Department of Communications and Networking

Radio Resource Management for Cellular Networks Enhanced by Inter-User Communication

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Chia-Hao Yu

Aalto University

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Chia-Hao Yu

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Abstract

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Abstract

The importance of radio resource management will be more and more emphasized in future wireless communication systems. For fair penetration of wireless services and for improved local services, inter-user communication has been receiving wide attention as it opens up various possibilities for user cooperation. The capability of inter-user communication imposes higher demands on radio resource management as additional considerations are needed. The demands for intelligent management of radio resources is also emphasized by the sparsity of radio resources. As the available spectral resources are assessed as under-utilized, much effort is devoted to developing advanced resource management methods for improving the spectral usage efficiency.

The research of this thesis has contributed to the radio resource management for cellular networks enhanced by inter-user communication. Recognizing that inter-user communication can be used for message relaying or for direct communication purposes, two use cases are considered that leverage the synergy of users: cooperative relay selection and Device-to-Device (D2D) communication. We identify the importance of stochastic geometry consideration on cellular users for evaluating system performance in cooperative networking. We develop an algorithm for efficiently selecting cooperative users to maximize an End-to-End (e2e) performance metric.

We analyze the optimal resource sharing problem between D2D communication and infrastructure-supported communication. We study the impact of imperfect Channel State Information (CSI) on the performance of systems with inter-user communication.

Simulation results show that the performance of users with unfavorable propagation conditions can be improved with cooperative communication in a multi-cell cellular environment, at the expense of radio resources. Further, our results show that the selection of multiple cooperative users is beneficial in cases where the candidate cooperative users are spatially distributed. For resource sharing between the D2D and infrastructure-supported communication, our results show that the proposed resource sharing scheme enables higher intra-cell resource reuse without blocking the infrastructure-supported communication.

Keywords Cellular systems, cooperative relaying, device-to-device communication

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Preface

The research work for this doctoral thesis has been carried out at the department of Communications and Networking (ComNet) of Aalto University during 2007–2011. The work was funded by Nokia, Tekes (the Finnish Funding Agency for Technology and Innovation), Ericsson, Nokia Siemens Networks, and the Nokia Foundation.

Firstly, I wish to express my deepest gratitude to my supervisor Prof. Olav Tirkkonen for his continuous support, and for many enlightening discussions that sometimes ended up in very late evening. It has been a pleasure and an honor to work with him during my doctoral program.

I would like to thank the thesis pre-examiners, Prof. Gerhard Bauch and Dr. Simone Redana for their constructive comments. I am grateful to Dr. Klaus Doppler and Dr. Cassio Ribeiro from Nokia, with whom I co-authored several publications. Special thanks to Dr. Klaus Hugl for his support during my joint work with Nokia, and to Prof. Jyri Hämäläinen for his helpful comments on co-authored publications.

I am grateful to my colleagues in ComNet, who make it a pleasant place to work. Special thanks to Lu Wei, Zhong Zheng, and Dr. Kalle Ruttik for interesting daily discussions on all subject matter. Mr. William Martin is also acknowledged for proofreading the language of the manuscript.

I wish to express my warmest gratitude to my parents and my wife. Their permanent encouragement and support has been essential during the past years.

Helsinki, January 8, 2012,

Chia-Hao Yu

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Chia-Hao Yu, Olav Tirkkonen, and Jyri Hämäläinen. Opportunistic Relay Selection with Cooperative Macro Diversity. *EURASIP Journal on Wireless Communications and Networking*, Vol. 2010, Article ID: 820427, 2010.

II Chia-Hao Yu and Olav Tirkkonen. Opportunistic Multiple Relay Selection with Diverse Mean Channel Gains. Accepted for publication in *IEEE Transactions on Wireless Communications*, Accepted date: 25, November 2011.

III Pekka Jänis, Chia-Hao Yu, Klaus Doppler, Cassio Ribeiro, Carl Wijting, Klaus Hugl, Olav Tirkkonen, and Visa Koivunen. Device-to-Device Communication Underlaying Cellular Communications Systems. *International Journal of Communications, Network and System Sciences*, vol. 2, no. 3, pp. 169–178, June 2009.

IV Chia-Hao Yu, Olav Tirkkonen, Klaus Doppler, and Cassio Ribeiro. On the Performance of Device-to-Device Underlay Communication with Simple Power Control. In *Proc. IEEE Vehicular Technology Conference (VTC Spring 2009)*, Barcelona, Spain, April 2009.

V Chia-Hao Yu, Olav Tirkkonen, Klaus Doppler, and Cassio Ribeiro. Power Optimization of Device-to-Device Communication Underlaying

Cellular Communication. In *Proc. IEEE International Conference on Communications (ICC'09)*, Dresden, Germany, June 2009.

VI Chia-Hao Yu, Klaus Doppler, Cassio Ribeiro, and Olav Tirkkonen. Performance Impact of Fading Interference to Device-to-Device Communication Underlaying Cellular Networks. In *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'09)*, Tokyo, Japan, September 2009.

VII Chia-Hao Yu, Klaus Doppler, Cassio Ribeiro, and Olav Tirkkonen. Resource Sharing Optimization for Device-to-Device Communication Underlaying Cellular Networks. *IEEE Transactions on Wireless Communications*, vol. 10, pp. 2752–2763, August 2011.

The author of this thesis has had the main responsibility for Publications [I, II, IV, V, VI, VII], where the author actively participated in planning and analyzing the research ideas, generating the simulation results, and writing the papers. In Publication III, the author has participated in the work of Section II and V. In particular, the author had the main responsibility for Section V on analyzing and generating the simulation results, and writing the context.

List of Abbreviations

3GPP	3rd Generation Partnership Project
AF	Amplify-and-Forward
AoA	Angle of Arrival
AP	Access Point
ARQ	Automatic Repeat Request
ARS	Ad hoc Relay Station
AWGN	Additive White Gaussian Noise
BS	Base Station
CDF	Cumulative Distribution Function
CM	Cellular Mode
CoMP	Coordinated Multi-Point
COST	European Cooperation in Science and Technology
CSI	Channel State Information
D2D	Device-to-Device
DF	Decode and Forward
e2e	End-to-End
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service
iCAR	integrated Cellular and Ad hoc Relaying
IEEE	Institute of Electrical and Electronics Engineering

IMT-A	International Mobile Telecommunications-Advanced
ITU	International Telecommunication Union
LDPC	Low-Density Parity Check
LOS	Line-of-Sight
LTE	Long Term Evolution
MANET	Mobile Ad hoc Network
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
NLOS	Non-Line-Of-Sight
NOS	Non-Orthogonal Sharing
OFDMA	Orthogonal Frequency Division Multiplexing Access
OS	Orthogonal Sharing
P2P	Peer-to-Peer
PPP	Poisson Point Process
QoS	Quality of Service
SC-FDMA	Single-Carrier Frequency Division Multiplexing Access
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Network
UCAN	Unified Cellular and Ad hoc Network
UE	User Equipment
UL	Uplink
WCDMA	Wideband Code Division Multiple Access
WINNER	Wireless World Initiative New Radio
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

1. Introduction

1.1 Motivation

With the progress of wireless communication technologies, mobile users of next generation communication systems expect seamless coverage with higher peak transmission rate than current broadband communication systems. For example, the International Telecommunication Union (ITU) has defined the requirements of International Mobile Telecommunications-Advanced (IMT-Advanced) systems to meet these expectations. To support advanced services and applications, IMT-A systems feature peak aggregate data rates up to 1 Gbps with a spectrum demand of approximately 100 MHz bandwidth [1, 2]. Such high demands on data rate do not appear feasible in current 3G architectures because of concerns regarding both the allocated spectrum and transmit power. The spectrum allocated will be above the 2GHz band which is more vulnerable to Non-Line-Of-Sight (NLOS) scenarios. For service coverage, the envisioned high data rates in IMT-A systems requires a high transmit power level which is usually highly regulated. In view of these restrictions, a scenario with many small cells seems the way to go. This unfortunately creates a linear cost with respect to the number of cells [3]. One cost-efficient alternative that has received much attention is the deployment of relays to extend the cell coverage of high capacity area. It is shown with enhanced cell edge performance and cell coverage [4, 5]. The deployment of in-band fixed relays has been studied as part of the infrastructure within the scope of 3rd Generation Partnership Project (3GPP).

Alternatively, mobile relays which consist of idle users can also be used to exploit the diversity and multiplexing advantages to benefit the outage behavior and the capacity without infrastructural support [6, 7]. In such systems, a user without demands on own data transmission can cooperate with other source nodes and act as geometrically distributed mobile relays to assist the transmission from the source nodes. Such wireless cooperative networking, which takes advantage of spatial diversity and multiplexing, has been shown to have the potential of meeting the needs of increased system capacity and coverage [8]. One important issue towards such user cooperation is to select proper users to cooperate with. However, a general guidance of this selection scheme is lacking in the literature.

On the other hand, as the demands for wireless transmissions rise, the value of spectrum resources are more and more appreciated. The assessment of the usage of spectrum shows that it is largely underutilized [9], especially in licensed bands. This motivates the extensive research into cognitive radio systems to allow opportunistic use of the spectrum [10, 11, 12]. In spite of the progress in cognitive radio systems, opportunistic use of the spectrum on licensed bands is still challenging as sensing white spaces in the spectrum is a difficult task [13]. Cellular operators are conservative about sharing their licensed bands with secondary systems. Therefore, a system functioning similar to cognitive radio systems but is under the control of cellular operators seems a proper step for motivating the willingness of cellular operators to share their spectrum.

Motivated by the importance of user cooperation and agile use of radio resources on further performance improvement, this thesis addresses both issues in a unified framework. It is hoped that the research conducted in this work will shed more light on user cooperation and agile use of radio resources for future networks

1.2 Scope of the thesis

The objective of this thesis is to contribute to cellular networks enhanced by the capability of inter-user communication. We consider a scenario where mobile users can communicate with each other, in addition to the normal operation of communicating with their serving Base Stations (BS). Such functionality opens up various possibilities for user cooperation. Depending on the degree of synergy of mobile users, attention is paid to opportunistic mobile relay selection for harvesting cooperative diversity, and Device-to-Device (D2D) communication as an underlay to cellular networks [PIII] for agile resource sharing to facilitate local Peer-to-Peer (P2P) data traffic.

The goal of this thesis is to complement the lack of general relay selection guidance for user cooperation, and to bridge the gap between the attitude towards cognitive radio of cellular operators and state-of-the-art technologies for agile use of spectrum resources. Further, the evaluation of system performance is done by taking into account the spatially separated positions of users. In channel modeling, the distance-dependent path loss, which depends on the distance between a transmitter and a receiver, is an essential part. With spatially separated users, different mean channel characteristics, and thus different Quality of Service (QoS), are experienced by different users. In this work, a consideration of stochastic geometry for user positions is performed for realistic results.

1.3 Contributions and structure of the thesis

This work contributes to resource management for cellular networks with inter-user communication. To utilize the capability of inter-user communication, we consider two use cases. In the first use case, we assume the communication between users is for relaying purposes. A multiple relay selection problem for cooperative relaying is considered. The second use case assumes the communication between users is for direct communication. The optimization of resource management of D2D underlay communications, where the user cooperation requires the dictation of the cellular infrastructure, for improving local services and spectrum utilization is dealt with.

In the analysis of relay selection for cooperative diversity in cooperative networks, stochastic geometry is applied to describe the spatially distributed nature of user positions. In addition to harvesting micro diversity for combatting the multipath fading effect of wireless channels, a macro diversity component is also considered by including the shadow fading effect in the wireless channel model. With a combined effect of a log-normal distributed shadow fading and a Rayleigh distributed multipath fading in the wireless channel model, the shadow fading part dominates the outage performance since the log-normal distribution exhibits heavier tails than the Rayleigh distribution. A consideration on only multipath fading in wireless channel models does not directly apply to realistic scenarios.

