Cooperative Communication in Wireless OFDMA Multi-Hop Networks

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Kurzfassung

Drahtlose Kommunikation findet aktuell hauptsächlich auf zentral gesteuerte Weise statt, wobei zwischen Sender und Empfänger eine direkte Verbindung besteht. Um eine weitreichende Kommunikation zu ermöglichen, wird üblicherweise ein drahtgebundener Zugriffspunkt verwendet, welcher die Kommunikation steuert und eine Anbindung an weitverzweigte Netze ermöglicht. Diese Art der Kommunikation bietet viele Vorteile, hat jedoch auch Grenzen, vor allem in Bezug auf die Abdeckung in bestimmten Szenarien und an Orten, welche nur schwierig durch eine drahtgebundene Infrastruktur erreichbar sind. Drahtlose Multi-Hop Netze bieten eine kostengünstige Möglichkeit, um eine flächendeckende Kommunikation zu ermöglichen, ohne dabei auf eine zentral gesteuerte, drahtgebundene Infrastruktur angewiesen zu sein. In Multi-Hop Netzen dient jeder Knoten im Netz als mögliches Relais für Nachrichten, welche nicht über eine direkte Verbindung übertragen werden können. Jedoch ermöglichen klassische Routingverfahren für Multi-Hop Netze, bei denen die Datenübertragung einer zuvor festgelegten festen Abfolge von Knoten folgt, nur einen sehr geringen Datendurchsatz und sind für datenintensive Anwendungen ungeeignet. Außerdem bieten die Routingpfade häufig keine verlässliche Grundlage für eine stabile Verbindung über längere Zeit. In dieser Arbeit wird Korridor-basiertes Routing untersucht, bei welchem Routingpfade erweitert werden und jeder Abschnitt des Routingpfads aus mehreren kooperierenden Knoten besteht. Anstatt einer festgelegten Abfolge von Knoten zu folgen, bietet ein Korridor in jedem Abschnitt mehrere Relais, auf welche die zu übertragenden Daten aufgeteilt werden können. Durch die verschiedenen Positionen der Knoten ergeben sich unterschiedliche Kanalzustände auf den verfügbaren Verbindungen. Somit ergibt sich eine Grundlage für Diversitätsgewinne für den Datendurchsatz. In Kombination mit der Orthogonal Frequency Division Multiple Access (OFDMA) Übertragungstechnik, welche aktuell die Grundlage für eine Vielzahl von Kommunikationsstandards ist, ermöglicht ein Korridor eine effiziente Verwendung der verfügbaren Frequenzbandbreite. Mit OFDMA wird die verfügbare Bandbreite in schmale, zueinander orthogonale Subträger aufgeteilt, welche entsprechend der aktuellen Kanalbedingungen den unterschiedlichen Verbindungen innerhalb eines Abschnitts des Korridor zugewiesen werden können. Die benötigten Kanalzustandsinformationen werden hierfür nur lokal in einem Abschnitt des Korridors bereitgestellt, um eine vom restlichen Pfad unabhängige, effiziente Ressourcenverteilung zwischen den Sendeknoten eines Abschnitts zu ermöglichen. Für jeden Subträger kann somit eine Verbindung mit möglichst großer Kanalkapazität gefunden werden und dadurch ein entsprechend hoher Datendurchsatz ermöglicht werden.

Als Grundlage für das Korridor-basierte Routing muss zunächst eine Auswahl an Knoten für jeden Abschnitt gefunden werden. Hierzu wird ein Verfahren vorgeschlagen, welches aus lokal ausgetauschten Kontrollnachrichten eine Lebenszeit für relevante Verbindungen ermittelt und diese bei der Auswahl geeigneter Knoten berücksichtigt. Hierdurch wird eine möglichst stabile Struktur aufgebaut, auf welcher die spätere Datenübertragung basiert. Darüber hinaus wird ein Wartungsprotokoll vorgestellt, welches eine proaktive Erneuerung des Korridors vollzieht, um möglichen Verbindungsabbrüchen zuvorzukommen. Es wird gezeigt, dass der Korridor als unterstützende Struktur für die Datenübertragung in Multi-Hop Netzen im Vergleich zu klassischen Routingverfahren eine deutliche Verbesserung bezüglich der potentiellen Übertragungskapazität, sowie der Verbindungsstabilität bietet.

Eine wesentliche Herausforderung beim Korridor-basierten Routing besteht in der Ressourcenallokation in den einzelnen Abschnitten. Um eine störungsfreie Kommunikation zu erreichen, müssen die verfügbaren Subträger exklusiv an die Sendeknoten eines Abschnitts zugewiesen werden. Um einen möglichst hohen Datendurchsatz zu erzielen, müssen dabei sowohl die Kanalzustände als auch die zu sendende Datenmenge der einzelnen Knoten berücksichtigt werden. Da sich die Zustände der Übertragungskanäle über der Zeit ändern, muss die Alloktion der Ressourcen dynamisch angepasst werden. Basierend auf einem Markov-Entscheidungsprozess-Modell und mit Hilfe von dynamischer Programmierung wird ein Zuweisungsverfahren entwickelt, welches die mittlere Anzahl an benötigten Zeitschlitzen für eine Weiterleitung der vorhandenen Daten minimiert. Um auch mit einer großen Anzahl von Zuständen im zugrundeliegenden Modell umgehen zu können, wird ein Approximationsverfahren vorgeschlagen. Dennoch erfordert das Zuweisungsverfahren große Rechen- und Speicherkapazitäten und ist beschränkt auf Modelle mit einer geringen Anzahl an Variablen und Zuständen. Deshalb wird des Weiteren ein suboptimales Ressourcenallokationsverfahren vorgeschlagen, welches auf einer Kanalqualität-vergleichenden Metrik als Entscheidungsgrundlage basiert. Es wird gezeigt, dass mit der suboptimalen Heuristik eine nur geringfügig schlechtere Performanz in Bezug auf den Datendurchsatz erreicht wird.

Schließlich wird der Betrieb von Korridor-basiertem Routing mit Fountain Codes untersucht. Fountain Codes ermöglichen im Gegensatz zu klassischen Kanalcodierungsverfahren eine automatische Anpassung der Datenübertragungsrate an den entsprechenden Übertragungskanal. Mit Fountain Codes kann eine theoretisch unbegrenzte Anzahl von kodierten Symbolen aus einer gegebenen Anzahl von Informationsbits generiert werden. Empfänger können aus einer beliebigen Teilmenge dieser kodierten Symbole die ursprünglichen Daten gewinnen, sobald die akkumulierte Transinformation aus den empfangenen Übertragungen ausreicht. Hierdurch ergeben sich Möglichkeiten, auch schwache Verbindungen über die Grenzen einzelner Etappen des Korridors hinaus für eine verbesserte Datenübertragung nutzbar zu machen. Weit entfernte Knoten können Übertragungen mithören und somit die benötigte Übertragungszeit in späteren Abschnitten verkürzen. Hierfür werden geeignete Verfahren zur Auswahl und Zuweisung von kodierten Datenpaketen und zur Ressourcenallokation entwickelt, die einen deutlich erhöhten Datendurchsatz durch das Ausnutzen der etappenübergreifenden Verbindungen erzielen. Außerdem wird ein Verfahren vorgeschlagen, welches die Kooperation der Sendeknoten erweitert, um eine verteilte Mehrantennen-Übertragung von Daten zu ermöglichen. Hierfür wird die Beschränkung der exklusiven Nutzung von Subträgern aufgehoben. Durch eine geeignete Signalverarbeitung, angepasst an die jeweiligen Übertragungskanäle, kann so eine Strahlformung der ausgesendeten Signale erreicht werden, wodurch ein verbesserter Signalpegel am entsprechenden Empfänger erzielt werden kann. Diese Übertragungstechnik erfordert allerdings die Verfügbarkeit der gleichen Datenpaketen an mehreren Sendern, was einen zusätzlichen Aufwand bedeutet. Es wird ein Verfahren vorgeschlagen, welches diese Verfügbarkeit auf eine effiziente und gewinnbringende Weise ermöglicht und so Gewinne im Datendurchsatz im Vergleich zu einer exklusiven Nutzung der Subträger ermöglicht.

Abstract

Today, wireless communication mainly takes place in a centrally controlled manner, whereby the sender and the receiver are connected over a single wireless connection. In order to enable connections over wide areas, usually, an access point is used that is connected to a wired backbone and enables a connection to a large network. This type of communication has many advantages, but also struggles with certain limitations, especially in terms of coverage in particular scenarios or at certain places that are difficult to cover with wired infrastructure. Wireless multi-hop networks offer a low-cost opportunity to enable wide-area communication, without the need for a centrally controlled wired infrastructure. In wireless multi-hop networks, each network node serves as a potential relay for messages that cannot be transmitted via a direct connection. However, traditional routing methods for multi-hop networks, which rely on a data transmission along a fixed predefined sequence of nodes, are limited in the achievable data throughput and are not suitable for data-intense applications. Furthermore, the routing paths often do not provide a reliable basis for a stable connection over a long period of time. In this thesis, Corridor-based Routing is investigated in which routing paths are widened such that each stage of the path spans multiple cooperating forwarding nodes. Instead of following a fixed routing path, a corridor offers multiple forwarding nodes per hop among which the data can be divided. Due to the varying positions of the nodes, different channel states occur on the available links. Thereby, a foundation is given for diversity gains for data throughput. In combination with Orthogonal Frequency Division Multiple Access (OFDMA), which is the basis for most of the current and future communication standards, the corridor enables efficient usage of the available frequency resources. In OFDMA, the available bandwidth is divided into narrow orthogonal subcarriers which can be assigned to different links according to the current channel states. The required channel state information is provided only locally within a stage of the corridor in order to enable an efficient allocation of the resources which takes place independently from the remaining stages. Therewith, a link with a preferably high channel capacity can be found for each subcarrier and therefore, a corresponding high data throughput can be achieved.

The operation of Corridor-based Routing requires the selection of adequate nodes for each stage of the corridor. For this purpose, a method is proposed to determines the expected lifetime of relevant links based on locally exchanged control messages. This information is then taken into account for the selection of suitable nodes. Thereby, a stable corridor is generated that serves as a support structure for the later data transmission. In addition, a proactive maintenance protocol is proposed that checks and renews the corridor structure in order to prevent link breakages before they take place. It is shown that the corridor used as a support structure for data transmission enables significant improvements in terms of the potential transmission capacity, as well as the connection stability, compared to traditional routing methods.

A major challenge in Corridor-based Routing is the resource allocation within the local stages of the corridor. To guarantee an interference-free communication, each available subcarrier needs to be allocated exclusively to a single forwarding node. To achieve the highest possible data throughput, the channel quality, as well as the data buffer levels of the nodes, need to be taken into account. Since channel states are changing over time, a dynamic adaptation of the resource allocation is required. Based on a Markov-Decision-Process model and using dynamic programming, a resource allocation policy is derived that minimizes the expected number of required time slots to forward the available data. To handle large state spaces in the underlying model, a state approximation technique is proposed. Nevertheless, the allocation procedure requires large amounts of computing and storage capacities and is limited to models with a small number of variables and states. Therefore, a suboptimal heuristic resource allocation scheme is presented, in which the decision making is based on a channel-state-comparative metric. It is shown that the suboptimal heuristic approach performs close to the optimal approach in terms of the achievable data throughput.

Finally, the operation of Corridor-based Routing with fountain codes is investigated. In contrast to traditional channel coding, fountain codes allow for an automatic adaptation of the data transmission rate to the corresponding channel. With fountain codes, a transmitter can theoretically generate an infinite number of encoded symbols from a given set of information bits. Receivers can recover the original data from an arbitrary subset of these encoded symbols as far as the accumulated mutual information from the received signals is sufficient and exceeds the entropy of the original data. Fountain codes open up the possibility to efficiently exploit weak links that go beyond the boundaries of the corridor stages to improve the performance of the transmission process. Distant nodes overhear transmissions and thus, the required transmission time in subsequent stages can be reduced. To this end, suitable methods for the selection and scheduling of coded data packets and the allocation of the subcarriers are proposed which significantly increase the achievable data throughput through the exploitation of inter-stage links. In addition, a forwarding scheme is proposed that extends the cooperation among the nodes and enables data forwarding through distributed multi-antenna transmissions. To this end, the restriction of exclusive usage of subcarriers is

canceled. By a suitable preprocessing of the transmit signals, which is adapted to the corresponding channel states, a beamforming effect can be achieved which results in an improved signal level at the corresponding receiver. However, this transmission scheme requires the availability of the same data packets at several transmitters, which goes along with an additional effort that needs to be spent. A procedure is proposed that enables distributed multi-antenna transmissions and includes them in Corridor-based Routing in a profitable way compared to the exclusive usage of subcarriers.

Contents

Chapter 1

Introduction

1.1 Wireless Multi-Hop Networks

Wireless communication is already omnipresent in everyday life even though it is still a growing and evolving technology. While having mobile access to the Internet almost everywhere and every time has already become natural for most of the people, there are many more applications to come.

Today, wireless communication is mostly dominated by single hop transmissions between an access point, for instance, a base station, and an end device, where the access point provides a gateway to a wired backbone. This means that wireless transmissions only occur on the last link. This infrastructure based communication is very successful since it provides an adequate solution for almost every use case. From wireless payments over a few centimeters taking place via Near Field Communication (NFC) up to wide-area cellular networks which cover multiple kilometers based on 2G to 5G, there are plenty of technologies based on a fixed wired infrastructure. However, there are still serious limitations and problems with which these centralized approaches are struggling.

A major problem is the coverage at any place in any situation. There are many scenarios in which a connection to a centralized access point is difficult or not possible to realize. For instance, devices that are placed deep inside buildings are challenging to reach by base stations that are placed outside of the building. The coverage can be increased by increasing the transmit power. However, due to health issues and in order to limit interference in co-existing networks, the transmission power of wireless transmissions is strictly limited and cannot be increased arbitrarily to solve any coverage problem. Even in case that the base station is able to reach devices within a certain area, the devices are not necessarily able to reach the base stations. With the Internet of Things (IoT), more and more wireless devices will be used that should run on a small battery for a long time which results in small transmission ranges. A possible solution is to increase the number of access points which corresponds to certain costs. Of course, network operators need to take a cost-benefit-analysis into account to decide whether it is worth building up an infrastructure or not. Therefore, coverage is a major issue, for instance, in sparsely populated areas, in nature reserves, in developing countries, and so on. Another important scenario in which infrastructure-based communication might be impossible occurs when the infrastructure is destroyed or the power supply of the access points cannot be guaranteed. Those scenarios include crises, natural disasters or major catastrophic events.

Wireless multi-hop networks can be used as an alternative approach or as an extension for these centralized infrastructure-based networks. In a wireless multi-hop network, devices can communicate directly with each other but, as the name suggests, messages are also conveyed over multiple wireless hops. Due to a limited transmission range of the network nodes, not all nodes might be able to directly communicate with each other. Therefore, cooperation among the nodes is required which means that they need to assist each other as relays and forward data over multiple hops to enable traffic over a wide area. Such a network can be set up on the fly with no need for a given infrastructure and hence, it can be easily deployed with low costs. There are several examples of successful existing wireless multi-hop networks. For instance, the Portsmouth Real-Time Travel Information System (PORTAL), uses multi-hop communication to provide real-time information on transportation service [BCG05]. Firechat [FC19] is a free messaging app that uses Bluetooth and WiFi to build a mesh network out of the participating devices. This allows for a multi-hop communication that is independent of other networks. Firechat has been used during natural disasters in Ecuador and Kashmir and also in events like the Burning Man festival. With the expected increase of communicating devices in the future [EMR19], especially related to IoT, the prerequisites for wireless multi-hop networks are getting better and better due to the higher device density that will be present almost everywhere. However, there are many challenges and also drawbacks that need to be considered in multi-hop communications. With each additional hop, an additional delay is introduced which makes multi-hop networks only useful for applications with a certain delay-tolerance. An ultra low latency, like it is required for a remote surgery, is not compatible to wireless multi-hop networks. Furthermore, the dynamic and unreliable behavior of wireless channels makes efficient routing very challenging. Due to node movements, links of a routing path can quickly become inefficient and the achievable data throughput can significantly drop.

Many centralized communication technologies achieve a high spectral efficiency by exploiting spatial diversity, for instance, based on multiple antennas at the access point.

Resources can be easily allocated through the control of the access point based on the current channel states. However, many devices that are usually used in multi-hop networks are only equipped with a single antenna and there is no centrally controlled resource allocation taking place. Furthermore, it is almost impossible to provide accurate current channel information over multiple hops in order to find a routing path. The quality of wireless channels is usually changing too quickly. Therefore, forwarding strategies are required that can handle the dynamic link behavior in wireless multi-hop transmissions and enable an efficient use of the available resources in order to achieve high data throughput in multi-hop communications.

1.2 State of the Art

1.2.1 Traditional Routing

Traditional routing protocols for wireless multi-hop networks stem from established techniques for wired networks. They can be classified into proactive (table-driven) and reactive (on-demand) protocols. In proactive protocols, like for instance, Optimized Link State Routing (OLSR) [JMC+01], nodes permanently exchange topology information in order to find a path to each destination in advance, even if there is no current request for a data transmission. On the other hand, reactive routing protocols, like for instance, Ad-hoc On-Demand Distance Vector (AODV) routing [PR99] or Dynamic Source Routing (DSR) [JM96], discover a missing route only on-demand in case that data needs to be transmitted. Of course, there are also hybrid schemes, like for instance, Zone Routing Protocol (ZRP) [Bei02], which are aiming for a good compromise by restricting the proactive routing to a neighborhood within a certain number of hops and by applying reactive routing for the remaining network.

Many traditional routing protocols rely on a simplified channel model in which a link between two nodes either exists or not and they are aiming at a path with the minimum possible number of hops. This binary channel model, called unit disk graph model [SNK05], ignores the actual channel quality. In a wireless network, this may result in a path along distant nodes with very low channel capacity and poor link stability. Therefore, advanced metrics for path selection have been proposed. In [DPZ04] and [DABM05], the expected transmission time (ETT) and the expected transmission count (ETX), respectively, are introduced and used to optimize the routing path based on physical layer information. The ETT metric estimates the required time to successfully transmit a data packet over a link, while the ETX metric estimates the expected number of transmissions. Thereby, the achievable data throughput can be improved. However, the strategy of preselecting a fixed end-to-end path before the actual data transmission starts does not adapt well to the dynamic behavior of wireless channels. These approaches usually fail in updating the path metrics at a fine-grained time scale at which wireless link variations are taking place.

1.2.2 Opportunistic Routing

In recent years, an alternative routing paradigm has emerged, referred to as Opportunistic Routing. The key idea of Opportunistic Routing is to overcome the drawbacks of unreliable wireless links by exploiting the broadcast nature of wireless transmissions. In this approach, wireless channels are considered as an opportunity rather than a limitation. Instead of selecting a fixed predefined forwarding node for each data packet before the transmission, any node which successfully received a data packet can be considered in a set of potential forwarding nodes. The best suited forwarder is selected after the transmission instead of prior to it. Thereby, spatial diversity across the multiple receiver options is exploited. This opportunistic forwarding concept was first introduced with Extremely Opportunistic Routing (ExOR) in [BM05] and has shown to significantly reduce the number of required retransmissions compared to traditional routing.

A major task in opportunistic routing is to define a priority metric to decide for a forwarding node in case that multiple nodes have successfully received a certain data packet. To this end, different metrics are used like the number of hops [YYW+05], [JD05], [Wes06], [NJE+07], [WCL12], the geographical distance [FWK+03], [ZR03], [BSV04], [ZLYB07], [ZLZ08], [YZY+09], the ETX [BM05], [CJKK07], [RSMQ09], [HLS09] or the ETT [ZKR08], [LYSS13]. Since the ETX metric does only depend on a single path, the authors in [ZN07] introduce the Expected Any-path transmissions (EAX) metric that takes into account the opportunistic routing mechanism and captures all possible paths. Accordingly, in [LDK09], the ETT metric is extended to the Expected Any-path Transmission Time (EATT) metric.

Another important task in opportunistic routing is the selection of the set of potential relays. Of course, only the nodes that provide a better situation compared to the source node need to be considered. However, it can be beneficial to further limit the number of candidates in order to reduce the required control overhead. In [CJKK07], [LSC09] and [KWH10], nodes with a low contribution to the transmission process are excluded from the set of potential candidates. Another problem that needs to be considered is the transmission of duplicates of certain data packets. This can occur in case that the candidates are not in each others' transmission range which makes a coordination difficult. As a consequence, in [RSMQ09] and [HLS09], the potential relay nodes need to be fully connected to each other.

Even though opportunistic routing provides a solution to handle the unreliable nature of wireless channels, it does not fully utilize the actual channel capacities in any case. In order to avoid frequent channel estimations, most opportunistic routing schemes rely on a single transmission rate [Cha15] and do not take into account rate control. Considering multiple possible transmission rates can increase the achievable data throughput [ZLZ08]. However, only a few opportunistic routing schemes consider rate control, like for instance, [ZLZ08], [RSMQ09] and [LVVK12]. Furthermore, by using a fixed priority order for the forwarding nodes, the actual channel states of the various links are ignored. Diversity is only exploited on the receiver side but a selection diversity on the transmitter side is dismissed.

1.2.3 Corridor-based Routing

In this work, Corridor-based Routing (CbR) is considered which was first introduced in [KKLH12a]. Similar to opportunistic routing, in CbR, each hop consists of a group of potential forwarding nodes, but unlike most of the opportunistic routing schemes, CbR relies on the utilization of current Channel State Information (CSI) to exploit selection diversity on the transmitter side and to enable an efficient rate control in each hop. The structure that is built by the potential forwarders is referred to as the corridor and it is considered as a support structure which enables a versatile adaptation to the wireless channels.

Wireless channels are usually frequency selective, i.e, the channel quality strongly varies over frequency. This feature can be exploited with CbR in combination with Orthogonal Frequency Division Multiple Access (OFDMA). In OFDMA, the available bandwidth is subdivided into multiple orthogonal subcarriers. By an adaptive allocation of the subcarriers and an efficient rate adaptation, both based on accurate CSI knowledge, the given link diversity within the corridor can be exploited to achieve a high data throughput. In [KKLH12a], global CSI knowledge is used to provide a centralized transmission strategy at the source node before the actual data transmission. Since the channel states of wireless channels are quickly changing, collecting accurate and up-to-date CSI over multiple hops is almost impossible. Therefore, in [KKLH12b], only local CSI about the current hop is considered and hop-by-hop resource allocation strategies for CbR are proposed. Practical implementations of a distributed OFDMA subcarrier allocation with multiple transmitters and receivers using software-defined radios are considered in [KLH13] and [LKH+13]. These practical considerations are extended to multi-hop transmissions for CbR in [LHKK14a], [LHKK14b] and [LHKK15].

The corridor construction procedure, i.e., the selection of the potential forwarders in each hop, is considered based on on a given unipath and geographical knowledge about the nodes in [KLHK13a]. In [LQH+14], the corridor is constructed in two steps: Firstly, a unipath construction based on geographical knowledge and secondly, a selection procedure for the additional corridor nodes based on link state information. The impact of the required overhead for the operation of CbR is crucial for the evaluation of its performance. The impact of the required control messages on the performance of CbR and a turning point at which this overhead pays off is investigated in [LQH+14]. Furthermore, the required channel estimation and CSI feedback are considered in [LHKK14b] and [Nav15], where it is shown that CbR can operate close to its optimum based on very coarse CSI feedback. In [LHN+13], it is shown that even 1-bit CSI preference feedback per subcarrier can be sufficient to perform close to an allocation based on exact CSI knowledge. Different strategies for the spatial reuse of channel resources is considered in [KLHK13b]. Further work on CbR also considers the use of interference alignment techniques within the corridor as an alternative forwarding mechanism [LNK+14], [Nav15].

1.3 Open Issues

In this section, the open issues arising from the review of the existing literature are summarized in the context of CbR. Two steps in the operation of CbR are considered in this thesis: First, the node selection in the construction procedure of the corridor. Second, the resource allocation problem for the data transmission within the corridor.

Although corridor construction has been studied, the stability of the corridor structure in a mobile scenario, i.e., the lifetime of the links within the corridor structure, has not been considered. Thus, the following questions arise:

1. How to construct and maintain stable corridors in the dynamic environment of a mobile network, i.e, how to select nodes such that the corridor structure has an adequate lifetime?
2. How to evaluate the quality of a constructed corridor?

The resource allocation problem in OFDMA based corridors has been studied under different assumptions, e.g., with global corridor-wide or with local stage-wide CSI knowledge. However, only suboptimal solutions have been presented. Regarding the resource allocation within the corridor, the following questions arise:

3. What is the upper bound for the achievable data throughput of CbR using an exclusive allocation of subcarriers within each stage?
4. Is it possible to derive an optimal solution or an optimal policy for the resource allocation problem and how to derive it?
5. How to deal with the increasing complexity of the problem for an increasing number of variables?
6. How to design a heuristic resource allocation such that it performs close to the optimal policy?

In the literature, the data transmission through the corridor always follows a strict pattern. Data is only exchanged between the transmitter-side group of nodes and the receiver-side group of nodes assuming an exclusive usage of subcarriers. However, additional links exist within a corridor that have been neglected for the purpose of data transmission. Furthermore, the use of fountain codes has been considered in previous work on CbR. However, fountain codes introduce some additional opportunities for the data transmission that need to be investigated. Moreover, advanced transmission schemes based on beamforming in a distributed manner might enable an increase in terms of data throughput. These schemes do not rely on an exclusive usage of subcarriers, but require an even closer cooperation of the nodes. Thus, the following questions arise:

7. How to efficiently exploit links that go beyond the stage boundaries?
8. How do distributed multi-antenna transmissions relate to an exclusive usage of subcarriers in terms of channel capacity?
9. How to enable and efficiently include beamforming in CbR using only single antenna nodes?

1.4 Contributions and Thesis Overview

In this section, an overview of the thesis is given along with the main contributions addressing the previously described open issues.

In Chapter 2, the system model is given and the main assumptions that are valid throughout the thesis are presented. Furthermore, the considered wireless multi-hop scenario is introduced and a description of the considered problem is provided. In addition, the channel model and a node movement model are introduced. Finally, the main performance measure that is used in this thesis is explained.

In Chapter 3, the corridor construction and maintenance are considered. The stability of the resulting corridor structures and the potentially achievable data throughput based on these structures are analyzed and compared to shortest unipath routing. Furthermore, the theoretical limits achievable by an exclusive subcarrier allocation in each corridor stage are investigated. Thereby, Chapter 3 addresses the open issues 1 to 3 by the following contributions:

1. A corridor construction and maintenance protocol is proposed that takes the current link state and the estimated link lifetime into account.
2. The performance of the protocol is evaluated in terms of the achievable throughput and the stability and is compared to traditional unipath routing.
3. An upper bound for the achievable data throughput through the corridor using an exclusive subcarrier allocation is provided.

Chapter 4 deals with the resource allocation problem in CbR under the use of traditional channel coding and under the condition of an exclusive usage of subcarriers. Herein, the open issues 4 to 6 are answered by the following contributions:

4. A Markov-Decision-Process is used to model the resource allocation problem and to find an optimal allocation policy that maximizes the expected data throughput.
5. A state approximation technique is proposed to handle large state spaces.
6. A low-complexity resource allocation strategy that is based on a comparative channel state metric is proposed and its performance is compared to optimal resource allocation policy.

In Chapter 5, CbR is considered under the use of fountain codes. Furthermore, an extended system model is introduced that takes into account links between nodes that belong to the same set of forwarders within a certain stage and links that go beyond the stage limits which means that they skip one set of forwarders. Modified forwarding strategies are presented that are aiming at exploiting these links. Thus, the open issues 7 to 9 are addressed by the following contributions:

7. A novel forwarding concept is proposed that combines opportunistic routing, fountain coding and OFDMA and makes use of overhearing over links that skip a set of forwarders in the corridor structure. For the operation of this concept, suitable algorithms for scheduling of data packets and resource allocation are presented.
8. Analytical expressions of the achievable channel capacity are presented for the application of an optimal exclusive subcarrier allocation and for the application of distributed multi-antenna transmissions.
9. A transmission strategy that integrates distributed multi-antenna transmissions in CbR is proposed. For the assignment of data packets to subcarriers, an algorithm is presented that minimizes the required number of time slots based on the Hungarian Method.

Finally, a summary of this thesis and a brief outlook are presented in Chapter 6.

Chapter 2

System Model

2.1 Introduction

In this chapter, the general system model is introduced and the main assumptions that are valid throughout this work are presented. In this thesis, communication in wireless multi-hop networks is investigated. To this end, corridors are considered as a potential support structure for data transmissions over multiple hops. The basic structure of a corridor and the main idea of CbR is explained in the following. Furthermore, the challenges of the use of CbR are identified and the pursued goals are defined.

