Performance Engineering of Mobile Broadband

- Capacity Analysis, Cellular Network Optimization, and Design of In-Building Solutions

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Abstract

The rapid evolution of mobile communication technologies is making mobile broadband a reality. With over 6 billion cellular connections and the booming of mobile data, mobile broadband leads the technology and service innovation within the domain of information and communication technologies. The thesis deals with performance engineering of mobile broadband. The problems investigated range from fundamental capacity analysis, resource planning and optimization of broadband cellular networks, to design of in-building solutions based on distributed antenna systems. Mathematical modeling and optimization methods have been used to approach the problems.

The first three papers address capacity analysis in wireless communications, where the establishment of any communication link is subject to the Signal to Interference plus Noise Ratio (SINR) threshold. Paper I addresses the maximum link activation problem. The paper introduces a new exact algorithm by reformulating the SINR constraints with equivalent but numerically more effective inequalities, leading to an approach performing significantly better in proving optimality in comparison to the conventional algorithm. Paper II explores the notion of collaborative rate selection for Interference Cancellation (IC) to maximize the transmission rate in wireless networks. The paper analyzes the problem complexity and develops integer programming models for both single stage single-link IC and single stage parallel IC. Paper III studies the performance gain of single-stage and multi-stage IC to optimal link activation. Compact integer programming formulations have been developed and a thorough numerical study is performed.

The next three papers are devoted to planning and optimization of radio resources in cellular mobile broadband networks. Paper IV considers a minimum-power coverage problem with overlap requirements between cell pairs. The paper develops two integer programming models and compares their strength in approaching global optimality. A tabu search algorithm has been developed for large-scale networks. Paper V deals with transmission power planning and optimization in High Speed Downlink Packet Access (HSDPA) networks. A method for enhancing the HSDPA performance by minimizing the power for coverage and reallocating the power to data transmission has been considered. A mathematical model targeting cell-edge HDSPA performance and accounting for soft handover in Universal Mobile Telecommunications System (UMTS) has been developed. In addition, heuristic algorithms

based on local search and repeated local search are developed. Paper VI focuses on frequency planning for inter-cell interference mitigation in Orthogonal Frequency Division Multiple Access (OFDMA) networks. The paper generalizes the standard Fractional Frequency Reuse (FFR) concept and addresses its performance for networks with irregular topology. Optimization algorithms using local search have been proposed to find the frequency reuse pattern of generalized FFR for maximizing the edge-user performance. The investigations in Papers IV-VI base the experiments on data sets representing realistic planning scenarios to demonstrate the effectiveness of the proposed approaches.

To face the challenge of in-building mobile broadband service, In-Building Distributed Antennas Systems (IB-DAS) has been proposed. Paper VII tackles the problem of optimal topology design of IB-DAS systems, where a number of in-building distributed antennas are connected to a base station via coaxial cables and power equipments. The paper develops efficient mathematical models for topology design as well as equipment selection, and presents case studies of realistic IB-DAS deployment scenarios.

Populärventenskaplig sammanfattning

Teknikutvecklingen inom mobil telekommunikation har varit synnerligen snabb, vilket medfört att vi idag har möjlighet att ansluta till Internet och uppnå höga dataöverföringshastigheter med mobila kommunikationsenheter. Tillgången till mobilt bredband har resulterat i en enorm ökning av datatrafik i mobila telekommunikationsnätverk, och detta driver på utvecklingen av såväl nya kommunikationstekniker som tjänster. Den här avhandlingen relaterar till ovanstående genom att problemformuleringarna kretsar kring att uppnå bättre funktionalitet i mobila nätverk avsedda för datatrafik, med specifikt fokus på kapacitetsanalys, och resursplanering och optimering. Avhandlingen berör även uppbyggnad av kommunikationsinfrastruktur i byggnader, där syftet är att optimera täckning och kapacitet för mobila användare som befinner sig inomhus. I avhandlingen framgår det hur förbättrad prestanda kan uppnås med hjälp av matematisk modellering och optimeringsmetoder.

Kapacitetsanalys gör att man kan erhålla värdefull information för hur resurser lämpligen ska fördelas mellan användare i mobila nätverk. I samband med trådlös kommunikation skickas information med hjälp av elektromagnetiska vågor, som är kopplade till specifika frekvenser. Om flera användare väljer att skicka information med samma frekvens så uppstår interferens, vilket medför att användarna stör varandra och överföringskapaciteten minskar. Genom kapacitetsanalys är det möjligt att identifiera hur många som maximalt kan skicka information samtidigt, utan att kommunikationen fallerar. I avhandlingen presenteras en kompakt heltalsmodell som har avsevärt bättre egenskaper i jämförelse med konventionella modeller. Dessutom behandlas kapacitetsanalys med inriktning mot interferenseliminering, där man drar nytta av den interferens som uppstår för att eliminera vissa signaler, vilket kan medföra högre överföringshastighet. Avhandlingen berör olika typer av interferenseliminering och numeriska studier som baseras på utvecklade kompakta heltalsmodeller, samt redovisar de effekter som kan uppnås.

