Continuous Ultra-Dense Networks

A System Level Design for Urban Outdoor Deployments

Petteri Kela
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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS1 of the school on 30 June 2017 at 12 o'clock noon.

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Abstract

Ultra-dense networks (UDNs) will play a critical role in the future of mobile communications. Especially within urban street canyons with an extensive amount of mobile users, the propagation environment prevents the efficient spatial densification by means of macro cell massive MIMO systems. Hence, increasing the amount of transmission and reception points (TRPs) is the key to success.

In this thesis, a system level continuous UDN (C-UDN) concept is developed. In particular, a novel radio frame structure is designed to meet the low-latency, high-capacity and mobility support requirements of the future generation wireless networks. Also the time and frequency domain scheduling framework is further developed in order to support spatial domain scheduling of highly mobile users. Moreover, transmit and receive beamforming that is based on user location estimates is studied in order to increase signal-to-interference-plus-noise ratio and decrease pilot overhead caused by full-band uplink reference signals, commonly used for channel state information (CSI) in time-division-duplex TDD systems.

Since one of the main challenges for wide-scale deployment of UDNs is the backhaul, also a massive MIMO based sub-6 GHz solution that exploits spatial multiple-access and TDD for UDN self-backhauling is given. This is shown to outperform self-backhauling that is based on time domain multiplexing only. What makes this study attractive is that with wireless alternatives to wired solutions, deployment costs can be lowered significantly. Furthermore, millimeter wave technologies typically require line-of-sight conditions, which significantly reduces deployment flexibility.

Lastly, an approach for dealing with uplink small packet transmissions from a massive amount of machine type communication (MTC) devices in UDNs is proposed. The proposed approach exploits beamforming based distribution of uplink grants for connectionless small data transmissions. Receive beamforming is also employed for receiving subsequent small packet transmissions. It is shown that with the proposed approach, low collision and decode failure probabilities can be achieved. Additionally, the results provided show that simultaneous reception of such small packet transmissions can be dealt with low latency and low physical resource usage by utilizing spatial receive filters that maximize received power towards the directions where grants were broadcasted.

Keywords 5G, NR, ultra-dense networks, radio resource management, multi-user MIMO, massive MIMO, massive MTC

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Tiivistelmä
Äärimmäisen tiheällä verkoilla tulee olemaan ratkaiseva merkitys tulevaisuuden matkaviestinnässä. Erityisesti kaupunkialueilla radiokanavan etenemisoinnaisuudet katkuu liuksa, tai liikkeen haljuudet tai näkyvät tehokkaan spatiaalisen tihentämisen makro-solujen massiivisilla MIMO -järjestelmillä. Siksi radionoiden huomattava lisääminen on avain menestykseen.

Tässä väitöskirjassa on kehitetty uusi yhtäjakoisensa peiton tarjoava tiheän verkon järjestelmämittason konsepti. Uusi radion kehysrakenne on suunniteltu täyttämään uuden sukupolvun verkojen matalan latenssin, suuren kapasiteetin ja käyttäjien liikkuvuuden vaatimuksi. Myös ajan ja taajuuden hallintaa on kehitetty, jotta myös tila otetaan huomioon yhtädimensiona radiointeressien hallinnassa. Lisäksi tutkitaan läheytyksen ja vastaanoton keilanmuodostusta, joka perustuu käyttäjän sijaintiin, jotta signaalinn ja häiriöin suhdetta saadaan parannetta.

Paikanmuutokseen perustuvalla keilanmuodostuksella voidaan myös pientää referenssisignaalien käyttämien radiointeressien määrää verrattuna koko kaistan pilottisignaalineihin, joita käytetään yleisesti kanavan tilan mittaamiseen TDD-järjestelmässä.

Koska yksi tärkeimmistä haasteista tiheiden verkojen laajamittaisen käyttöön on yleistymisessä on kustannustehokkaiden tiedonsiirtoratkaisujen puute radionoiden ja runkoverkon välille, myös massiivinen MIMO-pohjainen alle 6 GHz:n ratkaisu tuodaan esille. Väitöskirjassa osoitetaan, että ehdotettu ratkaisu suoriuttaa paremmin kuin pelkästään aikaan erotteluun perustuvat perinteisemmät ratkaisut. Mikä tekee tästä tutkimuksesta houkuttelevan on se, että langattomilla vaihtoehdoilla langallisiin verrattuna voidaan alentaa tiheiden verkojen rakennuskustannuksia merkittävästi. Lisäksi, vaihtoehtoiset millimetriaaltiteknologiat vaativat tyyppillisesti näkölinjaosuusteet lähetetietä ja vastaanottamien välille, mikä vähentää huomattavasti radionoiden ja runkoverkon rakentamisen joustavuutta.


Avainsanat
5G, NR, äärimmäisen tiheät verkot, radiointeressien hallinta, monikäyttäjä-MIMO, massiivinen MIMO, massiivinen konetyypinennen kommunikaatio

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Preface

I have had the pleasure of knowing and working with many people who have contributed to this dissertation, either directly or indirectly. Most of the research work for this thesis was carried out during the years 2015-2017 at Huawei Technologies Oy (Finland) Co. Ltd. This thesis was done under the supervision of Professor Riku Jäntti from the Department of Communications and Networking, Aalto University. Hence, I would like to first and foremost thank Prof. Jäntti for giving me the opportunity to work as a part-time doctoral student and for providing support and guidance throughout these doctoral studies.

Secondly, I would like to thank Dr. Mário Costa. You have been a truly great teammate at Huawei and provided indispensable support throughout all the efforts towards finalization of this thesis. In every great team there is also a great leader. In my case I am greatly indebted to Dr. Kari Leppänen for continuous support, guidance and valuable insights that were captured into this dissertation work.

I am grateful to the thesis pre-examiners, Professor David Gesbert and Professor Preben Mogensen, for their valuable reviews. I truly feel privileged to get such high-profile pre-examinators. The time and effort they have put in reviewing this dissertation is highly acknowledged. I also thank Adjunct Professor Antti Tölli for agreeing to act as the opponent at my defense.

I do appreciate the colleagues who co-authored publications in this thesis. Dr. Jussi Turkka, Dr. Jussi Salmi, Dr. Xavier Gelabert, Dr. Henrik Lundqvist, Dr. Kari Heiska, Christer Qvarfordt, Tuomas Hiltunen and Michal Hronec, thank you for taking the trouble of helping me. Many thanks also to my all other current and former colleagues at Huawei.
They include Dr. George Koudouridis, Dr. Andrey Krendzel, Dr. Tao Cai, Dr. Yinggang Du, Dr. Philip Ginzboorg, Dr. Oleksandr Puchko, Henrik Olofsson, Gunnar Hedby and Zhixi Wang, among others.

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The research work that led to this dissertation was initiated in 2007 with Professor Tapani Ristaniemi at the Department of Mathematical Information Technology, University of Jyväskylä. Hence, I would like to express my gratitude to my colleagues at that time, especially Prof. Ristaniemi and Dr. Jani Puttonen, who basically kicked off my engineering and research career. Thanks also to Niko Kolehmainen for being such a great workmate at that time. Thanks also to all of my former colleagues at Magister Solutions Ltd. in addition to Martti Moisio, Tero Henttonen and others from Nokia Oyj.

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I would like to thank my parents Leena and Kalervo Kela for supporting me in life and studies in every way. Without that foundation I would not have made it this far. I am also truly grateful to my parents-in-law Tuula-Riitta and Heikki Tiira for all of their support in running through these hectic years. Most of all, I want to thank my wife and family. Thank you Maria for constant support and love, and Eino and Elsa for keeping the focus where it matters the most.

Kaarina, April 27, 2017,

Petteri Kela
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List of Publications

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


V P. Kela, M. Costa, J. Turkka, M. Koivisto, J. Werner, A. Hakkarainen,
List of Publications


Author’s Contribution

Publication I: “Dynamic packet scheduling performance in UTRA long term evolution downlink”

The author was the main writer in this publication. The author implemented the packet scheduling and link adaptation models required for the dynamic system level simulator utilized. He also performed the simulations and analyzed the results. Rest of the authors provided valuable insights.

Publication II: “A novel radio frame structure for 5G dense outdoor radio access networks”

The proposed frame structure for ultra-dense networks was principally designed by the author. Simulation models used for this study were implemented together with the rest of the authors. The other authors also provided support for finishing the paper.

Publication III: “Borderless mobility in 5G outdoor ultra-dense networks”

The paper was primarily written by the author and it was based on the proposed borderless scheduling concept that was developed by the author. The author also implemented the system level simulator tools required for studying the proposed methods. The other authors participated in writing the paper. The stochastic channel model utilized was implemented and
described by the other authors.

**Publication IV: “Supporting mobility in 5G: A comparison between massive MIMO and continuous ultra dense networks”**

The paper was based on the author's research and simulation results concerning the matter studied. The ray tracing channel model utilized was implemented and described by the third author. Furthermore, the rest of the authors helped in writing and crystallizing the paper.

**Publication V: “Location based beamforming in 5G ultra-dense networks”**

The author was the main author of the paper. The results were obtained with the concepts described and the simulation tools developed by the author, with the exception of the methods used for the tracking of the directional parameters. These tracking methods were proposed, studied and described by the other authors, as well as the ray tracing channel model utilized. The rest of the authors also provided valuable insights.

**Publication VI: “Flexible backhauling with massive MIMO for ultra-dense networks”**

The proposed in-band backhauling concept for ultra-dense networks was developed by the author. He also performed all the feasibility studies in the form of system level simulations. The rest of the authors helped with the writing and provided valuable guidance throughout the work.

**Publication VII: “Connectionless access for massive machine type communications in ultra-dense networks”**

The core design of the proposed solution was based on the author’s original ideas. The ideas were further developed with the rest of the authors. The author did all the studies and simulations. The paper was finalized together with the other authors.
Abbreviations

3GPP 3rd generation partnership project
AI access intensity
BD block diagonalization
BET blind equal throughput
BF beamforming
BLER block error rate
C-RAN cloud radio access network
C-UDN continuous ultra-dense network
CoMP coordinated multi-point
CP cyclic prefix
CQI channel quality indicator
CS-MUD compressed sensing multi-user detection
CSI channel state information
CSIT CSI at transmitter
CSMA/CA carrier sense multiple access with collision avoidance
DL downlink
DLRS downlink reference signal
Abbreviations

**EKF** extended Kalman filter

**FD-PS** frequency domain packet scheduler

**FDD** frequency division duplex

**FFT** fast Fourier transform

**GP** guard period

**GSCM** geometry based stochastic channel model

**HARQ** hybrid automatic repeat request

**HoL** head of line

**HTC** human-type communications

**ILLA** inner loop link adaptation

**IoT** Internet of things

**IPv6** internet protocol version 6

**ISD** inter-site distance

**L1** physical layer

**LA** link adaptation

**LoS** line-of-sight

**LTE** long term evolution

**LTE-A** long term evolution-advanced

**M-MIMO** massive multiple-input multiple-output

**M2M** machine-to-machine

**MAC** medium access control

**MCS** modulation and coding scheme

**MF** matched filter

**MIMO** multiple-input multiple-output
Abbreviations

**mMTC**  massive machine-type communications

**mmW**  millimeter wave

**MT**  maximum throughput

**MTC**  machine-type communications

**MU-MIMO**  multi-user multiple-input multiple-output

**MU-MISO**  multi-user multiple-input single-output

**NLoS**  non line of sight

**NR**  new radio

**OFDM**  orthogonal frequency division multiplexing

**OFDMA**  orthogonal frequency division multiple access

**OLLA**  outer loop link adaptation

**PAPR**  peak-to-average power ratio

**PDU**  protocol data unit

**PF**  proportional fair

**PRB**  physical resource block

**QoE**  quality of experience

**QoS**  quality of service

**QPSK**  quadrature phase shift keying

**RA**  random access

**RACH**  random access channel

**RAT**  radio access technology

**RBF**  receive beamforming

**RRC**  radio resource control

**RRH**  remote radio head
Abbreviations

RRZF  robust regularized zero-forcing
RSRP  reference signal received power
RTT   round trip time
Rx    reception