The chapter is organized as follows. In Section 2.2, the considered scenario is presented and the problem description is given. The assumed channel model is introduced in Section 2.3. In Section 2.4, a movement model for the network nodes is presented and the considered performance measure is introduced in Section 2.5.

2.2 Considered Scenario and Problem Description

In this section, the considered wireless communication scenario is introduced along with basic assumptions that are valid throughout this work. Furthermore, general descriptions of the problems that are investigated in this work are given.

In this work, wireless networks are considered in which data needs to be transmitted from one source node to one destination node. Due to the limited transmission range of the nodes, it is assumed that the source node is not able to directly communicate with the destination node. In order to establish a connection between them, other nodes are required to act as relays.

All nodes within the network are assumed to be equipped with a single antenna. The nodes are assumed to be half-duplex, i.e., they cannot transmit and receive simultaneously, but only in separate time slots. For the communication between source and destination, the construction, the maintenance and the utilization of a multi-path support structure are investigated. This support structure follows a certain topology as shown in Figure 2.1 and is referred to as the corridor. The source and the destination are connected via multiple intermediate clusters of nodes. The corridor is organized in stages, each consisting of a transmitter and a receiver side. The stages overlap, i.e., the cluster that contains the receivers of stage s is the same cluster that builds the transmitter side of stage $s+1$. The overall number of stages is denoted by N_{stages} and the maximum number of nodes per cluster is denoted by $N_{\text{cn,max}}$. Depending on the availability of suitable nodes, the actual number N_{cn} of nodes in a cluster can be less.

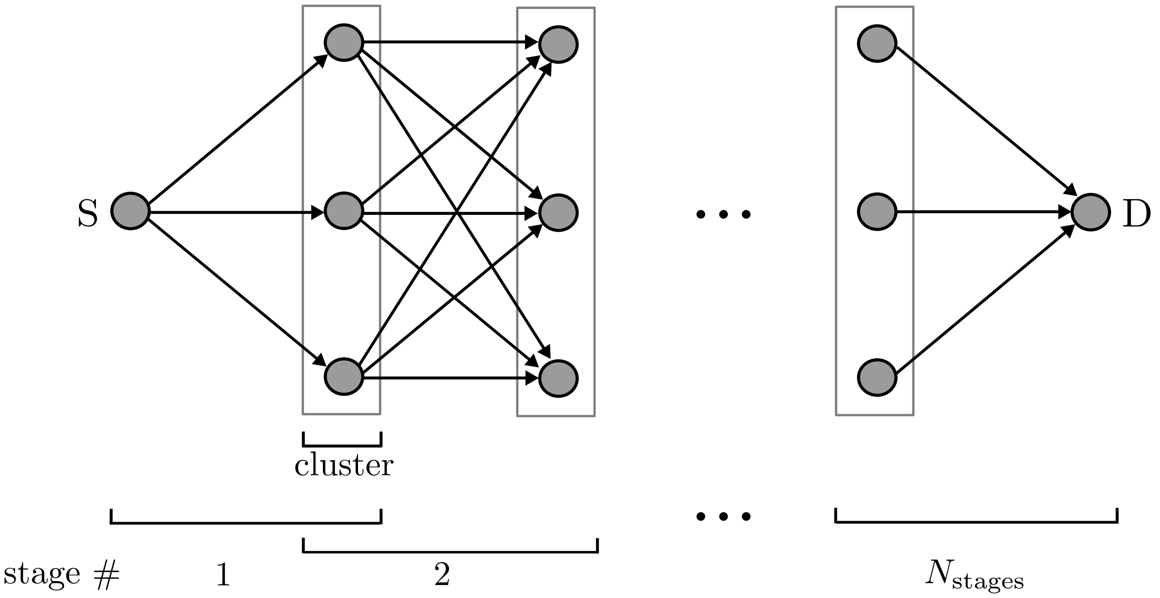

Figure 2.1. Example for a corridor between source (S) and destination (D) with $N_{\text{cn,max}} = 3$ nodes per cluster.

Data is forwarded using the decode-and-forward protocol, i.e., nodes always decode and re-encode received data before they forward it and thus, noise is not forwarded to the next node. The forwarding of the data is always done stage-by-stage, i.e., the transmitters of a stage start to forward after the transmission of the data from the previous stage is completed.

The main focus of this work is on the achievable data throughput, i.e., the amount of data that can flow from the source to the destination per time unit using a fixed and limited frequency bandwidth. In this work, OFDMA is used as a multiple access scheme. The underlying transmission scheme is called Orthogonal Frequency Division Multiplexing (OFDM) in which the available bandwidth B is subdivided into N_{sc} orthogonal subcarriers with a subcarrier spacing of $\Delta f = \frac{B}{N_{\mathrm{sc}}}$. By assigning subsets of the subcarriers to different transmitters, multiple access is enabled. The task of allocating the available channel resources among the nodes is the main subject in this work since it is crucial for the achievable data throughput. To this end, channel states are locally measured and the obtained information is shared between the transmitters of a cluster. The resource allocation problem is discussed based on this channel knowledge.

However, before data can be transmitted through the corridor, the corridor must first be constructed. This means that adequate nodes need to be selected that form the desired topology. Furthermore, the stability of the wireless links between the corridor nodes is crucial for the data transmission in dynamic networks. Therefore, the corridor construction and maintenance is also investigated in this work focusing on the lifetime of the links within the corridor structure in order to provide a stable support structure for the data transmission.

2.3 Channel Model

In this section, the applied channel model is introduced. Throughout this work, transmissions are considered in the equivalent baseband [Pro07].

The relation between the average received signal power and the distance between a transmitter i and a receiver j is determined by the path loss. In this thesis, the widely used log-distance model [Rap02] is considered in which the path loss of a channel is expressed by

$$L_{\mathrm{path},i,j} = \left(\frac{d_{i,j}}{d_0}\right)^{-\alpha}, \tag{2.1}$$

where $d_{i,j}$ denotes the distance between transmitter i and receiver j, d_0 denotes a minimum reference distance and α denotes the path loss exponent. The path loss exponent depends on the environment. In the case of Line-Of-Sight (LOS) conditions and no reflections of the signal between transmitter and receiver, the path loss exponent is equal to 2. This corresponds to the free space propagation loss. In this case, the path loss increases with the distance just as the surface of a sphere increases with the radius. In this work, Non-Line-Of Sight (NLOS) conditions are assumed for which α takes larger values and thus, the path loss increases.

The average link Signal-to-Noise Ratio (SNR) per subcarrier between transmitter i and receiver j is given by

$$\bar{\gamma}_{i,j} = \frac{L_{\mathrm{path},i,j} \cdot p_{\mathrm{sc}}}{\sigma_{\mathrm{n}}^2}, \tag{2.2}$$

where p_{sc} denotes the transmit power per subcarrier and σ_{n}^2 denotes the power of the Additive White Gaussian Noise (AWGN) per subcarrier at the receiver. For simplicity of the notation but without loss of generality, the noise power is considered to be equal at all nodes.

For NLOS conditions, the received signal consists of the superposition of different versions of the transmitted signal that reach the receiver through different paths with a different phase. Reflection, diffraction and scattering of the transmit signal lead to this multi-path propagation. The received signal power strongly depends on the phase shifts between the different versions of the signal. In case that they are mostly in-phase, they interfere constructively and increase the received signal power. In other cases, destructive interference takes place which reduces the signal strength. The multi-path channel is frequency-selective, i.e., the received signal strength strongly varies over frequency. The coherence bandwidth B_{c} is the range of frequencies over which the channel fading is considered to be approximately flat [Pro07]. It is given by the inverse of the largest delay difference between the received multi-path signals. Due to node movements, channels also change over time. The coherence time T_{c} is the time duration over which a channel can be considered as constant [Pro07].

In order to enable an efficient allocation of subcarriers in each time slot, it is assumed that the bandwidth of a subcarrier is smaller than the coherence bandwidth B_{c}, i.e. fading is flat for each subcarrier and is modeled by a complex channel transfer factor. Furthermore, it is assumed that the coherence time is larger than the time slot duration T_{s}, i.e., the channels are constant over the time slot. If the number of uncorrelated paths is large and if there is no dominant path present, the magnitude of the received signal follows a Rayleigh distribution [Mol11]. The corresponding channel transfer factor of the channel between transmitter i and receiver j on subcarrier n is given by

$$h_{i,j,n} = \sqrt{L_{\mathrm{path},i,j}} \cdot h'_{i,j,n}, \tag{2.3}$$

where $h'_{i,j,n}$ is a complex Gaussian distributed random variable with zero mean and variance one. Based on $h_{i,j,n}$, the SNR between transmitter i and receiver j on subcarrier

n is given by

$$\gamma_{i,j,n} = \frac{p_{i,n} \cdot |h_{i,j,n}|^2}{\sigma_{\mathrm{n}}^2}, \tag{2.4}$$

where $p_{i,n}$ denotes the transmit power of node i on subcarrier n.

The subcarriers are considered to be perfectly orthogonal to each other and it is assumed that there is no Inter-carrier interference (ICI) introduced by the channel.

2.4 Movement Model

In this section, a movement model is described. This model is used in order to investigate CbR under the dynamic behavior of mobile wireless networks.

In this work, static networks, as well as dynamic networks, are considered. The mobility of nodes needs to be managed in wireless multi-hop networks. In order to investigate dynamically changing wireless networks, a model for the location, the direction of movement, the velocity and how these parameters change over time is required. The Random Waypoint model, first introduced in [JM96], is a commonly used model to design the movement patterns of nodes and to evaluate the performance of wireless mobile networks.

According to the Random Waypoint model, each node is randomly placed on a predefined map of a fixed size. Next, a random waypoint on the map is selected for each node i, i.e., its destination on the map, to which the node moves with a randomly selected velocity v_i that is between 0 and a maximum velocity $v_{\max}$. This means that each node position, its direction of movement and its velocity are selected randomly and independently from the other nodes. After a node reaches its destination, it pauses for a time duration of t_{pause} before it starts to move to a new randomly selected waypoint on the map with a new randomly selected velocity. This scheme guarantees that the nodes only move on the predefined map.

2.5 Performance Measure

In this section, the performance measure for the evaluation of the presented forwarding schemes is introduced.

In order to measure the performance of the proposed transmission schemes, the achievable data throughput is considered, i.e., the amount of data that can be transmitted per second (s) and per Hertz (Hz). A fundamental upper bound for the amount of information that can be reliably transmitted over a communication channel is given by its capacity according to the Shannon-Hartley-theorem [Sha48]. The capacity of the channel between transmitter i and receiver j on subcarrier n is given by

$$C_{i,j,n} = \log_2(1 + \gamma_{i,j,n}) \quad [\text{bits/s/Hz}], \tag{2.5}$$

Throughout this work, unless otherwise stated, the use of optimal channel coding that achieves channel capacity at any rate is assumed. In addition, unless otherwise stated, it is assumed that data is splittable in any desired shares. In this case, the achievable data throughput of a link is given by its channel capacity. These assumptions allow an investigation of the information-theoretic limits of transmission schemes.

Furthermore, data transmission is considered on packet-level since data is usually organized in fixed shares. For consideration on packet-level, data packets are assumed to be the smallest data unit that can be transmitted, i.e, data packets are not splittable. This assumption brings certain challenges, but also reductions concerning the possibilities of forwarding data and the complexity of the transmission model. It follows that nodes can only transmit at certain data rates that correspond to an integer number of data packets and this data rate has to be smaller than or equal to the channel capacity. In this case, the achievable throughput is determined by the amount of transmitted data divided by the required time and the bandwidth used to perform this transmission.

In general, the stage throughput in a certain stage s is determined by

$$R^s_{\text{stage}} = \frac{D}{T^s_{\text{total}}}, \tag{2.6}$$

with D denoting the amount of data that is transmitted and T^s_{total} denoting the total time required in stage s to transmit this data.

The end-to-end network throughput is the rate at which data flows from the source to the destination and is given by

$$R_{\text{S}\to\text{D}} = \frac{D}{T_{\text{total}}}, \tag{2.7}$$

where T_{total} denotes the total transmission time that is required from the source to the destination and it is given by

$$T_{\text{total}} = \sum_{s=1}^{N_{\text{stages}}} T^s_{\text{total}}. \tag{2.8}$$

Since the total amount D of data that needs to be transmitted from source to destination is fixed, it is also adequate to consider the required time or the number of required time slots in order to compare the performance of different forwarding strategies.

Chapter 3

Corridor Construction and Maintenance

3.1 Link Stability in Wireless Multi-Hop Routing

In the operation of a routing scheme, three different tasks need to be handled. First, a path between source and destination needs to be established. Secondly, data packets have to be transmitted along this path. Finally, the path needs to be managed and maintained or in some cases reconstructed. Chapters 4 and 5 deal with strategies for data transmission through a given corridor. In this chapter, the first task, constructing the corridor as a multi-path routing support structure, and the last task, managing and maintaining this structure, are considered.

In case that a source node is not able to directly communicate with a certain destination node within the network, a multi-hop path of intermediate forwarding nodes is required to enable the end-to-end communication. There are many existing traditional routing schemes, such as Ad-hoc On-Demand Vector (AODV) Routing [PR99] or Dynamic Source Routing (DSR) [JM96] which are aiming at minimizing the required number of hops of the resulting path, i.e, minimizing the required number of intermediate forwarding nodes between the source and the destination. These strategies originate from wired networks and they have been very successful in this field. However, in wireless networks, the resulting path often consists of long-distance-links with low SNR conditions. Therefore, these links often provide low channel capacity and are prone to link failures which results in high demand for route maintenance or reconstruction overhead. As shown in [LSL+02], shortest path routing leads to short link lifetime (LLT) especially in networks with a high node density. With an increasing number of nodes in the network, the average number of required hops decreases. Thereby, the average distance between the nodes that are part of the routing path increases and the nodes are more likely located at the edge of each others' transmission range as illustrated in Figure 3.1. In the upper figure, a network with a low node density is given, while in the lower figure, a higher number of nodes is given. For shortest path routing, a higher density of nodes decreases the average required number of hops, but increases the probability that involved nodes are located at the edge of each others' transmission range. In the upper figure, three hops are required since there is no suitable forwarding node in the intersection area of the transmission ranges of source

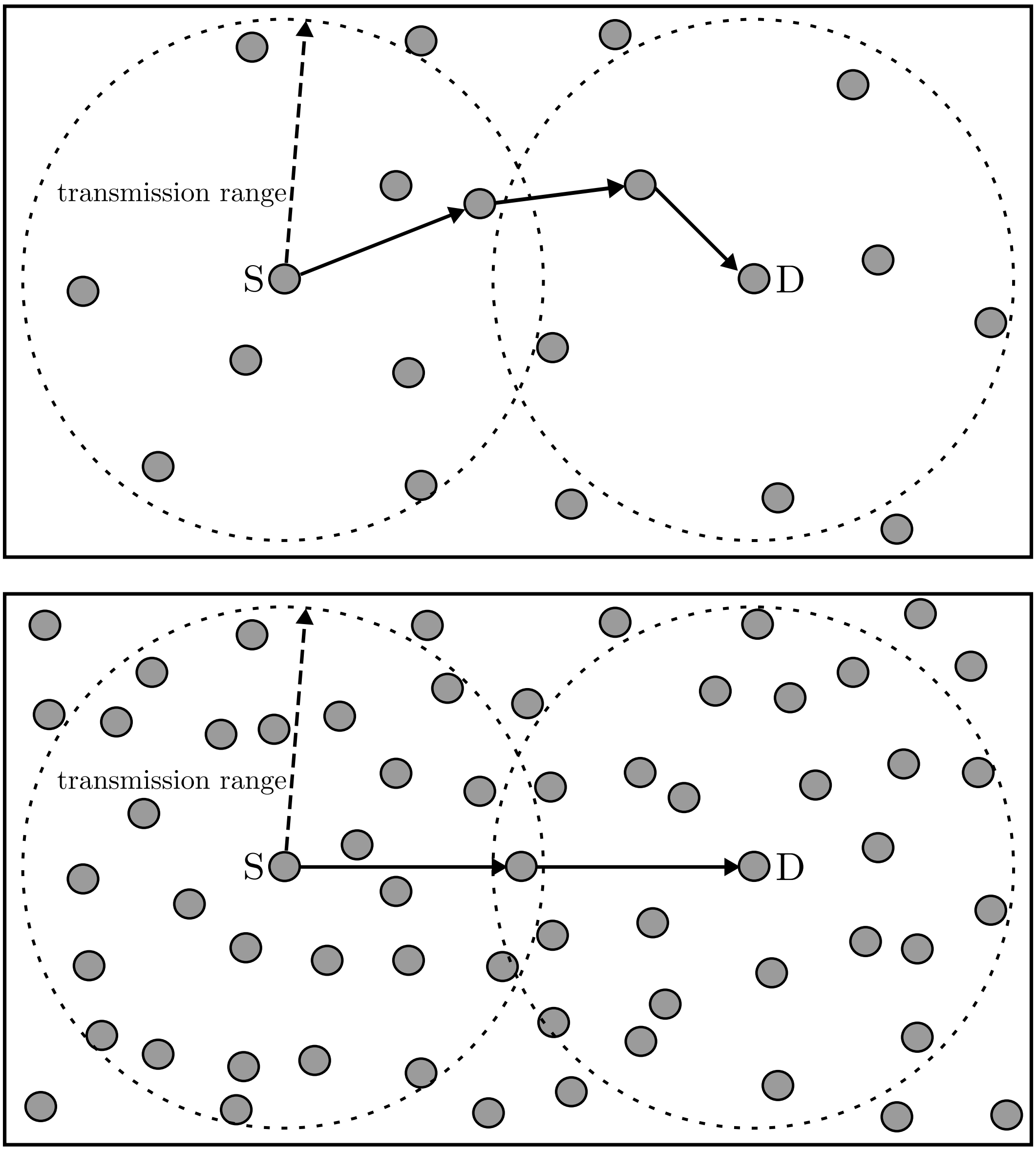

Figure 3.1. Shortest path routing in wireless networks with low node density (upper figure) and with high node density (lower figure), respectively.

and destination. In the lower figure, only two hops are required which becomes more likely due to the increased node density. This means that already small movements of the nodes can lead to link failures and therefore, the lifetime of the multi-hop path is rather short.

In order to provide routes with higher stability, the LLT between nodes can be estimated and taken into consideration in the routing procedure. The lifetime of a link between two nodes mainly depends on the relative movement of the nodes to each other. Of course, there are also other possible reasons for a link to break, for instance, in case that one device is switched off or in case that objects in the environment are moving and affecting the channel. However, forecasting these events is mostly impossible and therefore, they do not provide input for an estimation of the LLT. In the following, LLT estimation based on the movement of the nodes is discussed and a corridor construction and maintenance scheme is proposed which takes the estimated lifetime of links into account to provide a stable support structure for multi-hop data transmissions.

The rest of the chapter is organized as follows. In Section 3.2, the LLT estimation scheme is introduced. In Section 3.3, the corridor construction method is proposed that consists of a unipath construction strategy and a strategy to extend the unipath to a corridor. The maintenance of the corridor structure is discussed in Section 3.4 and Section 3.5, the performance of the proposed approaches is evaluated by means of numerical results. The proposed methods are an extension of the work in [LQH+14] and [Nav15]. Several parts of the content of this chapter have been originally published by the author of this thesis in [HKK+15].

3.2 Link Lifetime Estimation

In this section, an LLT estimation method is introduced that is required for the corridor construction that is discussed in the next section. A major problem of wireless routing schemes arises from the use of an oversimplified channel model. Many traditional routing schemes are based on the so-called unit disk graph model [SNK05]. In this model, each node has a disk centered around itself which covers its transmission range. Any node which is located inside this disk is considered to be directly connected to this node and any node which is located outside is considered to be out of range. Within the disk, there is no distinction based on the channel quality. Neither the location nor the direction of movement of the nodes is taken into account. This simplification results in a very simple binary channel model in which the connection either exists or not, but there is no metric used to further evaluate the channel.

In this work, it is assumed that the average channel quality depends on the distance between the nodes. In the following, the channel quality plays a key role in the node selection process for the corridor. The prerequisite for this is that the channel quality is measured and known by the involved nodes. In a wireless multi-hop network, nodes typically broadcast hello messages regularly to discover their neighboring nodes. Such a hello message usually contains an identifier of the emitting node as well as a list of its direct neighbors. In order to keep the required control overhead for an evaluation of the link states in a local neighborhood low, the exchanged hello messages can be used [LMZ13]. In this work, it is assumed that the received hello messages are used to measure the SNR of the channel between broadcasting and receiving node. Furthermore, the measured SNR values concerning direct neighbors can be appended to the next hello message such that all nodes can track the channel conditions and their changes within the direct and 2-hop neighborhood with only marginal additional overhead. Furthermore, based on this information, the nodes can predict upcoming channel conditions which can be used in the construction process to achieve a high link stability within the corridor.

Based on this tracking of the channel conditions, the lifetime of a link can be estimated. In [LSL+02], an advanced signal strength-based link stability estimation model is proposed in which links are considered to be stable not only in the case that the signal strength exceeds a certain threshold, but also in the case that weak links tend to become stronger. The difference between two consecutive measured SNR values can indicate the tendency of the link quality. In this work, a similar approach is used. In case that the measured average link SNR $\bar{\gamma}_{i,j}^{(t_1)}$ between node i and node j at time instant t_1 is smaller than the previously measured average link SNR $\bar{\gamma}_{i,j}^{(t_0)}$ at time instant t_0, the time until the SNR will fall below a certain SNR threshold $\gamma_{\min}$ can be estimated. It is assumed that for an average SNR of $\gamma_{\min}$, the nodes reliably receive each others' hello messages and the corresponding nodes are considered as direct neighbors. According to (2.1) and (2.2), the average link SNR can be expressed as a function of the distance $d_{i,j}$ between transmitter i and receiver j according to

$$\bar{\gamma}_{i,j} = \frac{\left(\frac{d_{i,j}}{d_0}\right)^{-\alpha} \cdot p_{\mathrm{sc}}}{\sigma_{\mathrm{n}}^2}. \tag{3.1}$$

By rearranging (3.1), the distance between the nodes is given by

$$d_{i,j} = d_0 \cdot \left(\frac{p_{\mathrm{sc}}}{\bar{\gamma}_{i,j} \cdot \sigma_{\mathrm{n}}^2}\right)^{\frac{1}{\alpha}}. \tag{3.2}$$

By inserting the minimum SNR $\gamma_{\min}$ in (3.2), the distance d_{range} at which the SNR equals the minimum SNR is given by

$$d_{\mathrm{range}} = d_0 \cdot \left(\frac{p_{\mathrm{sc}}}{\gamma_{\min} \cdot \sigma_{\mathrm{n}}^2}\right)^{\frac{1}{\alpha}}. \tag{3.3}$$

By inserting the SNR $\bar{\gamma}_{i,j}^{(t_1)}$ measured at time instant t_1 in (3.2), the estimated distance $\hat{d}_{i,j}^{(t_1)}$ at this time instant can be determined by

$$\hat{d}_{i,j}^{(t_1)} = d_0 \cdot \left(\frac{p_{\mathrm{sc}}}{\bar{\gamma}_{i,j}^{(t)} \cdot \sigma_{\mathrm{n}}^2} \right)^{\frac{1}{\alpha}} . \tag{3.4}$$

The estimated LLT is the expected time until the distance between the nodes exceeds the transmission range d_{range}. Assuming a constant movement behavior of the nodes, the estimated LLT is given by

$$\hat{t}_{\mathrm{LLT},i,j} = \frac{d_{\mathrm{range}} - \hat{d}_{i,j}^{(t_1)}}{\hat{d}_{i,j}^{(t_0)} - \hat{d}_{i,j}^{(t_1)}} \cdot t_{\mathrm{hello}}, \tag{3.5}$$

where t_{hello} denotes the time duration between two hello messages. In case that the distance between the nodes decreases, (3.5) returns a negative value which indicates that the nodes are moving closer together. In this case, the LLT cannot be estimated by this method, since the exact position and the direction of each node are unknown.

As mentioned before, the estimation of the LLT assumes a constant movement behavior of the nodes. Of course, in reality, this assumption does not hold. However, since the future behavior of the nodes cannot be foreseen, assuming a continuation of the observed movement is a reasonable method to predict the LLT.

3.3 Construction Strategies

3.3.1 Unipath Construction

In the following, a unipath construction scheme is introduced. A unipath that connects the source and destination is the foundation of a corridor. The nodes that are involved in the path act as master nodes that build up the clusters used in the corridor. In general, every unipath discovery scheme could serve for the construction of the corridor. In the literature, there already exist many path discovery schemes with regard to different metrics that are optimized. Furthermore, many approaches have been proposed to reduce the required overhead and to avoid complete flooding of the network with route request messages.

For instance, in [JMC+01], so-called multi-point relays for the distribution of control messages are appointed. Each node selects only a partial set of nodes from their neighborhood, the multi-point relays, such that this set covers the complete 2-hop neighborhood of the origin node. Only these multi-point relays will forward control messages that they receive from the origin node.

The path discovery process is not considered in detail in this work, but the proposed method builds on top of these approaches. For the corridor, the aim is to find a path with a minimum number of hops, but under consideration of two stability conditions. In order to build a stable path, only links with an estimated LLT above a threshold are considered:

$$\textbf{Condition 1}: \quad \hat{t}_{\mathrm{LLT},i,j} \geq t_{\mathrm{LLT,min}} \quad \text{or} \quad \hat{t}_{\mathrm{LLT},i,j} < 0,$$

with $t_{\mathrm{LLT,min}}$ denoting the minimum required LLT. As mentioned before, links with an increasing SNR over time will lead to negative values using (3.5). In this case, Condition 1 is also fulfilled. However, it can happen that nodes are moving at the edge of each others' transmission range and the SNR is getting slightly better over time. Nevertheless, the nodes can quickly leave each others' transmission range depending on their particular direction. Therefore, Condition 1 is not sufficient to achieve high link stability. Links also have to exceed a minimum SNR threshold to become part of the corridor:

$$\textbf{Condition 2}: \quad \bar{\gamma}_{i,j} \geq \gamma_{\mathrm{min,cor}}.$$

Condition 2 guarantees that a node is not placed too close to the edge of another nodes' transmission range while Condition 1 avoids node pairs that move away from each other too fast.

3.3.2 Extending the Unipath to a Corridor

In this section, a node selection scheme is introduced to extend the unipath to a corridor. In order to construct the corridor in a distributed manner, each node of the unipath is appointed as a so-called master node. Except for the source and the destination, each master node autonomously selects suitable nodes for its cluster using the local information about its neighborhood.

The maximum number of nodes per cluster is denoted by $N_{\mathrm{cn,max}}$. Increasing the number of cluster nodes leads to a higher link diversity between the clusters and therefore, potentially enables a higher data throughput. However, an increased number of cluster nodes also leads to higher required signaling overhead. Therefore, a good compromise between diversity and signaling overhead must be found. Furthermore, the node density of the network is crucial for each individual cluster size. In case that there are not enough suitable candidate nodes available, the cluster size will be smaller than $N_{\mathrm{cn,max}}$.

Cluster nodes need to meet certain conditions. The selection process is performed using Algorithm 1. Cluster nodes need to fulfill Conditions 1 and 2 with respect to each other as well as with respect to the adjacent master nodes of the corridor. The nodes within a cluster need to be fully connected in order to exchange channel information and to enable and to coordinate the resource allocation for data transmission, i.e., to guarantee an exclusive allocation of channel resources and to avoid unnecessary multiple transmissions of data. In addition, a reliable connection to adjacent master nodes is required since the master nodes broadcast information about the members of their clusters which needs to be known by all adjacent cluster nodes.

Out of the set of remaining candidates, a master node selects the node that provides the highest minimum link SNR concerning both adjacent master nodes. Thereby, nodes which are located centrally between the adjacent clusters are preferred. In case that a node is located close to the previous cluster, but far away from the next cluster, it might receive much data due to the strong channel conditions as a receiver. However, the channel conditions as a transmitter would tend to be weak. Therefore, data congestion might occur and the achievable throughput could be strongly reduced. The other way around, in case that the node is located close to the next cluster but far away from the previous one, it would probably receive only a low amount of data such that the strong channel conditions as a transmitter would not pay off.

After $N_{\mathrm{cn,max}}$ nodes have been found for the cluster or in case that no suitable candidates are left in the neighborhood, a new master node for the cluster is determined. Since the master nodes are the backbone of the corridor, the most reliable and stable connections are preferred for that task. Therefore, the new master node for a cluster is selected based on the highest minimum LLT with respect to the adjacent master nodes.