Optimering och god planering av mobila nätverk är av stor betydelse för att resurser som frekvenser och energi ska nyttjas på bästa sätt. Avhandlingen berör detta genom att bland annat attackera olika varianter av problem som syftar till att minimera den effektförbrukning som åtgår för att ge täckning till mobila användare inom en specifik geografisk yta. Om effektförbrukningen kan minskas ger det möjligheter att förbättra kommunikationsförutsättningarna för användare som befinner sig i utkanten av ett täckningsområde, och som därför ofta har dåliga kommunikationsförhållanden. Avhandlingen handlar även om utmaningar som relaterar till nyttjande av frekvenser och hur dessa kan återanvändas för mobila nätverk som avser täcka geografiska ytor med varierande karaktär. Arbetet kring detta har resulterat i nya optimeringsmodeller och -algoritmer som presenteras i avhandlingen.

För att förbättra möjligheten till god täckning och hög överföringskapacitet för mobila användare som befinner sig i byggnader kan antenner lämpligen placeras inomhus. Dessa inomhusantenner, som installeras i närhet till användarna, ger förbindelse till ett traditionellt mobilt nätverk genom att de är anslutna till kommunikationsutrustning som är lokaliserad utanför byggnaden, och som har goda förutsättningar för att kommunicera med den basstation som mobila nätverksoperatören har upprättat i syfte att täcka in den yta där byggnaden är placerad. I avhandlingen presenteras modeller för optimal utformning av kommunikationsinfrastruktur i byggnader. Modellernas egenskaper har undersökts med hjälp av fallstudier.

Acknowledgement

As one of the achievements of my PhD studies, this dissertation concludes the research carried out at the Division of Communication and Transport Systems (KTS) at Linköping University (LiU).

First and foremost, I would like to thank my supervisor, Professor Di Yuan, who gave me the opportunity to study and conduct research at the division. I am lucky enough to have such a great supervisor. His excellent guidance and continuous help have led to my academic maturity in both the area of operational research and telecommunications. It has been a fantastic experience to work with him and I am very pleased for what I have learned from him.

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Finally, I would like to express my thanks to my family for their love and support, and to my friends for their encouragement and support all the time.

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Contents

Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
ABSF	Almost Blank Sub-Frame
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone Service
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CoMP	Co-ordinated Multi-Point
D-AMPS	Digital AMPS
D2D	Device-to-Device
DC-HSPA	Dual-carrier High Speed Packet Access
DC-HSUPA	Dual-carrier High Speed Uplink Packet Access
DCA	Dynamic Channel Allocation
DCH	Dedicated Channel
E-DCH	Enhanced Dedicated Channel
EDGE	Enhanced Data rate for GSM Evolution

eICIC	Enhanced Inter-cell Interference Coordination
EUL	Enhanced Uplink
EV-DO	Evolution-Data Optimized
FAP	Frequency Assignment Problem
FDMA	Frequency Division Multiple Access
FFR	Fractional Frequency Reuse
FH	Frequency Hopping
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat-reQuest
HS-DSCH	High Speed Downlink Shared Channel
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IB-DAS	In-Building Distributed Antenna System
IC	Interference Cancelation
ICIC	Inter-cell Interference Coordination
IMS	IP Multimedia Subsystem
IMT-2000	International Mobile Telephone 2000
IP	Integer Programming
IP	Internet Protocol
ITU	International Telecommunication Union
LA	Link Activation
LA-IC	Link Activation with Interference Cancelation
LP	Linear Programming

LS	Local Search
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MBMS	Multimedia Broadcast/Multicast Services
MI-FAP	Minimum Interference Frequency Assignment Problem
MILP	Mixed Integer Linear Programming
MIMO	Multiple Input and Multiple Output
MTC	Machine Type Communications
MUD	Multi-User Decoding
NMT	Nordic Mobile Telephone
NP-hard	Non-deterministic Polynomial-time hard
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
OR	Operational Research
PAPR	Peak-to-Average Power Ratio
PC	Power Control
PDC	Personal Digital Cellular
PIC	Parallel Interference Cancelation
QAM	Quadrature Amplitude Modulation
R10	3GPP Release 10
R11	3GPP Release 11
R12	3GPP Release 12
R4	3GPP Release 4
R5	3GPP Release 5
R6	3GPP Release 6
R7	3GPP Release 7

R8	3GPP Release 8
R9	3GPP Release 9
RAT	Radio Access Technology
RN	Relay Node
RNC	Radio Network Controller
RRM	Radio Resource Management
SAE	System Architecture Evolution
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFR	Soft Frequency Reuse
SHO	Soft Handover
SIC	Successive Interference Cancelation
SINR	Signal-to-Interference-and-Noise Ratio
SIR	Signal-to-Interference Ratio
SLIC	Single Link Interference Cancelation
TACS	Total Access Communication System
TDMA	Time Division Multiple Access
TS	Tabu Search
UMTS	Universal Mobile Telecommunication Systems
WCDMA	Wideband Code Division Multiple Access

