective transmitters after each iteration. It is distributed, and does not require a node to know the transmission power or link condition of any other nodes. If there is a feasible solution to (2.28), i.e., $0 \leq P_{x_m,t} \leq P_{\max}$ for all $x_m \in \mathcal{A}_t$, then the dynamic power control converges to the optimum solution [71], which makes the equality in (2.28) to hold for all nodes in $\mathcal{A}_t$. Otherwise, the transmission power of at least one node reaches $P_{\max}$, while its transmission SINR is not satisfied. In the latter case, some nodes can be removed from $\mathcal{A}_t$ based on certain criteria, so that all the remaining nodes in $\mathcal{A}_t$ can transmit with satisfactory SINRs. Different removal criteria are available in the literature, e.g., [71, 73]. In general, gradually removing the nodes one by one works better than removing multiple nodes at a time [71] in the sense that more nodes can be supported after the removal process is completed. However, this is at the price of longer time for completing the link removal and power control process, which not only increases the implementation complexity, but also negatively affects the transmission throughput. We apply a simple criterion that removes all the nodes with $P_{x_m,t} = P_{\max}$ after the DCPC algorithm converges for the first time. When the power control process converges for the second time, S_m, D_m, and R_m are updated for all nodes with successful transmissions. If the R-node of link m has transmitted successfully, then $C_m = C_m + 1$.

Comments:

- The scheduling algorithm above is described for a saturated case, where the S- and D-nodes always have data to transmit. Extending the scheduling scheme to an unsaturated case is straightforward, in which case, an S- or D-node may not always have packets to transmit. An additional step can be added at the end of the first step to remove any S- or D-nodes from the set $\mathcal{A}_t$, if the nodes do not have data to transmit. The same power control algorithm is then performed to determine the transmission power of the nodes in $\mathcal{A}_t$.

- The scheduling scheme is designed for a constant transmission rate. In case the transmission rate can vary, some changes to the scheduling process are required. In the first step, S_m, D_m, and R_m should be redefined as the total amount of transmitted data up to the current time slot. That is, at time slot t, $S_m = \sum_{\tau=1}^{t} A_{s_m,\tau} B_{s_m,\tau}$, $D_m = \sum_{\tau=1}^{t} A_{d_m,\tau} B_{d_m,\tau}$, and $R_m = \sum_{\tau=1}^{t} A_{r_m,\tau} B_{r_m,\tau}$, where $B_{x_m,\tau}$ is the transmission rate of node x of link m at time slot τ. The values of S_m, D_m and R_m are compared and one node is selected and put into $\mathcal{A}_t$ based on the same criteria as in the original scheme. In the second step, the same power control process is performed, except that the SINR thresholds are different for different transmission rates.

- The above comments also apply to the scheduling scheme proposed for ANC in the next section.

2.3 Scheduling for a Network Using ANC

In this section, we consider a network using ANC. Consider a typical bidirectional link m. At time slot τ, the S-node transmits packet k_s to the R-node with transmission power $P_{s_m,\tau}$, and the D-node transmits packet k_d to the R-node with transmission power $P_{d_m,\tau}$. Packets k_s and k_d reach the receiver of the R-node with power $P_{s_m,\tau} G_{s_m,r_m,\tau}$ and $P_{d_m,\tau} G_{d_m,r_m,\tau}$, respectively. At the same time, the R-node of link

m also receives interference from all other transmitting nodes, and the interference level at the R-node receiver is given by

$$I_{r_m,\tau} = \sum_{\text{all } z_n \neq s_m, z_n \neq d_m} A_{z_n,\tau} P_{z_n,\tau} G_{z_n,r_m,\tau}. \tag{2.29}$$

Let t be the time slot that the R-node of link m forwards the mixed signal carrying packets k_s and k_d (which were received by the R-nodes at time slot τ). At time slot t ($t > \tau$), the R-node of link m amplifies the mixed signal, interference, as well as noise, that it received at time slot τ by $\beta_{m,t}$ times, and sends to both the S-node and the D-node. The transmission power for each portion in the amplified mixed signal at the R-node is given by i) $\beta_{m,t} P_{s_m,\tau} G_{s_m,r_m,\tau}$ for packet k_s, ii) $\beta_{m,t} P_{d_m,\tau} G_{d_m,r_m,\tau}$ for packet k_d, iii) $\beta_{m,t} I_{r_m,\tau}$ for the interference, and iv) $\beta_{m,t} P_n$ for the background noise. When the above mixed signal reaches the S-node, the received power for each portion becomes i) $\beta_{m,t} P_{s_m,\tau} G_{s_m,r_m,\tau} G_{r_m,s_m,t}$ for packet k_s, ii) $\beta_{m,t} P_{d_m,\tau} G_{d_m,r_m,\tau} G_{r_m,s_m,t}$ for packet k_d, iii) $\beta_{m,t} I_{r_m,\tau} G_{r_m,s_m,t}$ for the interference, and iv) $\beta_{m,t} P_n G_{r_m,s_m,t}$ for the background noise. Assume $\beta_{m,t}$ is known to all the nodes of link m, and the link gains between the S- and R-nodes are known to the S-node, the S-node can remove the portion of packet k_s from the mixed signal. In order for the S-node to recover packet k_d, portion ii) is the desired signal power, and portions iii) and iv) together are the interference and noise power that comes from time slot τ. In addition, the S-node also experiences background noise with power P_n at its own receiver, and receives interference from all other nodes that transmit at time slot t, and this interference level is given by

$$I_{s_m,t} = \sum_{\text{all } z_n \neq r_m} A_{z_n,t} P_{z_n,t} G_{z_n,s_m,t}. \tag{2.30}$$

Based on the above analysis, the following SINR condition should be satisfied in order for the S-node to correctly decode packet k_d at time slot t,

$$\frac{A_{r_m,t}\beta_{m,t}P_{d_m,\tau}G_{d_m,r_m,\tau}G_{r_m,s_m,t}}{\beta_{m,t}G_{r_m,s_m,t}(P_n+I_{r_m,\tau})+I_{s_m,t}+P_n} \geq \gamma A_{r_m,t}. \tag{2.31}$$

Similarly, assume that the D-node knows the link gain between itself and the R-node, then the SINR condition for the D-node to correctly decode packet k_s is given by

$$\frac{A_{r_m,t}\beta_{m,t}P_{s_m,\tau}G_{s_m,r_m,\tau}G_{r_m,d_m,t}}{\beta_{m,t}G_{r_m,d_m,t}(I_{r_m,\tau}+P_n)+I_{d_m,t}+P_n} \geq \gamma A_{r_m,t}, \tag{2.32}$$

where $I_{d_m,t}$ is given by

$$I_{d_m,t} = \sum_{\text{all } z_n \neq r_m} A_{z_n,t}P_{z_n,t}G_{z_n,d_m,t}. \tag{2.33}$$

An optimization problem can be formulated as follows in order to maximize the throughput of all the links, where we replace τ with τ_{mt} since the links having their R-nodes transmit at time slot t may have their S-nodes (and D-nodes) transmit at different time slots,

$$\text{P2:} \quad \max_{\{A_{x_m,t}\},\{P_{x_m,t}\},\{\beta_{m,t}\}} \sum_{m=1}^{M} C_m/T \tag{2.34}$$

$$\text{s.t.} \quad \frac{A_{r_m,t}\beta_{m,t}P_{d_m,\tau_{mt}}G_{d_m,r_m,\tau_{mt}}G_{r_m,s_m,t}}{I_{s_m,t}+P_n+\beta_{m,t}G_{r_m,s_m,t}(P_n+I_{r_m,\tau_{mt}})} \geq \gamma A_{r_m,t}, \text{ for all } m \text{ and } t \tag{2.35}$$

$$\frac{A_{r_m,t}\beta_{m,t}P_{s_m,\tau_{mt}}G_{s_m,r_m,\tau_{mt}}G_{r_m,d_m,t}}{I_{d_m,t}+P_n+\beta_{m,t}G_{r_m,d_m,t}(P_n+I_{r_m,\tau_{mt}})} \geq \gamma A_{r_m,t}, \text{ for all } m \text{ and } t \tag{2.36}$$

$$I_{r_m,\tau_{mt}} = \sum_{\text{all } z_n \neq s_m, z_n \neq d_m} A_{z_n,\tau_{mt}}P_{z_n,\tau_{mt}}G_{z_n,r_m,\tau_{mt}}, \text{for all } m \text{ and } \tau_{mt} \tag{2.37}$$

$$I_{s_m,t} = \sum_{\text{all } z_n \neq r_m} A_{z_n,t} P_{z_n,t} G_{z_n,s_m,t}, \text{ for all } m \text{ and } t \tag{2.38}$$

$$I_{d_m,t} = \sum_{\text{all } z_n \neq r_m} A_{z_n,t} P_{z_n,t} G_{z_n,d_m,t}, \text{ for all } m \text{ and } t \tag{2.39}$$

$$P_{r_m,t} = \beta_{m,t}(P_{s_m,\tau_{mt}} G_{s_m,r_m,\tau_{mt}} + P_{d_m,\tau_{mt}} G_{d_m,r_m,\tau_{mt}} + P_n + I_{r_m,\tau_{mt}}), \text{ for all } m \text{ and } t \tag{2.40}$$

$$\tau_{mt} = \max\{t_1 < t : A_{d_m,t_1} = 1\}, \text{ for all } m \text{ and } t \tag{2.41}$$

$$A_{s_m,t} = A_{d_m,t}, \text{ for all } m \text{ and } t \tag{2.42}$$

$$A_{s_m,t} + A_{r_m,t} \leq 1, \text{ for all } m \text{ and } t \tag{2.43}$$

$$0 \leq \sum_{\tau_{mt}=1}^{t} A_{s_m,\tau_{mt}} - \sum_{\tau_{mt}=1}^{t} A_{r_m,\tau_{mt}} \leq 1, \text{ for all } m \text{ and } t \tag{2.44}$$

$$A_{x_m,t} \in \{0,1\}, \text{ for all } m, x, \text{ and } t \tag{2.45}$$

$$0 \leq P_{x_m,t} \leq P_{\max}, \text{ for all } m, x, \text{ and } t \tag{2.46}$$

$$C_m = \sum_{t=1}^{T} A_{r_m,t}, \text{ for all } m \tag{2.47}$$

where (2.37)-(2.39) give the interference power experienced by respective nodes when they are at the receiving state, (2.40) gives the total transmission power of the R-node at time t, and (2.42)-(2.45) together specify the time constraints. Among the time constraints, (2.42) specifies that the S-node and D-node of the same link should transmit at the same time, (2.43) specifies that the S-node and R-node cannot transmit at the same time, and (2.44) is similar to (2.12) for DNC. The same condition as (2.44) for the S-node should also hold for the D-node, but there is no need to specify this, because the D-node always transmits together with the S-node of the same link. Problem P2 is non-linear and non-convex. Unlike problem P1 in the previous section, problem P2 cannot be easily converted into a problem that can be solved using the commercial available software. This difficulty mainly comes from the fact that the R-node of each link using ANC amplifies both the signals and interference that it received at previous time slots, and as a result, the SINRs at different time slots are correlated to each other in some complicated (non-linear) way.

Below we design a heuristic scheduling scheme that decouples such dependence. The basic idea of the heuristic scheduling is similar to that for DNC. At each time slot t, the scheduling is divided into two steps. In the first step, nodes that are eligible to transmit according to the time constraints are put into a set $\mathcal{A}_t$. The second step is to determine the transmission power of the nodes in $\mathcal{A}_t$ through an iterative power control process. The criterion for including nodes into $\mathcal{A}_t$ is based on the relative values of S_m and R_m, which are defined similarly as for DNC. Since the S- and D-nodes always transmit at the same time, there is no need to define D_m for ANC. For link m, the S- and D-nodes are included in the set if $S_m = R_m$; otherwise, the R-node is eligible to transmit next and included in $\mathcal{A}_t$. At the end of the first step, there can be S-, D-, and R-nodes in $\mathcal{A}_t$. Different from that in DNC, the S- and D-nodes in ANC do not directly participate in the power control process as their transmissions do not have a fixed target SINR. The optimum transmission power for each S- or D-node in $\mathcal{A}_t$ may depend on the number of nodes in the set and their channel and interference conditions, and can be very difficult to determine, especially in a network without a central controller. For this reason, we fix the transmission power for the S- and D-nodes to either $P_{\max}$ or zero (details will be given later). This simplified power allocations for the S- and D-nodes allows us to emphasize more on the power allocations for the R-nodes, which, as will be seen below, can still be complicated due to the inherent properties of ANC. Consider that the R-node of link m is in $\mathcal{A}_t$, then the transmission power of the node should satisfy the following two conditions:

$$\frac{\beta_{m,t} P_{d_m,\tau_{mt}} G_{d_m,r_m,\tau_{mt}} G_{r_m,s_m,t}}{I_{s_m,t} + P_n + \beta_{m,t} G_{r_m,s_m,t}(P_n + I_{r_m,\tau_{mt}})} \geq \gamma, \tag{2.48}$$

$$\frac{\beta_{m,t} P_{s_m,\tau_{mt}} G_{s_m,r_m,\tau_{mt}} G_{r_m,d_m,t}}{I_{d_m,t} + P_n + \beta_{m,t} G_{r_m,d_m,t}(P_n + I_{r_m,\tau_{mt}})} \geq \gamma, \tag{2.49}$$

which are obtained by letting $A_{r_m,t} = 1$ in (2.31) and (2.32), respectively. Further, from (2.40) we can solve $\beta_{m,t}$ as

$$\beta_{m,t} = \frac{P_{r_m,t}}{P_{s_m,\tau_{mt}} G_{s_m,r_m,\tau_{mt}} + P_{d_m,\tau_{mt}} G_{d_m,r_m,\tau_{mt}} + P_n + I_{r_m,\tau_{mt}}} = \frac{P_{r_m,t}}{V_{r_m,\tau_{mt}}}, \tag{2.50}$$

where

$$V_{r_m,\tau_{mt}} = (P_{s_m,\tau_{mt}} G_{s_m,r_m,\tau_{mt}} + P_{d_m,\tau_{mt}} G_{d_m,r_m,\tau_{mt}}) + I_{r_m,\tau_{mt}} + P_n \tag{2.51}$$

is the total power of the received signals, interference, and noise at the R-node of link m at time slot τ_{mt}. Define $U_{d_m,r_m,\tau_{mt}} = P_{d_m,\tau_{mt}} G_{d_m,r_m,\tau_{mt}}$, which is the signal power at the R-node of link m received from the D-node of the link at time slot τ_{mt}, and substitute $\beta_{m,t}$ in (2.50) into (2.48). We then have

$$\frac{\frac{P_{r_m,t}}{V_{r_m,\tau_{mt}}} U_{d_m,r_m,\tau_{mt}} G_{r_m,s_m,t}}{I_{s_m,t} + P_n + \frac{P_{r_m,t}}{V_{r_m,\tau_{mt}}} G_{r_m,s_m,t}(P_n + I_{r_m,\tau_{mt}})} \geq \gamma, \tag{2.52}$$

from which we can solve $P_{r_m,t}$ as

$$P_{r_m,t} \geq \frac{\gamma V_{r_m,\tau_{mt}}}{G_{r_m,s_m,t}\left[U_{d_m,r_m,\tau_{mt}} - \gamma(P_n + I_{r_m,\tau_{mt}})\right]} \times (I_{s_m,t} + P_n), \tag{2.53}$$

where $I_{s_m,t}$ can be measured by the S-node at time slot t, $V_{r_m,\tau_{mt}}$ can be measured by the R-node at time slot τ_{mt}, and $U_{d_m,r_m,\tau_{mt}}$ can be measured by the R-node at time slot τ_{mt}. Multiplying both the numerator and the denominator on the right-hand side of (2.53) by $P_{r_m,t}$, we have

$$P_{r_m,t} \geq P_{r_m,t} \frac{\gamma V_{r_m,\tau_{mt}}}{U_{r_m,s_m,t}\left[U_{d_m,r_m,\tau_{mt}} - \gamma(P_n + I_{r_m,\tau_{mt}})\right]} \times (I_{s_m,t} + P_n), \tag{2.54}$$

where $U_{r_m,s_m,t} = P_{r_m,t} G_{r_m,s_m,t}$ is the received signal power at the S-node from the R-node of link m at time slot t, and can be measured at the S-node. In order to satisfy the SINR at the S-node, the transmission power of the R-node can be controlled using an iterative scheme based on (2.54). Let $P_{r_m,t}(k)$ be the transmission power of the R-node at the kth iteration, then its transmission power in the next iteration is given by

$$P_{r_m,t}(k+1) = P_{r_m,t}(k) \frac{\tilde{\gamma}_s}{\gamma_{r2s,t}(k)}, \tag{2.55}$$

where

$$\tilde{\gamma}_s = \frac{\gamma V_{r_m,\tau_{mt}}}{U_{d_m,r_m,\tau_{mt}} - \gamma(P_n + I_{r_m,\tau_{mt}})}, \tag{2.56}$$

which can be calculated by the R-node based on its measured values of $V_{r_m,\tau_{mt}}$, $U_{d_m,r_m,\tau_{mt}}$, and $I_{r_m,\tau_{mt}}$ at time slot τ_{mt}, and

$$\gamma_{r2s,t}(k) = \frac{U_{r_m,s_m,t}(k)}{I_{s_m,t}(k) + P_n}, \tag{2.57}$$

which can be calculated at the S-node at time slot t during the power control process based on the measured values at each iteration, where $U_{r_m,s_m,t}(k)$ and $I_{s_m,t}(k)$, respectively, are the measured values of $U_{r_m,s_m,t}$ and $I_{s_m,t}$ at the kth iteration.

In order for the mixed signal transmitted by the R-node to reach the D-node with satisfactory SINR, the transmission power of the R-node should also be controlled to satisfy the following condition,

$$P_{r_m,t}(k+1) = P_{r_m,t}(k)\frac{\tilde{\gamma}_d}{\gamma_{r2d,t}(k)}, \tag{2.58}$$

where

$$\tilde{\gamma}_d = \frac{\gamma V_{r_m,\tau_{mt}}}{U_{s_m,r_m,\tau_{mt}} - \gamma(P_n + I_{r_m,\tau_{mt}})}, \tag{2.59}$$

and

$$\gamma_{r2d,t}(k) = \frac{U_{r_m,d_m,t}(k)}{I_{d_m,t}(k) + P_n}, \tag{2.60}$$

and $U_{r_m,d_m,t}(k)$ and $I_{d_m,t}(k)$, respectively, are the measured values of $U_{r_m,d_m,t}$ and $I_{d_m,t}$ in the kth iteration, and $U_{r_m,d_m,t} = P_{r_m,t}G_{r_m,d_m,t}$ is the signal power at the D-node received from the R-node of link m at time slot t. The values of $\tilde{\gamma}_d$ can be calculated by the R-node at time slot τ_{mt}, and the value of $\gamma_{r2d,t}(k)$ are calculated by the D-node at time slot t during the power control process based on the measured values at each iteration. By combining (2.55) and (2.58) and taking into consideration the maximum transmission power, we have

$$P_{r_m,t}(k+1) = \min\left\{P_{r_m,t}(k) \times \max\left\{\frac{\tilde{\gamma}_s}{\gamma_{r2s,t}(k)}, \frac{\tilde{\gamma}_d}{\gamma_{r2d,t}(k)}\right\}, P_{\max}\right\}, \tag{2.61}$$

where $\tilde{\gamma}_s$ and $\tilde{\gamma}_d$ can be considered as the target SINRs for the single hop transmissions from the R-node to the S-node and the D-node, respectively, both can be calculated at the R-node based on its measurements at time slot τ_{mt}; and $\gamma_{r2s,t}(k)$ and $\gamma_{r2d,t}(k)$ are the actual SINRs at the S-node and the D-node, respectively, in the kth iteration of the power control process, and can be calculated at the S- and D-nodes based on their measurements.

The iterative power control works similarly to the power control process for DNC. If the SINRs for the transmissions of all the R-nodes are satisfied when the power control converges, then $S_m = S_m + 1$ for all $S_m \in \mathcal{A}_t$, $R_m = R_m + 1$, and $C_m = C_m + 1$ for all $R_m \in \mathcal{A}_t$. When the SINR targets of some R-nodes are not satisfied after the power control algorithm converges for the first time, the transmission power of these R-nodes reaches $P_{\max}$. There can be different options in this case, for example, stopping the transmissions of some or all the S- and D-nodes in $\mathcal{A}_t$, reducing transmission power of the S- and D-nodes in $\mathcal{A}_t$, or removing some of the R-nodes from $\mathcal{A}_t$. Here we take a simple approach and stop transmissions of the S- and D-nodes, if the SINR of the transmissions of any R-node is not satisfied. When the power control converges for the first time, the R-nodes with $P_{r_m,t} = P_{\max}$ broadcast a special message. Upon receiving this message, the S- and D-nodes in $\mathcal{A}_t$ stop their transmissions, and the R-nodes in $\mathcal{A}_t$ keep the power control process until the process converges again. If the SINR of the transmissions from any R-node is still not satisfied, they will be scheduled to transmit in following time slots. In this case, the S_m's are kept unchanged for the current time slot; and both R_m and C_m are increased by 1 if the transmission of the R-node of link m is successful.

Similar to the scheduling scheme for DNC, the proposed scheduling algorithm for ANC can also be extended to non-saturated case and allow nodes to transmit at different rates.