SC-FDMA  single carrier frequency division multiple access
SCMA   sparse code multiple access
SD-PS  spatial domain packet scheduler
SDM    spatial division multiplexing
SILNR  signal-to-interference-plus-leakage-plus-noise ratio
SIMO   single-input multiple-output
SINR   signal-to-interference-plus-noise ratio
SISO   single-input single-output
SNR    signal-to-noise ratio

TD-PS  time domain packet scheduler
TDD    time division duplex
TDM    time domain multiplexing
TPM    throughput measurement
TRP    transmission and reception point
TSLB   time since last beacon
TTA    throughput to average
TTI    transmission time interval
Tx     transmission

UCA    uniform circular array
UDN    ultra-dense network
Abbreviations

**UDP** user datagram protocol

**UE** user equipment

**UL** uplink

**ULA** uniform linear array

**UPA** uniform planar array

**VoIP** voice-over-IP

**ZF** zero-forcing
**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_H$</td>
<td>array response due to horizontal excitation</td>
</tr>
<tr>
<td>$a_V$</td>
<td>array response due to vertical excitation</td>
</tr>
<tr>
<td>$d_n$</td>
<td>achievable throughput for $n$th user</td>
</tr>
<tr>
<td>$h$</td>
<td>channel vector</td>
</tr>
<tr>
<td>$\hat{h}$</td>
<td>estimate of channel vector</td>
</tr>
<tr>
<td>$h_{i,n,j,l,k}$</td>
<td>$(i,n,j,l,k)$th channel vector</td>
</tr>
<tr>
<td>$H$</td>
<td>channel matrix</td>
</tr>
<tr>
<td>$\hat{H}$</td>
<td>estimate of channel matrix $H$</td>
</tr>
<tr>
<td>$H^A$</td>
<td>access channel matrix</td>
</tr>
<tr>
<td>$H^B$</td>
<td>backhaul channel matrix</td>
</tr>
<tr>
<td>$H_{n,j,l,k}$</td>
<td>$(n,j,l,k)$th element of channel matrix $H$</td>
</tr>
<tr>
<td>$I^A_n$</td>
<td>interference experienced by the $n$th user</td>
</tr>
<tr>
<td>$I^B_{j,k}$</td>
<td>interference caused by $j$th TRP and experienced by the $k$th backhaul node</td>
</tr>
<tr>
<td>$J$</td>
<td>highest index</td>
</tr>
<tr>
<td>$K$</td>
<td>highest index</td>
</tr>
<tr>
<td>$L$</td>
<td>highest index</td>
</tr>
<tr>
<td>$M_n$</td>
<td>scheduling priority metric for $n$th user</td>
</tr>
<tr>
<td>$N$</td>
<td>number of users</td>
</tr>
</tbody>
</table>
List of Symbols

\( P \) transmit power

\( P_{n,j,l,k} \) \((n,j,l,k)\)th transmit power

\( r_{n,k} \) user past average throughput for \( n \)th user and \( k \)th PRB

\( t \) time instant

\( T \) period of time

\( w \) transmit antenna weight vector

\( w^A \) transmit antenna weight vector for access

\( w^B \) transmit antenna weight vector for backhaul

\( w_{n,j,l,k} \) \((n,j,l,k)\)th transmit antenna weight vector

\( x_n \) output of receive beamforming at \( n \)th user

\( y_n \) multichannel output of the multi-antenna receiver for \( n \)th user

\( z \) receive beamforming weight vector

\( z^A \) receive beamforming weight vector for access

\( z^B \) receive beamforming weight vector for backhaul

\( z_{n,j,l,k} \) \((n,j,l,k)\)th receive beamforming weight vector

\( \mathcal{B}(\cdot) \) beta function

\( \mathbb{C} \) set of complex numbers

\( \mathbb{R} \) set of real numbers

\( \alpha \) parameter for beta function

\( \beta \) parameter for beta function

\( \sigma^2 \) variance of the complex-circular zero-mean white Gaussian noise

\( \varphi \) azimuth angle

\( \vartheta \) co-elevation angle

\( \{\cdot\}^\dagger \) Moore-Penrose pseudo-inverse

\( \{\cdot\}^H \) Hermitian transpose

\( \{\cdot\}^T \) transpose
1. Introduction

1.1 Background and motivation

In ultra-dense networks (UDNs), the spatial degrees of freedom per unit area are extensively densified [1], [2], [3], [4], [5]. This can be achieved by decreasing inter-site distances (ISDs) of transmission and reception points (TRPs) in the network. Densification in spatial domain can be further increased by employing advanced multi-user multiple-input multiple-output (MU-MIMO) solutions [6], [7], [8].

Even though there has been work in order to mitigate border effects of traditional cellular networks like long term evolution-advanced (LTE-A) [9], next generation new radio (NR) systems will leverage advanced small cell and multiple-input multiple-output (MIMO) technologies to bring uniform quality of experience (QoE)\(^1\) for all mobile users. These technologies also generate grounds for a paradigm shift towards cell-less mobility handling as it has been envisioned in [11]. In order to bring services requiring low latency and high throughput also to vehicular users without delays and overhead caused by exhausting handover procedures [12], the concept of mobility handling needs to be rethought for the future generations of mobile communications.

UDN solutions are usually visualized as cloud radio access network (C-RAN) solutions [13], [14], where a central controller is assumed to control the individual densely deployed remote radio heads (RRHs) in some geographical area. Furthermore, it is often expected that a centralized con-

\(^1\)QoE is the subjective acceptability of the quality of a telecommunication service perceived by the user [10].
controller includes also baseband processing of multiple RRHs. For this kind of operation low latency and high capacity fronthaul links are required [13]. Hence, in practice, fiber fronthaul is required between a centralized controller and RRHs, which makes such solutions inflexible, poorly scalable and expensive to build. In order to make UDNs more attractive for practical deployments, new approaches are needed in order to enable enough coordination possibilities with relaxed requirements on fronthaul or backhaul requirements.

A rising challenge for wireless communications is a connectivity for anything, which has become a new dimension to the world of wireless communications. Hence, in order to support this ongoing Internet of things (IoT) [15], [16] explosion, in the future also small packet traffic generated by massive amounts of all kinds of devices has to be taken into account. This is because all kinds of sensors measuring and storing data around us are potential machine-type communications (MTC) devices [17]. The main challenge in massive machine-type communications (mMTC) is how to provide scalable and efficient connectivity also for massive amounts of these rather simple devices. Due to the high potential area capacity that can be achieved with densification and MU-MIMO, UDNs are an attractive approach for addressing also mMTC challenges especially in urban environments.

1.2 Objectives, scope and research problems

The objective of this thesis is to propose a system level continuous ultra-dense network (C-UDN) concept with novel solutions that will contribute to utilizing the full potential of the densification in urban outdoor environments. C-UDN coverage is assumed to be achieved by continuous coverage of TRPs employing antenna arrays, which are feasible for the MU-MIMO operation in UDNs. In order to build such C-UDN deployment for a certain geographical area, one possible solution in urban environments is to utilize existing infrastructure such as street lighting, as also considered in [18].

With the combination of MU-MIMO and TRP densification many benefits can be achieved. Short communication distances in UDNs provide
high average reference signal received powers (RSRPs) and line-of-sight (LoS) probability, which are good properties for efficient MU-MIMO operation [19]. However, densification also involves challenges such as high inter-TRP interference. Interference can be mitigated with MU-MIMOs by directing emitted energy from TRPs only towards desired directions [19]. However, emitting energy towards different directions at every transmission time interval (TTI) makes interference rather bursty in nature and thus hard to predict. This is especially bad for modulation and coding scheme (MCS) selection in link adaptation (LA).

In order to fulfill the dense urban performance and mobility requirements that were pushed into 3rd generation partnership project (3GPP) NR requirements and scenarios [20], a user centric approach is assumed for mobility handling [21], [22]. Hence, in this thesis utilization of uplink (UL) beaconing\(^2\) based mobility is proposed. This has to be taken into account in frame structure design, scheduling and beamforming schemes studied in this thesis. These UL-based mobility ideas have been recently noted also within 3GPP standardization studies for NR [23].

As already stated, C-RAN solutions with centralized baseband processing might not be very practical for all deployment scenarios. Especially when fiber fronthaul cannot be provided for each RRH. Even though in this study centralized control is still assumed for mobility handling, selecting the best serving TRPs and coordinating radio resource management in high layer, all time-critical procedures done in TTI-basis (like baseband processing) are assumed to be implemented at TRPs. Hence, also non-ideal wireless backhaul solutions for linking centralized controller and TRPs can be considered and studied for the proposed C-UDNs concept.

Furthermore, in order to note the importance of mMTC, one objective is to find a solution that is able to provide efficient access for massive amounts of MTC devices in UDN context.

Even though the millimeter wave (mmW) has also been a hot topic in recent literature [24], [25], the scope of this thesis is to find solutions adequate for sub-6 GHz bands.

\(^2\)Beacons can be understood as reference signals or pilots that can be used for channel state information (CSI) estimation and user tracking purposes.
1.3 Structure of the thesis

This dissertation consists of an introductory part and seven original publications. The introductory part provides an overview of the work in the publications. The dissertation is organized as follows. In Chapter 2, the physical layer and frame structure design for the proposed UDN radio access concept are described. Chapter 3 describes in detail the packet scheduling framework and the beamforming solutions developed for providing radio access in the proposed UDN concept. Chapter 4 considers, for the proposed outdoor UDN concept, a wireless in-band backhaul solution based on spatial division multiplexing (SDM). In Chapter 5, a novel solution for dealing with mMTC by means of UDNs and MU-MIMOs is investigated.

1.4 Summary of the publications

A brief overview of the original publications [I–VII] is given next.

In Publication I, a framework for decoupled time and frequency domain packet scheduling is presented. Simulation results with three basic packet scheduler combinations with different amount of fairness are presented. Four different 3GPPs simulation cases with macro cells are used to show the two extremes in tradeoff between fairness and spectral efficiency. In addition, the effect of multi-user diversity on packet scheduling performance is studied.

In Publication II, a novel frame structure for the next generation UDNs is proposed. The proposed frame structure has been designed to support multi-user spatial multiplexing, short latencies on the radio interface, as well as mobility and small packet transmissions.

In Publication III, the groundwork laid in Publication I is further developed for UDNs and MU-MIMO systems. In particular, a novel scheduling framework is proposed that also takes the spatial domain into account and achieves a more uniform distribution of user-throughput. Furthermore, the frame structure and UDN concept proposed in Publication II are further developed and studied by means of extensive system level simulations.

Publication IV proposes an approach for providing 5G services to mo-
bile users that is based on C-UDNs. The proposed C-UDN approach is compared with macro cell massive MIMO. It is shown that the proposed approach outperforms the widely accepted solution based on macro-cells and massive MIMO in urban environments.

In Publication V, transmit and receive beamforming schemes based on the location tracking of devices are considered. It is shown that the proposed approach based on location is particularly useful in UDNs due to the high probability of LoS. This is because, in addition to being an efficient solution for improving the mean user throughputs, the proposed beamforming scheme, based on tracking of the directional parameters, was also considered to reduce the pilot overhead when compared to the beamforming schemes requiring full-band CSI.

In Publication VI, in-band backhaul for UDNs based on massive MIMO systems in sub-6 GHz is studied. In particular, a scheme is considered for allowing simultaneous downlink (DL) transmissions in a backhaul and access network on a single frequency band that exploits a novel combination of the state-of-the-art practical transmit and receive beamforming techniques. The frame structure work is further extended in order to allow a co-existence between massive MIMO-based backhaul and UDNs. Moreover, a solution for in-band UL transmissions that exploits time division duplex (TDD) and spatial multiple-access is provided.