1 Mobile Broadband

1.1 Mobile Data Explosion

The great success of mobile data communications has been changing the way of people's working and living. Mobile services, nowadays, have become one of the essential parts for every day life. According to Cisco, global mobile data in 2012 grew by 70% to 885 petabytes (PB) (1PB = 10^{15} bytes) per month, which was over twelve times greater than the total global Internet traffic in 2000. Major factors which have contributed to the mobile data explosion include but are not limited to the following:

- Ever increasing capacity of radio networks: The continuous evolution of radio networks has brought the peak data rate to 14.4 Mbps for downlink and 5.76 Mbps for uplink in the current 3G networks. New advanced technologies will bring this data rate even higher.

- Powerful smart mobile devices: Today's mobile devices (smart phones, tabs, laptops, etc.) are equipped with powerful processors which are able to deal with faster and advanced computations. Cisco data shows that the number of mobile devices will exceed the world's population in 2013. In view of the data generated from those devices, the statistic from 2012 shows that a smart phone generates 50 times more data than a basic phone, while a mobile connected tablet and laptop generate 2.4 times and 7 times more traffic than a smart phone, respectively. It is estimated that in 2013, data traffic generated from handsets will exceed 50% of the total mobile data traffic. The popularity of smart devices continues driving the explosion of mobile data.

- Stunning innovative services: The powerful smart devices come with fresh innovative services. With the popularity of the mobile computing ecosystem such as Android from Google Inc., iOS from Apple Inc., as well as Windows mobile platform from Microsoft Corporation, services which can only be supported in wire-line networks before are migrating to the mobile platform. Multimedia streaming, social networking, various cloud based services, and so on, are all generating large amounts of data. With the evolution of mobile platforms, new data driven services will continue to appear and contribute to the mobile data explosion.

Innovative technologies have escalated customers' demand for being connected to the network anywhere and anytime. As shown in Fig. 1.1, the mobile

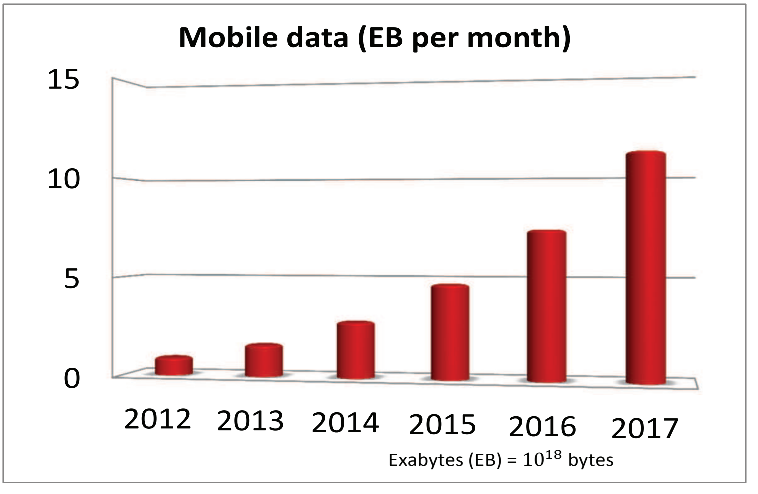

Figure 1.1: Mobile data explosion.

data is expected to grow significantly. A 13-fold increase of mobile data over 2012 is predicted by Cisco Visual Networking Index [1] for the year 2017. To deal with such a mobile traffic explosion, standardization groups such as 3GPP, together with industries and academics, have been working on continuously advancing the radio networks for the next generation, where various new concepts and technologies will be introduced.

1.2 Mobile Broadband Evolution

First introduced by Bell Laboratories in 1947, cellular technology has been widely applied in the radio communication networks. Since then, the fast developing cellular based radio networks has continuously pushed up the mobile network speed, making the mobile broadband a reality today.

The first generation (1G) cellular networks started to be deployed in the 1980s. Representative networks included the Nordic mobile telephone system (NMT) in Scandinavia, the total access communication system (TACS) in the UK, and the advanced mobile phone service system (AMPS) in America. 1G systems were based on analog technology and frequency division multiple access (FDMA). Due to the nature of analog technology, 1G systems provided very limited services and suffered from many limitations, such as poor communication quality, low frequency utilization, low security, and so on.

Since the 1990s, digital-communication-based second generation (2G) systems started to be deployed. The principle of digital communications is fundamentally different than that of analog technology. It brings with many advantages such as noise immunity, reliable communications, higher security, and so on. Besides FDMA, new access technologies such as time division multiple access (TDMA) and code division multiple access (CDMA) were adopted. Primary systems in 2G included the global system for mobile communications (GSM), interim standard 136 (IS-136, aka Digital AMPS, or D-AMPS), IS-95 (aka CDMAone), and the personal digital cellular (PDC) system. GSM, D-AMPS and PDC were based on TDMA while IS-95 was based on CDMA. GSM was firstly introduced in Europe and later was implemented in many countries in the rest of the world. D-AMPS evolved from AMPS and was deployed in America, Israel and some of the Asian countries. PDC was available in Japan only. IS-95 has been mostly implemented in North America and Asia.