2.4 Scheduling for a Network Using Pure Relaying

In order to better evaluate the performance of the network using network coding, we compare it with that of the network using pure relaying. Consider the same network with bidirectional communication links as before, but the relay node can only transmit to one end node at a time. It takes four time slots for the two end nodes to exchange one pair of packets through the relay node — one time slot for each end node to transmit to the R-node, and one time slot for the R-node to forward the packets to the two end nodes. Define a set of binary variables $A_{xy,m,t}$'s. When the node x of link m transmits to the node y of the same link at time slot t, $A_{xy,m,t} = 1$; otherwise, $A_{xy,m,t} = 0$, where $(xy) \in \{(sr), (dr), (rs), (rd)\}$. We then have

$$A_{sr,m,t} + A_{dr,m,t} + A_{rs,m,t} + A_{rd,m,t} \leq 1. \tag{2.62}$$

We further define $P_{xy,m,t}$ as the transmission power of the node x to the node y of link m at time slot t. Consider link m, the transmission power of node x should satisfy the following condition:

$$\frac{P_{xy,m,t} G_{x_m,y_m,t}}{I_{y_m,t} + P_n} \geq \gamma, \tag{2.63}$$

where $I_{y_m,t}$ is the co-channel interference from other simultaneous transmissions at the node y of link m and is given by

$$I_{y_m,t} = \sum_{\text{all} n \neq m} A_{x'y',n,t} P_{x'y',n,t} G_{x'_n,y_m,t}, \tag{2.64}$$

where x' and y' is a pair of the transmitter and receiver nodes, and $(x'y') \in \{(sr), (dr), (rs), (rd)\}$.

In order to have fair comparison with the DNC and ANC scheduling, the R-nodes are also limited to buffer at most one packet from each of the end nodes. That is,

$$0 \leq \sum_{\tau=1}^{t} A_{sr,m,\tau} - \sum_{\tau=1}^{t} A_{rd,m,\tau} \leq 1, \tag{2.65}$$

and

$$0 \leq \sum_{\tau=1}^{t} A_{dr,m,\tau} - \sum_{\tau=1}^{t} A_{rs_m,\tau} \leq 1. \tag{2.66}$$

Furthermore, as in the DNC or ANC cases, the same throughput should be achieved in both directions for each link, i.e.,

$$C_{sd,m} = C_{ds,m}, \tag{2.67}$$

where $C_{sd,m}$ is the total number of packets received by the D-node from the S-node of link m, and $C_{ds,m}$ is the total number of packets received by the S-node from the D-node of link m. We have $C_{sd,m} = \sum_{t=1}^{T} A_{rd,m,t}$, and $C_{ds,m} = \sum_{t=1}^{T} A_{rs,m,t}$.

By putting together all the above constraints, we can formulate an optimization problem as follows, and the objective is to maximize the overall throughput.

$$\text{P3:} \quad \max_{\{A_{xy,m,t}\},\{P_{xy,m,t}\}} \sum_{m} C_{sd,m}/T \tag{2.68}$$

$$\frac{A_{xy,m,t}P_{xy,m,t}G_{x_m,y_m,t}}{I_{y_m,t}+P_n} \geq A_{xy,m,t}\gamma, \text{ for all } xy,\ m \text{ and } t \tag{2.69}$$

$$I_{y_m,t} = \sum_{\text{all}_{n\neq m}} A_{x'y',n,t}P_{x'y',n,t}G_{x'_n,y_m,t}, \text{ for all } x'y',\ y,\ m \text{ and } t \tag{2.70}$$

$$C_{sd,m} = \sum_{t=1}^{T} A_{rd,m,t}, \text{ for all } m \tag{2.71}$$

$$C_{ds,m} = \sum_{t=1}^{T} A_{rs,m,t}, \text{ for all } m \tag{2.72}$$

$$C_{sd,m} = C_{ds,m}, \text{ for all } m \tag{2.73}$$

$$A_{sr,m,t} + A_{dr,m,t} + A_{rs,m,t} + A_{rd,m,t} \leq 1, \text{ for all } m \text{ and } t \tag{2.74}$$

$$0 \leq \sum_{\tau=1}^{t} A_{sr,m,\tau} - \sum_{\tau=1}^{t} A_{rd,m,\tau} \leq 1, \text{ for all } m \text{ and } t \tag{2.75}$$

$$0 \leq \sum_{\tau=1}^{t} A_{dr,m,\tau} - \sum_{\tau=1}^{t} A_{rs_m,\tau} \leq 1, \text{ for all } m \text{ and } t \tag{2.76}$$

$$A_{xy,m,t} \in \{0,1\}, \text{ for all } xy,\ m, \text{ and } t \tag{2.77}$$

$$0 \leq P_{xy,m,t} \leq P_{\max}, \text{ for all } xy,\ m, \text{ and } t \tag{2.78}$$

This problem can be reformulated into a linear programming problem using a similar approach as in Section 2.2.

2.5 Numerical Results

In this section we demonstrate the throughput performance of the proposed scheduling schemes for both DNC and ANC. In addition to demonstrate the throughput performance under different parameter settings, the throughput of the heuristic scheme for DNC is compared with the optimum solution, and the throughput of the heuristic schemes for DNC and ANC is compared with the optimum solution for pure relaying. The link gain between any two nodes x_m and y_n includes both distance-based path loss and log-normally distributed shadowing, and is given by $G_{x_m,y_n,t} = d_{x_m,y_n}^{-\alpha} \times 10^{-X}$, where X is a Gaussian distributed random variable with zero mean and standard deviation of 1 dB. The default values of the parameters are $P_n = 10^{-10}$ W, $\alpha = 3$, and $P_{\max} = 0.1$ W.

We first consider a network with a grid topology, where all the nodes of M bidirectional links are deployed in an $M \times 3$ grid. Fig. 2.1 shows the node locations for $M = 3$. For each link, all the three nodes are located in a row, the S-node is on the left, the D-node is on the right, and the R-node is located at the middle point between the S-node and the D-node. The distance between the R-node and the S-node of the same link is denoted as w_1, and the distance between the S-nodes of two neighboring links is denoted as w_2. The main reason for considering such a simple network topology is because of the complexity for solving the optimization problem, which is very time consuming due to that the scheduling decisions at all the time slots are jointly optimized. When w_1 is smaller, the distance between the desired transmitter and receiver is shorter, and relatively small transmission power is required in order to compensate for the path loss. The default value for w_1 is 100 m. When w_2 is smaller, the distance between interfering nodes is shorter, and higher transmission power may be required to combat the interference, or fewer nodes may be allowed to transmit simultaneously. The default value for w_2 is 1500 m.

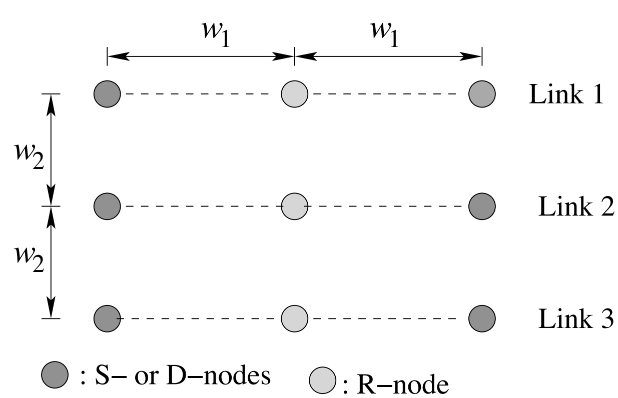

Figure 2.1: Grid topology with $M = 3$

Analytically, it takes three time slots to exchange one pair of packets between the S-node and the D-node of a given bidirectional link when using DNC. Therefore, the

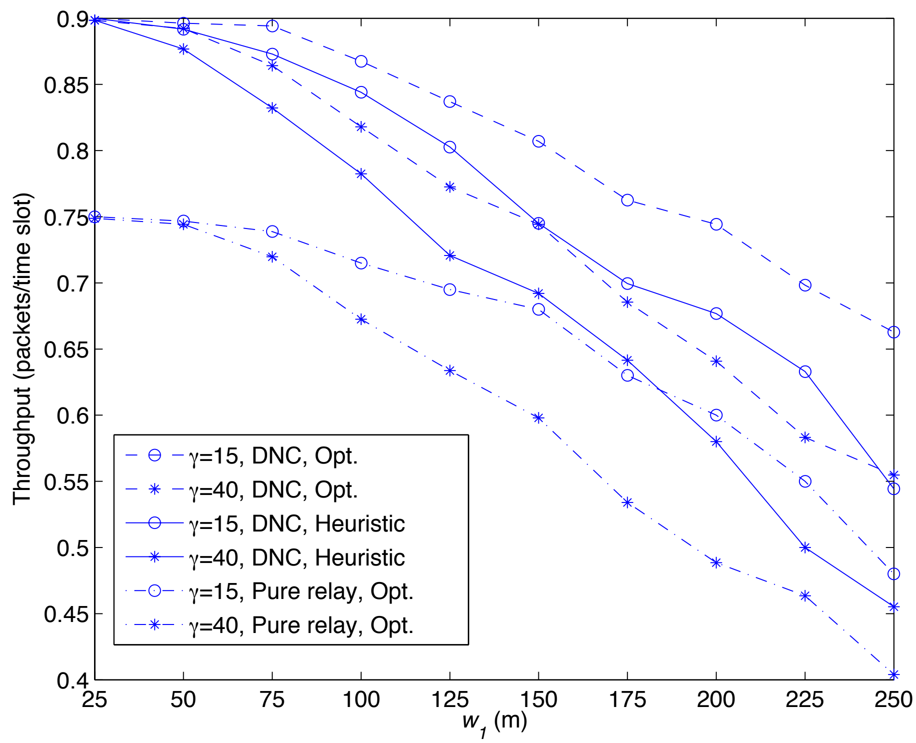

Figure 2.2: Throughput versus w_1 for DNC and pure relaying

maximum throughput in one direction (either from the S-node to the D-node or in the opposite direction) for each link is 1/3 packets per time slot. With three bidirectional links in the network, the maximum unidirectional throughput is one packet per time slot in total. For ANC, it takes two time slots to exchange one pair of packets in each bidirectional link. Therefore, the maximum unidirectional throughput is 1/2 packets per time slot for each link, or 1.5 packets per time slot for all the three links. The actual throughput is always lower due to the maximum power limit and mutual interference.

Fig. 2.2 shows the transmission throughput of a network using DNC and pure relaying for different values of w_1. For DNC, when w_1 is very small, the heuristic scheduling achieves approximately the same throughput as the optimum scheduling. In this case, the communication distance is short, the transmission power of the nodes is relatively low, and the effect of co-channel interference from other links on the network throughput performance is relatively weak. As w_1 increases, the transmission power of the nodes increases in order to compensate for the increased path loss, which increases the mutual interference and makes it more difficult to satisfy the SINR requirements. Therefore, the throughput decreases as w_1 increases. Furthermore, the throughput decreases with w_1 much faster for larger γ values, because higher target SINR requires higher transmission power, which causes higher mutual interference between transmissions of the nodes from different links.

For DNC, there are several reasons that cause the performance gap between the proposed heuristic scheduling and the optimum scheduling. First, the optimum scheduling solution is not causal, since it jointly optimizes the scheduling decisions of all the time slots, while the heuristic scheduling is only based on the information at the current time slot. Second, the node removal process is not optimized in the heuristic scheduling when the network cannot support all the nodes in $\mathcal{A}_t$ to transmit at a given time slot. With the simple node removal criterion, more nodes tend to be removed than necessary, causing throughput degradation. Third, the heuristic scheduling arbitrarily chooses to have the S-node to transmit earlier than the D-node. As w_1 increases, the effect of these on the throughput of the heuristic scheduling increases, and the throughput gap between the heuristic and the optimum scheduling increases.

On the other hand, the heuristic scheduling is suitable for a practical system, since it is simple, does not require global information about the mutual interference conditions among different nodes and links, and does not require future link gain information. In addition, it can be implemented distributively at individual nodes. Fig. 2.2 further shows that the throughput performance of the heuristic scheduling in a network using DNC can be much higher than the optimum throughput of the same network using pure relaying. Note that the throughput performance shown for pure relaying is the upper bound of any practical scheduling schemes. Therefore, using DNC and the proposed scheduling scheme achieves better throughput performance than using pure relaying.

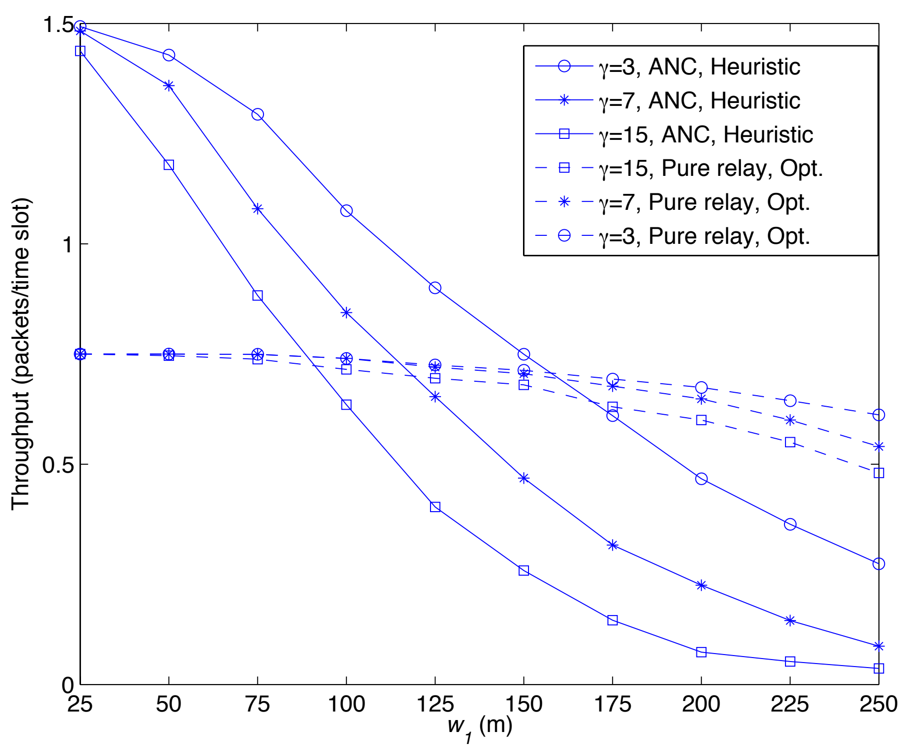

Figure 2.3: Throughput versus w_1 for ANC and pure relaying

Fig. 2.3 compares the throughput performance between the networks using ANC and pure relaying when w_1 changes. From the figure we can see that when w_1 is

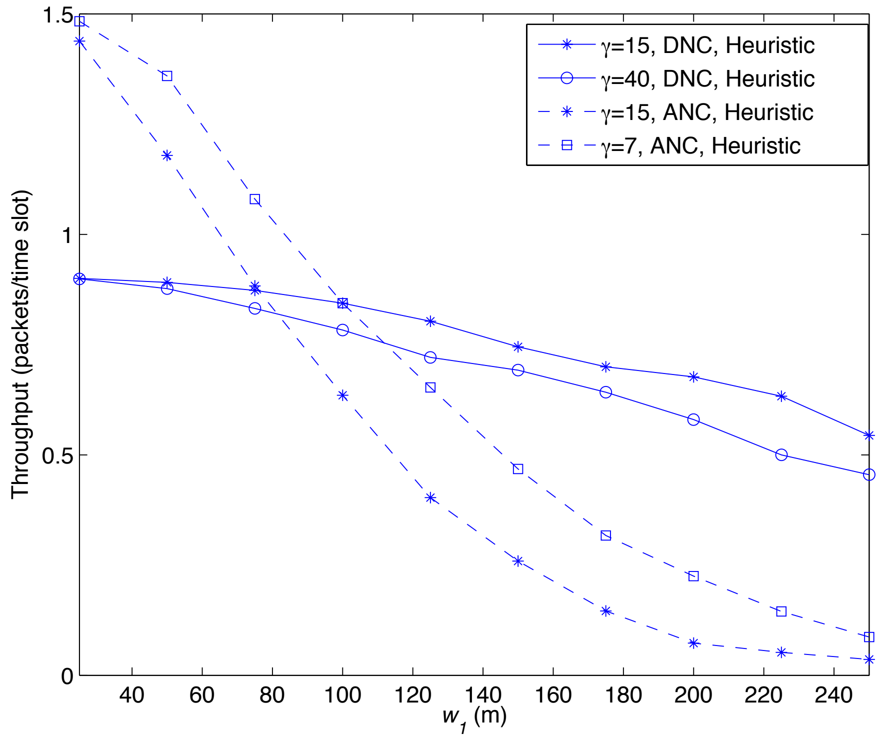

Figure 2.4: Throughput versus w_1 for DNC and ANC

relatively small, using ANC can achieve much higher throughput than using pure relaying. However, the throughput of the network using ANC can decrease quickly with w_1, and when w_1 is larger than a certain value, the throughput performance using ANC falls below that using pure relaying. When ANC is used, interference and noise at the R-nodes is all amplified and transmitted to the end nodes, which makes ANC very sensitive to high interference. When w_1 increases, signals transmitted by the S- and D-nodes reach the R-node with lower SINRs, and both the desired signals and the interference are amplified by the R-node and forwarded to the end nodes again, which require the R-node to transmit high power in order for the mixed signal to reach the S- and D-nodes with satisfactory SINRs (above γ), which further reduces the SINRs of the transmissions of other S- and D-nodes that transmit at the same time. Because of this effect, mutual interference can increase significantly in the network using ANC as w_1 increases. Similarly, performance of the network using ANC is also sensitive to the required SINR. When the required SINR increases, the throughput performance can decrease significantly. For relatively low SINR requirement, such as $\gamma = 3$ (about 4.8 dB), the throughput performance of the proposed scheduling scheme for ANC is better than that of the optimum scheduling for using pure relaying when w_1 is less than 150 m. On the other hand, when $\gamma = 15$ (about 11.8 dB), w_1 should be less than 85 m in order for the proposed scheduling scheme for ANC to achieve higher throughput than the optimum scheduling using pure relaying.

Fig. 2.4 compares the throughput performance between the networks using DNC and ANC when w_1 changes. From this figure we can see that when w_1 is small, using ANC and the proposed scheduling scheme can achieve much higher throughput than using DNC. Compared to using DNC, using ANC saves one time slot for the two end nodes of each link to exchange one packet. This allows ANC to achieve higher throughput than DNC. On the other hand, the throughput performance of the system using ANC is more sensitive to interference, and decreases with w_1 and γ more significantly than using DNC. When w_1 increases, it becomes more difficult to satisfy the SINR requirements for the network using ANC, which results in fewer chances for multiple nodes to transmit simultaneously. Therefore, the overall throughput of the network using ANC can be lower than that using DNC.

Fig. 2.5 shows the throughput performance of the proposed scheduling scheme for the network using DNC as w_2 changes. As w_2 increases, the distance between nodes of different links increases, which reduces the mutual interference among the links.

Therefore, throughput increases with w_2. When w_2 is relatively small, the effect of increasing w_2 on the throughput performance is obvious. After w_2 is larger than a certain value, changing w_2 has little effect on the throughput performance, since the performance is dominated by the link gains of the nodes within individual links. Fig. 2.5 also shows the optimum throughput performance of the network using pure relaying. It is seen that the proposed scheduling scheme for DNC can achieve much higher throughput than the optimum scheduling using pure relaying. The difference is much more obvious when γ and w_2 are smaller.

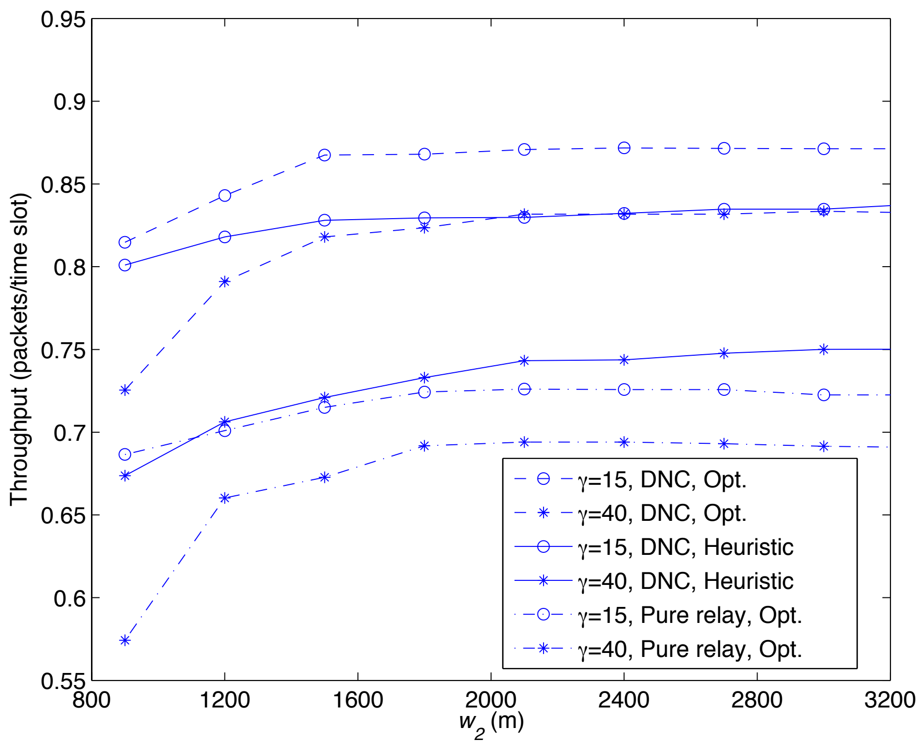

Figure 2.5: Throughput versus w_2 for DNC and pure relaying

Next we simulate a random network, where the S- and D-nodes are randomly distributed in an $a \times a$ m^2 square area, and the location of the R-node for each link is uniformly distributed in a circle that is centered at the middle point between its two end nodes and has a radius of 5 m. For different values of a, the throughput performance is shown in Fig. 2.6 for using DNC and in Fig. 2.7 for using ANC. For comparison, the optimum throughput performance of the network using pure relaying is also shown in each figure. As the parameter a increases, the network service area increases, the distance between nodes of different links increases on average, the average mutual interference decreases, and therefore, the overall throughput increases. Fig. 2.6 shows that the throughput performance of the proposed heuristic scheduling scheme for DNC is always higher than the optimum throughput using pure relaying for the simulated network settings. Fig. 2.7 shows that the throughput performance of the proposed distributed scheduling scheme for ANC is higher than the optimum throughput using pure relaying when the network area is relatively large or the required SINR is relatively low. When the network area is sufficiently large, the throughput performance of the proposed scheduling scheme for ANC can reach the upper bound, which is much larger than the throughput for pure relaying. On the other hand, when the required SINR is relatively high and mutual interference is very strong, using pure relaying can be better than using ANC (provided that a close-to-optimum scheduling scheme can be designed for pure relaying).

