

Contributions to Analysis and Mitigation of Cochannel Interference in Cellular Wireless Networks

Michal Čierný



Contributions to Analysis and Mitigation of Cochannel Interference in Cellular Wireless Networks

Michal Čierny

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Abstract

Cellular wireless networks have become a commodity. We use our cellular devices every day to connect to others, to conduct business, for entertainment. Strong demand for wireless access has made corresponding parts of radio spectrum very valuable. Consequently, network operators and their suppliers are constantly being pressured for its efficient use. Unlike the first and second generation cellular networks, current generations do not therefore separate geographical sites in frequency. This universal frequency reuse, combined with continuously increasing spatial density of the transmitters, leads to challenging interference levels in the network.

This dissertation collects several contributions to analysis and mitigation of interference in cellular wireless networks. The contributions are categorized and set in the context of prior art based on key characteristics, then they are treated one by one.

The first contribution encompasses dynamic signaling that measures instantaneous interference situations and allows only for such transmissions that do not harm each other excessively. A novel forward signaling approach is introduced as an alternative to traditional reverse signaling. Forward signaling allows the interference management decisions to be done at the receiver, where there is more relevant information available.

The second contribution analyzes cross-link interference in heterogeneous networks. Cross-link interference is interference between downlink and uplink transmissions that can appear in time-division duplex (TDD) networks. It is shown that uplink reception of small cells can be disturbed considerably by macrocell downlink transmissions. We propose an intuitive solution to the problem based on power control. Users in small cells have generally enough power headroom as the distance to the small base station is often short.

The third contribution provides an extensive analysis of a specific interference management method that the Long-Term Evolution (LTE) applies in cochannel heterogeneous deployments. We analyze this so-called time muting using a modern stochastic geometry approach and show that performance of the method strongly depends on residual interference in the muted sections of time.

The fourth and last contribution analyzes the impact of interference rank, i.e., number of spatial streams at the interferer, on a beamformed or spatially block coded transmission. It is shown that when the interferer chooses to transmit multiple spatial streams, spreading the power in spatial domain has potential to decrease probability of outage at neighbor receiver, especially if the neighbor transmission uses beamforming.

Keywords interference management, cellular, wireless

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Preface

This thesis is a culmination of research work that was done under supervision of Prof. Risto Wichman from Department of Signal Processing and Acoustics, which belongs to Aalto University's School of Electrical Engineering. I (who in other parts of the thesis is represented by *we*) would like to express my foremost gratitude to Risto for giving me the chance, freedom and support during this endeavor.

I would like to thank the pre-examiners, Prof. Harpreet Dhillon and Dr. Gunther Auer, for their time and effort spent while evaluating this thesis. Both have provided high quality expert opinions, acknowledged contributions of my work and did not hesitate to point out shortcomings where it was needed. I would also like to thank Prof. Chintha Tellambura for accepting to be an opponent when I defend this thesis. It will be an honor to be examined by a world class expert of his rank.

I did the accompanied research during 2009-2014 and continued writing this thesis until 2015. In the beginning I worked full time on a TEKES project under the wings of Nokia Research Center (NRC, currently Nokia Technologies). In 2010 I was accepted to prestigious Graduate School in Electronics, Telecommunications and Automation (a.k.a. GETA). Later on I joined a cooperation project called Wireless Innovation between Finland and US (a.k.a. WiFiUS) and decreased my activities at NRC to part time. Additionally, my work was supported by HPY Foundation and Nokia Foundation. I humbly thank each one of these institutions.

Many colleagues deserve gratitude for guiding my work and ultimately for shaping my research skills. At NRC it was Dr. Klaus Hugl, Prof. Olav Tirkkonen, Dr. Carl Wijting and most importantly Dr. Cássio Ribeiro, who had to deal with me the most and who is my inspiration in the ability of seeing the bigger picture of research problems. During the WiFiUS project I was guided by Prof. Zhi Ding and Prof. Jyri Hämäläinen. Prof.

Ding also hosted my visit at the University of California, Davis, where we had weekly discussions and where he unknowingly showed me what really makes a university stand out.

I would like to also acknowledge my other coauthors Dr. Pekka Jänis, Haining Wang and Prof. Xin Liu. I had a lot of nice colleagues at Aalto University, with whom I have sadly not had a chance to cooperate much, Pekka being an exception. On the other hand, we had some great time together, among others with Karol Schober, Pramod Mathecken, Jaakko Ojaniemi, Jayaprakash Rajasekharan, Dr. Taneli Riihonen, Eric Halbach, Vincent Boerjan and others. Separate thanks go to our department secretaries Mirja Lemetyinen and Heidi Koponen and the GETA coordinator Marja Leppäharju.

Extra humble thanks go to Prof. Risto Wichman, Dr. Cássio Ribeiro and Prof. Zhi Ding for providing me with recommendation letters and to my current boss Kaisu Iisakkila for reading them, giving me a chance and setting up a warm welcome at a new workplace. From my new colleagues I would like to thank Timo Lunttila and Dr. Kari Hooli; it is a pleasure to work with such dedicated and open-minded experts.

As I here and there return to my home country, a couple of good friends are always ready to meet me: Jakub Gécz, Adam Klimek, Marek Jurik and others, thank you. Here in Finland, I must not forget the Niinikangas family for helping me to assimilate in this dark corner of Earth. Eternal gratitude goes towards my family; mom, dad, sister and brother, thank you for everything and I am sorry I am so bad at keeping in touch. Finally, ultimate thanks to Silja, for understanding me and preventing me from becoming a robot.

Helsinki, July 3, 2016,

Michal Čierny

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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 M. Čierny, P. Jänis, R. Wichman, C. Ribeiro. Exclusion Regions via Handshaking Protocol for Inter-Cell Interference Management. In *45th Annual Conference on Information Sciences and Systems, CISS 2011*, Baltimore, MD, March 2011.

II M. Čierny, C. Ribeiro, R. Wichman, O. Tirkkonen. SINR Prediction Versus Reverse Reporting for Soft Reuse and Interference Management. In *11th European Wireless Conference, EW 2011*, Vienna, Austria, April 2011.

III M. Čierny, C. Ribeiro, R. Wichman, O. Tirkkonen. Inter-Cell Interference Management in OFDMA TDD Downlink Using Sounding/Silencing Protocol. In *IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2011*, Toronto, ON, pp. 839-843, September 2011.

IV M. Čierny, R. Wichman, J. Hämäläinen, C. Ribeiro, Z. Ding, X. Liu. On TDD Cross-Tier In-Band Interference Mitigation: A Practical Example. In *7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications, CROWNCOM 2012*, Stockholm, Sweden, June 2012.

V M. Čierny, H. Wang, R. Wichman, Z. Ding, C. Wijting. On Number of

Almost Blank Subframes in Heterogeneous Cellular Networks. *IEEE Transactions on Wireless Communications*, vol. 12, no. 10, pp. 5061-5073, September 2013.

VI M. Čierny, R. Wichman, Z. Ding. Impact of Base Station Time Synchronization Mismatch on Almost Blank Subframes. *IEEE Communications Letters*, vol. 17, no. 11, pp. 2092-2095, October 2013.

VII M. Čierny, Z. Ding, R. Wichman. Higher Rank Interference Effect on Weak Beamforming or OSTBC Terminals. *IEEE Transactions on Wireless Communications*, vol. 14, no. 9, pp. 4948-4957, May 2015.

Author's Contribution

Publication I: "Exclusion Regions via Handshaking Protocol for Inter-Cell Interference Management"

In Publication I we introduce the idea of using RTS and CTS control bursts in a fixed frame structure for the purpose of dynamic interference management. Power of the received bursts is compared to a threshold; transmission proceeds if the power does not exceed the threshold. An exception to the rule is proposed so that bursts do not cross-block transmissions. We study the concept in a small scale by mathematical analysis and in a larger scale by numerical simulations.

The present author designed the concept, performed the analysis and wrote major part of the article. Pekka Jänis authored the simulation framework that was adapted for the analysis and helped with editing of the article. Risto Wichman and Cássio Ribeiro guided the work and helped with editing of the article.

Publication II: "SINR Prediction Versus Reverse Reporting for Soft Reuse and Interference Management"

In Publication II we separated the signaling approach from Publication I into forward part and reverse part and in the forward part we introduced relative thresholding instead of absolute thresholding, thus making way to SINR prediction. We then performed elaborate indoor simulations that showed that SINR prediction achieves comparable fairness and higher spectral efficiency than reverse signaling approach.

The present author designed the concept, performed the evaluation and wrote major part of the article. Cássio Ribeiro, Risto Wichman and Olav

Tirkkonen guided the work and helped with editing of the article.

Publication III: “Inter-Cell Interference Management in OFDMA TDD Downlink Using Sounding/Silencing Protocol”

In Publication III we augmented the concept of SINR prediction in order to address especially strong interference scenarios. After a receiver predicts SINR, it is given an option to silence selected interferers, thus improving its SINR during data transmission. We evaluated the concept using numerical simulations and showed it has good potential to reduce outage of users that would normally suffer from bad location.

The present author defined minor details of the concept, performed the evaluation and wrote major part of the article. Cássio Ribeiro and Olav Tirkkonen designed the concept, guided the work and helped with editing of the article. Risto Wichman guided the work and helped with editing of the article.

Publication IV: “On TDD Cross-Tier In-Band Interference Mitigation: A Practical Example”

In Publication IV we studied cross-link interference in a heterogeneous scenario with macro cells and small cells. Small cell uplink reception was found to be vulnerable to interference from macrocell downlink. We proposed to increase transmission power of small cell users, which have sufficient power budget thanks to small distances (i.e., low default transmission powers) between them and small cell base stations. We presented a closed form solution for a small scenario with known channel conditions and a heuristic practical solution that could be adapted in a real network.

The present author designed the concept, performed the evaluation and wrote major part of the article. Risto Wichman, Jyri Hämäläinen, Cássio Ribeiro, Zhi Ding and Xin Liu guided the work and helped with editing of the article.

Publication V: “On Number of Almost Blank Subframes in Heterogeneous Cellular Networks”

In Publication V we studied time domain enhanced inter-cell interference coordination, a 3GPP LTE concept of blanking part of subframes in a radio frame to manage interference in heterogeneous networks. We used stochastic geometry framework and adapted it to calculate outage probability of users that are in vicinity of dominant interferers. We then used the result to calculate how many blank subframes are needed and how does the requirement change with different system parameters.

The present author performed the analysis and wrote major part of the article. Haining Wang, Risto Wichman, Zhi Ding and Carl Wijting guided the work and helped with editing of the article. In addition, an anonymous reviewer contributed to small part of the analysis.

Publication VI: “Impact of Base Station Time Synchronization Mismatch on Almost Blank Subframes”

In Publication VI we studied the effect of time synchronization error on viability of time domain enhanced inter-cell interference coordination. We adapted the analysis framework from Publication V and evaluated the effect of time mismatch on LTE's control channel located in the beginning of a subframe. The results showed that timing requirements defined for TDD are sufficient also for FDD network that uses TDM eICIC.

The present author performed the analysis and wrote major part of the article. Risto Wichman and Zhi Ding guided the work and helped with editing of the article.

Publication VII: “Higher Rank Interference Effect on Weak Beamforming or OSTBC Terminals”

In Publication VII we study SINR distribution and outage probability of beamforming and space-time block coding, with a special focus on the rank of interferers' transmissions. We show that forcing the interferer to transmit higher rank MIMO signal has potential to decrease probability of outage of vulnerable receivers.

The present author performed the analysis and wrote major part of the article. Zhi Ding and Risto Wichman guided the work and helped with

Author's Contribution

editing of the article.

List of Abbreviations

3GPP	third generation partnership project
ABSF	almost blank subframe
AMC	adaptive modulation and coding
AWGN	additive white Gaussian noise
BS	base station
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CDMA	code-division multiple access
CIA-MAC	cochannel interference avoidance MAC
CoMP	coordinated multipoint
CRE	cell range expansion
CRS	cell specific reference symbols
CSG	closed subscriber group
CTS	clear to send
DECT	digital enhanced cordless communications
DI	dominant interferer
DL	downlink
fBS	femto base station
FDD	frequency-division duplexing
fUE	femto user equipment
iBS	interfering base station
IC	interference cancellation
ICI	intercell interference
INR	interference to noise ratio
IRC	interference rejection combining
LAA	licensed-assisted access
LAN	local area network

LTE	Long-Term Evolution
MAC	medium access control
mBS	macro base station
MBSFN	multicast broadcast single frequency network
MCS	modulation and coding scheme
MIMO	multiple input multiple output
MRC	maximum ratio combining
MTI	maximum tolerable interference
mUE	macro user equipment
NSF	normal subframe
OFDM	orthogonal frequency-division multiplex
OFDMA	orthogonal frequency-division multiple access
OSTBC	orthogonal space-time block coding
pBS	pico base station
PDCCH	physical downlink control channel
PDF	probability density function
PDSCH	physical downlink shared channel
PHY	physical layer
PMF	probability mass function
PPP	Poisson point process
pUE	pico user equipment
QoS	quality of service
ReB	reverse burst
RF	radio frequency
RSRP	reference signal received power
RTS	request to send
RV	random variable
S/S	sounding/silencing
sBS	serving base station
SINR	signal to interference plus noise ratio
smBS	small cell base station
smUE	small cell user equipment
SNR	signal to noise ratio
SoB	sounding burst
TD-LTE	Time-division Long-Term Evolution

TD-SCDMA	Time-division Synchronous Code Division Multiple Access
TDD	time-division duplexing
TDM eICIC	time domain enhanced inter-cell interference coordination
TTI	transmission time interval
UE	user equipment
UL	uplink
UWB	ultra wideband
WLAN	wireless LAN

List of Symbols

${}_2F_1$	hypergeometric function
C_a	rate of a victim UE in an ABSF
C_i	spectral efficiency of i -th link
C_M	macro link capacity
c_M	number of bits per subcarrier
$C_{M,\min}$	minimum required macro link capacity
C_n	rate of a victim UE in a NSF
C_v	outage rate of a victim UE
d_0	sBS data symbol
F_c	CDF of channel gain
F_{r_m}	CDF of distance to the closest mBS
f_{r_m}	PDF of distance to the closest mBS
f_γ	PDF of SINR
F_τ	CDF of timing mismatch
g_{mn}	element of \mathbf{H}_i
$G_{p,q}^{m,n}$	Meijer G-function
\mathbf{H}_0	fast fading channel matrix from sBS
$\mathbf{h}_{\text{eq}}^{(i)}$	equivalent channel vector of i -th sBS
\mathbf{H}_i	fast fading channel matrix from i -th iBS
\bar{h}_k	channel gain threshold for transmission of k -th base station
h_{mn}	element of \mathbf{H}_0
I_d	interference from DIs
I_m	interference from mBSs
I_p	interference from pBSs
\mathcal{J}	Jain's fairness index
k_1	pBS association coefficient
k_2	DI-defining coefficient

\mathbf{n}	noise vector
N_a	number of ABSFs in a radio frame
N_d	number of dominant interferers
N_l	number of links
$N_L^{(i)}$	number of transmission layers at i -th iBS
N_R	number of receive antennas
N_r	number of resource blocks
N_{ReB}	number of detected ReBs that that are stronger than λ_{ReB}
N_s	number of subframes in a radio frame
N_{SC}	number of subcarriers
$N_{\text{SC},\text{min}}$	required number of successfully decoded subcarriers
$N_{\text{SC},\rho}$	number of successfully decoded subcarriers
N_{SoB}	number of detected SoBs
N_T	number of transmit antennas
N_{UE}	number of UEs
$N_{\text{UE},v}$	number of victim UEs
\mathbb{P}	probability
$p_{C_{\text{M},\text{min}}}$	probability of reaching minimum capacity requirement
p_{data}	insistence probability for data transmission
$p_{\gamma,\text{M}}$	PDF of γ_{M}
P_{m}	mBS transmission power
p_{m}	fraction of critical mBSs
P_{p}	pBS transmission power
p_{ReB}	insistence probability for ReB transmission
P_{s}	smUE transmission power
p_{s}	success probability at a victim pUE
$P_{\text{s},\text{max}}$	maximum smUE (subcarrier) transmission power
$P_{\text{s},\text{opt}}$	optimal smUE (subcarrier) transmission power
p_{w}	fraction of BSs considered in the analysis

p_ρ	probability of successful subcarrier decoding
\mathbf{r}	received sample vector
R_0	average received power from sBS
r_d	distance to closest DI
R_i	average received power from i -th iBS
$\tilde{\mathbf{r}}_i$	received sample vector from i -th iBS
r_m	distance to closest mBS
\mathcal{R}_{MM}	long term channel gain on mBS-mUE link
r_p	distance to closest pBS
\mathcal{R}_{SM}	long term channel gain on smUE-mUE link
\mathcal{S}_{MM}	fast fading on mBS-mUE link
\mathcal{S}_{SM}	fast fading on smUE-mUE link
t_{cp}	cyclic prefix length
t_{fft}	OFDM symbol length (without cyclic prefix)
\mathcal{T}_k	number of victim receivers for k -th base station
\mathbf{w}_0	precoding vector of sBS
\mathbf{w}_i	precoding vector of i -th iBS
w_m	element of precoding vector
\mathbf{X}^\dagger	Hermitian transpose of \mathbf{X}
x^*	complex conjugate of x
$\ \mathbf{X}\ _{\text{F}}$	Frobenius norm of \mathbf{X}
$x^{(m)}$	variable x at time instance m
α_m	path loss exponent on mBS-UE link
α_p	path loss exponent on pBS-UE link
Γ	Gamma function
γ	SINR
γ_0	SINR threshold
γ_a	SINR in an ABSF
γ_i	SINR of i -th link
γ_M	subcarrier SINR at the mUE
Δ	multiplicative coefficient of mismatched interference
η	Rayleigh fading distribution rate
Θ_m	mBS Poisson point process

Θ_p	pBS Poisson point process
Θ_{UE}	UE Poisson point process
κ	association bias
λ_m	intensity of mBS PPP
λ_{\max}	dominant eigenvalue
λ_p	intensity of pBS PPP
λ_{ReB}	power threshold for ReB
λ_{SoB}	power threshold for SoB
λ_{UE}	intensity of UE PPP
μ_m	mBS load
μ_p	pBS load
ρ_{dB}	subcarrier SINR threshold in decibels
ρ_r	residual interference fraction
σ_n^2	noise power
τ_i	timing mismatch of i -th BS
τ_w	timing mismatch of the serving BS
Υ	multiplicative coefficient of all interference
ϕ_{I_d}	subterm containing DI interference
ϕ_{I_m}	subterm containing mBS interference
ϕ_{I_p}	subterm containing pBS interference
Ω_a	round robin fraction in an ABSF
Ω_n	round robin fraction in a NSF

1. Introduction

If you happen to read this text, you most likely belong to one of three groups of people. You may be a family member or a friend of the author looking for another part of the thesis beyond the preface that you could understand. To you we thank greatly for your interest and encourage you to look no further and rather spend your time on a more joyful activity. The remainder of this book is very technical and not at all enjoyable for those that are not close to the matter. This matter is the field of *wireless communications* [56,132], a field of study that is partly science and partly technology. The second group of probable readers are (ex)colleagues of the author and “random” visitors at his public examination. These readers are very welcome to read on and evaluate how relevant is the author’s contribution, or ponder on the importance of theory versus practice and analyzing a problem versus finding a solution. We hope the text will not bore you to exhaustion. Finally the last and most important readers are our reviewers and genuinely interested researchers or engineers. To you we apologize for the rattle, it is merely an attempt to set a lighter tone. All the readers who are not discouraged to read on, please note that throughout the text *we* refers sometimes to the author himself and other times to author and his coauthors, most likely in relation to a specific part of the work.

It is important to study wireless communications because it has become an irreplaceable part of our everyday life and because the technology did not yet reach its imaginable potential. In our personal opinion, this limit is transfer of human thoughts with comparable latency as within our own brains [139]. But let us not get carried away. We use wireless communications in different ways. All systems were originally analog and some of them, for example radio and TV broadcast, still survive, although they are being replaced. The modern systems are digital, meaning that electro-

magnetic waves are modulated with symbols encoding a stream of zeros and ones. Beside broadcast systems, typical examples of wireless communication systems are point-to-point connections used to overcome certain distance or obstacle. These include (among others) satellite communication systems and microwave relays. Furthermore, by combining two or more wireless devices we build wireless networks. Depending on the transmission power and other design or regulation limitations, these networks then serve different ranges. Personal area networks such as Blue-tooth work within short distances in the range of 10s of meters. Local area networks (LANs) such as wireless LAN (WLAN) reach intermediate distances maybe in the range of 100s of meters. Wide area networks such as cellular networks or trunked systems can serve larger areas.

This book focuses on cellular systems, or more specifically on interference management in the radio access part of cellular systems. The focus is motivated by prevalent academic and business interest in next generation systems, especially third generation partnership project (3GPP) LTE-Advanced, an upgrade of Long-Term Evolution (LTE). From four major topical chapters present in this book two present ideas that can be used in other systems as well, while the other two are applicable solely to cellular systems. We will now list the four topics that this thesis deals with and try to pinpoint what is our specific contribution. The topics are listed in chronological manner.

- *Dynamic forward and reverse signaling for spatial separation of interference (topic 1)*. Our very first topic was initiated by a question whether cellular local area network should draw inspiration from WLAN and consider using random access mechanism instead of centralized radio resource management. The author as a young (and maybe a bit naive) researcher applied request to send (RTS)/clear to send (CTS) mechanism in orthogonal frequency-division multiple access (OFDMA) and find that while it does not help system performance, by applying smart thresholds on these bursts one can increase user fairness. We designed channel reservation protocols based on dynamic signaling and prediction of interference level or signal to interference plus noise ratio (SINR). We evaluated these using simulation studies and showed that forward signaling approach fares better than traditional reverse signaling. Our findings were published in Publication I, Publication II and Publication III. Later on we wanted to prove some of the findings also analytically,

but lack of time prevented us from continuing the work.