2G systems primarily provided voice services. New services such as short messaging and low speed data service were also provided. The successful deployment of 2G systems pushed people's demand for data services. As part of the International Mobile Telephone 2000 (IMT-2000), the International Telecommunication Union (ITU) defined the data requirements for the next generation radio networks, referred to as the third generation (3G), to 144 kbps at driving speeds, 384 kbps at pedestrian speeds, and 2 Mbps in indoor environments. Before 3G requirements became fully fulfilled, a number of upgrades were introduced as low-cost and intermediate solutions to provide data services. The high-speed circuit switched data (HSCSD) for GSM networks was the easiest to be deployed as it was circuit switched. However, it suffered from poor frequency utilization. Soon, packet-switching-based technology, the general packet radio service (GPRS), was introduced. GPRS provided best-effort data services by utilizing free TDMA channels dynamically. A speed up to 114 kbps could be provided. Further enhancements of GPRS led to the enhanced data rate for GSM evolution (EDGE), which pushed the data rate up to 384 kbps, satisfying ITU's requirements of 3G networks. The evolution of EDGE, aka Evolved EDGE, introduced downlink dual-carrier support, higher order modulation schemes, and so on, that pushed the data rate further up to 1.89 Mbps for downlink and 947 kbps for uplink. EDGE is widely deployed over the current GSM network as a complementary network with other 3G networks. Meanwhile, IS-95 systems evolved to the CDMA2000 1 times radio transmission technology (CDMA2000 1xRTT) and further to CDMA2000 EV-DO. Providing a speed up to 2.4 Mbps, CDMA2000 EV-DO was also considered one of the 3G standards.

Another 3G standard, which dominates the 3G network deployment, is the 3rd generation partnership project (3GPP) universal mobile telecommunication systems (UMTS). To offer a higher spectral efficiency and greater bandwidth, UMTS introduced wideband CDMA (WCDMA). The first release of UMTS was introduced in the year of 1999 and was referred to as 3GPP R99. R99 provided a peak user data rate of up to 350 Kbps for downlink and uplink. Practically, up to 300 Kbps can be achieved. The introduction of UMTS boosted the evolution of 3G networks. After R99, UMTS evolved rapidly. Release 4 (R4), introduced in 2001, started to support multimedia messaging, forming the first step towards the internet protocol based core network. In 2002, Release 5 (R5) was introduced. R5-enabled networks were also referred to as high speed downlink packet access (HSDPA) networks. HSDPA introduced new technologies such as hybrid automatic repeat-request (HARQ) , fast packet scheduling, adaptive modulation and coding (AMC) schemes, and so on, and provided fully IP transport. Up to 14 Mbps downlink speed and 384 kbps uplink speed were achieved with R5. In 2005 Release 6 (R6) was introduced, where the enhanced uplink (EUL), aka high speed uplink packet access (HSUPA) brought the uplink speed up to 5.76 Mbps. Moreover, multimedia service was also enhanced with the support of multimedia broadcast/multicast services (MBMS). HSDPA and HSUPA networks are together referred to as high speed packet access (HSPA) networks. Further enhancements of HSPA networks were provided in Release 7 (R7), aka HSPA+, introduced in 2007. Higher order modulation, such as 64 QAM for downlink and 16 QAM for uplink, was introduced. Multiple input and multiple output (MIMO) was introduced, and up to 2x2 MIMO was supported. This enabled a downlink speed of up to 42 Mbps and uplink speed of up to 11.5 Mbps. HSPA+ was further enhanced in Release 8 (R8), which was frozen in 2008, where dual-carrier HSDPA (DC-HSDPA) was supported. Meanwhile, simultaneous use of MIMO and 64 quadrature amplitude modulation (QAM) was supported. The enhancements enabled a downlink speed of up to 84 Mbps and uplink speed of up to 23 Mbps over a 10 MHz bandwidth.