Algorithm 1 Selection of additional forwarding nodes for a cluster

```
Require: Average SNR + estimated LLT concerning 1- and 2-hop neighbors of the master node
    Store master node in set $\mathcal{S}_{\text{cor}}$, store all of its neighbors in set $\mathcal{S}_{\text{candidates}}$ of candidates
    while $|\mathcal{S}_{\text{cor}}| < N_{\text{cn,max}}$ and $\mathcal{S}_{\text{candidates}} \neq \{\}$ do
        1) Cancel all nodes from set $\mathcal{S}_{\text{candidates}}$ which do not fulfill Conditions 1 and 2 concerning their links to all nodes within set $\mathcal{S}_{\text{cor}}$ as well as to the previous and the next master node.
        2) Out of set $\mathcal{S}_{\text{candidates}}$, determine the node with highest minimum SNR concerning adjacent master nodes, add it to set $\mathcal{S}_{\text{cor}}$ and cancel it from set $\mathcal{S}_{\text{candidates}}$
    end while
    Out of set $\mathcal{S}_{\text{cor}}$, determine the node with highest minimum LLT concerning adjacent master nodes and appoint this node as new master of the cluster
```

3.4 Structure Maintenance

In this section, a corridor maintenance strategy is introduced that is used to adapt the corridor structure to node movements. Using unipath routing, a new path has to be found every time one ore more links within the path break and are no longer available. This reconstruction procedure requires a large number of resources to be spent for signaling overhead. In the worst case, a completely new path has to be found. Instead of following a reactive approach, i.e, acting only after some link is already broken, a preventive strategy is proposed to maintain the corridor structure and to reduce wasteful overhead.

Node movements change the link qualities within the corridor. This effect is tracked by the nodes based on the regular exchange of hello messages. A significant SNR drop of a link may require an adaptation of the structure to avoid a link breakage before it takes place. A local maintenance strategy at a fixed time interval is proposed that includes a potential update concerning:

1. the number of clusters in the corridor,
2. the master node of each cluster,
3. the remaining cluster nodes.

Due to the movement of source and destination, it might be possible to reduce the number of clusters in the corridor or it might be necessary to increase the number of clusters. Furthermore, a new master node for each cluster is assigned according to the changed network conditions. Finally, the additional cluster nodes might be replaced by other nodes that provide better conditions.

For some steps of the maintenance process, Conditions 1 & 2 are used again. In other steps, Condition 2 is replaced by the following condition:

$$\textbf{Condition 2a} : \bar{\gamma} \geq \gamma^{'}_{\text{min,cor}} \quad \text{with } \gamma^{'}_{\text{min,cor}} < \gamma_{\text{min,cor}},$$

where $\gamma^{'}_{\text{min,cor}}$ is a minimum link SNR requirement that is slightly relaxed compared to Condition 2 and is used for the update of the master node of a given cluster. The relaxation should prevent an excessive increase in the number of clusters between source and destination. Since the initial composition of the unipath aims at minimizing the number of hops under Conditions 1 & 2, the links between master nodes tend to only marginally exceed Condition 2, especially in dense networks. Therefore, small movements could lead to the need for additional hops with regard to Condition 2. By replacing Condition 2 by Condition 2a, a small margin is introduced for SNR fluctuations between the master nodes. For which cases, Condition 2a is used instead of Condition 2 is explained in detail in the following.

For the structure maintenance process, each master node executes Algorithm 2 to deal with the number of required clusters in the corridor. Of course, it is always desirable to reduce the number of clusters in the corridor if this is possible. Therefore, at first, the master node checks if there is an appropriate link between its adjacent master nodes such that the intermediate cluster can be removed. To this end, the node checks if Conditions 1 & 2 are fulfilled by the link between the adjacent master nodes. If the cluster cannot be removed, next, the master node determines the best suited node to become the new master for its own cluster out of the set of its neighbors and itself, i.e., it determines the node that provides the highest minimum LLT concerning the adjacent master nodes and that fulfills Conditions 1 & 2a concerning adjacent masters. Here, the slightly relaxed Condition 2a is used in order to avoid a hasty addition of clusters. Since the maintenance is done cluster by cluster, the link conditions concerning a certain cluster can improve after the master node of this cluster has executed the maintenance procedure due to an update of the following cluster. If there is no suitable candidate that fulfills Conditions 1 & 2a, the number of clusters need to be increased. Therefore, the master node tries to find two nodes out of its neighborhood that build a path between the adjacent master nodes. All links of this path have to fulfill Conditions 1 & 2. If there are multiple node pairs that fulfill these

Algorithm 2 Corridor maintenance procedure (update of master nodes)

```
Require: Average SNR + estimated LLT concerning 1- and 2-hop neighbors of the master node
  if SNR between previous and next master node fulfills Conditions 1 and 2 then
    Remove current cluster
  else
    Store all nodes that fulfill Conditions 1 and 2a concerning adjacent master nodes in set $\mathcal{S}$ (candidates)
    if $\mathcal{S} \neq \{\}$ then
      Out of set $\mathcal{S}$, appoint node with highest minimum LLT concerning adjacent master nodes as new master of current cluster
    else
      Out of set $\mathcal{S}$, determine all node pairs that can build a path between previous and next master that fulfills Conditions 1 and 2 concerning all affected links;
      Appoint the pair that provides the highest minimum LLT concerning these links as two new master nodes
    end if
  end if
```

conditions, the node pair with the highest minimum LLT concerning these links is selected as two new master nodes which means that one cluster is replaced by two new clusters.

After Algorithm 2 has been executed by a master node, Algorithm 1 is used to update the cluster nodes. Due to the node movements, cluster nodes might need to be replaced by other nodes that provide better link conditions.

3.5 Performance Analysis

In this section, the performance of the proposed corridor construction and maintenance strategies are investigated by means of numerical results.

In Figure 3.2, one example of the corridor construction process is illustrated on a map of size 400 m x 100 m and a network of 100 nodes. In Figure 3.2 a), a network has been generated, where the positions of the source S (50,50) and the destination D (350,50) are predefined while the remaining 98 nodes are placed randomly. In Figure 3.2 b), a unipath between S and D has been established that fulfills Conditions 1 & 2 as described in Section 3.3.1. Next, the five selected intermediate forwarding nodes act as master nodes and each of them selects additional cluster nodes according to Algorithm 1. Here, the maximum number of cluster nodes is given by $N_{\text{cn,max}} = 3$. In Figure 3.2 c) it can be seen that not all master nodes are identical to the master nodes in Figure 3.2 b). According to the final step of Algorithm 1, a new master is appointed based on the highest LLT concerning the adjacent master nodes in order to provide higher robustness of the structure.

In the following, the system parameters given in Table 3.1 are assumed. All nodes are placed randomly on a map of size 400 m x 400 m with a minimum node distance of 1 m. Source and destination nodes are randomly appointed. In case that source and destination are direct neighbors, i.e, there exist a link between them with a link SNR larger than or equal to γ_{min}, the network is discarded and a new random network is generated. Different network sizes are considered ranging from 100 nodes to 300 nodes. Static networks are considered, as well as dynamic networks. In the dynamic networks, the maximum node velocity is $v_{\text{max}} = 2\,\text{m/s}$. All results are averaged over at least 20.000 independent network realizations.

The number of subcarriers is $N_{\text{sc}} = 64$. The transmit power per subcarrier is given by $p_{\text{sc}} = 1\,\text{mW}$. This means that the overall transmit power including all nodes is limited by $N_{\text{sc}} \cdot p_{\text{sc}} = 64\,\text{mW}$. A node that uses subcarrier n, transmits with power $p_{i,n} = p_{\text{sc}}$ on this subcarrier. The power cannot be shifted to other subcarriers. As a consequence, in each forwarding scheme, whether only a single node uses all subcarriers or the subcarriers are allocated among multiple nodes, the same overall transmit power is used. Even though, allocating power in the optimal manner according to the water-filling principle [CT06] could improve the throughput, the impact of power allocation is only significant for very low SNR regions. Therefore, power allocation is not considered in the following.

The noise power σ_{n}^2 is chosen such that for a distance of 100 m, the average link SNR equals 5 dB. The path loss exponent is $\alpha_{\text{PL}} = 3$. A minimum link SNR of $\gamma_{\text{min}} = 5\,\text{dB}$ is required between nodes to be direct neighbors and to receive each others' hello messages which are transmitted by each node every $t_{\text{Hello}} = 2\,\text{s}$. However, links that are selected for a routing path are not considered to fail instantly in case the link SNR falls below γ_{min}. In reality, the packet error rate would increase at the edge of the transmission range, but a link would not necessarily break immediately. Nodes would probably receive each others' hello messages only partially and the link would

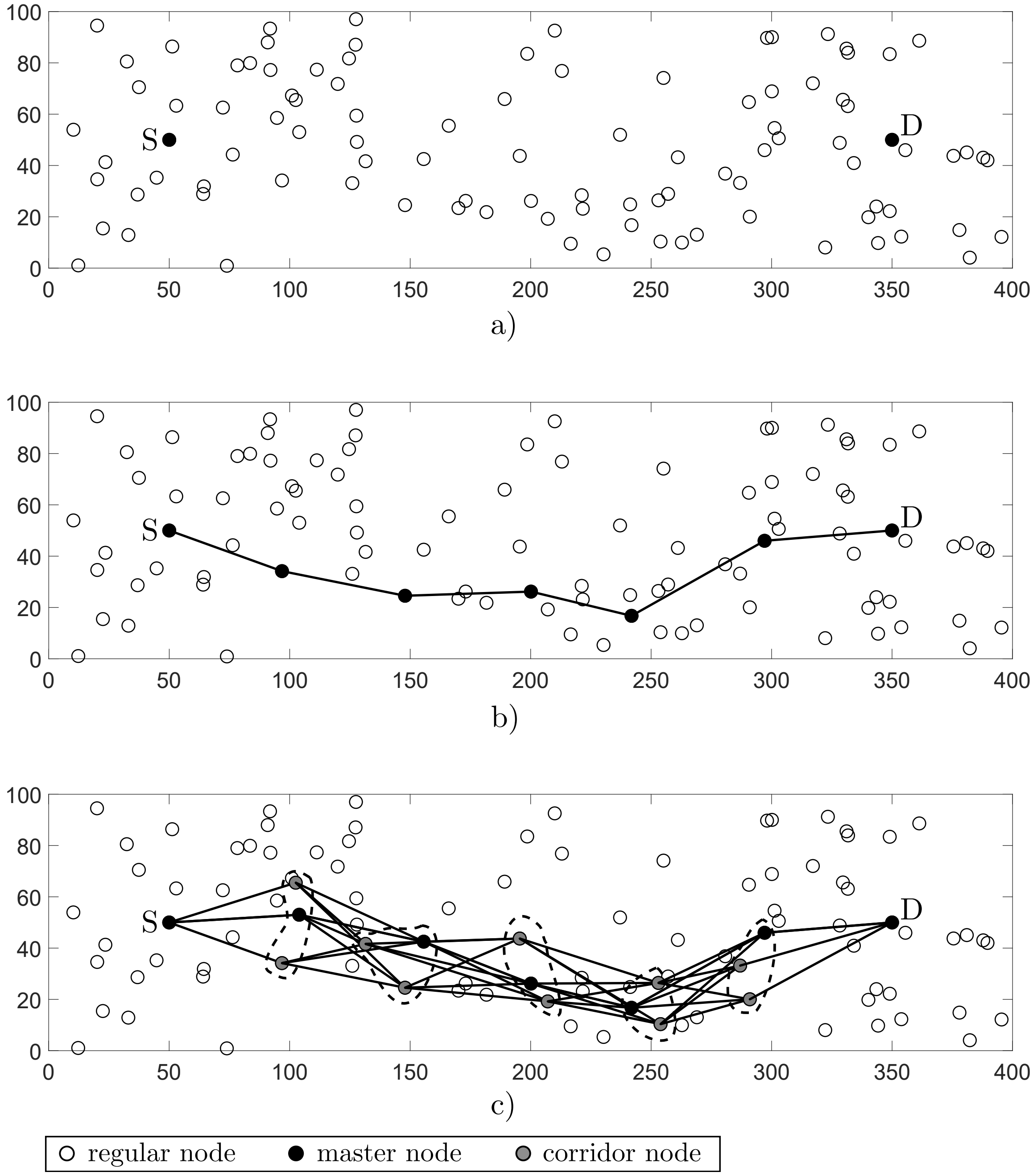

Figure 3.2. Steps of the corridor construction process. a) Random network with one source node S and one destination node D. b) Unipath has been established. Selected nodes serve as master nodes. c) Additional cluster nodes have been selected. Corridor construction is completed

be considered as unreliable and it would not be used to be part of a routing path. The packet error rate of such a link strongly depends on many different parameters like, for instance, the packet length, the modulation scheme, the channel coding, etc.. For simplicity, no particular complex model for transmission failures is considered. It is assumed that a link with an average SNR less than $\gamma_{\text{fail}} = 3$ dB completely fails, i.e., the channel capacity falls to zero. Above this threshold, a link provides the channel capacity according to (2.5).

Table 3.1. System parameters

Map size	400 m x 400 m
Minimum node distance d_0	1 m
Number N_{nodes} of nodes	100 - 300
Maximum node velocity $v_{\max}$	$\{0, 2\}$ m/s
Number N_{sc} of subcarriers	64
Transmit power per subcarrier p_{sc}	1 mW
Path loss exponent α_{PL}	3
Minimum link SNR $\gamma_{\min}$	5 dB
Hello interval t_{Hello}	2 s
Link failure SNR threshold γ_{fail}	3 dB

For the corridor construction and maintenance, the parameters according to Table 3.2 are used. The minimum LLT is set to $t_{\text{LLT,min}} = 30\,\text{s}$ (Condition 1). The minimum link SNRs are given by $\gamma_{\text{min,cor}} = 10\,\text{dB}$ (Condition 2) and $\gamma'_{\text{min,cor}} = 8\,\text{dB}$ (Condition 2a), respectively.

Table 3.2. Corridor parameters

Minimum LLT $t_{\text{LLT,min}}$ (Condition 1)	30 s
Minimum link SNR $\gamma_{\text{min,cor}}$ (Condition 2)	10 dB
Minimum link SNR $\gamma'_{\text{min,cor}}$ (Condition 2a)	8 dB
Maximum number of nodes per cluster $N_{\text{cn,max}}$	{2, 3, 4}

As a benchmark, unipath routing is considered that aims at the minimization of the required number of hops to connect source and destination without any further conditions. In the following, it is referred to as 'Shortest Unipath Routing'. The data throughput in hop h of the unipath is given by

$$R_{\text{uni}}^{h} = \sum_{n=1}^{N_{\text{sc}}} \log_2(1 + \gamma_{i,j,n}). \tag{3.6}$$

The transmission time in each hop is adapted such that the product of the throughput (in bits/s/Hz) and the hop transmission time is equal for all hops of the unipath. This means that the incoming amount of data equals the outgoing amount of data at each node. The resulting end-to-end throughput is given by

$$R_{\mathrm{S}\to\mathrm{D,uni}} = \frac{1}{\sum\limits_{h=1}^{N_{\mathrm{hops}}} \frac{1}{R^{h}_{\mathrm{uni}}}}. \tag{3.7}$$

In order to evaluate the performance of the corridor structure without considering a concrete resource allocation strategy, an upper bound for the data throughput is considered. Exclusive usage of each subcarrier n is assumed, only by the pair of transmitter i and receiver j that provides the highest channel capacity for this subcarrier. The upper bound of the throughput in stage s of the corridor is given by

$$R^{s}_{\mathrm{stage,ub}} = \sum_{n=1}^{N_{\mathrm{sc}}} \max_{i,j} \left(\log_2(1+\gamma_{i,j,n})\right). \tag{3.8}$$

Again, it is assumed that the transmission time T^{s}_{total} in stage s is adapted such that the product $T^{s}_{\mathrm{total}} \cdot R^{s}_{\mathrm{stage,ub}}$ is equal for all stages. The resulting end-to-end upper bound is given by

$$R_{\mathrm{S}\to\mathrm{D,ub}} = \frac{1}{\sum\limits_{s=1}^{N_{\mathrm{stages}}} \frac{1}{R^{s}_{\mathrm{stage,ub}}}}. \tag{3.9}$$

Note that this upper bound is not based on the amount of data that each node of a cluster has received. The amount of data that a node forwards to the next stage does not depend on the amount of data that this node has received. Instead, the total amount of data that the whole cluster receives equals the amount of data this cluster transmits in the next stage. Thereby, the resource allocation problem is simplified and the upper bound can be easily determined and used to show the potential throughput that the corridor structure provides. In the following this upper bound is termed 'CbR Upper Bound'.

In Figure 3.3, the average throughput of CbR Upper Bound and Shortest Unipath Routing is shown for different numbers of nodes in the network. Furthermore, CbR Upper Bound is evaluated for different maximum cluster sizes ($N_{\mathrm{cn,max}} = \{2,3,4\}$). In this case, the maximum node velocity is set to zero, i.e., only static networks are considered. It can be seen that the performance of the Shortest Unipath Routing does not significantly improve for an increasing number of nodes in the network. The reason for this is that the average required number of hops does only slightly decrease with an increased node density. For $N_{\text{nodes}} = 100$ nodes in the network, the node density is already high and there are usually no larger areas that are empty and could require long paths to reach the destination. In case that multiple paths with the same minimum number of hops exist, the resulting unipath is selected randomly since there is no kind of link quality considered in the path discovery process. Only the number of hops is considered and therefore, the quality of the unipath links does not improve with more node options in the network. The same holds for the unipath that builds the basis for the corridor structure. However, between 100 nodes and 200 nodes in the network, the average throughput of CbR Upper Bound increases by 9 % for $N_{\text{cn,max}} = 2$, by 10 % for $N_{\text{cn,max}} = 3$ and by 12 % for $N_{\text{cn,max}} = 4$. Due to the higher node density, more potential candidates for each cluster are available. Since the selection of the cluster nodes is based on the link quality, the average link conditions improve with a higher node density. For more than 200 network nodes, the average throughput does only slightly increase. It can be seen that for an increasing cluster size, the average throughput increases significantly, due to the higher available link diversity in each stage. However, the additional diversity gain decreases with each additional cluster node. While there is a throughput gain of 13 % between $N_{\text{cn,max}} = 2$ and $N_{\text{cn,max}} = 3$ cluster nodes, the throughput gain between $N_{\text{cn,max}} = 3$ and $N_{\text{cn,max}} = 4$ cluster nodes is only 8 % for 200 network nodes. Overall, it can be seen that the corridor can enable significantly higher data throughput, especially for a high node density.

In the following, the average throughput is evaluated over time in dynamic networks with a maximum node velocity of 2 m/s. A snapshot of the network is considered every 0.1 s. There is no maintenance of the Shortest Unipath Route nor the corridor structure taking place. In order to evaluate the performance of the corridor structure, a unipath through the corridor that provides the highest throughput is considered. This is referred to as 'CbR Max-Flow Unipath'. The upper bound is no longer used due to the disregard of a balanced incoming and outgoing amount of data at each individual node. In a mobile network, this condition becomes more crucial since nodes might move closer to an adjacent cluster which results in a significant increase of the channel capacity. However, nodes that move closer to one adjacent cluster most likely move farther away from the other adjacent cluster. In this case, the upper bound would profit from the increased channel capacity in one stage, while the decreased channel capacity in the other stage may not lead to a decreased capacity depending on the positioning of the remaining cluster nodes. Therefore, CbR Max-Flow Unipath is used to evaluate the performance of the corridor structure over time. Even though

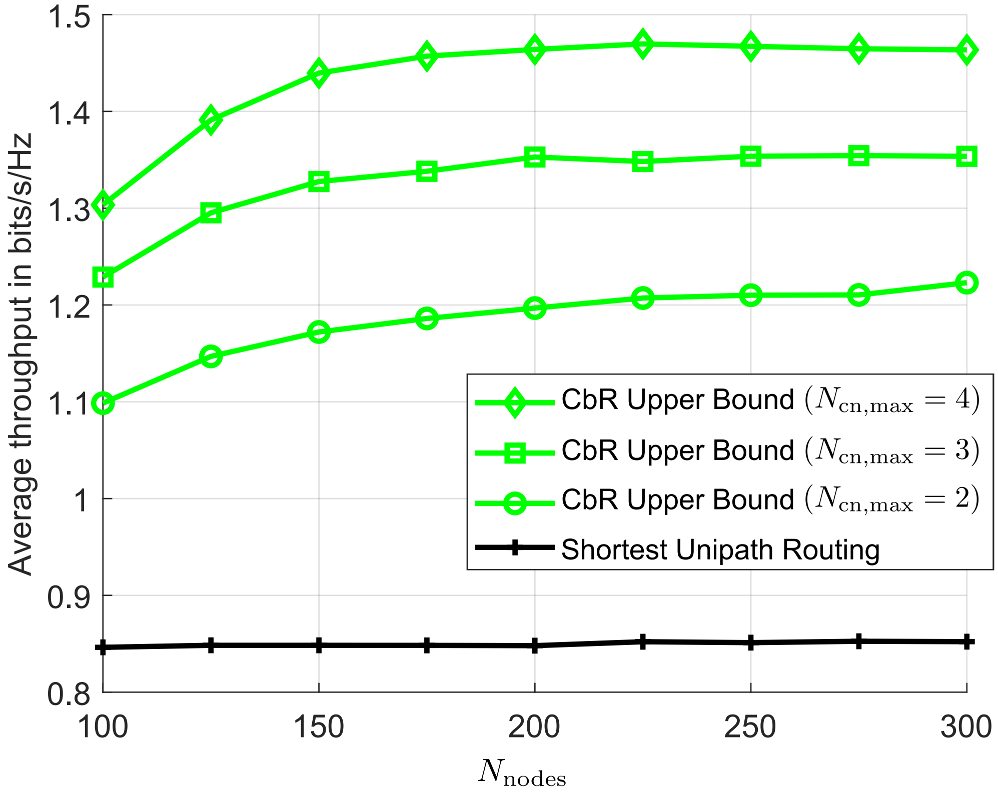

Figure 3.3. Average throughput for different numbers of nodes in the network.

it does not fully exploit the diversity of links for each subcarrier, it can show the benefits of the corridor in terms of link diversity and stability in an adequate manner. The unipath that provides the maximum possible throughput can be found using a Viterbi-based algorithm which is shown in Appendix A.1.

In Figure 3.4, the average throughput is shown over time for a time span of 60 s in a network with 200 nodes. Considering the performance of CbR Max-Flow Unipath, it can be seen that the maximum performance at the beginning does only slightly increase with an increasing number $N_{\text{cn,max}}$ of nodes per cluster. In the cluster node selection process, the nodes that provide the best channel conditions are selected first. Therefore, an increased number of cluster nodes only contributes to the performance of the CbR Max-Flow Unipath in very rare cases. Note that this holds true for the performance of the CbR Max-Flow Unipath within the corridor structure but not for the performance of CbR in general. Furthermore, it can be seen that the Shortest Unipath Routing roughly maintains its maximum performance only for the first 5 to 10 s. After this time, a significant drop in the average throughput sets in. The average throughput of Shortest Unipath Routing is reduced by 39 % after 30 s and by 68 % after 60 s. In contrast to Shortest Unipath Routing, the average throughput of CbR Max-Flow Unipath slightly decreases over time. With an increasing number $N_{\text{cn,max}}$ of nodes per cluster, the performance becomes more stable due to the higher number of path options. With $N_{\text{cn,max}} = 2$ cluster nodes, the average throughput reduces by 9 % and 35 % after 30 s and 60 s, respectively. With $N_{\text{cn,max}} = 4$ cluster nodes, the performance drops only by 4 % and 16 % after 30 s and 60 s, respectively. Compared to Shortest Unipath Routing, CbR Max-Flow Unipath with $N_{\text{t,max}} = 4$ cluster nodes achieves a throughput gain of 5 % at the beginning and of 179 % after 60 s.

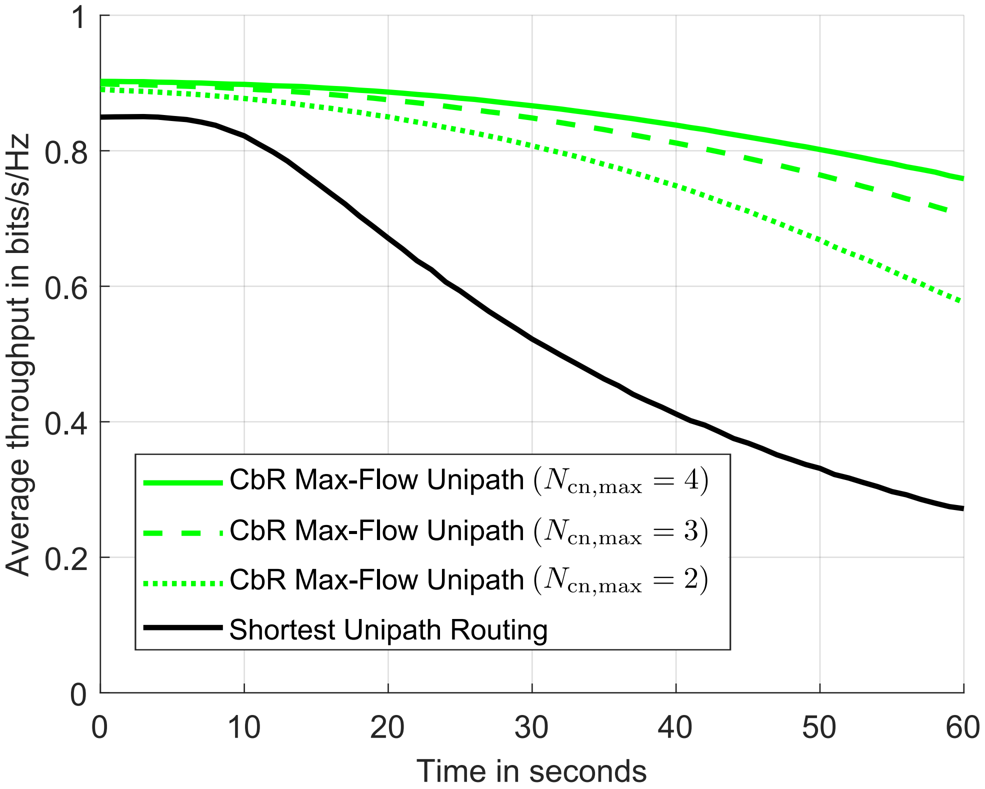

Figure 3.4. Average throughput over time with 200 nodes in the network.

Figure 3.5 shows the probability for a link failure over time for Shortest Unipath Routing and for the CbR Max-Flow Unipath. Furthermore, the probability for any link in the complete corridor structure is considered. It can be seen that the probability for a link to fail in the Shortest Unipath Routing approach increases approximately in a linear manner. After 10 s, the probability of a link to fail is 1 %. After 30 s and 60 s it equals 16 % and 33 %, respectively. In contrast, the probability of any link within the corridor to fail initially increases only slightly. For instance, after 30 s, the probability of a link to fail equals only 3 %. Only after more than 30 s, the failure rate significantly increases. After 60 s, it equals 22 %. Note, that this does not mean that there is no end-to-end path through the corridor available to reach the destination. This is considered by the failure rate of the CbR Max-Flow Unipath. It can be seen that the probability of a link failure using the CbR Max-Flow Unipath is very low for the considered time range. Even after 60 s, the link failure rate equals only about 2 %. It can be seen that only in very few cases, there is no path to be found through the corridor without any link failure. This means that without maintenance, the diversity of valid links within the corridor decreases, but a data transmission would still be possible based on the remaining links.

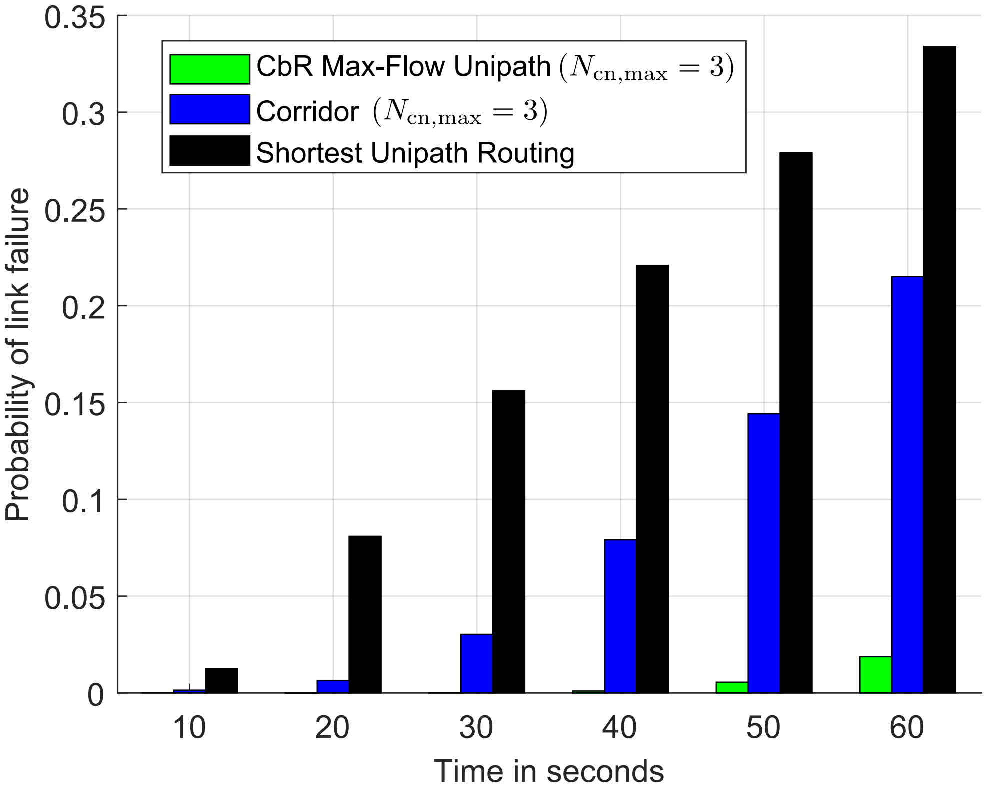

Figure 3.5. Probability for a link to fail over time with 200 nodes in the network.