- *Power control for TDD interference reduction (topic 2)*: Our second topic was related to 3GPP study item on dynamic time-division duplexing (TDD) operation [2]. We studied uplink-downlink interference in heterogeneous deployment with macrocells and femtocells. We identified that uplink reception in one layer is vulnerable to downlink interference from the other layer and proposed to solve the problem by means of power control, as femtocells transmissions happen over small distances and there is room for power optimization. In Publication IV we presented an analysis and a simulation study related to this topic.
- *Time domain enhanced inter-cell interference coordination (topic 3)*: This topic, although still 3GPP related, was our first venture into “hard” analytic approaches that is prevalent in the top journals of our field. The work is related to almost blank subframes that are designed to tackle problematic downlink interference scenarios in heterogeneous deployments. In Publication V we analyzed how many subframes in a radio frame need to be blanked to fulfill certain requirements, while in Publication VI we looked at the impact of base station timing errors on the concept. In both cases we used stochastic geometry framework, a mathematical toolbox that got very popular recently in the context of wireless network analysis. Additionally, we co-authored [140] that looked at the problem from a local (not network-wide) perspective.
- *Impact of interference rank on beamforming and OSTBC (topic 4)*: The last topic considers the effect of spatial multiplexing on other transmissions, especially on receivers in bad conditions. The topic was proposed by one of our mentors, although it was not completely crystallized in the beginning. The question was in the lines of “see what there is to study about higher rank transmissions and femtocells”. In the end we found that interference rank has not been studied comprehensively and were able to put together a study that glues existing pieces together and introduces a couple of novelties. Our main finding was that when an interferer transmits multiple spatial streams the power is spread in space and it is thus less likely to cause outage at a nearby receiver. We presented the findings in Publication VII.

At the first sight one could claim that our four topics are not exactly cohesive. While there is no hidden connection between them and no ultimate conclusion showing what is the best interference management technique ever, they all fall under the umbrella of interference management in cellular wireless networks. Although there is no profound reason why a universal solution could not exist, the researcher has to apply his skills where the demand¹ is.

After few years of doing research we can see two common dilemmas that influence the choice of a problem to work on and the way the work will be executed. First comes the dilemma of analyzing a problem versus looking for a solution. Strictly speaking, the dilemma should not exist; good solution should be based on proper analysis, hence the two should not be treated separately. In our fast moving world, it may however happen that commercial interest requires a solution to be found quickly; the research problem may be somewhat close to previously solved problems and a well tailored existing solution may just be the right thing. From our own works we would say the first two topics are about finding a solution, topic 1 for low user fairness and topic 2 for TDD interference. The third topic has a lot of analysis and a small bit of solution, while the fourth topic is a more balanced one but still contains more analysis.

The other dilemma is theory versus practice. Although this can mean many things, in our line of research practice is represented by evaluating ideas through simulation campaigns, while theoretical approach relies on rigorous mathematical analysis. The two approaches can serve different purposes. Rigorous analysis leads to an undeniable proof and cannot be obscured by programming bugs, but it requires considerable effort. At the same time, scale and complexity of the analyzed problem cannot be too high. Simulation campaign does not suffer from this limitation, but increasing number of system features and parameters may make it more difficult to draw good conclusions. Again, neither this dilemma has to actually appear; a good way to make use of both approaches is to draw “large scale” insights from an analysis and then use this insights to limit the scale of required simulation campaign. Our first topic used simulation campaign approach, because it originated from industrial environment where mathematical analysis is not as prevalent. The second topic was probably in between the two approaches. The third and the fourth topic rely on mathematical analysis. Stochastic geometry, the framework that

¹read: funding

we used in the third topic, is a nice example of analytical approach making its way into larger problems.

The structure of our thesis is as follows. In Chapter 2 we discuss interference and its management on a general level. Chapters 3-6 then contain topics 1-4, just as we introduced them above. Finally, in Chapter 7 we attempt to draw our conclusions and discuss what is left for the future.

2. Interference and its management

The centerpiece of this thesis is interference in wireless systems. This chapter is dedicated to interference and its management. While we do attempt to keep the discussion as general as possible, the reader will surely notice a bias towards cellular systems [56, Chapter 15], [132, Chapter 4]. This bias is not a result of personal preference, but rather of professional orientation. Well designed wireless networks are *interference limited*, meaning that their capacity is limited by interference rather than noise. If this was not the case, it would be possible to increase the spectral efficiency by lowering the frequency reuse or by increasing the load [10]. Interference management is therefore of paramount importance. During a search for good interference management solutions it is rather hard to refer to optimality, as optimal solutions are known only for simplistic setups, see for example [56, Chapter 14], [132, Chapter 6]. From information theory it is known when interference management is not needed [48]: when the interference power is sufficiently low, the optimal approach is to treat interference as noise. When the power is not so low, interference management is needed. Information theory suggests to use multi-user detection [137], but complexity issues often prevent multi-user detection from being feasible.

In the following sections we will discuss what types of interference there are, how can one specific interference type be modeled, what characteristics define an interference management technique and then give reference to some existing techniques.

2.1 Classification of interference

Interference in wireless network may surely be classified from many points of view. There would be certain level of satisfaction in creating an own

elaborate classification, especially because there are not that many available. We would however like to avoid that in fear that our creation may never get enough deserved appreciation (pun intended). Let us therefore take an existing classification that is good enough and try adding a comment here and there. One such good starting point is the creation of our earlier colleague in [70, Section 2.4]. We note here that because this exercise could be described as playing with terms that are well known within the field, we will refrain from searching for references that describe each type of interference. Who used which term first is not really relevant - unlike for example who proposed certain solution.

The first important classification categorizes interference into *cochannel interference* and *adjacent channel interference*. Cochannel interference, as the name suggests, come from wireless nodes that operate on the same channel as our node of interest. In this context, *channel* means a *carrier*, i.e., a part of licensed or unlicensed frequency spectrum that a certain wireless system occupies. In other context, channel could be a finer unit, for example part of a carrier that the system decided to assign to a subset of its nodes. Adjacent channel interference originates from a node or a system operating in an adjacent channel and typically leaks to our channel of interest as a result of radio frequency (RF) imperfections, most likely filtering.

Both cochannel and adjacent channel interference may come from a completely different wireless system, although in co-channel case this is possible only in unlicensed frequency bands. Unlicensed bands allow access to all users that abide by regulations, in contrast to licensed bands where only the owner of the corresponding license is allowed to operate. In [70] the interference from different wireless systems is denoted *coexistence interference*. Coexistence interference is not typical for cellular systems as those operate in licensed bands (that are not adjacent to unlicensed) bands. This may however change as 3GPP licensed-assisted access (LAA) will start getting deployed in the 5GHz ISM band [4].

The center-point of our focus lays in cochannel interference as it is the most critical interference in broadband cellular networks. It is sometimes denoted as *other cell interference* or *intercell interference (ICI)*, because its source is another cell of the same operator (as long as we are in licensed band). Intercell interference can be further divided into three sub-categories:

- *Cell edge interference* is the most general type of ICI arising at the border of cells where distance to a neighbour base station (BS) is comparable to distance to the serving BS. This is closely related to the concept of frequency reuse further explained in Section 2.4. Cell edge interference is relevant for both uplink (UL) and downlink (DL). It is expected to get worse as the density of network deployment is increasing.
- *Cross-link interference*, also called *uplink-downlink interference*, is ICI that arises in TDD networks that allow neighbour cells to have opposite link direction, i.e., one performing uplink and the other downlink, in the same time instance. This leads to BS-to-BS interference and user equipment (UE)-to-UE interference, the former being especially challenging in case of line-of-sight channel between the base stations.
- *Heterogeneous network interference* arises when a cellular operator deploys multiple tiers of cells with overlapping coverage, most commonly small cells (picocells, femtocells) as an underlay to the macro tier. This is an attractive way of increasing network capacity in a busy area (hot spot). However, cochannel deployment of overlapping cells by definition leads to challenging interference scenarios.

Another interference category according to [70] is *self interference*. This interference originates from the same transmitter as the signal of interest and largely depends on the chosen physical layer transmission technique. A classical example of self interference is *intersymbol interference* caused by channel spread, badly designed modulation waveform or imperfect time synchronization. In orthogonal frequency-division multiplex (OFDM), *intercarrier interference* arises among subcarriers in presence of oscillator imperfections or Doppler effect. When using multi-antenna transmission techniques, *interstream interference* may arise if different spatial streams are not orthogonal among each other. In full duplex wireless systems [42], self interference refers to leakage from transmitter to receiver in the same device.

Lastly, there is *multiple access interference*, which arises when multiple transmitters transmit to a single receiver at the same time. This happens on a common basis in the cellular uplink, even though it is often designed to assign orthogonal (time/frequency/code) resources to users. For example, spreading codes in code-division multiple access (CDMA) are not per-

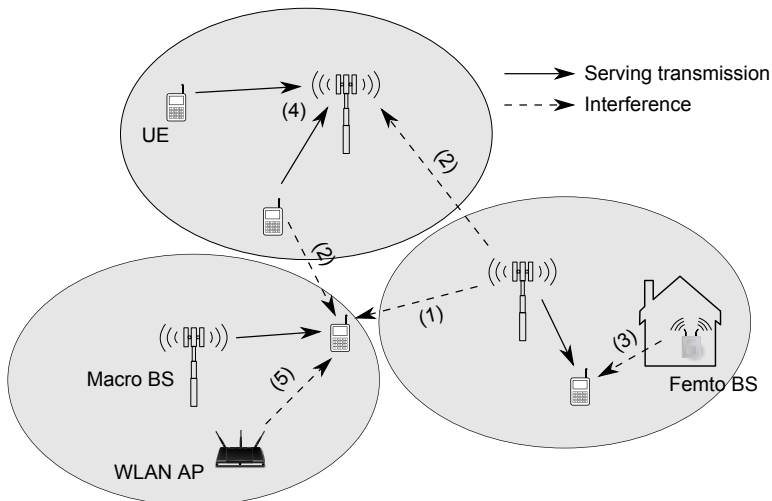


Figure 2.1. Illustrations of interference types in cellular network: (1) represents the most common cell edge interference; (2) represents cross-link interference that may appear in TDD networks; (3) represents heterogeneous interference usually associated with co-channel deployment of femtocells or picocells; (4) represents multiple access interference and (5) represents coexistence interference that may be possible in unlicensed bands in the future.

fectly orthogonal and with frequency selective channel this imperfection gets only amplified. In OFDMA users are assigned different subcarriers, but RF imperfections cause power leaks in the same manner as with adjacent channel interference.

This concludes the classification of interference. Some of the interference types are illustrated in Figure 2.1. Throughout our research activities that have lead to this thesis, the focus has always been on ICI. We focused on all three subcategories of ICI, although not all of them received the same amount of attention. More on that in Chapters 3-6.

2.2 Modeling of cochannel interference

Between realizing that there is a problem (interference) and trying to engineer a solution (an interference management technique) it may be useful to abstract the problem as much as possible, so that the search for a solution becomes more tractable. Sometimes it is not needed; if a researcher (or a company) has enough computational power, he can model the wireless network and interference inside it explicitly. Other times, when we want to prove things with scientific rigour, we need to find a simpler model.

Statistics of interference depends on three basic things [58]. Firstly, there is the distribution of transmitter locations. By taking into account only active transmitters, this distribution can account not only the spatial dimension, but also the temporal dimension of traffic distribution. Secondly, there is the spatial region or area where the transmitters are located. Thirdly, there is the propagation characteristics of the wireless medium. All these result in a rather complicated random process that is sometimes modeled as a shot noise process [27, 135]. A thorough work on interference modeling by a lifelong expert can be found in [96, 97]. Currently, a widely accepted approach is based on an assumption that location of the interferers follows a spatial Poisson distribution [58]. We use this approach in Chapter 5. In Chapters 3, 4 and 6 we model the interference explicitly.

2.3 Classification of interference management

Now that we classified types of interference in wireless network, let us try to classify methods for their management or mitigation. Before looking at specific interference management techniques we try to go one level of abstraction higher by listing and describing characteristics that are important for every existing and future technique.

While the goal of every interference management technique should be to increase capacity of a link or a network, not every technique may in practice fit a particular purpose. For example, a system that has latency constraints due to quality of service (QoS) requirements may not be able to use a technique that relies on large amount of signaling or adapts slowly to changes. A good categorization of interference management techniques may thus help when choosing the right technique for the right purpose.

We are not aware of any prior art related to this exercise. Disclaimer: our list may not be exhaustive and sometimes the entries are not completely independent.

2.3.1 What?

We call the first characteristic a *method*. It is probably the most important characteristic that defines what does a technique control in order to manage interference. In a broader scope we could ask what layer does the technique reside on: is it physical layer (PHY) or is it medium access

control (MAC)? Techniques residing on the physical layer may control for example:

- transmission power, as lower transmission power leads to less interference to other receivers;
- modulation and/or coding scheme, as robust transmission format is more resilient to interference;
- multi-antenna technique, as beamforming focuses the transmitted power (i.e., interference) in one direction while other techniques may not;
- transmission rank, as spatial multiplexing is more susceptible to interference than single-stream transmission.

Using receiver algorithms resilient to interference, such as interference rejection combining (IRC), may also be considered a PHY interference management technique.

On the MAC layer the techniques usually put restrictions on how links use available radio resources. For example, a link may be restricted to access certain resources that are being used in a neighbor link. In other words, MAC layer may schedule links so that they are separated in time, frequency, code or spatial domain. Separating the transmissions is a cornerstone of interference management, or one could rather say interference avoidance.

2.3.2 Where?

The second characteristic we call *control*, as in point of control, i.e. defining where the interference management decisions are done. In this context we mainly distinguish between a *centralized* approach and a *distributed* approach. A centralized technique performs interference management decisions at a central location with aggregated control over multiple links (multiple cells in a cellular networks), whereas distributed technique performs decisions locally. There is a clear trade-off between the two options. While centralized techniques may achieve better performance, the central controller needs to be provided inputs and distribute its decisions; hence demanding more signaling. At the same time, search for optimality will likely lead to complex algorithms with higher demands on computational power. Distributed approaches rarely achieve optimality but are obviously less demanding on the architecture.

Another possible distinction in *control* is whether the interference management decisions are made at the transmitter or at the receiver. This choice should be considered especially for distributed algorithms. In principle, receiver has more information available to perform good decisions, as it may “see” (i.e., measure) interference directly. On the other hand, if decisions are made at the receiver, they must be conveyed to the transmitter, which (again) raises demands on signaling.

2.3.3 How fast?

The third characteristic is *time scale* and it defines how fast does an interference management technique operate. We can divide most of existing techniques into three groups:

- A *static* approach sets up all interference management related settings only once, most likely when the network is deployed. This approach may be demanding on network planning, but does not require changes in the network protocols. A serious disadvantage is not being able to adapt interference management to changing user distribution or traffic pattern.
- *Semi-static* interference management technique can adapt its settings to current needs, but can do so only in longer time scale related to higher layer signaling. In 3GPP LTE this approximately means a time scale in 100s of milliseconds. Such approach is able to react to user mobility, but not for example to instantaneous changes in the traffic pattern.
- A *dynamic* approach makes interference management decisions instantaneously based on current conditions. Its biggest advantage over previous two is the ability to follow even fast channel condition or traffic pattern changes. On the other hand, it may lead to larger (often over the air) signaling overhead.

2.3.4 How verbose?

Our fourth characteristic is *signaling*. Signaling approaches may differ quantitatively by the amount of generated overhead, and qualitatively by choice of interface and effect on network architecture. For practical

purposes it is desirable to use existing interfaces or signaling channels and keep the overhead at minimum.

2.3.5 How intrusive?

The fourth and last characteristic is *compatibility* and it simply defines whether an interference management technique can be deployed in an existing network without harming users that do not support the technique. For example, in 3GPP LTE it is common that legacy (Release 8) UEs do not support features of later releases, but it should always be ensured that deployment of a new feature does not harm performance of legacy UEs.

2.4 Examples of interference management methods

Now it is time to introduce existing interference management techniques, because they serve as a starting point for any progress. From the different types of interference that we listed in Section 2.1 we will only discuss techniques that deal with ICI as ICI is the only one addressed in our published research.

The traditional approach in cellular networks, i.e., the mother of all interference management techniques, is so called *fixed frequency reuse* [8]. Frequency reuse N , where N is a positive integer, means that the available bandwidth is divided into N chunks. Each cell is then assigned a chunk in a way that maximizes distance between cells that operate on the same frequency, thus minimizing ICI. The approach is illustrated in Figure 2.2. An inherent weakness of frequency reuse higher than 1 is its negative effect on system capacity. For that reason, 3rd and 4th generation systems are designed around frequency reuse 1. Reuse 1 however increases the amount of interference in the system and stimulates search for better interference management techniques.

When it comes to cell edge interference, we refer the reader to [49, Sections 2.6, 2.7], [70, Section 4.1], [22, Section 2.3], or for example [10, 20]. Most of the existing approaches either adapt itself to the interference, for example by means of adaptive modulation and coding (AMC) and/or interference cancellation (IC), or then separate interfering transmissions in time, frequency or space (via various multi-antenna techniques) in a way that is not as limiting as the fixed frequency reuse. We would like to avoid repeating work that has already been published in aforementioned

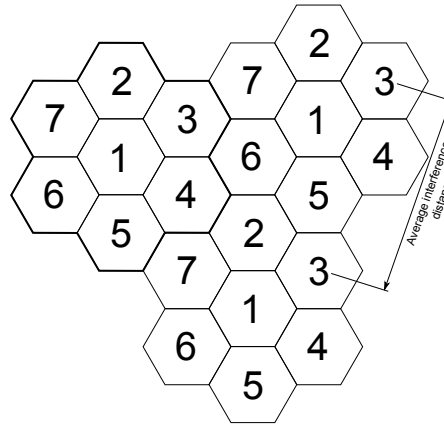


Figure 2.2. Depiction of the traditional frequency reuse with factor 7. Hexagons represent cells, numbers represent frequency channels. During network planning the channel pattern is defined in a way that maximizes the distance between base stations that occupy the same channel.

references, therefore we do not dig into details of the different techniques here. Instead, we collect the appropriate techniques from [70, Table 4.1] into Table 2.1 and attempt to categorize them based on the characteristics from Section 2.3. From our own works, Chapter 3 and partly Chapter 6 contribute to the topic on cell edge interference mitigation.

There is not much existing work on cross-link interference management techniques. What there is we describe in Chapter 4 as it is related to one of our own published works.

Heterogeneous network interference management has recently been an active area of research and there are quite some contributions to choose from. For an overview of the basic principles, see for example [90]. In addition to adaptation and separation approaches from the general cell edge interference management landscape, power control has been considered a viable approach. Power control is commonly used in cellular uplink, but not as much for interference management as for avoiding the near-far problem [56] in multiple access. Chapter 5 discusses deeply one time separation technique that gained significance in 3GPP LTE. The multi-antenna approach presented in Chapter 6 can also be used to manage heterogeneous network interference.

Technique	References	Method	Control	Time scale	Signaling	Compatibility
Fixed freq. reuse	[8]	Full cell freq. separation	Network planning, does not apply	Static	No signaling	No issue
Fractional freq. reuse, soft freq. reuse	[83, 102]	Partial cell freq. separation, power control	Centralized	Static, possibly semi-static	Possible BS-to-BS backhaul signaling	No issue
AMC (link adaptation), hybrid-ARQ	[25, 112]	Adapting transm. format to interf.	Distributed (BS level)	Dynamic	Reference symbols, PHY ACK/NACK	Exists already
Interf. cancellation	[9]	Pure signal processing (PHY)	No control	Dynamic	Reference symbols	Implementation specific, no issue
Network assisted interf. cancellation	[3]	PHY with signaling assistance	Distributed (BS level)	Dynamic	Interf. transm. format indication	Additional signaling, no issue
Beamforming	[10], for illustr. [19]	Spatial separation of interf.	Distributed (BS level)	Dynamic	Reference symbols	Different transm. mode
Network MIMO (a.k.a. CoMP)	[69, 84, 114, 136]	UL: spatial diversity + IC, DL: coord. spatial separation of interf.	UL: distributed, DL: centralized	Dynamic	Backhaul signaling, in DL also additional reference symbols	Different transm. mode
Interf. alignment	[24]	Joint encoding of interfering links	Centralized	Dynamic	Extensive backhaul signaling and reference symbols	Different transm. mode
Channel sensing (CSMA, cogn. radio), RTS/CTS	[28, 82], Chapter 3	Time separation of interf.	Distributed (link level)	Dynamic	RTS/CTS: OTA control signaling	Not compatible, major impact
Receiver beaconing	[66, 72], Chapter 3	Time separation of interf.	Distributed (link level)	Dynamic, possibly semi-static	OTA control signaling	Not compatible, major impact

Table 2.1. Characteristics of existing or proposed interference management techniques that target cell edge interference. The characteristics are evaluated from perspective of deployment in cellular network. Certain *control* and *signaling* requirements could be relaxed for the price of optimality. OTA stands for *over the air*.

3. Dynamic on/off interference management

One of the simplest things one can do to protect an active receiver from interference is to not allow any other transmission on the same resource (time, frequency, etc.) to exist. Or, if we cannot forbid all other transmissions, we should at least forbid those that are close to the active receiver. The *method* of such interference management approach is separation of interfering transmissions. One may also consider it a binary power control approach; at a given time/frequency/space instance a transmitter either transmits with full power, or not at all. Two important questions arise here. Firstly, still part of the *method*, how does one define what distance to the active receiver is dangerous? And secondly, moving to *signaling*, how does the interferer learn that it may disturb another transmission?

The idea of silencing an interferer in the vicinity of active receiver dates quite some time back. For example, the original concepts of busy tone [130] and RTS/CTS handshake [79] perform this technique implicitly. In the busy tone concept the active receiver transmits a busy tone signal in a separate control band during the whole time of reception. If a potential interferer detects the presence of busy tone, it realizes there is an active receiver and postpones its own transmission. The RTS/CTS handshake has the transmitter send an RTS burst and the receiver reply with a CTS burst before the data transfer commences. Another transmitter in the neighborhood may detect these bursts and refrain itself from interfering.