Together with the enhancements over HSPA networks, R8 specified the first release of the 3GPP long term evolution (LTE). Different from the previous UMTS networks, where radio access is based on WCDMA, LTE adopted orthogonal frequency division multiple access (OFDMA) for downlink radio access. OFDMA splits the frequency band into a number of orthogonal subcarriers, where each of them carries an independent data stream. Uplink radio access follows a similar concept. However, to combat the high peak-to-average power ratio (PAPR), a linearly pre-coded OFDMA, aka single carrier FDMA (SC-FDMA), was adopted for uplink. A flexible bandwidth utilization scheme was adopted, where bandwidth of 5, 10, 15, 20 MHz and bandwidth smaller than 5 MHz were supported. With 2x2 MIMO and 10 MHz bandwidth, LTE delivered a peak data speed of 70 Mbps for downlink and 35 Mbps for uplink. Together with the introduction of new radio access technologies, a flat all-IP network architecture evolution, aka system architecture evolution (SAE) was defined in R8. SAE evolved from the GPRS network, but with a substitution of the GPRS core network by the new evolved packet core (EPC). Compared with the previous GPRS architecture, SAE provided a simplified architecture which supported high throughput with low latency and handover among legacy 3GPP networks (such as GPRS and UMTS), LTE and non-3GPP systems (such as CDMA2000). The first commercial LTE service was provided by TeliaSonera in Stockholm and Oslo in 2009. Since then, the deployment of LTE networks has gained a very fast pace. At present, up to 150 LTE networks over 67 countries are in service while in total 450 networks are planned or in trial. Over 250 networks are expected to be in service by the end of 2013 [2].

In 2008, ITU issued the requirements for IMT-Advanced, aka the fourth generation (4G). With peak spectral efficiency up to 15 bps/Hz and the operation over 100 MHz bandwidth, the throughput can reach 1.5 Gbps in 4G networks. Normally, over 1 Gbps throughput is considered as the goal for the 4G networks. To meet the IMT-Advanced requirement, further enhancements and features have been continuously added to the standards. Advanced network topology, aka heterogeneous networks (HetNet), where different radio access technologies (RATs) are operating simultaneously, started to be considered for further increasing the spectral efficiency. In 2009, Release 9 (R9) was finalized, where dual-carrier HSUPA (DC-HSUPA) was introduced for HSPA networks. Combination of MIMO and DC-HSDPA was supported. For 3GPP LTE networks, further enhancements over the EPC and IP multimedia subsystem (IMS) architecture were included. Femto-cell started to be supported by 3GPP. Later in 2010, Release 10 (R10) became complete. The main feature of R10 is the introduction of LTE-Advanced (LTE-A) networks, where the 4G requirements become fulfilled. LTE-A introduced many new features and enhancements such as carrier aggregation (CA), enhanced MIMO operation for both downlink and uplink, relay nodes (RN) and enhanced inter-cell interference coordination (eICIC), and so on. For a 40 MHz bandwidth, LTE-A is able to provide a rate of up to 1.2 Gbps for downlink and 568 Mbps for uplink. Meanwhile, R10 also introduced quad-carrier support for HSPA networks. The current release under standardization is release 11 (R11), which is expected to be finalized early 2013. For LTE networks, co-ordinated multi-point (CoMP) transmission is introduced to allow coordinations between different cells. Enhancements have been made to the CA, eICIC, as well as downlink and uplink MIMO. Interference-cancellation enabled devices are introduced. For HSPA+ networks, 8-carrier operation is supported. Multi-point transmission, non-contiguous CA and 4x4 MIMO are also introduced for the downlink. For uplink, 64 QAM is introduced. With R11 approaching the final stage, release 12 (R12) has been planned and under discussion. Some potential features such as the enhanced HetNet operation, 3D MIMO and beamforming, machine type communications (MTC), device to device (D2D) communications, are under investigation. Further enhancement of HSPA+ networks are also considered.

Besides the 3GPP family, another standard that also fulfills the 4G requirements is the worldwide interoperability for microwave access (WiMAX). WiMAX is specified in the IEEE 802.16 series and was previously widely deployed worldwide. However, with the fast development and deployment of LTE standards, the deployment of WiMAX has slowed down or even stopped. It is anticipated that the future 4G network will be dominated by the 3GPP LTE standards.

Before 4G is fully in place, discussion on the fifth generation (5G) has started in the UK. However, at present, there is no clear definition or quantitative criteria for 5G. To summarize, we give an illustration of the evolution of mobile broadband networks in Fig. 1.2. More detailed discussion of the mobile broadband evolution can be found in [3, 4, 5, 6, 7, 8, 9].

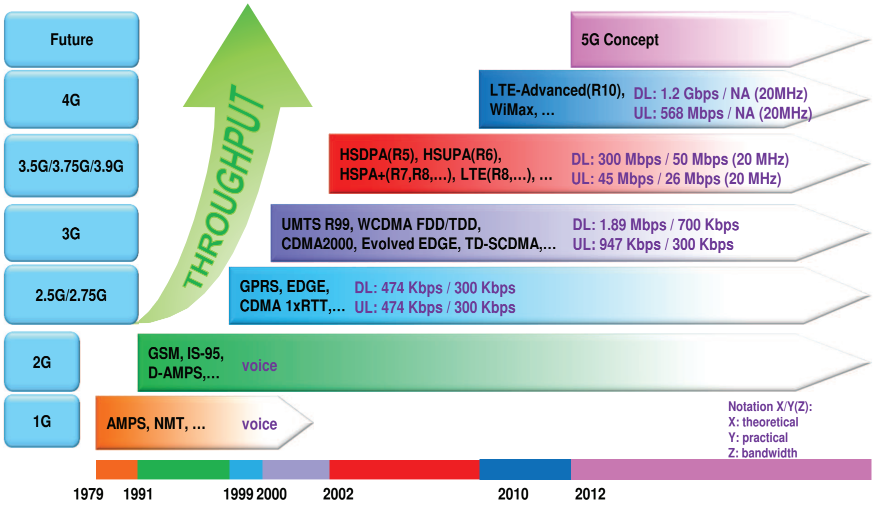

Figure 1.2: Evolution of cellular technology.