In Figure 3.6, the average throughput of the CbR Max-Flow Unipath with $N_{\mathrm{cn,max}} = 3$ nodes per cluster is shown over a time span of 200 s. In this case, corridor maintenance is performed every 20 s according to the maintenance scheme introduced in Section 3.4. It can be seen that the average throughput decreases within each 20 s time slot. However, by the maintenance, the average throughput recovers almost to the initial performance. The average throughput after 200 s is decreased only by 2 % compared to the initial performance.

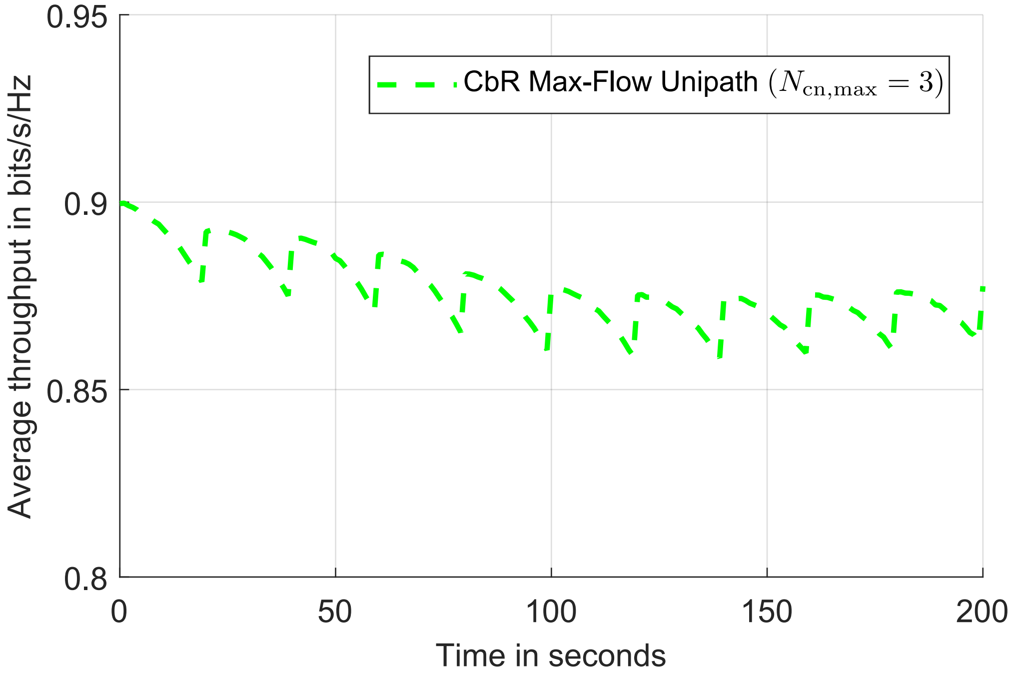

Figure 3.6. Average throughput over time with 200 nodes in the network and corridor maintenance every 20 s.

To summarize, the proposed corridor construction scheme successfully builds stable support structures for wireless multi-hop transmissions. Compared to Shortest Unipath Routing, it has been shown by the CbR Upper Bound that the corridor enables significant potential throughput gains based on the link diversity provided by the structure. Moreover, much higher link stability can be achieved based on the proposed construction scheme compared to the shortest path route discovery. Furthermore, it has been shown that in a mobile scenario, the structure can be kept in almost constant condition by proactive maintenance of the corridor.

Chapter 4

Resource Allocation in Corridor-based Routing

4.1 Diversity in Corridor-based Routing

In this chapter, the data transmission from the source to the destination is investigated using the corridor as a support structure that provides frequency, space and time diversity as illustrated in Figure 4.1. Each stage of the corridor consists of a certain number of links. Each link between a transmitter i and a receivers j offers frequency diversity, i.e, the channel quality varies among the subcarriers. Spatial diversity is provided by the variety of links since the frequency selective fading profile differs from link to link due to the different spatial placement of the node-pairs and the resulting multi-path propagation of signals. Moreover, all links provide time diversity since the channel conditions change over time. This channel-related diversity, offered by the corridor-structure, builds the basis for potential high data throughput. It can be exploited by an adaptive resource allocation in order to significantly increase the achievable data throughput compared to conventional unipath forwarding.

In the following, the problem of resource allocation within the corridor is investigated. First, the assumptions concerning the available CSI knowledge are discussed in Section 4.2. In Section 4.3, the transmission strategy in the first stage is explained, where only one transmitter, the source node, is present. Therefore, there is no need for an allocation of the available resources among multiple transmitters, but subcarriers need to be assigned to the available receivers. In Section 4.4, an optimal resource allocation policy that minimizes the expected number of required time slots to forward data packets is proposed and its limitations are discussed. Furthermore, a non-optimal but low-complexity resource allocation strategy is introduced. Parts of the results have been published by the author of this thesis in [HOK19].

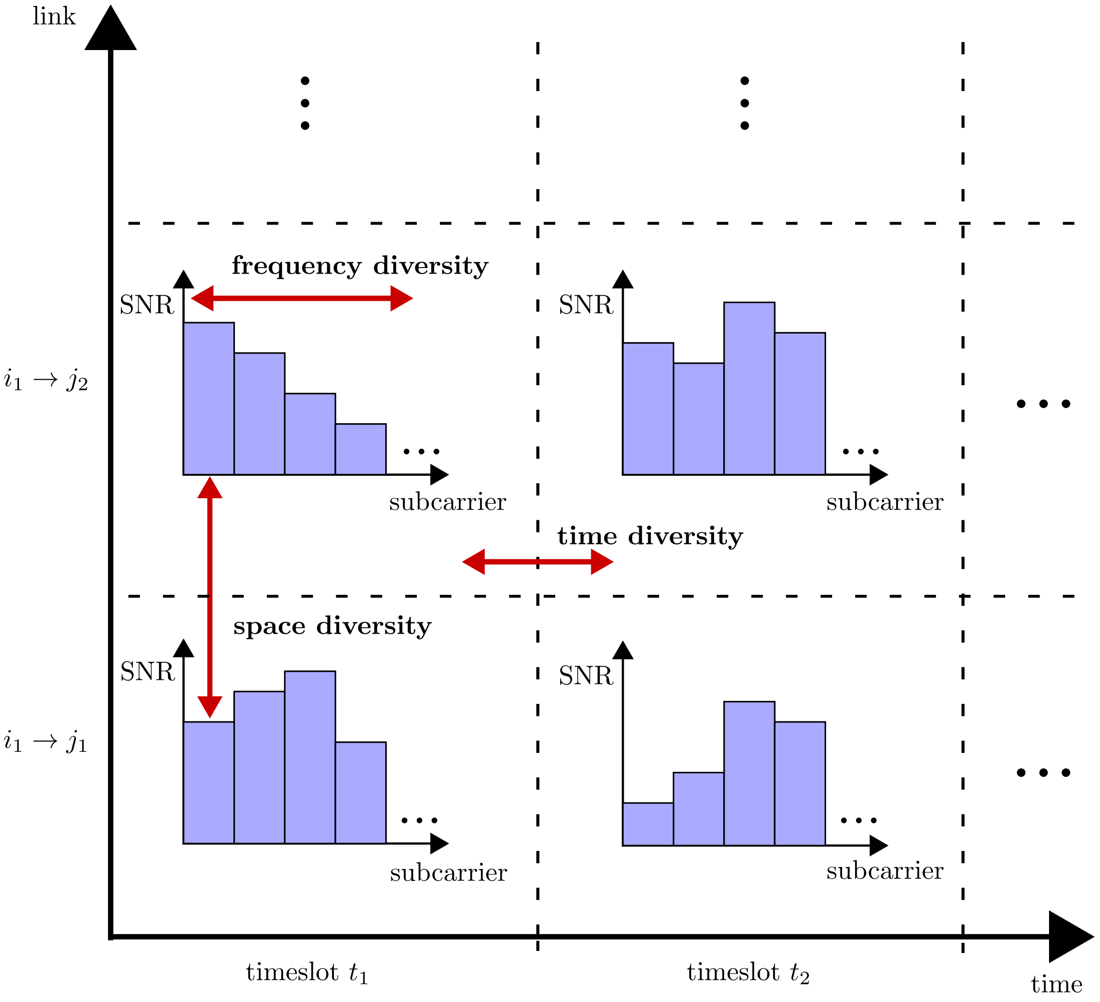

Figure 4.1. Frequency, space and time diversity.

4.2 Global vs. Local CSI

The main goal of the following investigations is the maximization of the data throughput between source and destination by adaptive resource allocation. In order to find an optimal solution for this problem, perfect global CSI knowledge would be required at the source node concerning all links within the corridor for the whole transmission time. This channel knowledge is impossible to provide in a wireless scenario. Due to the dynamic behavior of wireless channels, CSI from most stages of the corridor is very likely already outdated by the time it is measured and forwarded to the source node. In addition, during the time that data packets start to travel through the corridor, channels do also change. This means that CSI would be required to be provided to the source in an almost infinitely short time and furthermore, the source would need non-causal knowledge about the upcoming channel states. Only in case of a completely static scenario with constant channels, a global CSI knowledge at the source would be feasible to provide. Furthermore, even in the case that this knowledge is available, the corridor-wide resource allocation problem is a very complex problem of combinatorial nature which may only be solvable in an optimal manner by an exhaustive search with a non-manageable computational expense. In [KKLH12b], such static corridors are investigated and suboptimal resource allocation strategies are proposed.

In this thesis, the realistic case of non-static scenarios is considered. The channels are assumed to be constant only during a single time slot. Therefore, accurate current CSI knowledge is only assumed to be available locally within a stage, i.e., the CSI of the current stage is available at all cluster nodes of the transmitter side. The resource allocation problem is considered locally and independently in each stage of the corridor. This means that in each, stage the data throughput should be maximized in order to achieve a high data throughput between the source and the destination.

In order to provide the required information in each stage, channels need to be estimated and the obtained CSI needs to be shared over one hop to provide it at all nodes which are involved in the local resource allocation process. The channel measuring is assumed to be done in opposite direction to the data flow. This means that the designated receivers of a certain stage send out pilot symbols such that the designated transmitters obtain their corresponding transmit CSI directly and then exchange it with the other transmit nodes of the same stage. By doing it in this manner, the nodes always have the exact CSI of their own channels available since they measure it on their own. Even in case that the CSI that is exchanged between the nodes is coarsely quantized to reduce the required signaling overhead, nodes can still perfectly adapt their transmit data rates according to the exact CSI knowledge on each subcarrier they use for transmission.

4.3 First Stage Transmission

The first stage of the corridor is an exception regarding the transmit strategy, since there is only one transmitter, the source node, and all data packets are available at this node. Therefore, no resource allocation among multiple transmitters is required, but only concerning the receivers. In order to maximize the throughput in the first stage, a greedy assignment strategy can be used.

In each time slot, each subcarrier is assigned to the receiver that provides the highest SNR on this subcarrier. According to this SNR, the maximum possible transmission rate is selected for each individual subcarrier. On packet-level, this means that each subcarrier is allocated to the link which enables the transmission of the most data packets in the current time slot. This is illustrated in Figure 4.2, where it is assumed that 2 packets can be transmitted on each assigned subcarrier. Of course, in general, different numbers of data packets can be transmitted on each individual subcarrier depending on the current channel states. In case that multiple links provide the same capacity, receivers with fewer data packets in their data buffer are preferred in order to balance the load of the forwarding process. Data packets are always exclusively transmitted, i.e, they are distributed among the subcarriers. Therefore, the entire set of data packets is split among the different receivers of the first cluster. This procedure is repeated in each time slot until all data packets are transmitted. By this strategy, the data throughput in the first stage is maximized and the required number of time slots is minimized. In the following stages of the corridor, resources need to be shared among the cluster nodes and the distribution of data packets among the forwarding nodes needs to be taken into account.

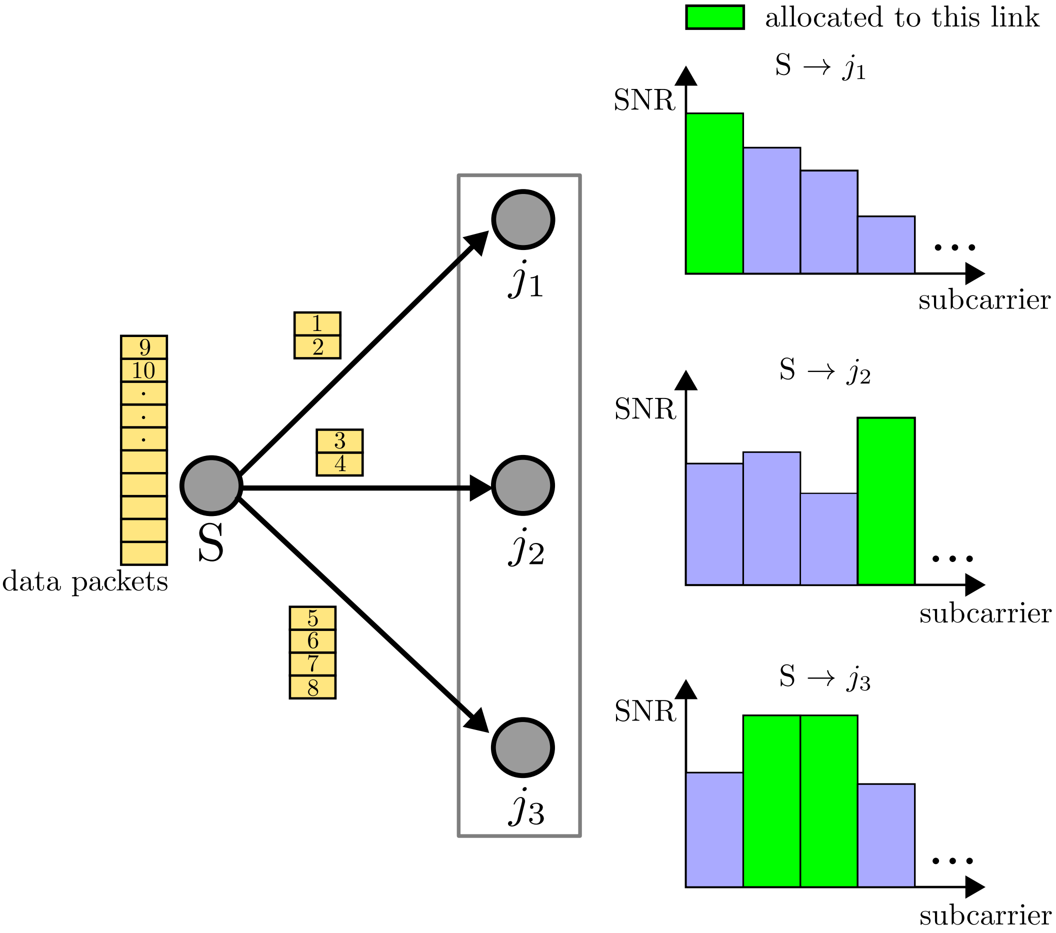

Figure 4.2. Illustration of data packet transmission in the first stage of the corridor. The source node assigns each subcarrier to the strongest receiver.

4.4 Resource Allocation

4.4.1 Resource Allocation Based on Markov Decision Process

4.4.1.1 Introduction

In this section, the resource allocation within the corridor from the second stage on is considered aiming at the maximization of the data throughput. From the second stage on, multiple transmitters are simultaneously involved in the forwarding process. Therefore, the available resources must be shared between the transmitters of each stage. Since a fixed predefined total number of data packets that need to be transmitted is assumed throughout this work, the aim can also be formulated as the minimization of the number of required time slots to forward all data packets. As explained in the previous section, a centralized resource allocation for the whole corridor based on global CSI knowledge is impractical and not feasible in a wireless mobile scenario, since channel conditions are quickly changing over time. Without global and non-causal CSI, an optimal solution for this problem cannot be found. Therefore, the overall problem is divided into multiple local resource allocation problems considering the corridor stage by stage.

An optimal transmission strategy that maximizes the data throughput in the first stage has been introduced in the previous section. The resulting problem in the following stages is illustrated in Figure 4.3, where data packets are distributed among the different forwarding nodes and all links provide a different SNR profile concerning the available subcarriers. The data packets should be forwarded as quickly as possible to the next cluster. To this end, the available subcarriers need to be allocated among the forwarding nodes of the stage in each time slot until the data packets are completely forwarded.

It is assumed that the overall number of data packets exceeds the capacity of the links of a time slot for which the channels remain constant. Therefore, even for the local resource allocation problem, it is not possible to find an optimal solution that maximizes the data throughput without non-causal knowledge about the future channel conditions. Instead of aiming for this optimal solution, the aim is to find an optimal resource allocation policy that maximizes the expected data throughput. Since the policy can only be based on stochastic knowledge about channel statistics, only the expected throughput can be considered.

Finding such an optimal policy is not straightforward. For instance, by allocating channel resources in a greedy manner, i.e, always assigning channel resources to the strongest available link, the data throughput is maximized only for a certain period. In case that one or more forwarding nodes have no data packets in their data buffers anymore and some nodes still have packets to forward, an important share in terms of diversity gets lost for the remaining time slots. The outgoing links of nodes with an empty buffer cannot be utilized anymore even if they provide exceptionally good channel conditions in the following time slots. Therefore, it is beneficial to take the data buffer levels of the nodes into account from the beginning and to sometimes allocate subcarriers to forwarding nodes which do not provide the highest SNR, but which provide a high SNR regarding their average channel conditions or which have more data packets in their data buffer compared to other nodes.

Dynamic programming can be used to solve complex optimization problems that are composed of independent subproblems, i.e, the optimal solutions of the subproblems need to add up to the optimal solution of the initial problem. The application of dynamic programming algorithms requires a perfect model of the environment as a Markov Decision Process (MDP).

An MDP model consists of a set of states where each state represents a subproblem. Each state is a unique combination of variables that are relevant for the considered problem. The initial problem can be viewed as the consecutive occurrence of the subproblems. In each state, certain actions can be taken, for instance, allocating a resource to one certain node out of multiple options. Furthermore, transition probabilities between the states need to be known and the resulting rewards need to be defined for the model. The transitions between different states need to satisfy the Markov property [SB98], which means that the process has to be memoryless. In other words, the transition probabilities only need to depend on the current state, but not on previous ones. It does not matter from which state the current state has been reached. As mentioned before, in order to find an optimal policy based on the model, it has to be a perfect model of the environment, i.e., all relevant deterministic variables need to be known and all relevant stochastic processes need to be described by their known probability distributions.

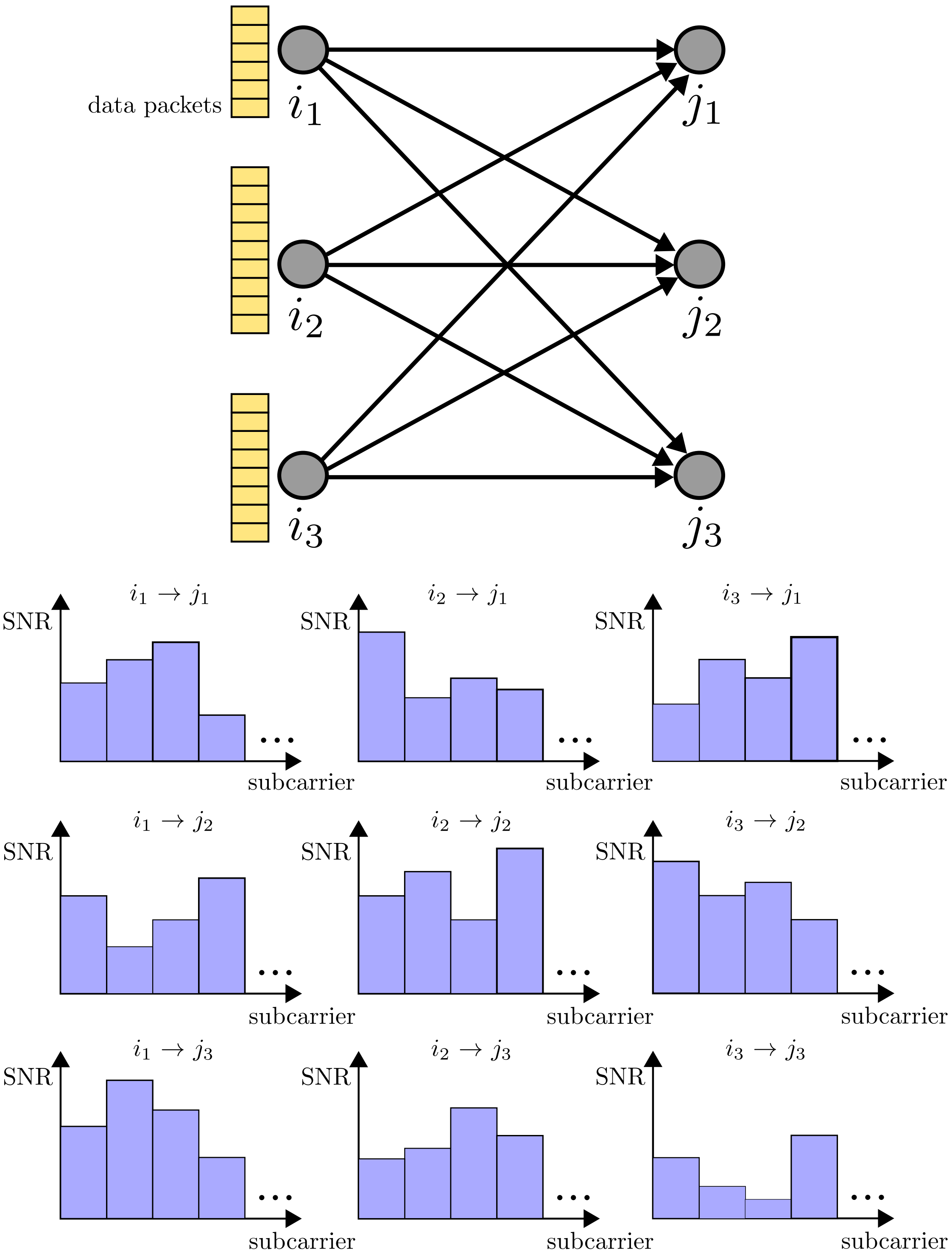

Figure 4.3. Transmission of data packets between two clusters, each consisting of 3 nodes.

Solving such a problem can be done beforehand and then a look-up table can be used to get the optimal action for each state quickly. However, large state spaces can require tremendous numbers of computational and storage resources. Therefore, state approximation techniques are useful to keep the expenditure manageable by reducing the number of considered states. In the following, an MDP model is defined for the considered resource allocation problem within one stage of the corridor and an optimal policy is derived using the policy iteration algorithm [SB98]. In addition, a state approximation technique is introduced in order to handle large state spaces. Several parts of the content of this section have been originally published by the author of this thesis in [HOK19].

4.4.1.2 Markov Decision Process Model

In order to keep the complexity of the problem manageable, only one channel resource, i.e., a single subcarrier, is considered at a time. In the following, the subcarrier index n is omitted in the denotation of the SNR $\gamma_{i,j}$ and the channel transfer factor $h_{i,j}$. For the MDP model of the considered problem, all relevant parameters need to be taken into account. For the considered problem, a state s is defined by the following parameters:

- The data buffer level B_i of each forwarding node i of the cluster.
- The channel conditions of the nodes, more precisely, the number of data packets $N_{\mathrm{p},i}^{\max}$ that each node i is able to transmit at most in the current time slot. This is only one value per node, since only one subcarrier is considered and the nodes always transmit to the strongest receiver.

Since the aim is to maximize the throughput of data packets, a transmitter always adapts its transmission rate to the strongest available receiver. Therefore, for each forwarding node i, only the strongest channel SNR is of interest, which is denoted by $\gamma_{i,\max} = \max_{j} \gamma_{i,j}$.

An action a refers to the allocation of the channel resource to a certain node. The reward $\mathcal{R}_{ss'}^{a}$ incurred by taking action a in the state s and leading to state s' is given by the number of data packets that can be transmitted by choosing this action.

The achievable data rates in practice depend on various parameters concerning the devices and the transmission protocol. Each device performs differently, for instance,

Table 4.1. Rate adaptation

SNR	capacity	$N_{\mathrm{p}}^{\max}$ / time slot
$< 4.8\,\mathrm{dB}$	$< 2\,\mathrm{bit/s/Hz}$	0
4.8 - 11.8 dB	2 bits/s/Hz	1
11.8 - 18 dB	4 bits/s/Hz	2
$> 18\,\mathrm{dB}$	6 bits/s/Hz	3

in terms of the receiver sensitivity. How many data packets can be transmitted depends on, for instance, the data packet size, the modulation and coding schemes, the carrier frequency and so on. The minimum required SNR to transmit data packets at all is usually in the range of 2-8 dB for most of the 802.11 protocols [ZTZ+08], [YLQ+17], [HLLS04]. In order to avoid any assumptions concerning specific parameters and to keep the investigation as general as possible, the following mapping is proposed. Without loss of generality, 2 bits/s/Hz are assumed as a minimum required capacity to transmit a single data packet within a time slot. This corresponds to a minimum SNR of 4.8 dB. It follows that 4 bits/s/Hz are the required channel capacity to transmit 2 packets per time slot, which corresponds to a minimum SNR of 11.8 dB and so on, as shown in Table 4.1. This mapping captures the general functioning of an adaptive selection of the Modulation and Coding Scheme (MCS) for transmission. Usually, there is a limited amount of MCS options available that can be applied for transmission. Each MCS results in a certain data rate.

The final step to complete the MDP model is to find the transition probabilities between the states $\mathcal{P}_{ss'}^{a} = \Pr\{s_{t+1} = s' | s_t = s, a_t = a\}$, where s_t denotes the initial state in time slot t and s_{t+1} denotes the resulting state in time slot $t+1$. Since the number of data packets in each data buffer and the number of data packets that can be transmitted by choosing action a are known, the data buffers levels in the resulting state are also known. The only unknown parameters are the channel conditions in the upcoming state. Of course, the actual upcoming channel states are unknown, but channel statistics, i.e., the average SNRs, are known. Furthermore, Rayleigh fading is assumed on the channels which means that the real and the imaginary part of a received signal are independent normally distributed variables with a variance of $\sigma_{i,j}^2$. The magnitude of a signal transmitted by node i and received by node j follows a Rayleigh distribution and is given by

$$A_{i,j} = \sqrt{p_{\mathrm{sc}}} \cdot |h_i|. \tag{4.1}$$

The Probability Density Function (PDF) of $A_{i,j}$ is given by

$$\mathrm{pdf}(A_{i,j}) = \frac{2A_{i,j}}{\sigma_{i,j}^2} e^{-\frac{A_{i,j}^2}{\sigma_{i,j}^2}}, \quad \text{for } A_{i,j} \geq 0, \tag{4.2}$$

The corresponding Cumulative Distribution Function (CDF), which gives the probability that $A_{i,j}$ lies below or is equal to a certain value, is given by

$$\mathrm{cdf}(A_{i,j}) = 1 - e^{-\frac{A_{i,j}^2}{\sigma_{i,j}^2}}, \quad \text{for } A_{i,j} \geq 0. \tag{4.3}$$

The PDF of the signal with maximum magnitude $A_{i,\max} = \max_j \sqrt{p_{\mathrm{sc}}} \cdot |A_{i,j}|$ is given by the probability that one magnitude is equal to a certain value while the magnitudes of the remaining signals are below that value

$$\begin{aligned} \mathrm{pdf}(A_{i,\max}) &= \sum_{j_1=1}^{N_{\mathrm{cn}}} \mathrm{pdf}(A_{i,j_1}) \prod_{\substack{j_2=1,\\ j_2\neq j_1}}^{N_{\mathrm{cn}}} \mathrm{cdf}(A_{i,j_2}) \\ &= \sum_{j_1=1}^{N_{\mathrm{cn}}} \frac{2A_{i,\max}}{\sigma_{i,j_1}^2} e^{-\frac{A_{i,\max}^2}{\sigma_{i,j_1}^2}} \prod_{\substack{j_2=1,\\ j_2\neq j_1}}^{N_{\mathrm{cn}}} \left(1 - e^{-\frac{A_{i,\max}^2}{\sigma_{i,j_2}^2}}\right). \end{aligned} \tag{4.4}$$

In Figure 4.4, an example with three Rayleigh channels with an average SNR of $\bar{\gamma}_{i,1} = 10\,\mathrm{dB}$, $\bar{\gamma}_{i,2} = 12.5\,\mathrm{dB}$ and $\bar{\gamma}_{i,3} = 15$ dB is illustrated. The individual PDFs are shown in Figure 4.4 a). The resulting PDF of $A_{i,\max} = \max_j \sqrt{p_{\mathrm{sc}}} \cdot |h_{i,j}|$ is given in Figure 4.4 b). The resulting Probability Mass Function (PMF), which gives the number of transmittable packets $N_{\mathrm{p},i}^{\max}$ assuming the mapping according to Table 4.1, is shown in Figure 4.4 c).