We provide a novel algorithm for selecting a fixed amount of optimal relays for a source node for cooperative transmission, with predetermined power constraints on relays. The algorithm is efficient so that the search of an optimal number, and thus an optimal set, of cooperative relays is possible. The work can be applied to Self-Organizing Networks (SON) [14, 15] where automatic searching for helping relays for a source is required.

In the second use case of providing D2D connection for local traffic, we analyze different resource sharing modes for sharing cellular resources between D2D and cellular communication. Resource and power allocation is optimized for different resource sharing modes. The analysis is based on practical considerations, such as rate constraints on cellular and D2D users, as well as the maximum power/energy constraint. We solve the optimal resource/power allocations for the resource sharing modes that allow coexistence of D2D and cellular communication in close form. This facilitates the applications in realistic systems. The analysis can also be applied to an inter-cell interference management problem when the interference coordination is managed in a pairwise manner.

This thesis is organized as follows. Chapter 2 presents the background on wireless system modeling. The important characteristics of wireless channels are first introduced, followed by an approach for wireless system modeling with stochastic geometry. We also describe a reference model based on the WINNER A1 office environment which will be used for evaluating system performance later. Chapter 3 provides an overview of cooperative communication. Cooperative schemes that attain full spatial diversity are discussed. Our contribution on multiple relay selection for cooperative relaying is also presented here. In Chapter 4, we present our contribution on D2D communication underlaying cellular networks. Discussions on the coexistence of cellular networks and ad hoc networks are also provided for comparison. Finally, Chapter 5 summarizes the results and the contribution of the thesis. Directions for future works are also outlined.

1.4 Summary of the publications

This thesis consists of an introductory part and seven original publications. The publications are listed as page 5, and appended at the end of the manuscript starting from page 65. Publications [PI] and [PII] address the issue of mobile relay selection for cooperative relaying. Publications [PIII]–[PVII] address the issue of D2D underlay communication.

In [PI], we study an opportunistic relay selection scheme with the consideration of stochastic geometry in a cooperative network. The opportunistic relay selection scheme selects either the direct path or one of the relaying paths for transmission. The macro diversity is also taken into account by including in the channel model a log-normal distributed shadow fading effect. The relay selection scheme is considered with different extent of CSI knowledge to simulate optimistic and practical environments. An analysis on outage probability based on the dominating macro diversity is given.

In [PII], multiple relay selection for cooperative relaying is considered in a scenario with the consideration of stochastic geometry. The relay selection is based on an End-to-End (e2e) performance metric. An algorithm for selecting a subset of relays with fixed cardinality, from a set of all candidate relays, is proposed. The complexity of the algorithm is $\mathcal{O}(N\log N)$ in the number of candidate RNs, N.

In [PIII], the D2D communication is studied as an underly network to an IMT-A cellular network. As the first publication of this paper series on D2D underlay communication, this article is to verify the application of D2D communication to cellular networks without generating much interference. An analysis based on a single cell scenario is first taken to demonstrate the potential gain from D2D communication when interference coordination is based on full CSI. Then, a practical indoor scenario is studied with parameterizations based on IMT-A systems.

In [PIV], a D2D power control scheme simply based on channel statistics is studied. The D2D transmit power is reduced to restrict the interference generated to the cellular user sharing the same resources non-orthogonally. A complete channel model including distance dependent path loss, shadow fading and multipath fading is considered. With only information on channel statistics, the D2D transmit power is determined by allowing a 3 dB degradation of the Signal-to-Interference plus Noise Ratio (SINR) of the cellular user at 0.05 outage probability.

In [PV], the optimal power allocation between D2D and cellular communication, when sharing non-orthogonal resources, is analyzed. Full knowledge on the Channel State Information (CSI) is assumed. The optimization considers practical rate constraints of user imposed by for example, practical Modulation and Coding Schemes (MCS). A finite set where the optimal power allocation resides is derived. Resource sharing modes of using dedicated resources for D2D and cellular communication are considered for comparison. With dedicated resources, a fixed resource allocation between both operations is used. The results are evaluated in a single cell scenario.

In [PVI], the results in [PV] are applied to study the impact of CSI imperfection. Full CSI is only available for links that the acquisition of the channel states are assisted by the BS, i.e. the links related to normal cellular UL/DL phases. For other links, only slow-faded values are known. A conservative planning scheme on user rate constraints is further proposed to leverage the improved cell throughput and the impact on the cellular user.

In [PVII], we extend the work in [PV] for more completed results and for better understanding of the indication of our analysis in realistic scenarios. We consider the same resource sharing modes as in [PV], but further optimize the resource assignment for orthogonal resource sharing modes. An asynchronous and distributed resource allocation method based on our analysis is constructed to assign the power/resources to D2D and cellular users. A realistic pico-cellular apartment building scenario is considered as a practical interference-limited indoor environment. Promising results on imposing rate constraints and power/energy constraints in the pico-cellular scenario are obtained.

2. Background on System Model

2.1 Introduction

The transmission of packet data dates back to the General Packet Radio Service (GPRS) system in the 90's which became the first standardized cellular system, with a limited data rate of only $56 - 114$ kbit/second [16]. Since then, the momentum has lead us to cellular systems with significant improvement in data transmission capability. The commitment to higher data system throughput has been guaranteed for next generation cellular systems by IMT-Advanced systems. With the introduction of the MIMO technique [17, 18] and iterative codes such as Turbo codes [19] and Low-Density Parity Check (LDPC) codes [20, 21], the link-level performance has been pushed very close to the Shannon limit. These technological components are merged to standardized 3G cellular systems and beyond, for example, Wideband Code Division Multiple Access (WCDMA) [22] and 3GPP Long Term Evolution (LTE) [23] systems. As further improvement on link-level performance is limited, the research energy is tilting towards system-level perspectives.

For better spatial spectral efficiency, 3G and beyond cellular systems have a frequency reuse factor of 1. With a smaller frequency reuse distance, the problem of inter-cell interference becomes an issue. Users located around the cell border are more vulnerable to the co-channel interference from the neighboring cells. As users in the cell center usually experience a more satisfactory SINR, research activities have been put in improving the throughput of cell edge users. This is also one of the main aims in IMT-Advanced systems [24]. In LTE-Advanced systems, proposals such as the deployment of relays, dual transmit antennas at users, and Coordinated Multi-Point (CoMP) transmission [25] are discussed. In

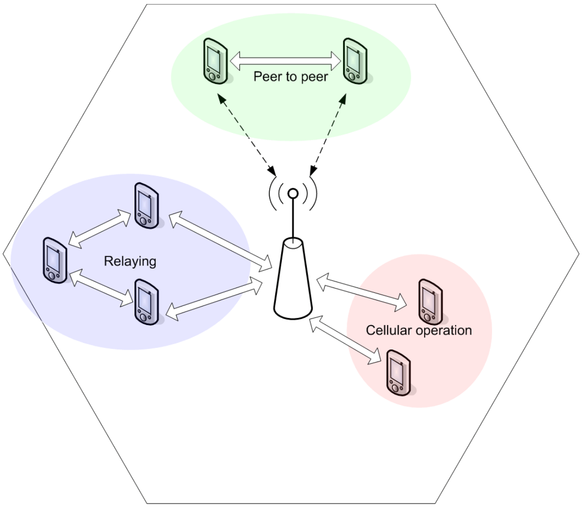

Figure 2.1. A cellular network with relaying concept. The thick lines indicate data transmission. The dashed lines indicate the signaling which may be required.

this work, we focus on the improvement enabled by inter-user communication. As we do not limit ourselves to the LTE-Advanced architecture, the discussions assume mobile relays, rather than fixed relay deployment, in order for cooperative relaying to target future mobile networks. The considered scenario is illustrated in Fig. 2.1 where inter-user communication between users is assumed. As illustrated in Fig. 2.1, the capability of inter-user communication enables the possibility of peer-to-peer and relaying communication, in addition to the normal cellular operation.

To facilitate the discussions, in the following we review the important features of wireless channels and present a reference channel model that will be used later for evaluation of system performance.

2.2 Basic properties of wireless channels

In communication networks, the underlying physical propagation channel places a fundamental limit, described by the Shannon's law [26], on performance. The propagation channel characteristics are dependent on the environments. While the propagation channel is stationary and more predicable for a wired channel, a wireless channel can be extremely random. A wireless channel can vary from a simple Line-of-Sight (LOS) scenario to a sophisticated one that is highly affected by terrain contour, obstacles, and the movement of terminal devices. As a generic analysis of wireless channels is not easy, modeling of the wireless channels is typically done in a statistical fashion. To capture the possibilities and restrictions that a propagation channel imposes on a wireless system, a wireless channel model should be able to reflect the essential properties of the environment honestly. Many wireless channel models have been developed for different applications. In this section, we will describe the basic properties of a wireless channel. For comprehensive discussions, please refer to, for example, [27]

The ultimate task for a channel model is to output estimates of the experienced path loss of a signal during its radio propagation, so that the statistics of the estimated path loss can simulate the real situation. The term *path loss* indicates the reduction in power density of the signal in its propagation. Path loss is the results of many effects, such as distance-dependent loss, reflection, diffraction, and scattering, and is very environment-specific. The same transmission distance between a transmitter and a receiver at two different locations does not indicate the same path loss, as the surrounding environmental clusters are typically very different. A precise channel model capable of predicting the path loss between two positions requires careful consideration of all kinds of effects encountered during the radio propagation, e.g., ray tracing [28]. These kinds of precise channel models are not plausible for applications in wide area communication due to their complexity. Typically, path loss is considered to consist of several parts that take into account different effects during radio propagation. They are distance-dependent path loss, shadow fading, and multipath fading.

The mechanism of electromagnetic wave propagation reveals that, in free space, the strength of a transmitted signal decays with a rate that is inversely proportional to the square of the travel distance. The simplest explanation is to consider an omni-directional antenna. The emitted power transmits towards all directions. The perceived power density in an unit area is then inversely proportional to the square of the travel distance. In a realistic environment, the transmitted signal encounters obstructions so that it is not attenuated in exactly the same way as in free space. However, the fundamental physical rules teach us that the signal strength is still decaying with increasing travel distance in a certain manner. Empirically, it is verified that the path loss increases logarithmically with distance [29].

The shadow fading term considers the environmental clusters where the transmitter and the receiver reside, respectively. The shadowing term simulates various effects that are introduced due to the obstructions encountered in the radio propagation, such as reflection, diffraction, etc. Inherently, shadow fading is a random loss around the average loss specified by the distance-dependent loss. Measurements have shown that a log-normal distribution describes the effect of shadow fading well. Thus, the path loss can be expressed by [30]

$$L(d) = L(d_0) + 10n \log \frac{d}{d_0} + \xi_\sigma, \tag{2.1}$$

where n is the path loss exponent indicating the rate at which the path loss increases with distance, ξ_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ, and $L(d_0)$ is the loss measured from a reference distance d_0.

Multipath fading is used to describe the rapid fluctuations of the received signal strength over a short movement. This is induced by the fact that the received signal is the sum of interfering signals arriving at different times. The difference in the arrival time of the interfering signals is because they arrive at the receiver via different transmission paths. In systems with carrier frequency in the order of Giga Hz, a movement of the receiver in the order of one meter is more than enough to bring the channel from a constructive interference to a destructive interference situation.

Distance-dependent path loss, shadow fading, and multipath fading are multiplicative in modeling a wireless channel. As distance-dependent path loss represents an average path loss, shadow and multipath fading effects describe the unpredictability of the wireless channel. It is noted that shadow fading usually fades in a much slower rate than multipath fading because it models the change of environmental clusters.