2 Network Planning and Optimization

Planning and optimization play a key role in reducing the capital expenditure (CAPEX) and operational expenditure (OPEX) for deploying and expanding systems for mobile broadband. Many issues arise during the development and deployment of mobile broadband radio networks. Fundamental issues such as capacity analysis for interference limited wireless communications remains as a challenge problem to solve. Efficient algorithms and advanced technologies for combating interference are critical to boost the network capacity. Practical issues such as coverage planning, capacity planning, radio resource management, and so on, form the core components for the successful deployment and operation of mobile broadband networks. 1G networks had little requirement for planning and optimization as the capacity demand was quite low. With the popularity of 2G and 3G networks, especially the explosion of data demand, mobile broadband network planning and optimization become more and more challenging. Radio resources, such as power and frequency spectrum, are valuable, thus, efficiently utilizing them is crucial for fulfilling the increasing capacity demand and boosting the users' experiences. In-building data traffic has already dominated the data services, and will contribute even more to the mobile traffic. However, due to the complex in-building radio propagation environment, coverage and capacity planning require new solutions. The thesis focuses on three major planning and optimization issues in mobile broadband networks. We give a brief introduction and present the background for each of them below. Additional discussions over mobile broadband network planning and optimization can be found in, for example, [10, 11, 12, 13].

2.1 Capacity Analysis for Wireless Communications

Wireless communication systems is typically interference limited, where co-channel transmissions are posing interferences to each other. To establish a transmission, the signal-to-interference-and-noise ratio (SINR) at the receiver side should reach a threshold [14], as illustrated in Fig. 2.1.

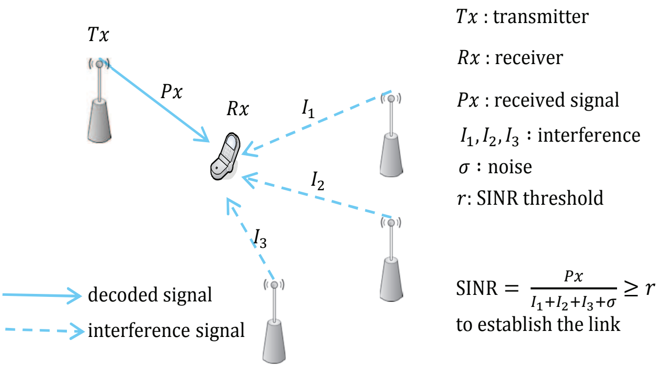

Figure 2.1: An illustration of interference.

One of the fundamental optimization problems in wireless network engineering is to find out the maximum number of simultaneous transmissions, subject to the SINR requirement at each receiver, aka maximum link activation (LA). Solving the problem is part of the radio resource management algorithms in wireless communications, such as scheduling, where a set of parallel transmissions need to be selected for a certain time slot. Solving LA involves numerically difficult SINR constraints, thus requiring large amount of computing resources and time. An efficient algorithm which can deliver the global optimal is highly desired.

Another aspect of capacity analysis is the introduction of advanced receivers with interference cancellation (IC) capability, such as in LTE-Advanced. IC allows the receiver to cancel interference from certain transmitters (usually strong interfering transmitters) if the receiver can decode the interference signal. Successful cancellation will remove the canceled interference from the total received interference, therefore, decoding the interested signal becomes easier. This potentially can activate a transmission which cannot be established without IC, or achieve a better SINR, thus higher transmission rate, for links which can be established but having poor signal condition. The concept of IC is shown in Fig. 2.2 where Rx_1 cancels the interference from Tx_2 before decoding the signal from Tx_1.

IC brings benefits and challenges. LA with IC (LA-IC) involves solving both the SINR constraints for each receiver, as well as similar conditions for determining whether IC can be enabled. This adds extra difficulties in solving the

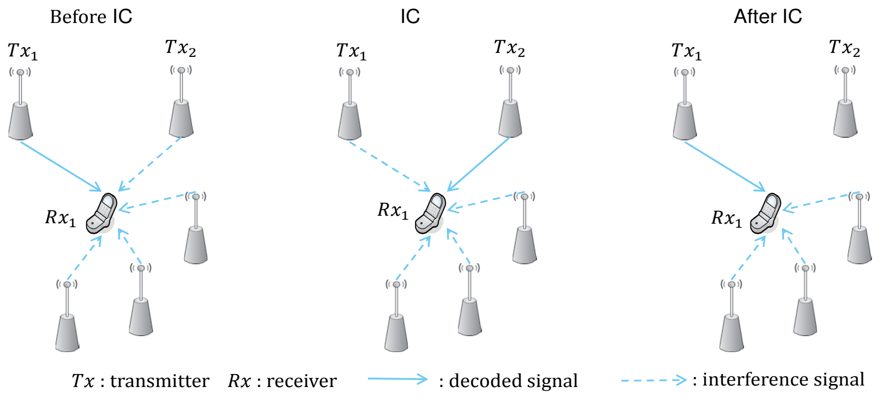

Figure 2.2: Illustration of interference cancellation.