Busy tone and RTS/CTS handshake have been proposed to tackle the so called hidden terminal problem, as explained in Figure 3.1. These concepts in principle define an exclusion region (or exclusion zone) around the active receiver. Exclusion region is a geographical area where all other transmissions are suppressed. Exclusion region has for the first time been mentioned within ultra wideband (UWB) networks [113]. It has been fur-

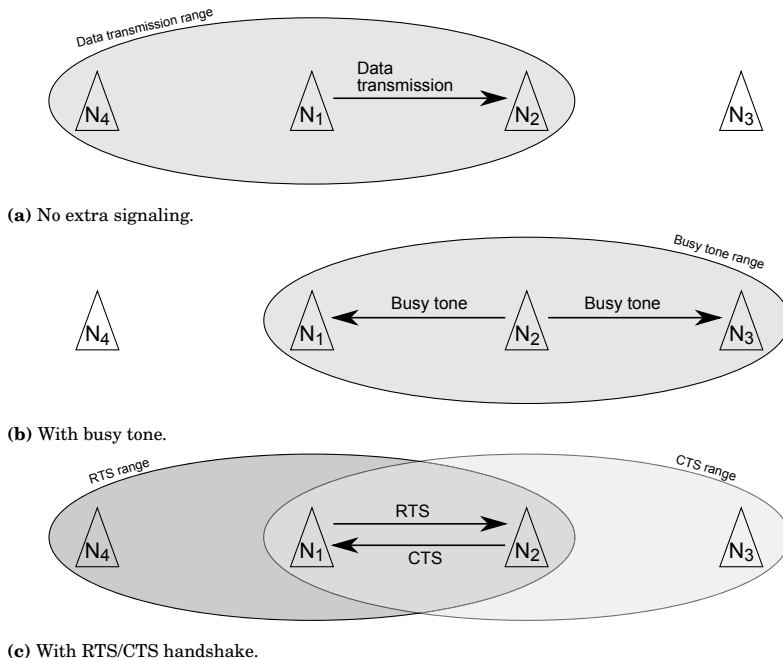


Figure 3.1. Hidden terminal and exposed terminal problems. Node N_1 communicates with node N_2 . In (a) there is no extra signaling and potential interferer N_3 , a so called hidden terminal, has no way of detecting the data transmission and deferring itself from disturbing it. In (b) a busy tone, present during the whole data transmission, informs N_3 that N_2 should not be disturbed. In (c) an RTS and a CTS bursts inform both N_3 and N_4 that they should avoid transmitting. Node N_4 , a so called exposed terminal, is however not located close to N_2 and could thus transmit to another receiver without harming N_2 .

ther studied in connection with multi-hop wireless networks [133], [134], CDMA ad hoc networks [64], indoor wireless networks [23] and two-tier femtocell networks [27].

When the work towards this thesis started it was built on an idea to use RTS/CTS handshake to do a more flexible interference management. There are two potential areas of improvement. Firstly, if a potential interferer detects an RTS or a CTS burst it may not automatically mean that its transmission would endanger the active receiver. From an SINR perspective, the active receiver may have a strong own link and may thus be able to withstand certain amount of interference. Secondly, while the role of CTS bursts to silence potential interferers is clear, the role of RTS bursts could be expanded. Looking at Figure 3.1(c), node N_4 learns from the RTS burst that N_1 is going to attempt a transmission, which means that N_4 should refrain from accepting transmission (i.e., being a receiver) from another source.

The research that followed this directions has lead to Publication I, Pub-

lication II and Publication III. We have developed a concept that challenges the approach of receiver announcements (busy tone, CTS, etc.) by using forward signaling, thus giving the decision responsibility to the active receiver. The concept has distributed *control* and dynamic *time scale*. *Compatibility* is not straightforward due to the signaling requirements. In the following sections we will first look at competing state-of-the-art techniques based on similar principles and then present our own findings.

3.1 Competing on/off techniques

We identified two concepts that are comparable to our approach that will be presented in Section 3.2. Both of them have an on/off *method*, decentralized *control* and dynamic *time scale*.

3.1.1 The concept of busy burst

Busy burst [49] is a mature interference management concept developed under the leadership of professor Harald Haas. It is targeted at OFDMA-TDD cellular systems and could be simply described as a time and frequency multiplexed busy tone broadcast after a successful data transmission and before a next data transmission. Busy burst is transmitted for every resource block separately (in an OFDMA manner). It exploits the channel reciprocity of TDD: a potential interferer may measure the received power of a busy burst and estimate how much harm would its transmission cause to the active receiver. The network is time synchronized so that all active receivers transmit their busy bursts at the same time instances. A potential interferer measures the aggregate busy burst power, compares it to a predefined threshold and if it the threshold is exceeded the interferer refrains from transmitting.

The principle of busy burst is illustrated in Figure 3.2. The most important assumptions and principles are summarized in the following list:

- Busy bursts are time and frequency multiplexed with the data in the manner of OFDMA. As a consequence they do not need a separate control band but require TDD.
- Busy bursts are evaluated for every resource block separately. They are placed after a successful data transmission in case the same resource

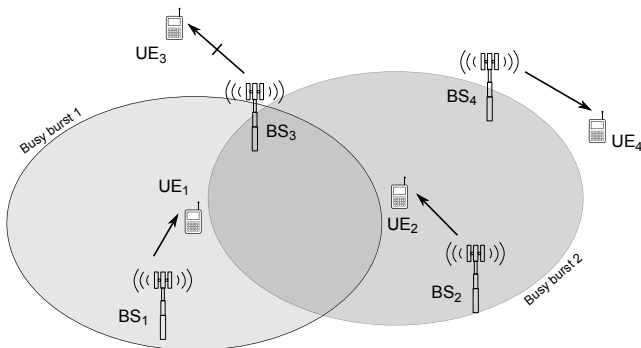


Figure 3.2. Functionality of busy burst illustrated on a single radio resource. Nodes BS_1 and BS_2 are active transmitters, therefore UE_1 and UE_2 transmit a busy burst. Nodes BS_3 and BS_4 are potential interferers. Node BS_3 detects large busy burst power and refrains from transmission to UE_3 . Node BS_4 detects only low busy burst power and is free to transmit to UE_4 .

block is going to be used again in the following time instance. As a consequence, certain level of persistence is required within the scheduler.

- Because of the persistence requirement, it matters who accesses a given resource at first.
- A transmitter that wants to access the medium first measures the busy burst power and compares it to a system wide threshold. If the threshold is exceeded, transmission on given resource is not allowed.
- The value of the threshold is important. Strict threshold reduces interference levels in the system and increases fairness, liberal threshold increases spatial reuse.

Busy burst has amassed a considerable publication record. It was for the first time mentioned in [106] and subsequently expanded to OFDMA in [61]. To resolve the problem of the first access, [54] proposed to have the probability of initial access to be $1/Q$, where Q is the number of cells that are close enough to interfere each other. A contention free alternative based on resource partitioning has been proposed in [13]. In [107] one may find an analytical delay throughput analysis of a single-carrier system using busy bursts. A good value of the busy burst threshold has initially been searched using simulations. To alleviate that [118] derives an optimal value for a small network with two links and proposes another heuristic value for a general network. In [117] the authors approxi-

mate distribution of the interference when using busy burst. The concept has been further enhanced to include power control [138] and to support beamforming [50], coordinated multipoint (CoMP) [51] and even optical wireless networks [52].

3.1.2 Cochannel interference avoidance MAC

Cochannel interference avoidance MAC (CIA-MAC) [95] is another interference management technique that shares similarities with the approach that we will introduce in Section 3.2. While its impact on the physical layer is smaller than that of busy burst, it requires a certain level of information exchange among base stations. That may be the reason why CIA-MAC did not receive as much attention as the concept of busy burst.

CIA-MAC focuses on cellular downlink transmissions. A downlink receiver, a UE, identifies dominant interfering base stations in the vicinity. A dominant interferer is such that its potential transmission would harm reception at the given UE beyond repair. The UE then reports the identities of the dominant interferers to its associated base station. Base stations subsequently exchange information so that each k -th base station learns how many UEs \mathcal{T}_k it may cause danger to. Whenever the k -th base station considers a transmission in a certain resource block, it only places the transmission if the channel gain on given resource block exceeds a threshold

$$\bar{h}_k = F_c^{-1} \left(\frac{\mathcal{T}_k}{1 + \mathcal{T}_k} \right), \quad (3.1)$$

where $F_c^{-1}(\cdot)$ represents an inverse function of $F_c(\cdot)$, a cumulative distribution function (CDF) of the channel power gain. Following such threshold leads to a probability of channel access to be

$$p_k = \frac{1}{\mathcal{T}_k + 1}. \quad (3.2)$$

Randomness provided by (3.2) ensures that the k -th base station will not harm the victim UEs in the neighborhood every time it accesses the medium. Formulas (3.1) and (3.2) are not heuristic, but derived to achieve proportional fairness from the work on random access networks [94]. CIA-MAC has another important threshold: a so called trigger, an interference-to-carrier-ratio threshold that identifies the dominant interferers. An optimal value is not provided, but some thoughts on its setting are present in the original work [95]. We summarize the steps of CIA-MAC in a form of a flowchart in Figure 3.3.

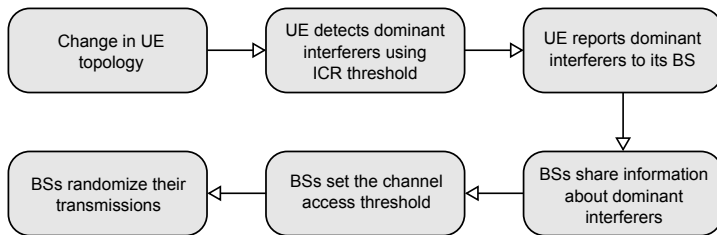


Figure 3.3. How CIA-MAC works. When there is a change in UE topology, the corresponding UE measures the presence of dominant interferer BSs and reports the outcome to its associated BS. The information is then shared among other BSs so that they may update the channel access thresholds and randomize their transmissions to attempt to achieve proportional fairness.

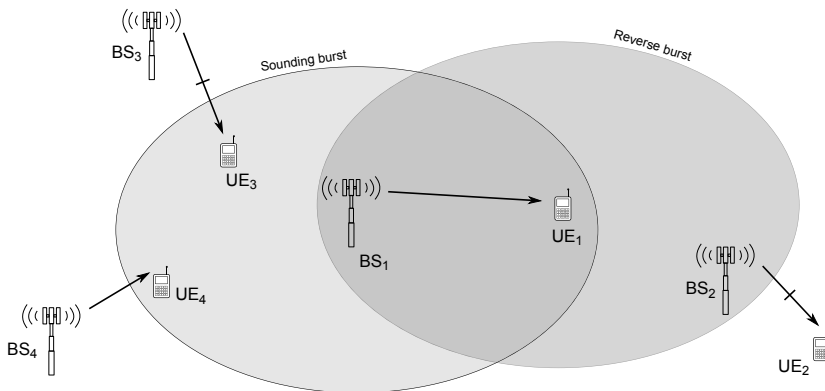


Figure 3.4. Reactions to a SoB and a ReB. Base station BS₁ wants to transmit to UE₁. Receiver UE₃ senses the SoB and evaluates that it is too close to BS₁, therefore it refuses to receive transmission from its associated BS₃. Receiver UE₄ is further from BS₁, or has a stronger own signal than UE₃, so it can proceed with reception from BS₄. Base station BS₂ senses the ReB, an equivalent of CTS or busy tone, and refrains from transmission to UE₂.

3.2 SINR prediction and reverse reporting

We consider our main contribution in this chapter to be the idea of using forward signaling as an alternative to reverse signaling (busy tone, busy burst) as means to enforce distributed interference management. Let us start from the RTS/CTS handshake concept. Researchers usually consider RTS/CTS a part of the handshake procedure that is used to establish a data session. We do not want to establish a data session, but to confirm or deny planned transmissions based on the results of the interference management procedure. To avoid confusion with the former we change our terminology and use *sounding burst (SoB)* instead of RTS and *reverse burst (ReB)* instead of CTS.

Let us assume that a receiver may sense an SoB that does not originate from the receiver’s associated transmitter. Based on the power of the SoB

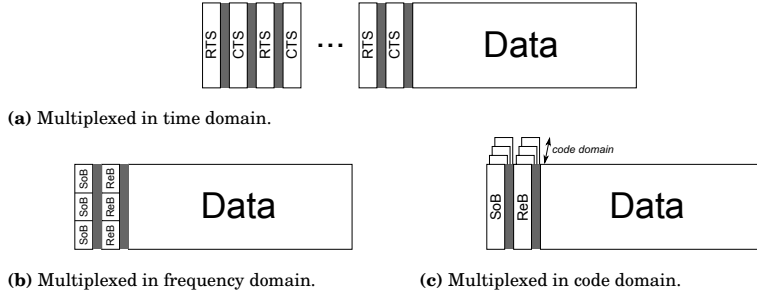


Figure 3.5. Placement of RTS and CTS bursts (SoBs and ReBs) in a synchronized frame structure to avoid bidirectionality problem. Option (a) shows the original proposition from [131]. Options (b) and (c) compress the format so that SoB and ReB can fit in a single OFDM symbol. Option (b) shows multiplexing in frequency domain and option (c) multiplexing in code domain using orthogonal codes.

and the receiver's own signal power, the receiver may consider whether this interference could pose a threat to its own reception. If that is the case, the receiver should inform its associated transmitter that it does not wish to receive a transmission.

We illustrate the principle behind forward signaling in Figure 3.4, where base stations BS_i want to transmit information to users UE_i . Focusing our thoughts on SoB transmitted by BS_1 : UE_3 observes that its reception would be hurt by transmission from BS_1 , so UE_3 denies transmission from BS_3 ; UE_4 observes that BS_1 is not too close, therefore UE_4 accepts transmission from BS_4 .

Using RTS and CTS-types of bursts (we must temporarily return to original terminology for reference purposes) for interference management does not come to mind easily. For example, node UE_3 from Figure 3.4 could transmit information to BS_3 as that would not harm the reception at UE_1 . However, in an asynchronous wireless network, like WLAN, it would not be able to receive a CTS from BS_3 because of interference from BS_1 . Similarly, UE_2 could transmit information to BS_2 , but BS_2 should not transmit a CTS as that could harm the reception at UE_1 .

In [131] this has been named a bidirectionality problem and as a solution the authors have proposed a synchronized system with a frame structure that contains RTS and CTS minislots as shown in Figure 3.5(a). Having dedicated space for multiple RTS and CTS bursts gives the nodes option to receive bursts from multiple sources and adjust their transmissions accordingly.

Let us for a moment think how an interference management technique based on SoBs and ReBs could be incorporated into LTE TDD system. In

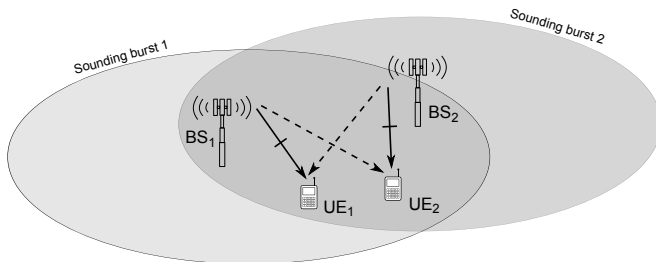


Figure 3.6. Two transmitters blocking each other with their SoBs.

LTE, a basic transmission time interval (TTI) is 1ms long and consists of 14 OFDM symbols. The smallest fraction of a TTI that an SoB or an ReB could take would be one OFDM symbol. Furthermore, LTE devices cannot switch their RF components between transmission and reception immediately. If we wanted to minimize the impact on receiver hardware and keep symbol timing intact, guard intervals between SoB and ReB and between ReB and data would thus together take up to another two OFDM symbols. For this reason, our proposition has only one pair of SoB/ReB minislots per TTI and multiplexing of SoBs and ReBs from different sources is done in frequency or code domain as depicted in Figure 3.5(b) and Figure 3.5(c). The bursts may be considered for each resource block separately using orthogonal codes [32], in which case the local flatness of the channel would support orthogonality among some number of transmitters. Other option may be to consider bursts for whole transmission blocks, i.e., a minimum of six resource blocks in LTE, and to impose orthogonality in frequency domain.

It is clear that these examples pose significant demands on SoB and ReB signal design. Allocation of frequency or code positions to the transmitters must be properly handled. Downlink and uplink need to be properly synchronized, taking into account processing delays of measurements and the fact that different users may have different propagation delays. Last but not least, tightly packed minislots may suffer from interference themselves. In any case, our propositions should merely be viewed as examples, as the main contribution lays elsewhere.

In Publication I we thus design an interference management protocol that uses SoB and ReB in a time synchronized frame access. It works as follows. Transmitter T_{X_1} has data scheduled to receiver R_{X_1} , so it firsts transmits an SoB. Receiver R_{X_1} listens to all SoBs it can detect. It measures a sum of powers of SoBs from all T_{X_i} , $i \neq 1$ and compares it to a threshold λ_{SoB} , a maximum tolerable interference (MTI) threshold. If the

threshold is not exceeded, R_{X_1} assumes that the interference will be bearable and transmits its ReB. Transmitter T_{X_1} listens to all ReBs it can detect. Summing ReB powers gives no insight, therefore T_{X_1} compares ReB from each R_{X_i} , $i \neq 1$ separately to a threshold λ_{ReB} . If no ReB exceeds the threshold, T_{X_1} assumes it will not be a dominant interferer for any R_{X_i} and is free to transmit data to R_{X_1} .

What happens when one of the λ_{SoB} , λ_{ReB} thresholds is exceeded? The first conclusion might be that T_{X_1} should abort its transmission. On the second thought, such strict approach may lead to waste of the medium. See, for example, an illustration in Figure 3.6 where two transmitters block each other out with their SoBs. A similar effect may happen with ReBs. In order to avoid this waste we propose in Publication I the principle of *insistence*. Let us assume our R_{X_1} from previous paragraph measures the sum of interferer SoB powers and it exceeds λ_{SoB} . Despite the threshold being exceeded, we let R_{X_1} insist on the transmission with probability

$$p_{\text{ReB}} = \frac{1}{N_{\text{SoB}}}, \quad (3.3)$$

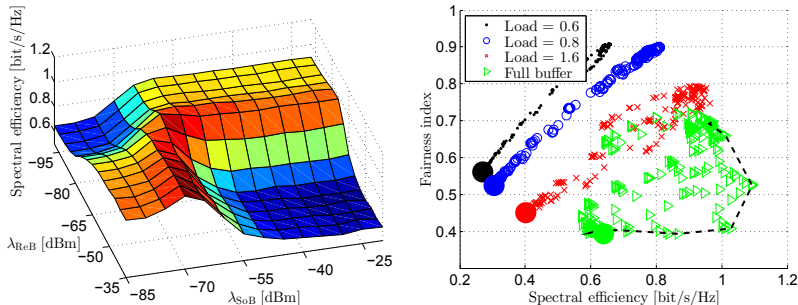
where N_{SoB} is the number of all SoBs it detected. In a situation depicted in Figure 3.6, each receiver would have 50% probability of sending an ReB. Similarly, if a transmitter senses some ReBs that are stronger than λ_{ReB} , we let it insist on the transmission with probability

$$p_{\text{data}} = \frac{1}{1 + N_{\text{ReB}}}, \quad (3.4)$$

where N_{ReB} is the number of detected ReBs that are stronger than λ_{ReB} . The values of insistence probabilities p_{ReB} and p_{data} were chosen as given because they intuitively fit the concept. In general though, they could be considered as moving parts in the concept. For example, p_{ReB} could be a function of SoB received powers directly, providing a more logical approach in case some of the interferers are clearly dominant. Yet another possibility is to use the variable insistence probabilities to enforce QoS in the system. We leave these considerations for future work.

Probability of data transmission p_{data} reminds of the implicit transmission probability of CIA-MAC (3.2). Our approach does however not need to know the distribution of channel gain or exchange information about the number of interfered receivers.

In Publication I we evaluated the performance of the interference management protocol based on SoBs and ReBs in an ad hoc scenario where transmitters and receivers are placed randomly on a disk. The scenario


 (a) Mean capacity vs. λ_{SoB} and λ_{ReB} .

(b) Scatter plot of fairness vs. mean capacity.

Figure 3.7. Simulation results from Publication I where five ad hoc links on a disk with radius of 100m use the interference management protocol with SoBs and ReBs. In (a) we see mean link capacity versus thresholds λ_{SoB} and λ_{ReB} . In (b) there is a scatter plot where each point represents one combination of λ_{SoB} and λ_{ReB} , with different network load settings. Filled circles represent uncoordinated access, dashed line connects points where only λ_{SoB} is active.

has been chosen because with two links on a disk we were able to tract the mean link capacity analytically. We show some of the results in Figure 3.7. The performance metrics were spectral efficiency $C_i = \log_2(1 + \gamma_i)$, where γ_i denotes SINR of the i -th link, and Jain's fairness index \mathcal{J} defined as

$$\mathcal{J} = \frac{\left(\sum_{i=1}^{N_1} C_i\right)^2}{N_1 \sum_{i=1}^{N_1} C_i^2}, \quad (3.5)$$

where N_1 is the number of links in the system. We acknowledge that Jain's fairness is not a perfect metric; in Subsection 3.2.1 we therefore use also 5th percentile of spectral efficiency, i.e., the 3GPP's definition of coverage. Figure 3.7(a) shows mean spectral efficiency as a function of λ_{SoB} and λ_{ReB} . Values of the thresholds must be carefully chosen as both too liberal and too strict setting negatively influences the performance. In Figure 3.7(b) there is a scatter plot of mean spectral efficiency and fairness index under different load conditions. We assume a simplistic constant load model; the transmitter attempts to access the channel in given frame if mean spectral efficiency aggregated over previous frames is below the requested constant load. When the load is lower it is possible to find a threshold combination that achieves both high spectral efficiency and fairness. With higher loads this is not valid anymore. Furthermore, the dashed line in Figure 3.7(b) connects points with full load when only λ_{SoB} is active. This mode of operation manages to achieve the highest possible spectral efficiency and close to the highest possible fairness, suggesting that thresholding ReBs may not be necessary. More on this in the

following Subsection.