2.3 Stochastic geometry in cellular systems

Traditionally, the geometry of cellular communication networks is modeled as a regular tessellation of congruent regular polygons. Regular hexagons are the most commonly adopted polygon for constructing a cellular network geometry [31]. An implication of a regular hexagonal network is that each cell of the network is of the same shape and size, in contrary to observations from the real world. Due to the non-uniform distribution of populations, irregular terrestrial landmarks, etc., the spatial structure of cellular networks is typically far from being regular. The ap-

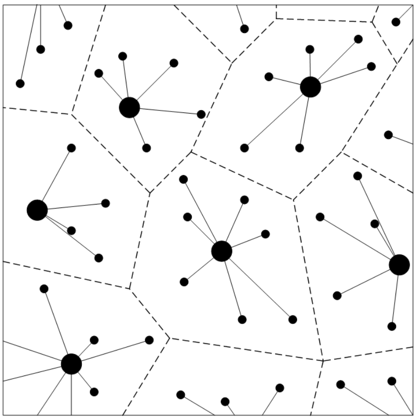

Figure 2.2. Stochastic geometry for modeling cellular networks.

plication of stochastic geometry to the modeling of cellular networks thus emerges [32, 33].

Stochastic geometry indicates the study of random spatial patterns by spatial point processes. In the application of communication networks, independent spatial point stochastic processes are usually used to model the realization of different types of objects (user equipment, BSs, etc.). The realized cellular structure of the communication network is an irregular tessellation which models the structural fluctuations of the terrain, and user distribution, etc. As some key characteristics of the networks can be expressed in functionals of the embedded point processes, analytical formulae can often be obtained by applying the properties of the point processes. Fig. 2.2 illustrates a network realization based on stochastic geometry, with the big dark spots indicating the BSs and the small dark spots indicating the User Equipment (UE). The BSs and UE are associated by solid lines and the irregular spatial structure of the cellular system is denoted by the dashed lines.

The fading effects considered in a wireless channel model takes into account the possible path loss fluctuation due to the obstructions caused by for example, buildings, terrains etc. As the fading effects are modeled by stochastic processes, this indicates that the irregularity of the environments between a transmission pair is modeled. In other words, fading effects serve to model similar effects as addressed in stochastic geometry, although they are usually carried out by different families of stochastic processes. However, stochastic geometry imposes random spatial patterns on both UE and network infrastructural elements (e.g., BSs). For compensation, in state-of-the-art system models, an additional stochastic process for user generation is considered to accompany the stochastic wireless channel modeling. Thus, the system modeling method featured with stochastic user generation, stochastic wireless channel modeling, and an embedded regular hexagonal tessellation of network geometry serves to address similar concerns attempted by stochastic geometry. With a slight abuse of the terminology, we shall refer to stochastic geometry as stochastic spatial user generation in this work, as this is the part that cannot be compensated by a stochastic channel modeling.

The stochastic UE generation impacts the calculation of the distance-dependent path loss in a wireless channel model. While this is crucial to consider the inherent feature of spatially distributed users in cellular networks, it often makes analytical approaches challenging in the investigation of system performance. To facilitate the analysis, one typically ignores this component and considers the fading effect that is not directly pertinent to the environmental fluctuations (i.e., multipath fading is considered only). Although the asymptotic analysis based on this simplification provides insights into the system properties, it also admits deviations from a more realistic settings.

2.4 Pico-cellular scenario

A comprehensive evaluation of communication systems requires channel models that allow realistic modeling of the propagation conditions in different environments. For this, channel modeling for different environments has been one of the earliest research fields in wireless communications. On the other hand, leaving the capability of capturing the propagational insights aside, we do need reference models based on which different techniques are able to be compared. A number of reference channel modes have been developed for this purpose. Examples include the 3GPP spatial channel model [34], COST [35], WINNER [36], and ITU [37]. In this work, we consider a WINNER A1 indoor office scenario. The WINNER A1 channel model provides a pico-cellular environment with strong inter-cell interference. We present the environmental parameters here, but address the simulation details later when this channel model is used.

The WINNER channel model is both a system- and link-level model. Here, only those parameters related to system-level simulations are considered. Fig. 2.3 illustrates the WINNER A1 scenario. It consists of 40 rooms and 2 corridor. Four Access Points (AP) are placed evenly in the cor-

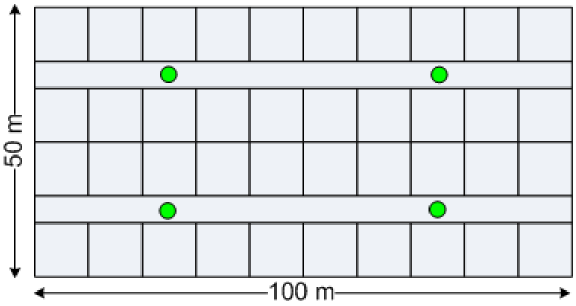

Figure 2.3. Floor layout of the WINNER A1 scenario.

ridors, as illustrated with green spots in Fig. 2.3. The propagation characteristics follow those of the WINNER A1 model. Distance-dependent path loss is calculated from the parameters A, B, C as

$$PL = A\log_{10}(d) + B + C\log_{10}(f_c/5) + X + FL, \tag{2.2}$$

where f_c is the carrier frequency, X is the wall loss, and FL is the floor loss. The most important characteristics of the path loss model are given in Table 2.1.

Table 2.1. Parameters of the WINNER II A1 path loss model

Building dimensions	100 m x 25 m
Room dimensions	10 m x 10 m
Corridor width	5 m
Room height	3 m
BS height	2 m
UE height	1 m
Floors	6
Boundary conditions floor direction	wrap-around
Antenna patterns	omni directional
Carrier frequency	2.6 GHz
Line-of-sight (LOS)	in same room/corridor
LOS path loss	$A = 18.7,\quad B = 46.8,\quad C = 20$
Corridor-to-room path loss	$A = 36.8,\quad B = 43.8,\quad C = 20$
Room-to-room path loss	$A = 20,\quad B = 46.4,\quad C = 20$
LOS shadow fading std.	3 dB
Corridor-to-room shadow fading std.	4 dB
Room-to-room shadow fading std.	6(light walls) or 8(heavy walls) dB
Inner wall loss	5 dB per wall
Floor loss	$17 + 4(N_{\text{floors}} - 1)$ dB

3. Cooperative Networks

Cooperative Communication [8] [6] [7] [38] indicates the capability for users in a system to coordinate their resources to enhance the transmission quality. Cooperative communication is also referred to as cooperative relaying, cooperative diversity and coded cooperation. Conceptually, cooperative communication exploits the spatial diversity inherent in a multi-user system by enabling users with different channel conditions to cooperate and relay each other's message to destination nodes. This is beneficial in wireless environments where different users are likely to experience diverse channel conditions. For users who are in deep channel fades, co-operative users can offer better transmission paths for message delivery. System performance can be enhanced by improving both coverage and throughput of users experiencing worse channel conditions [8], such as those experienced by cell-edge users in cellular networks.

3.1 Introduction

At the link level, the spatial diversity has been traditionally harvested through the use of multiple antenna elements at both ends of a transmission path. In principle, this is investigated in the scope of Multiple-Input Multiple-Output (MIMO) systems and their applications, see for example, [39, 40]. In MIMO systems, signal streams are multiplexed at a transmitter and are de-multiplexed at a receiver by various adaptive algorithms in order to efficiently utilize the wireless channel. At the system level, the spatial diversity in multi-user systems has been exploited from the point of view of multi-user diversity. There, users are assumed to be independent without cooperation, and compete for resources. The multi-user diversity is realized by opportunistic scheduling where resources are allocated to users with good channel conditions [41]. To further impose fairness on scheduling decisions, different kinds of fairness metrics are taken into account. Unfortunately, multi-user diversity schemes do not improve the channel conditions experienced by users. For users in worse channel conditions, their throughput can be improved only by allocating more resources. For users who are out of coverage, there is hardly any means to serve them from the perspective of multi-user diversity.

User cooperation has been studied in the context of P2P and multi-hop networks. Popular examples include Mobile Ad hoc NETworks (MANET) [42] and Wireless Sensor Networks (WSN) [43]. Depending on the applications, the requirements on user cooperation are different. Both MANETs and WSNs are self-configuring networks and the primary challenge for them is to properly maintain the routing information for each device. In WSNs, additionally, whose network operation is usually subject to limited power and radio resources, sensor cooperation for extending network lifetime is usually an issue. In cellular systems, the cooperation (if one consider cooperative relaying as an extension to the deployment of fixed relays) is mostly for extending service coverage and throughput improvement [44]. The cooperation itself has no impact on network life time, although individual power consumption of user equipment is still a concern for users who offer the assistance.

Cooperation between neighboring nodes was first explicitly considered in [8], where two active nodes act as relay nodes for each other. The distributed beamforming method proposed coherently combines two received signals, one from the source node and the other from the relay node, at a receiver node. In general, a multi-hop scheme can be devised by sequentially applying a dual-hop scheme, for example, the one proposed in [8], on intermediate nodes between a source node and a destination node. Extensions to *multi-hop diversity* are discussed in, for example, [45] where the concurrent reception of the transmitted signals from previous relays is assumed to fully exploit the broadcasting nature of the wireless channel. Although the results suggest improved performance of the multi-hop diversity scheme over a multi-hop scheme, the challenging issues such as resource assignment in multi-hop chains, load on the feedback requirement etc., may cause high complexity for applying the approach.

In [6], a variety of low complexity cooperative protocols are considered information theoretically under the framework of diversity-multiplexing tradeoffs. Depending on the signal processing procedures performed on received signals at a relay node, two well-studied relay protocols in the

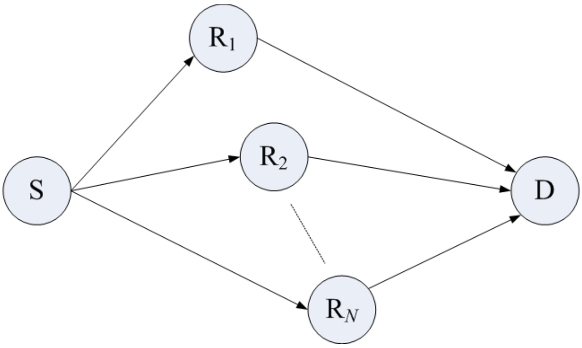

Figure 3.1. Cooperative relaying network.

literature are:

- Amplify-and-Forward (AF) [6][46]: Relays act as analog repeaters by re-transmitting an amplified version of the received signal. The Additive White Gaussian Noise (AWGN) is at the same time amplified and transmitted.

- Decode-and-Forward (DF) [6][47]: Relays attempt to decode the received signal and then construct a copy of the original signal for transmission.

There are variants that are hybrid forms of AF and DF, known as hybrid relaying [48][49][50]. To fully utilize the available relay nodes, the relay nodes with hybrid relaying protocol can decide to engage in AF or DF relaying protocols on their own. If the channel between the source and one relay is good enough for the relay to decode the received signal, the relay uses the DF protocol. On the other hand, if the relay fails to decode the received signal, the relay uses the AF protocol to forward the received signal.