Using the known average SNR information of the current stage, the PMF for the number $N_{\mathrm{p},i}^{\max}$ of transmittable packets for each forwarding node i in the cluster can be determined. Based on this, the transition probabilities between the states are given by the combination of these probabilities. Since the individual channel states are assumed to be independent of each other, the probability of a certain combination of channel states is given by the multiplication of the individual probabilities.

4.4.1.3 Optimal Resource Allocation Policy based on Dynamic Programming

A policy π provides a certain action a for each state s. An optimal policy π^* does this in such a way that the expected reward $E\{\mathcal{R}_{ss'}^a\}$ is maximized. To find an optimal

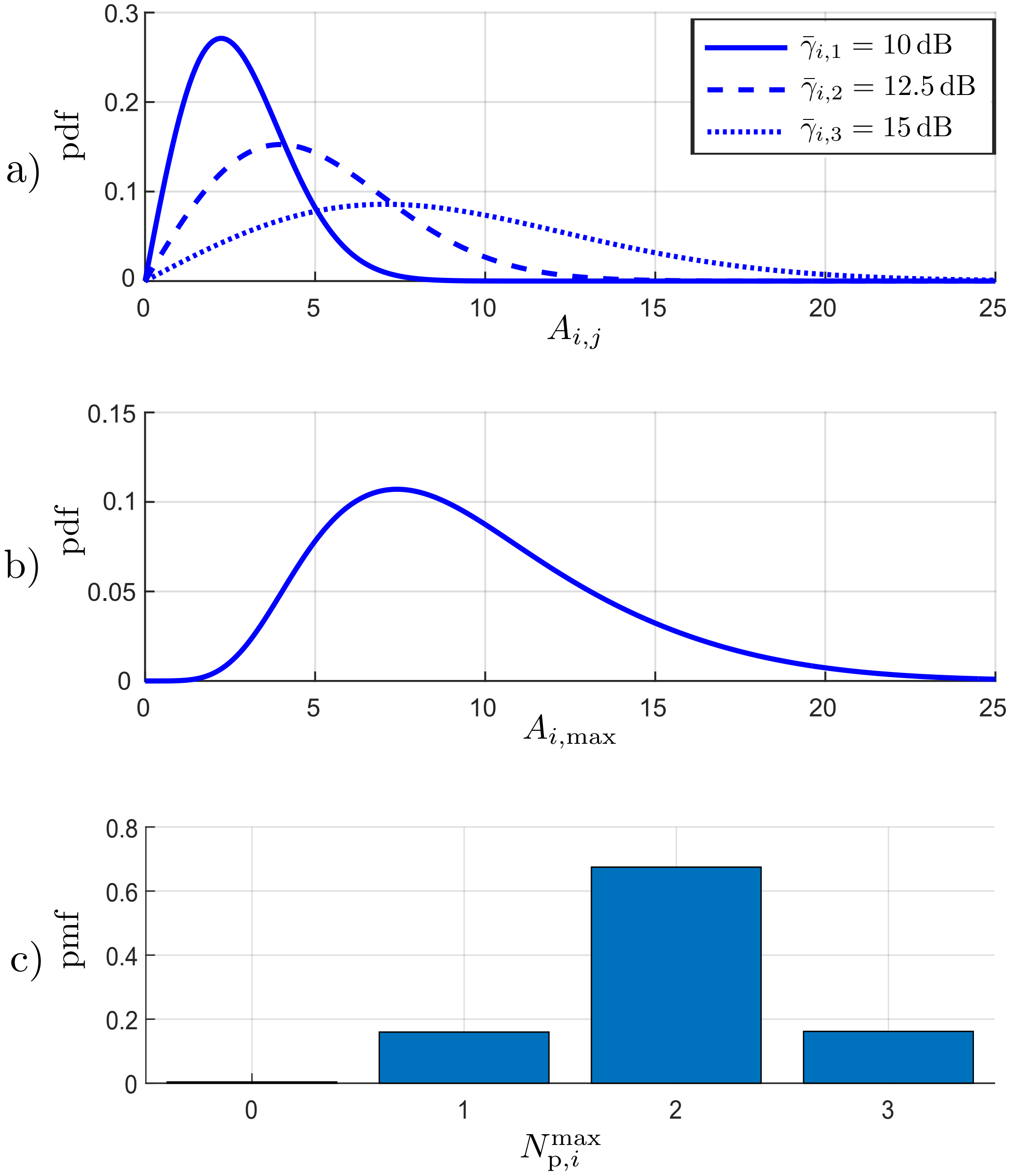

Figure 4.4. a) PDF of the magnitude of three signals that are transmitted over Rayleigh fading channels with an average SNR of 10/12.5/15 dB. b) Resulting PDF by the selection of the strongest out of the three channel options. c) Resulting PMF for the number of transmittable packets $N_{\mathrm{p},i}^{\mathrm{max}}$

policy, the policy iteration algorithm [SB98] can be used. In the considered case, the expected number of transmitted packets should be maximized, which corresponds to a minimization of the required number of time slots to forward all data packets. The optimal policy for the considered problem is determined using Algorithm 3. In the beginning, an initial policy π' is required. This can be an arbitrary policy. However, starting with a policy that is already similar to the optimal policy, the required iterations can usually be reduced. Therefore, a greedy policy is used that takes the action with highest reward in each state. Next, a method is required to evaluate the performance of the policy to find possible improvements. To this end, the state value function $V(s)$ is used to rate the value of a state under the current policy. This function does not only consider the immediate reward, but it determines the value of a state in the long run. In other words, it gives the expected accumulated reward for the state under the current policy. As a next step, the current policy is improved based on the action value function Q which returns the expected reward when choosing a certain action. The current policy is then improved by making it greedy with respect to the action value function. This procedure is repeated until the optimal policy π^* is found.

Algorithm 3 Policy iteration algorithm

```
Require: Initial value function $V$ ($V(s) = 0, \forall s \in \mathcal{S}$, initial policy $\pi'$, $\Delta = 0$)
    while $\Delta > \epsilon = 0.0001$ do
      for each $s \in \mathcal{S}$ do
        $v \leftarrow V(s)$
        $V(s) = \sum_{s'} \mathcal{P}^a_{ss'}(\mathcal{R}^a_{ss'} + V(s'))$
        $\Delta = \max(\Delta, v - V(s))$
      end for
    end while
    for each $a \in \mathcal{A}(s)$ do
      for each $s \in \mathcal{S}$ do
        $Q(s, a) = \mathcal{R}^a + \sum_{s'} \mathcal{P}^a_{ss'} \cdot V(s')$
      end for
    end for
    set $\pi = \pi'$
    $\pi' := \arg\max_a(Q(s, a))$ (policy improvement)
    Repeat until $\pi = \pi'$
```

4.4.1.4 State Approximation Technique

The number $|\mathcal{S}|$ of states in the MDP model is very critical for computational and storage reasons. In the considered case, the number of required states is given by

$$|\mathcal{S}| = (N_{\text{rates}} \cdot (B_{\max} + 1))^{N_{\text{cn}}}, \tag{4.5}$$

where N_{rates} denotes the number of available MCSs or data rates (including a rate equal to zero), $B_{\max}$ denotes the maximum data buffer level and N_{cn} denotes the number of transmit nodes. The number of available MCSs sets the number of different channel states that need to be distinguished since the channel needs to be known only as precisely such that the different data rates are covered. However, the number of states is already huge for a small number of MCSs, data packets and forwarding nodes. For instance, having 4 different MCSs, 10 data packets as maximum data buffer level and $N_{\text{cn}} = 3$ forwarding nodes, will result in $|\mathcal{S}| = 85184$ different states. Storing the transition probabilities between these states requires a matrix of size 85184x85184. As can be seen, already small numbers of data packets, data rates and forwarding nodes create a considerable amount of data that needs to be considered.

As a consequence, a state approximation technique is introduced in order to limit the required number of states while capturing the most important features of the problem as good as possible. By means of test simulations, it is found that the actual number of data packets in each data buffer is not crucial in most of the states. Instead, the ratio between the levels of different data buffers is the most important feature. For instance, let us consider two different states of an example scenario with two transmit nodes. In the first state, the two nodes have a data buffer level of $B_1 = 110$ and $B_2 = 100$ data packets, respectively. The ratio between the data buffer levels is given by $\frac{B_1}{B_2} = 1.1$. In the second state, with for instance, $B_1 = 99$ data packets and $B_2 = 90$, the ratio is the same. If the channel conditions are the same in both states, the optimal action will most likely also be the same. Of course, considering the resulting states, the ratios of the resulting data buffer levels will slightly differ. However, the larger the actual numbers of data packets, the smaller this difference will be and the smaller the impact on the optimal action. Therefore, an approximation technique is proposed that scales down the actual data buffer levels in case one of them exceeds a maximum data buffer level $B_{\max}$ that is defined for the considered model. This means the actual values are mapped to smaller values so that their ratio remains as constant as possible.

By applying the approximation, the actual data buffer level B_i of forwarding node i is replaced by an approximated data buffer levels B_i^{approx}. These values are used to approximately reflect the ratio of the actual data buffer levels by the following method. Let the maximum value of the actual data buffer levels be $B_{\max}^{\text{actual}} = \max_i B_i$. The approximated buffer level of forwarding node i is then given by

$$B_i^{\text{approx.}} = \text{round}\{\frac{B_i \cdot B_{\max}}{B_{\max}^{\text{actual}}}\}, \quad \forall i, \tag{4.6}$$

where the operator round$\{\cdot\}$ rounds to the closest integer. By this method, the approximated data buffer levels do not exceed $B_{\max}$. The maximum actual data buffer level $B_{\max}^{\text{actual}}$ is replaced by $B_{\max}$. Furthermore, the remaining actual data buffer levels are replaced such that ratio between the approximated data buffer levels roughly equals the ratio between the actual data buffer levels. A small error is introduced by the rounding operation which means that the derived policy is not optimal anymore in case of usage of this approximation technique. However, by using this method, the underlying MDP model to derive the allocation policy must only cover states with data buffer levels up to $B_{\max}$. Nevertheless, larger data buffer levels can be handled by mapping a state with larger data buffer values to the closest state in terms of the channel conditions and the ratio of the data buffer levels that is covered by the MDP model. Thereby, a large number of data packets can be handled while the number of required states in the MDP mode can be selected as desired and can be kept in a reasonable range.

4.4.1.5 Complexity and Limitations

Having a complete and perfect model of the environment, dynamic programming methods are a powerful tool to find optimal policies in polynomial time with regards to the number of actions and states [SB98]. Compared to an exhaustive search for the policy, the savings of computational expenses are significant. Moreover, in case of a good initial policy, the iterative algorithm usually converges much faster compared to the use of a random policy at the beginning of the algorithm. As explained in the previous section, the number of states in the MDP model increases rapidly with an increasing number of different options for each state variable. This results in large computational and storage expenses. Considering the example with 85184 states from the previous section, the transition probability matrix would have about 7.2 trillion elements. In case that, for instance, 4 Bytes are used to store one of the elements, a total storage capacity of about 29 Gigabytes is required.

Furthermore, the number of states increases exponentially with the number of state variables. This means that for a higher number of forwarding nodes, the number of data buffer levels and the number of channel states that need to be taken into account increases which results in an exponential growth of states. Therefore, the applicability of the proposed model is limited to a relatively small number of forwarding nodes and MCSs. As a consequence, a low-complexity heuristic approach is considered in the following.

4.4.2 Low-Complexity Resource Allocation

4.4.2.1 Motivation

In order to find a resource allocation strategy with lower computational and storage expenses, suboptimal heuristic algorithms provide a suitable approach. A quite simple intuitive solution is a subcarrier allocation in a greedy manner, i.e., allocating each subcarrier to the strongest available link of the current stage. As pointed out before, this strategy maximizes the throughput, but only for a limited period of time. It is more beneficial when data is flowing off evenly from the different forwarding nodes with regards to their corresponding data buffer levels. In other words, the expected number of time slots that each node requires to forward all buffered data packets should be approximately the same. Thereby, the full diversity provided by the stage links can be exploited over the whole transmission process. To this end, the aim is to find a resource allocation algorithm that, while still striving for an allocation of each subcarrier to a link with a high SNR, takes the data buffer levels of the nodes into account.

In the following, an iterative algorithm is introduced that uses a comparative channel state metric for the allocation of resources. Furthermore, the data buffer levels of the nodes are taken into account in order to adapt the data flow accordingly.

4.4.2.2 Comparative Greedy Resource Allocation

A fixed division of the subcarriers according to the proportion of data packets that each node has buffered is not necessarily a suitable solution because in certain circumstances, the average channel conditions of the different nodes may differ significantly. Instead, an iterative algorithm is proposed in which the subcarriers are allocated in a fair manner with respect to the data buffer levels and the channel states of the forwarding nodes. Furthermore, a subcarrier should not be allocated only based on the channel condition of the corresponding forwarding node, but also based on the channel conditions of the other nodes on this subcarrier. For instance, consider the case that a certain forwarding node i_1 has the same channel conditions on subcarrier n_1 and n_2 but forwarding node i_2 has significantly better channel conditions on subcarrier n_1 than on n_2. In this case, forwarding node i_1 should prefer subcarrier n_2 because n_1 might be allocated to node n_2 later on which would result in a higher overall data throughput. To this end, subcarriers are not allocated based on their actual SNR, but on a comparative SNR which is given by

$$\gamma^{'}_{i_1,j,n} = \gamma_{i_1,j,n} - \max_{i_2, i_2 \neq i_1} \gamma_{i_2,j,n}. \tag{4.7}$$

This comparative SNR of a forwarding node i for subcarrier n is given by the difference between its SNR and the highest SNR of the remaining forwarding nodes regarding the same subcarrier n.

For the subcarrier allocation, Algorithm 4 is used. In each iteration of the comparative iterative greedy algorithm, the first step is to determine the forwarding node i for which a subcarrier should be found. This decision is based on the highest transmission time that a forwarding node would require if it forwards all its buffered data packets using a total data rate of $R_{\text{total},i}$. This data rate is given by the sum of the individual data rates that node i achieves using the subcarriers that are already allocated to it for the upcoming time slot. Hence, in the beginning of the subcarrier allocation procedure $R_{\text{total},i} = 0,\ \forall i$. Therefore, in the initial iterations, when there are forwarding nodes without any subcarriers that are assigned to them so far, forwarding node i is selected out of these nodes only based on the maximum data buffer level $\max_i B_i$.

After forwarding node i has been found, the subcarrier n to be used and the corresponding receiver j are determined based on the highest comparative SNR $\max_{n,j} \gamma^{'}_{i,j,n}$. The corresponding subcarrier n is then allocated to the link between forwarding node i and receiving node j and the data rate $R_{i,j,n}$ is added to the total data rate $R_{\text{total},i}$ of node i. The allocated subcarrier n is taken out of consideration and the next iteration of the algorithm starts. This procedure is repeated until all subcarriers are allocated for the upcoming time slot.

4.4.3 Performance Analysis

In this section, the performance of the resource allocation policy based on dynamic programming without and with the proposed state approximation technique, in the following termed 'RA Dynamic Programming' and 'RA Dynamic Programming Approx.', and the lower complexity comparative greedy resource allocation scheme, in the following termed 'RA Comparative Greedy', is evaluated.

Algorithm 4 Comparative iterative greedy algorithm for subcarrier allocation

```
Require: Current stage CSI, data buffer levels $B_i,\ \forall i$
    Create set with all subcarriers $\mathcal{S}_{\mathrm{sc}}$;
    Initialize total transmit rate $R_{\mathrm{total},i} := 0,\ \forall i$
    Determine comparative SNR $\gamma^{'}_{i,j,n},\ \forall i, j, n$ according to (4.7)
    while set of subcarriers $\mathcal{S}_{\mathrm{sc}}$ not empty do
        if $R_{\mathrm{total},i} = 0$ for some $i$ then
            Out of forwarding nodes with $R_{\mathrm{total},i} = 0$, determine $i$ with $\max_i B_i$
        else
            Determine forwarding node $i$ with $\max_i \frac{B_i}{R_{\mathrm{total},i}}$
        end if
        Determine subcarrier $n$ and receiver $j$ with $\max_{n,j} \gamma^{'}_{i,j,n}$;
        Assign subcarrier $n$ to link between forwarding node $i$ and $j$;
        Update $R_{\mathrm{total},i} = R_{\mathrm{total},i} + R_{i,j,n}$;
        Cancel subcarrier $n$ out of set $\mathcal{S}_{\mathrm{sc}}$
    end while
```

As a benchmark, a random unipath forwarding scheme based on the corridor structure is considered. In this scheme, all data packets are forwarded to only one randomly selected node in each stage of the corridor. As for the other considered schemes, local CSI is assumed to be available. Therefore, in each time slot, the data rate on each subcarrier is adapted according to the corresponding channel state. In the following, this scheme is termed 'Unipath'.

Furthermore, a fixed-order policy is considered as a benchmark, in the following termed 'Fixed Order'. Again, the corridor is used as a basis for the transmission, but this time all cluster nodes take part in the data forwarding process. In the first stage, the optimal transmission policy introduced in Section 4.3 is applied. In the following stages, the nodes transmit according to a fixed order. First, the transmitter with the lowest index i transmits using all subcarriers until its data buffer is empty. Next, the transmitter with the second lowest index starts to transmit using all subcarriers and so on. Following this policy, there is always only one node transmitting at a time, but all receivers of a stage are considered and the data rate on each subcarrier is adapted to the strongest available receiver of the current stage in each time slot.

In the following, the system parameters according to Table 4.2 are assumed. Corridors consisting of three stages are considered. Additional stages would not provide any more insights into the performance of the considered schemes since the proposed approaches are based on local decisions in each stage. Additional stages would lead to the same problem and performance as in the second stage. The resource allocation problem with multiple transmitters with different data buffer levels and channel conditions and multiple receiver options would just occur multiple times. The last stage provides a different situation since there is only one receiver present. Corridors with 2 or 3 nodes per cluster are considered. The transmit power per subcarrier is $p_n = 1\,\mathrm{mW}$. The distances between the nodes are randomly generated such that the average link SNR $\bar{\gamma}_{i,j}$ between a transmitter i and a receiver j in a stage lies between 10 and 15 dB.

Table 4.2. System parameters

Number N_{stages} of stages	3
Maximum number $N_{\mathrm{cn,max}}$ of nodes per cluster	$\{2, 3\}$
Number N_{sc} of subcarriers	$\{1, 64\}$
Total transmit power per subcarrier p_n	1 mW
Average link SNR $\bar{\gamma}_{i,j}$	10-15 dB

First, only one subcarrier is considered and a total number of 15 data packets are forwarded from the source to the destination in each simulation run. This number of data packets is completely covered by the underlying MDP model. Therefore, no state approximation is required. In this case, the policy generated by the proposed RA Dynamic Programming scheme is optimal in terms of minimizing the expected number of required time slots to forward the data packets to the next stage.

In Figure 4.5, the performance of the RA Dynamic Programming scheme is compared to the Fixed Order policy and the Unipath scheme. The performance of the proposed RA Comparative Greedy scheme is not considered in Figure 4.5, since this scheme is designed for the use of multiple subcarriers. In case of a single subcarrier, the average performance is exactly the same as for the Fixed Order policy since in both schemes, the best receiver is selected but the transmitter is chosen independently of the actual channel states. It can be seen that the number of required time slots for the Unipath scheme is constant for all stages due to the same average link conditions in each stage. In the first stage, the transmission strategy used by the RA Dynamic Programming policy and by the Fixed Order policy is the same. By exploiting the diversity provided by the multiple receiver options, the required number of time slots is reduced by 24 % compared to the Unipath scheme. In the second stage, the RA Dynamic Programming scheme requires 31 % fewer time slots compared to the

Unipath scheme due to the higher link diversity in the second stage with multiple receivers and multiple transmitters. This corresponds to a throughput gain of 45 %. Compared to the Fixed Order policy, 11 % less time slots are required. In the last stage, the Fixed Order policy requires slightly more time slots than the Unipath scheme. In both schemes, there is no diversity gain achieved since the transmitter and the receiver in each time slot are not selected based on any channel information. However, due to the distribution of the data packets among multiple transmitters in the last stage, the performance of the Fixed Order policy is worse compared to the Unipath scheme. The reason for that is an under-usage of the given channel capacity. This happens when the given channel capacity exceeds the remaining number of data packets in the data buffer of a transmitter, i.e., the channel capacity cannot be fully exploited. This effect can occur multiple times for the Fixed Order policy, but only once in the Unipath scheme. The RA Dynamic Programming policy requires 17 % fewer time slots compared to the Fixed Order policy in the last stage.

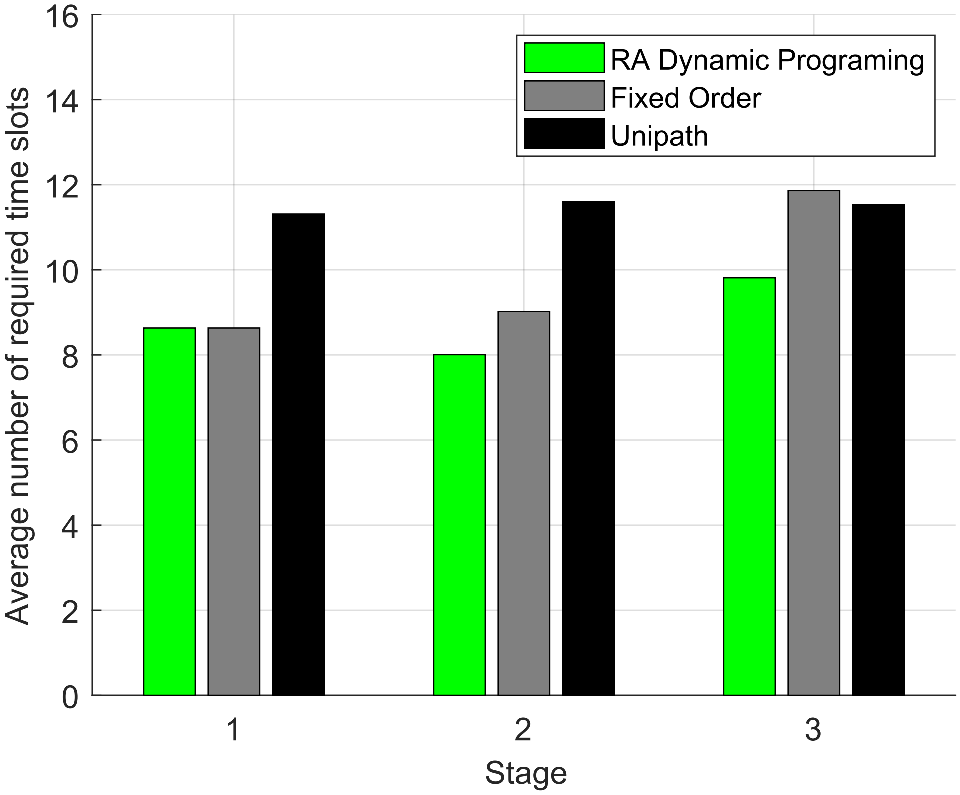

Figure 4.5. Average number of required time slots for each stage to forward 15 data packets with two forwarding nodes per cluster.

In Figure 4.6, the transmission of 10.000 data packets from source to destination is considered in each simulation run and 64 subcarriers are available for transmission. The RA Dynamic Programming Approx. scheme is considered which includes the state approximation technique introduced in Section 4.4.1.4. The maximum number $B_{\max}$ of data packets that is covered by the underlying MDP model is still equal to 15. The policy is applied subcarrier by subcarrier. This means that first, the policy gives the action for the first subcarrier. Next, this action leads to a transition to another state in the underlying MDP model which is then used to find the action for the second subcarrier and so on. The RA Comparative Greedy policy applies the same transmission strategy as the RA Dynamic Programming Approx. policy and the Fixed Order policy in the first stage. Therefore, all three schemes require the same amount of time slots in the first stage. Compared to the Unipath scheme, they require 25 % fewer time slots which is a small improvement compared to Figure 4.5. This is based on a smaller impact of an under-usage of the given channel capacity on the overall performance in this stage. This also leads to increased savings in the second stage. The RA Dynamic Programming Approx. policy requires 36 % fewer time slots compared to the Unipath scheme. Even though the RA Dynamic Programming Approx. policy is not an optimal policy anymore, due to the applied approximations and the consideration of multiple subcarriers, the performance is improved compared to the Unipath scheme. Again, this improvement is based on a lower impact of residual data packets, which is very critical in the case of only 15 data packets but which has only marginal impact in case of 10.000 data packets. The RA Comparative Greedy policy achieves almost the same performance compared to the RA Dynamic Programming Approx. policy. Only 0.6 % and 1.3 % less time slots are required by the RA Dynamic Programming Approx. policy in the second stage and in the third stage, respectively. It can be concluded that in most cases, the RA Comparative Greedy policy takes the same actions as the RA Dynamic Programming Approx. policy.

In Figure 4.7, three forwarding nodes per cluster are considered. Again, 64 subcarriers are available and 10.000 data packets are transmitted per simulation run. The maximum number $B_{\max}$ of data packets that is covered by the underlying MDP model that is used for the RA Dynamic Programming Approx. policy is equal to 5. The number is limited by the available memory for the simulations. Due to the higher link diversity in the corridor with three nodes per cluster, the savings compared to the Unipath scheme increase. In the first stage, the RA Dynamic Programming Approx. policy, the RA Comparative Greedy policy and the Fixed Order policy require 32 % fewer time slots compared to the Unipath scheme. In the second stage, the RA Dynamic Programming Approx. policy requires 44 % fewer time slots compared to the Unipath scheme. Again, the performance of the RA Comparative Greedy policy is very close to the performance

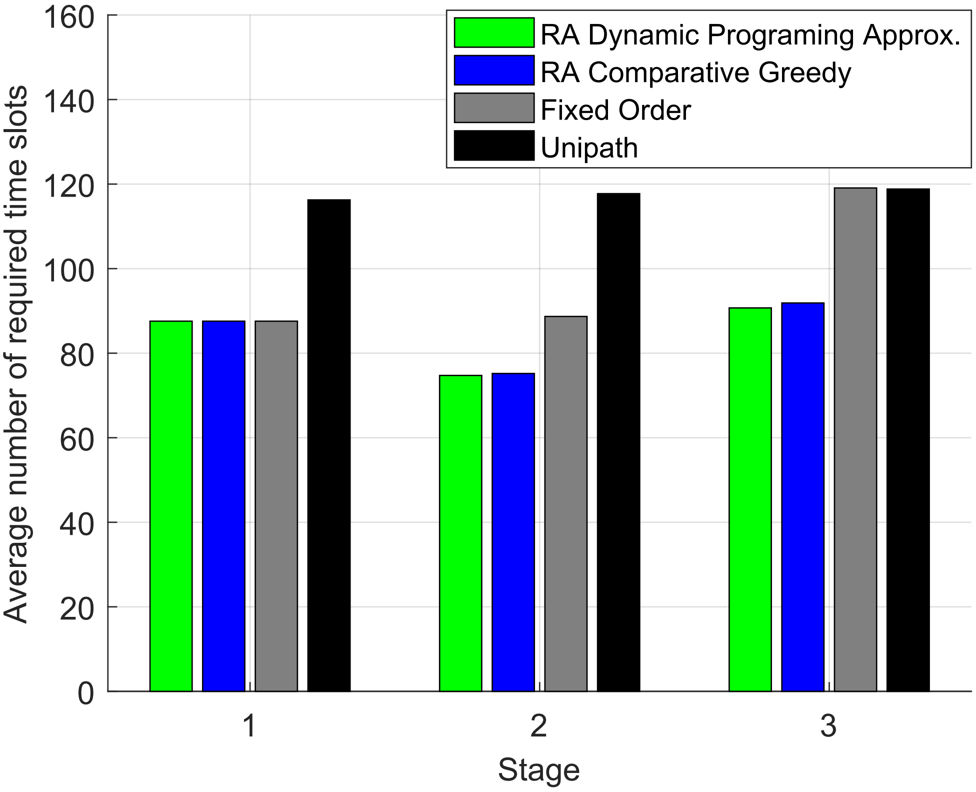

Figure 4.6. Average number of required time slots for each stage to forward 10.000 data packets with two forwarding nodes per cluster.

of the RA Dynamic Programming Approx. policy in the second and in the third stage.