problem. With the fast deployment of LTE networks and the rapid standardization of LTE-A, it can be foreseen that future hand devices will mostly have IC enabled. Therefore, solving LA-IC not only gives insight for the capacity of future networks, but also provides methods to further explore the spectral efficiency.

2.2 Radio Resource Management (RRM)

RRM is a fundamental function in mobile broadband networks. It ensures that the networks operate efficiently by scheduling the resources carefully, such as frequency, power, time slots, etc.

- *Frequency planning* is a vital issue in wireless communication networks. The frequency spectrum is limited and has to be utilized efficiently. As transmissions over the same frequency band cause interference to each other, different frequencies should be assigned to neighboring cells to avoid interference. One example is shown in Fig. 2.3. The differentiation between frequencies are shown with colors. The fading of the color indicates that received signal level decreases in the distance from the radio base station.

  Frequency assignment problem (FAP) is one of the classic problems in 2G GSM networks. FAP involves assigning a small number of frequencies to a large number of sites to maximize the spectrum ef-

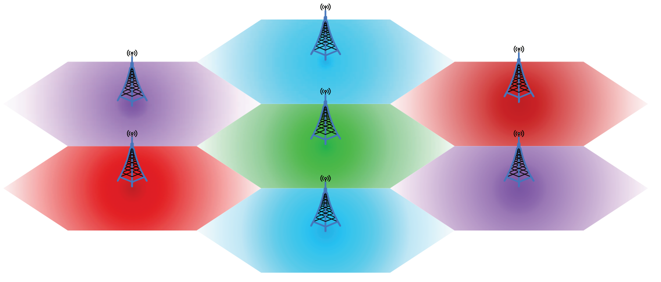

Figure 2.3: An illustration of frequency assignment.

ficiency and minimize the interference. Many optimization methods and algorithms have been proposed for FAP in GSM networks [15, 16, 17, 18, 19, 20, 21, 22, 23]. Planning strategies for more advanced frequency use, such as frequency hopping (FH) [24, 25] and dynamic channel allocation (DCA) [26, 27], have also been proposed. 3G UMTS networks are based on WCDMA with full frequency reuse, but differentiate transmissions with codes, thus frequency planning is not present. With the use of OFDMA in 4G LTE networks, frequency planning again becomes important. Co-channel deployment will cause severe inter-cell interference to the cell-edge users, leading to very poor SINR for those users. Inter-cell interference coordination (ICIC) techniques by frequency planning, such as fractional frequency reuse (FFR) [28, 29, 30] and soft frequency reuse (SFR) [31] schemes have been proposed in R8 and R9. The aim of those methods are to reach a balance between the spectral efficiency and the performance for cell-edge users.

A heterogenous network topology consists of multiple tiers of networks (Macro, Micro, Pico, Femto, RN, etc). The tiers apply different RATs (3GPP family, WiMAX, Wi-Fi, etc.). The RATs may be working within the same frequency band for improving the spectral efficiency, thus causing again inter-cell interferences, aka cross-tier interferences. 3GPP R10 considers the heterogenous networking scenario and proposes the enhanced inter-cell interference coordination (eICIC) schemes [32].

- *Power control (PC)* is another issue in wireless networks. Radio transmission power plays a key role in interference management, energy consumption, as well as service quality. In 2G systems, where the service is mainly voice and with a fixed target signal-to-interference ratio (SIR), PC is mainly used to combat the near-far effect. Later in 3G networks, the achievable SIR varies, depending on the resource allocation algorithms used. PC in such systems is of high significance for improving the network performance. Extensive research has been done for PC mechanisms with both fixed SIR and variable SIR. A number of algorithms have been proposed such as opportunistic PC, PC based on game theory, joint PC and beamforming, etc. A survey of PC algorithms in 2G and 3G systems can be found in [33].

In 4G networks, PC serves one of the major methods in ICIC and eICIC, together with frequency planning. For example, a high power profile can be used for cell-edge users, which are more interference sensitive, on frequencies that are not used by neighboring cells; a lower power profile can be used for center users, which can tolerate a certain level of interference, over all available frequencies. To deal with cross-tier interference in heterogeneous networks, a PC method called almost blank sub-frame (ABSF), is proposed. ABSF indicates some cells not to put traffic on some of the frequencies so that other cells can transmit traffic over those frequencies without cross-tier interference. It is worth mentioning that PC in RRM is closely working with other methods, such as frequency planning.