3.2 Full spatial diversity with cooperative relaying

The concept of cooperative relaying is illustrated in Fig. 3.1 where N relays assist the transmission between a source-destination pair. The transmission of a message from the source node takes two phases. In the first phase, the message is transmitted from the source node. Due to the broadcasting nature of the wireless channel, each relay node receives one copy of the message. In the second phase, the relays process the received signal according to the relaying protocol, and re-transmit the processed signal to the destination node. In principle, the destination node receives $N+1$ independent copies of the original message, one from the source node and N from the relays. Spatial diversity gains from the cooperation are expected due to the independence between different transmission paths. Such a two-step cooperative scheme is termed *half duplex* as relay nodes cannot transmit and receive at the same time. The half duplex cooperative relaying scenario is studied in [51]. In addition, $N+1$ orthogonal channels are used for transmission so that no mutual interference is considered to simplify the receiver design. The scheme achieves a diversity gain of the order $N+1$. Despite the capability of harvesting spatial diversity, the scheme proposed in [51] is fundamentally limited by the orthogonal partitioning of system resources. This overhead to cooperation is particularly devastating in large networks with many nodes.

3.2.1 Single relay selection

The same spatial diversity order can be achieved by simply selecting one relay node [52, 53, 54, 55, 56, 57, 58]. In [52], a distributed relay selection scheme utilizing instantaneous channel information was proposed. The selection is based on a delay process with carrier-sense multiple access on relay-destination links. The scheme is proven to be optimal in the sense that it achieves the same diversity-multiplexing tradeoffs as in [6], that is

$$d(r) = (N+1)(1-2r), \tag{3.1}$$

where r is the multiplexing gain and $d(r)$ is the diversity order as function of r, as defined in [59].

In [55], comparison on the performance of a best relay selection scheme and the all relaying strategy in [51] is conducted, assuming orthogonal resources for different nodes. Optimal power allocation among the source and relay nodes is considered in both scenarios. The analysis on outage probability shows that the best relay selection maintains the full diversity. Additionally, using a single relay is more spectrally efficient as less resources are allocated to the relay-destination links. When requiring a fixed rate transmission with the same amount of resources, the single relaying scheme can outperform the all relaying scheme in outage probability.

A DF selection cooperation scheme where a single relay node is selected out of a decoding set is introduced in [58]. The decoding set is defined as the relay set consisted of all relays that can decode the message sent by the source node. This is different from the selection relaying in [51] where all relays in the decoding set forward the message from the source node. The single DF relay selection scheme is applied to a network with multiple sources. If one node is selected as relay by more than one source, the available power of the relay is allocated evenly among the sources who selected the node. Similar conclusions as [55] are drawn by comparing the selection cooperation and the selection relaying schemes. In addition to the full diversity order, the selection cooperation scheme outperforms the selection relaying scheme on outage probability when attempting to maintain a fixed transmission rate.

For spectral efficiency, cooperative relaying can be combined with hybrid Automatic Repeat reQuest (ARQ). This is termed *incremental relaying* in [6] and further extended in, for example, [60, 61, 62, 63, 64]. For a fixed rate transmission, the spectral inefficiency also comes from the fact that the relays repeat the transmission from the source node all the time, no matter if it is needed or not. In incremental relaying, the relays take care of the retransmissions required when the direct transmission (i.e., the source-destination link) fails. Incremental relaying can be combined with relay selection for further spectral efficiency. Variants of incremental relaying scheme that incorporate relay selection can be found in [60, 61, 62, 63, 64]. In [63, 64], the authors merge the concept of hybrid relaying, in addition to incremental relaying and relay selection, so that the selected relay can switch between the AF and DF relaying protocols. The results show a further gain due to the additional flexibility of allowing hybrid relaying.

In [PI], a single relay selection scheme is considered under a framework with stochastic geometry and macro diversity possibility. The considered scheme is a fully opportunistic one so that selection between the best relaying path and the direct path is performed for better efficiency. We characterize an e2e Signal-to-Noise Ratio (SNR), which is an indicator of the system throughput if an adaptive transmission scheme allowing a variable rate transmission is taken. This setting is different from a fixed rate scheme where outage probability is used as the figure of merit. The availability of instantaneous CSI is assumed to vary from perfect knowledge to partial awareness complying with practical cellular architectures, for example, LTE systems. In cellular systems, BSs can learn the Uplink (UL) channel information by the insertion of training symbols at users. This in-

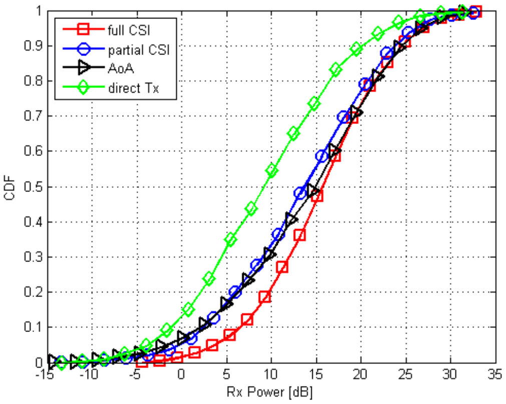

Figure 3.2. CDF of UL received power for different transmission strategies, under fully opportunistic relay selection.

dicates that the instantaneous CSI of relay-destination links is available to the BSs, which is denoted by partial CSI in [PI]. To acquire full CSI, additional signalling for source-relay links is required. In principle, relay selection with the partial CSI is diversity suboptimal, i.e., with diversity order of 1, as shown by [65, 66, 67]. Nevertheless, significant SNR gains over the direct path are already achieved by relay selection using partial CSI. To leverage between the overhead of collecting full knowledge of CSI on all the links and the benefits of perfect relay selection, additional information on the Angle of Arrival (AoA) of the relay-destination links is assumed on top of the partial CSI.

For demonstration, a single cell scenario (radius 1) with a source node uniformly and randomly distributed in a 120-degree sector, but is at least 0.4 away from the BS, is assumed. There exists N relay nodes uniformly distributed at random in the sector area. The parameter N follows a Poisson distribution with mean value of 10. The channel is modeled by considering distance-dependent path loss, log-normal distributed shadow fading (with standard deviation 7 dB) and Rayleigh distributed multipath fading. The distance-dependent path loss is modeled by a single-slope path loss model with a path loss exponent of 4. The transmit power is assumed to be 1.

Fig 3.2 illustrates the Cumulative Distribution Function (CDF) curves of the UL received signal power for different relay selection strategies. The results show that the additional AoA information is especially constructive in a high SNR regime where the performance is close to that attained by using full CSI. It is also observed that one starts to suffer from incomplete CSI when the received signal power is reduced. This is where the higher diversity order comes to play for reducing the outage probability so as to increase the throughput. However, one should notice that in terms of average throughput inferred by checking the average received power, the loss due to incomplete CSI is not devastating.

3.2.2 Multiple relay selection

A natural extension from single relay selection is to select multiple relay nodes [65, 68, 69, 70]. In [65], simple multinode selection schemes have been shown to yield some coding gain in addition to full diversity. However, the optimal selection of relays requires in general an exhaustive search. In [68], the problem of multiple relay selection is related to knapsack problems for efficient search over the combinatorial space for optimization. A multiple relay selection scheme based on the relay-destination links is proposed in [69]. There, relays with the strongest relay-destination links are selected. In [70], multiple relays are selected by including relays in a random ordering manner until the combined SNR at the destination node reaches a target value. Since there is no optimal ordering for relays [65], the selected set of relays is in general suboptimal.

The difficulties for selecting multiple relays come from the fact that a dual-hop cooperative relaying channel with multiple relays generates an imbalanced channel conditions on the first and the second hop. This can be observed more clearly by checking the e2e channel power gain. Without loss of generality, lets assume that an active relay set $\mathcal{M}$ with cardinality $|\mathcal{M}| = m$ is to be selected from a candidate relay set $\mathcal{N}$ with cardinality $|\mathcal{N}| = N$, where $N \geq m$. For a half-duplexing DF relaying protocol, the e2e channel power gain can be expressed by

$$g_{\mathrm{e2e}} = \min\left(\min_{i\in\mathcal{M}} g_{\mathrm{r}_i}, \sum\nolimits_{i\in\mathcal{M}} g_{\mathrm{a}_i}\right) \equiv \min(g_{\mathrm{r},\mathcal{M}}, g_{\mathrm{a},\mathcal{M}}), \tag{3.2}$$

where g_{r_i} and g_{a_i} are the channel power gains of the source-relay link and the relay-destination link, respectively, associated with RN$_i$, $g_{\mathrm{r},\mathcal{M}} = \min_{i\in\mathcal{M}} g_{\mathrm{r}_i}$, and $g_{\mathrm{a},\mathcal{M}} = \sum_{i\in\mathcal{M}} g_{\mathrm{a}_i}$. In (3.2), we have assumed that all nodes use the maximum transmit power since this maximizes g_{e2e}.

For the first hop with a channel power gain denoted by $g_{\mathrm{r},\mathcal{M}}$, the transmitted signal from a source node is received by relays. This hop, which consists of the source-relay links, is a diversity order 1 transmission. In the second hop, the destination node is capable of harvesting spatial diversity by combining the received signal from different relays and the source node. This indicates that the second hop i.e., the relay-destination links, is inherently stronger than the first hop. From (3.2), the selection of relay nodes should balance the channel power gains of the first and the second hops in order to maximize the e2e gain g_{e2e}. The performance degradation in outage probability due to imbalanced cooperative channel is investigated in [71]. The degradation in e2e channel power gain due to imbalanced cooperative channel can be found in [PI].

3.3 Perspective of variable rate transmission in cooperative relaying

The discussions on cooperative relaying so far mostly assume a fixed transmission rate is to be maintained. The outage probability then characterizes the system performance. In DF relaying protocol, a fixed rate system enables the construction of a decoding set of relays [51, 58]. This is termed reactive relaying in [72]. The construction of the decoding set allows one to discuss the outage probability based on simply relay-destination links. It simplifies the analysis as one needs not to deal with the dual-hop cooperative channel. On the other hand, it would be interesting to look at the same problem from the perspective of optimizing the transmission rate. This is considered in the following as variable rate transmission, and is termed proactive relaying in [72].

With the variable rate transmission in cooperative relaying, one attempts to maximize the e2e transmission rate (and therefore, throughput). One major difference from fixed rate transmission is that no decoding set can be defined beforehand. The decoding set is known only after an instantaneous rate is determined. From (3.2), the first hop, $g_{\mathrm{r},\mathcal{M}}$, is constrained by the worst relay among the selected relay set $\mathcal{M}$. A dummy selection of including all the available relays is undesired as this in general largely under-estimates the cooperative channel capacity. Therefore, relay selection is essential in variable rate transmission from the system throughput perspective. The optimization of the e2e performance in a variable rate system is to generate a balanced first and second hop through the process of relay selection. The decoding set is to be optimized for maximum throughput. It is noted that while both proactive and reactive relaying strategies are outage-optimal [72], it was proven that proactive relaying scheme achieves a slightly better effective ergodic capacity [73].

In [74], the proposed multiple relay selection method maximizes an e2e capacity by allowing channel dependent resource allocation among the two hops in a dual-hop scenario, i.e., the harmonic mean of individual rates on two hops is optimized. The method includes the relays with strongest source-relay links to the set $\mathcal{M}$ till the e2e capacity is maximized. In cases where the channel conditions on the relay-destination links are unknown, a method of selecting a fixed amount of relays by including the relays with the strongest source-relay links is proposed. Discussions on multiple relay selection in variable rate systems are also considered in [PII] from the perspective of g_{e2e} in (3.2). There, we argue that including as many relays as possible for optimal system throughput may be undesired due to factors such as cooperation overhead. In addition, in a large network with many source-destination pairs, unlimited number of cooperative nodes make it more likely for one node to be selected as a relay by many source nodes. Due to limited transmit power per node, the potential gain that is estimated by each source-destination pair may vanish if the relay is shared by many other source nodes. Thus, a multiple relay selection scheme with cardinality constraints is to the flavor for practical applications. An optimal relay selection scheme with cardinality constraints is devised as given in Algorithm 1. The algorithm stops when it finds the best relay set $\mathcal{M}^{\mathrm{o}}$, with cardinality m.