To summarize, an optimal policy for the considered resource allocation problem can only be determined for a strictly limited number of data packets, cluster nodes, MCSs and channel resources per time slot. For increasing numbers regarding these parameters, approximation techniques and a subcarrier by subcarrier consideration are required to generate a resource allocation policy based on an MDP model and dynamic programming. The RA Dynamic Programming schemes outperform the other considered schemes. Compared to the Unipath scheme and the Fixed Order policy, significant gains are achieved. However, compared to the RA Comparative Greedy policy, the performance is only slightly better. Both schemes exploit the diversity not only on the receiver side, but also on the transmitter side of a stage by selecting an appropriate transmitter in each time slot based on the current channel state. In the Fixed Order policy, only the best receiver is selected but the transmitter is predetermined in each time slot. In the Unipath scheme both, the transmitter and receiver are fixed and independent on the actual channel conditions.

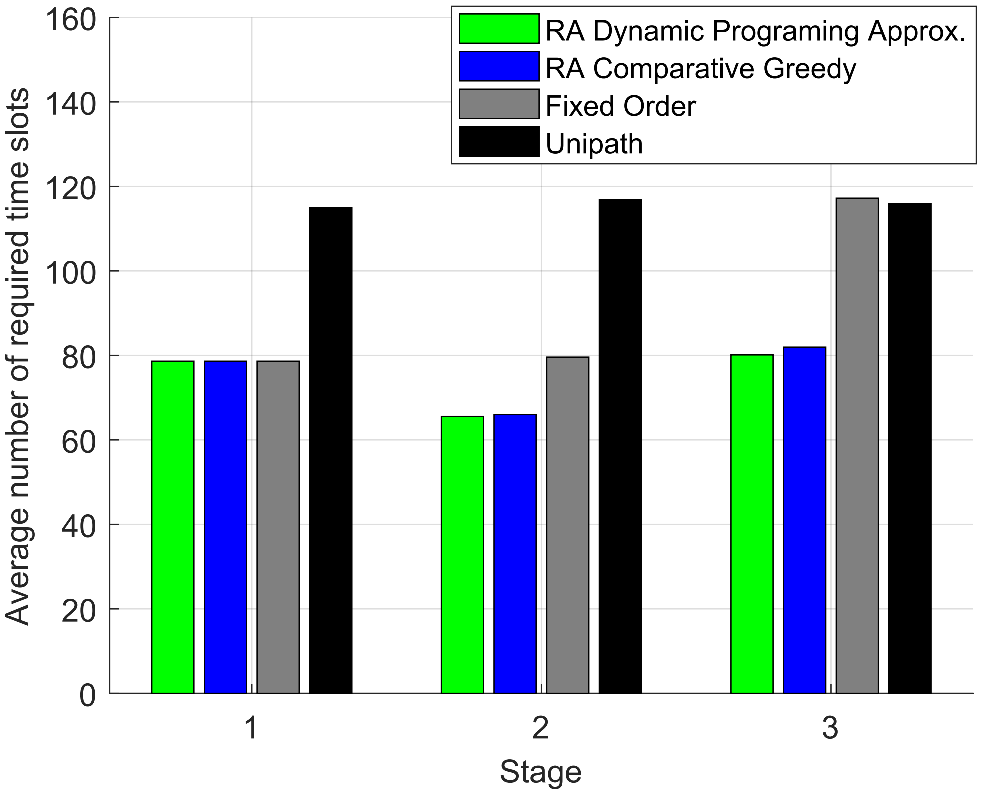

Figure 4.7. Average number of required time slots for each stage to forward 10.000 data packets with three forwarding nodes per cluster.

Chapter 5

Rateless Operation of Corridor-based Routing

5.1 Introduction

In this chapter, corridor-based routing in combination with fountain codes is investigated. Wireless data transmissions conventionally rely on fixed-rate channel coding. Thereby, an appropriate combination of channel code rate and modulation scheme is selected at the transmitter based on CSI or based on packet delivery success rates. This selection always comes with a trade-off between the achievable data rate and the robustness of the transmission. A higher transmission rate goes along with a higher risk for transmission failures. In the case of packet failures, costly retransmissions are required. Furthermore, providing accurate CSI at the transmitter in a wireless mobile network can be very challenging. Due to the dynamic nature of the wireless channels, the CSI can quickly become inaccurate and outdated.

An alternative approach to fixed-rate channel codes is given by fountain codes, also known as rateless codes. With fountain codes it is theoretically possible to generate an infinite number of encoded symbols from a set of source symbols [BYAH11] such that it is possible to recover these source symbols from any subset of encoded symbols that is only slightly larger than the set of source symbols. This property can be exploited to further improve the performance of corridor-based routing in multiple different ways. In the following, two different strategies based on fountain codes are investigated.

The rest of this chapter is organized as follows. In Section 5.2, the features and the basic functionality of fountain codes are explained. An extended system model is presented in Section 5.3. In Section 5.4, corridor-based routing based on a practical example of a fountain code, named Strider [GK11], is investigated. In Section 5.5, the utilization of distributed Multiple Input Single Output (MISO) transmissions in the corridor based on fountain codes is considered.

5.2 Fundamentals of Fountain Codes

The first fountain code was published by Michael Luby in [Lub02], followed by other fountain codes like Raptor [Sho06] or Strider [GK11]. The encoder of a fountain code can, like a fountain, theoretically provide an infinite number of encoded data packets from a fixed set of source data packets. A receiver can recover the corresponding source data from any set of a sufficient number of encoded packets. The required number of encoded data packets depends on the channel conditions. A transmitter continues to generate and transmit more encoded packets until the receiver is able to decode and sends back an Acknowledgment (ACK). Thereby, the resulting data rate automatically adapts to the channel conditions. With every additional transmission, the rate drops stepwise.

Fountain codes provide an important advantage for multi-hop transmissions. In a multi-hop network, not only the desired receiver can receive a signal but also subsequent nodes of the multi-hop transmission path can overhear the transmission. Based on the use of fountain codes, nodes can accumulate mutual information from multiple different signals which are transmitted by any transmitter and in any time slot. For this, each signal has to contain a differently encoded versions of a packet. In case that a packet is encoded in the same manner, a receiver could only accumulate energy from the signals instead of mutual information. In [MMYZ07], is has been shown that mutual information accumulation has a superior performance compared to energy accumulation. By using differently encoded versions, a receiver is able to decode as soon as

$$\sum_{s} \log_2(1+\gamma_s) \geq H_{\mathrm{data}}, \tag{5.1}$$

where γ_s denotes the SNR concerning a received signal with index s and H_{data} denotes the entropy of the source data packet. As a consequence, the number of encoded data packets that need to be transmitted along a multi-hop path might significantly decrease compared to the case of no overhearing by the following nodes or compared to the case without using fountain codes.

5.3 Extended System Model

In order to exploit the properties of fountain codes for corridor-based routing, an extended system model as depicted in Figure 5.1 is considered in the following. In the previous chapters, only the links between the transmitters and the receivers within a stage, referred to as stage links, are considered for the data transmission from the source to the destination. In the following, additional links within the corridor are taken into consideration. The links between transmitters of stage s to receivers of stage $s+1$ are referred to as inter-stage links. The links between the nodes within a cluster are referred to as intra-cluster links.

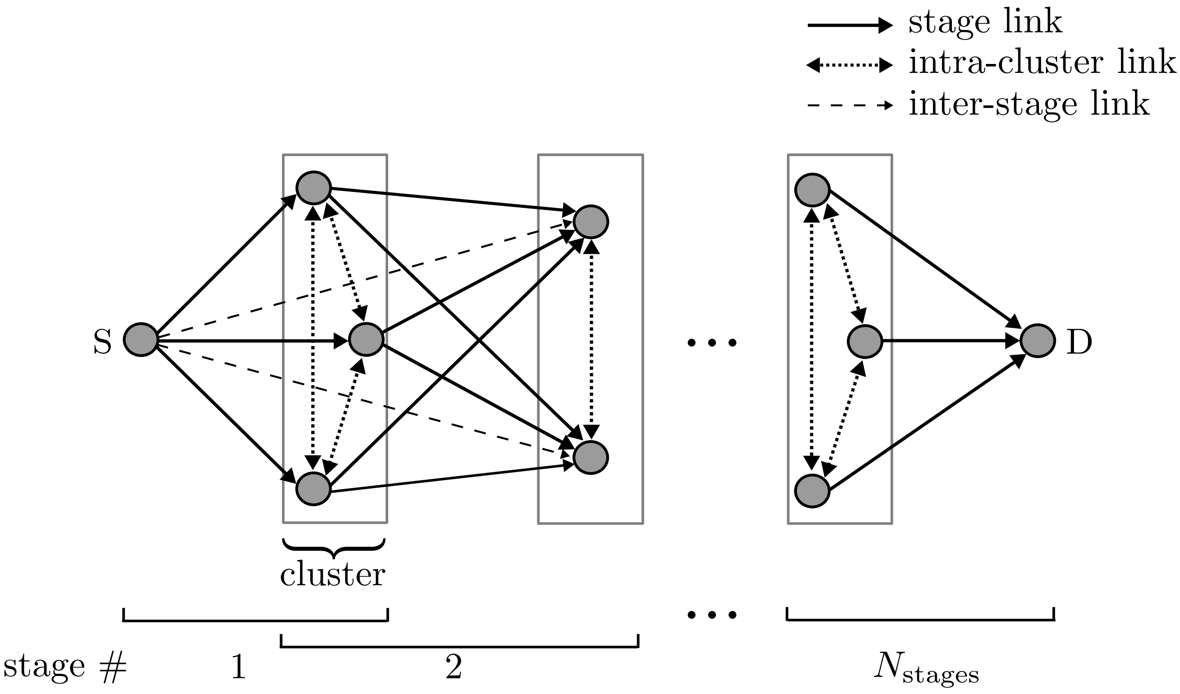

Figure 5.1. Extended system model including intra-cluster links, stage links and inter-stage links.

The underlying channel model is the same for all links as described in Section 2.3. In the following, two strategies are proposed to exploit inter-stage links and intra-cluster links, respectively, based on the use of fountain codes in the corridor.

5.4 Rateless Transmissions Using Strider

5.4.1 Automatic Rate Adaptation with Strider

In this section, Strider [GK11] is considered as a practical example to demonstrate the usefulness of fountain codes in corridor-based routing. Strider owes its name to a **Stri**pping Deco**der** that is used. Several parts of the content of this section have been originally published by the author of this thesis in [HK16]. Using Strider, data bits are first encoded using a 1/5 convolutional channel code and then mapped to complex Quadrature Phase Shift Keying (QPSK) symbols. A data packet contains QPSK symbols. The data packets are organized in data batches, each consisting of K data packets. To generate a transmit packet, the data packets of one certain data batch with index b are linearly combined using the coefficient matrix $\mathbf{R}$. The m-th linear combination is given by

$$\mathbf{p}_b^{(m)} = \rho_{1m}\mathbf{x}_1 + \rho_{2m}\mathbf{x}_2 + ... + \rho_{Km}\mathbf{x}_K, \tag{5.2}$$

where ρ_{im} is the i-th coefficient from the m-th row of $\mathbf{R}$ and the vector $\mathbf{x}_i$ contains the complex symbols of the i-th data packet in the corresponding data batch b. With each row of $\mathbf{R}$, a transmitter generates a different linear combination. A receiver needs to know the coefficients used for the generation of the linear combination for the decoding process. To this end, the coefficient matrix $\mathbf{R}$ is used as a codebook that is available at all nodes. A transmitter only needs to indicate which row was used for the generation of a transmit packet. In order to make use of mutual information accumulation, different linear combinations are required at a receiver. In case that a receiver would get the same linear combination twice, only energy could be accumulated. Therefore, the linear combinations are exclusively transmitted within each stage until a receiver is able to decode the corresponding data.

In the following stages, a certain linear combination is only used again by a forwarding node in case that the upcoming receivers have not overheard this linear combination before. It is assumed that only nodes in adjacent stages can overhear transmissions, i.e., only the receivers of stage s and the receivers of stage $s+1$ can receive transmissions from the transmitters of stage s. Therefore, the reuse of the rows of the coefficient matrix $\mathbf{R}$ is performed in every second stage in the corridor. A more detailed description of the functionality of Strider can be found in [GK11].

5.4.2 Resource Allocation Strategy Based on Strider

Applying Strider in corridor-based routing, the availability of CSI at the source is not necessarily required since there is no need for choosing a transmission rate. Nevertheless, CSI knowledge could be used to monitor the progress of mutual information accumulation of the different nodes concerning the different data batches and adapt the batch to subcarrier scheduling accordingly. However, the achievable gains are expected to be rather small, especially because the cost for channel estimation needs to be compensated. Therefore, a fixed ordered batch-subcarrier-scheduling is used at the source node.

In the first stage, a different data batch is assigned to each subcarrier. In the first time slot, the first linear combination of the corresponding data packets is transmitted according to the coefficient matrix $\mathbf{R}$. In each following time slot, a new linear combination is generated and transmitted until at least one receiver acknowledges the successful decoding of a certain data batch. In this case, the vacant subcarrier is loaded by the next data batch in line. In case that the number of remaining data batches to be transmitted is below the number of subcarriers, multiple different linear combinations of the remaining data batches are transmitted simultaneously on different subcarriers.

An example of the batch-subcarrier-scheduling procedure with $N_{\text{sc}} = 4$ subcarriers and four data batches that need to be transmitted is given in Figure 5.2. In this example, an ACK is transmitted concerning data batch $b = 2$ after the first time slot. In the second time slot, the vacant second subcarrier is used to transmit the third linear combination of the first data batch in parallel to the transmission of the second linear combination of this data batch on the first subcarrier. By receiving the ACK concerning data batch $b = 1$ after the second time slot, only two data batches are left. Therefore, two different linear combinations of each remaining data batches are transmitted on the four available subcarriers. After the third time slot, the remaining data batches ($b = 2, 3$) are successfully received.

By broadcasting ACKs after the successful decoding of a data batch, the receiver does not only inform the preceding transmitter, but also the other nodes within its own cluster. This means that all cluster nodes can store the availability of the different data batches within their cluster in a matrix $\mathbf{A}$. The (i, b)-th element $a_{i,b}$ in this availability-matrix equals 1 in case that node i of the cluster was able to decode data batch b and it equals 0 if this was not the case. If a data batch is available at multiple forwarding nodes of a cluster, matrix $\mathbf{A}$ is used for the coordination of the data batch forwarding. From the second stage on, the transmission strategy for each time slot is performed in two steps. In the first step, the data batches to be transmitted and their corresponding transmit nodes are selected for the upcoming time slot. Since there is one data batch transmitted on each subcarrier, N_{sc} data batches need to be selected.

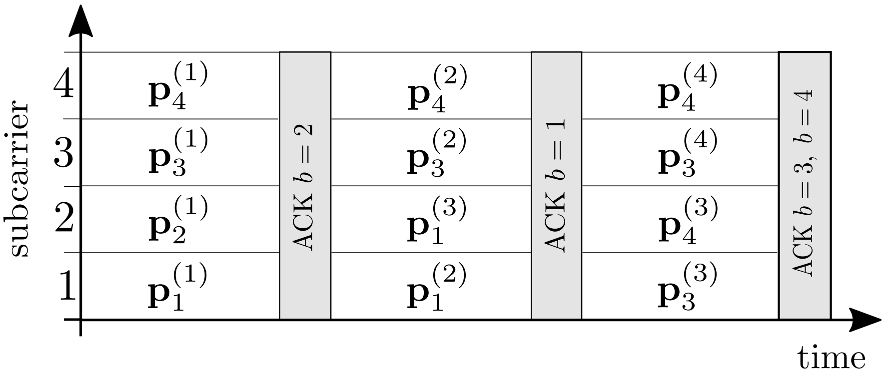

Figure 5.2. Batch-subcarrier-scheduling example with $N_{\text{sc}} = 4$ subcarriers and four data batches.

In the second step, the available subcarriers are allocated among the forwarding nodes.

The data batch scheduling for each time slot is performed using Algorithm 5. To balance the load of the forwarding process and to efficiently exploit the diversity of links within a stage, the algorithm is designed to preferably assign the same amount of data batches to each forwarding node of the current cluster. The data batches to be transmitted by node i in the upcoming time slot are stored in set $\mathcal{S}_i^{\text{batch}}$ which is initially empty for all forwarding nodes. Furthermore, the availability-matrix $\mathbf{A}$ as well as a temporary copy $\mathbf{A}^{\text{temp}}$ are required. First, transmitter i is selected which has the minimum number of data batches in its set $\mathcal{S}_i^{\text{batch}}$ but at least one data batch available for transmission ($a_{i,b}^{\text{temp}} = 1$ for any b). In case that multiple transmitters have the same number of available data batches, the node with the lowest index i is selected. Next, data batch b is selected which is available at node i and which is available at a minimum number of other nodes. Thereby, data batches are preferred that are exclusively available at certain nodes. Thereby, these data batches are forwarded first which enables more options at the end of the data batch scheduling process when only a few data batches are left to be forwarded. Next, the selected data batch b is added to set $\mathcal{S}_i^{\text{batch}}$ and all elements $a_{i,b}^{\text{temp}}$ are set to 0 for all transmitters i. This ensures that data batch b is not selected again. Finally, it is checked if there are data batches left to be transmitted in matrix $\mathbf{A}^{\text{temp}}$. If this is not the case, this means that the remaining number of data batches that need to be transmitted is lower than the number of subcarriers. In this case, the elements in matrix $\mathbf{A}^{\text{temp}}$ are set back to the default values of matrix $\mathbf{A}$. This enables multiple selections of the same data batches within one time slot. As mentioned before, in this case, different linear combinations of the data batch are generated and transmitted in parallel on the different subcarriers.

Algorithm 5 Batch scheduling

```
Require: Availability-matrix $\mathbf{A}$, $\mathbf{A}^{\text{temp}}$ and a set $\mathcal{S}_i^{\text{batch}} := \{\}$ for each transmitter $i$ in current stage to store assigned data batches
  for $n = 1$ to $N_{\text{sc}}$ do
    1) Select transmitter $i$ with $\min_i |\mathcal{S}_i^{\text{batch}}|$ and $\sum_{b=1}^{N_{\text{batches}}} a_{i,b}^{\text{temp}} \neq 0$;
    in case of conflict select node with lowest index $i$
    2) Select data batch $b$ with $\min_b \sum_{i=1}^{N_{\text{cn}}} a_{i,b}^{\text{temp}}$ and $a_{i,b}^{\text{temp}} = 1$;
    in case of conflict select data batch with lowest index $b$
    3) Add data batch $b$ to set $\mathcal{S}_i^{\text{batch}}$ and set $a_{i,b}^{\text{temp}} := 0$ for all transmitters $i$
    4) If $\sum_{b=1}^{N_{\text{batches}}} \sum_{i=1}^{N_{\text{cn}}} a_{i,b}^{\text{temp}} = 0$ set $\mathbf{A}^{\text{temp}}$ back to default values of $\mathbf{A}$
  end for
```

Algorithm 6 Subcarrier allocation

```
Require: SNR values $\gamma_{i,j,n}$ of current stage and set $\mathcal{S}_i^{\text{batch}}$ of batches to transmit for each transmitter $i$ of current stage
  for $n = 1$ to $N_{\text{Sc}}$ do
    1) Determine subcarrier $n$ and transmitter $i$ with $\max_{n,i} (\gamma_{i,j,n})$ and $|\mathcal{S}_i^{\text{batch}}| \neq 0$
    2) Allocate subcarrier $n$ to the corresponding transmitter $i$ and cancel out first batch of set $\mathcal{S}_i^{\text{batch}}$
  end for
```

After the data batches and their corresponding transmitters are selected, the subcarriers are allocated for the upcoming time slot using Algorithm 6. Each forwarding node requires one subcarrier per assigned data batch. The allocation process is based on the SNR values of the subcarriers and the sets $\mathcal{S}_i^{\text{batch}}$ of assigned data batches. In each iteration of the algorithm, subcarrier n and the corresponding transmitter i are determined which provide the highest SNR. Of course, only transmitters with a non-empty set of data batches are considered. Next, the first data batch out of set $\mathcal{S}_i^{\text{batch}}$ is assigned for transmission on subcarrier n and canceled out of the set before the next iteration of the algorithm begins. This procedure is repeated until all sets are empty which means that all data batches are assigned to a certain subcarrier. If a receiver of the current stage sends an ACK to declare a successful decoding of a data batch b, the corresponding elements in matrix $\mathbf{A}$ are set to 0 ($a_{i,b} := 0,\ \forall i$) which means that batch b is not considered in upcoming scheduling cycles. Algorithm 5 and 6 are executed within each time slot until all data batches are decoded by the receivers of the current stage.

5.4.3 Performance Evaluation

In this section, the performance of the proposed corridor-based forwarding strategy using Strider, in the following termed 'CbR Strider', is investigated and compared to forwarding bases on an unipath through the corridor. In order to investigate the impact of overhearing on the performance of the proposed corridor-based forwarding scheme, the CbR Strider scheme is also considered without overhearing ('CbR Strider w/o OH'). Without overhearing means that the inter-stage links are ignored and not exploited. Nodes only receive transmissions from the transmitter of their corresponding stage.

The unipath scheme which is considered as a benchmark also uses Strider for its transmissions. The transmission strategy along the unipath is equal to the proposed corridor-based strategy that is used in the first stage. For the unipath scheme, only a single randomly selected receiver is used in each stage of the corridor. This means that the transmission is continued until this single receiver has successfully received the whole data. In the unipath scheme, no overhearing is considered using the inter-stage links.

In the following, the system parameters according to Table 5.1 are assumed. Corridors with $N_{\text{stages}} = 4$ stages are considered with a maximum cluster size of $N_{\text{cn,max}} = 2, 3$ or 4. The number of available subcarriers is $N_{\text{sc}} = 12$. It is assumed that the average distance between a transmitter of stage s and a receiver of stage $s + 1$ (inter-stage link) equals twice the distance between a transmitter and a receiver of stage s (stage link). According to the path loss exponent $\alpha_{\text{PL}} = 3$, this leads to an additional path loss of 9 dB for inter-stage links compared to stage links. The transmit power per subcarrier is $p_n = 1\,\text{mW}$. In each simulation run, 40 data batches are transmitted from the source to the destination. Each data batch consists of 33 data packets and each data packets contains 378 bits. In [GK11], the used values for the size of the data packets and the data batches have shown a good performance in the considered SNR region.

In Figure 5.3, the average end-to-end throughput between the source and the destination is shown for a corridor with $N_{\text{cn,max}} = 3$ nodes per cluster and different average stage link SNR conditions. It can be seen that the corridor-based schemes significantly outperform the Unipath scheme for all considered SNR values. The relative achieved gain of CbR Strider compared to the Unipath scheme decreases

Table 5.1. System parameters

Number of stages N_{stages}	4
Maximum number $N_{\text{cn,max}}$ of transmit nodes per cluster	$\{2, 3, 4\}$
Number N_{sc} of subcarriers	12
Path loss exponent α_{PL}	3
Total transmit power per subcarrier p_n	1 mW
Data packet size	378 bits
Batch size K	33 data packets
Total number of batches	40

for increasing SNR. For an average stage link SNR of 10 dB, CbR Strider achieves a 77 % higher throughput compared to the Unipath scheme. For an average stage link SNR of 25 dB, the gain equals 63 %. The decreasing relative gain for higher SNR values is based on the logarithmic growth of the channel capacity with the SNR. This results in a stronger impact of diversity for low SNR conditions. The gain achieved by overhearing using the inter-stage links varies over the SNR. The 1/5 static channel coding and the QPSK modulation used in Strider are selected to achieve the best performance in a target SNR range of 3 - 25 dB [GK11]. However, due to its granularity, Strider does not adapt equally good at all SNRs. For an average stage link SNR of 10 dB, the average inter-stage link SNR equals only 1 dB. In this case, CbR Strider achieves 14 % higher throughput than CbR Strider w/o OH. The highest gain is achieved for an average stage link SNR of 20 dB. In this case, the throughput is increased by 35 % by utilizing the overhearing via inter-stage links. For an average stage link SNR of 25 dB the gain drops to 31 %.

For high stage link SNRs, the impact of Strider's granularity becomes more critical. For instance, the resulting throughput drops by 50 % in case of using 2 transmissions instead of just one. In the case of using 6 transmissions instead of 5, the throughput drops only by 17 %. This means that for high SNR conditions in which only a small number of transmissions are required, the relative drop in terms of the throughput caused by an additional transmission is bigger than for low SNR conditions.

In Figure 5.4, the average number of required transmitted linear combinations is shown in each stage of the corridor for an average stage link SNR of 20 dB. Of course, in the first stage, the overhearing via inter-stage links has no impact. Therefore, CbR Strider and CbR Strider w/o OH perform the same. Compared to the Unipath scheme, CbR Strider requires 23 % less linear combinations for successful decoding in the first

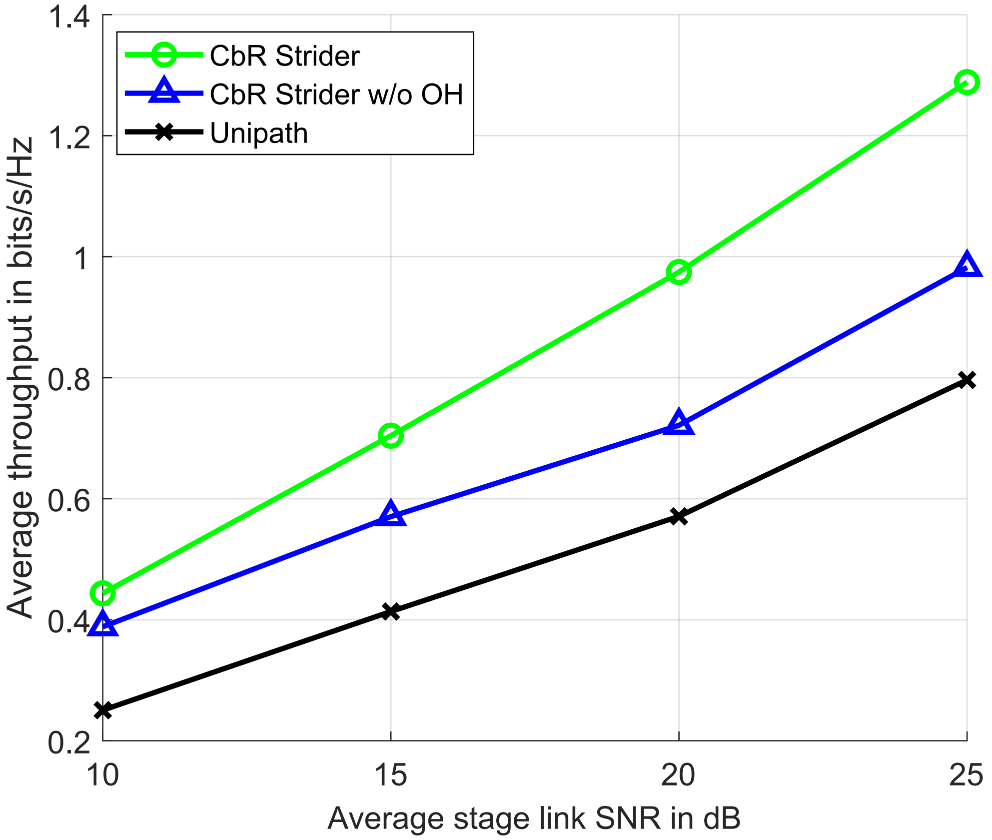

Figure 5.3. Average achievable throughput in a corridor with 4 stages and 3 nodes per cluster based on Strider.

stage. In the second stage, the benefit of overhearing is demonstrated. Due to the already accumulated mutual information at the receivers of the second stage, in most of the cases, only one or two additional linear combinations are required to be sent by the transmitters of the second stage. This results in 65 % and 73 % less required linear combinations compared to CbR Strider w/o OH and to the Unipath scheme, respectively. Because of the low number of transmissions in the second stage, the overhearing does not lead to significant savings in the third stage. In most of the cases, the overheard transmissions do not reduce the required number of transmissions in the third stage. Therefore, CbR Strider and CbR Strider w/o OH perform almost the same. CbR Strider requires 24 % less linear combinations than the Unipath scheme. Due to the higher number of transmissions in the third stage, the impact of the overhearing becomes more significant in the last stage. Compared to the Unipath scheme, CbR Strider requires 47 % less linear combinations.