3.2.1 The power of relative thresholding

By the time of Publication II we realized what the strength of interference management via forward signaling may be: when a receiver measures SoBs from its associated transmitter as well as interfering transmitters, it has a possibility of putting own power and interference power into a relation. We call this step *SINR prediction*, as the receiver practically attempts to predict the SINR that it will experience during following data transmission. This prediction is not perfect, because some of the transmissions will be denied. However, applying a relative threshold on dynamic interference management signaling offers new possibilities; it is something that cannot be done by means of reverse signaling such as the busy burst. Quantitative setting of the SINR threshold is just as important as with MTI threshold; looking for the right value by other means than system simulations is outside of our scope.

In Publication II we build a protocol that contains both SINR prediction and reverse signaling approaches. It is not very different from the MTI version in Publication I. Transmitter T_{X_1} has data scheduled to receiver R_{X_1} , so it firsts transmits an SoB. Receiver R_{X_1} listens to all SoBs it can detect, i.e. from own transmitter T_{X_1} and from interferers T_{X_i} , $i \neq 1$. Receiver R_{X_1} also measures the noise power and constructs an SINR prediction, which is then compared to an SINR threshold γ_0 . If the threshold is not exceeded, R_{X_1} assumes that the SINR will be acceptable and transmits its ReB. Transmitter T_{X_1} listens to all ReBs it can detect and compares ReB from each R_{X_i} , $i \neq 1$ separately to a threshold λ_{ReB} . If no ReB exceeds the threshold, T_{X_1} assumes it will not be a dominant interferer for any R_{X_i} and is free to transmit data to R_{X_1} . Insistence probabilities p_{ReB} from (3.3) and p_{data} from (3.4) apply here as well. A simplified flowchart of the protocol is shown in Figure 3.8.

Although the protocol in question contains both SINR prediction and reverse signaling, in here we focus on the two border cases when only one of the approaches is active. We evaluate the performance of these by means of Monte Carlo simulations. We use an indoor scenario based on WINNER A1 [92], similarly as it was used to evaluate busy bursts in [53]. For every snapshot of the simulation, we drop 5 ad hoc links into the $100\text{m} \times 50\text{m}$ scenario, the only limitation being that a receiver cannot be located further than 50m from its transmitter. The transmitters then repeatedly contend

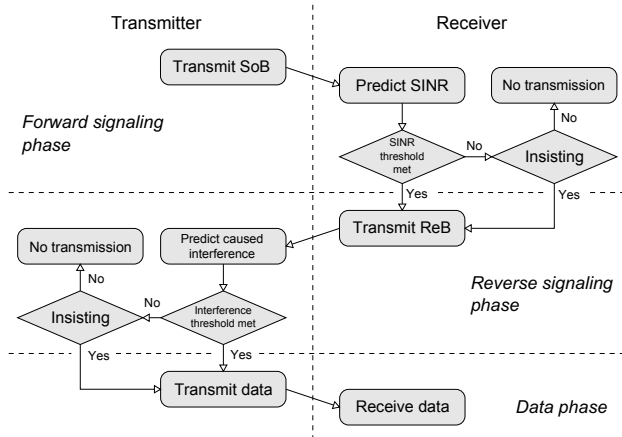


Figure 3.8. Interference management protocol with forward and reverse signaling phases. Forward signaling allows relative thresholding in the form of SINR prediction. Reverse signaling allows transmitter to estimate how much interference it would cause.

for a single radio resource every time slot, hence modeling full buffer traffic. For a more complete list of simulation assumptions we refer the reader to Publication II. The ad hoc nature of transmitter and receiver locations and the full buffer traffic assumption result in challenging interference situations, with a sole purpose to test the protocol to its limits.

The main findings, i.e., performance of the protocol with only one of the interference management phases active, are shown in Figure 3.9. With forward signaling we compare relative SINR thresholding to absolute thresholding, with and without insistence. With reverse signaling we use heuristic thresholding defined in [118].

We can draw several observations from our results. For a start, we note that the selected scenario is quite challenging, as only strict threshold setting (low absolute or high relative threshold) provides non-zero coverage. Insistence is crucial from fairness perspective in such a scenario; without insistence the system is less fair than uncoordinated one. Next, we observe that forward signaling is able to provide noticeably higher spectral efficiency than reverse signaling, especially when using relative SINR threshold. This is the result of making the decisions at the receiver. In terms of coverage and fairness, forward signaling with absolute threshold is able to perform as well as reverse signaling, while relative threshold decrease the fairness slightly. All in all, we may say that forward signaling has the potential to support more efficient dynamic interference management mechanism than reverse signaling.

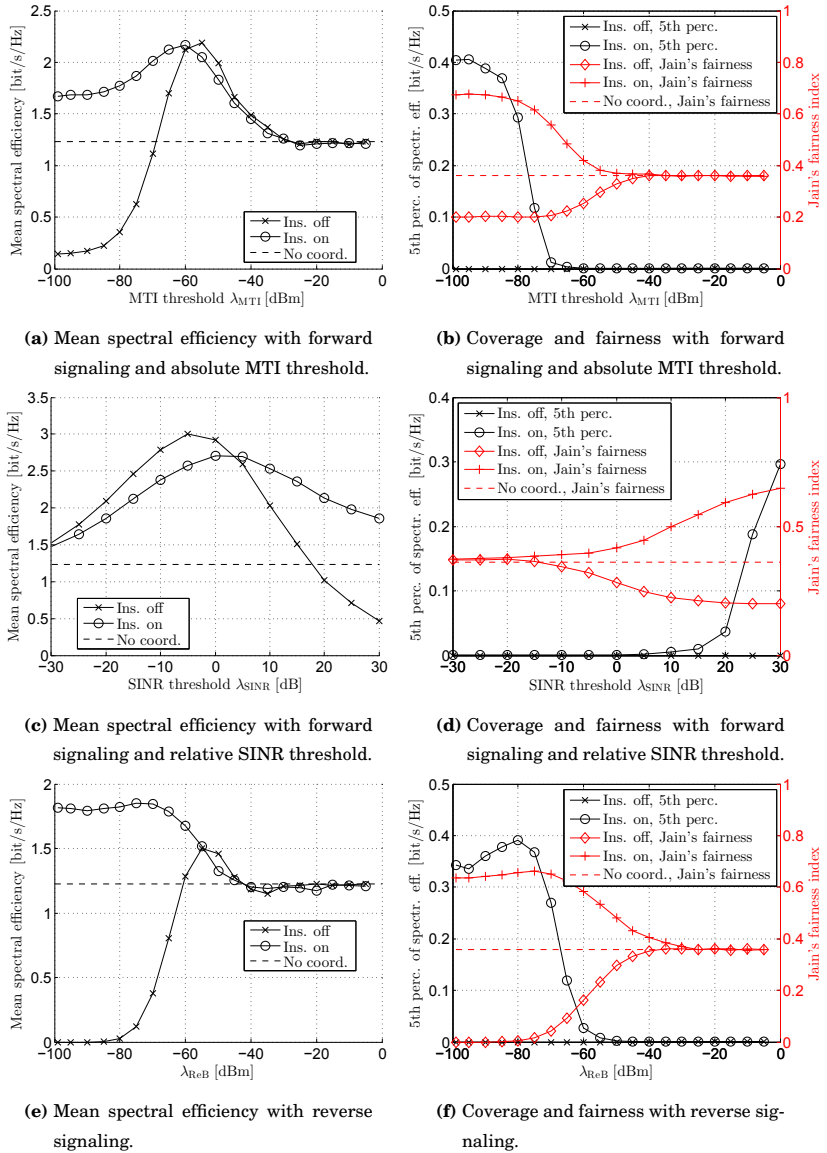


Figure 3.9. Performance of interference management using forward or reverse signaling, in terms of mean spectral efficiency, coverage (5th percentile of spectral efficiency) and Jain's fairness index. Uncoordinated case is marked by dashed line. Subfigures (a) and (b) use forward signaling with absolute threshold; ins. denotes insistence. Subfigures (c) and (d) use forward signaling with relative threshold. Subfigures (e) and (f) use reverse signaling with heuristic threshold from [118]. Insistence is crucial for coverage and fairness. Reverse signaling can achieve same coverage and fairness as forward signaling, but lacks behind in terms of mean spectral efficiency. Forward signaling with relative threshold is able to provide the best spectral efficiency.

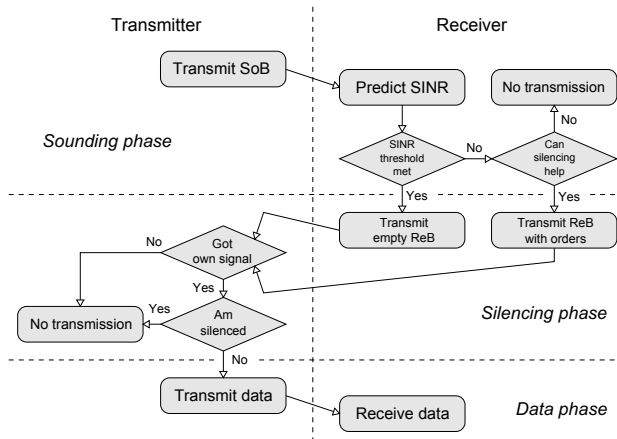


Figure 3.10. The sounding/silencing protocol. Forward signaling part with SINR prediction is the same as in Figure 3.8. In the reverse signaling part the receivers are directly ordering their dominant interferers to remain silent.

3.2.2 Sounding/silencing protocol

Publication III may look like a side step. We took the interference management approach from Figure 3.8 and modified it to offer cellular coverage for users that are in extremely challenging interference situations. As an example of such situation we used an indoor scenario where four closed subscriber groups (CSGs) are located in a single building. A user of a CSG can only connect to base stations of the same CSG. In the indoor scenario that we used, some spaces were available to everyone while other spaces were restricted to a specific CSG. We named the new interference management approach a sounding/silencing (S/S) protocol; a simplified flowchart is shown in Figure 3.10. The forward signaling part is similar as before, although there is a difference how the potential receivers handle the SoBs. Instead of sending out the generic ReB and hoping for the best, the receiver gets a chance to transmit a silencing signal that directly orders some of the dominant interferers to not interfere.

The S/S protocol has obviously higher demands on signaling (ReB must be able to carry orders) and also, one may say, stricter requirements on interfering transmitters to follow orders. Our approach is therefore to designate only part of the available resources, e.g. a fifth of the subframes, for S/S protected access. Based on the geometry factor (long term SINR), part of the users are marked as vulnerable users and have higher priority of accessing the protected subframes. Without going into details, we claim that the approach serves its purpose well. In Publication III we show

that, assuming realistic model of signaling, the S/S protocol manages to decrease the number of users that are in outage by more than 50%.

3.2.3 Discussion

How to conclude a chapter on on/off interference management? Although we were not able to continue the work to the point that we think it would deserve, we stand behind our results and claim that dynamic interference management via forward signaling using SINR prediction may offer a viable alternative to other prevalent approaches based on reverse signaling. Publication II shows that it has potential for higher spectral efficiency while keeping the fairness comparable to that of reverse signaling approach. The ultimate reason behind this is that when thresholding a predicted SINR, we are shifting the interference management decisions from the transmitter to the receiver. And it turns out that receiver is the right place to make the decisions, as it can see interference contributions from all interferers and relate their powers to the own, useful received power. This is not possible when making the decisions at the transmitter, because the transmitter can at most estimate how much interference it would cause to other receiver.

There is of course the issue of multiplexing SoBs and high demands on processing latency. However, using forward signaling has one other important advantage. It does not depend on channel reciprocity and can be therefore used also in frequency-division duplexing (FDD) systems. The receiver still must send the result of its decision to the associated transmitter, but this message is no more used to estimate caused interference and may be send by means of traditional control channel. This is not a minor thing. Majority of existing LTE networks are still running FDD. And in the end, the link adaptation mechanism used in LTE, although not as dynamic as the interference management approach under discussion, is also based on forward signaling. Base stations sound the channel with reference signals, the users measure the reference signals and recommend a modulation and coding scheme (MCS) that fits the circumstances.

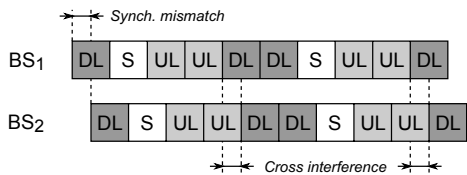
4. Management of cross link interference

Cross link interference appears in TDD system when we allow downlink (base station to user) and uplink (user to base station) transmissions to coexist at the same time instance, whether it is by design or by absence of time synchronization. This short chapter takes the reader through motivation, challenges, prior art solutions and our own contribution related to the issue.

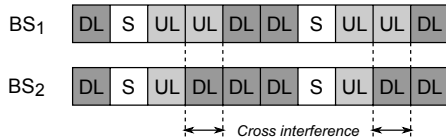
4.1 Motivation and description

Earlier cellular systems were designed around FDD [45]. Although TDD was at that time used for shorter range systems such as digital enhanced cordless communications (DECT), for cellular systems it was not being considered. There was not much need for it as the earlier systems were built for circuit switched voice transfer that generates symmetric uplink and downlink traffic. With increasing demand for generic data transfer, things were not so clear anymore. A TDD base station has the possibility to adapt the amount of uplink and downlink time slots (subframes in LTE terminology) according to instantaneous traffic requirements [73]. This can provide a nice performance edge, especially when the traffic is bursty and load is not too high [71, 125]. Also, as the channel in TDD is to large extent reciprocal, channel estimates from uplink transmission could be used to optimize downlink transmission, thus eliminating the need for dedicated feedback. Further advantages and disadvantages of FDD and TDD are discussed in [26]. Considering the potential benefits, the work towards the third generation cellular systems has therefore taken TDD back into consideration. However, since the beginning it has been known [111] that a TDD system may suffer from new type of interference.

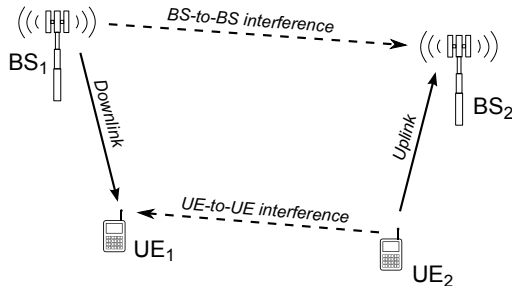
The new type of interference is called BS-to-BS interference and UE-to-



(a) Cross link interference in unsynchronized TDD system.



(b) Cross link interference in synchronized TDD system.



(c) BS-to-BS and UE-to-UE interference in TDD system.

Figure 4.1. Sources of cross link interference. In (a) we have two LTE base stations having so-called frame structure 1; DL stands for downlink subframe, UL stands for uplink subframe and S stands for special subframe. The synchronization mismatch causes parts of some subframes to experience cross link interference. In a synchronized case (b), BS₁ has frame structure 1, whereas the BS₂ is using frame structure 2. This way, whole subframes may experience cross link interference. In (c) we illustrate the two specific cross link interference types, BS-to-BS interference and UE-to-UE interference.

UE interference. Its existence stems simply from the fact that downlink and uplink transmissions are not separated in frequency as in FDD system. We illustrate the interference and its relation to LTE frame structure in Figure 4.1.

It has been quite clear since early considerations that the BS-to-BS interference may be considerably more harmful than the UE-to-UE interference [65, 74, 125, 147]. This is because base stations transmit at higher power levels and also because they are often located within line of sight from each other, whereas UE transmissions are weaker in power and scattered in space and among obstacles. The limitation is still valid today, when TDD networks finally enjoy wider deployment (mostly thanks to Time-division Synchronous Code Division Multiple Access (TD-SCDMA) followed by Time-division Long-Term Evolution (TD-LTE) in China) and interests are shifting towards smaller cells [81, 116]. Although small base

stations, such as pico base stations, may not have as strong coupling to macro base stations as macro base stations may have among each other, BS-to-BS interference is still considered a limiting factor and deployment of dynamic TDD is mostly being discussed for cells with certain level of isolation.

4.2 Survey of solutions

Prior art on how to manage cross link interference is rather scarce. The most simple and obvious approach to avoid it is to divide the base stations in the network into clusters of strongly coupled members and then keep the frame structure constant within each cluster [125]. While efficient in preventing excessive BS-to-BS interference, such approach suppresses the possibility to adapt the frame structure to local traffic requirements. In [98] the reader can find an idea to leverage knowledge of UE position within a cell to avoid UE-to-UE interference. Users that are located at the cell edge are considered vulnerable to cross link interference and are therefore not scheduled in flexible subframes. Another work [146] proposes to use a combination of TDD and FDD to avoid both BS-to-BS and UE-to-UE interference. In addition to downlink and uplink located in different carriers (FDD), they are separated also in time, such that a UE cannot transmit and receive in the same subframe (TDD). This transforms the intra-carrier cross link interference into inter-carrier cross link interference and is quite an expensive solution as it doubles the amount of required spectrum.

Several works have considered solving the cross link interference issue using some flavour of optimization approach. In [6] the authors propose a centralized framework that incorporates the decision between uplink and downlink on a given subframe into RB scheduling. The framework maximizes average user throughput, hence the interference management is done implicitly. A similar effort [43] determines the ratio of uplink and downlink resources by filtering average rate values and in addition to resource block assignment it optimizes also transmission power. A decentralized optimization approaches have been shown in [41], where the authors attempt to maximize user throughput, and in [44] where other authors aim for minimum delay.

4.3 Power control in heterogeneous cross link cases

In Publication IV we have addressed one particular issue that may arise in heterogeneous TDD network scenarios when small cells are deployed in the same frequency band as the overlay macro tier. Small cells have better chance to benefit from flexible TDD than macrocells, because they tend to serve lower number of users and the cell traffic is more likely to be biased towards one direction. Small cell uplink transmissions are potentially vulnerable to macro downlink interference. However, because transmission distances in a small cell are smaller than in macro tier, users associated to small cells may have the option to increase their transmission power in order to increase robustness against macro interference.

To analyze the problem in a tractable way we first assumed a minimalistic scenario with two links: a macro link (macro base station (mBS)-macro user equipment (mUE)) in downlink mode and a small cell link (small cell user equipment (smUE)-small cell base station (smBS)) in uplink direction. To protect small cell uplink reception from mBS-smBS interference, we propose to increase transmission power of the smUE, but only as much so that the macro downlink reception does not suffer extensively. To express this formally, we want to find a maximum smUE (subcarrier) transmit power $P_{s,\text{opt}}$ that would still ensure that the macro link capacity C_M will be at least $C_{M,\text{min}}$. SINR of a single subcarrier at the mUE may be written as

$$\gamma_M = \frac{P_m \mathcal{R}_{MM} \mathcal{S}_{MM}}{P_s \mathcal{R}_{SM} \mathcal{S}_{SM} + \sigma_n^2}, \quad (4.1)$$

where P_m is the mBS transmission power, \mathcal{R}_{MM} is long term channel gain (path loss, shadowing, etc.) on the mBS-mUE link, \mathcal{S}_{MM} is fast fading channel gain on the mBS-mUE link, P_s is smUE transmission power, \mathcal{R}_{SM} is long term channel gain on the smUE-mUE link, \mathcal{S}_{SM} is fast fading channel gain on the smUE-mUE link and σ_n^2 is the noise power. We model the fast fading channel components by the standard Rayleigh fading, therefore \mathcal{S}_{MM} and \mathcal{S}_{SM} independently follow exponential distributions with rate η . In a snapshot with static \mathcal{R}_{MM} and \mathcal{R}_{SM} , the SINR γ_M can be expressed as $X/(Y+1)$, where X and Y are independent exponential random variables (RVs). The probability density function (PDF) of γ_M , denoted as $p_{\gamma,M}(x)$, can then be easily found [108]. Probability that a subcarrier SINR is higher than threshold ρ_{dB} , conditioned on \mathcal{R}_{MM} and \mathcal{R}_{SM} , can be

evaluated as

$$p_\rho = \int_{\rho_{\text{dB}}}^{\infty} p_{\gamma, \text{M}}(x) dx \quad (4.2)$$

$$= \frac{P_{\text{m}} \mathcal{R}_{\text{MM}}}{P_{\text{s}} \mathcal{R}_{\text{SM}} 10^{\frac{\rho_{\text{dB}}}{10}} + P_{\text{m}} \mathcal{R}_{\text{MM}}} \exp\left(-\frac{\eta}{P_{\text{m}} \mathcal{R}_{\text{MM}}} 10^{\frac{\rho_{\text{dB}} + \sigma_{\text{n}}^2}{10}}\right). \quad (4.3)$$

For simplicity we further assume that the symbols to be transmitted are ideally interleaved among subcarriers. Under this assumption, subcarrier statistics are i.i.d. and we can treat each subcarrier separately. The reader will note that this is not especially realistic, but for our purposes good enough. Given a particular MCS, which defines also the value of ρ_{dB} , each subcarrier carries c_{M} bits. To fulfill the $C_{\text{M}, \text{min}}$ requirement we must then ensure that SINR of at least $N_{\text{SC}, \text{min}} = \lceil C_{\text{M}, \text{min}} / c_{\text{M}} \rceil$ subcarriers surpasses ρ_{dB} . Because of our i.i.d. assumption, the number of such successful subcarriers $N_{\text{SC}, \rho}$ follows a binomial distribution with the number of subcarriers in the system N_{SC} representing the number of trials and p_ρ being the success probability in each trial. With that, we can choose an arbitrarily high $C_{\text{M}, \text{min}}$ success probability $p_{C_{\text{M}, \text{min}}}$ and formulate the optimal smUE subcarrier transmission power as

$$P_{\text{s}, \text{opt}} = \min \left[\frac{P_{\text{m}} \mathcal{R}_{\text{MM}} (1 - \Omega)}{\mathcal{R}_{\text{SM}} 10^{\frac{\rho_{\text{dB}}}{10}} \Omega}; \frac{P_{\text{s}, \text{max}}}{N_{\text{SC}}} \right], \quad (4.4)$$

where $P_{\text{s}, \text{max}}$ is the maximum total smUE transmission power and

$$\Omega = \frac{I^{-1}\left(p_{C_{\text{M}, \text{min}}}, N_{\text{SC}, \text{min}} + 1, N_{\text{SC}} - N_{\text{SC}, \text{min}}\right)}{\exp\left(-\frac{\eta}{P_{\text{m}} \mathcal{R}_{\text{MM}}} 10^{\frac{\rho_{\text{dB}} + \sigma_{\text{n}}^2}{10}}\right)}, \quad (4.5)$$

where $I^{-1}(\cdot)$ is inverse of the regularized incomplete beta function, a CDF of binomial distribution.