Algorithm 1 Optimal-m Relay Selection

```
1. Sort $g_{\mathrm{r}_i}$ in descending order, i. e. $g_{\mathrm{r}_i} \geq g_{\mathrm{r_j}}$ if $i < j$.
2. Initialize candidate set,
   the $m$ RNs with best first links: $\mathcal{M}^m \leftarrow \{1, 2, \cdots, m\}, \quad i \leftarrow m.$
3. Calculate $g_{\mathrm{e2e}}$ with $\mathcal{M}^m$ by (3.2), $g^m_{\mathrm{e2e}} \leftarrow g_{\mathrm{e2e}}$.
4. if $\mathcal{M}^m$ is not relaying hop constrained then
5.     iterate by constructing new trial set,   $i \leftarrow i + 1$
6.     add the not considered RN with best first link:   $\mathcal{M}^{m+1} \leftarrow \mathcal{M}^m \cup i$
7.     remove RN with worst access link:
       $\tilde{\mathcal{M}} \leftarrow \mathcal{M}^{m+1} - j$, where $j = \arg\min_{k \in \mathcal{M}^{m+1}} g_{\mathrm{a_k}}$
8. end if
9. Calculate $g_{\mathrm{e2e}}$ for trial set $\tilde{\mathcal{M}}$ by (3.2), $\tilde{g}_{e2e} \leftarrow g_{\mathrm{e2e}}$.
10. if trial set better than candidate set, $\tilde{g}_{e2e} > g^m_{\mathrm{e2e}}$ then
11.     make trial set candidate set:   $\mathcal{M}^m \leftarrow \tilde{\mathcal{M}}, \; g^m_{\mathrm{e2e}} \leftarrow \tilde{g}_{e2e}$, go to line 4
12. end if
13. Output candidate set: $\mathcal{M}^{\mathrm{o}} \leftarrow \mathcal{M}^m$
```

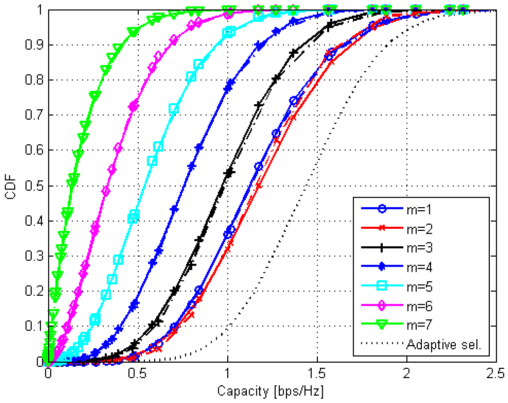

Figure 3.3. CDF of e2e capacity by using optimal$-m$ relay selection with a same mean channel gain. Simulation results(dash-dotted lines), derived approximations(solid lines), and an upper bound [74] denoted by adaptive m(dotted line) are shown for comparison.©2011 IEEE

The complexity of Algorithm 1 in N is dominated by the sort in Step 1, and is $\mathcal{O}(N\log N)$ [75]. The complexity in m is linear. It should be noted that, with variable rate transmission, single relay selection, i.e., the cardinality $|\mathcal{M}| = 1$, is optimal if the cooperative relays are subject to a total power constraint [72]. This is because e2e performance is maximized by allocating all power to the relay with the strongest relay-destination link in $\mathcal{M}$. Any form of power allocation among relays in $\mathcal{M}$ would be throughput suboptimal. Thus, multiple relay selection in variable rate system should be considered in a scenario with individual power constraints on relay nodes. In [PII] where relays are subject to predetermined transmit power constraints, more selected relays mean more transmit power. The optimal e2e channel power gain g_{e2e} is expressed by

$$g_{\mathrm{e2e}}^{\mathrm{O}} = \max_{\mathcal{M}\in\mathcal{N}_m} \min\left(g_{\mathrm{r},\mathcal{M}}, g_{\mathrm{a},\mathcal{M}}\right), \tag{3.3}$$

where $\mathcal{N}_m$ consists of $\binom{\mathcal{N}}{m}$ $m-$subsets, with each of the $m-$subset being one realization of selecting m relays from the relay set $\mathcal{N}$.

For a given cardinality constraint m, there are $N-m+1$ different m-subsets from Algorithm 1. When going through these m-subsets, the CDF of the first hop is described by the i^{th} order statistic, for $m \leq i \leq N$. For the second hop, however, one selects m strongest links among the i RNs. Based on the observations, a distribution approximation of $g_{\mathrm{e2e}}^{\mathrm{O}}$ is devised.

For demonstration, we assume a single cell scenario in UL phase. A source node is to communicate with a destination, i.e., the BS, with $N = 7$ idle users as candidate relays. We assume equal mean power among all the links. The maximum transmit power is adjusted to result in an SNR value of 0 dB at the cell border. Fig. 3.3 illustrates the CDF curves of e2e capacity for optimal$-m$ relay selection. The results using Algorithm 1(dash-dotted lines) and the derived approximations (solid lines) from [PII] are given. For comparison, the method in [74] for selecting an optimal set of active relays without the cardinality constraint is also given as an upper bound (dotted line) and is denoted as adaptive selection. The e2e capacity is obtained by mapping g_{e2e} through the Shannon formula. From Fig. 3.3, there is hardly any benefit from using more than one RN. As balanced access and relaying hops are preferred from the e2e performance perspective, it is not sensible to increase m when the combined receiving power from the selected relays is already higher than the first hop. Enforcing equal power on all links leaves little room for further optimization from the perspective of selecting multiple RNs. The match between simulated and approximated curves is good. With adaptive selection of the cardinality of the active relay set and dynamic resource allocation among the first and second hop (dotted line), one is able to do slightly better.

3.4 Impact of stochastic geometry and macro diversity on cooperative relaying

In the context of cooperative relaying, stochastic geometry should be considered since the candidate nodes where the cooperative relays are selected from are by definition spatially distributed at random. The stochastic geometry assumption also gives rise to the possibility of macro diversity, in addition to the micro diversity. If micro diversity is harvested from combatting multipath fading as in traditional single-hop transmissions, the channel is described by an average power gain and the multipath fading. However, spatial diversity discussed in the context of cooperative diversity should be generalized to include both micro and macro diversity, as the spatially separated nodes indicate different shadowing fades experienced. As shown in [76, 77, 78], macro diversity which by definition helps to avoid deep shadowing fades, is an efficient tool for improving SNR. With macro diversity, the small-scale average signal level is enhanced directly and is applied to all instantaneous channel realizations.

Shadow fading is often described to follow a log-normal distribution, while the simplest form of multipath fading is described to follow an exponential distribution (or to follow a Rayleigh distribution in fading strength). It is essential to note that a log-normal distribution is a heavier tailed distribution than an exponential distribution. When combined, shadow fading effect dominates the outage behavior, and the combined effect of a log-normal and an exponential distributions can be further modeled by the log-normal distribution with different parameters [79]. Analysis conducted by considering only multipath fading does not allow immediate application to realistic environments. The gain from cooperation may be overestimated if there are dominant relaying paths, for example, a strong path accompanied by some weak relaying paths.

Different characterization of the underlying channel statistics may lead to very different asymptotic behavior of the outage probability. To define the terms *diversity order* and *multiplexing gain* [59], the underlying channel distribution should be of *exponential order* with average SNR. This is the case for a Rayleigh faded channel model. However, a log-normal distribution is not of exponential order, and therefore, the diversity order and multiplexing gain are not well-defined in a channel model with a log-normal faded shadowing effect. In [PI], the asymptotic outage probability with consideration of a complete channel model i.e., the one that includes stochastic geometry, shadow fading and multipath effects, is considered by modeling the complete channel with another log-normal distribution. It is shown that the diversity order increases as the number of candidate relays increases, although the conventional definition of diversity order is no longer applicable.

The benefit of selecting multiple relays for assistance can be more appreciated with stochastic geometry. As (3.2) suggests, the channel gain of the second hop, $g_{\mathrm{a},\mathcal{M}}$, becomes stronger as the cardinality of $\mathcal{M}$ increases since the total transmit power on the second hop increases. On the other hand, the channel gain of the first hop, $g_{\mathrm{r},\mathcal{M}}$, may become weaker as the cardinality of $\mathcal{M}$ increases since the weakest source-destination link determines the channel quality of the hop. Consequently, the second hop can bridge a larger distance than the first hop, and the relays selected are more likely to be clustered around the source node when the cardinality of $\mathcal{M}$ increases.

For demonstration, we consider a similar setting as in Fig. 3.3 and use Algorithm 1 to find optimal relay set. In a cell with radius 1, we assume that the source node is at the cell border and $N = 7$ idle users serving as candidate RNs reside uniformly at random within a sector area with an

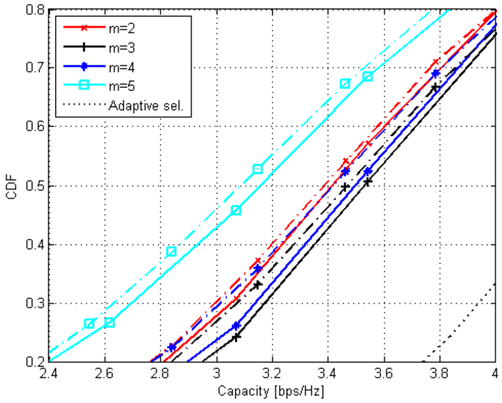

Figure 3.4. CDF of e2e capacity by using the optimal relay set $\mathcal{M}^{o}$, with path loss consideration. Optimal$-m$ relay selection with algorithmic search (solid lines), ordered method [65] (dash-dotted lines), and adaptive selection [74] (dotted line) are shown for comparison.©2011 IEEE

angular spread of $\pi/3$. The source node is situated in the middle of the angular spread. In addition to Rayleigh fading, the mean channel gain is dictated by the distance-dependent path loss modeled by a single-slope path loss model, for example, g_{r_i} is expressed by $g_{\mathrm{r}_i} = P_{\max} l_{r_i}^{-\alpha}\xi$, where l_{r_i} is the link distance, $\alpha = 4$ is the path loss exponent, and ξ is a random fading gain modeled by an exponential distribution (i.e., Rayleigh fading). The maximum transmit power is adjusted to result in SNR$= 0$ dB in the cell border.

Fig. 3.4 presents the CDF curves of the e2e capacity by using the optimal$-m$ relay selection. The e2e capacity is obtained by mapping g_{e2e} through the Shannon formula. For comparison, the method in [65] (dashed-dotted lines, termed ordered method) and the adaptive selection method in [74] are also given. With a cardinality constraint on the selected relays, the proposed method (solid lines) performs better than the method proposed in [65], which is a direct results of the optimality of our method. The adaptive relay selection method shows the best results due to the additional freedom of adapting the number of selected relays and dynamic resource allocation among the first and the second hop.

Comparing Fig. 3.3 and Fig. 3.4, one notices the difference induced by varying mean channel gains. To understand it, consider the ratio of the source-relay gain to the relay-destination gain for the individual candidate RNs. A geometry-based path loss induces a correlation of this ratio between nearby RNs, whereas with equal mean channel gains, they are not correlated. With different mean channel gains, these ratios are ex-

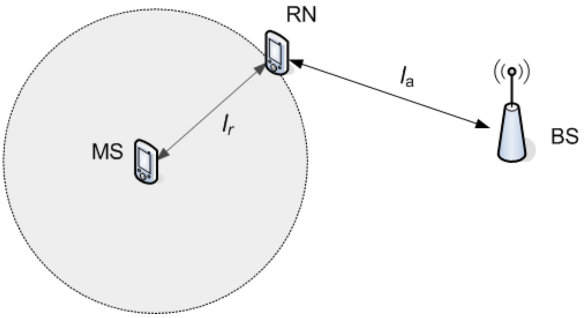

Figure 3.5. Gainful area of a second RN for one selected RN.©2011 IEEE

pected to be less than 1, which favours the use of multiple relays.