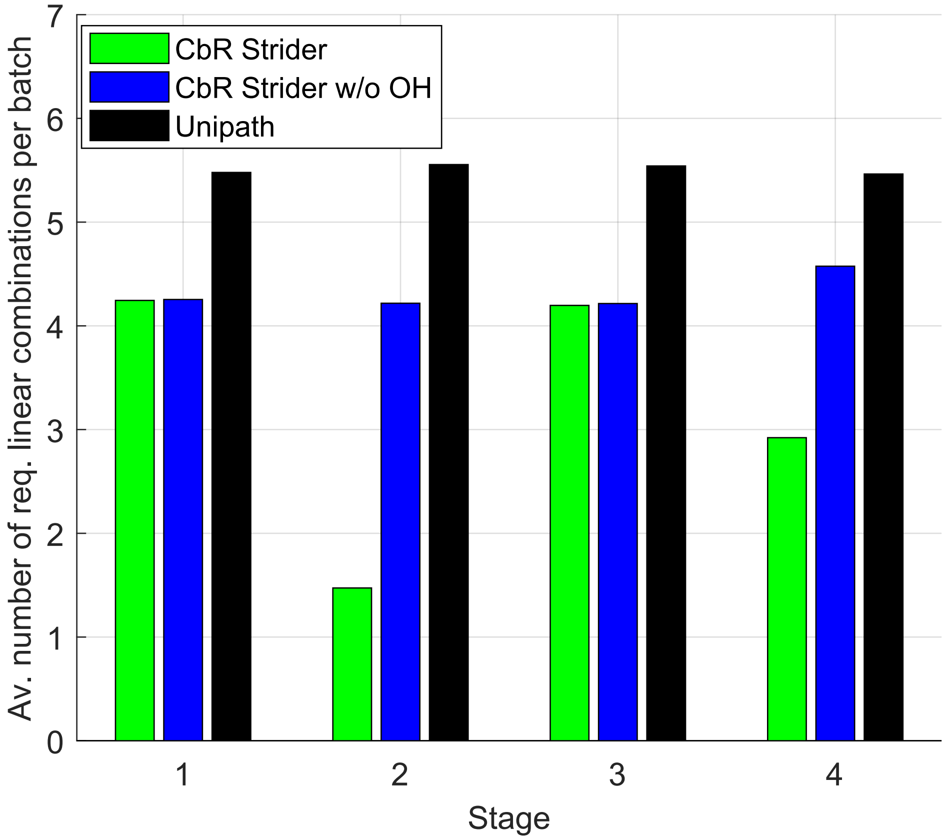

Figure 5.4. Average number of required linear combinations per batch for successful decoding for an average stage link SNR of 20 dB.

Figure 5.5 shows the impact of the number of cluster nodes on the average end-to-end throughput for an average link SNR of 20 dB. It can be seen that the average throughput increases with and without overhearing with each additional cluster node. Furthermore, the gain that is achieved by overhearing increases with an increasing number of cluster nodes. However, the additional gain decreases with each additional cluster node. With three cluster nodes CbR Strider achieves a 6 % higher throughput compared to a corridor with only two cluster nodes. Increasing the number of cluster nodes to four leads to an additional gain of 3 % compared to a cluster size of three.

To summarize, based on fountain coding, mutual information accumulation can be exploited in the corridor not only for stage links, but simultaneously for inter-stage links. This overhearing strategy can further improve the performance of corridor-based routing compared to a forwarding strategy along a unipath by up to 77 % in terms of end-to-end throughput.

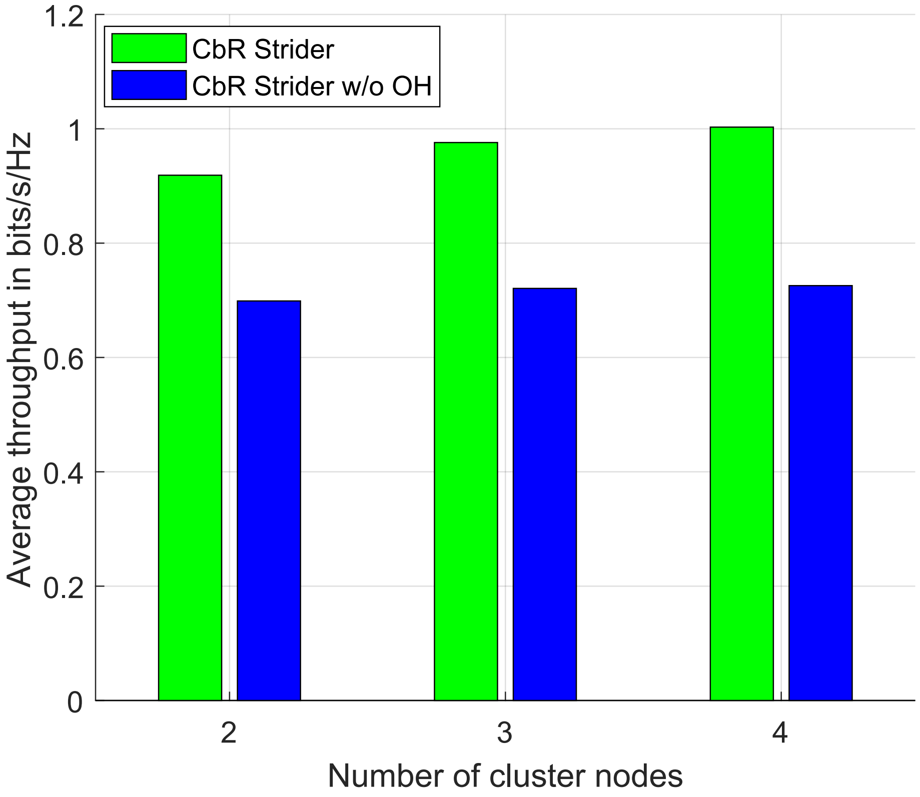

Figure 5.5. Average achievable end-to-end throughput for different cluster sizes for an average stage link SNR of 20 dB.

5.5 Corridor-based Routing Using Distributed MISO

5.5.1 Beamforming with Single Antenna Nodes

In the following, the utilization of the intra-cluster links based on fountain codes is investigated. For simplicity reasons, the previously proposed exploitation of the inter-stage links is not considered in this section. However, the proposed schemes in this section could be easily extended to also benefit from overhearing through the inter-stage links.

In many recent wireless communication systems, multiple antenna techniques are used to improve the performance compared to single antenna systems. Multiple Input Multiple Output (MIMO) technology uses multiple antennas at a transmitter and a receiver. The spatial diversity between the different antennas can be exploited to provide an increased link capacity or to increase the reliability of the link. Multiple antennas can be used to generate a spatial filtering also known as beamforming. By a signal processing adapted to the wireless channels, signals are manipulated such that they constructively interfere at the receiver which leads to an amplification of the signal strength. However, many mobile devices and sensor nodes are only equipped with a single antenna and in this work, only single antenna nodes are considered.

Nevertheless, beamforming can be performed also with multiple cooperative single antenna nodes. The prerequisite for this is that the corresponding data that should be transmitted is available at multiple transmit nodes. By adjusting the phase of the transmit signals according to the channels to the desired receiver, a distributed Multiple Input Single Output (MISO) system is created and a beamforming effect can be exploited.

In the following, the potential gains of distributed MISO transmissions within the corridor are analyzed. Furthermore, a forwarding strategy is introduced that enables distributed MISO transmissions within the corridor. Several parts of the content of this section have been originally published by the author of this thesis in [HK17].

5.5.2 Best-of-Selection vs. MISO Diversity Gain Analysis

A major advantage of the corridor structure compared to unipath transmissions relies on the availability of multiple potential receivers and the individual adaptation of the data rate on each subcarrier to only the strongest receiver. Thereby, each transmitted data packet is usually successfully received by only one node. In order to enable distributed MISO transmissions within the corridor, the same data packet needs to be available at multiple forwarding nodes of a certain cluster. To enable successful decoding at multiple receivers, either the data rates need to be reduced and adapted to weaker links or additional transmissions between the cluster nodes are required to exchange the data packets within the cluster. In both cases, additional effort needs to be spent to enable distributed MISO transmissions and it is questionable if this effort pays off in the resulting achievable data throughput.

In the following, in order to verify the usefulness of this approach within the corridor, the potential gains of distributed MISO transmissions are analyzed. As a benchmark, a best-of-selection of a single transmitter out of multiple options is considered, as this is used by the previously introduced approaches in this work. For simplicity reasons, a scenario consisting of N_{cn} potential transmit nodes but only a single receiver and only a single subcarrier is considered. Therefore, only the transmitter index i is considered in the channel transfer factor h_i without an index for the receiver or the subcarrier.

First, the average capacity using Single Input Single Output (SISO) transmissions, i.e, using only a single transmitter and a single receiver, is derived. It is assumed that multiple transmitter options are available. Out of the transmitter options only the best transmitter is selected for transmission. The magnitude of the received signal using the strongest channel is given by

$$A_{\mathrm{max}} = \max_i \sqrt{p_{\mathrm{sc}}} \cdot |h_i| \tag{5.3}$$

The PDF of A_{max} can be derived analogously to the derivation given in Section 4.4.1.2. The resulting PDFs for different numbers N_{cn} of transmitters is shown in Figure 5.6 a). The resulting average channel capacity of the best-of-N_{cn} selection is given by

$$\bar{C}_{\text{best-of}} = \int_0^{\infty} \mathrm{pdf}(A_{\mathrm{max}}) \cdot \log_2 \left(1 + \frac{(A_{\mathrm{max}})^2}{\sigma_{\mathrm{n}}^2}\right) \mathrm{d}A_{\mathrm{max}}. \tag{5.4}$$

Next, the average capacity of distributed MISO transmissions is considered in case that all available transmitters participate in the transmission. In order to maximize the SNR at the receiver, each transmitter needs to use a specific beam weight to adapt its transmit signal to its channel. To this end, each transmitter i uses a beam weight $\alpha_i = \frac{h_i^*}{|h_i|}$ that compensates the phase of its transmit channel. Thereby, the signals from the different transmitters interfere in a constructive manner at the receiver and the resulting SNR is maximized and is given by

$$\begin{aligned} \gamma_{\mathrm{miso}} &= \frac{\left(\sum_i^{N_{\mathrm{cn}}} \sqrt{p_{i,n}} |h_i|\right)^2}{\sigma_{\mathrm{n}}^2} && (5.5) \\ &= \frac{A_{\mathrm{miso}}^2}{\sigma_{\mathrm{n}}^2}, && (5.6) \end{aligned}$$

where the total transmit power per subcarrier p_{sc} is equally distributed among the different transmitters such that the transmit power of each transmitter is given by $p_{i,n} = \frac{p_{\mathrm{sc}}}{N_{\mathrm{cn}}}$. The PDF of the magnitude A_{miso} of the received MISO signal for different numbers N_{cn} of transmitters is shown in Figure 5.6 b). The average channel capacity using the distributed MISO transmissions is given by

$$\bar{C}_{\mathrm{miso}} = \int_0^{\infty} \mathrm{pdf}(A_{\mathrm{miso}}) \cdot \log_2 \left(1 + \frac{(A_{\mathrm{miso}})^2}{\sigma_{\mathrm{n}}^2}\right) \mathrm{d}A_{\mathrm{miso}}. \tag{5.7}$$

The average achievable capacities of the best-of-selection and of the distributed MISO approach are shown in Figure 5.6 c). All considered links provide an average SNR of 10 dB. It can be seen that the distributed MISO approach significantly outperforms the best-of-selection approach. The achievable capacity gain of distributed MISO compared to the best-of-selection increases for an increasing number of transmitters. For $N_{\mathrm{cn}} = 4$, distributed MISO provides a 69 % higher average capacity compared to the case with $N_{\mathrm{cn}} = 1$ while the best-of-selection only provides a 46 % higher average capacity. It can be seen that distributed MISO transmissions provide a high potential gain for corridor-based routing.

However, as mentioned before, the same data packets need to be available at multiple cluster nodes to enable these distributed MISO transmissions within the corridor. Therefore, additional effort needs to be spent compared to the previously proposed forwarding strategies. In the following, a strategy is introduced to enable distributed MISO transmissions within the corridor based on an additional data exchange phase between the nodes within each cluster.

5.5.3 Resource Allocation Based on Cluster Transmission Phases

5.5.3.1 Introduction

According to the previously investigated forwarding strategies, transmitters adapt the data rate on each subcarrier, which they use, to the strongest available receiver of the current stage. Under the use of fountain codes, the transmission of certain data is stopped as soon as the strongest receiver was able to decode it successfully. Thereby, usually, only one receiver is able to decode each data packet. It may happen, due to multiple available receivers with similar SNR conditions, that multiple receivers are able to decode the same data packets. However, this only happens by chance and in rare cases following the previously discussed strategies.

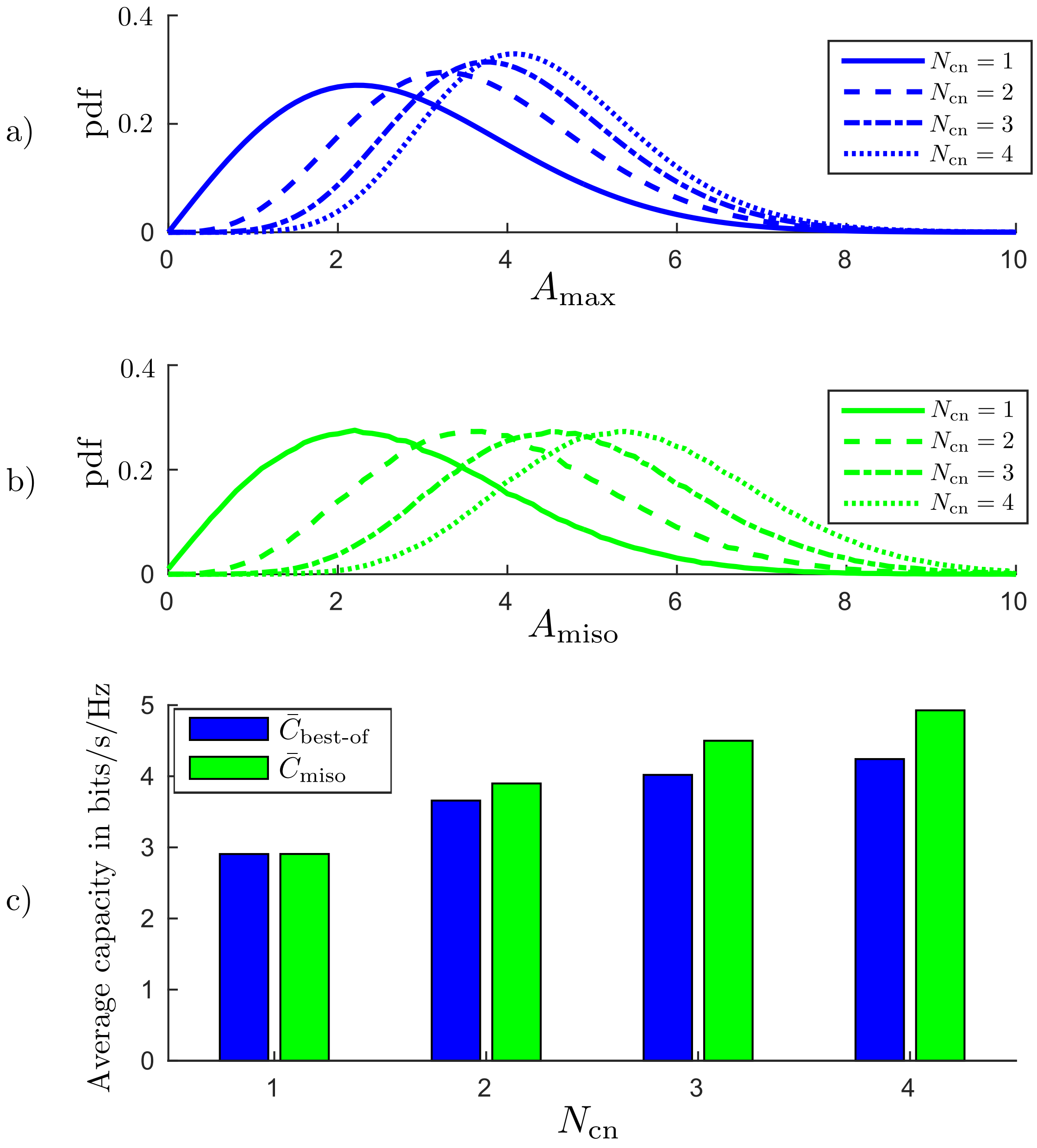

Figure 5.6. Comparison between best-of selection and MISO transmissions for different numbers N_{cn} of transmitters. a) PDF of the signal magnitude A_{max} resulting from a best-of selection. b) PDF of the signal magnitude A_{miso} resulting from a distributed MISO transmission approach. c) Average channel capacity of best-of selection and distributed MISO approach for different numbers of transmitters.

When fountain codes are used for transmissions, all receivers accumulate mutual information from the different received signals up to a certain level. Even if a certain receiver is not able to decode data by the time the strongest receiver is able to, the overheard transmissions can be very useful. To enable the weaker receivers to decode the corresponding data packets, only a remaining gap needs to be filled which is given by

$$H_{\text{gap}} = H_{\text{data}} - \sum_{s} \log_2(1 + \gamma_s), \tag{5.8}$$

where H_{data} denotes the entropy of the data packet and γ_s denotes the SNR of a signal with index s that has been received and contained an exclusively encoded version of the corresponding data packet. The remaining gap can be filled by additional transmissions of the currently transmitting nodes. However, by the time one receiver of a certain cluster has successfully decoded the data, it also becomes able to generate additional encoded data to fulfill this task. Since the nodes within a certain cluster are on average placed closer to each other than the transmitters to the receivers of a stage, the links within the cluster tend to have a higher SNR. Therefore, it is more efficient to exchange data between the cluster nodes in order to fill up the remaining gaps in terms of mutual information and to make data available at multiple forwarding nodes within a certain cluster.

To this end, a two-phase protocol is proposed, consisting of an intra-cluster distribution phase and an inter-cluster forwarding phase. In the intra-cluster distribution phase, the cluster nodes are aiming for an exchange of data within the cluster to make it available at multiple nodes. Due to the half-duplex limitation of the nodes, there is always only a single node transmitting at a time while the other cluster nodes are receiving. In the inter-cluster forwarding phase, the cluster nodes forward data jointly utilizing distributed MISO transmissions. In the following, a detailed description of the intra-cluster distribution and the inter-cluster forwarding strategy is given.

5.5.3.2 Intra-Cluster Distribution Phase and Inter-Cluster Forwarding Phase

In the first stage, the transmission strategy introduced in Section 5.4.2 is used. This leads to a certain distribution of the data packets among the nodes in the first cluster. The distribution of the data packets is tracked by the cluster nodes by receiving each others' ACKs. After all data packets are successfully decoded by at least one cluster node of the first cluster, the intra-cluster distribution phase begins. In this phase, there is always only a single node of the cluster transmitting at a time. This allows the other nodes of the same cluster to receive the transmissions as illustrated in Figure 5.7 a). The cluster nodes utilize this transmission phase in a round robin manner such that each node can distribute the data packets that could not be decoded by the other nodes of the cluster so far. During this transmission phase, also the nodes of the next cluster can overhear the transmission to reduce the required transmission time for the following inter-cluster forwarding phase.

Since there is always only one node transmitting at a time in the intra-cluster distribution phase, this node uses all available resources and there is no adaptive allocation of the subcarriers taking place. As a consequence, the achievable stage throughput, regarding the links to the next cluster, is significantly lower compared to a simultaneous cooperative transmission of multiple nodes with an adaptive subcarrier allocation. Therefore, the intra-cluster distribution phase comes at the cost of a temporarily lowered data throughput to the next cluster which should at least be compensated by the increased throughput by the utilization of distributed MISO transmissions.

The question arises how much data should be exchanged among the nodes within a cluster for an optimal overall result. It may be too expensive to provide all data packets to all cluster nodes. Therefore, two approaches are proposed in the following. In the first approach, a full distribution of data packets within the cluster is performed, while in the second approach, an adaptive partial distribution is performed based on the CSI knowledge of the nodes.

In the inter-cluster forwarding phase, all cluster nodes transmit simultaneously while sharing the available channel resources. Therefore, the corresponding transmit nodes are not able to receive any more data packets, but only the nodes of the next cluster are receiving during this time as shown in Figure 5.7 b). When data packets are available at multiple forwarding nodes of the current cluster, they can share a common subcarrier to transmit the same data packet. In this case, the nodes also share the transmit power such that the transmit power per subcarrier is always constant. For an optimal power allocation, water filling [CT06] could be used. However, since power allocation according to water-filling does only provide considerable gains for very low SNR conditions it is not considered in this work. Furthermore, a fixed power limitation per subcarrier enables a fair comparison between different approaches.

5.5.3.3 Forwarding Based on Full Intra-Cluster Distribution

In this section, forwarding based on full intra-cluster distribution of the data packets is considered. By overhearing each others' ACKs, all nodes within a cluster are

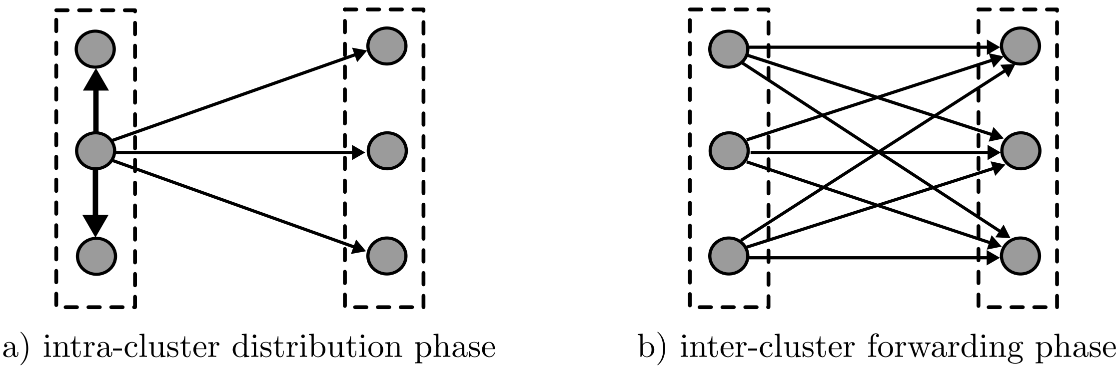
a) intra-cluster distribution phase b) inter-cluster forwarding phase

Figure 5.7. a) Intra-cluster transmission phase: A single cluster node is transmitting. All other nodes are receiving. b) Inter-cluster forwarding phase: All nodes within the cluster share the available resources and transmit simultaneously. Data packets that are available at multiple transmitters can be forwarded using distributed MISO transmissions.

aware of the availability of the data packet at the other cluster nodes. Based on this information, each node i maintains a set $\mathcal{S}_i$ that contains all data packets that are available at node i of the cluster, but which are not available at all other nodes of the cluster. The cluster nodes successively utilize the intra-cluster distribution phase. The scheduling of the data packets from set $\mathcal{S}_i$ to the subcarriers is done using Algorithm 7. According to this algorithm, different data packets are assigned to each subcarrier. In case that the number of data packets in set $\mathcal{S}_i$ is smaller than the number of subcarriers, the data packets are assigned to multiple subcarriers, but using different fountain codes to represent the data packet. By using different fountain coded versions of the data packets, the receiver can accumulate mutual information from the different received signals instead of accumulating energy by receiving the same coded version of the data packets on multiple subcarriers. Each node utilizes the intra-cluster distribution until its set $\mathcal{S}_i$ is empty and all of its data packets are available at all other nodes within the current cluster. Therefore, by the end of the intra-cluster distribution phase, all data packets are available at all nodes of the cluster.

In the inter-cluster forwarding phase, the cluster nodes cooperate and transmit in a distributed MISO manner on all subcarriers. For the scheduling of data packets to subcarriers, again Algorithm 7 is used. The set $\mathcal{S}_i$ is replaced by set $\mathcal{S}$ that contains all data packets that are not decoded by at least one node of the next cluster. Next, for each subcarrier n, a receiver j needs to be found to which the transmit nodes adapt their beam weight. This receiver is selected based on the expected time that each receiver would require to successfully decode the corresponding data packet k under the current channel state of subcarrier n. This required time is given by

$$t_{\mathrm{req},j,n_k} = \frac{H_{\mathrm{data}} - H_{j,k}}{C_{\mathrm{miso},j,n}}, \tag{5.9}$$

where $H_{j,k}$ denotes the mutual information that node j has already accumulated during the inter-cluster forwarding phase and $C_{\mathrm{miso},j,n}$ denotes the channel capacity on subcarrier n provided by adapting the beam weights of all transmitters to the channel to receiver j. The already accumulated mutual information $H_{j,k}$ can be determined and tracked by the transmitters based on the exchanged CSI. The achievable MISO capacity is given by

$$C_{\mathrm{miso},j,n} = \log_2\left(1 + \frac{\left(\sum_i^{N_{\mathrm{cn}}} \sqrt{p_{i,n}}|h_{i,j,n}|\right)^2}{\sigma_{\mathrm{n}}^2}\right), \tag{5.10}$$

with $p_{i,n} = p_{sc}/N_{\mathrm{cn}}$. For each subcarrier n, the receiver j is determined which provides the lowest t_{req,j,n_k}. The corresponding beam weight used at transmitter i is given by

$$\alpha_{i,n} = \frac{h_{i,j,n}^*}{|h_{i,j,n}|}. \tag{5.11}$$

Data packets that are decoded by at least one node of the next cluster are removed from set $\mathcal{S}$. The inter-cluster forwarding phase is continued until the set $\mathcal{S}$ is empty which means that all data packets are available at the nodes of the next cluster.

Algorithm 7 Assignment of data packets to subcarriers

```
Require: Set $\mathcal{S}_{\mathrm{packets}}$ of all undecoded data packets
    set $\mathcal{S}^*_{\mathrm{packets}} := \mathcal{S}_{\mathrm{packets}}$ (temporary copy)
    for $n = 1$ to $N_{\mathrm{sc}}$ do
        1) Assign first element of $\mathcal{S}^*_{\mathrm{packets}}$ to subcarrier $n$
        2) Cancel selected packet out of set $\mathcal{S}^*_{\mathrm{packets}}$
        if $\mathcal{S}^*_{\mathrm{packets}} = \{\}$ (empty) then
            3) Set $\mathcal{S}^*_{\mathrm{packets}} := \mathcal{S}_{\mathrm{packets}}$
        end if
    end for
    Cancel acknowledged packets out of $\mathcal{S}_{\mathrm{packets}}$
```

5.5.3.4 Forwarding Based on Partial Adaptive Intra-Cluster Distribution

As mentioned before, the required intra-cluster distribution phase, in which only a single node is transmitting at a time, comes at the cost of reduced data throughput to the next cluster compared to a common transmission of all cluster nodes with an adaptive subcarrier allocation. Therefore, this phase should be kept as short as possible. Furthermore, an additional transmitter that takes part in a distributed MISO transmission does not necessarily lead to a higher data throughput in case that the total transmit power stays the same. According to (5.6), the resulting SNR at the receiver of the MISO transmission only increases by adding a transmitter with index $i = N$ to a group of $N - 1$ transmitters in case that the following inequality holds:

$$\left(\sum_{i=1}^{N} \frac{|h_i|}{\sqrt{N}} \right)^2 \geq \left(\sum_{i=1}^{N-1} \frac{|h_i|}{\sqrt{N-1}} \right)^2 . \tag{5.12}$$

It follows that, in order to improve the resulting SNR at the receiver, the channel transfer factor h_N of the additional transmitter $i = N$ needs to fulfill the following condition:

$$\textbf{Condition MISO: } |h_N|^2 \geq \left(\sqrt{\frac{N}{N-1}} - 1 \right) \cdot \left(\sum_{i=1}^{N-1} |h_i| \right)^2 .$$

If this is not the case, the additional transmitter does not lead to an improved SNR. It follows that not all data packets need to be available at all cluster nodes in order to achieve the highest possible data throughput to the next cluster. However, in order to exactly determine how many data packets at which node are required according to Condition MISO, non-causal CSI knowledge of the future channel states is required. Therefore, a heuristic solution is proposed based on the causal channel knowledge that is available at the nodes.

What needs to be found is the percentage of data packets that should be available based on the knowledge of the average SNR conditions between the clusters. In case that the SNRs of the links between transmitter i and the receivers of the current stage are on average larger compared to the SNRs between the other transmitters and the receiver of the current stage, node i should probably have more data packets available than the remaining nodes.