Next, we fix the network service area to be 700×700 m^2 and study the throughput performance versus the distance between the S- and D-nodes. We randomly place all the S-nodes in the simulated network service area, and then choose the location of the corresponding D-node along the circle that is centered at the S-node. The radius of the circle, or the distance between the S- and D-nodes is changed during the simulation and used as the x-axis for Figs. 2.8 and 2.9. The location of the R-node

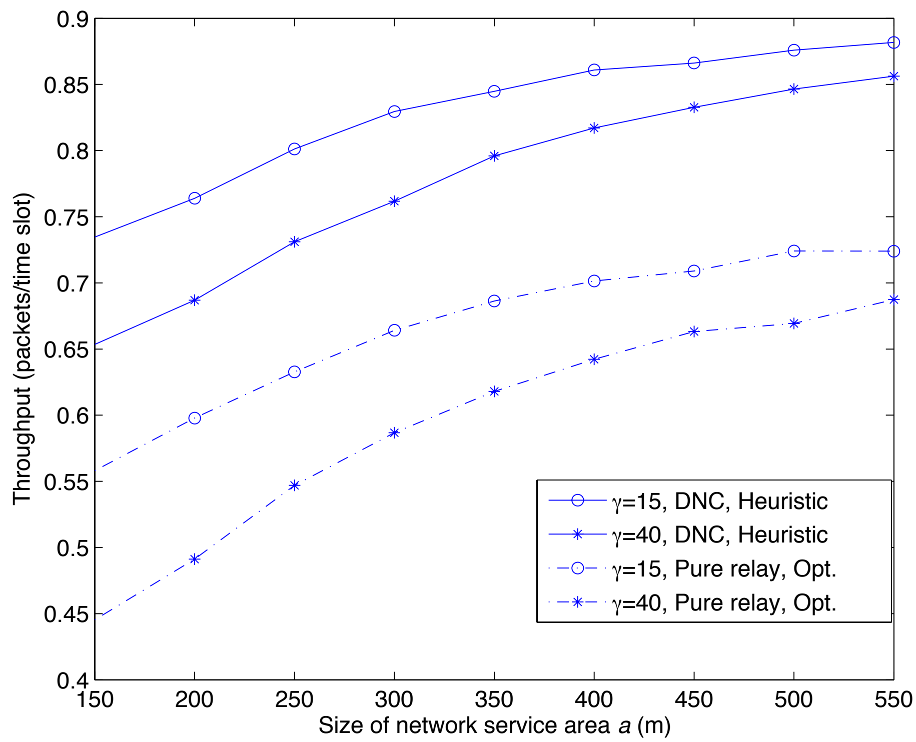

Figure 2.6: Throughput versus simulation area in random topology for DNC and pure relaying

for each link is uniformly distributed in a circle that is centered at the middle point between its two end nodes and has a radius of 5 m. Fig. 2.8 shows the performance of the heuristic scheduling for DNC, and Fig. 2.9 shows the performance of the heuristic scheduling for ANC. Fig. 2.8 shows that using DNC outperforms pure relaying for the simulated settings, and Fig. 2.9 shows that when the distance between the S- and D-nodes is relatively small, using ANC can achieve much higher throughput than using pure relaying. These observations are consistent with that from the previous simulations.

Fig. 2.10 shows the throughput of the network with different number of links (M).

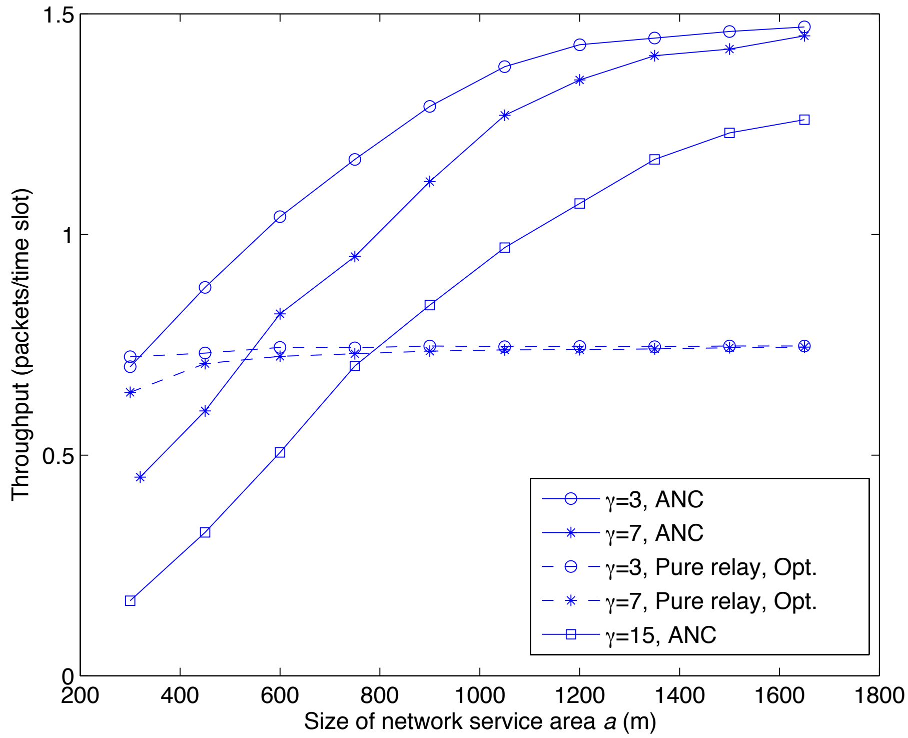

Figure 2.7: Throughput versus simulation area in random topology for ANC and pure relaying

The throughput of the network using DNC for $\gamma = 3$ and 7 is not shown in order to keep clarity of the figure. In general, the throughput increases with the number of links for both DNC and ANC. The throughput of the network using DNC increases with M faster than that using ANC. For the same SINR requirements (e.g., $\gamma = 15$ and 40), when M is relatively small, using ANC can achieve higher throughput than using DNC; when M is relatively large, using DNC may achieve higher throughput than using ANC. Using ANC can achieve much higher throughput than using DNC when the required SINR is relatively low, such as $\gamma = 3$ or 7; on the other hand, the throughput of the network using ANC can drop significantly when the required SINR is high, such as $\gamma = 40$, in which case the throughput hardly increases with M due to strong co-channel interference.

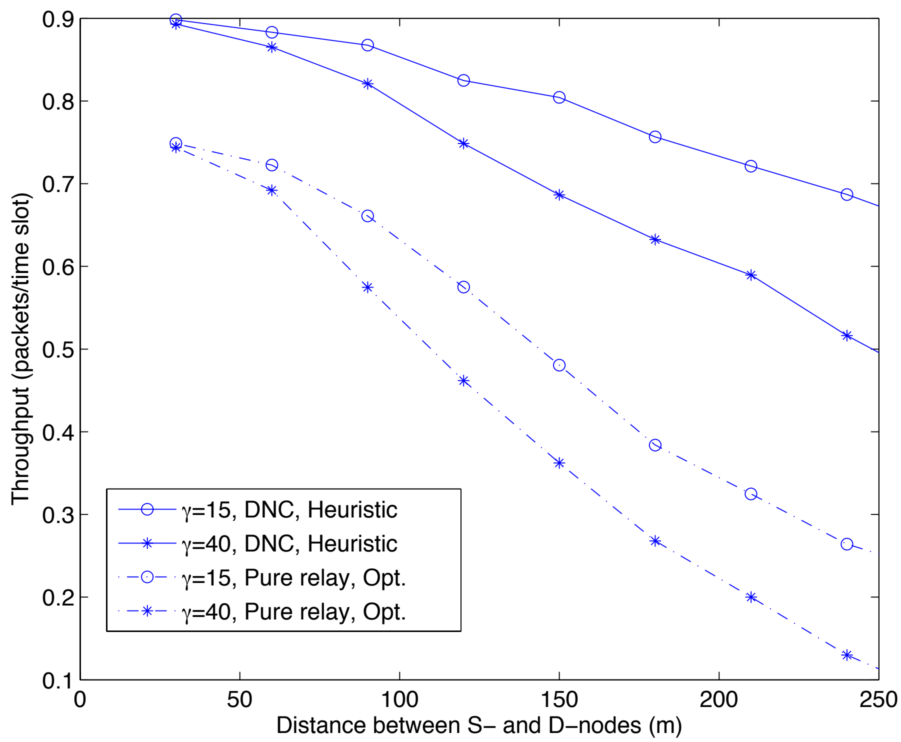

Figure 2.8: Throughput versus S-D distance in random topology for DNC and pure relaying

2.6 Summary

We have studied transmission time and power scheduling for a network with bidirectional links and network coding. Optimum scheduling has been solved for the network using digital network coding, and heuristic and distributed scheduling schemes have been proposed for both the digital network coding and analog network coding. In

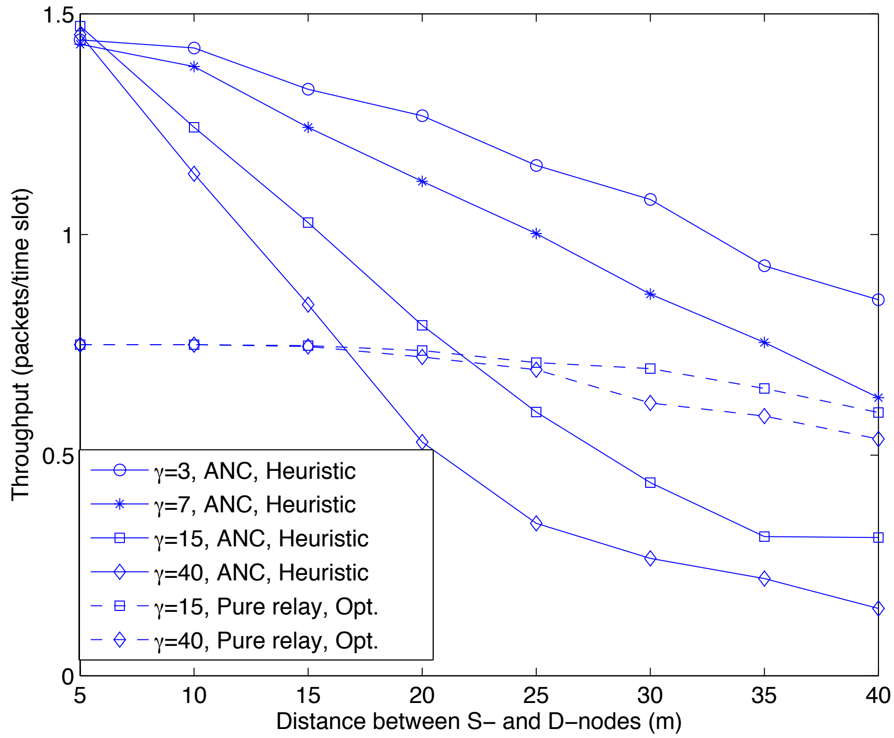

Figure 2.9: Throughput versus S-D distance in random topology for ANC and pure relaying

terms of complexity, the scheduling scheme for ANC is more complicated than that for DNC, because transmissions at different time slots for the network using ANC are dependent on each other. Our numerical results have demonstrated that the proposed scheduling scheme for DNC achieves higher throughput than the optimum throughput for pure relaying. When the SINR requirement is relatively low and channel conditions are good, using ANC can achieve higher throughput than using DNC and pure relaying; and in other cases, using DNC or pure relaying may achieve higher throughput than using ANC. Meanwhile, we have noticed that the scheduling schemes can be very complicated in order to efficiently utilize the network resources

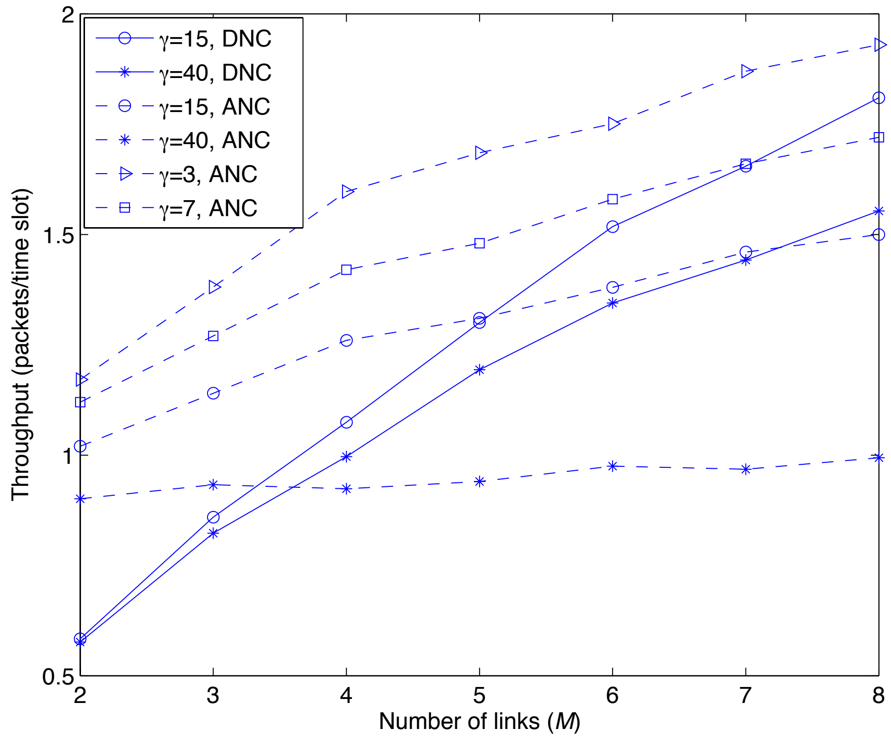

Figure 2.10: Throughput of DNC and ANC versus total number of links in random topology

when co-channel interference exists.

Chapter 3

Frequency Channel and Time Allocations in a WNBRL

In Chapter 2, we have studied a WNBRL, where all transmissions share the same frequency channel. In this chapter we consider a WNBRL with multiple available frequency channels and combine the benefits of NC and multi-channel diversity for network throughput improvement. We study both time scheduling and channel allocations. Each channel is assigned to only one node in order to avoid interference. An optimization problem is first formulated. The objective is to maximize the system throughput, subject to the proper channel allocation and transmission time constraints. Heuristic scheduling schemes are then proposed. The remainder of the chapter is organized as follows. In Section 3.1 we describe the system that this work is based on. The channel allocation and scheduling problem for networks with NC is formulated and heuristic schemes are proposed in Sections 3.2 and 3.3, respectively. Numerical results are demonstrated in Section 3.4 to show the performance of the scheduling and channel allocation schemes. Section 3.5 summarizes the chapter.

Some preliminary results of this work has been published in [74].

3.1 System Description

We consider a network with M bidirectional links, indexed by $m = 1, 2, \ldots, M$. Each link has two end nodes, referred to as S- and D-nodes, which communicate with each other through a relay node, referred to as R-node. Multiple frequency channels are available to the network, indexed by $k = 1, 2, \ldots, K$, where K is the total number of channels. We consider a saturated case, and assume that both the S-nodes and the D-nodes always have packets to transmit. The R-node uses a simple XOR operation to combine the packets from the S-node and D-node, and forwards the data to both the end nodes, i.e., the same as DNC described in the previous Chapter. Data packets received from the end nodes of different links are first buffered in the R-node and wait for chances to be forwarded by the R-node. There is one buffer at the R-node for each end node, and the maximum size of the buffer is $B_{\max}$.

We use $x = s, d, r$ to represent the type of the node with s for the S-node, d for the D-node, and r for the R-node, and use P_x to represent the transmission power of node x. We consider T time slots, indexed by $t = 1, 2, \ldots, T$. Let $G^{xy}_{m,k,t}$ represent the link gain (normalized to background noise power) between nodes x and y of link m at frequency channel k and time slot t, and $(xy) \in \{(sr), (dr), (rs), (rd)\}$. Based on the Shannon capacity formula, the transmission rate between nodes x and y of link m at frequency channel k and time slot t can be calculated as $U^{xy}_{m,k,t} = \log_2(1 + P_x G^{xy}_{m,k,t})$. We consider fixed transmission power for all nodes, i.e., $P_s = P_d = P_r = P_{\max}$.

3.2 Optimum Problem Formulation

We define three sets of binary variables, $X_{m,k,t}$, $Y_{m,k,t}$, and $Z_{m,k,t}$. When $X_{m,k,t} = 1$, frequency channel k is assigned to the S-node of link m at time slot t, and $X_{m,k,t} = 0$ otherwise. When $Y_{m,k,t} = 1$, frequency channel k is assigned to the D-node of link m at time slot t, and $Y_{m,k,t} = 0$ otherwise. When $Z_{m,k,t} = 1$, frequency channel k is assigned to the R-node of link m at time slot t, and $Z_{m,k,t} = 0$ otherwise. Based on these definitions, we have

$$\sum_k (X_{m,k,t} + Y_{m,k,t} + Z_{m,k,t}) \leq 1, \text{all } m,\ t, \tag{3.1}$$

$$\sum_m (X_{m,k,t} + Y_{m,k,t} + Z_{m,k,t}) = 1, \text{all } k,\ t, \tag{3.2}$$

where (3.1) guarantees that each link is assigned to at most one channel at each time slot, and also guarantees that there is at most one node from each link transmitting at a time. (3.2) guarantees that each channel is assigned to one link at a time.

Define $C_{x,m,t}$ as the transmission rate of node x of link m at time slot t. We have

$$C_{s,m,t} = \sum_k X_{m,k,t} \times U^{sr}_{m,k,t}, \tag{3.3}$$

$$C_{d,m,t} = \sum_k Y_{m,k,t} \times U^{dr}_{m,k,t}, \tag{3.4}$$

$$C_{r,m,t} = \sum_k Z_{m,k,t} \times \min\{U^{rs}_{m,k,t}, U^{rd}_{m,k,t}\}. \tag{3.5}$$

Consider a time period of T slots. The cumulate rate of link m during this period is given by

$$C_m = \textstyle\sum_{t=1}^{T} C_{r,m,t}, \tag{3.6}$$

which considers the rate at only one direction. Because of the use of NC, the rates in both directions of each bidirectional link are the same. We normalize the duration of one time slot to one, so that the transmission rate is equivalent to the amount of data that are transmitted during one time slot. Our objective is to maximize the total throughput of all the links during this period. That is, to maximize $\sum_{m=1}^{M} C_m/T$.

In addition to the link gains, buffer occupancy at the R-node also limits the transmission rate of each hop. That is, the transmission rate of an S- or D-node is limited by the available space in the buffer, and that of the R-node is limited by the available data in the buffer. Overall, the following constraint should guarantee that transmissions of the S- and D-nodes never overflow their buffers at the R-node, and the R-node always transmits no more than the available data in the buffer.

$$0 \leq \sum_{\tau=1}^{t} C_{s,m,\tau} - \sum_{\tau=1}^{t} C_{r,m,\tau} \leq B_{\max}, \tag{3.7}$$

$$0 \leq \sum_{\tau=1}^{t} C_{d,m,\tau} - \sum_{\tau=1}^{t} C_{r,m,\tau} \leq B_{\max}, \tag{3.8}$$

Define $\mathbf{X}=[X_{m,k,t}]$, $\mathbf{Y}=[Y_{m,k,t}]$, $\mathbf{Z}=[Z_{m,k,t}]$, and $\mathbf{C}=[C_{\cdot,m,t}]$. Based on the above description, an optimization problem can be formulated as follows

$$\text{P1:} \max_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{C}} \sum_{m} C_m/T \tag{3.9}$$

$$\text{s.t. } C_m = \sum_{t} C_{r,m,t}, \text{ all } m \tag{3.10}$$

$$C_{s,m,t} \leq \sum_{k} X_{m,k,t} U^{sr}_{m,k,t}, \text{ all } m,\ t \tag{3.11}$$

$$C_{d,m,t} \leq \sum_{k} Y_{m,k,t} U^{dr}_{m,k,t}, \text{ all } m,\ t \tag{3.12}$$

$$C_{r,m,t} \leq \sum_{k} Z_{m,k,t} \min\{U^{rs}_{m,k,t}, U^{rd}_{m,k,t}\}, \text{ all } m,\ t \tag{3.13}$$

$$0 \leq \sum_{\tau=1}^{t} C_{s,m,\tau} - \sum_{\tau=1}^{t} C_{r,m,\tau} \leq B_{\max}, \text{all } m,\, t \tag{3.14}$$

$$0 \leq \sum_{\tau=1}^{t} C_{d,m,\tau} - \sum_{\tau=1}^{t} C_{r,m,\tau} \leq B_{\max}, \text{all } m,\, t \tag{3.15}$$

$$\sum_{k} (X_{m,k,t} + Y_{m,k,t} + Z_{m,k,t}) \leq 1, \text{all } m,\, t \tag{3.16}$$

$$\sum_{m} (X_{m,k,t} + Y_{m,k,t} + Z_{m,k,t}) = 1, \text{all } k,\, t \tag{3.17}$$

$$X_{m,k,t} \in \{0, 1\},\ \text{all } m,\, k, \text{ and } t \tag{3.18}$$

$$Y_{m,k,t} \in \{0, 1\},\ \text{all } m,\, k, \text{ and } t \tag{3.19}$$

$$Z_{m,k,t} \in \{0, 1\},\ \text{all } m,\, k, \text{ and } t \tag{3.20}$$

The problem above is a mixed integer linear optimization problem, and can be solved by commercial software. However, implementing the solutions is difficult in a practical system. First, the scheduling solution jointly optimizes the resource allocations at all the time slots. It requires future information of link gains at the time of making the decisions, which is impossible in time-varying channels. For relatively static channels, an optimum scheduling can be solved for a period of $T = T_w$, during which the link gains are kept constant. This is referred to as "window-based optimum method". The basic procedure is shown in Algorithm 1, where T_{total} is the number of time slots. When solving the problem for the ith window, all the variables with subscript $t \leq (i-1) \times T_w$ are known. Performing Line 3 generates the channel and time slot allocations for the ith time window, i.e., $(i-1) \times T_w + 1 \leq t \leq i \times T_w$. The window-based optimum solution is based on the assumption that the link conditions are known at the beginning of each window. Solutions from the previous windows are used for solving the problem for the next window. The window-based method still suffers from the causality problem, and cannot be implemented in networks where link gains may change within a window. Even for stable channels, its computational complexity can be very high when T_w is large. Therefore, below we seek heuristic methods with lower complexity.