The superiority of multiple relay selection over single relay selection, with variable rate transmission, can also be intuitive explained. In Fig. 3.5, the RN is assumed the best node for relaying messages from the MS to the BS, if one single relay is to be selected. Considering only distance-dependent path loss and assuming that the distance of the relaying link is smaller than the distance of the access link, i.e., $l_r < l_a$. In view of (3.2), it is clear that an additional RN located within the shaded area are beneficial for g_{e2e}. It is noted that additional random fading consideration in channel gains does not change this fact qualitatively.

3.5 Perspectives of spectral efficiency and interference penalty with multiple relays

It may be of concern that the use of multiple relay in a half-duplexing protocol requires orthogonal resources among the source and relay nodes as in [51], which is spectrally inefficient. However, it is possible to reuse the same resources among the selected relay nodes for relaying and still benefit from the spatial diversity, if a multiple access scheme allowing perfect equalization of time dispersion is used. Examples include Orthogonal Frequency Division Multiplexing Access (OFDMA) and Single-Carrier Frequency Division Multiplexing Access (SC-FDMA). In these multiple access schemes, the delay spread of the received copies of forwarded messages from different relay nodes can be assumed smaller than a guard interval so that the received power can be combined at the destination node. Since there is no need to orthogonalize the resources for the relay nodes, there is no penalty of using multiple relays from the perspective of radio resources.

Another practical aspect of using multiple relays with individually predetermined power constraints comes from the interference penalty. As extra transmit power from the multiple relays is introduced to other unintended receivers, the impact to the whole system may be undesired. However, this can be addressed by spreading the extra transmit power over the frequency dimension in systems where resource allocation in the frequency domain is applied, and the power control is defined to maintain a target power spectral density, for example, the 3GPP LTE system. Like other power-controlled systems, their interference penalty to others will be under control as long as their received power spectral density remains the same. In this sense, higher SNR simply indicates more resources should be allocated. An attractive use case for this multiple relay selection is to enhance the QoS to cell-edge users in a cellular system, in the expense of radio resources. It is noted that the interpretation above decouples the interference penalty and the relay selection, if one relay is exclusively used by one source. The discussion for a multi-cell environment can be simplified to a single cell scenario. Further investigation is needed for this interpretation in terms of, for example, resource allocation over frequency selective channels.

4. Device-to-Device Communication underlaying Cellular Networks

The demand on enhanced data transmission for diverse mobile multimedia-rich services has been addressed in next generation communication systems under, for example, the scope of IMT-Advanced systems. One aspect that deserves more attention in considering IMT-Advanced systems is the emerging needs for high data rate local services. In [PIII], a proposal has been made to handle local P2P traffic by enabling direct D2D communication as an underlay to the IMT-Advanced cellular systems. The introduction of D2D communication achieves higher spectral efficiency as D2D connections reuse the same resources as the underlying cellular network. The mutual interference between D2D and normal cellular connections can be coordinated since users engaged in D2D communication are still under the control of their serving BSs (e.g., evolved NodeBs in IMT-Advanced systems). D2D communication is a promising technology component which allows a tight integration into an LTE-Advanced network [80, 81, 82].

4.1 Introduction

Fig. 4.1 illustrates the concept of D2D communication as an underlay to a cellular network. In Fig. 4.1, UE_1 and UE_2 communicate with each other directly via D2D radio, and are controlled by the BS. The cellular services are provided to other UE as usual with the D2D operation transparent to them. In principle, D2D communication is different from cooperative relaying in that the D2D connections are to handle possibly bidirectional local P2P traffic in a spectrally more efficient manner than it would be when using the BSs as relay i.e., normal cellular operation. Nevertheless, it is possible to extend the D2D concept in that sense.

D2D communication can operate in different modes for resource shar-

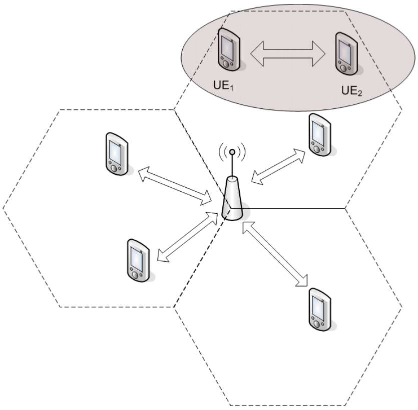

Figure 4.1. D2D Communication, indicated in the shaded area, works as an underlay to a cellular network.

ing both in cellular DL/UL transmission. The cellular network can assign dedicated resources to the D2D links so that the mutual interference between the two types of systems is negligible. Alternatively, the D2D connections can reuse the same resources used by the cellular links non-orthogonally. Similar to the principles of cognitive ratio systems, it is crucial that D2D communication does not generate harmful interference to the primary system (i.e., the cellular system in this case). This is easier with D2D communication as it is controlled in cooperation with the cellular network. D2D communication enables cellular operators to offer cost-efficient access to the licensed spectrum [82] as those promised by Wireless Local Area Networks (WLAN). WLANs have become increasing popular in recent years as they provide economic and convenient access to the Internet and local services in the license exempt bands. Similar services enabled by D2D communication exhibit additional advantage of providing a planned environment for more reliable transmissions.

Different standards addressing the needs for D2D operation in the same bands as infrastructure-based operation can be found, such as HiperLAN2 [83], TETRA [84], and Wi-Fi [1]. In HiperLAN2, D2D communication takes place in reserved resources. This restriction limits the interference from D2D connections. However, it also leads to inefficient utilization of resources as there is no flexibility for other services to access the reserved resources. This is the same in TETRA designed by authorities where dedicated resources are reserved country-wide for D2D communication. For the part of Wi-Fi technology that is based on IEEE 802.11 standards, UE

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[1] see `http://www.wi-fi.org/`

can sense and access the radio medium only if the channel is free. Accordingly the access points do not have full control over the resources used by the ad hoc D2D links. Wi-Fi technology supports a Wi-Fi direct mode that allows direct D2D connection between peers. However, Wi-Fi direct mode requires users to manually pair the peers, as is the case for Bluetooth technology. In the D2D underlay communication, the pairing can be handled by BSs and thus provides new use cases and better user experiences [PIII][82].

4.2 Coexistence of cellular and ad hoc networks

The idea of embedding ad hoc networks in cellular networks to enable D2D operation can be found in, for example, [85, 86, 87]. The discussions are based on the use of two air interfaces for cellular and ad hoc connections, respectively. In [87], a multihop cellular system is envisioned by allowing ad hoc D2D connections. Every UE in the multihop cellular system can participate in tasks of relaying traffic towards BSs. The coverage area of each BS is therefore extended. This results in a reduced number of required BSs. Since it is assumed that inter-cell traffic is handled by transmissions between BSs, the network capacity can be increased only when the communicating entities are in the same cell. In [85], an integrated Cellular and Ad hoc Relaying (iCAR) system is introduced for balancing traffic loads between cells. For this purpose, special mobile relays, denoted by Ad hoc Relay Stations (ARS), are strategically deployed to divert traffic from an overloaded cell to a lightly loaded cell. In [86], a Unified Cellular and Ad hoc Network (UCAN) architecture is proposed. The ad hoc D2D connections are assumed to use IEEE 802.11-based P2P connections. The UCAN is targeted for providing fair throughput to cellular users with poor channel qualities. The data from a BS is sent to users with poor channel qualities through proxy UE with good channel qualities.

The embedded ad hoc network introduced in [85, 86, 87] is for relaying purpose. In principle, ad hoc networks can be embedded for handling local P2P traffic in cellular networks since this is how the ad hoc networks were designed for in the very beginning. Nevertheless, some problems remain for applying the ad hoc networks in a two-tier network. Firstly, the spectral utilization of the licensed bands is not improved since two different frequency bands are assumed for two different air interfaces. In addition, the ad hoc D2D connection supported by WLAN protocols may be inefficient as interference coordination is usually not possible. Although opportunistic use of ad hoc D2D connections by WLANs provide performance improvement, WLANs cannot be counted on as reliable means for this purpose [86].

The spectral utilization efficiency can be improved by allowing ad hoc networks to operate in the under-utilized licensed bands for cellular networks. In [88], the spectrum sharing between the cellular and the ad hoc networks is considered. A stochastic geometry approach is taken so that the transmitters such as BSs, UE, and ad hoc transmitters, are described by independent two-dimensional Poisson Point Processes (PPP). The sharing of a pool of radio resources between the cellular and the ad hoc networks is considered in two different manners. In a underlay scheme, both types of networks can access all the available resources such that the resources are shared non-orthogonally. In an overlay scheme, the resources are adaptively split into two parts, one part for the cellular network and the other part for the ad hoc network, based on the traffic loads. Independent traffic is assumed between the two types of networks, so that the mutual interference between them can simply be described by the density of the transmitters due to PPP assumptions. Transmitted signals are assumed to be modulated with a frequency-hopping spread spectrum technique for interference management purposes. The analysis provides a basis for adapting the node density of the ad hoc network to the dynamic traffic in the cellular network under an outage constraint. For this spectrum sharing scheme to work, some extent of communication between the two networks is required for coordinating the tolerable node density of the ad hoc network. It is also required for the cellular network to notify the ad hoc network of the granted resources in the overlay scheme of resource sharing.

The D2D operation discussed in [PV] and [PVII] assumes that the cellular and D2D connections are under the control of cellular networks. The traffic originated from users can be either provided through the cellular or the D2D connections. Thus, D2D and cellular traffic can be treated as coming from the same pool as opposed to the case in [88]. The interference situation can be planned for effective interference management. In addition, the possibility of selecting different resource sharing schemes in [PV] and [PVII] facilitates more efficient spectral usage. This allows not only better spectral utilization of licensed bands, but also provides the possibility of more effective protection of the cellular network.

In [89], D2D operation aimed at short range communication for handling local traffic is considered, with similar aims as in [PIII]. Architectures for D2D operation are proposed in two directions for implementation based on the requirement of an additional air interface. In the *single air interface* approach, the same air interface for cellular and D2D operation is assumed. However, reserved resources, though the amount could be adaptive, are assumed for D2D operation, leading to inefficient use of resources as in the HiperLAN2 and TETRA systems. In the *multi-modality approach*, D2D operation assumes an independent air interface, for example, Bluetooth. This makes D2D operation vulnerable as interference coordination is not likely.

4.3 D2D communication with non-orthogonally shared resources

Proposals for D2D communication underlaying cellular networks that share the radio resources non-orthogonally can be found in [81, 80] [82] [90, 91, 92] [93] [94] [95] [96, 97, 98, 99, 100], and [PIII], [PV], and [PVII]. Similar to [88], a single air interface for D2D and cellular operation is assumed here. Furthermore, in these proposals, D2D users are under the control of the cellular network to facilitate the coordination of mutual interference. Tight cooperation of D2D and cellular operation is envisioned, depending on the extent of local awareness of the BSs to the interference situation between cellular and D2D users sharing the same resources.