The result (4.4) is practically closed form, which is nice. However, it comes for a price: the initial assumptions are limiting and the solution requires knowledge of scenario parameters, which would make it difficult to generalize for larger networks. But these are typical drawbacks of an analytical approach. In Publication IV we therefore propose also a more practical solution. Assuming that the frame structure is decided for the moment and we can only control transmission powers, a small cell may be informed by the overlay mBS about presence of a vulnerable mUE, the knowledge of which may be inferred from reference signal received power (RSRP) measurement at the mUE. In case there is a vulnerable mUE, smUE sets the transmission to the most robust MCS and targets

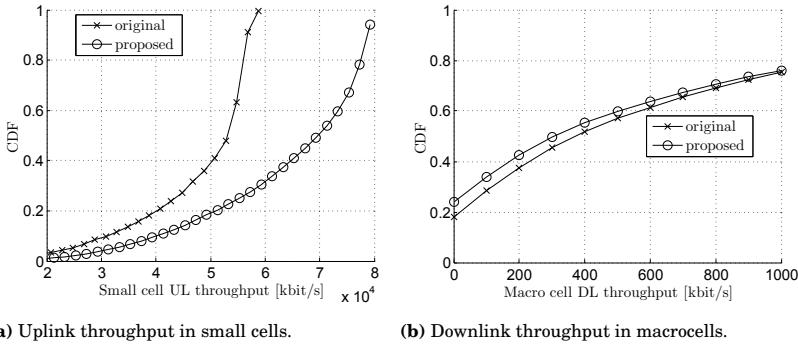


Figure 4.2. Simulation results from Publication IV where small cell uplink transmissions are interfered by overlay macro downlink transmissions. In (a) we show the small cell uplink throughput with original open loop uplink power control and with our proposed technique that boosts the uplink power unless it disturbs a nearby macro user. In (b) we show the effect of this technique on macro downlink throughput.

lower transmission power. If there is no vulnerable mUE, smBS may increase the transmission power and only has to worry if there are other small cells in the vicinity. This technique is practical as it relies on past measurements and only minimal exchange of information among the base stations. Recalling our five characteristics from Chapter 2, the *method* is power control, *control* is distributed among base stations and *time scale* is semi-static. The approach requires only minor BS-to-BS *signaling* and *compatibility* should not be a problem.

We have simulated this power control approach in a fully loaded 3GPP-like heterogeneous scenario with 21 macro sectors traditionally deployed in a hexagonal grid and closed access small cells deployed in buildings. In each macro sector there is a dual-stripe building with 240 rooms, from which 10% contain a small cell with a single user. There are 20 macro UEs in each sector, from which 35% are located inside a building. For more complete description of the scenario, please refer to Publication IV. In Figure 4.2 we demonstrate that the technique described in the previous paragraph can considerably improve throughputs in uplink of the small cells, as compared to the baseline open loop power control. Note that small cell uplink performance improvement comes despite the fact that the small cells are partly isolated from the macro transmitter due to the building. Macro layer downlink does not perform well in this scenario, due to the fact that considerable fraction of mUEs is located indoors; but, what is important, our power control mechanism causes only a minor degradation of it.

5. Semi-static on/off interference management

The title of this chapter refers to almost blank subframes (ABSFs), a concept that is also known as time domain enhanced inter-cell interference coordination (TDM eICIC). The concept belongs to 3GPP Release 10 and aims to provide means of downlink interference management by muting certain base stations in a heterogeneous network during a fraction of time instances. Compared to the dynamic on/off approach described in Chapter 3, *method* is similar but *time scale* is larger. Our contribution to the topic lies not in proposing a new solution, but instead in thoroughly analyzing an existing one in a novel way. We use a very exciting and modern mathematical toolbox to do that.

5.1 About almost blank subframes

After a short detour into management of cross-link interference, we are returning to the idea of turning some transmitters off in order to improve radio conditions of other links. Or at least *almost* off, as the name of this section suggests. TDM eICIC has been proposed to tackle specific co-channel heterogeneous scenarios, or HetNets. There are two [90]: macro/femto with CSGs and macro/pico with cell range expansion (CRE). In the macro/femto scenario a private access femto base station (fBS) is deployed within a mBS coverage, thus creating a coverage hole for mUEs that cannot access the fBS. In the macro/pico scenario a pico base station (pBS) uses an association bias (UEs connect to pBS, even if mBS gives stronger signal) to expand its range and offload the macro layer, thus creating a pBS cell edge area that is susceptible to strong mBS interference. The scenarios are depicted together in Figure 5.1. Femtocells seem not to have gained wide popularity. With picocells, or rather *small cells*, the story is different. They are gaining popularity and are expected to play

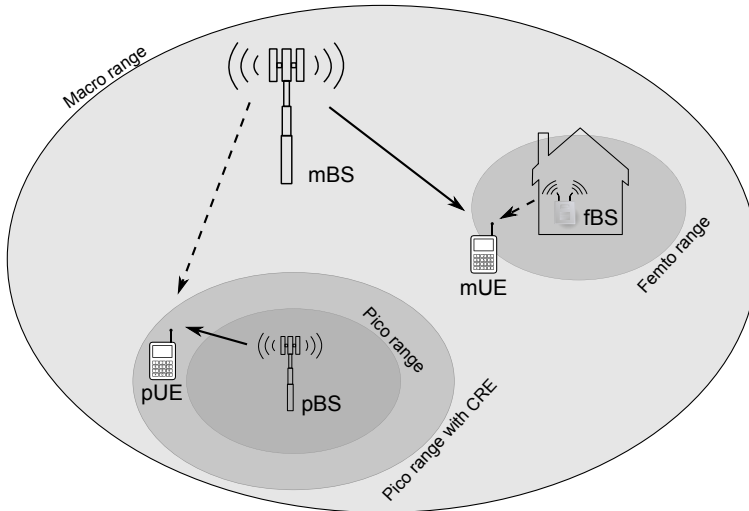


Figure 5.1. Macro/femto and macro/pico HetNet scenarios depicted in a single figure. Solid arrows represent association links, dashed arrows represent interference. A closed access fBS creates a coverage hole that makes life hard for a mUE in its vicinity. A pBS that uses cell range expansion to increase offloading from the macrocell creates a cell edge area where pico user equipments (pUEs) may fall victim to strong mBS interference.

an important role also in the next generation of the cellular system.

Almost blank subframe [1, 16.1.5] is exactly what it sounds like, a subframe where at a certain base station almost nothing is transmitted. The *almost* refers to reference symbols that must be present in every downlink subframe, and to the fact that the base station may decide to reduce data transmission power instead of transmitting no data at all. ABSF can be a normal physical downlink shared channel (PDSCH) subframe with no data, or it can be a multicast broadcast single frequency network (MBSFN) subframe [115, 31.2.2]. MBSFN subframe has an advantage of less reference symbols; however it is less flexible as some subframes cannot be configured that way. In macro/femto scenario ABSF is applied at the fBS and the victim mUE in the vicinity may be scheduled within the ABSF and thus get a chance to escape the coverage hole. Similarly, in the macro/pico scenario some of the mBS subframes are blanked so that a victim pUE may escape strong mBS interference. This principle is illustrated in Figure 5.2.

Although one may think deploying ABSF simply means not scheduling associated UEs at certain time instances, there are some technical and conceptual difficulties. Firstly, as we mentioned above, cell specific reference symbols (CRS) must be by definition present in every subframe

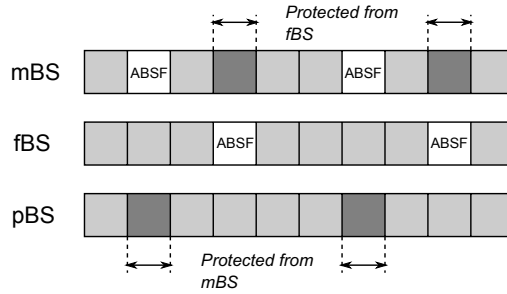


Figure 5.2. Almost blank subframes at the mBS give pBS a chance to schedule victim pUEs so that they avoid critical mBS interference. At the fBS the ABSFs allow the mBS to serve mUEs that are caught in the fBS coverage hole.

[34, 67]. Some additional control channel information may have to be transmitted as well. For a victim UE, a beneficiary of the ABSF, these reference symbols and control information are still interference and should be taken into account, e.g. by means of interference cancellation. Secondly, the presence of ABSF may cause disturbance to CQI measurements. A UE that measures high interference power in normal subframe and low interference power in ABSF may deduce that true value lies somewhere in between, which is not the case [75, 109]. Release 10 and newer standards allow BSs to set up gaps to prevent measurements during ABSF, but older UEs may suffer from the issue. Thirdly, as relevant interference may come from multiple transmitters, setting of TDM eICIC should be to some extent coordinated. The BS-to-BS X2 interface may be used to exchange messages for this purpose [109, 110] and the network is expected to manage the setting in a self-organized manner [63, 10.4.4]. The X2 interface is not very fast, but for semi-static update strategy [35] it is more than enough. *Control* is thus distributed among base stations, *signaling* is light and there are minor issues with *compatibility* corresponding to the legacy UEs.

The TDM eICIC concept enjoyed great interest in 3GPP and academic community. From research point of view it can be therefore considered a success. For further insights one may look at the conceptual work [78], generic macro/femto simulation studies [55, 141], macro/pico analysis [60], generic macro/pico simulation studies [105, 142–144], macro/pico simulation studies with reduced transmission power ABSFs [122, 123], macro/pico simulation studies that include CRS interference [109, 124] or macro/pico simulation study with details on resource allocation [76]. Concerning the coordination of TDM eICIC among multiple cells, there is a simulation study [110], a thorough study including many practical

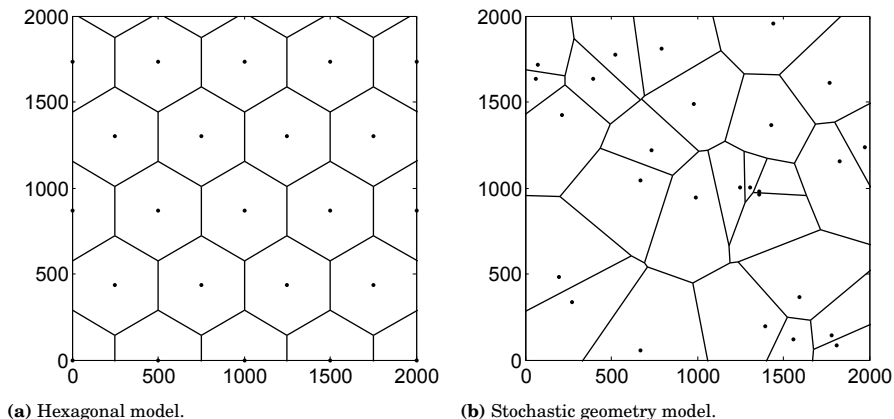


Figure 5.3. Example of a network layout. Dots represent deployed base stations, lines represent cell range based on distance to base station, axes represent distance in meters. In (a) we have a regular hexagonal grid (500m inter-site distance) commonly used for example in 3GPP studies. In (b) the deployment is random as typical for analysis that uses stochastic geometry.

issues [35] and a recent work that promotes macro/pico self organization based on stochastic approximation [126].

5.2 Stochastic geometry background

Let us now talk about one important aspect of modeling (at least cellular) wireless networks. For practical reasons, we typically divide our studies into two types: system level studies and link level studies. These names are quite self-explanatory. Within system level studies we model spatial relations between many transmitters and receivers in the radio network and as a quality metric we calculate received signal powers or signal-to-interference-plus-noise-ratios. In link level studies we focus on a single link - we might have a given SINR value, model all physical layer processing and evaluate the achievable spectral efficiency. Evaluating spectral efficiency for all links in the network is usually too complex, which is why smart people designed link-to-system mapping algorithms [68, 104].

In a system level study of a cellular system, one of the very first steps is to model positions of base stations. This is traditionally done by placing the mBSs in a hexagonal grid, as shown in Figure 5.3(a). Small cells are then optionally added on a per-macrocell basis. While this model is nicely illustrative, it is not analytically tractable, hence useless for people who want to rigorously prove something. However, a couple of years back a fresh perspective arose from the academic circles. It turned out that by de-

ploying the model BSs at random positions and using tools from *stochastic geometry* [30] one can improve tractability significantly. What is more, this model maintains roughly the same level of precision in respect to real life macro deployments as the traditional hexagonal grid [12]; the random deployment is found to be too pessimistic from interference perspective, the hexagonal model is too optimistic and the truth lies somewhere in between. An example random deployment of BSs and their coverage (based on vicinity) is shown in Figure 5.3(b).

Application of stochastic geometry has had a profound effect on the communications society. Excellent tutorials and references to seminal works may be found for example in [11, 62]. Important earlier works are for example [16, 17, 21, 47]. Achievements in analyzing ad hoc networks are also worth a special note [145]. When it comes to cellular networks, the breakthrough came with [12]. Building upon earlier success with Aloha channel access [14], [12] managed to incorporate the spatial relation between base station and a user equipment within its coverage and derive tractable formula of downlink success probability, a complementary cumulative distribution function (CCDF) of downlink SINR. An important assumption is that user association to its serving base station is based on long-term channel conditions, i.e., fast fading does not affect it. The approach has been then used for example when analyzing downlink performance of K -tier HetNet [99], evaluating energy efficiency in HetNet [121], analyzing uplink performance in macro-tier [101], analyzing fractional frequency reuse [102, 103] and analyzing carrier aggregation [88]. An alternative approach with user association based on instantaneous SINR has been introduced in [38] and then expanded with base station load in [37], presenting thus an upper bound to coverage probability in case of association based on long-term signal power.

When using the basic stochastic geometry approach, positions of base stations are modeled by a homogeneous Poisson point process (PPP). In a homogeneous PPP the number of points k within a certain area is a random variable that follows a Poisson distribution with probability mass function (PMF)

$$f(k) = \frac{(A\lambda)^k}{k!} e^{-A\lambda}, \quad (5.1)$$

where A is area and λ is intensity of the PPP. Conditional on the number of points k , they are then independently and uniformly distributed in the given set (area). Analysis is then performed for a user located at the origin, but thanks to Slivnyak's theorem [30] it is valid for any point in

the plane where the homogeneous PPP is deployed. In cellular scenarios, user in most cases connects to a base station that provides the strongest long-term signal power. If long-term signal power is influenced only by BS transmission power and path loss, this is equivalent to simply connecting to the closest base station. Coverage area of each BS is then represented by the Voronoi cell of given point, as long as transmission powers and path loss formulas are the same for each BS. Looking at Figure 5.3(b), for example around coordinates (1300; 1000), one may notice one weakness of the random placement model - the points may end up being closer to each other than observable in the real world. The issue causes stronger interference to appear in the analysis and leads to results that are on the pessimistic side compared to the real world. In [12] it was however concluded that the traditional hexagonal model is in a similar way too optimistic, hence precision of the two approaches is roughly the same. The issue with random approach stems from the fact that each point is deployed independently. One effort to alleviate this has been presented in [128]; the work introduces pairwise interaction into the point model for the price of considerable loss of tractability. Another way is to enforce a minimum distance between points, leading to so-called hard-core models [15, 2.1.3], with similar consequences.

An important aspect of modeling (not only cellular) wireless networks is realistic representation of fading. The framework in [12] can take any kind of fading, although the most tractable results are obtained for flat Rayleigh fading, which is what we use in our works as well. However, there is no fading assumed when establishing association of a UE to its serving base station. The issue has been solved in [36, 80], where it is shown that fading can be modeled by a transformation of a given PPP. Let the downlink received power at a UE k be

$$P_k = P_t h_k \chi_k \|r_k\|^{-\alpha}, \quad (5.2)$$

where P_t is transmission power of the corresponding base station, h_k represents fast fading, χ_k represents shadowing, r_k is distance to the corresponding base station and α represents path loss exponent. Under assumption $\mathbb{E}\{\chi_k^{\frac{2}{\alpha}}\} < \infty$ it can be shown that shadowing can be incorporated into the model by constructing a new homogeneous PPP with intensity $\lambda_\chi = \lambda \mathbb{E}\{\chi_k^{\frac{2}{\alpha}}\}$. We did not know about this elegant solution until Publication V and Publication VI were already accepted for publication, therefore the rest of the chapter does not include shadowing in the analysis.

One last note on the use of stochastic geometry: although it brings new dimension of tractability into modeling of cellular networks, the mathematical framework is rather advanced and many features of the system are not straightforward to incorporate into the analysis. An example of this is MIMO processing that has been mastered in the context of PPP only in limited manner [39, 59]. A counter example is cell sectorization, which I personally thought would not be possible to incorporate; but a solution has been proposed in [91]. The tool set seems to be very strong and we will probably see more of its applications in our field.

5.3 How many are needed?

Deciding on the appropriate number of ABSFs comprises a tradeoff between helping victim macro or pico UEs and harming femto or macro UEs. Every fraction of resource that is blanked to protect mUEs in a femto coverage hole is taking transmission/reception opportunities from femto user equipments (fUEs) that own the coverage hole. Likewise, protecting pUEs in the expanded coverage region around a pico base station comes at the cost of UEs connected to the overlay macro base station.

Additionally, in a live network the number of ABSFs may need to change from time to time as the number of UEs connected to corresponding base stations and/or their traffic patterns keep changing. A macro base station that is serving multiple UEs at the cell edge will have less resources to spare for protecting underlay pUEs than in a case when most of its UEs experience good channel conditions. Obviously, what is needed is a network function that semi-statically tracks the distribution of UEs and their traffic demands and sets the number of ABSFs while communicating with dynamic schedulers of the base stations so that they can take advantage of the ABSFs when distributing the resources.

We have taken a different, academic approach. Using a model based on stochastic geometry, we express the minimum number of ABSFs based on system parameters (intensity of UEs and base stations, residual interference power in ABSFs) and minimum average rate of victim UEs. Although the solution is not dynamic, it offers a good initial estimate and gives us an excellent possibility to study the effect of system parameters on the outcome. We were the first to apply the novel stochastic geometry approach to analyze time domain blanking in heterogeneous networks. A little bit behind was [119] that analyzed the macro/pico scenario and in-

cluded association bias in the optimization, but did not include residual interference. A capacity analysis with a similar approach was published in [93]. In [77] a much simpler model was assumed, with fixed number of picocells and UEs per macrocell coverage, with a simple intuitive outcome.

In the next few subsections we will introduce our approach and show some illustrative results. We demonstrate how the calculations are done for the macro/pico scenario as such deployment is more likely to see the light of the real day and because it is also used in Section 5.4.

5.3.1 System model

Let us model the overlay mBS layer by a homogeneous PPP Θ_m with intensity λ_m , the underlay pBS layer by another homogeneous PPP Θ_p with intensity λ_p and UEs by a third homogeneous PPP Θ_{UE} with intensity λ_{UE} . All three PPPs are independent from each other. Base station load is represented in the same manner as in [37] by coefficients μ_m and μ_p that thin the corresponding PPPs Θ_m and Θ_p , respectively. Long term wireless channel effects are modeled by distance dependent path loss $r^{-\alpha}$, where r represents distance and α represents path loss exponent, α_m for mBS layer and α_p for pBS layer. Short term effects are captured by Rayleigh fading with power distributed according to $\exp(1)$.

Association of UEs to BSs is done in a following manner. For a given UE, let r_m be its distance to the closest mBS and r_p its distance to the closest pBS. This UE will connect to the closest pBS (and become a pUE) if $r_p < k_1 r_m$, where k_1 is a coefficient that incorporates mBS and pBS transmission powers P_m and P_p , respectively, and the association bias κ . Otherwise, the UE will connect to the closest mBS. With $\alpha_m = \alpha_p = \alpha$ the coefficient $k_1 = (\kappa P_p / P_m)^{1/\alpha}$ defines a contour of equal biased long-term received power, otherwise it approximates it. Hence, in our model the UE connects to a BS based on the highest biased long-term received power. In a normal subframe a pUE receives full interference from all non-serving mBSs and pBSs. In an ABSF there is still full interference from non-serving pBSs, but only residual interference from mBSs, represented by a multiplicative coefficient ρ_r .

Our analysis concentrates mostly on *victim pUEs*. Intuitively, a victim pUE is a pUE that suffers from interference with somehow stronger long term power than UE's serving signal power. We call such interferer a dominant interferer (DI). By definition, such interference should come only from mBSs, because if there was a pBS with stronger power, the

pUE would associate to that pBS instead. Formally, a DI mBS fulfills $r_p > k_2 r_m$, where k_2 is a DI defining coefficient. With $\alpha_m = \alpha_p = \alpha$ we could for example set $k_2 = (P_p/P_m)^{1/\alpha}$ that would make a DI every mBS that gives more interference power than pUE's serving power. A pUE that has one or more DIs is subsequently called a victim pUE.

Note that it is also possible to define DI such that the DI's power does not have to be larger than own power. In such case, it is theoretically possible that dominant interference would come from a pBS, as the nature of the PPP model does not prevent two or more pBSs to be close to each other. This case is not in our focus; the biggest problem of CRE is really the fact that interference from mBS is stronger than the desired signal.