Publication VII proposes an approach for receiving small uplink data transmissions from a massive amount of MTC devices in UDNs. A solution based on beamforming is proposed for distributing (broadcasting) UL grants for small connectionless data transmissions. Receive beamforming is employed in order to receive the subsequent connectionless UL small data transmissions. The proposed solution was shown to provide high success probability, low physical resource usage and low latency for mMTC UL in urban environments, where UDNs are likely to be deployed.
Introduction
2. Frame Structure Design

2.1 Introduction

When long term evolution (LTE) was being standardized by 3GPP, the aims were considered ambitious. As described in Publication I, the goal was to support e.g. peak data rates of 100 Mbps and 50 Mbps in uplink, improved below 5 ms user plane latency and scalable bandwidth from 1.25 MHz to 20 Mhz [26], [27]. In order to achieve these goals LTE was optimized for packet data transfer. As illustrated in Fig. 2.1, DL time and frequency resources were divided into 1 ms TTIs and 180 kHz physical resource blocks (PRBs). Additionally, frame structure was designed to support both the TDD and frequency division duplex (FDD) modes. For DL, orthogonal frequency division multiple access (OFDMA) was selected as the access technology, and for UL, single carrier frequency division multiple access (SC-FDMA). Even though OFDMA has been shown to be an advantageous solution due to its robustness in the presence of multipath signal propagation [28], SC-FDMA was chosen for uplink due to lower peak-to-average power ratio (PAPR).

As soon as 3GPP standardization reached the point of introducing NR for the next generation of mobile networks, a new set of goals was introduced [29], [2]. As also described in Publication II, the general consensus on the requirements is: a 1000x increase in area capacity with respect to LTE-A, a 1 ms round trip time (RTT) latency, a 10-100x reduction in the cost of deployment and mobility support and always-on connectivity of users that have high throughput requirements.

In order to reach the aforementioned targets, network densification is
Frame Structure Design

Figure 2.1. Time and frequency structure of LTE FDD DL.

one of the main solutions [29], [30], [31]. Besides being relevant to outdoor scenarios, UDNs are also attractive solutions for the indoor deployments [32].

In addition to high area capacities, densification also facilitates reaching small RTT latencies. This is because the frame structure can be designed to attain the below 1 ms latency requirements due to short communication distances. Short ISDs also enable low-power wireless communication, which is expected to be an extremely important feature of future mobile networks [33].

2.2 Frame structure design for ultra-dense network

The objective for the new frame structure design for outdoor UDNs was to minimize both power consumption and RTT latencies. Furthermore, one of the design principles was to support a UL based mobility solution. UL mobility is based on the UL reference signals, from which the network can acquire the CSI as well as location information [34]. Thus, the proposed design makes possible a paradigm shift towards truly user-centric networks [22].

TDD was adopted due to its well known beneficial features including channel reciprocity, dynamic traffic allocation, higher frequency diversity and unpaired band allocation [35].

The novel frame structure design, disclosed in Publication II, is illustrated in Fig. 2.2. The first 5 symbols are reserved for UL beacons. The purpose of these reference signals is to provide enough resources for keeping track of all users, including both active and inactive, and to provide CSI for MU-MIMO to enable efficient usage of radio resources. The next
Figure 2.2. Outline of the frame structure proposed in Publication II.

2 symbols are reserved for UL and DL control signaling. The rest of the subframe can be allocated for the data transmissions in DL or UL direction or both. In all switching points of the communication link direction a short guard period (GP) of $0.4 \mu s$ is inserted. Such a GP is sufficient for tackling UL/DL switching times for the UDN deployments [36], [37], [38].

The radio frame structure was further refined in Publication III and Publication IV. Publication III proposed a control channel with small bandwidth at the center of the frequency. This allows for low-power control channel monitoring during the active on-duration time due to the smaller sampling rate. Furthermore, the first symbol within the subframe was dedicated for narrowband UL beaconing. The purpose of the narrowband beaconing is to enable efficient user location tracking [39]. In addition to obtaining just user location information, such positioning allows for UL based mobility solutions including seamless TRP selection without handovers and multi-cell paging-free type of solutions.

In Publication IV the numerology was further tuned in order to achieve TTIs and subcarrier spacing that are multiples of the ones that LTE is using. This allows better possibilities for building support multiple radio access technologies (RATs) by reusing the same modem hardware components [40].

In order to allow multi-antenna capable users to calculate the receive beamforming weights, the first symbol of the DLL data transmission was allocated in Publication V for transmitting full-band DL precoded pilots. Hence, the outcome of the frame structure design is illustrated in Fig. 2.3 and the related numerology in Table 2.1, which also presents numerologies of 802.11 AC and LTE-A for comparison.
Figure 2.3. Frame structure design proposed in Publication IV including also DL pilot introduced in Publication V.
Table 2.1. Frame structure numerologies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proposed</th>
<th>802.11 AC</th>
<th>LTE-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth [MHz]</td>
<td>200</td>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>Subcarrier spacing [kHz]</td>
<td>240</td>
<td>312.5</td>
<td>15</td>
</tr>
<tr>
<td>Symbol length [μs]</td>
<td>4.1667</td>
<td>3.2</td>
<td>66.67</td>
</tr>
<tr>
<td>FFT size</td>
<td>1024</td>
<td>512</td>
<td>5 × 2048</td>
</tr>
<tr>
<td>Effective subcarriers</td>
<td>833</td>
<td>484</td>
<td>6000</td>
</tr>
<tr>
<td>TTI duration [ms]</td>
<td>0.2</td>
<td>variable</td>
<td>1</td>
</tr>
<tr>
<td>Number of GPs</td>
<td>2</td>
<td>none</td>
<td>2</td>
</tr>
<tr>
<td>GP duration [μs]</td>
<td>0.53</td>
<td>none</td>
<td>66.67</td>
</tr>
<tr>
<td>Symbols per subframe</td>
<td>42</td>
<td>N/A</td>
<td>14</td>
</tr>
<tr>
<td>cyclic prefix (CP) duration [μs]</td>
<td>0.57</td>
<td>0.8</td>
<td>4.7 (short)</td>
</tr>
<tr>
<td>HARQ processes</td>
<td>4</td>
<td>none</td>
<td>Up to 75</td>
</tr>
</tbody>
</table>

The reasoning behind the selection of higher subcarrier spacing was to have robustness against phase noise and to reduce CSI latencies for high user densities. Even though full band CSI latencies and overhead can be reduced by selecting larger subcarrier spacing, a severe disadvantage is that the CP overhead is increased. However, the CP selected is sufficient because of the shorter expected delay spread and the propagation delay in short range scenarios. Furthermore, due to the same reasons it is foreseen that the timing advance can be also tackled with adequate GP duration [36]. Hence the time alignment, as in LTE, is not needed with the next generation UDNs.

2.3 Discussion

Some rather similar designs have been proposed for frame structure to achieve the 5G targets with below 6 GHz frequency bands. Especially allowing usage of larger subcarrier spacing values that are currently used in LTE are considered beneficial for reaching latency requirements. For example, a new radio interface entitled 5G flexible TDD based local area (5GETLA) is described in [41], [42], [43]. The main design principle in 5GETLA was to increase subcarrier spacing in order to decrease the fast Fourier transform (FFT) size needed, yielding a better possibility to reach
1 ms latency requirements.

In [44], [37], [45] another rather conservative proposal for TDD frame structure for the small cell deployments is proposed. The idea is to shorten subframes and to include both DL and UL control channels in each subframe in order to reach the 5G latency requirements.

The frame structure design proposed in this thesis uses approaches for addressing higher bandwidth and reduced latency requirements similar to the aforementioned ones. However, the frame structure illustrated in 2.3 is, additionally, designed to support low power user location tracking [34] and advanced MIMO solutions also for highly mobile users in urban outdoor propagation environments.

The main goal of this thesis was to study serving mobile users and usage of MU-MIMO in UDN deployments. Hence, the frame structure design in this thesis did not consider the frequency domain division of data transmissions. However, the frequency domain can be divided into PRBs as in LTE. As envisioned in [43], it can be assumed that the number of users served by single UDN TRP is relatively low. Hence, the frequency domain can be divided into a rather low number of PRBs that can be used for allocating smaller portions of the carrier bandwidth to individual users and for separating the users in the frequency domain in case the users cannot be adequately separated in the spatial domain with MU-MIMO techniques.
3. Downlink Scheduling and Beamforming in Ultra-Dense Networks

3.1 Packet scheduling framework

Since LTE-based radio access technologies are optimized for the packet data transfer and the core network is purely packet switched, packet scheduling has a really critical role. In [46], the importance of frequency domain scheduling with LTE macro cells was shown. This was studied further in Publication I, where in addition to the frequency domain scheduling also time domain scheduling was considered. Hence, this rather efficient decoupled scheduling framework solution [47] for the available radio resources in LTE was described and studied in Publication I. In Publication II and Publication III, spatial domain scheduler aspects to be included in the decoupled time and frequency scheduler framework were studied in the UDN context.

3.1.1 Decoupled time and frequency domain scheduling

In Publication I a framework of decoupled time and frequency domain packet scheduling was presented for the LTE downlink. This framework was also studied in [47] with different simulator tools. In this framework, a first time domain packet scheduler chooses a subset of all connected users with DL data in buffer as scheduling candidates. Pending hybrid automatic repeat request (HARQ) retransmissions can be taken into account in a way that either all users with the pending retransmissions are automatically chosen or retransmissions are prioritized.

After time domain scheduling, a frequency domain scheduler chooses a
user to be allocated for each PRB from the scheduling candidate set that was formed with the time domain scheduler.

It was shown in Publication I that the framework of decoupled time and frequency packet scheduling can further improve the frequency domain scheduling described in [46]. Furthermore, scheduling can be tuned with different scheduling priority metrics to obtain desired tradeoffs between throughput performance and fairness. In [48], the tradeoff between overall LA and packet scheduling performance and signaling overhead related to the channel quality indicator (CQI) feedback was studied. In [49], [50] voice-over-IP (VoIP) performance in LTE utilizing the decoupled time and frequency packet scheduling framework with packet bundling and mobility was studied.

### 3.1.2 Spatial domain scheduling

The spatial domain packet scheduler embedded within the decoupled packet scheduler is illustrated in 3.1. First, the time domain packet scheduler (TD-PS) selects a subset of users from all users that have data in their buffers. In large-scale MU-MIMO and coordinated multi-point (CoMP) systems where channel aging is one of the major factors limiting performance [51], the time since last beacon (TSLB) value can be used for selecting scheduling candidates for the next scheduling step as proposed in Publication III. If the user-specific channel coherence time is unknown, a threshold for maximum acceptable TSLB can be tuned e.g. based on HARQ feedbacks.

After a scheduling candidate set has been selected using TD-PS, a scheduling loop involving a frequency domain packet scheduler (FD-PS) and a spatial domain packet scheduler (SD-PS) will take place. In this phase a certain scheduling priority metric is used for selecting the first scheduled user. After each user selection by FD-PS, SD-PS strikes out those users from the scheduling candidate set that cannot be scheduled to the the same time and frequency resources. For this purpose e.g. the semi-orthogonality principle [52] or an approach based on the signal-to-interference-plus-leakage-plus-noise ratio (SILNR) [53] can be used. This FD-PS/SD-

---

1 Packet bundling enables the base station to bundle one or more VoIP packets into one physical layer protocol data unit (PDU), thus improving spectral efficiency together with LA due to better resource utilization.
PS phase is looped until there are no more scheduling candidates left or no more candidates that fulfill the spatial orthogonality criteria.

In order to calculate user-specific scheduling priority metrics, the packet scheduler closely cooperates with the CSI, throughput measurement (TPM) and HARQ entities. After scheduling decisions are made, the LA entity chooses the best MCS for each scheduled user based on the scheduling decision, CSI measurements and the transmit antenna weight vectors utilized. Antenna weight vectors can be dynamically calculated for each scheduled user, or the best beam from static beams can be selected for each user. Finally, the allocation (allocated PRBs and MCSs) is pushed to the physical layer (L1).