In order to get some reliable values for the percentage of data packets that should be available at each transmitter, simulations with varying average SNR conditions are used. A scenario is considered with multiple transmitters and a single receiver in which all data packets are available at all transmitters. The average SNR between the transmitter i and all receivers of the stage is denoted by $\bar{\gamma}_i$ and the average SNR considering all stage links of the current stage is denoted by $\bar{\gamma}_{\text{stage}} = \frac{\sum_i^{N_{\text{cn}}} \bar{\gamma}_i}{N_{\text{cn}}}$. In each time slot, random Rayleigh fading channels are generated. Based on Condition MISO,

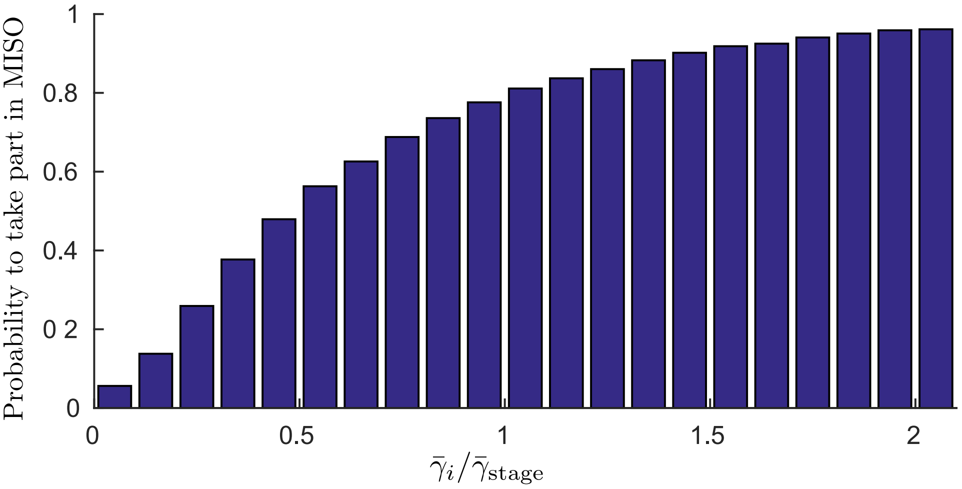

Figure 5.8. Probability to take part in MISO transmission depending on average link conditions and according to Condition MISO for $N_{\text{cn}} = 3$ cluster nodes.

the transmitters are determined which can improve the achievable MISO SNR. To this end, first, only the node with the strongest channel is selected as the transmitter. Next, the remaining transmitters are considered one after the other in decreasing order of their channel magnitude $|h_{i,j}|$. Additional transmitters are only selected for a MISO transmission in case that their channel transfer factor fulfills Condition MISO.

In Figure 5.8, the percentage of data packets that are transmitted by node i depending on the ratio $\frac{\bar{\gamma}_i}{\bar{\gamma}_{\text{stage}}}$ is shown. It can be seen that for a ratio of $\frac{\bar{\gamma}_i}{\bar{\gamma}_{\text{stage}}} = 0.4$, node i takes part in the MISO transmissions in less than 50 % of the cases. In case that $\bar{\gamma}_i$ is higher than the average SNR ($\frac{\bar{\gamma}_i}{\bar{\gamma}_{\text{stage}}} > 1$), node i is participating in the MISO transmission in more than 80 % of the cases.

The percentage of data packets transmitted by node i also depends on the number of cluster nodes. Therefore, the simulations are also performed with different cluster sizes. The results are given in Table 5.2. These values are used for the intra-cluster distribution for each corresponding cluster size. For each node i, the ratio $\frac{\bar{\gamma}_i}{\bar{\gamma}_{\text{stage}}}$ is determined and the corresponding value from the table gives the desired percentage of data packets that should be available at node i after the intra-cluster distribution phase. The intra-cluster distribution by each node i is adapted according to the desired values. Node i stops the exchange of data packets as soon as the desired number of data packets is achieved at the other nodes of the cluster. For the data packet to subcarrier scheduling, again Algorithm 7 is applied, but based on an ordered set $\mathcal{S}_i^{\text{ordered}}$ of the data packets. In $\mathcal{S}_i^{\text{ordered}}$, the data packets that are available at node i are ordered according to the number of cluster nodes at which they are available in ascending order. This means that packets that are exclusively available at node i are selected first in Algorithm 7.

Table 5.2. Probability to take part in MISO

$\frac{\bar{\gamma}_i}{\bar{\gamma}_{\text{stage}}}$	$N_{\text{cn}} = 2$	$N_{\text{cn}} = 3$	$N_{\text{cn}} = 4$
0.05	0.1116	0.0562	0.0271
0.15	0.2153	0.1378	0.0969
0.25	0.3552	0.2592	0.2038
0.35	0.4798	0.3771	0.3208
0.45	0.5563	0.4793	0.4257
0.55	0.6397	0.5630	0.5137
0.65	0.6995	0.6259	0.5823
0.75	0.7576	0.6880	0.6393
0.85	0.7994	0.7360	0.6885
0.95	0.8373	0.7760	0.7279
1.05	0.8677	0.8111	0.7635
1.15	0.8950	0.8370	0.7929
1.25	0.9178	0.8603	0.8181
1.35	0.9410	0.8827	0.8390
1.45	0.9526	0.9018	0.8623
1.55	0.9689	0.9185	0.8787
1.65	0.9772	0.9250	0.8912
1.75	0.9872	0.9406	0.8973
1.85	0.9950	0.9506	0.9142
1.95	1	0.9589	0.9253
2.05	1	0.9614	0.9345

In case that the number of data packets in set $\mathcal{S}_i^{\text{ordered}}$ falls below half of the number of subcarriers ($\mathcal{S}_i^{\text{ordered}} < N_{\text{sc}}/2$), node i stops the intra-cluster distribution. This rule avoids the use of time slots for the exchange of only a few data packets that are left which might be wasteful in many cases. As a consequence, the number of desired data packets is not achieved in any case for all cluster nodes.

After the intra-cluster data exchange is completed, the inter-cluster forwarding phase begins. Due to the partial availability of the data packets, the assignment of data packets to subcarriers is crucial for the achievable throughput. Since not all nodes are transmitting on all subcarriers, different combinations of data packets and subcarriers lead to different channel capacities. The assignment of data packets to subcarriers is done in two steps. In the first step, the data packets that are transmitted in the upcoming time slot are selected using Algorithm 7, but without assigning them directly to any subcarrier. In the second step, the data packets are assigned to the subcarriers based on a cost matrix $\mathbf{C}$ of size $N_{\text{sc}} \times N_{\text{sc}}$. The (k, n)-th element in this cost matrix is given by

$$\mathbf{C}(k, n) = \min_{j}(t_{\text{req},j,n_k}). \tag{5.13}$$

For each combination of data packet k and subcarrier n, the receiver j and the transmitters are determined that provide the minimum expected time t_{req,j,n_k} for decoding success. The corresponding transmitters for the MISO transmission which provide this minimum value are selected based on the availability of the data packet and based on Condition MISO. Of course, only transmitters at which data packet k is available can take part in the MISO transmission. Furthermore, transmitters are added stepwise in descending order of their corresponding channel magnitude to receiver j only if their channel fulfills Condition MISO. The expected time t_{req,j,n_k} is determined for all receivers and only the receiver with the minimum value is considered in the cost matrix $\mathbf{C}$.

The elements of the cost matrix cover all combinations of the N_{sc} subcarriers and the N_{sc} data packets that are selected for transmission in the upcoming time slot. The aim is to find an assignment that minimizes the sum of the resulting costs. The assignment problem is solved using the Hungarian method [Kuh55] which finds an optimal assignment in polynomial time. The Hungarian method is a combinatorial optimization algorithm that can find a maximum- or a minimum- weight matching in a bipartite graph, which means it can find an optimal assignment of elements from one set to elements of another set such that the resulting cost is minimized or the resulting gain is maximized. In the considered problem, the available subcarriers need to be assigned to the data packets. The cost of each assignment is given by the time t_{req,j,n_k} that is required by the receiver for a successful decoding of the data packet. A more detailed description of the Hungarian method can be found in Appendix A.2.

5.5.4 Performance Analysis

In this section, the performance of the proposed forwarding schemes that utilize distributed MISO transmissions is evaluated. The two schemes, in the following named 'CbR MISO full' and 'CbR MISO adaptive', respectively, are compared to a forwarding scheme that is based only on SISO transmissions, in the following named 'CbR SISO'. The SISO scheme corresponds to the CbR adaptive MISO forwarding strategy presented in Section 5.3.3.4, except that there is no intra-cluster distribution phase taking place. The corresponding cost matrix $\mathbf{C}$ is determined based on the SISO capacities. The subcarrier allocation is also based on the Hungarian method as described in Section 5.5.3.4.

In the following, the system parameters according to Table 5.3 are assumed. Random networks are generated. The positions of the source and the destination are fixed. In order to decode a data packet, the entropy $H_{\mathrm{data}} = 0.2\,\mathrm{bits/Hz}$ needs to be accumulated by a receiver. Without loss of generality, the entropy is given in bits/Hz to avoid any assumptions on the available bandwidth B. The entropy per data packet is chosen such that an appropriate granularity for the fountain coding is achieved for a time slot duration of 10 ms. Increasing the time slot duration results in a more coarse granularity which means that the actual channel capacity might be under-used in many cases. For a decreased time slot duration, the transmitters need to pause more often to wait for ACKs from the receivers.

Table 5.3. System parameters

Map size	300m x 100m
Position of source	(50,50)
Position of destination	(250, 50)
Number of nodes	$\{100-300\}$
Minimum node distance d_0	1 m
Number N_{sc} of subcarriers	16
Path loss exponent α_{PL}	3
Transmit power per subcarrier p_{sc}	1 mW
Total number of data packets	100
Entropy of each data packet H_{data}	0.2 bits/Hz
Time slot length T_{s}	10 ms

For the construction of the corridor, the construction protocol according to Section 3.3 is applied using the parameters of Table 5.4. In this chapter, only static scenarios are considered. Therefore, the minimum LLT required by Condition 1 is set to 0 s. The minimum link SNR is $\gamma_{\mathrm{min,cor}} = 10\,\mathrm{dB}$ (Condition 2). The maximum cluster size is $N_{\mathrm{cn,max}} = 2, 3$ or 4.

Table 5.4. Corridor construction parameters

Minimum LLT $t_{\mathrm{LLT,min}}$ (Condition 1)	0 s
Minimum link SNR $\gamma_{\mathrm{min,cor}}$ (Condition 2)	10 dB
Maximum number $N_{\mathrm{cn,max}}$ of nodes per cluster	{2,3,4}

In Figure 5.9, the achievable end-to-end throughput is depicted in dependency of the number of nodes in the network. It can be seen that for an increasing node density in the network, the performances of all considered schemes improve slightly. With more node options for the corridor construction, the average SNRs of the stage links, as well as, of the intra-cluster links increase due to decreasing average distances between the nodes. For a cluster size of $N_{\mathrm{cn,max}} = 2$ nodes, CbR SISO and CbR MISO full achieve almost the same throughput. The achievable gain of the distributed MISO transmissions is compensated by the reduced throughput to the next cluster during the intra-cluster distribution phase. For $N_{\mathrm{cn,max}} = 3$ and 4, the CbR MISO full scheme only slightly outperforms the CbR SISO scheme. The best performance for all considered cluster sizes and all considered node densities is achieved by the CbR MISO adaptive scheme. By the partial intra-cluster distribution, a good trade-off between the benefits of distributed MISO transmissions and the benefits of exploiting the diversity of stage links is found. The throughput gain of CbR MISO adaptive compared to CbR MISO full and CbR SISO lies between 5 and 7 %. By increasing the maximum cluster size from 2 to 3, the CbR MISO adaptive scheme improves by approximately 6 %. By increasing the maximum cluster size from 2 to 3, the gain is approximately 8 %.

In summary, distributed MISO transmissions can further enhance the performance of Corridor-based routing. However, the additional required exchange of data packets within a node cluster can hurt the performance. An adaptive partial exchange of the data packets provides the best performance.

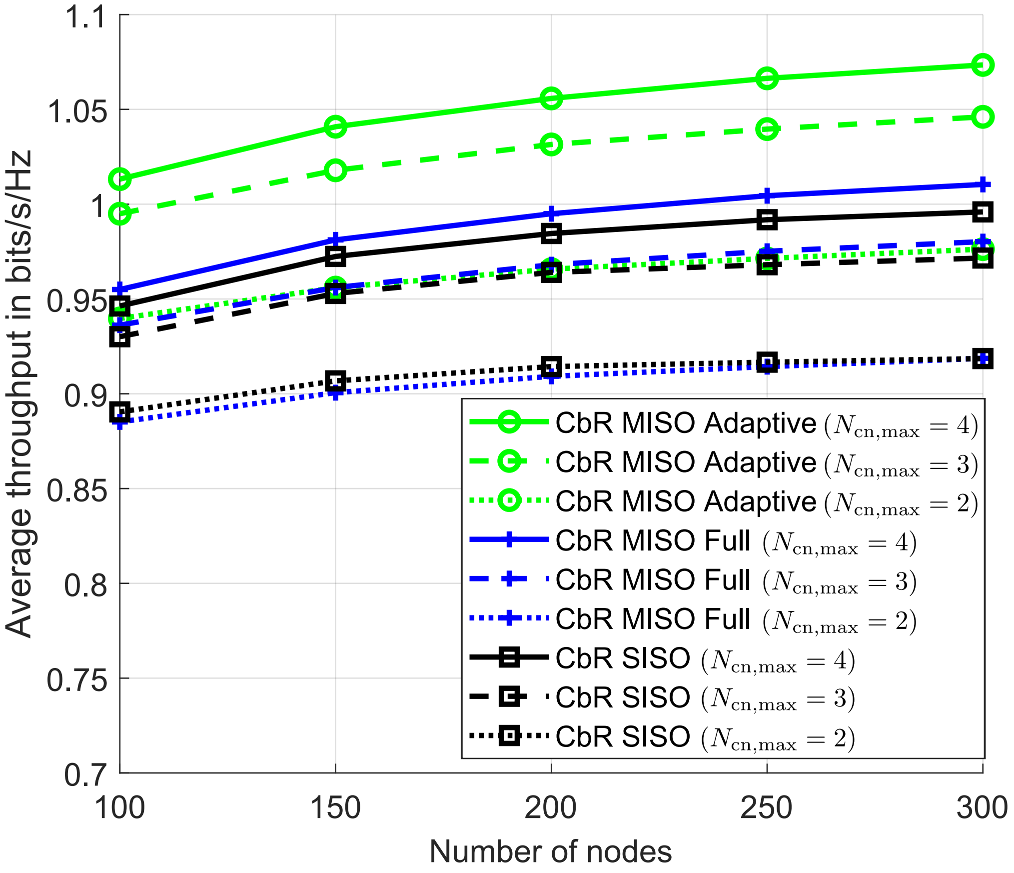

Figure 5.9. Average achievable throughput for different network sizes.

Chapter 6

Summary and Outlook

6.1 Summary

In this work, CbR is studied which is a routing paradigm that relies on groups of potential forwarding nodes that build a wireless multi-hop connection. The diversity of link options provided by the corridor enables potentially high data throughput. Besides the node selection process, the main focus of this work is on the resource allocation problem brought in by the use of OFDMA.

In Chapter 1, the motivation for wireless multi-hop networks is discussed. The state of the art is presented and based on that open issues are formulated. Furthermore, the contributions of this work are stated and an overview of the thesis is given.

In Chapter 2, the system model along with the basic assumptions that are made for this work are introduced.

Chapter 3 deals with the node selection process for CbR. A corridor construction and maintenance protocol is proposed that uses estimated link lifetimes to build stable corridor structures for data transmissions. It is shown that the resulting corridors enable significantly higher potential data throughput compared to traditional unipath routing based on the diversity of links within the corridor. Furthermore, the resulting corridors provide better stability in mobile scenarios. The corridor structure can be maintained with low effort. Thereby, link breakages can be avoided.

In Chapter 4, the local resource allocation problem in the stages of the corridor is addressed. An optimal policy that minimizes the expected number of required time slots to forward data packets to the next stage is presented. Based on an MDP model, a dynamic programming approach is used to derive the optimal policy. In order to handle large state spaces, a state approximation technique is proposed. Furthermore, a low-complexity heuristic resource allocation is proposed which uses a channel-comparative metric and which performs close to the optimal policy. Significant gains are achieved by the CbR strategies compared to forwarding along a fixed unipath.

In Chapter 5, CbR in combination with fountain codes is investigated. A forwarding strategy that exploits inter-stage links is presented. Based on Strider as a practical example of a fountain code, algorithms for data scheduling and for subcarrier allocation are introduced. The achievable data throughput is successfully improved by making use of overhearing through inter-stage links. Furthermore, including distributed MISO transmissions in CbR is investigated. Due to the requirement for the availability of the same data packets at multiple forwarding nodes, a novel forwarding strategy is proposed that uses intra-cluster distribution of data packets prior to the joint forwarding process. By this approach, distributed MISO transmission are beneficially included in CbR, which leads to a further enhancement of the achievable data throughput.

6.2 Outlook

In this thesis, only a limited number of topics related to the operation of CbR have been considered. However, there are many related issues still open. In this section, some open topics are briefly discussed.

CbR is not aiming at providing the single best forwarding scheme that fits for all scenarios. Instead, the corridor can be viewed as a support structure that enables the exploitation of diversity as a basis for high data throughput in wireless multi-hop transmissions. In this work, CbR is considered using local CSI knowledge at the transmitter side in order to benefit from selection diversity. However, the impact of the required channel measuring overhead on the performance does strongly depend on the type of experienced channel fading. In the case that the channel coherence time is very short, the provision of CSI might become too expensive or even impossible. Therefore, alternative forwarding strategies that do not rely on current CSI knowledge become beneficial. The main challenge is to identify the best strategy under several different conditions and to find the corresponding optimal switching points for changing it. Since the stages of the corridor operate independently of each other, each stage can be adapted locally according to the individual stage profile.

Another important topic is heterogeneity in networks concerning devices and spectrum bands. In this work, all nodes are assumed to be equal and the data transmission relies on one fixed frequency band. However, wireless multi-hop networks can be built out of heterogeneous devices with different capabilities that support different technologies. Some nodes might be equipped with multiple antennas and some nodes might support multiple different frequency bands. Dealing with this variety is a difficult challenge, but the corridor provides a suitable platform for a cooperative approach that allows for such extensions.

Appendix

A.1 Viterbi-Based Max-Flow Algorithm

In the following, the derivation of the highest possible end-to-end data throughput based on a unipath through the corridor is explained which is used in Section 3.5. The corresponding data throughput is used to evaluate the performance of the corridor construction and maintenance procedure, especially in terms of the stability of the structure in dynamic networks.

The aim is to find the path through which a fixed amount D of data can be transmitted as fast as possible. The time that it takes to forward the data from transmitter i to receiver j in stage s of the corridor is given by

$$T^s_{\text{total}} = \frac{D}{C_{i,j}}, \tag{A.1}$$

where $C_{i,j}$ denotes the link capacity using all N_{sc} subcarriers that is given by

$$C_{i,j} = \sum_{n=1}^{N_{\text{sc}}} \log_2(1 + \gamma_{i,j,n}). \tag{A.2}$$

The transmitter in the first stage is given by the source node. Therefore, the aim is to find the corresponding receiver in each stage such that the sum $\sum_{s=1}^{N_{\text{stages}}} T^s_{\text{total}}$ is minimized. Since the corridor is a trellis-structured graph, a Viterbi-based max-flow algorithm can be used to find the optimal path [GT88]. As a metric for each edge of the graph, the required time $t_{i,j}$ to forward 1 bit/Hz is used for the determination of the optimal path. This metric is given by

$$t_{i,j} = \frac{1\text{bit/Hz}}{C_{i,j}}. \tag{A.3}$$

The max-flow algorithm works as follows. Starting with the first cluster, for each potential receiver j, the minimum required time $t_{j,\min}$ to transmit 1 bit/Hz to this node is given by

$$t_{j,\min} = \min_i \left(t_{i,\min} + t_{i,j}\right), \tag{A.4}$$

where i denotes the transmitter from which node j receives the data. Of course, for the receivers of the first cluster, there is only one transmitter candidate i, which is the source node with $t_{i,\min} = 0$. In order to find the best path from source to destination, the minimum required time $t_{j,\min}$ is calculated cluster by cluster for each node j in the graph. Along the way, the corresponding best path to each node is stored until the destination is reached.

For each node in the corridor, only the incoming links of the corresponding stage need to be compared, but not the whole previously used path. Therefore, the complexity order of the algorithm is given by $\mathcal{O}(N_{\text{links}})$, where N_{links} denotes the number of links in the corridor.

A.2 The Hungarian Method for the Assignment Problem

In the following, finding an assignment of N_{sc} data packets to N_{sc} subcarriers with minimum cost is explained based on the Hungarian method [Kuh55] which is used in Section 5.5.3.4.

The cost is represented by the time that it takes to transmit a data packet to a receiver such that it can successfully decode the data packet. The cost for each possible combination of data packet to subcarrier is stored in a cost matrix $\mathbf{C}$ of size $N_{\text{sc}} \times N_{\text{sc}}$. The Hungarian algorithm works as follows:

Step 1: In each row of matrix $\mathbf{C}$, subtract the smallest element from all elements in this row. This means that the minimum in each row will become 0.

Step 2: In each column, subtract the smallest element from all elements in this column.

Step 3: Count the minimum number of horizontal and vertical lines that are required to cover all zeros in the matrix. If the number of lines equals N_{sc}, the optimal assignment has been found. If less than N_{sc} lines are required, move on with Step 4.

Step 4: Determine the smallest element that is not covered by any line. Subtract this element from all uncovered rows and add this element to all covered columns. Then, repeat Step 3.

The optimal assignment with minimum cost is indicated by the zeros in the matrix. The complexity order of a brute force approach to this problem is $\mathcal{O}(N_{\mathrm{sc}}!)$. By the Hungarian algorithm, the complexity order can be reduced to $\mathcal{O}({N_{\mathrm{sc}}}^3)$.

List of Acronyms

ACK	Acknowledgement
AODV	Ad-hoc On-Demand Vector
AWGN	Additive White Gaussian Noise
CbR	Corridor-based Routing
CDF	Cumulative Distribution Function
CSI	Channel State Information
D	Destination
DSR	Dynamic Source Routing
EATT	Expected Any-path Transmission Time
EAX	Expected Any-path transmissions
ETT	Expected Transmission Time
ETX	Expected Transmission Count
ExOR	Extremely Opportunistic Routing
ICI	Inter-Carrier Interference
IoT	Internet of Things
LLT	Link Lifetime
LOS	Line-Of-Sight
MCS	Modulation and Coding Scheme
MDP	Markov Decision Process
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
NLOS	Non-Line-Of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

PDF	Probability Density Function
PMF	Probability Mass Function
PORTAL	Portsmouth Real-Time Travel Information System
QPSK	Quadrature Phase Shift Keying
S	Source
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
w/o OH	Without Overhearing

List of Symbols

a	Action
$a_{i,b}$	(i, b)-th element of the Availability matrix $\mathbf{A}$
$\mathbf{A}$	Availability matrix
$A_{i,j}$	Magnitude of the received signal at node j transmitted by node i
$A_{i,\max}$	Magnitude of the signal transmitted by node i at the best receiver
$A_{\max}$	Magnitude of the received signal based on the strongest channel option
A_{miso}	Magnitude of the received signal based on a MISO transmission
b	Data batch index
B	Available bandwidth
B_{c}	Coherence bandwidth
B_i	Buffer level of node i
$B_{\max}$	Maximum data buffer level
c	Speed of light
$C_{i,j}$	Overall channel capacity between transmitter i and receiver j using all subcarriers
$C_{i,j,n}$	Channel capacity between transmitter i and receiver j on subcarrier n
$\mathrm{cdf}(x)$	Cumulative distribution function of x
d_0	Minimum reference distance
$d_{i,j}$	Distance between transmitter i and receiver j
$\hat{d}_{i,j}^{(t)}$	Estimated distance between transmitter i and receiver j at time instant t
d_{range}	Radio transmission range
D	Amount of transmitted data
$E\{\cdot\}$	Expectation operator
f_{c}	Carrier frequency
$f_{\mathrm{d,max}}$	Maximum Doppler frequency
$h_{i,\max}$	Channel transfer factor of the channel from transmitter i with highest SNR
$h_{i,j}$	Channel transfer factor between transmitter i and receiver j
$h_{i,j,n}$	Channel transfer factor including path loss between transmitter i and receiver j using subcarrier n
$h_{i,j,n}^{'}$	Channel transfer factor between transmitter i and receiver j using subcarrier n

H_{data}	Entropy of a data packet
H_{gap}	Remaining mutual information required to decode a data packet
i	Index of transmitter
j	Index of receiver
k	Data packet index
K	Number of data packets in a data batch
$L_{\text{path},i,j}$	Path loss between transmitter i and receiver j
N_{cn}	Number of cluster nodes
$N_{\text{cn,max}}$	Maximum number of nodes per cluster
$N_{\text{p}}^{\text{max}}$	Maximum number of transmittable data packets
$N_{\text{p},i}^{\text{max}}$	Maximum number of transmittable data packets for transmitter i
N_{nodes}	Number of nodes in the network
N_{packets}	Total number of data packets
N_{sc}	Number of subcarriers
N_{stages}	Number of stages in the corridor
N_{rates}	Number of available data rates
$p_{i,n}$	Transmit power of node i on subcarrier n
p_{sc}	Transmit power per subcarrier
$\text{round}\{x\}$	Rounds x to the closest integer
$\text{pdf}(x)$	Probability density function of x
$\mathbf{R}$	Strider coefficient matrix
R_{uni}^{h}	Achievable data throughput of unipath routing in hop h
$R_{\text{S}\to\text{D,ub}}$	Upper bound for the achievable end-to-end data throughput
$R_{\text{S}\to\text{D,uni}}$	Achievable end-to-end data throughput of unipath routing
R_{stage}^{s}	Throughput in stage s
$R_{\text{stage,ub}}^{s}$	Upper bound for the achievable throughput in stage s
$R_{\text{S}\to\text{D}}$	Network throughput from source to destination
$R_{\text{S}\to\text{D,ub}}$	Upper bound for the network throughput from source to destination
$R_{\text{S}\to\text{D,uni}}$	Achievable unipath throughput from source to destination
$R_{\text{total},i}$	Total transmission rate of transmitter i
$\mathcal{R}_{ss'}^{a}$	Reward by taking action a in state s leading to state s'
s	Stage index
$\mathcal{S}$	Set of states
$\mathcal{S}_{\text{candidates}}$	Set of node candidates
$\mathcal{S}_{i}^{\text{batch}}$	Set of data batches that are available at transmitter i

t	Time slot index
t_{hello}	Time interval of hello messages
$t_{i,j}$	Time required to transmit 1 bit/Hz from transmitter i to receiver j
$t_{j,\min}$	Time metric at node j
$\hat{t}_{\mathrm{LLT},i,j}$	Estimated link lifetime between node i and node j
$t_{\mathrm{LLT},\min}$	Minimum link lifetime
T_{c}	Channel coherence time
T_{s}	Time slot duration
T_{total}	Total transmission time from source to destination
T^{s}_{total}	Total transmission time in stage s
v_i	Velocity of node i
$v_{\max}$	Maximum node velocity
α	Path loss exponent
$\gamma_{i,j}$	SNR of the channel between transmitter i and receiver j
$\gamma_{i,j,n}$	SNR of the channel between transmitter i and receiver j on subcarrier n
$\gamma^{'}_{i,j,n}$	Comparative SNR of the channel between transmitter i and receiver j on subcarrier n
γ_{fail}	Link failure SNR threshold
$\gamma_{\mathrm{min,cor}}$	Minimum SNR threshold for corridor construction
$\gamma_{\min}$	Minimum link SNR for path discovery
$\gamma_{i,\max}$	Strongest SNR of links from transmitter i
$\bar{\gamma}_i$	Average SNR between transmitter i and all receivers of the current stage
$\bar{\gamma}_{i,j}$	Average SNR between transmitter i and receiver j
$\bar{\gamma}^{(t)}$	Average SNR at time instance t
$\bar{\gamma}_{\mathrm{stage}}$	Average SNR of all links within the current stage
Δf	Subcarrier spacing
π	Policy
π'	Current policy
π^{*}	Optimal policy
ρ_{im}	The i-th coefficient from the m-th row of $\mathbf{R}$
$\sigma^2_{i,j}$	Variance of the real and imaginary part of the received signal transmitted between the nodes i and j
σ^2_{n}	Noise variance
$\lceil\cdot\rceil$	Ceiling operation

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Own Publications

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[HOK19] F. Hohmann, A. Ortiz, and A. Klein, “Optimal Resource Allocation Policy for Multi-Rate Opportunistic Forwarding”, in *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2019.

Supervised Student Theses

Name	**Title of the thesis**	**Thesis type**	**Date**
Tesmer, Henning	Utilizing Rateless Codes in Corridor-based Routing	Bachelor Thesis	10/2015
Halbleib, Tobias	Bidirectional Transmissions using Network Coding in OFDMA Multihop Networks	Bachelor Thesis	06/2017

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