Focusing our analysis on victim UEs is actually one of the nice contributions of Publication V. Our main kudos goes to [29], the paper that inspired us to do so.

5.3.2 Distance to serving base station

PDF of distance of a general UE to the closest mBS has been derived in [12]. The derivation starts by finding the CDF from the null probability of a PPP:

$$F_{r_m}(R) = \mathbb{P}[r_m \leq R] \quad (5.3)$$

$$= 1 - \mathbb{P}[r_m > R] \quad (5.4)$$

$$= 1 - \mathbb{P}[\text{No mBS closer than } R] \quad (5.5)$$

$$= 1 - e^{-\pi\lambda_m R^2} \quad (5.6)$$

From the CDF $F_{r_m}(R)$ we derive PDF $f_{r_m}(r)$ by differentiation:

$$f_{r_m}(r) = \frac{dF_{r_m}(r)}{dr} = 2\pi\lambda_m r e^{-\pi\lambda_m r^2} \quad (5.7)$$

Similarly, one can derive PDF of distance to the closest pBS. Once again, that was for a general UE. To do the same for a victim pUE, let us first derive a probability that a UE is actually a victim pUE, i.e., that $k_2 r_m < r_p < k_1 r_m$:

$$\mathbb{P}[k_2 r_m < r_p < k_1 r_m] = \int_0^\infty \mathbb{P}[k_2 x < r_p < k_1 x] f_{r_m}(x) dx \quad (5.8)$$

$$= \int_0^\infty \int_{k_2 x}^{k_1 x} f_{r_p}(y) dy f_{r_m}(x) dx \quad (5.9)$$

$$= \frac{\lambda_m}{\lambda_m + k_2^2 \lambda_p} - \frac{\lambda_m}{\lambda_m + k_1^2 \lambda_p} \quad (5.10)$$

We continue by deriving CDF of distance from a victim pUE to its serving pBS using Bayes's theorem:

$$F_{r_p|k}(R) = \mathbb{P}[r_p \leq R | k_2 r_m < r_p < k_1 r_m] \quad (5.11)$$

$$= \frac{\mathbb{P}[r_p \leq R, k_2 r_m < r_p < k_1 r_m]}{\mathbb{P}[k_2 r_m < r_p < k_1 r_m]} \quad (5.12)$$

$$= \int_0^R \int_{x/k_1}^{x/k_2} f_{r_m}(y) dy f_{r_p}(x) dx \left(\frac{\lambda_m}{\lambda_m + k_2^2 \lambda_p} - \frac{\lambda_m}{\lambda_m + k_1^2 \lambda_p} \right)^{-1} \quad (5.13)$$

$$= \left(\frac{k_1^2 \lambda_p \left(1 - e^{-\pi \left(\frac{\lambda_m}{k_1} + \lambda_p \right) R^2} \right)}{\lambda_m + k_1^2 \lambda_p} - \frac{k_2^2 \lambda_p \left(1 - e^{-\pi \left(\frac{\lambda_m}{k_2} + \lambda_p \right) R^2} \right)}{\lambda_m + k_2^2 \lambda_p} \right)^{-1} \times \left(\frac{\lambda_m}{\lambda_m + k_2^2 \lambda_p} - \frac{\lambda_m}{\lambda_m + k_1^2 \lambda_p} \right)^{-1} \quad (5.14)$$

The PDF can then be obtained by differentiation:

$$f_{r_p|k}(r) = \frac{dF_{r_p|k}(r)}{dr} = 2\pi r \frac{(\lambda_m + k_1^2 \lambda_p)(\lambda_m + k_2^2 \lambda_p)}{(k_1^2 - k_2^2) \lambda_m} \times \left(e^{-\pi \left(\frac{\lambda_m}{k_1} + \lambda_p \right) r^2} - e^{-\pi \left(\frac{\lambda_m}{k_2} + \lambda_p \right) r^2} \right) \quad (5.15)$$

5.3.3 Interference, SINR and success probability

In this part we will show how the distance distribution from Section 5.3.2 can be used to calculate success probability of a victim pUE. The success probability is defined as

$$\mathbb{P}[\gamma > \gamma_0], \quad (5.16)$$

where γ represents SINR and γ_0 represents outage threshold. Downlink SINR of a victim pUE scheduled in ABSF is defined as

$$\gamma_a = \frac{P_p h r_p^{-\alpha_p}}{I_p + \rho_r (I_m + I_d)}, \quad (5.17)$$

where I_p denotes sum interference from pBS layer, ρ_r coefficient denotes residual ABSF interference, I_m represents sum interference from non-DI mBSs and I_d denotes sum interference from DI mBSs. In case of a normal subframe the ρ_r coefficient is not present. Now, we can write down success

probability of a victim pUE (which we will simply denote p_s) as

$$p_s = \mathbb{P}[\gamma_a > \gamma_0 | k_2 r_m < r_p < k_1 r_m] \quad (5.18)$$

$$= \int_0^\infty \mathbb{E}_I \left\{ \mathbb{P} \left[\frac{P_p h r^{-\alpha_p}}{I_p + \rho_r (I_m + I_d)} > \gamma_0 \right] \right\} f_{r_p|k}(r) dr \quad (5.19)$$

$$= \int_0^\infty \mathbb{E}_I \left\{ \mathbb{P} \left[h > \frac{\gamma_0 (I_p + \rho_r (I_m + I_d))}{P_p r^{-\alpha_p}} \right] \right\} f_{r_p|k}(r) dr \quad (5.20)$$

$$= \int_0^\infty \mathbb{E}_I \left\{ \exp \left(-\frac{\gamma_0 r^{\alpha_p}}{P_p} (I_p + \rho_r I_m + \rho_r I_d) \right) \right\} f_{r_p|k}(r) dr \quad (5.21)$$

$$= \int_0^\infty \phi_{I_p}(r) \phi_{I_m}(r) \phi_{I_d} \left(\frac{\gamma_0 \rho_r r^{\alpha_p}}{P_p} \right) f_{r_p|k}(r) dr, \quad (5.22)$$

where

$$\phi_{I_p}(r) = \mathbb{E}_{I_p} \left\{ \exp \left(-\frac{\gamma_0 r^{\alpha_p}}{P_p} I_p \right) \right\}, \quad (5.23)$$

$$\phi_{I_m}(r) = \mathbb{E}_{I_m} \left\{ \exp \left(-\frac{\gamma_0 \rho_r r^{\alpha_p}}{P_p} I_m \right) \right\}, \quad (5.24)$$

$$\phi_{I_d}(s(r)) = \mathbb{E}_{I_d} \left\{ \exp(-s(r) I_d) \right\}. \quad (5.25)$$

We did not plug $s(r) = \gamma_0 \rho_r r^{\alpha_p} / P_p$ directly into (5.25) in order to make the derivation of $\phi_{I_d}(s(r))$ later on easier to follow. The first term ϕ_{I_p} has been solved in [12]. The interference is integrated over the distance of r to infinity, because the closest interferer can be only as close as the own pBS. And as the power and path loss exponent are the same as for the own pBS, the expression is rather elegant. It is given by

$$\phi_{I_p}(r) = \exp(-\pi \mu_p \lambda_p r^2 \rho(\gamma_0, \alpha_p)), \quad (5.26)$$

where

$$\rho(\gamma, \alpha) = \int_{\gamma^{-\frac{2}{\alpha}}}^\infty \frac{\gamma^{\frac{2}{\alpha}}}{1 + u^{\frac{\alpha}{2}}} du. \quad (5.27)$$

The second term ϕ_{I_m} can be derived using the same approach. This time the interference is integrated over the distance of r/k_2 to infinity, as the closest non-DI interferer can be located r/k_2 far from our user of interest. This time the powers and path loss exponents of the own signal and interfering signals are different, leading to a more complex expression

$$\phi_{I_m}(r) = \exp \left(-\pi \mu_m \frac{\lambda_p}{k_2^2} r^2 \rho \left(\frac{\gamma_0 k_2^{\alpha_m} \rho_r P_m r^{\alpha_p}}{P_p r^{\alpha_m}}, \alpha_m \right) \right), \quad (5.28)$$

Deriving the third term ϕ_{I_d} was one of our own contributions in Publication V. We started from a special case $\phi_{I_d}^{(1)}$ that contains only one DI:

$$\phi_{I_d}^{(1)}(s(r)) = \mathbb{E}_{I_d^{(1)}} \left\{ \exp \left(-s(r) I_d^{(1)} \right) \right\} \quad (5.29)$$

$$= \mathbb{E}_{h, r_d} \left\{ \exp \left(-s(r) P_m h r_d^{-\alpha_m} \right) \right\} \quad (5.30)$$

$$\stackrel{(a)}{=} \mathbb{E}_{r_d} \left\{ \frac{1}{1 + s(r) P_m r_d^{-\alpha_m}} \right\} \quad (5.31)$$

$$= \int_{r_d} \frac{1}{1 + s(r) P_m u^{-\alpha_m}} f_{r_d}(u) du \quad (5.32)$$

$$\stackrel{(b)}{=} \int_{r/k_1}^{r/k_2} \frac{1}{1 + s(r) P_m u^{-\alpha_m}} \frac{2uk_1^2 k_2^2}{(k_1^2 - k_2^2) r^2} du \quad (5.33)$$

$$= \frac{k_1^2 k_2^2}{k_1^2 - k_2^2} \left(\frac{1}{k_2^2} {}_2F_1 \left(1, -\frac{2}{\alpha_m}, \frac{\alpha_m - 2}{\alpha_m}, -\frac{s(r) k_2^{\alpha_m} P_m}{r^{\alpha_m}} \right) \right. \\ \left. \times \frac{1}{k_1^2} {}_2F_1 \left(1, -\frac{2}{\alpha_m}, \frac{\alpha_m - 2}{\alpha_m}, -\frac{s(r) k_1^{\alpha_m} P_m}{r^{\alpha_m}} \right) \right) \quad (5.34)$$

In the above equations, $I_d^{(1)}$ denotes interference that comes from a single DI mBS, r_d denotes distance from the victim pUE to given DI mBS, $f_{r_d}(u)$ represents PDF of this distance and ${}_2F_1(\dots)$ represents the hypergeometric function. In (a) we perform averaging over fast fading h via Laplace transform and in (b) we take advantage of the fact that DIs are distributed uniformly over the plane.

The next task is to use $\phi_{I_d}^{(1)}$ and obtain the version with arbitrary number of DI mBSs ϕ_{I_d} . In case of full load $\mu_m = 1$, an exact result can be obtained as suggested by one of the anonymous reviewers of Publication V:

$$\phi_{I_d}(s(r)) = \mathbb{E} \left\{ \phi_{I_d}^{(1)}(s(r))^{N_d} \right\} \quad (5.35)$$

$$= \text{PGF}_{N_d} \left(\phi_{I_d}^{(1)}(s(r)) \right) \quad (5.36)$$

$$= \frac{\exp \left(\phi_{I_d}^{(1)}(s(r)) \pi \left(\frac{1}{k_2^2} - \frac{1}{k_1^2} \right) \lambda_m r^2 \right) - 1}{\exp \left(\pi \left(\frac{1}{k_2^2} - \frac{1}{k_1^2} \right) \lambda_m r^2 \right) - 1}, \quad (5.37)$$

where N_d represents the number of DI mBSs (a random variable) and PGF_{N_d} is the probability generating function of N_d , the derivation of which we skip here. This result cannot be extended for a general load value μ_m , since probability generating function is defined only for discrete random variables and, to the best of our knowledge, there is no continuous domain equivalent that would fit our purpose. Instead, we use a good approximation

$$\phi_{I_d}(s(r)) \approx \phi_{I_d}^{(1)}(s(r))^{\mu_m \overline{N_d}}, \quad (5.38)$$

where $\overline{N_d}$ is the average number of DI mBSs that we calculated to be

$$\overline{N_d} = \frac{\pi \left(\frac{1}{k_2^2} - \frac{1}{k_1^2} \right) \lambda_m r^2}{1 - \exp \left(-\pi \left(\frac{1}{k_2^2} - \frac{1}{k_1^2} \right) \lambda_m r^2 \right)}. \quad (5.39)$$

At this point we have all that is necessary to calculate the success probability using (5.22). Although not closed form, the result is usable enough, provided how complicated phenomenon it represents.

5.3.4 Average rate

The last piece of the puzzle before we formulate the condition for the number of ABSFs is the rate of a UE. It is rather obvious that by blanking a certain number of subframes at the mBS we “steal” transmission opportunities from UEs that are served by mBSs. The idea is therefore to have a minimum acceptable rate for a victim pUE and then blank just enough subframes to fulfill that requirement. We assume that at a pBS, non-victim pUEs are allowed to be scheduled only in normal subframes while victim pUEs may be scheduled in both ABSFs and normal subframes. In order to design a robust condition for the number of ABSFs, we consider a worst case scenario: a victim pUE that operates at the outage threshold and is scheduled using the simplest round-robin algorithm. The average rate at the outage threshold (outage rate) of a pUE is

$$C_v = \mathbb{E}_{N_{UE}, N_{UE,v}} \left\{ \frac{N_a}{N_s} C_a (N_{UE}, N_{UE,v}) + \frac{N_s - N_a}{N_s} C_n (N_{UE}, N_{UE,v}) \right\}, \quad (5.40)$$

where N_{UE} is number of pUEs associated to a given pBS, $N_{UE,v}$ is number of victim pUEs associated to given pBS, N_s is number of subframes in a radio frame, N_a is number of ABSFs in a radio frame, C_a is outage rate during ABSF and C_n is outage rate during a normal subframe. Variables N_{UE} and $N_{UE,v}$ are obviously correlated, therefore also C_n and C_a are correlated. However, for the sake of tractability, we will create an approximation by assuming them to be independent. In Publication V it is shown that numerical results match our formulas well, which at least visually proves that the approximation does not affect precision detrimentally. The rates are given by

$$C_n (N_{UE}) \approx N_r \mathbb{P} [\gamma_n > \gamma_0] \log (1 + \gamma_0) \Omega_n (N_{UE}), \quad (5.41)$$

$$C_a (N_{UE,v}) \approx N_r \mathbb{P} [\gamma_a > \gamma_0] \log (1 + \gamma_0) \Omega_a (N_{UE,v}), \quad (5.42)$$

where N_r is the number of resource blocks, Ω_a is asymptotic round robin fraction of resources given to a victim pUE in ABSF and Ω_n is asymptotic

round robin fraction of resources given to any pUE in a normal subframe. The round robin fractions Ω_a and Ω_n are inversely proportional to the number of victim pUEs and all pUEs in a picocell, respectively. The number of Poisson points in a given area depends solely on its size. Although an exact distribution of Voronoi cell size in a Poisson field is not known, an approximation that fits our purpose has been found in [46]. For example, PDF of a macrocell size in our model is

$$f_S(x) \approx \lambda_m \frac{343}{15} \sqrt{\frac{7}{2\pi}} (\lambda_m x)^{\frac{5}{2}} \exp\left(-\frac{7}{2}\lambda_m x\right). \quad (5.43)$$

However, a couple of tricks are needed on top of (5.43) to approximate Ω_a and Ω_n . Firstly, every cell that we evaluate has at least one victim pUE. We therefore derive a PDF of a cell area conditioned on a presence of at least one victim pUE. The main idea is that UEs are more likely to lie in a larger cell, therefore a cell that has one or more UEs is statistically larger than a cell with no UEs. In [36] this was identified to be related to the waiting bus paradox and in [120] the biasing was solved in a manner that is more pleasing to the eye. Secondly, we need to formulate a relation between size of a picocell and an overlay macrocell and identify how big part of the picocell area contains victim pUEs. For that we transform (5.43) using probability that UE is a pUE or a victim pUE (5.10) and the average number of picocells per macrocell λ_p/λ_m . For further details, an interested reader is referred to Publication V. We would also like to acknowledge [148] as it has served as a major source of inspiration for these derivations.

5.3.5 Results

Let us now illustrate what we have derived in Subsection 5.3.4. We have derived the average outage throughput of a victim pUE, therefore we can set a minimum required value for it and then evaluate how many of the macrocell subframes need to be blanked. In Table 5.1 we summarize system parameter values that we assumed for our illustration. We consider these to be roughly realistic.

Our illustrative results are presented in Figure 5.4, where each subfigure shows dependence of the number of required ABSFs on a single system parameter. Other parameters are kept at their default values from Table 5.1. Firstly, Figure 5.4(a) shows how is the number of required ABSFs affected by variable λ_p while λ_m is static, i.e., by the average number of pBSs per macrocell λ_p/λ_m . By increasing λ_p the UEs

Parameter	Value
mBS intensity λ_m	10^{-5}m^{-2}
pBS intensity λ_p	$4\lambda_m$
UE intensity λ_{UE}	$20\lambda_m$
mBS transmission power P_m	43dBm
pBS transmission power P_p	30dBm
mBS load μ_m	1
pBS load μ_p	0.8
mBS-UE path loss exponent α_m	2.5
pBS-UE path loss exponent α_p	3
Macro/pico association bias κ	7dB
Macro/pico association-defining k_1	$\left(\frac{\kappa P_p}{P_m}\right)^{\frac{2}{\alpha_m + \alpha_p}} = 0.471$
Macro/pico DI defining k_2	$\left(\frac{P_p}{P_m}\right)^{\frac{2}{\alpha_m + \alpha_p}} = 0.262$
ABSF residual interference ρ_r	-20dB
Outage threshold γ_0	-5dB
Number of subframes N_s	10
Number of resource blocks N_r	25
Resource block bandwidth	180kHz
Minimum victim outage throughput $C_{v,\min}$	100kbits/s

Table 5.1. Reference parameters for showing results on the number of ABSFs in macro/pico scenario.

have more available pBSs to connect to, which decreases number of associated pUEs per pBS, hence easing requirement for the number of ABSFs. Secondly, Figure 5.4(b) shows the effect of residual interference in ABSF. This is maybe the most interesting result in Publication V showing that in macro/pico scenario it is important to keep the residual interference as low as possible, otherwise the requirement on the number of ABSFs quickly increases. Thirdly, in Figure 5.4(c) we show how fast the required number of ABSFs increases when we increase association bias κ . Increasing κ stimulates offloading from macrocell to picocells, but also increases a possibility of suffering from strong interference coming from an mBS. Lastly, Figure 5.4(d) shows the effect of DI defining coefficient k_2 via ϵ as in $k_2 = (P_p / (\epsilon P_m))^{\frac{2}{\alpha_m + \alpha_p}}$. Increasing ϵ decreases DI defining k_2 , which increases the number of victim pUEs per pBS in the system, hence leading to more stringent requirement on the number of ABSFs.

For further results we direct the reader directly to Publication V. The results focus on the victim UEs. The effect of TDM eICIC on users in the tier where ABSFs are applied is not uninteresting, but it is trivial: throughputs of these users will be decreased by N_a/N_s . Although we did not treat this issue in our work, the decision whether to use TDM eICIC must take this aspect into account.

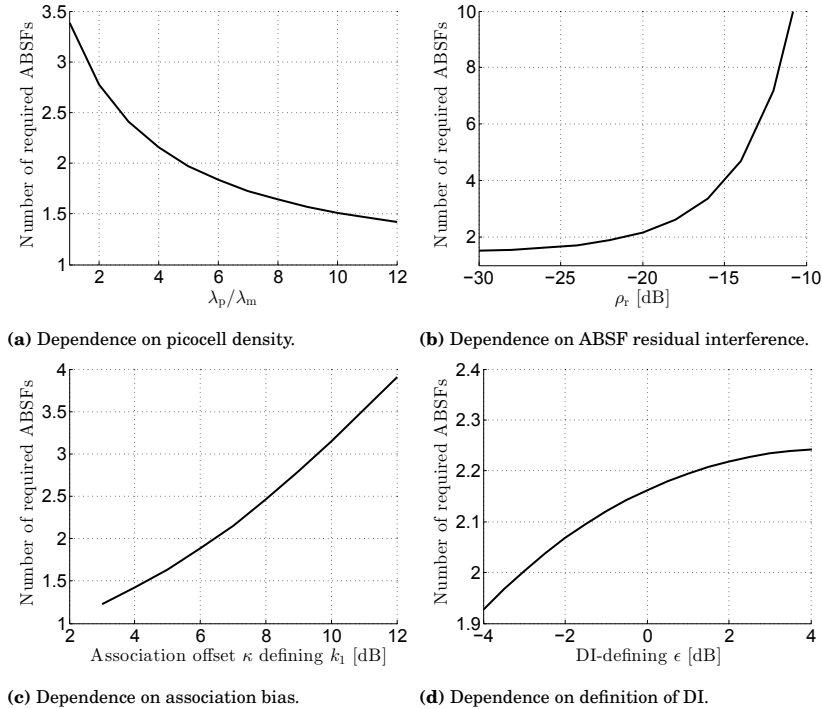


Figure 5.4. Dependence of the number of required ABSFs on selected system parameters. In each plot one parameter is being changed while the rest are kept at their default values from Table 5.1.

5.4 Time synchronization issues

One thing about TDM eICIC is that it requires base stations in the network to be time synchronized. This comes from the fact that when (for example) a pUE has multiple strong mBS interferers, these interferers should align their blanking patterns so that the pUE is able to avoid interference from all of them at the same time. However, even if ABSF alignment is in place, time synchronization is never perfect. In Publication VI we therefore analyze the effect of base station time synchronization mismatch on performance within ABSF.