### 3.2 Scheduling priority metrics

In Publication I, by means of a fully dynamic simulator, different well-known scheduling priority metrics [54] were evaluated using a decoupled scheduling framework. Similar studies were also conducted in [47] with a different type of simulator.

The scheduling priority metrics used for evaluations in Publication I
were maximum throughput (MT), proportional fair (PF), blind equal throughput (BET), and throughput to average (TTA). The MT priority metric is given by:

\[ M_n = d_n, \]

(3.1)

where \( d_n \) is the instantaneous supportable data rate for user \( n \). Hence, the MT scheduler aims at maximizing spectral efficiency. In order to improve fairness while still trying to avoid users with poor momentary channel conditions, the PF priority metric takes into account user CSI and uses average throughput estimation as the scheduling metric. Hence, the PF priority metric is calculated by dividing the predicted throughput estimation of the user by the past average user throughput \( r_n \):

\[ M_n = \frac{d_n}{r_n}. \]

(3.2)

The BET priority metric aims at reaching the same throughput for all users, regardless of their current CSI. The BET priority metric is calculated with:

\[ M_n = \frac{1}{r_n}. \]

(3.3)

The TTA priority metric has the effect of averaging the resources evenly between users. However, TTA can be only used in the frequency domain scheduling, because the achievable throughput for a particular PRB applies only in frequency domain scheduling. The TTA metric is:

\[ M_n = \frac{d_{n,k}}{r_n}, \]

(3.4)

where \( d_{n,k} \) is the achievable user throughput on the \( k \)th PRB.

As illustrated in 3.2, different scheduling priority metrics provide different tradeoffs between degrees of fairness\(^2\) and throughput. As can be expected, the best spectral efficiency can be achieved with MT. A combination of BET and TTA achieves good fairness at the cost of throughput performance. PF offers a rather good tradeoff between spectral efficiency and fairness.

CSI aging wastes system capacity especially in MU-MIMO systems with electrically large antenna arrays, due to time variation in the channel

\(^2\)In order to get comparable fairness index that is perceivable from throughput CDF [55], fairness here is defined as the 5th percentile of the user throughput divided by the 95th percentile.
Therefore, in Publication III it was proposed that for the CSI aging-sensitive systems, TSLB should be taken into account in scheduling priority metrics. Hence, the MT scheduling priority metric weighted with TSLB for $n$th user is:

$$M_n = \frac{d_n}{TSLB_n}.$$  \hspace{1cm} (3.5)

Respectively, the TSLB-weighted PF scheduling priority metric for user $n$ is:

$$M_n = \frac{d_n}{r_nTSLB_n}.$$  \hspace{1cm} (3.6)

Due to the above-mentioned reasons, for the rest of the thesis the TSLB-weighted MT is used as the default scheduling priority metric in the frequency domain scheduling phase for UDN performance evaluations.

### 3.2.1 Borderless quality of experience for ultra-dense networks

The scheduling priority metrics utilized in Publication I are a traditional way of adjusting the tradeoff between fairness and spectral efficiency that have been shown to be effective with legacy RATs like the LTE macrocell deployments. However, with the NR UDNs it is expected that all users can be reached with good received signal power, but as ISDs get shorter,
interference starts to limit the performance, especially at the cell borders. Hence, crowded UDNs are systems that are even more limited by interference. Therefore, achieving the required fairness is not straightforward. For example in [57], one of the 5G targets is to reach 50 Mbps minimum user data rate regardless of user location. Such QoE for high densities of mobile outdoor users requires dynamic interference coordination.

In Publication III such a simple interference coordination solution was introduced, consisting of scheduling coordination and beamforming coordination. In order to get some tradeoff between area throughput and fairness, every $n$th TTI is dedicated to scheduling users whose past average throughput is below the $x$th percentile among the connected users. The algorithm can be tuned by selecting adequate values for $n$ and $x$. Scheduling only a subset of users with low past average throughput in some TTIs reduces leaked interference, thus increasing the signal-to-interference-plus-noise ratio (SINR) for users. On the other hand, scheduling users with high estimated SINR in other subframes increases total area capacity. Hence, one could say that a traditional PF-like outcome for UDN utilizing MU-MIMO can be achieved.

3.3 On link adaptation with dynamic beamforming

Dynamic MU-MIMO beamforming brings new challenges to LA as brought up in Publication III and Publication V. Because scheduling decisions can vary at each TTI, also the directions, in which transmission (Tx) energy is emitted, changes at every TTI [58]. This gives the interference a rather bursty nature. Therefore, the interference is hard to predict, and inner loop link adaptation (ILLA) adjusted with outer loop link adaptation (OLLA) cannot adapt properly to user-experienced interference levels as in legacy systems without dynamic beamforming. Descriptions of ILLA and OLLA algorithms can be found in [59], [60], [61].

With cooperative link adaptation solutions, this problem of rapidly changing TRP Tx radiation patterns can be better tolerated. When interference leakage from the closest neighbors for each scheduled user is known and taken into account in MCS selection, OLLA can be used for fine-tuning link adaptation behavior towards desired block error rate (BLER). In a
UDN system, information on interference leakage can be shared through the centralized node\(^3\) controlling multiple TRPs. Furthermore, as stated in Publication V, if reception (Rx) beamforming is applied by users, OLLA is beneficial for learning achievable gain from a receive filter utilized by an individual user.

### 3.4 Pilot contamination and reusing uplink pilot resources

In Publication III and Publication IV, pilot contamination in the UDN context, among other things, was studied. In UDNs, UL pilots can be reused more often spatially than with larger cells, because of small transmission powers and shorter ISDs. However, in order to truly benefit from advanced MIMO techniques, reliable CSI, without causing too much pilot overhead in frame structure, is a key to success. As is well stated in [64], the CSI overhead is independent of the number of TRP antenna elements, but it is proportional to the number of users. Hence, in addition to a frame structure design allowing enough beaconing resources, these resources used for mobility tracking and CSI at transmitter (CSIT) measurements have to be coordinated spatially in order to find a good tradeoff between pilot contamination and CSI aging.

In Publication III pilot contamination was dealt with using a location-aware UL CSI beacon scheduler. Beaconing resources were allocated to users in such a way that the same time and frequency resources were not reused within a pilot reuse distance. Furthermore, also a short CP length was taken into account. To avoid inter-symbol interference, users transmitting beacons on adjacent orthogonal frequency division multiplexing (OFDM) symbols were within a CP compensation distance as illustrated in Fig. 3.3.

### 3.5 Multi-user MIMO for ultra-dense networks

Emitting energy in desired directions only can improve area capacity and decrease interference leakage towards undesired directions. As stated in

\(^3\)It is assumed that a single NR cell controlled by gNB can be comprised of multiple TRPs [62], [63].
MU-MIMO is more immune to propagation limitations plaguing traditional point-to-point MIMO solutions. This is true especially in UDNs, where LoS paths dominate over reflected and diffracted paths and therefore cause severe degradation in point-to-point MIMO schemes. As illustrated in Publication IV, typical LoS probability in UDNs is higher than 80%. Due to these facts MU-MIMO can be considered a good MIMO scheme for UDN purposes.

3.5.1 Downlink multi-user MIMO precoder design

In this thesis the focus is on linear rather than non-linear precoding. This is because the performance difference between linear and more complex nonlinear precoding schemes vanishes when the number of antenna elements \(L\) grows with respect to the number of scheduled users \(K\) [8]. Hence, the linear precoders, zero-forcing (ZF) and matched filter (MF), are considered in this thesis for obtaining antenna weight vectors for UDN access as follows [8]:

\[
\begin{align*}
\mathbf{w}_{\text{MF}} &= \tilde{\mathbf{H}}_j^H, \\
\mathbf{w}_{\text{ZF}} &= \tilde{\mathbf{H}}_j^\dagger,
\end{align*}
\]

(3.7)

where \(\{\cdot\}^\dagger\) denotes the Moore-Penrose pseudo-inverse. \(\tilde{\mathbf{H}}_j \in \mathbb{C}^{L_j \times K}\) contains the estimated channel-vectors of the \(K\) scheduled users at the \(j\)th TRP:

\[
\tilde{\mathbf{H}}_j = \left[ \hat{h}_{1,j}, \ldots, \hat{h}_{K,j} \right].
\]

(3.8)

MF precoder is known to be an optimal solution when the antenna array size approaches infinity [8]. However, ZF can cancel inter-beam interference in such a way that it typically outperforms MF with practical array sizes. On the other hand, as shown in Fig. 3.4, MF is able to outperform ZF in the low signal-to-noise ratio (SNR) regime. Moreover, when the CSI error value \(\zeta\) is varied, the offset in precoded SINR stays at a rather con-
Downlink Scheduling and Beamforming in Ultra-Dense Networks

Figure 3.4. Performance of MF and ZF precoders in terms of SINR as a function of the SNR used for channel estimation. CSI aging is modeled by parameter $\zeta$ ($\zeta = 1$ means that the CSI is up-to-date). It is assumed that the number of antenna elements $L$ and the number of scheduled users $K$ approaches infinity. It is also assumed that $L/K = 2$. The illustration is based on equations provided in Table I of [8].

stant 1 dB level with MF. On the other hand, with ZF channel aging is a more severe issue, especially in the high SNR regime. Furthermore, a large inconstant difference in precoded SINR with different $\zeta$ causes severe problems to the link adaptation. Knowing also the fact that the MF precoder is computationally less complex, the MF precoder provides a good tradeoff between performance and complexity when serving highly mobile users with large antenna arrays.

In case of multi-antenna user equipments (UEs), receive beamforming schemes can be utilized in order to mitigate the effect of inter-TRP interference. The output of the receive beamforming at the $n$th scheduled UE can be written as [65]:

$$x_n = z_n^H y_n,$$  \hspace{1cm} (3.9)

where $z_n \in \mathbb{C}^{N_{\text{UE}} \times 1}$ and $y_n \in \mathbb{C}^{N_{\text{UE}} \times 1}$ denote the receive beamforming weight vector and the multichannel output of the multi-antenna receiver of the $n$th UE, respectively.

In this thesis it is assumed that all TRPs transmit precoded DL pilots to all scheduled users simultaneously, using the physical resources illustrated in Fig. 2.3. These DL reference signals are used for determining the receive beamforming weights. The single-input multiple-output
(SIMO) channel used for calculating the receive beamforming weights at the \( n \)th user is then
\[
\tilde{h}_n = H_{n,j} \sum_{i=1}^{N} w_i,
\]
(3.10)
where \( H_{n,j} \) denotes the MIMO channel matrix between the \( n \)th user and a transmitting \( j \)th TRP. The transmit precoding vector for the \( i \)th user is \( w_i \). The receive beamforming weight-vector \( z_n \) is then a function of \( \tilde{h}_n \in \mathbb{C}^{N_{\text{UE}} \times 1} \).

Hence, the SINR experienced by the \( n \)th user being served by the \( j \)th TRP can be expressed as:
\[
\text{SINR}_n = \frac{P_{n,j} |z_n^H H_{n,j} w_{n,j}|^2}{\sum_{i=1,i\neq n}^{N} P_{i,k} |z_n^H H_{n,k} w_{i,k}|^2 + \sigma_n^2},
\]
(3.11)
where \( P_{n,j} \) denotes the transmit power for precoder \( w_{n,j} \) and \( \sigma_n^2 \) is the variance of the complex-circular zero-mean white Gaussian noise at the \( n \)th user.