Algorithm 1 Window-based optimum problem

```
for i = 1 : ⌈T_total/T_w⌉ do
    T = min{T_total, iT_w}
    Solve the optimization problem.
end for
```

3.3 Proposed Heuristic Schemes

We propose two heuristic schemes. The scheduling is performed at time-slot basis. At each time slot, the process is to decide which channel assigned to which node. At the end of the simulation, $\sum_m C_m/T$ is calculated as the system throughput.

3.3.1 CNSCA Scheme

This scheme is shown in Algorithm 2. It includes two steps. The first step (Lines 2-8) is to find possible transmission rate for each node at each channel ($\tilde{C}_{x,m,k}$), and the second step (Lines 10-25) is to assign channels to nodes based on the calculated rates. In the first step, the possible transmission rate of each node at each channel is limited by both the channel gain and the buffer occupancy. We use $b_{sr,m}$ and $b_{dr,m}$, respectively, to represent the amounts of data buffered at the R-node from the S-node and D-node of link m. The subscript t is removed from the notations, since all variables are for the current time slot. In the second step, two sets are defined,

$\mathcal{M}$ initially includes all the links and $\mathcal{K}$ initially includes all the channels. After channel k^* is assigned to a node of link m^*, channel k^* is removed from $\mathcal{K}$, and link m^* is removed from $\mathcal{M}$. The basic idea for the channel assignment is to find the combination of node and channel that achieves the highest rate, and then assign that channel to the node. This process is repeated until the channel set is empty.

Algorithm 2 CNSCA Scheme

{Step 1: rate calculation.}
for $m = 1 : M$ **do**
    for $k = 1 : K$ **do**
        $\tilde{C}_{s,m,k} = \min(U^{sr}_{m,k}, B_{\max} - b_{sr,m})$
        $\tilde{C}_{d,m,k} = \min(U^{dr}_{m,k}, B_{\max} - b_{dr,m})$
        $\tilde{C}_{r,m,k} = 2\min(U^{rs}_{m,k}, U^{rd}_{m,k}, b_{sr,m}, b_{dr,m})$
    end for
end for
{Step 2: node selection and channel assignments.}
Define $\mathcal{M} = \{1, 2, \ldots, M\}$ and $\mathcal{K} = \{1, 2, \ldots, K\}$.
while $\mathcal{K} \neq \emptyset$ **do**
    Find $(n_s, k_s) = \arg\max_{m\in\mathcal{M},k\in\mathcal{K}} \tilde{C}_{s,m,k}$
    Find $(n_d, k_d) = \arg\max_{m\in\mathcal{M},k\in\mathcal{K}} \tilde{C}_{d,m,k}$
    Find $(n_r, k_r) = \arg\max_{m\in\mathcal{M},k\in\mathcal{K}} \tilde{C}_{r,m,k}$
    if $\tilde{C}_{s,n_s,k_s} = \max\{\tilde{C}_{s,n_s,k_s}, \tilde{C}_{d,n_d,k_d}, \tilde{C}_{r,n_r,k_r}\}$ **then**
        $m^* = n_s$ and $k^* = k_s$
    else
        if $\tilde{C}_{d,n_d,k_d} = \max\{\tilde{C}_{s,n_s,k_s}, \tilde{C}_{d,n_d,k_d}, \tilde{C}_{r,n_r,k_r}\}$ **then**
            $m^* = n_d$ and $k^* = k_d$
        else
            $m^* = n_r$ and $k^* = k_r$
        end if
    end if
    Update $\mathcal{K} = \mathcal{K} \setminus \{k^*\}$, and $\mathcal{M} = \mathcal{M} \setminus \{m^*\}$
end while

After the selected nodes transmit, buffers at the relay nodes are updated accordingly. Mathematically, if an S-node or D-node of link m transmits at channel k, we have $b_{sr,m} = b_{sr,m} + \tilde{C}_{s,m,k}$ or $b_{dr,m} = b_{dr,m} + \tilde{C}_{d,m,k}$. If the R-node of link m transmits at channel k, then the buffers are updated as $b_{sr,m} = b_{sr,m} - 0.5\tilde{C}_{r,m,k}$ and $b_{dr,m} = b_{dr,m} - 0.5\tilde{C}_{r,m,k}$, and the total amount of transmitted data for the link is updated as $C_m = C_m + 0.5\tilde{C}_{r,m,k}$.

3.3.2 SNSCA Scheme

The scheme is shown in Algorithm 3. It also includes two steps. The first step (Lines 2-21) selects one node from each link based on the buffer occupancy at the relay node, and the second step assigns channels to the selected nodes based on possible transmission rates of the nodes at different channels. In the first step, a set $\mathcal{A}_t$ is defined, which should include one node from each link at the end of step 1. A simple criterion is used for the node selection. For a given link, if both buffers at the R-node have data, then the R-node transmits; otherwise, the S-node (or D-node) transmits if the buffer for storing data from the S-node (or D-node) is empty. The transmission rates of the selected nodes at different channels in set $\mathcal{A}_t$ are also calculated. Variable x_m^* is used to record which node for link m is selected.

The second phase is to assign channels to nodes in $\mathcal{A}_t$ so that the maximum rate can be achieved. This becomes a standard matching problem in the bipartite graph as shown in Fig. 3.1. In a weighted bipartite graph, each edge has an associated value. A maximum weighted bipartite matching is defined as a matching, where the sum of the values of the edges in the matching has a maximal value. Finding such a matching is known as the assignment problem. In this work, the weight of each edge is the corresponding instantaneous rate for a pair of channel and node of link m ($\tilde{C}_{m,k}$). Different bipartite algorithms can be used for this assignment problem, such

Algorithm 3 SNSCA Scheme

{Step 1: node selection.}
Initialize $\mathcal{A}_t = \emptyset$.
for $m = 1 : M$ **do**
  if $b_{sr,m} > 0$ and $b_{dr,m} > 0$ **then**
    $x_m^* = r$, and $\mathcal{A}_t = \mathcal{A}_t \cup \{r_m\}$.
    for $k = 1 : K$ **do**
      Find $\tilde{C}_{m,k} = 2\min(U_{m,k}^{rs}, U_{m,k}^{rd}, b_{sr,m}, b_{dr,m})$.
    end for
  else
    if $b_{sr,m} = 0$ **then**
      $x_m^* = s$, and $\mathcal{A}_t = \mathcal{A}_t \cup \{s_m\}$.
      for $k = 1 : K$ **do**
        Find $\tilde{C}_{m,k} = \min(U_{m,k}^{sr}, B_{\max} - b_{sr,m})$.
      end for
    else
      $x_m^* = d$, and $\mathcal{A}_t = \mathcal{A}_t \cup \{d_m\}$.
      for $k = 1 : K$ **do**
        Find $\tilde{C}_{m,k} = \min(U_{m,k}^{dr}, B_{\max} - b_{dr,m})$.
      end for
    end if
  end if
end for
{Step 2: channel assignments}
Use a bipartite assignment algorithm.

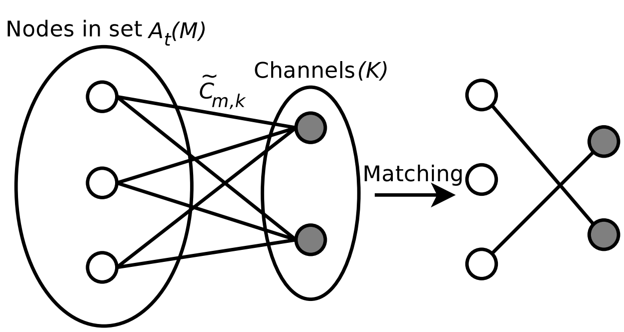

Figure 3.1: Assigning two channels to three nodes

as the Hungarian algorithm [75] and its improvements [76, 77]. After the selected nodes transmit, buffers at the relay nodes are updated accordingly.

3.3.3 Complexity analysis

Each scheme includes two steps. When M and K are large, the complexity mainly comes from step 2. For CNSCA scheme, the second step includes K iterations. In the first iteration, the algorithm is to find three $\arg\max$ pairs, each from MK values. Assume the complexity for performing $\arg\max$ is proportional to the number of the values. The complexity of the second step is $O(MK) + O((M-1)(K-1)) + \ldots + O((M-K+1)) = O(MK^2)$. SNSCA Scheme allows to use existing assignment problems. For example, the improved Hungarian algorithm [76, 77] has complexity of $O(V^2 \log(V) + VE)$, where $V = M + K$ is the total number of vertices and $E = MK$ is the total number of edges in the graph. That is, the complexity is $O((M+K)^2 \log(M+K) + (M+K)(MK))$.

Comparing the required memory space of the two schemes, the first one should store $3M$ rates, one for each of the $3M$ nodes, while the second one should store M rates, one for a node from each of the M links. Therefore, the first scheme requires more memory space than the second one.

3.4 Numerical Results

In this section we demonstrate the throughput performance of the proposed schemes. The distance between each end node to the relay node is w_1. The link gain between an end node and the relay at channel k and time slot t includes both distance-based path loss and log-normally distributed shadowing, and is given by $\tilde{G}^{xy}_{m,k,t} = d^{-\alpha}_{x_m,y_m} \times 10^{-(X_t/10)} \times (c_0/4\pi f_k)^2$, where X_t is Gaussian distributed with zero mean and standard deviation of 10 dB, and c_0 is the speed of light. Also, P_n denotes the background noise power. The default values of the parameters are $\alpha = 3$, $M = 3$, $K = 2$, $T = 400$, $w_1 = 100$ m, $f_1 = 900$ MHz, $f_2 = 1.8$ GHz, $P_n = 10^{-10}$ W, $B_{\max} = 100$, and $P_{\max} = 0.1$ W.

The window-based optimum method can be considered as an upper bound for the heuristic schemes, since it makes the scheduling decisions based on knowing a period of future link gains, and jointly optimizes the scheduling during this period. Fig. 3.2 shows the transmission throughput for different values of w_1. It shows that the throughput decreases with w_1 due to increased path loss, which decreases the link gains, and further reduces the instantaneous transmission rates. The figure shows that CNSCA scheme can achieve throughput performance very close to the window-based optimum solution, which SNSCA scheme achieves lower throughput in general. On the other hand, when w_1 is sufficiently large, both schemes achieve the same throughput performance as the window-based optimum solution. In this case, large path loss prevents most nodes from transmitting at high rate, and the effect of intelligent scheduling on the throughput becomes not obvious.

Fig. 3.3 shows throughput performance of the heuristic schemes as number of links changes. With more links, the opportunity of having links with high link gains increases, which improves the throughput. The throughput increase becomes saturated as the number of links is beyond a certain limit, because the total throughput is limited by the total number of available channels. Meanwhile, we notice that average throughput per link decreases with number of links, since more links share the same amount of channel resource. This is shown in Fig. 3.4. Both Figs. 3.3 and 3.4 show that CNSCA scheme achieves close-to-optimum throughput performance.

Fig. 3.5 shows throughput performance as number of channels changes, where $M = 11$. In this figure, the frequency of channels changes from 800 MHz to 1.6 GHz. As more channels are available, the throughput increases almost linearly.

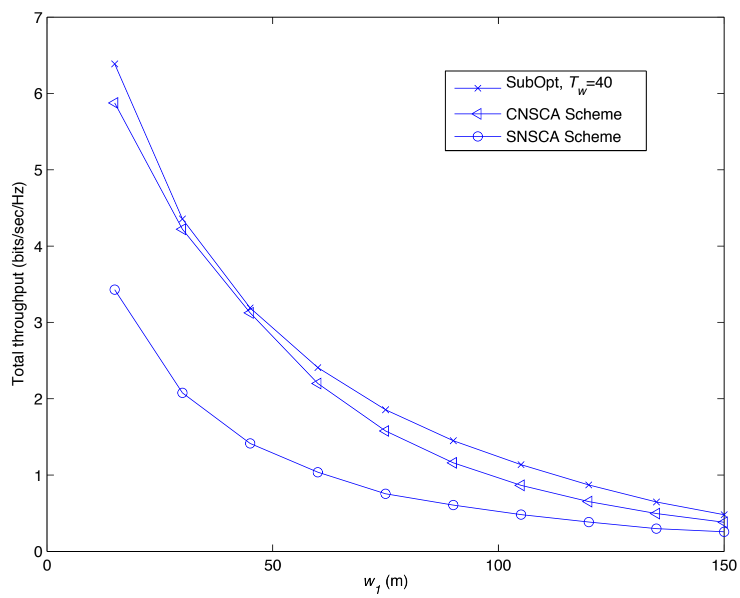

Figure 3.2: Throughput versus w_1

3.5 Summary

We have studied transmission time scheduling and frequency channel allocations for a multi-channel network with bidirectional links and using network coding, and proposed two scheduling schemes (CNSCA and SNSCA). Compared to the SNSCA

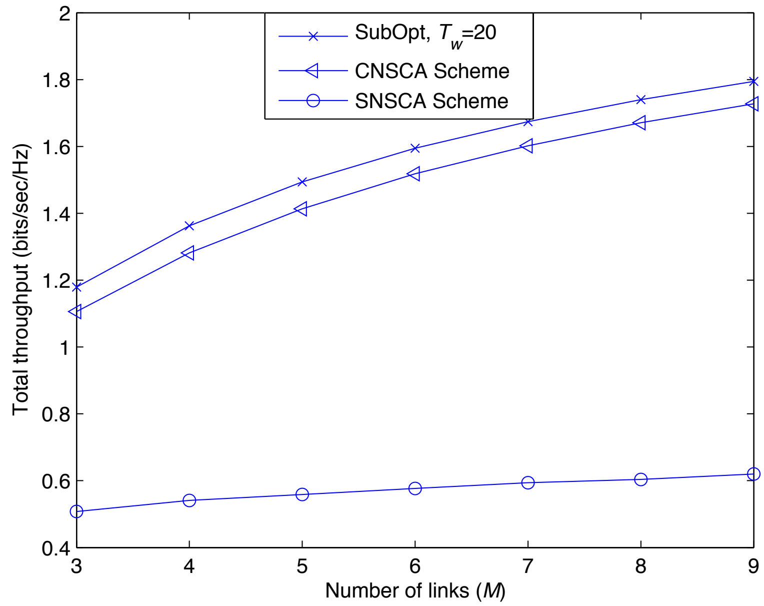

Figure 3.3: Throughput versus M

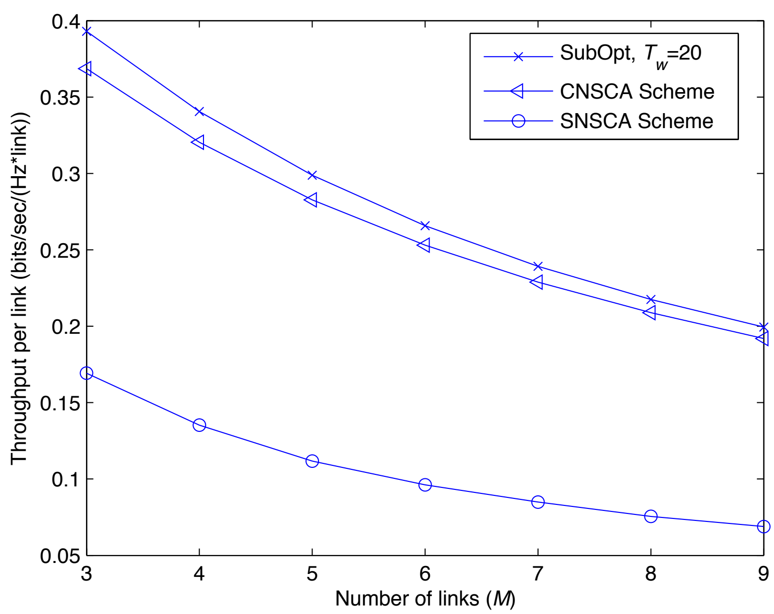

Figure 3.4: Throughput per link versus M

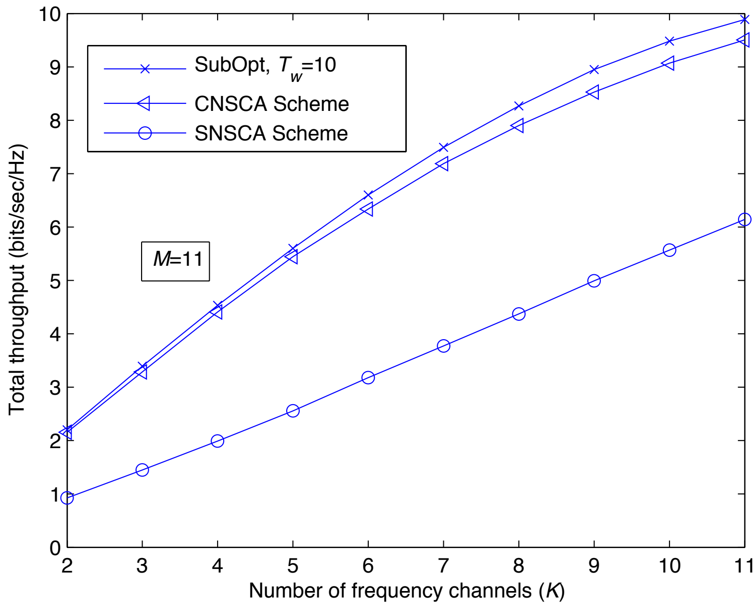

Figure 3.5: Throughput versus K

scheme, the CNSCA scheme requires more memory space to store possible transmission rates of all nodes, and achieves close-to-optimum throughput performance.

Chapter 4

Achieving Long-term Fair Throughput in a WNBRL

In the previous chapter, the objective of the scheduling is to maximize the total throughput. The proposed schemes can efficiently use available network resources, but may result in that links with good channel conditions starve other links, which may not be desired in some service scenarios. In this chapter, we will study time scheduling and channel allocations for a WNBRL in order to provide proportional fair throughput among different links. Providing fair throughput to multi-hop transmission links is difficult, and is even more challenging for bidirectional relying links because the use of network coding. To our knowledge, no works are available in the literature on the physical and medium access control layers to provide fair throughput for multihop transmission links, and no works to provide fair throughput in a network using NC. In this chapter we consider a bidirectional relaying network, where network coding is used by the relay node for data forwarding, and study both frequency channel and time slot allocations in order to provide proportional fair throughput to different links. An optimum problem is first formulated and a sub-optimum solution is obtained in Section 4.1, and a heuristic scheduling scheme is then proposed in Section 4.2. Numerical results are shown in Section 4.3, which demonstrates that the performance of the proposed heuristic scheme is very close to the sub-optimum solutions. Compared to the scheduling that maximizes the total throughput, the proposed PF scheduling scheme provides significantly higher fairness index with relatively minor throughput reduction. Section 4.4 summarizes the chapter.

4.1 Optimum Problem Formulation

The system studied in this chapter is basically the same as in the previous chapter, and the same notations are used as in the previous chapter. One difference is that in this chapter we consider a centralized (star) topology, where different links can share the radios at the R-node. In other words, two end nodes of each link communicate through a relay node, which is equipped with multiple radios. Therefore, constraint (3.1) in Chapter 3 is replaced with the following two constraints:

$$\sum_k (X_{m,k,t} + Z_{m,k,t}) \leq 1, \tag{4.1}$$

$$\sum_k (Y_{m,k,t} + Z_{m,k,t}) \leq 1, \tag{4.2}$$

for all m and t. First, each of the end nodes has one radio, and therefore, cannot transmit and receive at the same time; and furthermore, when it transmits or receives, only one channel is used. As the R-node is equipped with multiple radios, these two constraints allow the two end nodes of link m to simultaneously transmit to different radios (at different channels) of the R-node.

We consider proportional fairness (PF) for the long-term average throughput of the links. Compared to the objective that maximizes the total transmission rate of all links, achieving rate allocations with PF is a better tradeoff between user's satisfaction and system revenue [78]. After the system reaches the PF state, if any link's rate is increased by a certain percent, then other links' rate will be decreased by at least the same percent. In [78], PF is proved to be equivalent to maximizing a logarithmic utility function of the transmission rate.