To incorporate D2D operation into a cellular network without harmful impact on cellular operation, resources of cellular UL phases provide features that admit less overload than cellular DL phases. In the cellular UL phases, the transmit power of cellular users is power-controlled to maintain a target, for example, received SNR at the BSs. The impact of D2D transmitters on the BS can thus be learnt without any extra mechanism compared to state-of-the-art cellular architectures. In principle, no such power control scheme is assumed in the cellular DL phases. In [95], the cellular UL power control is assumed to reach a target SINR. Assuming the awareness of the SINR target and the power control results i.e., the maximum allowed transmit power, at D2D users, D2D transmitters can decide the D2D transmit power to emit a tolerable interference to cellular UL transmissions. In [90] [93] and [PIII], the D2D transmit power in cellular UL phases is determined in a similar way, though using the SNR

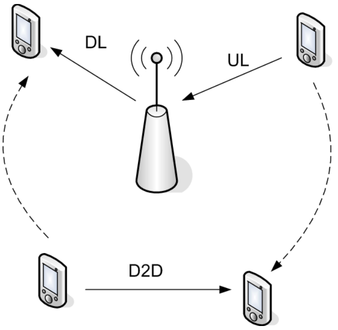

Figure 4.2. Illustration of the links that can benefit from multi-user diversity.

as UL power control target. D2D operation in [95] is initiated by users if they, for example, are not assigned resources due to congested traffic. Thus, users need also an efficient ad hoc route discovery mechanism in order to generate D2D connections with the intended users. More discussions on dynamic route discovery mechanisms for this type of two-tier networks can be found in [95] [94]. In [81] [82] [90] [93], [PIII], [PV], [PVII], the initiation of D2D operation is assisted by the BSs so that there is no need for local route discovery at users.

Exploiting multi-user diversity gain by interference-aware resource allocation provides another opportunity for improving the cellular transmission in the cellular DL phases and the D2D transmission in the cellular UL phases [90] [91] [92]. The multi-user diversity gain can be harvested by properly pairing the cellular and D2D users for sharing the resources. D2D operation allows higher spatial spectrum utilization and it can be assumed that for each D2D pair, there is a corresponding cellular link that the D2D pair share the radio resources with. The multi-user diversity arises from selecting a beneficial interference scenario through the selection of a cellular link for sharing the resources with. Equivalently, the selection can be conducted among different sub-bands, once the sub-bands are mapped to different cellular links. For a specific D2D pair, its interference path to the BS is fixed, indicating that there is no such diversity for the cellular transmission in the cellular UL phases and the D2D transmission in the cellular DL phases. Fig. 4.2 illustrates the links that could be improved by proper resource allocation to exploit the multi-user diversity. It is reported in [90] that the performance improvement can be large in a local area scenario. In addition, the multi-diversity gain can be available already with a small amount of cellular users for selection. In [92], the resource allocation scheme over multiple cellular users and

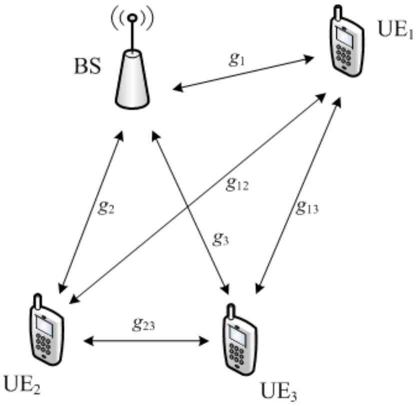

Figure 4.3. D2D communication as an underlay network to a cellular network. UE$_1$ is a cellular user whereas UE$_2$ and UE$_3$ are in D2D communication.©2011 IEEE

D2D users considers the local interference situations, making it possible for inter-cell interference avoidance at the same time. Interference randomization through resource hopping is considered in [98]. This provides more homogeneous services among users in challenging interference environments, for example, when one cellular connection shares resources with multiple D2D pairs at the same time.

The performance of D2D connections can be improved with slightly more D2D-oriented considerations. For D2D operation in the cellular DL phases, conservative D2D transmit power can be planned to limit the degradation of cellular DL users, for example, [PIII]. However, this results in limited space for D2D operation in the cellular DL resources. For enhancement, an interference-avoiding MIMO scheme is proposed in [93]. As the interference to the D2D receivers is generated by the BSs in the cellular DL phases, it is possible to mitigate the interference by precoded DL transmission if the BSs are equipped with multiple antennas. By knowing the interference channel between a BS and a D2D receiver, the BS can align its transmission to the null space of the interference channel. Furthermore, the BS is still free to apply any MIMO transmission scheme for its DL transmission on the projected subspace. The results show significant SINR gain for D2D operating in cellular DL phases in the cost of minor cellular SINR degradation. In [100], D2D users reuse UL cellular resources and are assumed with interference cancelation capability. Together with full duplex assumption at BSs, the authors proposed a scheme for retransmitting interference from BSs for assisting the interference cancelation at D2D users.

With full CSI, the resource sharing between the cellular and D2D connections can be optimized [PV, PVII]. Considering a case where one cellular user (UE_1) and two D2D users (UE_2 and UE_3) share the radio resources, as illustrated in Fig. 4.3, where g_i is the channel response between the BS and UE_i and g_{ij} is the channel response between UE_i and UE_j. The sum rate for sharing the resources non-orthogonally (Non-Orthogonal Sharing, NOS) can be found by summing up rates from the cellular link and the D2D link

$$R_{\mathrm{NOS}}(P_c,P_d)=\log_2\left(1+\Gamma_{\mathsf{c}}(P_c,P_d)\right)+\log_2\left(1+\Gamma_{\mathsf{d}}(P_c,P_d)\right), \tag{4.1}$$

where $\Gamma_{\mathsf{c}}(P_c,P_d)=g_1P_c/(g_{dc}P_d+I_c)$ and $\Gamma_{\mathsf{d}}(P_c,P_d)=g_{23}P_d/(g_{cd}P_c+I_d)$. We have denoted by g_{cd} the channel response of the interference link from the cellular connection to the D2D connection, and vice versa for g_{dc}. We used I_c and I_d to indicate the interference-plus-noise power at the receiver of the cellular link and the D2D link, respectively. To simplify the notation, we assume that all receivers experience the same interference-plus-noise power I_0. However, it is straightforward to consider it again whenever it is needed, for example, for performance evaluation.

With a greedy sum rate maximization strategy, the optimal power allocation of (4.1) is a feasible solution of the optimization problem

$$\begin{aligned}(P_c^*,P_d^*)&=\arg\max_{(P_c,P_d)\in\Omega_1}R_{\mathrm{NOS}}(P_c,P_d),\\ \Omega_1&=\{(P_c,P_d):0\le P_c,P_d\le P_{\max}\},\end{aligned} \tag{4.2}$$

where Ω_1 defines the feasible set of (P_c,P_d). It is shown that the optimal power allocation to (4.2) is searched over the following 3 possible sets $\Delta\Omega_1=\{(P_c,P_d):(0,P_{max}),(P_{max},0),(P_{max},P_{max})\}$ [101][PV].

To prioritize the cellular connection, we can set a SINR constraint to lower-bounded Γ_{c}. In practice, the higher transmission rate is also constrained by the limited amount of MCS. For this, one can impose an upper limit on the SINR. The sum rate optimization subject to the mentioned constraints is

$$\begin{aligned}(P_c^*,P_d^*)&=\arg\max_{(P_c,P_d)\in\Omega_2}R_{\mathrm{NOS}}(P_c,P_d),\\ \Omega_2&=\{(P_c,P_d):0\le P_c,P_d\le P_{\max},\\ &\qquad\gamma_l\le\Gamma_{\mathsf{c}}(P_c,P_d)\le\gamma_h,\Gamma_{\mathsf{d}}(P_c,P_d)\le\gamma_h\},\end{aligned} \tag{4.3}$$

where Ω_2 defines the feasible set of (P_c,P_d), γ_h is the SINR needed for using the highest MCS, and γ_l is the guaranteed SINR to prioritize the cellular connection. It is proven in [PV] that the optimal power allocation to (4.3) can be again searched over a set with finite points

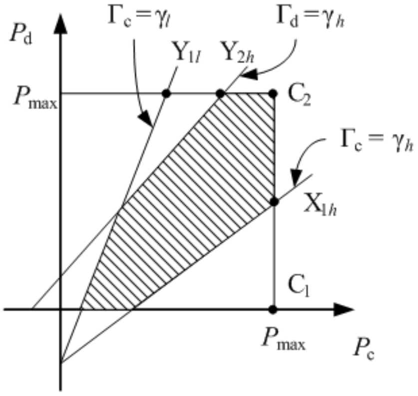

Figure 4.4. Feasible power allocation region Ω_2 when the optimal power allocation (P_c^*, P_d^*) falls within $\delta\Omega_1$.©2011 IEEE

$\Delta\Omega_2 = \{X, X_{1l}, X_{1h}, X_{2h}, Y_{1l}, Y_{1h}, Y_{2h}, C_1, C_2\}$, where we have denoted the intersection of $P_c = P_\mathrm{max}$ with $\Gamma_\mathrm{c} = \gamma_l$, $\Gamma_\mathrm{c} = \gamma_h$ and $\Gamma_\mathrm{d} = \gamma_h$ by X_{1l}, X_{1h} and X_{2h}, respectively, and the intersection of $P_d = P_\mathrm{max}$ with $\Gamma_\mathrm{c} = \gamma_l$, $\Gamma_\mathrm{c} = \gamma_h$ and $\Gamma_\mathrm{d} = \gamma_h$ by Y_{1l}, Y_{1h} and Y_{2h}, respectively. Additionally, we denote $C_1 = (P_\mathrm{max}, 0)$, $C_2 = (P_\mathrm{max}, P_\mathrm{max})$, and the intersection between $\Gamma_\mathrm{c} = \gamma_h$ and $\Gamma_\mathrm{d} = \gamma_h$ by X.

Some of the points in $\Delta\Omega_2$ are mutually exclusive because they cannot fulfill the maximum transmit power constraint simultaneously. We can summarize the optimal power allocation as:

- If X is feasible, $(P_c^*, P_d^*) = \{X\}$.
- Otherwise, the optimal power allocation (P_c^*, P_d^*) is searched in the only feasible set among:
  $\delta\Omega_1 = \{X_{1h}, C_2, \max_x(Y_{1l}, Y_{2h})\}$,
  $\delta\Omega_2 = \{Y_{1h}, \max_x(Y_{1l}, Y_{2h})\}$,
  $\delta\Omega_3 = \{X_{1h}, \min_y(X_{1l}, X_{2h})\}$,
  $\delta\Omega_4 = \{C_1, \min_y(X_{1l}, X_{2h})\}$,
  $\delta\Omega_5 = \{C_1, C_2, \max_x(Y_{1l}, Y_{2h})\}$.

Here the operator $\max_x$ selects the element with the largest x-coordinate value, and likewise for the operator $\min_y$. As an illustration, the feasible region Ω_2 when the optimal power allocation (P_c^*, P_d^*) falls within $\delta\Omega_1$ is shown in Fig. 4.4.

In [PV] and [PVII], the optimization is also performed for both transmit power and radio resources for an orthogonal resource sharing mode. The optimization of a reference mode where the BS is used as a relay for D2D operation (conceptually the same as traditional cellular connection) is addressed. The optimization of resource sharing is shown to admit a closed form solution, except for the reference case.

As shown in, for example, [PV][PVII], non-orthogonal resource sharing between D2D and cellular communication does not always yield better performance than orthogonal resource sharing where dedicated resources are assigned separately for both types of communication. Therefore, it is sensible to admit mode selection on resource sharing between D2D and cellular communication for better spectrum utilization, in a single cell scenario as illustrated in Fig. 4.3, if the BS is empowered for coordination. The circuit-switched type of power optimization for attaining target SINRs of different users between the paired cellular and D2D connections can be found in [96] [97].

The optimization of resource sharing between paired connections does not impede the application of inter-cell interference control mechanisms for efficiently managing inter-cell interference based on the power control or resource scheduling. In fact, the resource sharing schemes in [PV] [PVII] [96] [97] which aim at improving intra-cell spatial reuse of spectrum enabled by D2D underlay communication shall work on top of the inter-cell interference control schemes from the perspective of overall system performance. The proposed mechanism in [81] [82] for integrating D2D functionality in LTE-Advanced systems indicates that proper coordination from BSs, including mode selection, is feasible.