### 3.5.2 Location-based transmit and receive beamforming

Since UDN provides high LoS probability, it is possible to use the UL beaconing and extended Kalman filter (EKF) for obtaining transmit and receive angles of the LoS path [39], [66]. In Publication V this angle information was used for obtaining a synthesized multi-user multiple-input single-output (MU-MISO) matrix for further calculating transmit and receive beamforming weight vectors. Let \( \theta_n \in [0, \pi] \) and \( \varphi_n \in [0, 2\pi) \) denote the co-elevation and azimuth angles obtained for beamforming. The synthesized MU-MISO matrix is then given by:
\[
\tilde{H} = [a_{\text{TRP}_H}(\theta_1, \varphi_1), \ldots, a_{\text{TRP}_H}(\theta_N, \varphi_N)]^T \\
+ [a_{\text{TRP}_V}(\theta_1, \varphi_1), \ldots, a_{\text{TRP}_V}(\theta_N, \varphi_N)]^T,
\]
(3.12)
where \( a_{\text{TRP}_H}(\theta, \varphi), a_{\text{TRP}_V}(\theta, \varphi) \in \mathbb{C}^{N_{\text{TRP}} \times 1} \) denote the TRP’s array responses due to horizontal and vertical excitation, respectively. It should be noted that (3.12) assumes equal power allocation for the two polarizations. Then MF and ZF precoders can be calculated (equations 3.7) with a constructed synthesized MU-MISO matrix, instead of using the measured CSIT.

In transmit beamforming, exploiting information on the location of the user relative to the serving TRP makes it possible to replace fullband UL
reference signals, commonly employed for acquiring the CSIT in TDD systems, by narrowband UL beacons. Furthermore, for users that are being tracked also the control channel can be beamformed with the location-based method as shown in [67], in order to reduce inter-TRP interference and to increase control channel capacity.

In the location-based receive beamforming, DL pilots are not needed. Instead, the TRP provides directional parameters to the users using the DL control channel prior to data transmission. This enables the user to obtain a synthesized single-input single-output (SISO) channel $h_n$ for the location-based receive filter calculation.

### 3.6 Downlink performance experiments with ultra-dense networks

The UDN performance evaluations for this thesis were performed with a dynamic system level simulator. Scheduling, UL beaconing and downlink transmissions were simulated with TTI resolution. Descriptions and a comparison of the geometry based stochastic channel model (GSCM) and the map-based ray tracing channel model [68], utilized in this thesis, can be found in [69].

#### 3.6.1 Borderless scheduling in ultra-dense network

Borderless scheduling algorithms with ZF and MF precoders were simulated in METIS highway scenario [70]. Constant velocities of single antenna UEs were varied from 3 km/h to 100 km/h. For these simulations GSCM was used. More details on the simulation parameters are provided in Publication III.

In addition to evaluating proposed scheduling algorithms, feasible antenna array geometries were evaluated with ZF and MF precoding. Fig. 3.5 shows an area throughput comparison of uniform circular array (UCA), uniform planar array (UPA) and uniform linear array (ULA). As also concluded in [71], horizontal ULA is best suited for large MU-MIMO arrays. However, it should be noted that if the test scenario were different (e.g. served users were on different floors of high building), then the degrees of freedom also in the vertical domain would bring more gain. However, the physical size of the ULA may not be so practical for example for the
envisioned lamp-post UDN deployment. UCA on the other hand performs rather similarly to UPA although their geometries are quite different. For the rest of the simulations in this thesis, UCA geometry is used for UDN deployments due to its good performance with MF precoding in high velocities and due to the rather compact physical size of the antenna array. Furthermore, it could be expected that network planning and plug-and-play type of installation would be easier with circular arrays than planar arrays, which are only emitting energy properly towards the front.

As illustrated in Fig. 3.6, ZF outperforms MF with all utilized realistic antenna arrays in low-mobility test cases. When mobility is increased, better area throughput with MF precoding can be achieved. Borderless scheduling decreases area throughput, because less users per TTI are scheduled on average. However, borderless scheduling reduces interference which increases SINRs of the scheduled users 1 to 2 dB better than the area throughput maximizing MF and ZF precoding strategies as shown in Fig. 3.7.

A scheduler which tries to maximize area capacity cannot guarantee decent QoE for all active users as shown in Fig. 3.8. However, in order to increase fairness it is beneficial in some TTIs to limit the scheduling candidate set to those users that fulfill the coherence time criteria and are most discriminated in terms of past average throughput. It can be also
observed that ZF has difficulties with serving all the users satisfactorily due to its sensitivity to channel uncertainties. It should be noted that the scheduling fairness can be further tuned by adjusting the parameters described in Section 3.2.1.
3.6.2 Serving mobile users in urban environments

In Publication IV simulations were performed to compare the performance of massive MIMO\(^4\) and the proposed C-UDN in a realistic urban city environment with mobile UEs. UDN TRPs were comprised of 25 Tx antennas in a circular domain. The massive MIMO array in turn was a 20\(\times\)20 planar array. The Madrid grid simulation scenario [70] utilized is illustrated in Fig. 3.9. The simulation parameters are described more precisely in Publication IV.

The simulated mean user throughputs of macro cell massive MIMO are shown in Fig. 3.10. As stated in [74], ZF’s ability to eliminate intra-cell interference comes with the cost of transmission power consumption. This can be seen in Fig. 3.10 in the observation that when CSI is not aging, the optimal number of beams settles around 20 with the utilized constant of 46 dBm per 20 MHz massive MIMO Tx power budget. MF, on the other hand, is not able to keep beams, directed towards non line of sight (NLoS) users, well enough separated spatially. Therefore, performance starts to saturate with the planar rooftop array used when 30 beams are formed. When added velocity brings CSI aging into the picture, the performance of ZF collapses due to its high sensitiveness to the channel estimation.

\(^4\)Massive MIMO refers to the idea of equipping cellular base stations with a very large number of antennas [72], [73], [74].
Figure 3.9. The Madrid grid based C-UDN deployment scenario considered in the simulator. 43 TRPs, illustrated as green dots, are placed at the edges of pavements of ordinary streets. In the pedestrian street and the highway TRPs are in the center of the street. In case of massive MIMO macro cell, a planar array, illustrated as an orange rectangular, was placed on top of the bottom right building facing the opposite corner. Users are illustrated as red circles.

Figure 3.10. Effect of channel aging, precoder selection and link adaptation in massive MIMO macro cell. The maximum number of formed beams per TTI is varied. Grey color shows performance loss due to imperfect SINR estimation for the link adaptation.

uncertainties. This is well in line with the demonstration shown in Fig. 3.4.

It was observed in Publication IV that in the simulated scenario C-UDN did not have much difficulties in serving mobile users. Especially with
the MF precoding the channel aging effect is rather small. This is illustrated in Fig. 3.11. A similar illustration for the ZF precoder can be found in Fig. 3.12. As anticipated, the performance of ZF was slightly better without the channel aging, but a bit worse otherwise. Additionally it was demonstrated that when the beacon reuse distance is over 150 m, pilot contamination no longer has a major effect on the performance. With the ZF precoding it can be demonstrated that with different levels of the channel aging and the pilot contamination, the optimal beacon reuse distance settles at a different point. This is because increasing the beacon reuse distance increases the channel aging, but decreases the effect of pilot contamination.

3.6.3 Location-based transmit and receive beamforming

Location-aware transmit and receive beamforming was studied in Publication V. The simulation scenario was the same as illustrated for C-UDN deployment in Fig. 3.9. In order to form transmit beams, antenna arrays at TRPs were comprised of 20 dual-polarized 3GPP patch antennas [75]. The Rx antenna model at UEs was a circular array with 4 cross-dipoles. The simulation setup is more precisely described in Publication V. For the location-based beamforming a 2 degree static error was added to both azimuth and elevation angles. As shown in Publication V, an accuracy well below 2 degrees is achievable for all directional parameters. Additionally,
aging of the location information was based on the CSI latency. Channel-based beamforming was based on least-square channel estimation from the CSI beacons.

As can be observed in 3.13, ZF and MF precoders have similar performances in the simulated scenario. This can be explained by the large number of antennas at the TRPs compared to the amount of served users per TRP. However, the channel-based transmit beamforming was slightly better than the position-based alternative with ZF precoding. When CSI is used for beamforming, ZF’s ability to utilize the full channel and null inter-beam interference is slightly better.

The results in Fig. 3.13 also illustrate that the position-based receive beamforming outperforms those based on the precoded DL full-band reference signals. This is because with the position information beams can be directed with a small angular error towards the dominant LoS path. Furthermore, simultaneous transmission of precoded DL reference signals minimizes the channel capacity used but causes pilot contamination.

### 3.6.4 Link adaptation cooperation

In addition to the beamforming performance, Publication V also revisited the cooperative LA, and the LA problems caused by dynamic beamforming, identified in Publication III. As shown in 3.14, with around 100 m LA cooperation radius, performance starts to saturate in the simulated
Figure 3.13. The performance of CSI and position based beamforming schemes in terms of mean user-throughput with users moving at 50 km/h. Transmit-only beamforming (BF) with a single antenna at the receiver as well as transmit and receive beamforming (RBF) schemes are shown. The effect of utilizing unused wideband DL/UL pilot symbols for data transmission is illustrated with gray color.

UDN scenario. It can also be seen that in case of ZF, SINR estimation ends up being more off than in the case of MF, because in the estimation phase TRP's beams are not expected to interfere with each other at all. However, this does not fully correspond to user experienced SINR when users are moving and beams are always formed with more or less out-dated information. Moreover, because the receive beamforming gain cannot be obtained without user measurements and CSI reporting, OLLA was used in Publication V for fine-tuning SINR estimations and learning the receive beamforming gain.

3.7 Discussion

As is well stated in [76], more spectrum being used more flexibly, higher spectral efficiency, and additional cells seem to be a reasonable breakthrough for reaching the 5G main challenge, i.e. 1000x increase in area capacity. In this chapter this issue was addressed by introducing novel scheduling and MU-MIMO beamforming solutions for NR UDNs. Furthermore, the results shown suggest that the proposed UDN solutions
Figure 3.14. The cumulative SINR distribution function of the SINR mismatch of scheduled users moving at 50 km/h velocity. Here SINR mismatch refers to the difference between SINR estimation used for link adaptation without OLLA and actual received SINR for different interference leakage information sharing radii.

can address both high capacity and low-latency requirements of future networks.

In this thesis Massive MIMO performance in urban environment was studied with ZF and MF precoders. It was shown that the performance of ZF suffered severely from channel ageing and that of MF from not being able to separate beams for users within urban street canyons. However, as shown in [77], these effects can be mitigated to some extent with robust regularized zero-forcing (RRZF) beamforming, which in practice allows for finding a tradeoff between capacity maximizing ZF and robustness in case of imperfect CSI.

Traffic models were not utilized in the simulations, mainly because the high complexity of the dynamic simulator utilized, with realistic channel models and scenarios, forced the simulation time of single random realization to be rather short. Hence, e.g. the quality of service (QoS), required in challenging services as in real-time downlink communications, was not considered. Studies addressing also these issues exist, e.g. [78]. However, in case of the UDN scenarios studied it is expected that such scheduling algorithms do not play such a big role because of the high degrees of freedom in spatial domain.
In this thesis only DL was considered in the packet scheduler design work. In Publication VI uplink performance with in-band backhaul was also studied, but the UDL configuration was fixed. Hence, the interference problem caused by dynamic UL/DL frame allocation was not studied in this thesis. For this problem an adaptive scheduling algorithm was proposed in [45]. The proposed algorithm switches transmission direction to UL dynamically based on head of line (HoL) delay and scheduling requests. Performance of Massive MIMO UL with pilot contamination and channel aging was studied e.g. in [64].

CoMP was not considered in this thesis due to impracticality reasons described in Publication III. In most beam coordination schemes [79], usually the centralized controller collects all the CSI from the TRPs, calculates all the precoders, and then distributes the knowledge of the precoders to the corresponding transmitting nodes. This is not practical in most of the deployment scenarios because of low-latency and capacity limited links between the centralized controller and TRPs [80], [81].