Consider a general network with M links. Channel time is divided into discrete time slots. The throughput of link m at time slot t is $C_{r,m,t}$, and $\overline{C}_m = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} C_{r,m,t}$ is the long-term average throughput of link m. At each time slot, $\overline{A}_m(t+1)$ is used to represent a weighed average rate for link m up to time t, and is given by,

$$\overline{A}_m(t+1) = \gamma \overline{A}_m(t) + (1-\gamma) C_{r,m,t}, \tag{4.3}$$

where $0 < \gamma < 1$ is a parameter that balances the weights of the throughput in the past and the most recent time slot. For a special case, $\overline{A}_m(0) = 0$. A general scheduling problem can be formulated to maximize a certain objective function $U(\overline{A}(t))$, where $\overline{A}(t) = [\overline{A}_1(t), \overline{A}_2(t), ..., \overline{A}_M(t)]$. When $U(\overline{A}(t)) = \sum_{m=1}^{M} \log \overline{A}_m(t)$, PF is achieved for the average throughput among the links. It is proved in [79] that this objective can be achieved through iterative scheduling, and the objective at each iteration is to find the scheduling decision in order to maximize $\sum_{m=1}^{M} C_{r,m,t}/\overline{A}_m(t)$.

Together with other constraints as in Chapter 3, an optimization problem for achieving PF for the average throughput among the links can be formulated as follows

$$\text{P1:} \qquad \max_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{C}} \sum_{m=1}^{M} \frac{C_{r,m,t}}{\overline{A}_m(t)} \tag{4.4}$$

$$\text{s.t.} \quad C_{s,m,t} \leq \sum_k X_{m,k,t} U^{sr}_{m,k,t}, \forall m, t \tag{4.5}$$

$$C_{d,m,t} \leq \sum_k Y_{m,k,t} U^{dr}_{m,k,t}, \forall m, t \tag{4.6}$$

$$C_{r,m,t} \leq \sum_k Z_{m,k,t} \min\{U^{rs}_{m,k,t}, U^{rd}_{m,k,t}\}, \forall m, t \tag{4.7}$$

$$0 \leq \sum_{\tau=1}^{t} (C_{s,m,\tau} - C_{r,m,\tau}) \leq B_{\max}, \forall m, t \tag{4.8}$$

$$0 \leq \sum_{\tau=1}^{t} (C_{d,m,\tau} - C_{r,m,\tau}) \leq B_{\max}, \forall m, t \tag{4.9}$$

$$\sum_k (X_{m,k,t} + Z_{m,k,t}) \leq 1, \forall m, t \tag{4.10}$$

$$\sum_k (Y_{m,k,t} + Z_{m,k,t}) \leq 1, \forall m, t \tag{4.11}$$

$$\sum_m (X_{m,k,t} + Y_{m,k,t} + Z_{m,k,t}) \leq 1, \forall k, t \tag{4.12}$$

$$X_{m,k,t}, Y_{m,k,t}, Z_{m,k,t} \in \{0, 1\}, \forall m, k, t \tag{4.13}$$

For a network with single hop transmissions, each iteration is performed in one time slot. The basic idea of the slot-by-slot scheduling is that at each time slot, the transmission priority is given to the links with the highest $\frac{C_{r,m,t}}{\overline{A}_m(t)}$. That is, links that either can achieve high throughput in the current time slot (i.e., high $C_{r,m,t}$) or did not transmit much (i.e., low $\overline{A}_m(t)$) in the past have a better chance to transmit in the current time slot. In each time slot, the weighted average throughput $\overline{A}_m(t)$ is updated using the past information, and the scheduling decision in the current time slot is based on the updated $\overline{A}_m(t)$'s and the current channel and link states. However, such slot-by-slot iterative scheduling is difficult to implement for multihop links. Take for an example the two-hop transmissions considered in this work, one major problem is that although any transmissions from an end node affect the long-term throughput of the link, such effect cannot be seen until the transmitted data are forwarded to the other end node by the relay. Therefore, based on the objective in (4.4), transmissions of the multiple hops that have to happen at different time slots must be jointly considered. In this case, the objective function is not convex, and the optimization problem cannot be easily solved.

In order to make the problem solvable, we seek an alternate solution. Note that when $T \to \infty$, for a stable service system, the throughput in all the three transmission stages for a given link should be the same, i.e., $\lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} C_{s,m,t} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} C_{d,m,t} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} C_{r,m,t} = \overline{C}_m$. Therefore, instead of having $C_{r,m,t}$'s only in the numerator of the objective function, we also include the throughput from the end nodes to the relay node, and the new objective function becomes $\max \sum_{m=1}^{M} (C_{s,m,t} + C_{d,m,t} + 2C_{r,m,t})/\overline{A}_m(t))$. With this new objective function, the optimization problem becomes

$$\begin{aligned} \text{P2:} \quad & \max_{\mathbf{X_t},\mathbf{Y_t},\mathbf{Z_t},\mathbf{C_t}} \sum_{m=1}^{M} \frac{C_{s,m,t} + C_{d,m,t} + 2C_{r,m,t}}{\overline{A}_m(t)} \\ \text{s.t.} \quad & \text{Constraints (4.5)-(4.13)} \end{aligned} \tag{4.14}$$

where $\mathbf{X}_t = [X_{m,k,t}, \forall m, k]$, $\mathbf{Y}_t = [Y_{m,k,t}, \forall m, k]$, $\mathbf{Z}_t = [Z_{m,k,t}, \forall m, k]$, and $\mathbf{C}_t = [C_{x,m,t}, \forall x, m]$ are the variables to be optimized at time slot t. The problem is solved slot-by-slot. At each slot t, $\overline{A}_m(t)$ can be calculated based on information before t, and the optimization problem is a mixed integer linear program. At the end of time slot $t-1$ or beginning of time slot t, $\overline{A}_m(t)$ is updated as

$$\overline{A}_m(t) = \begin{cases} \gamma\overline{A}_m(t-1) + (1-\gamma)C_{r,m,t-1}, & \text{if R-node transmitted at } t-1 \\ \gamma\overline{A}_m(t-1), & \text{otherwise.} \end{cases} \tag{4.15}$$

By adding two extra terms in the objective function, we can effectively decouple the scheduling in different time slots, and the scheduling process can be performed iteratively slot-by-slot. Although solving problem P2 both resolves the causality problem of problem P1 and reduces the complexity, it does not give the optimum solution that achieves perfect fairness among the average throughput of the links, because the scheduling is forced to maximize $\sum_{m=1}^{M} \frac{C_{s,m,t}+C_{d,m,t}+2C_{r,m,t}}{\overline{A}_m(t)}$ in each time slot, which may not be necessary if the decisions over a longer period can be jointly optimized. However, given the difficulties for achieving long-term PF over multihop (two-hop in our case) communication links, alternative solutions are not available for achieving PF in multihop networks. Even for solving P2, it is still time consuming, and designing a heuristic scheme with lower complexity is necessary for a practical system.

4.2 Heuristic Scheduling Scheme

In this section we propose a heuristic scheduling scheme for achieving PF among the long-term throughput of different links. The heuristic scheme is performed at the R-node. We assume that the R-node has the link gain information between itself and all the end nodes at each time slot. The scheduling is performed on time-slot basis. At each time slot, the process is to decide which channel should be assigned to which node. The subscript t is removed from the notations in this section, since all the processes are described for the current time slot. We use $b_{sr,m}$ and $b_{dr,m}$, respectively, to represent the amounts of data buffered at the R-node from the S-node and D-node of link m. The maximum transmission rate of each end node is limited by both the link conditions and the available buffer space at the R-node, and the maximum transmission rate of the R-node is limited by both the link conditions to the end nodes and the amount of buffered data from both the end nodes. Define $\hat{C}_{s_m,k}$, $\hat{C}_{d_m,k}$, and $\hat{C}_{r_m,k}$, respectively, as the maximum transmission rate of the S-, D-, and R-nodes of link m at frequency channel k, we have

$$\hat{C}_{s_m,k} = \min(U^{sr}_{m,k}, B_{\max} - b_{sr,m}), \quad (4.16)$$

$$\hat{C}_{d_m,k} = \min(U^{dr}_{m,k}, B_{\max} - b_{dr,m}), \quad (4.17)$$

$$\hat{C}_{r_m,k} = 2\min(U^{rs}_{m,k}, U^{rd}_{m,k}, b_{sr,m}, b_{dr,m}). \quad (4.18)$$

The scheme is shown in Algorithm 1. Several sets are defined, including $\mathcal{S}$, $\mathcal{D}$, $\mathcal{R}$, $\mathcal{X}$, $\mathcal{K}$, and $\mathcal{M}_r$. If the S-node of link m has not been scheduled to transmit or receive, $s_m \in \mathcal{S}$; if the D-node of link m has not been scheduled to transmit or receive, $d_m \in \mathcal{D}$; and if both the S- and D-nodes of link m have not been scheduled to transmit or both of them have not been scheduled to receive, $r_m \in \mathcal{R}$. Initially, $\mathcal{S}$ includes all the S-nodes, $\mathcal{D}$ includes all the D-nodes, and $\mathcal{R}$ includes all r_m for $m = 1, 2, \ldots, M$. In addition, $\mathcal{X}$ is a union of $\mathcal{S}$, $\mathcal{D}$, and $\mathcal{R}$, $\mathcal{K}$ is a set of all the channels that have not been used by any transmissions, and $\mathcal{M}_r$ is a set of all the links whose R-nodes have been scheduled to transmit. All these sets are updated during the scheduling process.

Algorithm 1 Achieving long-term PF

Input: $\mathcal{S} = \{s_1, s_2, \ldots, s_M\}$, $\mathcal{D} = \{d_1, d_2, \ldots, d_M\}$, $\mathcal{R} = \{r_1, r_2, \ldots, r_M\}$, $\mathcal{X} = \mathcal{S} \cup \mathcal{D} \cup \mathcal{R}$, $\mathcal{K} = \{1, 2, \ldots, K\}$, and $\mathcal{M}_r = \emptyset$. $\mathbf{X} = \mathbf{Y} = \mathbf{Z} = \mathbf{0}$

Output: $\mathbf{X}$, $\mathbf{Y}$, and $\mathbf{Z}$

```
while K ≠ ∅ and X ≠ ∅ do
    Find (x*_{m*}, k*) = arg max_{x_m ∈ X, k ∈ K} Ã_{x_m,k}
    switch x* do
        case s
            X_{m*,k*,t} = 1
            S = S \ {s_{m*}}, R = R \ {r_{m*}}
        case d
            Y_{m*,k*,t} = 1
            D = D \ {d_{m*}}, R = R \ {r_{m*}}
        otherwise
            Z_{m*,k*,t} = 1
            Ā_{m*} = γĀ_{m*} + (1 − γ)Ĉ_{r_{m*},k*},
            M_r = M_r ∪ {m*}
            S = S \ {s_{m*}}, D = D \ {d_{m*}}, R = R \ {r_{m*}}
        endsw
    endsw
    Update K = K \ {k*}, X = S ∪ D ∪ R
end
for ∀m ∉ M_r do
    Ā_m = γĀ_m
end
```

All the nodes calculate their respective utility $\tilde{A}_{x_m,k}$ values at each channel as

$$\tilde{A}_{x_m,k} = \frac{\hat{C}_{x_m,k}}{\overline{A}_m}, \tag{4.19}$$

where $x \in \{s, d, r\}$. After that, the node that can achieve the highest utility is selected to transmit. The node is denoted as $x^*_{m^*}$, where x^* is the type of the node, m^* is the link that the node belongs to, and k^* is the channel at which the node achieves the highest utility. If x^* is an S-node, s_{m^*} is removed from $\mathcal{S}$, and r_{m^*} is removed from $\mathcal{R}$ because the S-node cannot receive message from the R-node. Similarly, if x^*

is a D-node, d_{m^*} is removed from $\mathcal{D}$, and r_{m^*} is removed from $\mathcal{R}$. If x^* is an R-node, s_{m^*} is removed from $\mathcal{S}$, d_{m^*} is removed from $\mathcal{D}$, and r_{m^*} is removed from $\mathcal{R}$. The channel used by the scheduled transmission is removed from set $\mathcal{K}$. Each time after the R-node of link m is scheduled to transmit at channel k^*, $\overline{A}_m$ is updated as

$$\overline{A}_m = \gamma \overline{A}_m + (1-\gamma)\hat{C}_{r_m,k^*}; \tag{4.20}$$

and if the R-node of link m is not scheduled to transmit, $\overline{A}_m$ is updated as

$$\overline{A}_m = \gamma \overline{A}_m. \tag{4.21}$$

The process is repeated until either $\mathcal{K}$ or $\mathcal{X}$ is empty. Compared to the sub-optimum solution in the previous section, the heuristic scheme has much lower complexity. The main complexity is to find $x^*_{m^*}$ and k^* from all the node and channel combinations.

4.3 Numerical Results

We consider a network topology as shown in Fig. 4.1. The relay node is located in the center of the circular system service area. In order to create a scenario so that achieving PF is not straightforward, we divide the system area into one inner circle and a ring, and have some end nodes uniformly distributed within the inner circle and the remaining end nodes uniformly distributed in the ring. The radii of the inner and outer circles are $w_{1\,\min}$ and $w_{1\,\max}$, respectively. The link gain normalized to background noise power between an end node and the relay at frequency channel k and time slot t includes both distance-based path loss and log-normally distributed shadowing, and is given by $G^{xy}_{m,k,t} = G(d_0)\left(\frac{d_{x_m,y_m}}{d_0}\right)^{-\alpha} \times 10^{-X_t/10}$, where $d_0 = 10$ m is the reference distance, d_{x_m,y_m} is the distance between nodes x_m and y_m, $\alpha = 3$ is the path loss exponent, X_t is Gaussian distributed with zero mean and standard deviation of 4 dB, and $G(d_0) = 7 \times 10^3$ is the path loss at the reference distance d_0 normalized to background noise power. The Shannon capacity formula is used to find $U^{xy}_{m,k,t} = \log_2(1 + P_x G^{xy}_{m,k,t})$, where P_x is the transmission power of node x, and $P_x = 0.1$ W for all x. Other default values of the parameters are $M = 8$, $K = 2$, $T = 20000$, $w_{1\,\min} = 50$ m, $w_{1\,\max} = 100$ m, and $B_{\max} = 100$. We use the Jain's fairness index defined in [80]. Figs. 4.2-4.5 show the numerical results, where "PF, opt" refers to the sub-optimum solution, "PF, heuristic" refers to the heuristic scheme, and "Max C" refers to the maximum throughput of the system without considering fairness. The maximum throughput is obtained by changing the objective function in the optimization problem P1 in Section 4.1 to $\max_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{C}} \sum_{m=1}^{M} 2C_{r,m,t}$ and solving the problem jointly over all $t \in [1, T]$.

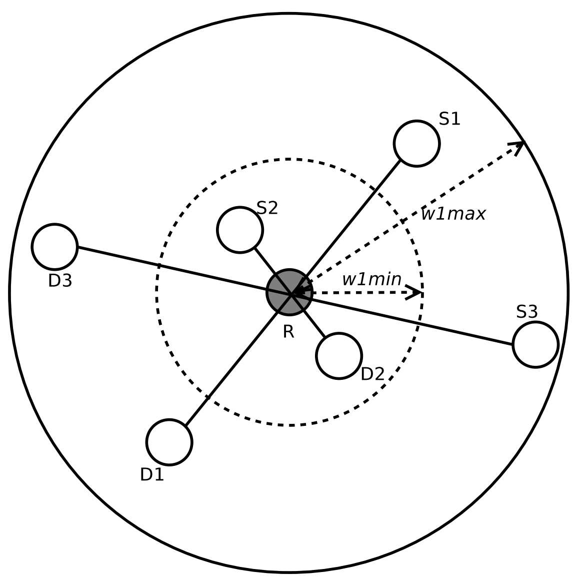

Figure 4.1: Star topology with M=3

We consider a network with $M = 8$, i.e., 8 links, among which the end nodes of two links are randomly located within the ring between the inner and outer circles, and the end nodes of the other six links are randomly located within the inner circle. Figs. 4.2 and 4.3, respectively, show the transmission throughput and fairness index for different number of channels. Fig. 4.2 shows that the throughput performance of the proposed heuristic scheme is almost the same as the sub-optimum solution; while the Max C scheme achieves higher total throughput than both the PF solutions. Fig. 4.3 shows that the fairness index of the proposed PF scheme is between 0.81 and 0.87, which is also very close to the fairness index of the sub-optimum solution, and much better than the Max C scheme. Note that neither the sub-optimum nor the proposed PF scheme achieve a fairness index of 1. This is due to the special feature in multihop transmission scenarios, where achieving perfect PF can be very difficult. Comparing Figs. 4.2 and 4.3 we can see that compared to the Max C scheme, the proposed PF scheme can improve the fairness index up to 4 times, while losing only 25% of the total throughput. This indicates that the proposed PF scheme achieves a good tradeoff between the throughput and fairness.

Next we change the end node distributions, so that the end nodes of N among the M links are distributed within the inner circle, and the end nodes of the remaining $M-N$ links are distributed within the ring region. Fig. 4.4 and Fig. 4.5, respectively, show the throughput and fairness index as N changes. Fig. 4.4 shows that the total throughput of all the links increases with N, because as N increases, more nodes have good channel conditions to the relay node. Fig. 4.5 shows that the fairness index of the proposed PF scheme is almost the same as optimum, and much higher than the Max C scheme. In addition, we can see that the fairness index of the PF scheme is

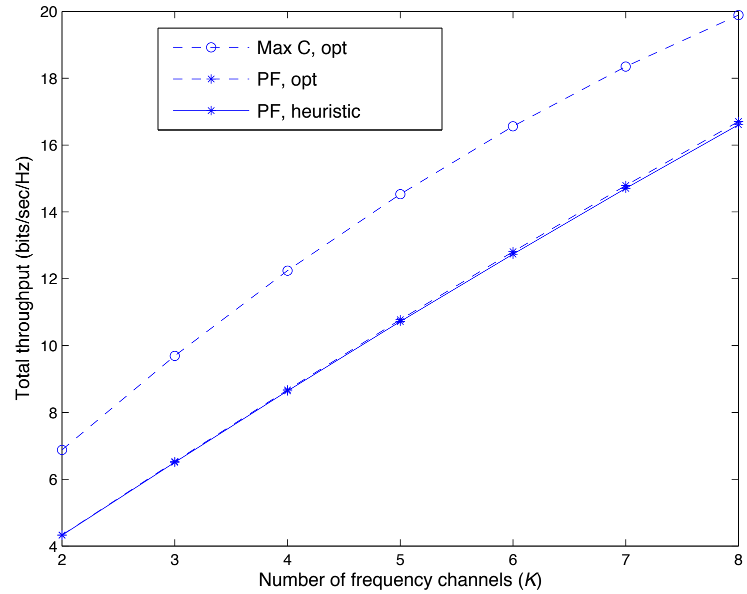

Figure 4.2: Total throughput versus K

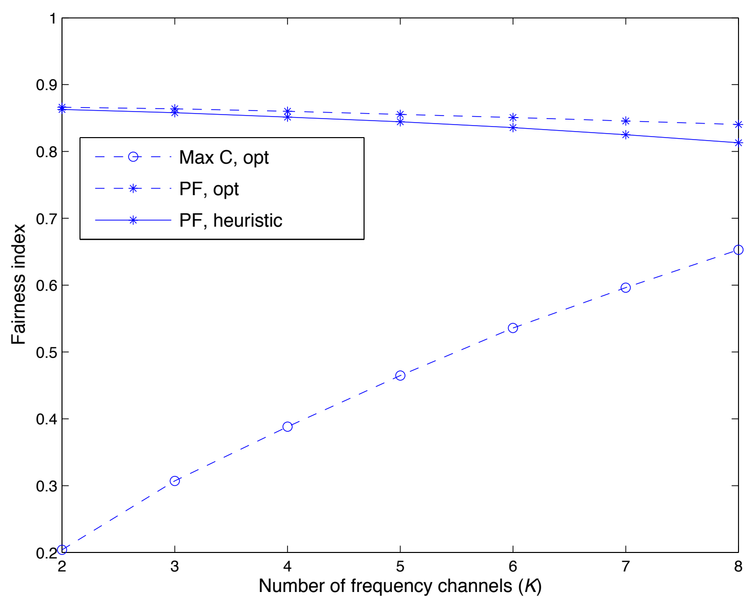

Figure 4.3: Fairness index versus K

the highest when $N = M$. When all the end nodes are distributed in the inner circle, the link gain variation from the end nodes to the relay node is the minimum, which makes it easier to achieve better fairness. Comparing Figs. 4.4 and 4.5, we can see that compared to the Max C solution, the proposed PF scheme can improve the fairness index by about 3 times, while losing only 40% or less of the total throughput. Again, this shows that the PF scheme can make a good tradeoff between total throughput and fairness performance.