In Figure 5.5 we illustrate how timing mismatch affects the subframe where pBSs schedule victim users. If we assume pBS timing as reference, mBS with a positive mismatch (*late mBS*) causes NSF interference to leak to the beginning of a given pBS subframe. An *early mBS* on the other hand causes the NSF interference to leak to the end of given pBS subframe. In 3GPP LTE, beginning of a subframe (first 1-3 OFDM symbols) carries PDCCH, a channel that contains scheduling information, i.e., information on position of user data, for the data-carrying PDSCH that

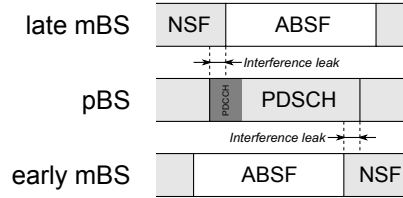


Figure 5.5. Effects of base station time synchronization mismatch on pBS operation during ABSF. An mBS with positive timing mismatch (late mBS) causes normal subframe (NSF) interference to leak to the beginning of subframe where pBS schedules victim users, negatively affecting physical downlink control channel (PDCCH). An mBS with negative timing mismatch (early mBS) causes NSF interference to leak to the end of subframe where pBS schedules victim users, negatively affecting PDSCH.

fills the rest of the subframe. We think that interference in PDSCH may be addressed by means of link adaptations, channel coding, etc. However, if a pUE fails to detect and decode PDCCH it will not find its data in PDSCH, making the subframe all together lost. In the following analysis we therefore focus on success probability of the pBS PDCCH under late mBS interference.

5.4.1 Problem formulation and analysis

We reuse the system model for macro/pico scenario as given in Subsection 5.3.1, with addition that every BS experiences a timing mismatch τ_i . Timing mismatch τ_i is an i.i.d. random variable governed by unspecified PDF $f_\tau(x)$ and CDF $F_\tau(x)$. Looking a bit ahead, we want the derived success probability to hold (or be better) for p_w fraction of pBSs. We therefore conduct the analysis for pUE who's serving pBS has a mismatch of τ_w coming from

$$\tau_w = F_\tau^{-1}(1 - p_w). \quad (5.44)$$

One can think of this intuitively as a worst case scenario where the analyzed pUE is served by an early pBS, i.e., pBS that is extra susceptible to interference from late mBSs. Now, interference from all mBSs that have a mismatch $\tau_i > \tau_w + t_{cp}$, where t_{cp} denotes cyclic prefix length, will be leaking into control channel transmitted by the serving pBS. We thus define a fraction of *critical mBS interferers* as

$$p_m = 1 - F_\tau(\tau_w + t_{cp}). \quad (5.45)$$

Based on OFDM properties, the impact of interference coming from mBS with time mismatch τ_i can be formally described by coefficient $\Delta(\tau_i)$ that

was shown in [18] to be

$$\Delta(\tau) = \begin{cases} 0 & \text{if } \tau < t_{\text{cp}} \\ \frac{\tau - t_{\text{cp}}}{t_{\text{fft}}} \left(1 + \frac{t_{\text{fft}} - (\tau - t_{\text{cp}})}{t_{\text{fft}}} \right) & \text{if } t_{\text{cp}} \leq \tau \leq t_{\text{cp}} + t_{\text{fft}} \\ 1 & \text{if } \tau > t_{\text{cp}} + t_{\text{fft}} \end{cases}, \quad (5.46)$$

where t_{fft} denotes length of one OFDM symbol. If we then add the leaked mismatched interference to the matched interference from the same mBS we get a timing dependent power multiplicative coefficient

$$\Upsilon(t) = \rho_r + (1 - \rho_r) \Delta(t - \tau_w). \quad (5.47)$$

To calculate the success probability (5.16) we use (5.22) with (5.15), but we modify terms ϕ_{I_m} and ϕ_{I_d} in order to incorporate timing mismatch. We thus get

$$p_s = \int_0^\infty \phi_{I_p}(r) \phi_{I_m}(r) \phi_{I_m}^{(m)}(r) \phi_{I_d}(r) \phi_{I_d}^{(m)}(r) f_{r_p|k}(r) dr \quad (5.48)$$

and we explain the separate $\phi_x^{(y)}(r)$ terms one-by-one. The first term $\phi_{I_p}(r)$ is of the same shape as in (5.26), because interference from pBS layer is not affected by timing mismatch. The second term $\phi_{I_m}(r)$ contains the part of interference from non-DI macro layer that does not leak into control channel of our analyzed pUE. It is given by thinning (5.28):

$$\phi_{I_m}(r) = \exp\left(-\pi(1 - p_m)\mu_m \frac{\lambda_p}{k_2^2} r^2 \rho \left(\frac{\gamma_0 k_2^{\alpha_m} \rho_r P_m r^{\alpha_p}}{P_p r^{\alpha_m}}, \alpha_m\right)\right) \quad (5.49)$$

The third term $\phi_{I_m}^{(m)}(r)$ incorporates interference from those non-DI mBSs that have mismatch $\tau_i > \tau_w + t_{\text{cp}}$ and their NSF interference leaks into the control channel of our pUE. To calculate $\phi_{I_m}^{(m)}(r)$ we thin (5.28) by p_m and average out the effect of timing mismatch:

$$\phi_{I_m}^{(m)}(r) = \int_{\tau_w + t_{\text{cp}}}^\infty \exp\left(-\pi p_m \mu_m \frac{\lambda_p}{k_2^2} r^2 \rho \left(\frac{\gamma_0 k_2^{\alpha_m} \rho_r \Upsilon(t) P_m r^{\alpha_p}}{P_p r^{\alpha_m}}, \alpha_m\right)\right) f_\tau(t) dt \quad (5.50)$$

The fourth term $\phi_{I_d}(r)$ contains interference from dominant mBSs that does not leak into the control channel of our pUE. It is given by

$$\phi_{I_d}(r) \approx \phi_{I_d}^{(1)} \left(\frac{\gamma_0 \rho_r r^{\alpha_p}}{P_p}\right)^{(1-p_m)\mu_m \overline{N_d}}, \quad (5.51)$$

where $\phi_{I_d}^{(1)}$ and $\overline{N_d}$ are given by (5.34) and (5.39), respectively. The last term $\phi_{I_d}^{(m)}(r)$ then incorporates interference from critical DI mBSs. Correspondingly, we apply thinning and integration across τ and get

$$\phi_{I_d}^{(m)}(r) \approx \int_{\tau_w + t_{\text{cp}}}^\infty \phi_{I_d}^{(1)} \left(\frac{\gamma_0 \rho_r \Upsilon(t) r^{\alpha_p}}{P_p}\right)^{p_m \mu_m \overline{N_d}} f_\tau(t) dt. \quad (5.52)$$

Parameter	Value
Cyclic prefix length t_{cp}	$5.21\mu s$
OFDM symbol length t_{fft}	$66.67\mu s$
Fraction of successful BSs p_w	0.95

Table 5.2. Additional parameters for demonstrating the effect of BS time synchronization mismatch on performance in ABSF.

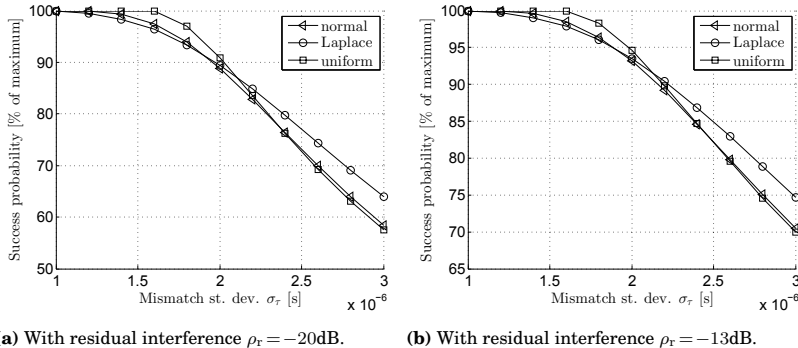


Figure 5.6. Relative success probability of ABSF control channel at a pUE receiver versus standard deviation of BS timing mismatch for normal, Laplace and uniform distributions of timing mismatch.

We have now all terms ready, except distribution of timing mismatch $f_\tau(t)$, to apply numerical integration and calculate success probability of pUE's control channel during ABSF.

5.4.2 Results

Unfortunately we do not know how a timing mismatch distribution in a real network could look. To demonstrate our results we therefore consider a few generic shapes and attempt to draw conclusions from that. Default system and scenario parameters are reused from Table 5.1. Additional parameters are summarized in Table 5.2.

The final results are presented in Figure 5.6, with two different values of residual interference ρ_r and with three different shapes of timing mismatch distribution: uniform, normal and Laplace. Our metric is the relative success probability of the ABSF control channel at the pUE versus standard deviation of the timing mismatch. The absolute values are not large even without mismatch (0.62 with $\rho_r = -20\text{dB}$, 0.29 with $\rho_r = -13\text{dB}$), but they are not necessarily precise because of lot of design intricacies. When it comes to the effect of timing mismatch, relative values should provide sufficient insight.

The results show that while shape of the timing mismatch distribution

does influence success probability, the influence is not major. If we look at $\rho_r = -20\text{dB}$, the success probability for all three shapes stays above 90% until mismatch deviation of $2\mu\text{s}$ and decreases to approximately 60% with $3\mu\text{s}$ deviation. Because with larger residual interference the success probability is low in the first place, the effect of timing mismatch is lower. To conclude the analysis we can say that the effect of BS timing mismatch on ABSF is not detrimental in a major way. Existing synchronization requirements for a TDD LTE network allow mismatch of $\pm 1.5\mu\text{s}$, which with uniform distribution corresponds to deviation of $0.87\mu\text{s}$. Applying existing TDD timing requirements on FDD networks is hence sufficient to avoid excessive interference in ABSF control channel.

6. Controlling interference rank

Our most recent research contribution, Publication VII, deals with the effect of interference rank on a serving link that uses one of two common single-user multi-antenna techniques: beamforming or orthogonal space-time block coding (OSTBC). When we say transmission rank we refer to the number of data streams (or layers) transmitted using spatial multiplexing. Spatial multiplexing is known to linearly increase channel capacity [129]. It is also known that spatial multiplexing is sensitive to interference [10]. What has however not been studied sufficiently is how spatial multiplexing affects other, single stream links. By the end of this chapter the reader will learn that higher interference rank can have a positive effect especially on beamforming transmission. We can thus imagine an interference management technique where *method* consists of controlling interference rank. In 3GPP LTE this functionality resides in the scheduler, on the MAC layer. The *control* could be centralized or distributed (BS level) and *time scale* could be semi-static or dynamic. *Signaling* would depend on *control* as the distributed option would need certain information exchange between base stations. There would be no issues with *compatibility*. Our work provides an initial analytic insight into link layer performance of the concept.

6.1 Problem description and system model

Our main motivation lies in a situation where the serving link is weak and an interfering transmitter (or multiple of them) has a relatively strong link to its own receiver. This can happen for example in cellular downlink when the served UE is located on the cell edge, or in a co-channel heterogeneous deployment with femtocells or range expanded picocells. Our system model shall consist of a serving base station (sBS), a served UE

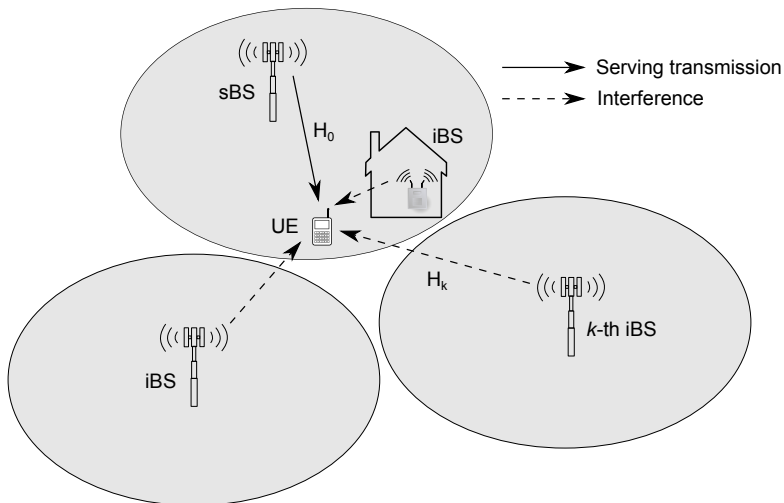


Figure 6.1. An example scenario with an UE receiving signal from sBS under interference from one femto and two macro iBSs.

and K interfering base stations (iBSs). We show an illustrative scenario in Figure 6.1.

The weak link of interest will perform a single-stream transmission, specifically beamforming or OSTBC. At the receiver, beamformed signal shall be processed by means of maximum ratio combining (MRC) [89], while signal using OSTBC shall be correspondingly decoded [7,127]. Links from the interferers to their associated receivers are considered strong, hence the interferers have a choice of doing a single-stream or a multi-stream transmission. Note that multi-stream transmission techniques do not fare well in low SINR regime. Our analysis is heavily inspired by [5] and closely related to [85–87, 149], with details on the novelty of our contribution discussed directly in Publication VII.

Transmitters in our model are equipped with N_T antennas, receivers then with N_R antennas. Although full rate OSTBC exists only for $N_T = 2$, the results can be extrapolated for illustration purposes. The average (long term) received power from sBS is denoted as R_0 , corresponding received interference power from i -th iBS is denoted as R_i . The long term components typically include path loss and shadowing effects. The short term fading effects are incorporated into $N_R \times N_T$ matrices with i.i.d. Rayleigh fading components, \mathbf{H}_0 and \mathbf{H}_i . We assume unit transmission symbol energy and additive white Gaussian noise (AWGN) power σ_n^2 . Rank of i -th iBS's transmission is denoted $N_L^{(i)}$. In case i -th iBS performs OSTBC $N_L^{(i)} = 1$. Beamforming at sBS is the ideal version based on

eigendecomposition of \mathbf{H}_0 . All receiver processing assumes perfect channel estimation.

6.2 Analysis of beamforming

The received beamformed signal vector \mathbf{r} at our UE is given by

$$\mathbf{r} = \sqrt{R_0} \mathbf{H}_0 \mathbf{w}_0 d_0 + \sum_{i=1}^K \sqrt{R_i} \mathbf{h}_{\text{eq}}^{(i)} + \mathbf{n}, \quad (6.1)$$

where \mathbf{w}_0 is a $N_T \times 1$ sBS precoding vector with unit Frobenius norm, d_0 is sBS data symbol, $\mathbf{h}_{\text{eq}}^{(i)}$ is $N_R \times 1$ equivalent channel vector of the i -th interferer and \mathbf{n} is $N_R \times 1$ noise sample vector. The insides of $\mathbf{h}_{\text{eq}}^{(i)}$ depend on the specific transmission technique of the i -th iBS. The postprocessing SINR is then defined as

$$\gamma \triangleq \frac{R_0 \|\mathbf{w}_0^\dagger \mathbf{H}_0^\dagger \mathbf{H}_0 \mathbf{w}_0\|^2}{\sum_{i=1}^K \sum_{j=1}^{N_L^{(i)}} R_i \|\mathbf{w}_0^\dagger \mathbf{H}_0^\dagger \mathbf{h}_{\text{eq}}^{(ij)}\|^2 + \|\mathbf{w}_0^\dagger \mathbf{H}_0^\dagger\|^2 \sigma_n^2}. \quad (6.2)$$

Following our assumption of ideal beamforming we get $\|\mathbf{w}_0^\dagger \mathbf{H}_0^\dagger\|^2 = \lambda_{\max}$, where λ_{\max} is the dominant eigenvalue of $\mathbf{H}_0^\dagger \mathbf{H}_0$. We now divide the numerator and denominator of (6.2) by $\lambda_{\max} \sigma_n^2$ and transform the SINR expression into the shape of

$$\gamma = \frac{x}{y+1}, \quad (6.3)$$

which is important for further derivations. The numerator RV x is given by

$$x = \psi_0 \lambda_{\max}, \quad (6.4)$$

where ψ_0 denotes the long term signal to noise ratio (SNR) R_0/σ_n^2 . Distribution of x is known from [40] to be

$$f_x(x) = \sum_{k=1}^M \sum_{l=N-M}^{(N+M-2k)k} \varphi_{kl} \frac{x^l}{\Gamma(l+1)} \left(\frac{k}{\psi_0}\right)^{l+1} e^{-\frac{xk}{\psi_0}}, \quad (6.5)$$

where $M = \min\{N_R, N_T\}$, $N = \max\{N_R, N_T\}$, $\Gamma(x)$ denotes the gamma function and φ_{kl} are weight coefficients given by

$$\varphi_{kl} = \frac{l! c_{kl}}{k^{l+1} \prod_{s=1}^M (M-s)!(N-s)!}, \quad (6.6)$$

where c_{kl} ensures that $\sum_{k=1}^M \sum_{l=N-M}^{(N+M-2k)k} \varphi_{kl} = 1$. Values of φ_{kl} can be found by symbolic or numeric software, but for the most common antenna configurations they have been tabulated in [40].

The denominator RV y turns out to be a sum of exponential RVs weighted by coefficients ψ_i . For k -th iBS performing precoding (beamforming or spatial multiplexing) and l -th iBS performing OSTBC the weights are

$$\psi_k = \frac{R_k}{N_L^{(k)} \sigma_n^2}, \quad (6.7)$$

$$\psi_l = \frac{R_l}{N_T \sigma_n^2}. \quad (6.8)$$

The number of summed exponential RVs in y is $\sum_{m=1}^K N_L^{(m)}$. The contributions can be divided into p' groups with i -th group having t'_i entries so that entries with the same weight ψ_i are in the same group. In case there is only one group, y will be gamma distributed with shape t'_1 and scale ψ_1 . For a general case with $p' > 1$ the PDF of y is known from [33] to be

$$f_y(y) = \sum_{i=1}^{p'} \sum_{j=1}^{t'_i} b_{ij} \frac{1}{\Gamma(j) \psi_i^j} y^{j-1} e^{-\frac{y}{\psi_i}}, \quad (6.9)$$

where b_{ij} is given by

$$b_{ij} = (-1)^{t'_i+j} \sum_{\theta(i,j)} \prod_{\substack{k=1 \\ k \neq i}}^{p'} \binom{t'_k + q_k - 1}{q_k} \frac{\left(\frac{\psi_k}{\psi_i}\right)^{q_k}}{\left(1 - \frac{\psi_k}{\psi_i}\right)^{t'_k + q_k}}, \quad (6.10)$$

where $\theta(i, j)$ is a set of p' -tuples with nonnegative integers according to

$$\theta(i, j) = \left\{ (q_1 \ q_2 \ \dots \ q_{p'}) : q_i = 0, \sum_{k=1}^{p'} q_k = t'_i - j \right\}. \quad (6.11)$$

Knowing the distributions of x and y we can express distribution of SINR

$$\begin{aligned} f_\gamma(\gamma) &= \int_0^\infty (y+1) f_x((y+1)\gamma) f_y(y) dy \quad (6.12) \\ &\stackrel{(a)}{=} \sum_{i=1}^{p'} \sum_{j=1}^{t'_i} \sum_{k=1}^M \sum_{l=N-M}^{(N+M-2k)k} b_{ij} \varphi_{kl} \gamma^l e^{-\frac{k\gamma}{\psi_0}} \sum_{r=0}^{l+1} \binom{l+1}{r} \frac{\Gamma(r+t'_i)}{l! \Gamma(t'_i)} \\ &\quad \times \left(\frac{k}{\psi_0}\right)^{l+1} \left(\frac{1}{\psi_i}\right)^j \left(\frac{\psi_0}{k\gamma + \Lambda_i}\right)^{r+j}, \quad (6.13) \end{aligned}$$

where $\Lambda_i = \psi_0/\psi_i$. Several derivation steps using [57, (1.111)] and [57, (3.351.3)] are hidden behind step (a) from (6.12) to (6.13). The probability of outage is derived in a similar manner

$$p_{\text{out}} = \mathbb{P}[\gamma < \gamma_0] \quad (6.14)$$

$$= \int_0^{\gamma_0} \int_0^\infty (y+1) f_x((y+1)\gamma) f_y(y) dy d\gamma \quad (6.15)$$

$$\begin{aligned} &\stackrel{(a)}{=} \sum_{i=1}^{p'} \sum_{j=1}^{t'_i} \sum_{k=1}^M \sum_{l=N-M}^{(N+M-2k)k} b_{ij} \varphi_{kl} \left(1 - e^{-\frac{k\gamma_0}{\psi_0}} \left(\frac{\Lambda_i}{k\gamma_0 + \Lambda_i}\right)^j\right) \\ &\quad \times \sum_{r=0}^l \sum_{s=0}^r \binom{r}{s} \frac{\Gamma(s+j)}{r! \Gamma(j)} \left(\frac{k\gamma_0}{\psi_0}\right)^r \left(\frac{\psi_0}{k\gamma_0 + \Lambda_i}\right)^s, \quad (6.16) \end{aligned}$$

where γ_0 denotes the outage threshold and (a) uses [57, (3.351.1)] in addition to the aforementioned formulas.