As shown in Publication V, location-based transmit and receive beamforming are appealing alternatives to traditional full-band CSI based options in the UDN scenarios, especially if the CSI overhead can be reduced substantially. In this thesis pathloss information was not used for location-based beamforming. Hence, it would be possible to extend the proposed precoding design methodology to take also Tx power domain into account. This would allow division of available Tx power budget between beams based on user channel conditions. In UDNs, however, differences in pathlosses are not so notable, as illustrated in Publication IV, which decreases the possible significance of such a complication in precoder design. Moreover, it should also be remembered that in this study vehicular users were assumed. Hence, due to vehicle rooftop antennas, array orientation was not changing rapidly. This allowed better estimation of user orientation by providing sufficiently accurate directional parameters transmitted to users for receive beamforming. For DL transmit beamforming user orientation is not an issue.

Moreover, the borderless scheduling together with the location-aware beamforming with block diagonalization (BD) [82] precoding was later studied in [83]. The results further confirmed that the location information can be used efficiently in the radio network for the geometric location-
based beamforming.
4. Wireless In-Band Backhaul with Massive MIMO

4.1 Introduction

In Publication IV it was shown that the macro cell massive MIMO cannot successfully address the capacity needs of 5G for urban vehicular users. However, promising results with the ZF precoding were obtained for static UEs. Therefore, in Publication VI the feasibility of utilizing massive MIMO for proving backhaul links for C-UDN TRPs deployed on urban streets was studied. Because of the limited spectrum available in sub-6 GHz, it was studied whether it would be beneficial to separate the massive MIMO backhaul links and the UDN access links in the spatial domain, instead of pairing the available spectrum between UDN and its wireless backhaul. Hence, each C-UDN TRP consists of two antenna arrays in order to allow for simultaneous in-band DL transmissions in the backhaul and the access layers. The proposed in-band backhaul solution can be considered one flavor of self-backhauling, where the same wireless technology and spectrum is used for both the access and the backhaul links. In the self-backhaul, the backhaul and the access links are usually time division multiplexed [84]. An artistic illustration of the proposed self-backhauling concept is visualized in Fig. 4.1.

4.2 Frame structure modifications for supporting in-band backhaul

In order to enable the in-band backhaul operation with C-UDN, the frame structure has to be designed to support the co-existence of massive MIMO based backhaul and C-UDN TRPs. The frame structure design proposed
in Publication VI is illustrated in Fig. 4.2. The proposed frame structure is similar to that defined in Section 2.2, but the reference signals required by the backhaul and the access layer are separated in the time domain. Additionally, backhaul nodes are prohibited to transmit during UDN layer reference signaling time slots, and every $k$th TTI is dedicated to measurement gaps used for measuring channels between massive MIMO and C-UDN TRPs. During measurement gaps, TRPs are muted in order to avoid interference. Moreover, massive MIMO backhaul nodes can utilize a fraction of the measurement gap, e.g., one OFDM symbol for transmitting DL downlink reference signals (DLRSs) [85].

DL data transmissions on the access network and the backhaul are transmitted simultaneously by exploiting SDM schemes. UL data transmissions are separated by means of TDD. It was noticed that when both TRPs and UEs transmit uplink data simultaneously from the street level, UE transmissions are interfering remarkably with backhaul UL signals. This is because the UE transceiver’s electrical-size is not sufficiently large to allow very directive transmissions. Hence, the UL of backhaul and access layers can be flexibly separated with TDD instead of SDM. This also allows the use of electrically smaller backhaul arrays at TRPs.

Example numerologies, which were also utilized in evaluation simulations, for the in-band backhaul of C-UDN and massive MIMO are provided in Table 4.1. TTI lengths are aligned to 0.2 ms in order to provide
Wireless In-Band Backhaul with Massive MIMO

Figure 4.2. The proposed TDD frame structure for in-band inter-operation of massive MIMO based backhaul and UDN. Simultaneous in-band DL transmissions for backhaul and UDN are allowed while the corresponding UL transmissions are separated in the time domain.

flexible TDD and SDM operation. In order to take longer communication distances into account, 4.7 μs CP length was adopted from LTE-A for the backhaul. Hence, it is reasonable to decrease the subcarrier spacing in order to save on the CP overhead. Therefore, if 28 C-UDN OFDM symbols are allocated for the DL data slot and 10 for the UL data slot, then 6 OFDM symbols can be allocated for backhaul DL and 2 symbols for UL. With such a configuration, the timing advance can be tackled during the same UL/DL slots including adjacent GPs. It should be further noted that it is possible to utilize exactly the same numerologies for both backhaul and UDN layers, but then the UL reference signaling overhead needed for handling the user mobility and the CSI acquisition would increase significantly.

4.3 Precoder and receive filter design

Precoder and receive filter designs play a crucial role when two co-located layers of DL transmissions are sharing the same time and frequency resources. In case of the backhaul transmissions major challenge is to mitigate self-interference\(^1\). Channel aging is not significant issue for the backhaul transmissions due to stationary TRPs. For the access layer the

\(^1\)Self-interference here refers to the interference caused by two multi-antenna transceivers co-located at each TRP.
Table 4.1. Example of 5G numerologies for in-band backhaul of C-UDN based on massive multiple-input multiple-output (M-MIMO).

<table>
<thead>
<tr>
<th>parameter</th>
<th>C-UDN</th>
<th>M-MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth [MHz]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Subcarrier spacing [kHz]</td>
<td>240</td>
<td>60</td>
</tr>
<tr>
<td>Symbol length [μs]</td>
<td>4.1667</td>
<td>16.6667</td>
</tr>
<tr>
<td>FFT size</td>
<td>1024</td>
<td>4096</td>
</tr>
<tr>
<td>Effective subcarriers</td>
<td>833</td>
<td>3333</td>
</tr>
<tr>
<td>TTI duration [μs]</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Number of GPs</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Symbols per subframe</td>
<td>42</td>
<td>8</td>
</tr>
<tr>
<td>CP duration [μs]</td>
<td>0.57</td>
<td>4.7</td>
</tr>
<tr>
<td>GP duration [μs]</td>
<td>0.53</td>
<td>-</td>
</tr>
</tbody>
</table>

The challenge is to serve mobile users efficiently and to tolerate interference caused by the simultaneous backhaul transmissions. For this it is helpful that in C-UDN communication distances are rather short and multi-antenna UEs are able to form their receive beams towards serving TRP.

4.3.1 Downlink backhaul transmissions

In order to improve the performance of the ZF precoding with massive MIMO, which was used in Publication IV, BD precoding [82] was chosen instead. The BD algorithm has several advantages when compared to other schemes. First of all, it gives a good tradeoff between complexity and performance. Moreover, an especially attractive feature in BD is that beams can be optimized for the multi-antenna receivers, enabling transmission of multiple spatial streams from the single massive MIMO backhaul node to several TRPs. How transmit and receive beamforming weight vectors are obtained is described in [82], but a brief description is also given in Publication VI.

In order to model system performance, all transmit and receive beamforming vectors as well as inter-layer interference must be taken into account in the simulations. Hence, the DL SINR experienced by the $j$th ($j \in \{1, \ldots, J\}$) UDN TRP being served by the $l$th ($l \in \{1, \ldots, L\}$) massive MIMO backhaul node for the $k$th ($k \in \{1, \ldots, K\}$) spatial DL backhaul
stream is:

$$\text{SINR}_{j,l,k}^{DL} = \frac{P_{j,l,k}|z_{j,k}^H H_{j,l,k}^B w_{j,l,k}^B|^2}{\sum_{\ell=1}^{L} \sum_{\kappa=1}^{K} P_{\ell,\kappa} |z_{j,k}^H H_{j,l,k}^B w_{\ell,l,k}^B|^2 + I_{j,l,k}^B + \sigma_n^2},$$

(4.1)

where $P_{j,l,k} \in \mathbb{R}$ denotes the transmit power allocated to the $k$th spatial stream at the $\ell$th massive MIMO backhaul node for the $j$th UDN TRP. $H_{j,l,k}^B$ is the MIMO channel matrix between $\ell$th massive MIMO backhaul node and the backhaul transceiver of $j$th UDN TRP. $w_{j,l,k}^B$ and $z_{j,k}$ are transmit and receive weight vectors used for the DL transmission of $k$th stream between $\ell$th massive MIMO backhaul node and $j$th UDN TRP. $I_{j,l,k}^B$ is the interference caused by simultaneous access layer transmissions:

$$I_{j,l,k}^B = \sum_{\ell=1}^{J} \sum_{n=1}^{N} P_{\ell,n} |z_{j,k}^H \tilde{H}_{j,l,k}^B w_{\ell,n}^A|^2,$$

(4.2)

where $P_{\ell,n} \in \mathbb{R}$ denotes power allocated to the $n$th UE at the $\ell$th UDN TRP. $w_{\ell,n}^A$ is the transmit precoder of $\ell$th UDN TRP for the $n$th UE.

### 4.3.2 Downlink ultra-dense network access

In backhaul, the massive MIMO node designs both the transmit and the receive antenna weight vectors. This is practical with a limited number of stationary TRPs. In order to reduce signaling overhead, UEs are expected to measure the DLRS sent by UDN TRPs and design their own receive filters based on the measurements. Moreover, UEs can also utilize the measurement gaps for measuring the precoded backhaul DLRS and utilize these measurements for mitigating the backhaul interference. For minimizing the overhead, the precoded DLRS are transmitted simultaneously by all massive MIMO backhaul nodes. Then the DL channel matrix observed by the $n$th UE scheduled by the $j$th UDN TRP is given by:

$$H_n^A = \left[ \sum_{j=1}^{J} H_{n,j}^A \sum_{i=1}^{N} w_{i,j}^A \sum_{\ell=1}^{L} H_{n,\ell}^A \sum_{k=1}^{K} w_{\ell,k}^B \right].$$

(4.3)

Therefore, the receive beamforming weight vector $z_n^A \in \mathbb{C}^{M_{Rx}}$ for the $n$th UE corresponds to the first row of the Moore-Penrose pseudo-inverse of $H_n^A$. The DL SINR experienced by the $n$th UE being served by the $j$th UDN TRP is:

$$\text{SINR}_{n,j}^{DL} = \frac{P_{n,j}|z_n^A H_{n,j}^A w_{n,j}^A|^2}{\sum_{\eta=1}^{N} \sum_{j=1}^{J} P_{\eta,n} |z_n^A H_{n,j}^A w_{\eta,n}^A|^2 + I_n^A + \sigma_n^2},$$

(4.4)
Wireless In-Band Backhaul with Massive MIMO

where $P_{n,j}$ denotes the transmit power allocated to precoder $w^A_{n,j}$. Moreover, $I^A_n \in \mathbb{R}$ denotes the interference experienced by the $n$th UE that is caused by DL backhaul transmissions, and it is given by:

$$I^A_n = \sum_{l=1}^L \sum_{k=1}^K P_{k,l} |z^A_n \tilde{H}^A_{n,l} w^B_{k,l}|^2.$$  

(4.5)

4.3.3 Uplink

For the uplink direction the same MU-MIMO principles can be utilized. Transmissions in the UL direction can be separated into two problems i) how to separate simultaneous UE UL transmissions spatially in the access layer and ii) how to separate UL transmissions in the access layer and in the backhaul layer. Regarding the first challenge, the only difference from DL is that now transmitters do not have electrically-large antenna arrays due to the limited physical sizes. However, if connected users in C-UDN are assumed to transmit periodical reference signals during the time they are active, the same channel measurements can be used also for calculating the receive filters, allowing the reception of data simultaneously from several users. For example MF and ZF based receive filters can be efficiently utilized for receiving data from multiple users.