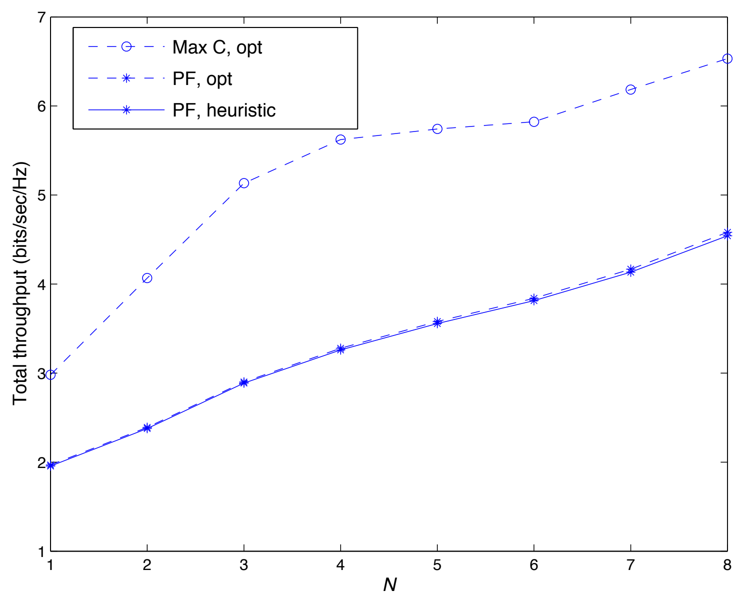

Figure 4.4: Total throughput versus N

4.4 Summary

In this work, we have studied the frequency channel and time slot allocations in a network with bidirectional relaying links. The objective is to achieve proportional

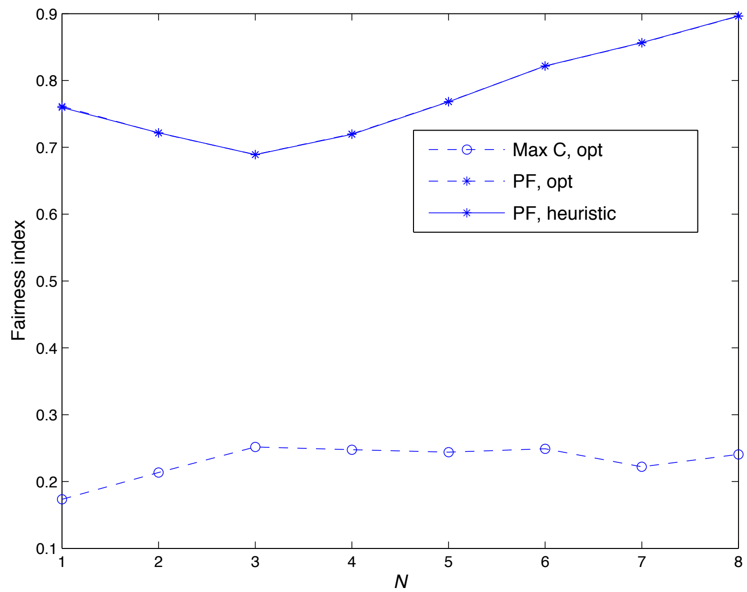

Figure 4.5: Fairness index versus N

fairness of the long-term throughput among the links. Our results have shown that the proposed heuristic scheme achieves performance very close to the sub-optimum solution. Furthermore, the good fairness is achieved at the price of slightly reduced total throughput. In addition, the fairness performance is not sensitive to the number of available channels in the system.

Chapter 5

Scheduling in a WNBRL Using NC and Opportunistic Relaying

In previous chapters we have studied the scheduling problem for a WNBRL, where the relay nodes use NC to forward packets to the end nodes. Combining NC and the traditional one-way relaying technique provides more flexibility for the relay nodes to further take advantage of the random channel conditions and improve the system throughput. In this work we study time slot scheduling and channel allocations jointly for a network with bidirectional relaying links, where the two end nodes of each link can exchange data through a relay node. Two scenarios are considered when the relay node forwards packets to the end nodes. In the first scenario, the relay node always uses NC and sends to both the end nodes simultaneously (i.e., two-way relaying only); and in the second scenario, the relay node opportunistically uses traditional one-way relaying and NC. For each scenario, an optimization problem is first formulated for maximizing the total network throughput. The optimum scheduling is not causal because it requires future information of channel conditions. We then propose heuristic scheduling schemes for each scenario, one slot-based scheduling method that maximizes the total transmission rate of all the nodes at each time slot, and one node-based scheduling method that schedules the network nodes based on their achievable transmission rates at individual channels. The remainder of the work is organized as follows. In Section 5.1 we describe the system that this work is based on. An optimization problem is formulated in Section 5.2 for the time slot and channel allocations in each scenario. Slot-based scheduling is proposed in Section 5.3, and node-based scheduling is proposed in Section 5.4. Numerical results are demonstrated in Section 5.5 to show the performance of the scheduling and channel allocation schemes. Section 5.6 summarizes the work.

5.1 System Description

We consider a network with M bidirectional links, indexed by $m = 1, 2, \ldots, M$. Each link has two end nodes, each can be a data source and destination. For convenience, we refer one of the end nodes as S-node, and the other one as D-node. The two end nodes of each link communicate through a relay node, referred to as R-node. We consider two types of network topologies. In a centralized topology, the R-node is equipped with multiple radios that are shared by all links, and each end node has one radio. In a distributed topology, each link has its own dedicated R-node, and all the nodes are equipped with a single radio. A number of K frequency channels, indexed by $k = 1, 2, \ldots, K$, are available for all the transmissions. Each channel can be used by at most one transmission, i.e., there is no co-channel interference. For a given link, in order for the two end nodes to exchange data, each end node should first send data to the R-node, which then forwards the data to the other end. We consider a saturated case, and assume that the end nodes always have packets to transmit. The achievable transmission rate for a given node is limited by the channel conditions and buffer occupancy. Data packets received from the end nodes of different links are first buffered in the R-node and wait for chances to be forwarded by the R-node. There is one buffer with size of $B_{\max}$ packets at the R-node to store data from each end node.

We consider two scenarios, depending on the relaying techniques available at the R-node. In the first scenario, the R-node always uses NC; and in the second scenario, it can opportunistically use NC and traditional relaying. For NC, the R-node uses a simple XOR operation to combine one packet from the S-node and one packet from the D-node of the same link, and multicasts to both of them. Upon receiving the XORed packet, the S-node and D-node can each recover the packet from the other end. In this way, it takes three transmissions for the two end nodes to exchange one packet, two from the end nodes, and one from the R-node. When using the traditional relaying, the R-node sends to only one node at a time. Our objective is to maximize the total data transmission throughput of all the links.

We use $x = s, d, r$ to represent the type of the node with s for the S-node, d for the D-node, and r for the R-node. For the R-node, rs, rd and $r2$, respectively, represent that the R-node is transmitting to an S-node, a D-node, and both S- and D-nodes of a given link. Channel time is divided into equal length time slots, indexed by $t = 1, 2, \ldots, T$, where T is the total number of time slots over which the throughput is considered. Let $G^{xy}_{m,k,t}$ represent the link gain (normalized to background noise power) between node x and node y of link m at frequency channel k and time slot t, where $(x, y) \in \{(s, r), (d, r), (r, s), (r, d)\}$ gives the (transmitter, receiver) node pair for a link. The maximum transmission rate between nodes x and y of link m at frequency channel

k and time slot t can be calculated as $U^{xy}_{m,k,t} = \log_2(1 + P_x G^{xy}_{m,k,t})$ using Shannon's formula, where P_x is the maximum transmission power of node x. Note that the expression for $U^{xy}_{m,k,t}$ can be changed to other format based on specific modulation and coding schemes used. The problem formulation and proposed work below does not depend on the format of this expression. We consider that $G^{xy}_{m,k,t} = G^{yx}_{m,k,t}$, and therefore, $U^{xy}_{m,k,t} = U^{yx}_{m,k,t}$. The transmission power can be adjusted according to the transmission rate, which is limited by both the link conditions and buffer occupancy as will be detailed.

5.2 Optimum Problem Formulation

5.2.1 Scenario 1: using NC only

We start with the first scenario, i.e., the R-node always uses NC when forwarding packets, and define three sets of binary variables, $X_{m,k,t}$, $Y_{m,k,t}$, and $Z_{m,k,t}$. When $X_{m,k,t} = 1$, frequency channel k is assigned to the S-node of link m at time slot t, and $X_{m,k,t} = 0$ otherwise. When $Y_{m,k,t} = 1$, frequency channel k is assigned to the D-node of link m at time slot t, and $Y_{m,k,t} = 0$ otherwise. When $Z_{m,k,t} = 1$, frequency channel k is assigned to the R-node (or one radio of the R-node for the centralized topology) for transmitting to the end nodes of link m at time slot t using NC, and $Z_{m,k,t} = 0$ otherwise.

Based on these definitions, we have the following constraints. First, for the centralized topology, each of the end nodes has one radio, and therefore, cannot transmit and receive at the same time; and second, when it transmits or receives, only one channel is used. Therefore, we have

$$\sum_{k=1}^{K}(X_{m,k,t}+Z_{m,k,t})\leq 1, \tag{5.1}$$

$$\sum_{k=1}^{K}(Y_{m,k,t}+Z_{m,k,t})\leq 1, \tag{5.2}$$

for all m and t. In addition, the total number of transmitting nodes at all channels is no more than the number of radios at the R-node L, i.e.,

$$\sum_{m=1}^{M}\sum_{k=1}^{K}(X_{m,k,t}+Y_{m,k,t}+Z_{m,k,t})\leq L. \tag{5.3}$$

For the distributed topology, each link has its own dedicated R-node, and all the nodes are equipped with one radio. For each link, at most one node can transmit at a time, and the following constraint applies,

$$\sum_{k=1}^{K}(X_{m,k,t}+Y_{m,k,t}+Z_{m,k,t})\leq 1, \tag{5.4}$$

for all m and t, which allows only one node per link to transmit at a time.

Next, for both topologies, each channel can be assigned to at most one node at a time. Therefore, we have

$$\sum_{m=1}^{M}(X_{m,k,t}+Y_{m,k,t}+Z_{m,k,t})\leq 1, \tag{5.5}$$

for all k and t.

Define $C_{s,m,t}$ and $C_{d,m,t}$, respectively, as the transmission rate of the S- and D-nodes of link m at time slot t, and $C_{r2,m,t}$ as the transmission rate of the R-node when it transmits to both the end nodes of link m. We have

$$C_{s,m,t} \le \sum_{k=1}^{K} X_{m,k,t} \times U_{m,k,t}^{sr}, \tag{5.6}$$

$$C_{d,m,t} \le \sum_{k=1}^{K} Y_{m,k,t} \times U_{m,k,t}^{dr}, \tag{5.7}$$

$$C_{r2,m,t} \le \sum_{k=1}^{K} Z_{m,k,t} \times \min\{U_{m,k,t}^{rs}, U_{m,k,t}^{rd}\}. \tag{5.8}$$

We normalize the duration of a time slot to one, so that the numerical value of the transmission rate is equal to the amount of data transmitted during one time slot. In addition to the link gains, the transmission rates are also limited by buffer occupancy at the R-node. That is, for a given link, the transmission rate of an S- or D-node is limited by the available space in the buffer, and that of the R-node for each link is limited by the amount of buffered data from both the end nodes. Overall, the following constraints guarantee that transmissions of the S- and D-nodes never overflow their respective buffers at the R-node, and the R-node always transmits no more than the available data in the buffer.

$$0 \le \sum_{\tau=1}^{t} (C_{s,m,\tau} - C_{r2,m,\tau}) \le B_{\max}, \tag{5.9}$$

$$0 \le \sum_{\tau=1}^{t} (C_{d,m,\tau} - C_{r2,m,\tau}) \le B_{\max}, \tag{5.10}$$

Consider a time period of T slots. The total amount of transmitted data of link m in both directions is given by

$$C_m = \sum_{t=1}^{T} 2C_{r2,m,t}. \tag{5.11}$$

Our objective is to maximize the total throughput of all the links. That is, to maximize $\sum_{m=1}^{M} C_m/T$.

Define $\mathbf{X} = [X_{m,k,t}, \forall m,k,t]$, $\mathbf{Y} = [Y_{m,k,t}, \forall m,k,t]$, $\mathbf{Z} = [Z_{m,k,t}, \forall m,k,t]$, and $\mathbf{C} = [C_{x,m,t}, \forall x,m,t]$. Based on the above description, an optimization problem can be formulated as follows

$$\text{P1:} \quad \max_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{C}} \sum_{m=1}^{M} C_m/T \tag{5.12}$$

$$\begin{aligned} \text{s.t.} \quad & \text{(5.1)-(5.3) and (5.5)-(5.11) for centralized topology,} \\ & \text{(5.4)-(5.11) for distributed topology,} \\ & X_{m,k,t}, Y_{m,k,t}, Z_{m,k,t} \in \{0,1\}, \forall m,k,t. \end{aligned} \tag{5.13}$$

5.2.2 Scenario 2: opportunistic relaying

For the second scenario, the R-node can opportunistically use traditional one-way relaying or NC when forwarding packets to the end nodes. We define two additional sets of binary variables, $V_{m,k,t}$ and $W_{m,k,t}$, to describe the one-way relay activity of the R-node. When $V_{m,k,t} = 1$, frequency channel k is assigned to the R-node for transmitting to the S-node of link m at time slot t, and $V_{m,k,t} = 0$ otherwise. When $W_{m,k,t} = 1$, frequency channel k is assigned to the R-node for transmitting to the D-node of link m at time slot t, and $W_{m,k,t} = 0$ otherwise.

With this, we have the following constraints for the centralized topology:

$$\sum_{k=1}^{K} (X_{m,k,t} + Z_{m,k,t} + V_{m,k,t}) \leq 1, \tag{5.14}$$

$$\sum_{k=1}^{K} (Y_{m,k,t} + Z_{m,k,t} + W_{m,k,t}) \leq 1, \tag{5.15}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K}(X_{m,k,t}+Y_{m,k,t}+Z_{m,k,t}+V_{m,k,t}+W_{m,k,t})\leq L, \tag{5.16}$$

and

$$\sum_{k=1}^{K}(X_{m,k,t}+Y_{m,k,t}+Z_{m,k,t}+V_{m,k,t}+W_{m,k,t})\leq 1, \tag{5.17}$$

for the distributed topology.

Similar to (5.5) in the previous subsection, the following constraint should hold for scenario 2 in both topologies:

$$\sum_{m=1}^{M}(X_{m,k,t}+Y_{m,k,t}+Z_{m,k,t}+V_{m,k,t}+W_{m,k,t})\leq 1. \tag{5.18}$$

For transmission rates, constraints (5.6)-(5.8) in the previous subsection also apply to the opportunistic relaying. In addition, we define $C_{rs,m,t}$ and $C_{rd,m,t}$, respectively, to be the transmission rates of the R-node to the S-node and D-node of link m at time slot t as follows

$$C_{rs,m,t}\leq\sum_{k=1}^{K}V_{m,k,t}\times U^{rs}_{m,k,t}, \tag{5.19}$$

$$C_{rd,m,t}\leq\sum_{k=1}^{K}W_{m,k,t}\times U^{rd}_{m,k,t}. \tag{5.20}$$

Constraints (5.9) and (5.10) for scenario 1 in the previous subsection are revised as follows to incorporate different transmissions of the R-node for scenario 2,

$$0\leq\sum_{\tau=1}^{t}(C_{s,m,\tau}-C_{r2,m,\tau}-C_{rd,m,\tau})\leq B_{\max}, \tag{5.21}$$

$$0 \leq \sum_{\tau=1}^{t} \left(C_{d,m,\tau} - C_{r2,m,\tau} - C_{rs,m,\tau} \right) \leq B_{\max}. \tag{5.22}$$

The total amount of transmitted data for each link in a time period of T slots is given by

$$C_m = \sum_{t=1}^{T} \left(2C_{r2,m,t} + C_{rs,m,t} + C_{rd,m,t} \right). \tag{5.23}$$

Define $\mathbf{V} = [V_{m,k,t}, \forall m, k, t]$ and $\mathbf{W} = [W_{m,k,t}, \forall m, k, t]$, an optimization problem for opportunistic relaying can be formulated as follows

$$\text{P2:} \quad \max_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{V},\mathbf{W},\mathbf{C}} \sum_{m=1}^{M} C_m/T \tag{5.24}$$

s.t. (5.6)-(5.8), (5.14)-(5.16), (5.18)-(5.23) for centralized topology,

(5.6)-(5.8), (5.17)-(5.23) for distributed topology,

$$X_{m,k,t}, Y_{m,k,t}, Z_{m,k,t}, V_{m,k,t}, W_{m,k,t} \in \{0,1\}, \forall m, k, t. \tag{5.25}$$

The optimization problems above are mixed integer linear problems (MILP), and can be solved using commercial software, such as AMPL. However, implementing the optimum solutions is not possible in a practical system. The scheduling solution jointly optimizes the resource allocations over all the time slots. This requires future information of link gains at the time of making the decisions, which is impossible in time-varying channels. For relatively static channels, causality is not a problem, but the computational complexity for solving the optimization problem can be very high when T is large. For these reasons, we will seek more practical scheduling solutions. In the slot-based scheduling proposed in Section 5.3, the basic idea is to maximize total transmission rate of all the nodes at each time slot; and in the node-based scheduling proposed in Section 5.4, the basic idea is to assign a channel to a node so that the node-channel combination achieves the highest rate possible. All these proposed schemes require a central node to collect channel information and make the scheduling decisions. In the centralized topology, the central node can be the R-node. In the distributed topology, having a central node to perform the scheduling function is also possible. For example, scheduling for device-to-device communications in LTE-A is performed at the cellular base station.

5.3 Slot-based Scheduling Schemes

For a practical scheme, channel conditions in the future are unavailable, and the scheduling decisions should be based on channel and buffer information at the present, which determines the physical transmission rates of individual nodes. At any given time slot, the transmission rate of each end node is limited by both the link conditions and the available space in its buffer at the R-node, and the transmission rate of the R-node is determined by both the link conditions and the amount of buffered data. When NC is used, the transmission rate of the R-node is determined by the link conditions and buffer occupancy in both directions. Before describing details of the scheduling schemes, we define the following rates:

$$\hat{C}_{s_m,k} = \min(U^{sr}_{m,k}, B_{\max} - b_{sr,m}), \tag{5.26}$$

$$\hat{C}_{d_m,k} = \min(U^{dr}_{m,k}, B_{\max} - b_{dr,m}), \tag{5.27}$$

$$\hat{C}_{r2_m,k} = 2\min(U^{rs}_{m,k}, U^{rd}_{m,k}, b_{sr,m}, b_{dr,m}), \tag{5.28}$$

$$\hat{C}_{rs_m,k} = \min(U^{rs}_{m,k}, b_{dr,m}), \tag{5.29}$$

$$\hat{C}_{rd_m,k} = \min(U^{rd}_{m,k}, b_{sr,m}), \tag{5.30}$$

where $\hat{C}_{s_m,k}$ and $\hat{C}_{d_m,k}$, respectively, are the maximum achievable rates for the S- and D-nodes of link m at channel k, $\hat{C}_{r2_m,k}$, $\hat{C}_{rs_m,k}$, and $\hat{C}_{rd_m,k}$, respectively, are the maximum achievable rates of the R-node when it transmits to both the end nodes, S-node only, and D-node only of link m at channel k, and $b_{sr,m}$ and $b_{dr,m}$, respectively, represent the amounts of data buffered at the R-node from the S-node and D-node of link m.

The long-term objective should be reduced to short-term objectives. At any given time slot t, the problem is to assign the available channels to the nodes, so that over a long period of time, the total throughput of all the links is maximized. The subscript t is removed from the notations, since all variables are for the current time slot. With the objective of maximizing the aggregate transmission rates of all the nodes at a given time slot, the optimization problem for scenario 1 is reduced to

$$\text{P3:} \quad \max_{\mathbf{X},\mathbf{Y},\mathbf{Z}} \sum_{m=1}^{M} \sum_{k=1}^{K} \left(X_{m,k}\hat{C}_{s_m,k} + Y_{m,k}\hat{C}_{d_m,k} + Z_{m,k}\hat{C}_{r2_m,k} \right) \tag{5.31}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} (X_{m,k} + Z_{m,k}) \leq 1, \text{ for centralized topology,} \tag{5.32}$$

$$\sum_{k=1}^{K} (Y_{m,k} + Z_{m,k}) \leq 1, \text{ for centralized topology,} \tag{5.33}$$

$$\sum_{m=1}^{M} \sum_{k=1}^{K} (X_{m,k} + Y_{m,k} + Z_{m,k}) \leq L, \text{ for centralized topology,} \tag{5.34}$$

$$\sum_{k=1}^{K} (X_{m,k} + Y_{m,k} + Z_{m,k}) \leq 1, \text{ for distributed topology,} \tag{5.35}$$

$$\sum_{m=1}^{M} (X_{m,k} + Y_{m,k} + Z_{m,k}) \leq 1, \text{ for both topologies,} \tag{5.36}$$

$$X_{m,k}, Y_{m,k}, Z_{m,k} \in \{0, 1\}, \ \forall m, k. \tag{5.37}$$

where $\mathbf{X} = [X_{m,k}, \forall m, k]$, $\mathbf{Y} = [Y_{m,k}, \forall m, k]$, and $\mathbf{Z} = [Z_{m,k}, \forall m, k]$. Constraints (5.32)-(5.36) replace constraints (5.1)-(5.5) in problem P1, and other constraints in problem P1 are not needed for slot-by-slot scheduling.