6.3 Analysis of OSTBC

Assuming 2×2 multiple input multiple output (MIMO) channel and OSTBC processing at the sBS, the received sample vector is given by

$$\mathbf{r} = \bar{\mathbf{r}} + \sum_{i=1}^K \tilde{\mathbf{r}}_i + \mathbf{n}, \quad (6.17)$$

where $\bar{\mathbf{r}}$ represents the useful signal part and $\tilde{\mathbf{r}}_i$ represents the interference part from i -th iBS. The useful part of the received signal can be expressed as

$$\begin{bmatrix} \bar{r}_1^{(1)} \\ \bar{r}_1^{(2)*} \\ \bar{r}_2^{(1)} \\ \bar{r}_2^{(2)*} \end{bmatrix} = \sqrt{R_0} \begin{bmatrix} h_{11} & h_{12} \\ h_{12}^* & -h_{11}^* \\ h_{21} & h_{22} \\ h_{22}^* & -h_{21}^* \end{bmatrix} \begin{bmatrix} d_0^{(1)} \\ d_0^{(2)} \end{bmatrix}, \quad (6.18)$$

where m in $\bar{r}_m^{(n)}$ represents receive antenna index, n in $\bar{r}_m^{(n)}$ represents time instance/symbol index, h_{mn} is an element of \mathbf{H}_0 , m in $d_0^{(m)}$ represents time instance index and $*$ denotes complex conjugate. In case of j -th iBS performing OSTBC, $\tilde{\mathbf{r}}_j$ has the same structure as $\bar{\mathbf{r}}$. In case of k -th iBS performing beamforming the interference part (omitting k index when not needed) is

$$\begin{bmatrix} \tilde{r}_1^{(1)} \\ \tilde{r}_1^{(2)} \\ \tilde{r}_2^{(1)} \\ \tilde{r}_2^{(2)} \end{bmatrix}_k = \sqrt{R_k} \begin{bmatrix} d^{(1)} (g_{11}w_1 + g_{12}w_2) \\ d^{(2)} (g_{11}w_1 + g_{12}w_2) \\ d^{(1)} (g_{21}w_1 + g_{22}w_2) \\ d^{(2)} (g_{21}w_1 + g_{22}w_2) \end{bmatrix}, \quad (6.19)$$

where g_{mn} denotes element of \mathbf{H}_k and w_m denotes element of \mathbf{w}_k , a $N_T \times 1$ beamforming vector. If l -th iBS was performing spatial multiplexing, each row on the RHS of (6.19) would be a sum of contributions from the transmission layers. At the receiver we estimate the transmitted symbols using $\hat{\mathbf{r}} = \mathbf{F}\mathbf{r}$, where \mathbf{F} is the receive filter given by

$$\mathbf{F} = \begin{bmatrix} h_{11}^* & h_{12} & h_{21}^* & h_{22} \\ h_{12}^* & -h_{11} & h_{22}^* & -h_{21} \end{bmatrix}. \quad (6.20)$$

Now we move on to the calculation of SINR. Using the same framework as in the case of beamforming (6.3), the numerator RV x is known from [100] to be

$$x = \frac{R_0}{4\sigma_n^2} \|\mathbf{H}_0\|_{\mathbf{F}}^2, \quad (6.21)$$

where $\|\mathbf{H}_0\|_{\text{F}}$ is a Frobenius norm of \mathbf{H}_0 . In a general case x is gamma distributed with shape $N_{\text{R}}N_{\text{T}}$ and scale $\psi_0 = R_0/N_{\text{T}}^2\sigma_{\text{n}}^2$. The denominator RV y is given by a sum of contributions from iBSs. If j -th interferer performs OSTBC [31], its contribution y_j is given by a sum of N_{T} exponentially distributed RVs with rate $1/\psi_j = N_{\text{T}}^2\sigma_{\text{n}}^2/R_j$. For k -th interferer performing beamforming the contribution can be expressed as

$$y_k = \frac{R_k}{2\sigma_{\text{n}}^2} (\Omega_1 + \Omega_2), \quad (6.22)$$

where Ω_m represent independent power contribution from m -th time instance/transmission symbol. These (sub)contributions (without index k) are

$$\Omega_1 = \frac{|h_{11}^* d^{(1)} (g_{11}w_1 + g_{12}w_2) + h_{21}^* d^{(1)} (g_{21}w_1 + g_{22}w_2)|^2}{\|\mathbf{H}_0\|_{\text{F}}^2}, \quad (6.23)$$

$$\Omega_2 = \frac{|h_{12} d^{(2)} (g_{11}w_1 + g_{12}w_2) + h_{22} d^{(2)} (g_{21}w_1 + g_{22}w_2)|^2}{\|\mathbf{H}_0\|_{\text{F}}^2}. \quad (6.24)$$

The distribution of Ω_m is not straightforward to establish. In Publication VII we were able to approximate it as

$$f_{\Omega_m}(x) \approx \frac{N_{\text{L}}^{(k)}\Gamma(N_{\text{R}}N_{\text{T}})}{\Gamma(N_{\text{R}})} G_{1,2}^{2,0} \left(\begin{matrix} N_{\text{T}}N_{\text{R}} - 1 \\ N_{\text{R}} - 1, 0 \end{matrix} \middle| N_{\text{L}}^{(k)}x \right), \quad (6.25)$$

where $G_{p,q}^{m,n}$ is the Meijer G-function. Using [57, (7.811)] we also derived the mean value to be $1/N_{\text{T}}N_{\text{L}}^{(k)}$. Although our approximation (6.25) is more precise and insightful, we were unable to use it further in derivation of y and had to content with using exponential distribution instead, as in [85, 86, 149]. The final approximation with exponential distribution holds well and starts to deviate only at high SNR values ψ_0 or low outage threshold values γ_0 . Going further with the derivation: k -th iBS, whether it performs precoding or OSTBC, contributes to y by a sum of $N_{\text{T}}N_{\text{L}}^{(k)}$ terms Ω_m . Each of the Ω_m terms is exponentially distributed with rate $1/\psi_k = N_{\text{T}}^2N_{\text{L}}^{(k)}\sigma_{\text{n}}^2/R_k$, in case of OSTBC exactly and in case of precoding approximately. Now, we can use the same arsenal as with beamforming and derive the PDF of SINR to be

$$f_{\gamma}(\gamma) \approx \sum_{i=1}^{p'} \sum_{j=1}^{t'_i} b_{ij} \gamma^{N_{\text{R}}N_{\text{T}}-1} e^{-\frac{\gamma}{\psi_0}} \left(\frac{1}{\psi_0}\right)^{N_{\text{R}}N_{\text{T}}} \left(\frac{1}{\psi_1}\right)^j \sum_{r=0}^{N_{\text{R}}N_{\text{T}}} \binom{N_{\text{R}}N_{\text{T}}}{r} \\ \times \frac{\Gamma(r+j)}{\Gamma(N_{\text{R}}N_{\text{T}})\Gamma(j)} \left(\frac{\gamma}{\psi_0} + \frac{1}{\psi_1}\right)^{-(r+j)} \quad (6.26)$$

and the probability of outage to be

$$p_{\text{out}} \approx \sum_{i=1}^{p'} \sum_{j=1}^{t'_i} b_{ij} \left(1 - e^{-\frac{\gamma_0}{\psi_0}} \left(\frac{1}{\psi_i} \right)^j \sum_{r=0}^{N_R N_T - 1} \sum_{s=0}^r \binom{r}{s} \frac{\Gamma(j+s)}{r! \Gamma(j)} \times \left(\frac{\gamma_0}{\psi_0} \right)^r \left(\frac{\gamma_0}{\psi_0} + \frac{1}{\psi_i} \right)^{-(j+s)} \right). \quad (6.27)$$

6.4 Results and discussion

In Figure 6.2 we show some of our results on the effect of interference rank. Figures 6.2(a) and 6.2(b) plot probability of outage of beamforming and OSTBC, respectively, as a function of outage threshold γ_0 . Both assume SNR = 15dB, a single interferer with interference to noise ratio (INR) of 10dB and $\sigma_n^2 = 1$. The probabilities of outage are presented for different MIMO configurations and for each configuration with low rank and high rank interference. And for all cases, looking at the useful range of $p_{\text{out}} < 0.2$, we can claim that higher interference rank leads to lower probability of outage. The improvement is less pronounced with OSTBC; we also illustrate with the white interference case that there is not much room for improvement there.

This is the most interesting result of our study. When iBS applies multi-stream processing, the interference power is distributed into different spatial directions and the probability of severely harming our UE of interest decreases. Exactly how much may can the UE benefit we try to illustrate in Figure 6.2(c) and 6.2(d). As a metric we define γ_0 gain. For a fixed $p_{\text{out}} = 0.01$, γ_0 gain represents horizontal distance between high rank interference and low rank interference case in Figure 6.2(a) and 6.2(b), or in other words the gain in supported SINR threshold, i.e., MCS class. The gain is indifferent to SNR, as SNR shifts all curves in Figure 6.2(a) and 6.2(b) horizontally. In Figure 6.2(c) we show the γ_0 gain as a function of INR, with SNR = 15dB and $\sigma_n^2 = 1$. The gain increases with INR, at first fast and then slower. Especially with beamforming the achievable gain is worth considering, surpassing 2dB when comparing rank 4 to rank 1 interference. Finally in Figure 6.2(d) we plot γ_0 gain as a function of K , with SNR = 15dB, $\sigma_n^2 = 1$ and constant interference sum corresponding to INR = 15dB. As one could expect, with increasing number of iBSs the potential gain decreases.

Our study has indeed shown that controlling interference rank has a potential and should be considered when the opportunity arises. We have

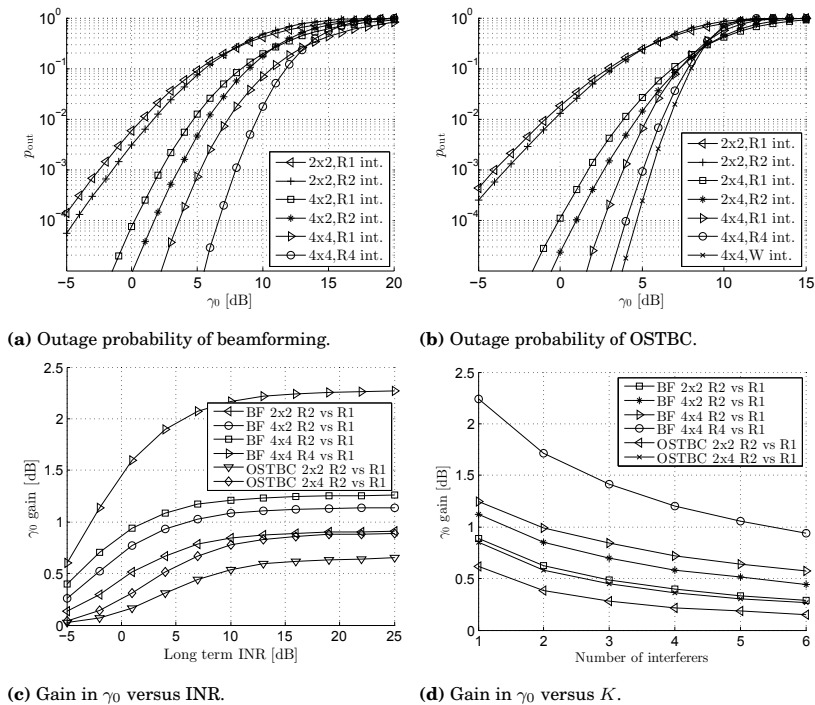


Figure 6.2. Illustrating the effect of interference rank on beamforming and OSTBC. In (a) we show outage probability of beamforming with single interferer that uses precoding. In the useful range of p_{out} higher interference rank leads to higher supported γ_0 . In (b) corresponding results are shown also for OSTBC own transmission, including also a curve for white interference case to show there is not much room for improvement. In (c) we show γ_0 gain as a function of INR; higher INR results in higher potential gain when increasing interference rank. In (d) we show γ_0 gain as a function of number of interferers, keeping the sum interference constant.

however shown only one part of the story. Firstly, the choice of interference rank has a strong effect on the performance of the iBS's own link. Therefore, the scheduler at the iBS has to carefully consider whether using multi-stream transmission can provide a sustainable service. Secondly, we have focused solely on tractable evaluation of the link level performance. We have thus shown potential gains in an isolated scenario, but we have deliberately not studied how our approach would affect performance of the system as a whole. Our interference management approach needs a robust triggering mechanism, and then it needs to be evaluated at the system level. This can most likely be done only by means of simulations; it is waiting as a challenge for next students or researchers willing to pick up the ball.

7. Conclusions

This thesis listed a few contributions on interference management in cellular wireless networks. All four of the contributions are targeted at cochannel interference, but that is maybe the only thing they have in common. This is simply because the author was moving between different research projects and relying on different funding sources. The specific problems were partly selected and solved by the author himself, therefore this thesis documents his journey. It is clearly visible how his approach to solving problems has evolved in relation to what is expected of a researcher in order to be accepted in the community. As a certain professor at Aalto University has said, this book is a *driving license* of the author to the world of research.

Our first contribution studies how interference can be managed by separating transmissions in spatial domain using dynamic forward and reverse signaling. The reverse signaling approach, where active receivers “announce” themselves by transmitting a signal, is well known and conceptually considered as capable. Our concept of forward signaling offers an alternative. Inspired by RTS/CTS signaling, an optional feature of WLAN MAC, we propose an approach where transmitters provide a sounding signal, thus enabling the receivers to predict SINR and permit or deny the transmission. This idea, combined with random persistence avoiding cross-blocking of sounding signals, shifts the interference management decisions to the receiver. And because the receiver has more complete knowledge of the interference situation, it is a better place to make the decisions.

Our second contribution focuses on cross-link interference in heterogeneous network. When a small cell is deployed on the same carrier frequency as the overlay macro network, its uplink transmissions are vulnerable to interference coming from macro downlink. Luckily, small cell

users have power budget to increase their transmission power to counter the problem, as the distances between small cell user and base station tend to be short (i.e., baseline transmission power is low).

Our third contribution analyzes an interference management approach adopted by LTE, called time domain enhanced inter-cell interference coordination. The concept introduces almost blank subframes, which (in the more prevalent scenario) create time holes in macro base station transmission that enable cochannel small cells to expand their range and hence offload more users from the macrocell. With the help of stochastic geometry we analyzed the concept on a system level. An interesting part of the analysis was taking existing performance formulas valid for a general user and modifying them so that they apply specifically to victim users potentially suffering from strong interference. We then use the formulas to evaluate effect of system parameters on the number of required blank subframes, and to show that the design is not especially sensitive to time synchronization errors.

Our fourth contribution analyzes the effect of interference rank, i.e., the number of spatial streams transmitted by an interferer, on a receiver that receives beamformed or space-time block coded signal. We put together existing pieces of the puzzle, add some own enhancements and built the most comprehensive study on the topic so far. In the end, we find that controlling interference rank can be used to lower probability of outage. Higher rank causes the interference power to spread over spatial dimension, thus lowering probability that major part of the power harms reception at a particular receiver.

How can four such different contributions be combined into a single, consistent research outcome? This is an almost impossible task. A good imaginary thesis would compare the interference management approaches to each other in terms of performance, under common assumptions. Except that in our case, this does not always make sense, as some of the approaches are targeted at quite different interference scenarios.

The first and the third contribution, for example, both try to separate interferers in time and space by occasionally turning some transmitters off. However, the first contribution closed subscriber groups, where the interferer may be located extremely close to the victim receiver. From that perspective, the target scenario may resemble unlicensed band a little. The third contribution is clearly targeting a specific licensed deployment of single operator's macrocells and picocells, where the interference can-

not be so harsh. Because of that, in the context of our third contribution it is not necessary to think about complex dynamic signaling with non-negligible overhead.

In the second and the fourth contribution we do not switch part of the transmissions off; instead, we alter existing transmissions in some way. But also here the target scenario is different. TDD interference that we tackle in the second contribution can be very harsh, and trying to solve it only by modifying spatial characteristics of the transmissions (without changing the powers) would not be feasible.

Maybe one thing we could try to do is to think about which of the interference management approaches that we evaluated could work together. The dynamic on/off approach from the first contribution could work with any of the other methods. Whether this is practical is another question, due to the target scenario and signaling issues that we touched above. Interference management approaches from the second, third and fourth contribution could easily be used in the same system. One particularly nice example could be macro/femto heterogeneous deployment with coverage holes the femtocells. If a victim mUE suffered only moderately, the fBS could try to increase rank of its transmission. If this does not solve the problem, the fBS would set up some number of ABSFs and the mBS would schedule the victim mUE in these subframes.

One clear advantage of working on multiple distantly related research topics is that the researcher gets to see the field from a broader perspective. This can be of great use, for example in environments where manageable complexity and time to market are more important than the ultimate scientific truth. At the same time, working on this many topics means that not everything is explored to the deepest detail. And that leaves quite a few interesting possibilities for further research.

Throughout the thesis we have mostly considered capacity and/or outage as the metrics of interest. Therefore, one general direction for future work could be to study the interference management approaches from latency perspective. Here we mean latency experienced by user, not the *time scale* of the approaches. For example, in the first and the third contribution, the fact that we turn some of the transmitters off will effect users depending on these. In the fourth contribution, choosing higher rank at the aggressor node may lead to higher error rate, more retransmissions and thus increased latency.

Other possibilities for future work are related to specific topics. In the

first and second contributions we evaluated the interference management approaches under the assumption of full buffer loading; valuable insights could be gained if this assumption was changed to a more realistic traffic model. Furthermore, we feel that the topic of forward and reverse signaling would deserve a larger simulation campaign to identify what kinds of scenarios require such dynamic approach, and a deeper mathematical analysis that would prove or disprove the performance edge of forward signaling and SINR prediction in comparison to reverse signaling. Especially when we learned how to use the stochastic geometry framework we started to wonder whether it could be used in the context of our first contribution too. Yet another path for future work lays in the physical layer design of the corresponding dynamic signaling, taking into account challenges listed in Section 3.2.

Concerning our third contribution, we already mentioned earlier that we did not focus on the users in the aggressor tier, i.e., the mUEs in the macro/pico scenario and the fUEs in the macro/femto scenario.

However, maybe the biggest opportunity comes from our fourth contribution, the topic of interference rank. We did not take into account performance of the interferer's own link, neither we considered how would the approach fare from a system perspective. When we limit rank of the interference to subset of possible values we reduce flexibility of the scheduler, which may have an adverse effect on network performance. Solid work could be done here in the future.

Interference in wireless networks is a complex issue and we believe it will haunt researchers and engineers in the field still for some years to come. The demand for faster, more reliable, omnipresent connectivity does not seem to be slowing down. On the contrary, each technological step has opened a new door. Augmented or virtual reality, machine-to-machine or vehicle-to-vehicle communications, remote control with instantaneous tactile feedback: today, these concepts seem to place tough requirements for future networks. In a few years however, they may be considered a no-brainer.

At the time of writing this thesis, 3GPP has finished Rel. 12 of its standard and started working on Rel. 13. There are two features of Rel. 12 that can be classified as interference management. One of them is the expansion of Rel. 11 CoMP into deployments with non-ideal backhaul. This means that the multipoint coordination and multipoint transmission concepts designed to take into account own signal and interference powers

from multiple transmission points can now be used when the transmission points are interconnected only via the X2 interface.

The second interesting Rel. 12 feature is called network assisted interference cancellation. Network assistance comes in form of limiting the interference transmission format, which in connection with receiver technological advances enables blind detection of interference and its subsequent subtraction from the useful signal.

In Rel. 13 there will most probably be no new interference management features. However, one related part of Rel. 13 is expansion of LTE into unlicensed bands. Regulation in many parts of the world require systems in unlicensed bands to perform listen-before-talk (a.k.a. channel sensing), not unlike in WLAN. This is in a way interference management, as it leads to nodes within a certain range to multiplex their transmissions in time domain.

Beyond that, it is hard to predict what will become relevant. It seems that LTE will be deployed maybe up to 6GHz carrier frequency, but it is still not clear what is viable for 5G above that. If 5G makes it to millimeter waves it will need narrow beams just to overcome free space attenuation, thus making interference more bursty and complicated to predict or counter. It remains to be seen.

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Errata

Publication IV

In the right column on page 3, we have written that variable $\rho_{\min,\text{dB}}$ follows Bernoulli distribution. This is not correct; $\rho_{\min,\text{dB}}$ follows binomial distribution instead.

Publication V

There is a mistake on the right hand side of (50). The correct equation reads:

$$\mathbb{E}_{\text{IDI}}^{(1)} = \frac{k_1^2 k_2^2}{k_1^2 - k_2^2} \left(\frac{1}{k_2^2} {}_2F_1 \left(1, -\frac{2}{\alpha_m}, \frac{\alpha_m - 2}{\alpha_m}, -\frac{\gamma_0 k_2^{\alpha_m} \rho_A P_m r^{\alpha_P}}{P_P r^{\alpha_m}} \right) \right. \\ \left. \times \frac{1}{k_1^2} {}_2F_1 \left(1, -\frac{2}{\alpha_m}, \frac{\alpha_m - 2}{\alpha_m}, -\frac{\gamma_0 k_1^{\alpha_m} \rho_A P_m r^{\alpha_P}}{P_P r^{\alpha_m}} \right) \right)$$

Publication VI

When introducing (6), we have written that it stems from combining time matched and mismatched interfering base stations. This is not correct; term (6) corresponds to a single interfering base station, combining interference from normal subframe that leaks beyond cyclic prefix and the (normally present) residual interference from almost blank subframe.

Further, there is a mistake on the right hand side of (17). The correct

equation reads:

$$\xi(K, r) = \frac{k_1^2 k_2^2}{k_1^2 - k_2^2} \left(\frac{1}{k_2^2} {}_2F_1 \left(1, -\frac{2}{\alpha_m}, \frac{\alpha_m - 2}{\alpha_m}, -\frac{\gamma_0 k_2^{\alpha_m} K P_m r^{\alpha_p}}{P_p r^{\alpha_m}} \right) \right. \\ \left. \times \frac{1}{k_1^2} {}_2F_1 \left(1, -\frac{2}{\alpha_m}, \frac{\alpha_m - 2}{\alpha_m}, -\frac{\gamma_0 k_1^{\alpha_m} K P_m r^{\alpha_p}}{P_p r^{\alpha_m}} \right) \right)$$

Finally, in Section IV we have written that 3GPP requirement for timing mismatch in TDD allows maximum error of $3\mu\text{s}$. This is not correct; the error interval is $3\mu\text{s}$ wide, which allows for a maximum error of $\pm 1.5\mu\text{s}$.

Publication VII

For consistency, probability density functions $p_\gamma(\gamma)$ in (3), $p_x(x)$ in (11), $p_y(y)$ in (15) and $p_y(y)$ in (16) should be denoted $f_\gamma(\gamma)$, $f_x(x)$, $f_y(y)$ and $f_y(y)$, respectively.

Cellular wireless networks have become a commodity. We use our cellular devices every day to connect to others, to conduct business, for entertainment. Strong demand for wireless access has made corresponding parts of radio spectrum very valuable. Consequently, network operators and their suppliers are constantly being pressured for its efficient use. Unlike the first and second generation cellular networks, current generations do not therefore separate geographical sites in frequency. This universal frequency reuse, combined with continuously increasing spatial density of the transmitters, leads to challenging interference levels in the network.

It is important to study wireless communications because it has become an irreplaceable part of our everyday life and because the technology did not yet reach its imaginable potential. In our personal opinion, this limit is transfer of human thoughts with comparable latency as within our own brains.



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