As already discussed, the challenge of separating the access and the backhaul layer transmissions originates from the fact that access layer transmissions from UEs with small antenna arrays are not very directive. Thus, UL transmissions of UEs are leaking interference towards the massive MIMO backhaul nodes. Due to these reasons, TDD is deployed for flexible UL in-band backhauling. During UL time slots, either TRPs are receiving data from the users or the massive MIMO backhaul nodes are receiving data from the C-UDN TRPs. These time slots can be dynamically allocated in the time domain so that the throughput ratio between the backhaul and the access links becomes the desired one.

As also described in Publication VI, the precoder and receive filter design employed for the backhaul transmissions in UL is formed by reusing the transmit antenna weight vectors from DL in UL. In particular, the precoder employed by the $j$th UDN TRP for the $k$th spatial stream is $\tilde{w}^B_{j,k} \triangleq z^B_{j,k}$. Similarly, the receive beamforming vector employed by the $l$th massive MIMO backhaul node for the $k$th spatial stream and trans-
mitted by the $j$th UDN TRP is $\tilde{z}_{j,l,k}^B \triangleq \mathbf{w}_{j,l,k}^B$. The corresponding SINR experienced at the $l$th massive MIMO backhaul node for the $k$th spatial stream transmitted by the $j$th UDN TRP is:

$$\text{SINR}^{UL}_{j,l,k} = \frac{P_{j,k}|\tilde{z}_{j,l,k}^B \mathbf{H}_{j,l,k}^{BT} \tilde{w}_{j,k}^B|^2}{\sum_{i=1}^{J} \sum_{\kappa=1}^{K} P_{i,k}|\tilde{z}_{j,l,k}^B \mathbf{H}_{j,l,i}^{BT} \tilde{w}_{i,k}^B|^2 + \sigma_j^2}.$$  \hspace{1cm} (4.6)

In the UDN access layer, the precoder employed by the $n$th UE is a MF that is found from the precoded DL reference signals as follows:

$$\tilde{w}_{n}^A = \left( \sum_{j=1}^{J} \mathbf{H}_{n,j}^{A} \sum_{i=1}^{N} w_{i,j}^A \right)^H.$$ \hspace{1cm} (4.7)

Note that the precoded DL reference signals are transmitted simultaneously by all UDN TRPs for all scheduled UEs. This is done in order to reduce the overhead due to channel estimation. However, the interference leakage caused by this approach is not significant due to the electrically-large antenna arrays employed at the UDN TRPs and LoS conditions in a typical outdoor C-UDNs scenario. The receive beamforming vectors at the UDN TRPs are identical to those used for DL transmission. In particular, the receive beamforming vector employed by the $j$th UDN TRP for the $i$th UE is $\tilde{z}_{i,j}^A \triangleq \mathbf{w}_{i,j}^A$. The SINR experienced by the $j$th UDN TRP for the $n$th UE is:

$$\text{SINR}^{UL}_{n,j} = \frac{P_{n}|\tilde{z}_{i,j}^A \mathbf{H}_{n,j}^{AT} \tilde{w}_{n}^A|^2}{\sum_{\eta=1}^{N} P_{\eta}|\tilde{z}_{i,j}^A \mathbf{H}_{n,j}^{AT} \tilde{w}_{\eta}^A|^2 + \sigma_j^2}.$$  \hspace{1cm} (4.8)

### 4.4 Performance evaluations

Both the UL and the DL of the proposed in-band backhaul solution were evaluated in Publication VI. C-UDN deployment is the same as in Publication V. However, now 3 massive MIMO backhaul nodes are attached to the center-most building in order to provide backhaul links for the TRPs as illustrated in Fig. 4.3. For the backhaul transmissions, each TRP was equipped with an additional linear array of 2 dual-polarized dipoles attached 1 meter above the UCA with 20 dual-polarized 3GPP patch antenna elements.
Figure 4.3. Massive MIMO backhaul nodes, planar arrays, illustrated as orange rectangles, were placed on the upper-edge of the walls of the center-most building and tilted towards street level.

The results in Fig. 4.4 show that a near-equal division between the backhaul and the access network throughput is achieved in the simulated scenario when the power budget for each UDN TRP is 20 dBm. These results also indicate that the proposed in-band scheme reaches $\sim 58\%$ of the performance achievable with ideal backhaul while only $\sim 24\%$ of massive MIMO backhaul performance is lost due to the interference caused by UDN TRPs. The results shown are for the simulation case where user velocity was fixed to 50 km/h. In Publication VI, results for the 0 km/h case were also shown. It was observed that increased velocity causes only slight performance loss due to the channel aging for the C-UDN access layer DL transmissions.

The results in Fig. 4.5 indicate that the average throughput that was achieved per UDN TRP for UL backhaul is only slightly larger than that required for handling the access network transmissions when 35% of sub-frames are allocated for the backhaul and the remaining 65% for the UL access. Hence, a 35/65 configuration between UL backhaul and UL access provides a good trade-off in the simulated scenario.
Figure 4.4. The performance of the proposed solution for in-band backhaul of UDNs using a massive MIMO system in terms of DL throughput per UDN TRP. The green bars correspond to the case where users exploit the precoded DL reference signals transmitted by massive MIMO backhaul nodes for mitigating backhaul interference. The results with ideal backhaul (e.g., wired connection) are also illustrated for comparison. The UDN TRPs’ power budget was varied from 0 dBm to 30 dBm.

Figure 4.5. The performance of the proposed in-band backhaul scheme in terms of average UL throughput per UDN-AN.

4.5 Discussion

It was shown that SDM with massive MIMO is more efficient for self-backhauling than traditional solutions based on time domain multiplexing.
Wireless In-Band Backhaul with Massive MIMO

ing (TDM). It should be noted that also full-duplex techniques are considered for self-backhauling [86], [87], [88]. An especially attractive feature in a full-duplex solution is that the need of having two antenna arrays on each UDN TRP would be avoided, when compared to the proposed SDM alternative. Hence, the physical size required by a TRP would be reduced. However, it is expected that first the releases of 5G will use TDD and FDD operation modes. Moreover, deploying two separate arrays with e.g. outdoor UDN lamp post deployment should not be an issue as sketched in Fig. 4.1.

As an alternative to wireless backhaul on sub-6 GHz bands, also mmW based solutions have been considered in recent literature [89], [90], [91]. Such high frequency solutions are especially attractive because of the spectrum that is already available in the millimeter-wave bands for the fixed wireless access [91]. However, a decision was made at the 2015 world radio communication conference (WRC’15) to postpone regulatory aspects of mmW-bands for mobile broadband communications until 2019 [92]. Moreover, mmW based backhaul solutions typically require LoS conditions between the aggregation point and the UDN TRPs, or proper network planning [91].

In the end it should be remembered that the best backhaul option depends on various challenges to be solved case by case. Hence, there is no single solution solving the holistic 5G backhaul problem [93].
5. Dealing with Massive Machine Type Communications

5.1 Random access procedure

MTC [94], [17], also known as machine-to-machine (M2M) communication [95], where there is no human involved as either sender or receiver, is one of the fastest growing areas within mobile communications. As identified also in 3GPP [96], one of the most critical bottlenecks for mMTC rollout in the current LTE-A standard is the random access (RA) procedure needed for transmitting or receiving data. This is one among the other challenges that are identified in [95], [97].

Connection establishment in LTE-A RA is a contention-based procedure, where UE initiates the procedure by randomly picking a preamble sequence for transmission on a random access channel (RACH). However, the number of available preambles is rather limited and collisions occur when multiple devices have chosen the same preamble [95]. The remedy available for reducing the risk of overloading the RA procedure is the so-called access class barring [98], [99]. However, the possibility of blocking access for devices of a specific access class, at least with a certain probability, is not truly solving the mMTC problem, because in fact it just postpones the access for some UEs. Increasing the access latency also increases energy consumption for the MTC devices, because the energy efficiency of these devices depends heavily on channel monitoring and the signaling overhead that occurs before the actual payload transmission. This is notably problematic for devices that need long battery lifetime.
5.2 Connectionless access for small uplink packet transmissions

In Publication VII one possible solution for dealing with mMTC is proposed. The solution utilizes the spatial degrees of freedom available in UDN with MU-MIMO capable antenna arrays. Furthermore, a concept of allowing small UL packet transmissions without establishing the radio resource control (RRC) connection is suggested.

In particular, at every periodical RA occasion, UL grants for the connectionless small packet transmissions are being broadcasted spatially around the TRPs. In order to receive the subsequent UL transmissions efficiently, the transmit precoders can be utilized as receive filters. As illustrated in Fig. 5.1, each beam is assigned with a different UL grant. A random beam steering offset is applied in order to randomize the inter-TRP interference and to improve the probability of the successful decoding for all MTC devices.

The proposed scheme is illustrated in Fig. 5.2. In the first step the network broadcasts precoded random access grants. Once the user has decoded the grant, it can perform small packet data transmission or request RRC connection with Msg3\(^1\). In the third step the network can acknowledge the received data packet or transmit Msg4\(^2\) for the purpose of random access contention resolution. Hence, the proposed design can be

---

\(^1\)Msg3 refers to the 3rd message in the LTE-A RA procedure, which is used for identifying the user for RRC connection establishment [95].

\(^2\)I.e., the 4th message involves contention resolution. In LTE-A RA it is used for replying the Msg3 with the user identifier [95].
used for both the random access procedure and the connectionless small packet transmission.

It should be noted that in the proposed scheme the first step of LTE-A RA is omitted. This is because the LTE-A RA is originally designed for supporting human-type communications (HTC) from small cells to large macro cells. Thus, the main purpose of using a preamble in LTE networks is to measure the timing advance for further UL transmissions. However, in UDNs timing advance can be tackled by choosing an appropriate CP, as already stated in section 2.2.

5.3 Performance evaluation

In order to evaluate the proposed method for the connectionless UL transmissions, an extensive system level simulation study was carried out as described in Publication VII. In the study a massive number of devices were randomly dropped on the street areas of the Madrid grid simulation scenario. The same UDN TRP locations as visualized in Fig. 3.9 were used. Each of 43 TRPs were utilizing antenna arrays comprised of 16 dual-polarized 3GPP patch antenna elements [75]. For the connectionless data transmission occasions, 5 ms periodicity is assumed. A random back-off time between 0 and 20 ms was used for preventing repeating col-
Dealing with Massive Machine Type Communications

Collisions of the same users. The MCS of random access grants is fixed to quadrature phase shift keying (QPSK) and 1/3 coding rate. All UL transmissions that are using the same grant are interpreted as failures due to collision. Decoding failure depends on SINR and the fixed MCS used for broadcasting the connectionless UL grants. Further details on the employed simulation parameters are described in Publication VII.

In order to form beams towards desired directions, the synthesized MU-MISO channel matrix can be utilized, as described with Equation 3.12 in Section 3.5.2.

5.3.1 Traffic models for machine type communications

In Publication VII two different models were assumed [96]. In the first traffic model (TM1), MTC devices access the network uniformly over a period of time $T$. As suggested in [96], the value chosen for $T$ is one minute i.e. $T = 60$ seconds. This model can be considered a realistic scenario for typical MTC communications. In the second traffic model (TM2) a beta distribution was used to simulate an extreme scenario (e.g. after a power outage) in which a large number of MTC devices access the network in a highly synchronized manner within $T = 10$ seconds [96].

In case of the time limited beta distribution, it is assumed that all MTC devices are activate between $t = 0$ and $t = T$. Then, the access intensity (AI), i.e. number of new arrivals in the $i$th access opportunity, is given by [96]:

$$ AI_i = N \int_{t_i}^{t_{i+1}} \frac{t^{\alpha-1}(T-t)^{\beta-1}}{T^{\alpha+\beta-1}B(\alpha, \beta)} \, dt \quad \alpha > 0, \beta > 0, $$ (5.1)

where $t_i$ is the time of the $i$th access opportunity and $B(\cdot)$ denotes the beta function. As recommended in [96], the values of $\alpha = 3$ and $\beta = 4$ are used. The total number of MTC devices within the simulation area is denoted by $N$. In order to simulate mMTC scenarios, $N = 10,000$, $N = 30,000$ and $N = 100,000$ was chosen in Publication VII.