Similarly, the optimization problem for scenario 2 is reduced to

$$\text{P4:} \quad \max_{\mathbf{X},\mathbf{Y},\mathbf{Z},\mathbf{V},\mathbf{W}} \sum_{m=1}^{M} \sum_{k=1}^{K} \left(X_{m,k}\hat{C}_{s_m,k} + Y_{m,k}\hat{C}_{d_m,k} + Z_{m,k}\hat{C}_{r2_m,k} + V_{m,k}\hat{C}_{rs_m,k} + W_{m,k}\hat{C}_{rd_m,k} \right) \quad (5.38)$$

$$\text{s.t.} \quad \sum_{k=1}^{K} (X_{m,k} + Z_{m,k} + V_{m,k}) \le 1, \text{ for centralized topology,} \quad (5.39)$$

$$\sum_{k=1}^{K} (Y_{m,k} + Z_{m,k} + W_{m,k}) \le 1, \text{ for centralized topology,} \quad (5.40)$$

$$\sum_{m=1}^{M} \sum_{k=1}^{K} (X_{m,k} + Y_{m,k} + Z_{m,k} + V_{m,k} + W_{m,k}) \le L, \text{ for centralized topology} \quad (5.41)$$

$$\sum_{k=1}^{K} (X_{m,k} + Y_{m,k} + Z_{m,k} + V_{m,k} + W_{m,k}) \le 1, \text{ for distributed topology} \quad (5.42)$$

$$\sum_{m=1}^{M} (X_{m,k} + Y_{m,k} + Z_{m,k} + V_{m,k} + W_{m,k}) \le 1, \text{ for both topologies,} \quad (5.43)$$

$$X_{m,k}, Y_{m,k}, Z_{m,k}, V_{m,k}, W_{m,k} \in \{0, 1\}, \ \forall m, k. \quad (5.44)$$

Problems P3 and P4 are MILPs, but have lower complexity than Problems P1 and P2 because all the variables are for one time slot only. For the distributed topology, each of the problems can be solved by translating to a minimum cost flow problem, which can be solved with much higher efficiency. For the centralized topology, constructing similar graph models is very difficult due to the complication that the radios at the R-node are shared by all the links.

5.3.1 Minimum cost flow problem for distributed topology

For scenario 1 (i.e., using NC only), Fig. 5.1 shows the graph model for $M = 3$ and $K = 2$. In addition to a virtual source SC and a virtual sink T, there are three sets of graph nodes (GNs) representing the links, the transmitting nodes, and the channels. Specifically, GN Lm connected to the virtual source represents link m, Sm and Dm, respectively, represent that the S- and D-nodes of link m are transmitting, R2m represents that the R-node of link m is transmitting. The GNs connected to the virtual sink are indexes of the channels. The total amount of flow coming from the virtual source and going to the virtual sink is $\min\{M, K\}$. The capacity for each edge is 1. Therefore, the outgoing flow from each Lm GN can only select one of the three outgoing GNs, and this corresponds to constraint (5.35). Each GN representing the channel has one outgoing edge connected to the virtual sink, and this corresponds to constraint (5.36). The cost for all the edges is zero except the edges that connect a GN representing a transmitting node and a GN representing a channel. Each of these edges has a cost equal to the negative of the achievable rate for the transmitting node and channel combination ($-\hat{C}_{x_m,k}$).

For scenario 2 (opportunistic relaying), a slightly different graph model is given in Fig. 5.2. Compared to Fig. 5.1, two additional GNs are connected to each GN that represents a link. Specifically, the GNs RSm and RDm, respectively, represent that the R-node is transmitting to the S-node and D-node of link m.

5.4 Node-based Scheduling Schemes

The slot-based scheduling limits the required information to be within the current time slot, and has much lower complexity than the long-term optimum solution. However, for the centralized topology, it still needs to solve a mixed integer and linear programming problem. To further reduce the computation complexity, we design node-based scheduling in this section.

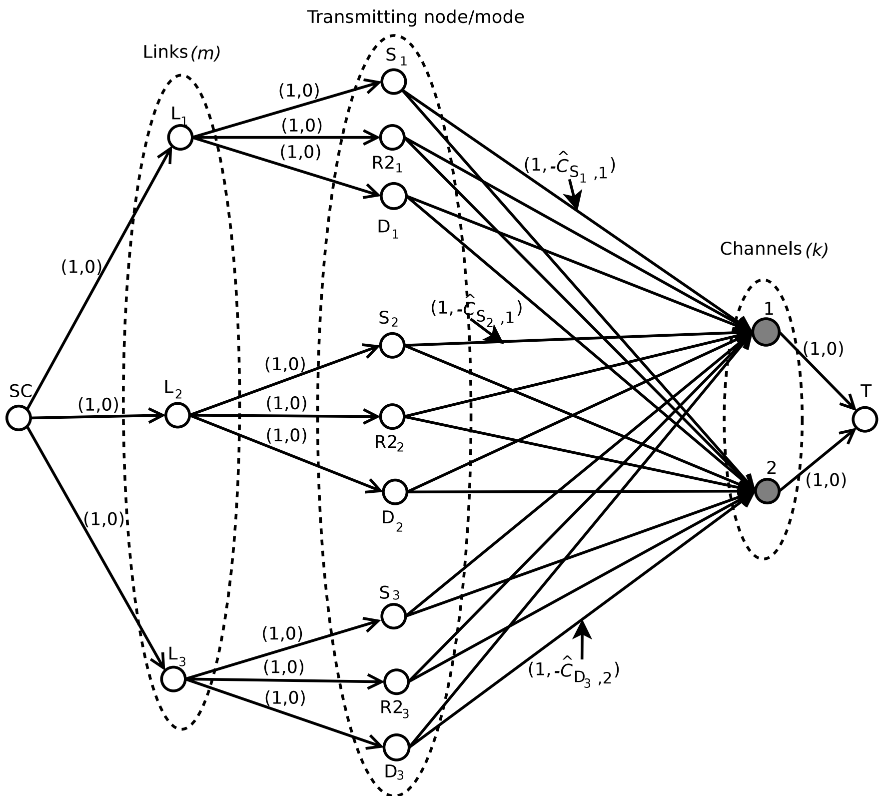

Figure 5.1: Network flow model for NC scheme with M=3 and K=2

5.4.1 Scenario 1: using NC only

Algorithm 1 shows the scheme. Before presenting details of the scheme, we describe several sets defined at the beginning of the algorithm. Specifically, $\mathcal{S}$, $\mathcal{D}$, and $\mathcal{R}$, respectively, are sets of the S-nodes, D-nodes, and R-nodes (for the distributed topology) or number of radios at the R-node (for the centralized topology) that have not been scheduled to transmit or receive. For example, $s_m \in \mathcal{S}$ if the S-node of link m has not been scheduled to transmit or receive; $d_m \in \mathcal{D}$ if the D-node of link m has not been scheduled to transmit or receive, and $r_m \in \mathcal{R}$ if the R-node has not been scheduled to transmit to or receive from the end nodes of link m. Initially, $\mathcal{S}$ includes all the S-nodes, $\mathcal{D}$ includes all the D-nodes, and $\mathcal{R}$ includes all the radios at

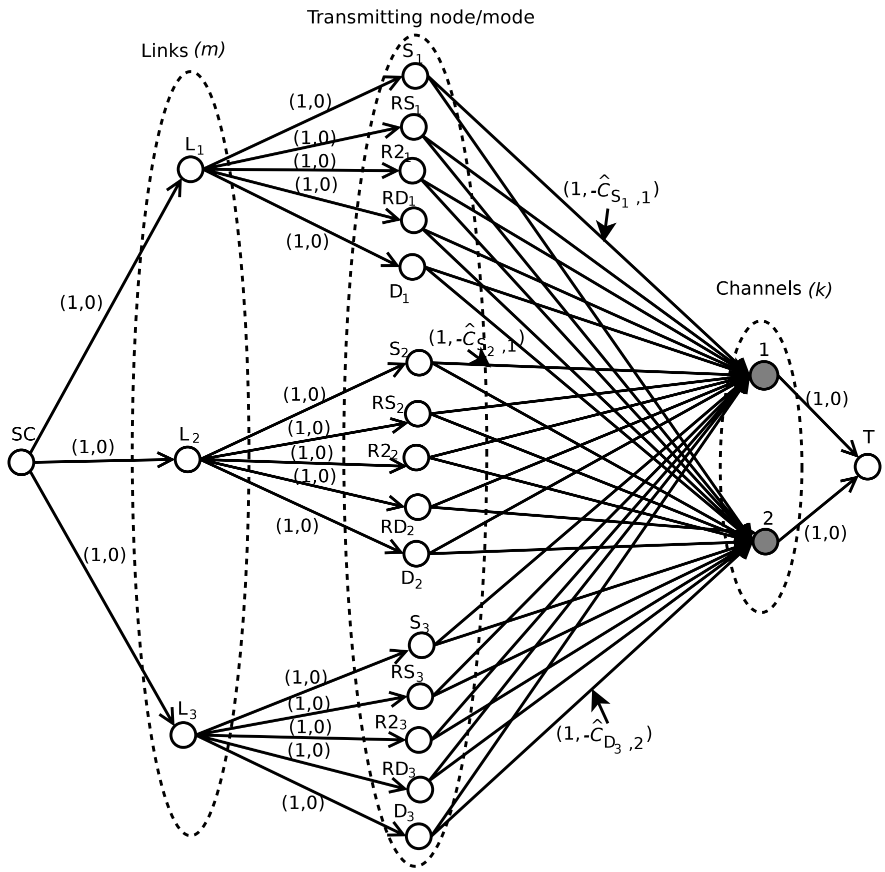

Figure 5.2: Network flow model for opportunistic scheme with M=3 and K=2

the R-node(s). In addition, $\mathcal{X}$ is a union of $\mathcal{S}$, $\mathcal{D}$, and $\mathcal{R}$, and $\mathcal{K}$ is a set of all the channels that have not been assigned to any nodes. All these sets are updated during the decision making process. Binary variables X_{mk}, Y_{mk}, and Z_{mk}, respectively, are defined as 1 if the S-, D-, and R-node of link m transmits at channel k and 0 otherwise. They are all initialized to 0. The variable $\tilde{L}$ is defined for the centralized topology to represent the number of radios at the R-node that have not been scheduled to transmit or receive, and is initialized to be L. Such a variable is unnecessary for the distributed topology because each link has a dedicated R-node.

We first describe the scheme for the centralized topology. The achievable rates of all the nodes at different channels are calculated using (5.26)-(5.30). After that, node $x^*_{m^*}$ is selected to transmit at channel k^* since this node-channel combination achieves the highest rate. If x^* is an S-node, $X_{m^*k^*} = 1$, the S-node of link m^* is removed from $\mathcal{S}$; and at the same time, the R-node is not allowed to transmit to the end nodes of the same link, and therefore r_{m^*} is removed from $\mathcal{R}$. Similarly, if x^* is a D-node, $Y_{m^*k^*} = 1$, the D-node of link m^* is removed from $\mathcal{D}$, and r_{m^*} is removed from $\mathcal{R}$. If the transmitter is the R-node, $Z_{m^*k^*} = 1$, and in addition to removing r_{m^*} from $\mathcal{R}$, the two end nodes of link m^* should also be removed from their respective sets. After this, the set $\mathcal{X}$ is updated. Meanwhile, channel k^* is removed from set $\mathcal{K}$. With the new sets of eligible transmitters and channels, the next transmitting node and channel are selected, and the sets are updated. This is repeated until either $\mathcal{K}$ or $\mathcal{X}$ is empty. For the distributed topology, whenever one node is schedule to transmit, all the other nodes for the same link cannot transmit. For the centralized topology, each time after any node is scheduled to transmit, $\tilde{L}$ is reduced by 1, because one radio at the R-node should either receive or transmit. When $\tilde{L}$ becomes zero, the scheduling process should also end.

This scheme is basically the same as the concurrent node selection and channel assignment (CNSCA) scheme proposed in [74], where another scheme referred to as sequential node selection and channel assignment (SNSCA) scheme is also proposed, which achieves lower throughput performance compared to CNSCA.

5.4.2 Scenario 2: opportunistic relaying

Algorithm 2 shows the scheduling for opportunistic relaying, which is similar to Algorithm 1, except that two more transmission options are added to the R-node. $r^s_m \in \mathcal{R}^s$

Algorithm 1 Using NC only

Input: $\mathcal{S} = \{s_1, s_2, \ldots, s_M\}$, $\mathcal{D} = \{d_1, d_2, \ldots, d_M\}$, $\mathcal{R} = \{r_1, r_2, \ldots, r_M\}$, $\mathcal{X} = \mathcal{S} \cup \mathcal{D} \cup \mathcal{R}$, $\mathcal{K} = \{1, 2, \ldots, K\}$, $\tilde{L} = L$, and $X_{mk} = Y_{mk} = Z_{mk} = 0 \; \forall m, k$.

Output: $X_{mk}, Y_{mk}, Z_{mk} \; \forall m, k$.

while $\mathcal{K} \neq \emptyset, \mathcal{X} \neq \emptyset,$ and $\tilde{L} > 0$ **do**

  Find $(x^*_{m^*}, k^*) = \arg\max_{x_m \in \mathcal{X}, k \in \mathcal{K}} \hat{C}_{x_m,k}$

  switch x^* **do**

    case s

      S-node of link m^* transmits at channel k^*, $X_{m^*k^*} = 1$,

      $\mathcal{S} = \mathcal{S} \setminus \{s_{m^*}\}$, $\mathcal{R} = \mathcal{R} \setminus \{r_{m^*}\}$,

      for distributed topology only: $\mathcal{D} = \mathcal{D} \setminus \{d_{m^*}\}$

    case d

      D-node of link m transmits at channel k^*, $Y_{m^*k^*} = 1$,

      $\mathcal{D} = \mathcal{D} \setminus \{d_{m^*}\}$, $\mathcal{R} = \mathcal{R} \setminus \{r_{m^*}\}$,

      for distributed topology only: $\mathcal{S} = \mathcal{S} \setminus \{s_{m^*}\}$

    otherwise

      R-node transmits to end nodes of link m^* at channel k^*, $Z_{m^*k^*} = 1$,

      $\mathcal{S} = \mathcal{S} \setminus \{s_{m^*}\}$, $\mathcal{D} = \mathcal{D} \setminus \{d_{m^*}\}$, $\mathcal{R} = \mathcal{R} \setminus \{r_{m^*}\}$

    endsw

  endsw

  Update $\mathcal{K} = \mathcal{K} \setminus \{k^*\}$, $\mathcal{X} = \mathcal{S} \cup \mathcal{D} \cup \mathcal{R}$,

  for centralized topology only: $\tilde{L} = \tilde{L} - 1$

end

and $r^d_m \in \mathcal{R}^d$, respectively, represent that the R-node is eligible to transmit to the S-node and to the D-node of link m using one-way relaying. When the S-node of link m^* is selected to transmit, i.e., $x^* = s$, $X_{m^*k^*} = 1$, and s_{m^*} is removed from $\mathcal{S}$; in addition, $r^s_{m^*}$ is removed from $\mathcal{R}^s$ and r_{m^*} is removed from $\mathcal{R}$ so that the R-node does not transmit to the S-node of link m^* using either one-way relaying or NC. Similar operations should be done when the D-node of link m^* is selected to transmit. When the R-node is scheduled to transmit to both the S- and D-nodes of link m^*, i.e., $x^* = r$, $Z_{m^*k^*} = 1$, and r_{m^*} is removed from $\mathcal{R}$; meanwhile, the R-node cannot transmit to either of the end nodes of the same link using traditional relaying, i.e., $r^s_{m^*}$ is removed from $\mathcal{R}^s$ and $r^d_{m^*}$ is removed from $\mathcal{R}^d$; and in addition, none of the end nodes of the link can transmit, i.e., s_{m^*} is removed from $\mathcal{S}$ and d_{m^*} is removed from $\mathcal{D}$. Similar operations should be done when the R-node is scheduled to transmit to only one of the end nodes of a given link using one-way relaying.

5.5 Numerical Results

In this section we demonstrate the performance of the proposed schemes. In the network with the centralized topology, there are one R-node with M radios (i.e., $L = M$) and M links; and in the network with the distributed topology, there are M R-nodes, each for one of the M links. The distance between each end node and the respective R-node is w_1, which is randomly chosen between 80 m and 120 m. The link gain (normalized to background noise power) between an end node x and the R-node at channel k and time slot t includes both distance-based path loss and log-normally distributed shadowing, and is given by $A \times (w_1/d_0)^{-\alpha} \times 10^{-(X_t/10)}$, where $\alpha = 3$ is the path loss exponent, X_t is Gaussian distributed with zero mean and standard deviation of 8 dB, and $A = 7 \times 10^6$ is the path loss at the reference distance d_0 and is normalized to the background noise power. The default values of other parameters are $B_{\max} = 100$ packets and $P_{\max} = 0.1$ W.

We first compare throughput performance of the long-term optimum (by solving problems P1 and P2 in Section 5.2), the slot-based scheduling, and the node-based scheduling for using NC only and opportunistic relaying in both topologies. In order to generate results for the long-term optimum scheduling, we have to use small numbers of links and channels. Here, we fix K to 2 and change M from 3 to 10. Figs. 5.3 and 5.4 show the throughput performance of the system using NC only and using opportunistic relaying, respectively, for the distributed topology, and Figs. 5.5

Algorithm 2 Opportunistic Relaying

Input: $\mathcal{S} = \{s_1, s_2, \ldots, s_M\}$, $\mathcal{D} = \{d_1, d_2, \ldots, d_M\}$, $\mathcal{R} = \{r_1, r_2, \ldots, r_M\}$, $\mathcal{R}^s = \{r_1^s, r_2^s, \ldots, r_M^s\}$, $\mathcal{R}^d = \{r_1^d, r_2^d, \ldots, r_M^d\}$, $\mathcal{X} = \mathcal{S} \cup \mathcal{D} \cup \mathcal{R} \cup \mathcal{R}^s \cup \mathcal{R}^d$, $\mathcal{K} = \{1, 2, \ldots, K\}$, $\tilde{L} = L$, and $X_{mk} = Y_{mk} = Z_{mk} = V_{mk} = W_{mk} = 0\ \forall m, k$.

Output: $X_{mk}, Y_{mk}, Z_{mk}, V_{mk}, W_{mk}\ \forall m, k$.

```
while K ≠ ∅, X ≠ ∅, and L̃ > 0 do
    Find (x*_{m*}, k*) = arg max_{x_m ∈ X, k ∈ K} Ĉ_{x_m,k}
    switch x* do
        case s
            S-node of link m* transmits at channel k*, X_{m*k*} = 1,
            S = S \ {s_{m*}}, R^s = R^s \ {r^s_{m*}}, R = R \ {r_{m*}},
            for distributed topology only: D = D \ {d_{m*}}, R^d = R^d \ {r^d_{m*}}
        case d
            D-node of link m* transmits at channel k*, Y_{m*k*} = 1,
            D = D \ {d_{m*}}, R^d = R^d \ {r^d_{m*}}, R = R \ {r_{m*}},
            for distributed topology only: S = S \ {s_{m*}}, R^s = R^s \ {r^s_{m*}}
        case r
            R-node transmits to both end nodes of link m* at channel k*, Z_{m*k*} = 1,
            S = S \ {s_{m*}}, D = D \ {d_{m*}}, R^s = R^s \ {r^s_{m*}}, R^d = R^d \ {r^d_{m*}},
            R = R \ {r_{m*}}
        case r^s
            R-node transmits to S-node of link m* at channel k* , V_{m*k*} = 1,
            S = S \ {s_{m*}}, R^s = R^s \ {r^s_{m*}}, R = R \ {r_{m*}},
            for distributed topology only: D = D \ {d_{m*}}, R^d = R^d \ {r^d_{m*}}
        otherwise
            R-node transmits to D-node of link m* at channel k*, W_{m*k*} = 1,
            D = D \ {d_{m*}}, R^d = R^d \ {r^d_{m*}}, R = R \ {r_{m*}},
            for distributed topology only: S = S \ {s_{m*}}, R^s = R^s \ {r^s_{m*}}
        endsw
    endsw
    Update K = K \ {k*}, X = S ∪ D ∪ R ∪ R^s ∪ R^d,
    for centralized topology only: L̃ = L̃ − 1
end
```

and 5.6 show the throughput performance of the system using NC only and using opportunistic relaying, respectively, for the centralized topology. All the figures show that with more links, the opportunity of having good link gains increases, which improves the overall throughput. The difference between the throughput of the optimum and the heuristic schemes is because the heuristic schemes do not have the future link information. As shown in both Figs. 5.3 and 5.5, when the R-node is allowed to use NC only, the throughput performance of the two heuristic schemes is very close to each other. This is because the R-node may not have an opportunity to transmit until the channel conditions to both the end nodes of a link are sufficiently good and there is enough data buffered from both the end nodes. Such a restriction makes it more difficult for the R-node to take advantage of the instantaneous good channel condition to individual end nodes, compared to opportunistic relaying. Although the slot-based scheduling can better coordinate the channel allocations, the use of NC only at the R-node limits the freedom at the R-node, which results in little advantage of the slot-based method over the node-based method. Compared to the centralized topology, the distributed topology does not allow sharing the radios of the R-nodes, and further limits the performance of the slot-based scheduling. This can be seen by comparing throughput of the heuristic schemes in Figs. 5.3 and 5.5, where the two heuristic schemes in Fig. 5.3 have almost the same throughput, while in Fig. 5.5 the throughput gap between the two heuristic schemes is more obvious. Figs. 5.4 and 5.6 show that when opportunistic relaying is used at the R-node, the gap between throughput of the slot-based scheduling and the optimum solution is much smaller than that between the two heuristic schemes. The main reason for this is that opportunistic relaying provides the flexibility for the R-node to transmit to either one of the end nodes or to both, depending on both channel and buffer conditions. With this, the advantage of slot-based scheduling that maximizes the total transmission rate of all the nodes in each time slot is more obvious.