The analysis on resource sharing in [PVII] is also examined in a Manhattan grid with WINNER A1 office buildings. Propagation inside the building is modeled according to the WINNER A1 model [36], and propagation between the buildings is modeled as the Manhattan-grid path loss model B1 of [36]. The floor layout and important parameters of the WINNER A1 environment are described in Section 2.4. A fraction of system bandwidth is considered, with three uniformly distributed active users served by every BS that will share the resources. Among the three users, the two with stronger mutual link gain are defined as a D2D pair and the remaining one as a cellular user. Within the D2D pair, a D2D transmitter and a D2D receiver are defined at random. The optimized resource allocation scheme is applied in each cell without considering the inter-cell interference. The SINR constraints are assumed to be $\gamma_h = 18$ dB and

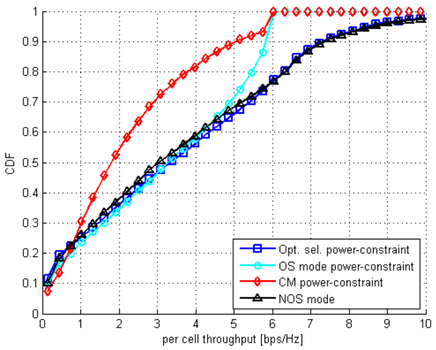

Figure 4.5. Cell throughput distributions with sum-rate maximization subject to the SINR and maximum power constraints in the Manhattan grid scenario. The results attained by the mode selection (Opt. sel.) and the three distinctive modes (NOS: Non-Orthogonal Sharing, OS: Orthogonal Sharing, CM: Cellular Mode) are presented.©2011 IEEE

$\gamma_l = -6.5$ dB, which map to the spectral efficiency of 6 and 0.3 bps/Hz, respectively, using the Shannon formula.

The results are illustrated in Fig. 4.5 where the distributions of the cell throughput by using three distinctive resource sharing modes (NOS: Non-Orthogonal Sharing, OS: Orthogonal Sharing, CM: Cellular Mode) and the mode selection among the three distinctive modes (Opt. Sel.: Optimal mode Selection) are presented. The results show, with full intra-cell coordination, significant gain from the D2D underlay system in this challenging environment.

When the resource sharing takes place in the frequency domain, there is an additional possibility to use all the available energy for the assigned bandwidth in order to enhance the power spectrum density in orthogonal resource sharing mode [PVII]. Although this promises additional gain in a single cell analysis where inter-cell interference does not exist, the results in the realistic Manhattan grid with office buildings indicate that the interference penalty shows up when applying excessive energy on exclusively assigned frequency bands.

4.4 D2D communication with limited CSI

With practical considerations, the CSI between a transmission pair is acquired at the receiver by the insertion of training symbols at the transmitter. In time-varying channels, reliable CSI requires frequent enough insertion of training symbols. In addition, for Frequency Division Duplex

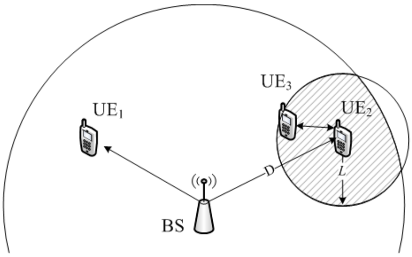

Figure 4.6. Illustration of the system setting in [PIV].©2009 IEEE

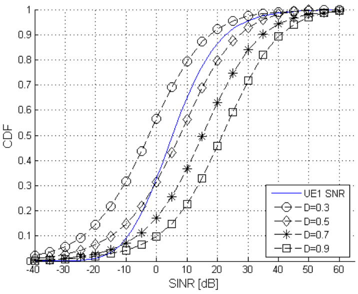

Figure 4.7. D2D SINR distribution under a D2D power reduction scheme that limits the cellular communication SINR degradation due to the D2D communication to 3dB at the 5 percentile of the SINR CDF when sharing the UL resources of the cellular communication, with $L = 0.3$.©2011 IEEE

(FDD) systems where the channel reciprocity property does not exist, the acquisition of DL CSI at the BSs requires users to feed the measurement of channel responses back. The feedback rate required for achieving reliable CSI at BSs depends on the channel fading rate, which is related to user mobility. In principle, reliable CSI at BSs is not problematic in state-of-the-art cellular systems such as 3GPP LTE [23]. However, for interference coordination in D2D underlay systems, additional loads on users for inter-user channel measurement are required. Tracing instantaneous CSI on inter-user links may indicate a high feedback rate (dependent on user mobility) which may not be favored for practical implementation. To reduce the amount of such channel reports, it is likely that users only report an average version of CSI. As instantaneous interference coordination such as the analysis in [PVII] requires reliable CSI, using only average CSI usually indicates performance degradation.

One interesting aspect of the D2D underlay system would be the achieved performance with very limited CSI for coordination. In [PIV], a single cell scenario with one cellular user and one D2D pair is studied, assuming only channel statistics on all the related links for coordination. The cellu-

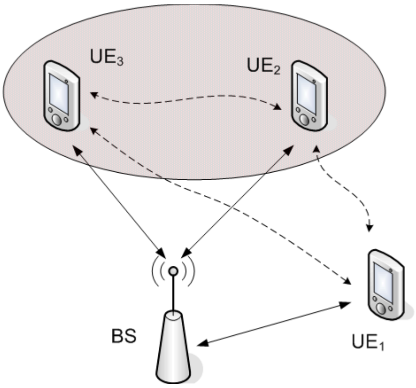

Figure 4.8. Illustration of the links with slow-faded channel responses for coordination.

lar user (UE$_1$) is assumed to reside in the cell area with uniform probability. One of the D2D users (UE$_2$) is assumed to stay at a fixed distance D from the BS, and the other D2D user (UE$_3$) is assumed to reside at most L distance from UE$_2$ with uniform probability, as illustrated in Fig. 4.6. The upper limit on the D2D transmission range can be justified by the fact that D2D communication is generically for short range communication. To prioritize the cellular services, the D2D transmit power is reduced to maintain a 3-dB SINR degradation of the cellular user at 0.05 outage probability. The results show that a dynamic power control based on the position of the D2D pair i.e., distance D, is more needed in the cellular UL phases. This is because in the cellular UL phases, the interference generated from the D2D transmission is only related to the distance D, but not the position of the cellular users. With such a power control scheme which admits only a small amount of D2D transmit power compared to the cellular transmit power, we observe that the realized D2D SINR is comparable or higher than the cellular SINR in most of the cell area. For illustration, Fig. 4.7 which shows the D2D SINR distribution after the D2D power reduction when sharing the UL resources of the cellular user with $L = 0.3$ is presented.

A more realistic assumption on CSI would consider the availability of instantaneous CSI for links whose acquisition of the channel states are assisted by the BS. For other links i.e., the links between users, only slow-faded values are assumed, with the channel uncertainty comes from additional untraceable Rayleigh fading. This is illustrated in Fig. 4.8 where the solid lines indicate the links with full CSI at the BS and the curved-dashed lines indicates the links with slow-faded channel responses. The scenario is studied in [PVI]. Although the results show only mild performance degradation, the QoS of the cellular services are now difficult to guarantee. With instantaneous CSI, the cellular services are provided with certain outage probability. Once the channel uncertainty is present, outage probability arises and in the cases studied in [PVI], the outage probability can be up to 0.25 depending on the placement of the D2D pair. To lower the outage probability to a tolerable level, a conservative scheme by intentionally planning higher QoS for the cellular services can be constructed. In this way, the impact of the channel uncertainty is buffered by the extra QoS support and the ultimate outage probability would be under control. Although it costs additional performance loss, D2D underlay communication can be still very beneficial on system throughput.

5. Conclusions

Inter-user communication in cellular networks is a promising feature that enables enhanced system performance. Such technology can be considered for providing services with higher QoS, for achieving better fairness to users experiencing poor channel qualities, and for improving services in local areas. Two exemplary use cases are considered to discuss the potential of inter-user communication: for relaying purposes and for P2P local communication.

In the first use case, users are considered to work cooperatively for transmitting messages between a transmission pair. Such cooperative communication provides cost-efficient solutions to the demanding requirements on the data transmission for future communication networks. It enables the opportunistic utilization of close-by nodes without the need for detailed planning as opposed to the case of the deployment of fixed relays. The inherent flexibility makes it more adaptive to the surrounding environments, thus offering higher potential for different applications.

In this work, cooperative communication is considered by taking into account the spatially distributed nature of the cooperative nodes. As its impact on the system performance can be either positive or negative, more tradeoffs, which are not visible without the consideration on the spatial distribution, are introduced in the system design. It has been demonstrated that the large-scale characteristics of the surrounding environment can dominate the outage behavior of the transmission over small-scale characteristics. The issue of the selection of cooperative nodes has been addressed from the perspective of variable rate transmission aimed for maximizing the e2e throughput. The relay selection algorithm devised is generic for different applications. The algorithm assumes a constrained cardinality of the set of cooperative nodes, which is likely to be imposed by practical considerations. The analysis can be readily applied for, for example, OFDMA/SC-FDMA based systems and can be of special interests for cell-edge users.

Within the same framework, attention has also been paid to D2D operation for handling local P2P data traffic within cellular networks, as the second exemplary use case. As short range communication, D2D communication shows benefits such as higher spectral efficiency and lower transmit power. It also provides a smooth bridge from state-of-the-art towards cognitive radio systems. The D2D operation considered in the literature mostly has assumed to use an independent air interface from the cellular operation, or to use dedicated resources for better interference isolation in the two-tier network. Such assumptions do not improve the spectral utilization.

The discussions in this work take care of the issue of under-utilized licensed bands by allowing intelligent resource sharing between D2D and cellular connections. The intelligence can be two folds. On one hand, multi-user diversity gain can be obtained by properly pairing the cellular and the D2D connections that share the same resources. On the other hand, the paired cellular and D2D connections can select the most beneficial resource sharing mode from a pool of available candidate modes. The discussed D2D underlay communication may be integrated to work together with inter-cell interference control mechanisms. While the inter-cell interference control schemes attempt to constrain the inter-cell interference penalty, D2D underlay communication intends to improve the intra-cell spatial reuse of the spectrum. The demonstrated potential of D2D communication to be considered as a component for LTE-Advanced networks, for facilitating high transmission demands in local areas, is promising.

Possible directions for future research include extending the work towards self-organizing principles. Self-organizing features which enable mobile network elements to react to network changes in an automated manner have received wide attention because of their potential for enhancing network performance, as well as reducing complexity and operational costs [14, 15]. In LTE-advanced systems, automatic mechanisms for self-optimization, self-configuration, and self-healing are considered as use cases for SON applications. Inter-user communication addressed in this work is assisted by BSs. With SON, it could take place in an automatic manner through negotiations within the neighborhoods of nodes. In such situation, the convergence of the SON method, that is, the interaction between local changes in reaction to surrounding environment and global behavior of a network, is of special interest.

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The progress of wireless communication technologies promises seamless coverage with higher peak transmission rate than current broadband communication systems. These demands are challenged by highly regulated transmit power as well as already congested spectrum. In this dissertation, inter-user communication for cellular systems is studied as an approach forward. On one hand, inter-user communication can extend service coverage and achieve more uniform Quality of Service, by having users in proper positions to cooperate. On the other hand, inter-user communication enables better spectrum usage efficiency with advanced radio resource management schemes. The outcome of this study includes a relay selection algorithm for user cooperation, radio resource allocation schemes for sharing same spectrum, and related performance analysis.

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