5.3.2 Numerical results

It was observed in Publication VII that the equally spaced azimuth directions used for ZF and MF beamforming did not have very significant differences in radiation patterns when the number of beams was near the
Dealing with Massive Machine Type Communications

Figure 5.3. Illustration of the radiation patterns obtained using ZF precoding and a circular array composed of 16 3GPP patch antennas. The ZF precoder nulls the inter-beam interference for the center paths of 10 equally spaced beams with random offset. Blue solid and red dashed lines illustrate two different zero-correlating codes, whose usage order is randomized.

optimal level. Furthermore, with both tested precoder options, the optimal number of beams was the same. However, ZF gave just slightly better performance with a higher number of beams, due to reduced inter-beam interference; see Fig. 5.3. Therefore, ZF was chosen for further studies.

Because each beam carried a separate UL grant, collision probability can be decreased by increasing the number of beams per TRP. Then, however, the probability of a decode failure is increased due to the fact that transmit beams become narrower and the chances are higher that there is interference to MTC devices from other beams sent by serving or neighboring TRPs. As can be seen from the results in 5.1, the optimal number of beams without utilizing coding settled to 6 beams per TRP. If inter-beam and inter-TRP interference is reduced by introducing the use of orthogonal codes, then collision and decode failure probabilities can be reduced. It has to be remembered that reducing decoding failures also reduces collisions, due to the lesser number of retransmitting users per RA occasion. Thus, the optimal number of beams settles to 10 when 2 zero-correlating codes were used. This is also illustrated in Fig. 5.4, where it can be seen that with 10 beams and 2 codes, the simulated access intensity is closer to the optimal. The optimal here is the new arrival access intensity, without
Table 5.1. Numerical results for obtaining valid grants with traffic model TM2. A total of 30,000 devices and a 5 ms connectionless access occasion periodicity is used.

<table>
<thead>
<tr>
<th></th>
<th>4 beams</th>
<th>6 beams</th>
<th>8 beams</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ZF w/o coding</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collision prob.</td>
<td>16.23 %</td>
<td>10.21 %</td>
<td>9.83 %</td>
</tr>
<tr>
<td>Decode failure prob.</td>
<td>20.97 %</td>
<td>21.77 %</td>
<td>33.99 %</td>
</tr>
<tr>
<td>Mean no of attempts</td>
<td>1.36</td>
<td>1.31</td>
<td>1.43</td>
</tr>
<tr>
<td>Attempt success prob.</td>
<td>66.4 %</td>
<td>70.5 %</td>
<td>60.2 %</td>
</tr>
<tr>
<td><strong>ZF w/ 2 codes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collision prob.</td>
<td>5.77 %</td>
<td>4.99 %</td>
<td>4.25 %</td>
</tr>
<tr>
<td>Decode failure prob.</td>
<td>5.99 %</td>
<td>6.67 %</td>
<td>8.38 %</td>
</tr>
<tr>
<td>Mean no of attempts</td>
<td>1.12</td>
<td>1.12</td>
<td>1.13</td>
</tr>
<tr>
<td>Attempt success prob.</td>
<td>88.6 %</td>
<td>88.7 %</td>
<td>87.6 %</td>
</tr>
</tbody>
</table>

Table 5.2. Simulation results for obtaining valid grant with 10 beams using 2 codes in random order and 5 ms connectionless access occasion periodicity

<table>
<thead>
<tr>
<th>Traffic model</th>
<th>no of devices</th>
<th>per attempt success prob. [%]</th>
<th>mean no of attempts</th>
<th>total success prob. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM2</td>
<td>100,000</td>
<td>77.1</td>
<td>1.24</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>88.6</td>
<td>1.12</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>92.4</td>
<td>1.08</td>
<td>100</td>
</tr>
<tr>
<td>TM1</td>
<td>100,000</td>
<td>90.7</td>
<td>1.09</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>90.8</td>
<td>1.08</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>92.8</td>
<td>1.07</td>
<td>100</td>
</tr>
</tbody>
</table>

retransmission attempts, obtained with Equation 5.1.

Table 5.2 shows simulation results related to UL grant reception that were obtained in citepubc5. It can be seen that with 10 beams and 2 zero-correlating codes rather high per attempt success probabilities can be achieved and all users are able to receive the grant in all simulated test cases. Furthermore, the mean number of attempts before successful grant decoding in all simulated mMTC test cases is close to unity.

Fig. 5.5 illustrates the UL SINR distribution when ZF precoding with 10 beams is used as a spatial filter for receiving UL transmissions transmitted using the same time, frequency and code resources. It can be seen that
Figure 5.4. TM2 new arrival access intensity with 30,000 devices and averaged simulated access intensities for ZF beamforming with optimal amount of beams for the cases of 2 codes and without coding. It can be seen that by using different codes the number of simultaneous attempts is close to optimal.

with uniformly distributed UL transmissions (TM1), there are on average fewer users who interfere with the transmissions of each other.

Table 5.3 shows simulated performance results obtained from the reception of small UL packets. In order to make 95% of UL data transmissions successful, the default MCS for connectionless UL transmissions is based on the 5th percentile SINR obtained in each simulation scenario. With this MCS, a simulated throughput was obtained separately for each test case. From this it was further calculated how many OFDM symbols from the frame structure shown in section 2.2 would be required in order to support the mMTC UL packet size of 200 bytes as suggested in [96]. On top of the application packet size, 40 bytes of internet protocol version 6 (IPv6) header, 8 bytes of user datagram protocol (UDP) header, and 5 bytes estimated for 5G NR protocol stack headers were assumed. In this study a 100 MHz bandwidth was assumed. With such a bandwidth assumption, mMTC UL transmissions would typically require less than 1% of the available physical time and frequency resources. Even if 100,000 devices should be handled within the simulated area during the high peak in access intensity, less than 3% of the physical resources allocated to mMTC UL would suffice.
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Figure 5.5. Cumulative SINR distribution function for connectionless UL transmissions when ZF precoding weight vectors for 10 beams are used as receive filters. All uplink transmissions are assumed to use the same time, frequency and code resources.

Table 5.3. 5th percentile device throughput and radio resource demand for providing successful connectionless UL transmissions for 95 % of the devices.

<table>
<thead>
<tr>
<th>Traffic model</th>
<th>no of devices</th>
<th>5th P SINR [dB]</th>
<th>Shannon simulated throughput [b/s/Hz]</th>
<th>resource demand [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM2</td>
<td>100,000</td>
<td>-6.18</td>
<td>0.31</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>-0.62</td>
<td>0.90</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>5.96</td>
<td>2.31</td>
<td>1.33</td>
</tr>
<tr>
<td>TM1</td>
<td>100,000</td>
<td>5.02</td>
<td>2.06</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>30,000</td>
<td>14.99</td>
<td>5.02</td>
<td>3.35</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>21.52</td>
<td>7.16</td>
<td>4.87</td>
</tr>
</tbody>
</table>

5.4 Discussion

It was shown that the method proposed in this thesis is able to handle mMTC UL transmissions with high success probability, low latency and low usage of physical resources. Thus, with a decent bandwidth plenty of resources are still available for HTC traffic, such as voice calls, video streaming, online gaming, social networking and web surfing. Furthermore, it can be expected that due to reduced latencies and signaling load also energy consumption is improved. Even though the main focus of this thesis is UDNs, it can be expected that a similar approach can be
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made applicable for larger cells with massive MIMO systems, too. Then, however, massive antenna arrays and deployment environments have to be considered in precoder design. Furthermore, timing advance should be considered by e.g. introducing guard periods for the UL resources granted for connectionless transmissions. Due to larger cell sizes also the number of MTC devices per beam is expected to increase. Hence, it might be appropriate to assign more than one grant per beam with separated physical resource allocation in order to reduce collision probability.

Problems caused by MTC and HTC sharing the same LTE-A RACH are also identified in many other papers. E.g. in [100] the severity of the problem was identified with realistic RA system level simulations. In [101] LTE RA is investigated in such a way that HTC is treated with higher priority than MTC. [102] studies RA parametrization in such a way that RACH preambles can be separated between HTC and MTC. In [103] a proposal is made to utilize a carrier sense multiple access with collision avoidance (CSMA/CA) overlay mechanism on a medium access control (MAC) layer. This allows MTC and HTC traffic to share the same RACH resources. However, in these studies NR technologies like advanced transmit and receive beamforming, which enable better utilization of spatial degrees of freedom, are not considered.

In [17] other solutions dealing with MTC are proposed. E.g. one interesting approach are grant-free\(^3\) transmissions. Grant-free solutions can reduce the signaling required by infrequent small packet UL transmissions to a minimum. However, due to the mostly occasional and unpredictable nature of the MTC traffic, grant-free solutions are potentially inefficient in the consumption of physical resources. Furthermore, the grant-free approach is designed for the RRC connected mode. Therefore, signaling is needed for establishing and/or maintaining the connection. The solution introduced in [17] is based on compressed sensing multi-user detection (CS-MUD) as well as sparse code multiple access (SCMA). This would allow TRPs to resolve multiple colliding transmissions in the code domain without knowing the number of transmissions in advance. However, in this approach the gain comes at the cost of additional receiver complexity. In [104], [105] grant-free transmissions are modified to be

\(^3\)A grant-free transmission can be defined as a transmission that does not require a grant indicating scheduled resources for the transmission.
OFDM compatible, which simplifies the receiver structure as well as the channel estimation. Benefits of the contention based small packet transmission mechanisms similar to the aforementioned grant-free schemes are also perceived for LTE in [106], [107].
6. Conclusions

Extensive densification of wireless networks and advanced MIMO solutions are the key building blocks for providing uniform desktop-like QoE also for the highly mobile UEs within the urban street canyons. As was shown in this thesis, the massive MIMO is not able to provide such service quality and capacity for highly mobile users in urban propagation environments. However, it is important to take also mobility into account because passengers in cars and buses become indoor-like users with high potential towards large data consumption. These users have time to spare for high data rate services like high quality video streaming, or accessing multiplayer cloud gaming services, to name but a few.

In order to design a NR concept that is able to reach targets like below 1 ms round trip time latency, to support advanced MIMO and location tracking of UEs, frame structure design plays a critical role. In this thesis guidelines for such a frame structure design were given in UDN context.

In this thesis a framework with decoupled time and frequency domain scheduling was described and further extended to also support spatial domain scheduling. These scheduling principles can be utilized in UDN as well as in larger cell deployment scenarios. Moreover, transmit and receive beamforming solutions, an alternative to the full-band CSI based beamforming, were studied. In particular, it was shown that the location based transmit and receive beamforming is an attractive alternative with low pilot overhead in UDN scenarios, where the line-of-sight probability is high.

Even though the massive MIMO had its difficulties in serving the mobile UEs, it was shown that massive antenna arrays can be well utilized (in addition to serving low mobility UEs) for efficient self-backhauling of
Conclusions

UDNs. This is important, because self-backhauling can offer a cost efficient alternative to building costly fiber links from a centralized control entity to each TRP under its control. Furthermore, it was shown that instead of the traditional TDM based division between backhaul and access links, SDM based solutions can be used with adequate frame structure and precoder designs.

Due to the rapid ongoing growth in the amount of connected things all around us, it is important to also consider the mMTC when designing solutions for the NR. In this thesis it was shown that with novel solutions extensive capacity potential of the urban UDN deployments can be harnessed for providing the mMTC access. In particular, it was shown that with the proposed UL access solution, small packet UL transmissions with low latency and high success probability can be provided with a fraction of the available physical time and frequency resources.

Moreover, these studies have provided insight for NR standardization. For example, the importance of supporting mobile users in dense urban outdoor environments was captured for 3GPP studies [20]. Additionally, UL-based mobility solutions, also proposed in this thesis, are being currently studied in 3GPP standardization [23] as an alternative solution for DL-based mobility.
References


References


References