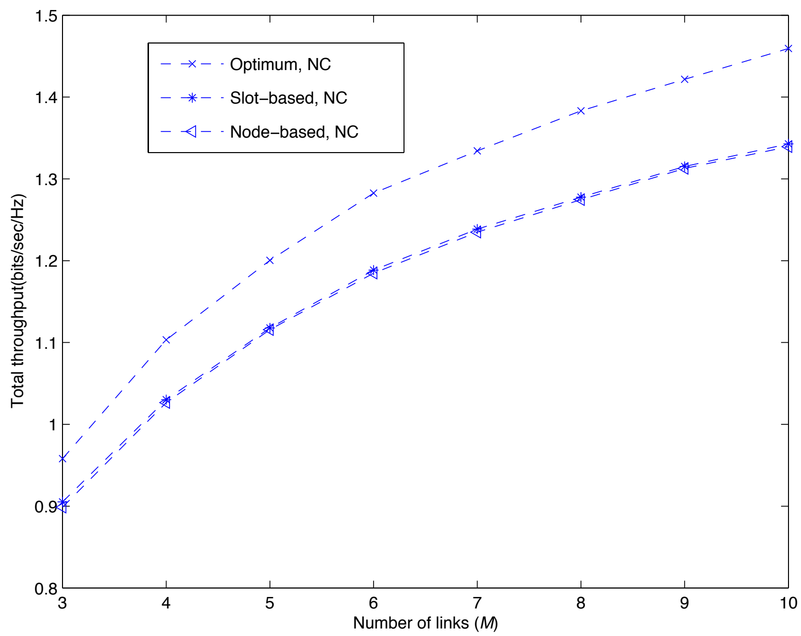

Figure 5.3: Distributed topology: throughput of using NC versus total number of links

Meanwhile, we also notice that the difference between throughput performance of the optimum and the heuristic schemes is relatively small in all the four figures, which indicate the effectiveness of the proposed schemes. In order to demonstrate performance of the proposed schemes in more practical cases, next we increase the number of links and channels, but can only generate results for heuristic solutions. The time for generating the long-term optimum results is prohibitively long and it is unpractical to include the numerical results here. Below the default values for K and M are both 20.

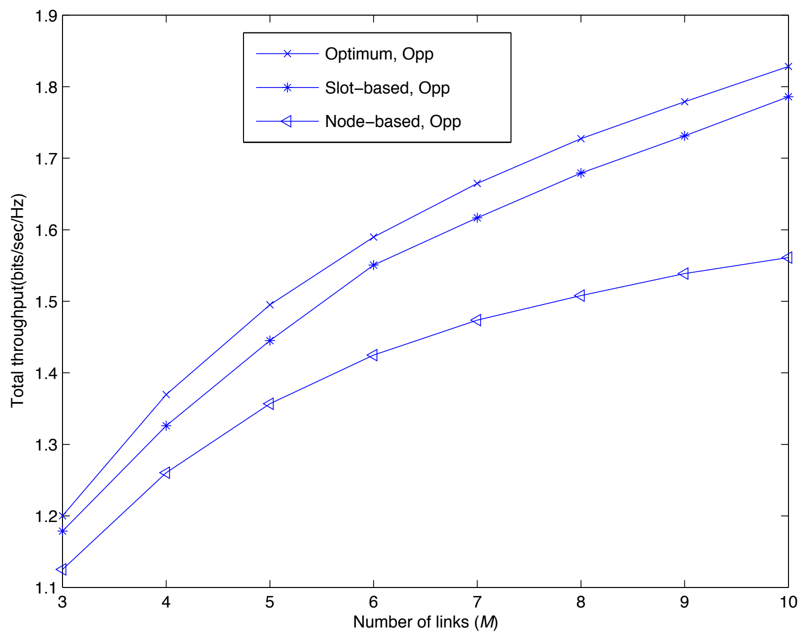

Figure 5.4: Distributed topology: throughput of using opportunistic relaying versus total number of links

Fig. 5.7 shows the throughput performance of opportunistic relaying as the number of links changes. As the number of links increases, the total throughput first increases linearly and then becomes gradually saturated. This is because of the limited number of channels. When M is relatively small, channels are always available, and increasing the number of links means more nodes can transmit at each time slot. As M becomes large, the number of simultaneously transmitting nodes is limited by K. In this case, the total throughput can still benefit from multiplexing channel conditions of different links at different channels, but the increase of throughput with M is much slower. Fig. 5.8 shows the throughput performance of using opportunistic relaying as the number of channels changes. It shows that as the number of channels increases, the throughput increases almost linearly first and then much slower. In general, when the

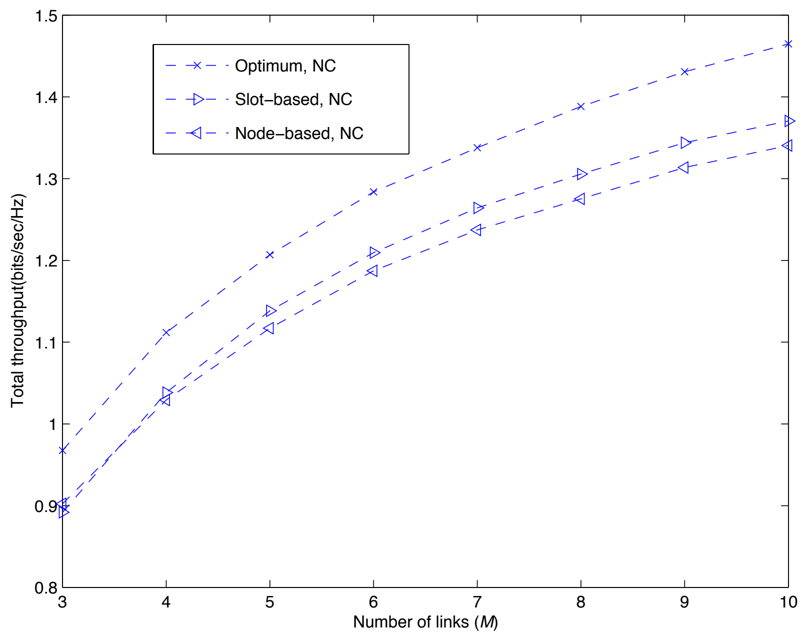

Figure 5.5: Centralized topology: throughput of using NC versus total number of links

number of channels is relatively small, increasing number of channels increases number of transmitting nodes, and therefore, increases the total transmission throughput. The maximum number of simultaneously transmitting nodes is equal to the total number of radios at the R-node (or R-nodes). After the number of channels is larger than L (which is equal to M in our simulation), further increasing the number of channels does not change the total number of transmitting nodes, but may still change the decisions about which nodes should transmit at a given time slot. Both Figs. 5.7 and 5.8 show that the throughput performance in the distributed topology is less than that in the centralized topology. This is because the centralized topology allows the links to better utilize the radios of the R-node so that the S- and D-nodes of the same link can transmit simultaneously; while in the distributed topology, the

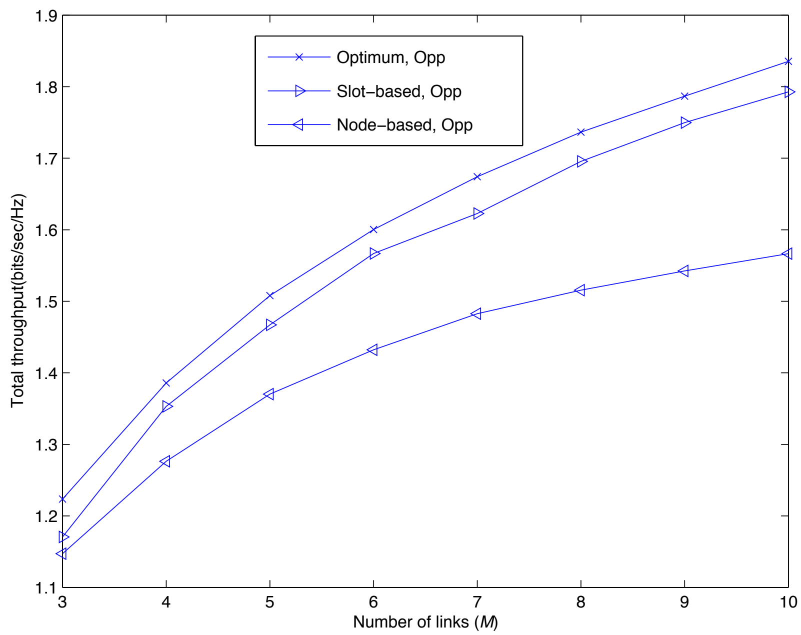

Figure 5.6: Centralized topology: throughput of using opportunistic relaying versus total number of links

single radio at the R-node of each link can only support one end node to transmit. On the other hand, we can see that the difference between the throughput of the two topologies is very small, which indicates that allowing both the end nodes of the same link to transmit at the same time does not bring significant benefit to the overall throughput. Both figures also show that the difference between the slot-based and node-based scheduling in both topologies is very small, which indicates that the node-based scheduling is almost as effective as the slot-based scheduling.

For the node-based scheduling, Figs. 5.9 and 5.10 further show the throughput performance in different scenarios and topologies. Both figures show that using opportunistic relaying can improve the throughput, compared to NC only, and the difference is only slightly larger in the centralized topology than in the distributed

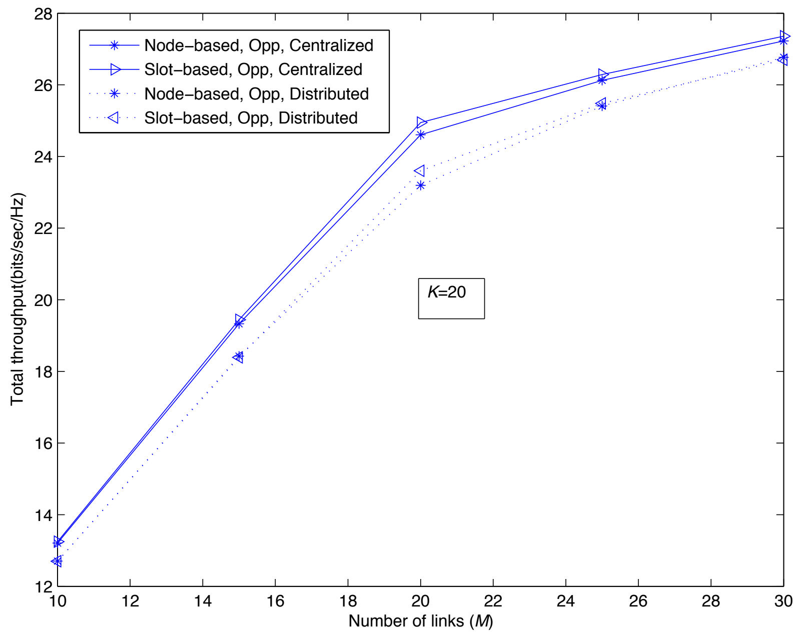

Figure 5.7: Opportunistic relaying: throughput versus total number of links

topology and does not change much with total number of links or channels. This observation is basically consistent with that from Figs. 5.7 and 5.8. Fig. 5.10 shows that the difference between opportunistic relaying and NC is more obvious when the number of channels is larger. When the number of channels is small, fewer transmission opportunities are available, and the difference between NC and opportunistic relaying is small. As more channels are available, NC cannot take better advantage of the available channels because the rate of each transmission from the R-node is limited by the worst channel, while opportunistic relaying allows the R-node to transmit at the highest rate that each channel can provide.

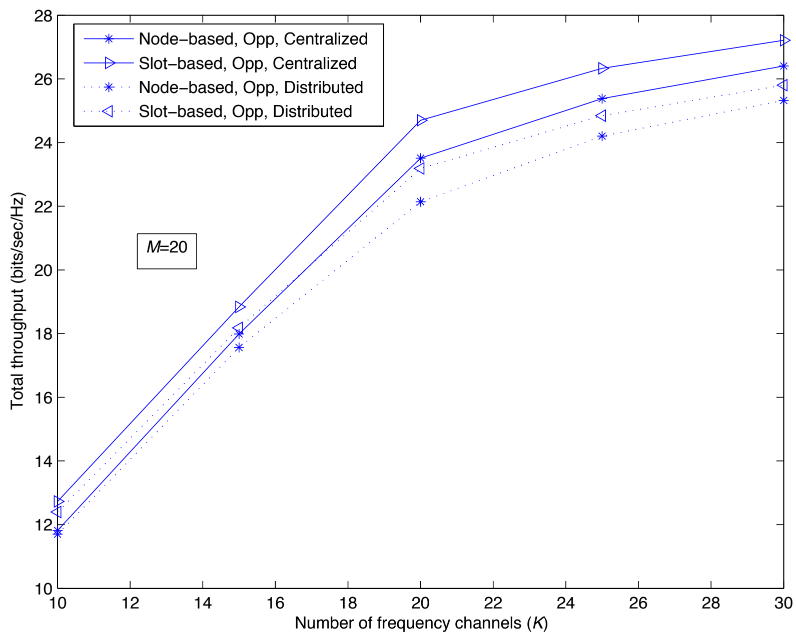

Figure 5.8: Opportunistic relaying: throughput versus total number of channels

5.6 Summary

We have studied time slot and frequency channel allocations for a network with bidirectional relaying links. Both centralized and distributed topologies have been considered, and the relay node is either restricted to use NC only or allowed to opportunistically use NC and traditional one-way relaying. Two heuristic scheduling schemes have been proposed, slot-based scheduling and node-based scheduling. Although the node-based one has lower complexity and achieves slightly lower throughput, compared to the slot-based one, both the proposed scheduling schemes are effective and the difference between their throughput performance and the optimum is relatively small. For the distributed topology, the complexity of the slot-based scheduling can be greatly reduced by solving a minimum cost flow problem. Our results have also

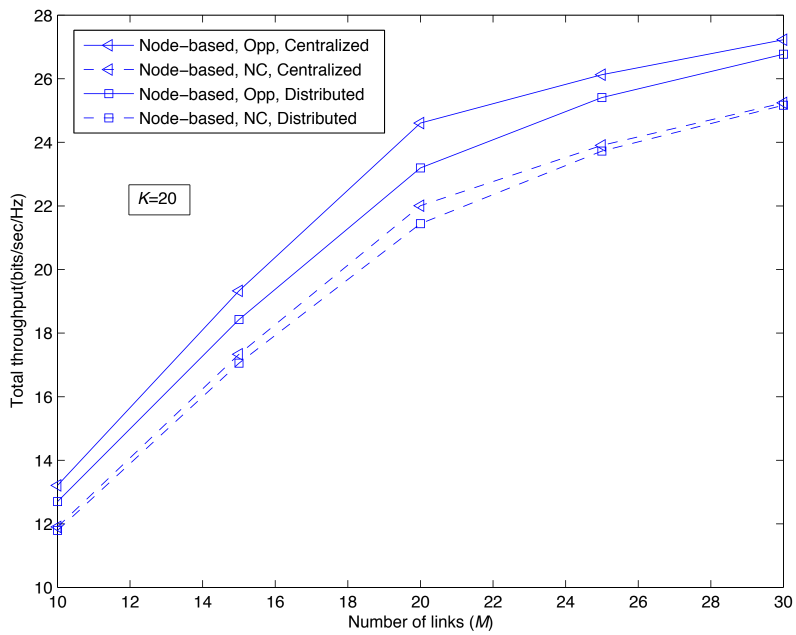

Figure 5.9: Node-based: throughput versus total number of links

shown that although using opportunistic relaying can achieve higher throughput than using NC only, the effect of sharing the radios of the relay nodes on the throughput is very minor.

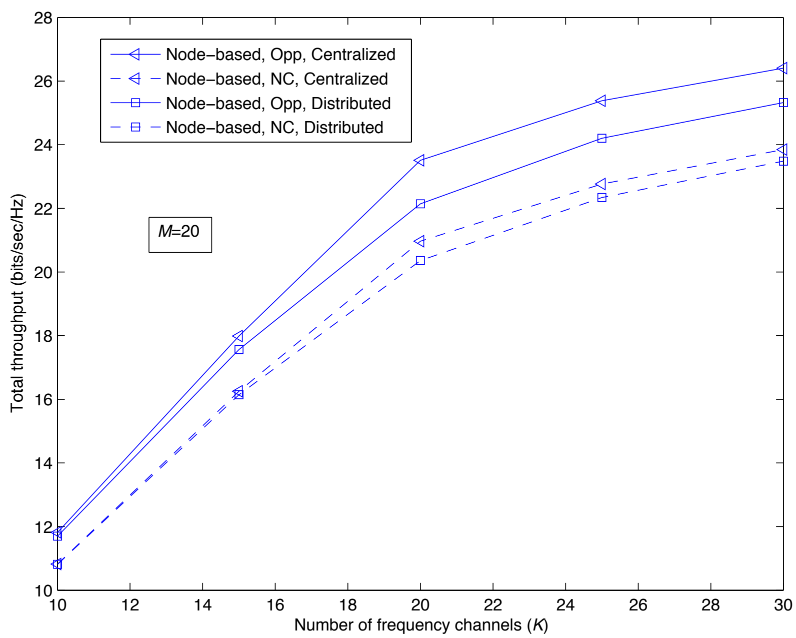

Figure 5.10: Node-based: throughput versus total number of channels

Chapter 6

Conclusions and Future Work

We have studied transmission scheduling for wireless networks with bidirectional relaying links. Different scenarios have been considered, heuristic scheduling schemes have been proposed and their performance has been compared to the optimum solutions.

Our results from Chapter 2 indicate that in a WNBRL, jointly managing the transmission power and allocating time slots is critically important in order to control the mutual interference while maximizing the overall transmission throughput. Both ANC and DNC can outperform each other under some conditions. Although ANC is more sensitive to interference changes, it can achieve much higher throughput than DNC when co-channel interference is relatively weak; on the other hand, although scheduling node transmissions and determining transmission power is less complex for DNC in general, the requirement that the relay node should first decode the received message sets a minimum transmission power from the end nodes, which limits the maximum transmission rate when using DNC. These results are based on an assumption that all transmissions are at a fixed transmission rate. Removing this constraint may add more flexibility to the scheduling process, where the nodes can adaptively adjust both their transmission rate and power in order to maximize the transmission throughput. However, the complexity of the scheduling will be increased.

In Chapter 3 we have studied the scheduling problem by jointly allocating time slots and frequency channels in order to maximize the overall throughput. By taking into consideration both the buffer and channel conditions, the proposed CNSCA scheme can achieve very close-to-optimum throughput without knowing any future information about channel conditions. The work can be further extended by allowing multiple transmissions to share the same frequency channels, which can potentially improve the throughput performance, but coordinating mutual interference will become a main issue in making the scheduling decisions.

In Chapter 4 we have proposed a scheduling scheme that coordinates the frequency channel and time slot allocations in order to achieve fair throughput among the bidirectional relaying links. Although providing fairness among multihop transmission links while efficiently utilizing the network resources has been a very challenging issue, our results indicate that a significant improvement can be achieved in throughput fairness at a price of slight throughput reduction, compared to the scheduling that maximizes the total throughput; in addition, the fairness performance of the proposed scheme is not sensitive to number of available channels. Providing fair throughput in such a network by allowing multiple transmissions to reuse the same frequency channel will be another challenging issue worth to be studied in the future.

In Chapter 5 we have further compared scheduling for WNBRLs with different topologies and using different relaying strategies. It has been seen that although opportunistically using NC and traditional one-way relaying can better utilize the channel resources than restricting the relay nodes to always use NC, the advantage of the opportunistic relaying may depend on network topology and specific criteria in making the transmission decisions.

Overall, the work considered in this thesis assumed that the relay nodes are pre-selected. When there are multiple candidate relay nodes available, and each link can dynamically select the best relay node, jointly studying relay node selection and traffic scheduling can be jointly studied to further improve the resource utilization.

Appendix A

Iterative Power Control Formulas for DNC

From (2.28) $P_{x_m,t}$ can be solved as

$$P_{x_m,t} \geq \frac{\gamma \left(\sum_{z_n \in \mathcal{A}_t,\, z_n \neq x_m} P_{z_n,t} G_{z_n,y_m,t} + P_n \right)}{G_{x_m,y_m,t}}. \tag{A.1}$$

Multiplying both the numerator and denominator on the right-hand side of (A.1) by $P_{x_m,t}$, we have

$$P_{x_m,t} \geq P_{x_m,t} \times \frac{\gamma \left(\sum_{z_n \in \mathcal{A}_t,\, z_n \neq x_m} P_{z_n,t} G_{z_n,y_m,t} + P_n \right)}{P_{x_m,t} G_{x_m,y_m,t}} = P_{x_m,t} \times \frac{\gamma}{\gamma_{y_m,t}}, \tag{A.2}$$

where $\gamma_{y_m,t} = \frac{P_{x_m,t} G_{x_m,y_m,t}}{\sum_{z_n \in \mathcal{A}_t,\, z_n \neq x_m} P_{z_n,t} G_{z_n,y_m,t} + P_n}$ is the SINR at the receiver of node y_m. Let $P_{x_m,t}(k)$ be the transmission power of node x_m at the kth iteration of the power control process. For an S- or D-node to transmit, i.e., $x = s$ or d, the desired receiver is the R-node of the same link, and the iterative formula for its transmission power is given by

$$P_{x_m,t}(k+1) = \min\left\{P_{\max}, P_{x_m,t}(k) \times \frac{\gamma}{\gamma_{r_m,t}(k)}\right\}, \tag{A.3}$$

where $\gamma_{r_m,t}(k)$ is the value of $\gamma_{r_m,t}$ measured at the R-node of link m in the kth iteration. When $x = r$, i.e., the R-node transmits, its transmission should reach both the S- and D-nodes of the same link with satisfactory SINR, and the iterative formula for its transmission power is given by

$$P_{r_m,t}(k+1) = \min\left\{P_{\max}, P_{r_m,t}(k) \times \frac{\gamma}{\min\{\gamma_{s_m,t}(k), \gamma_{d_m,t}(k)\}}\right\}, \tag{A.4}$$

where $\gamma_{s_m,t}(k)$ and $\gamma_{d_m,t}(k)$, respectively, are the values of $\gamma_{s_m,t}$ and $\gamma_{d_m,t}$ measured at the S- and D-nodes in the kth iteration. The formula in (A.4) indicates that the transmission power of the R-node is determined by the link conditions to both the S- and the D-nodes, whichever is worse, and also upper limited by $P_{\max}$.

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