Frequency and power are not independent resources and they need to be scheduled jointly. The main function of RRM is to allocate the resources, such as frequency, power, and so on, and schedule them in an efficient way to improve the network performance. In 3GPP R99, where a dedicated channel (DCH) is defined, scheduling is done at the radio network controller (RNC). In order to adapt to the channel conditions rapidly, HSDPA introduced a downlink shared channel (HS-DSCH) and moved the scheduling to the Node B. HSUPA implemented fast scheduling with the introduction of enhanced DCH (E-DCH) for uplink. A vast amount of literature has been devoted to scheduling algorithms and RRM strategies [34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44].

The adoption of OFDMA gives LTE full flexibility in the allocation of frequencies and power. LTE downlink resource grids consist of resource blocks (RBs), where each RB includes a number of sub-carriers and a number of OFDM symbols. Fig. 2.4 shows a typical scenario where each RB consists of 12 sub-carriers that together take a total bandwidth of 180 KHz, and 7 OFDM symbols which form one time slot of 0.5 ms.

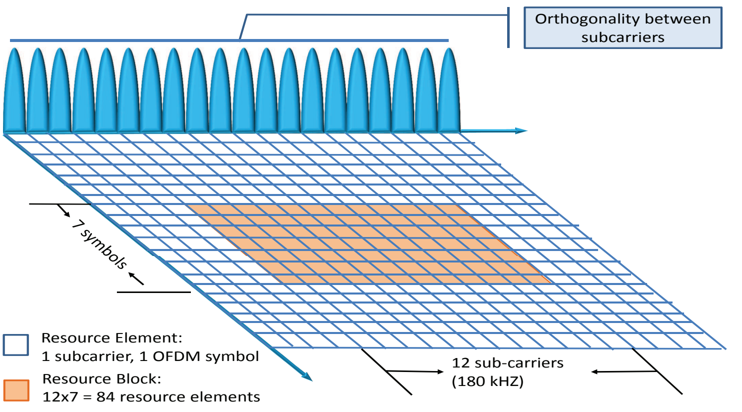

Figure 2.4: Resource Block in LTE networks.

The number of RBs depends on bandwidth. In LTE, up to 100 RBs can be allocated for a bandwidth of 20 MHz. The number will be doubled when a 40 MHz bandwidth is supported in LTE-A. The power allocation is jointly done with RB allocation. RB scheduling in LTE networks is a core function of RRM and plays a critical role in improving the network performance and mitigating the inter-cell interference. Numerous articles investigated resource allocation strategies for OFDMA networks [45, 46, 47, 48, 49, 50, 51, 52, 53]. For LTE, algorithms can be found in [54, 55, 56, 57, 58, 59, 60, 61, 62, 63].

2.3 In-building Solutions

Along with the mobile data explosion, the mobile traffic distribution has shown a very uneven trend. More than 70% of the total traffic has been generated by in-building users, necessitating an efficient in-building solution. In-building environment is naturally unfavorable for signal transmission because of the signal loss for wall penetration and multi-path propagation. The in-building users who are served by conventional macro-cells usually have low signal quality, resulting in poor user experiences. Typically, wall penetration brings 20-25 dB power loss, resulting in either poor in-building coverage, or high transmit power at the base station and the user equipment. Wi-Fi access has long been used by home users for wireless connection. It has been considered in the heterogeneous network architecture as an integral part, where it is expected to be able to connect to the mobile broadband core network in the future. Femto-cells, aka home eNodeBs, are small radio cells connected to the mobile broadband core network, and usually cover a very small area for home and office users. The current deployment of Wi-Fi and Femto-cells, in most of the cases, are customer based, although it can also be deployed by operators. Therefore, the operators have little control of the deployment, thus cross-tier interference is a potential problem.

Another systematic solution for medium to large sized buildings is to use in-building distributed antenna system (IB-DAS). Instead of using macro-cells, IB-DAS deploys a number of in-building antennas for coverage. In-building antennas are preferably serving the users via a line-of-sight transmission, thus a much better propagation condition can be achieved.

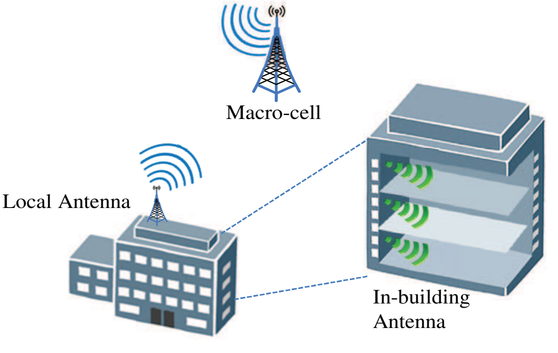

Figure 2.5: In-Building Distributed Antenna Systems.

Deploying IB-DAS involves connecting all the in-building antennas to the roof antenna which is then connected to the macro-cell via radio links, as illustrated in Fig. 2.5. The indoor connections are mostly done with coaxial cable and power equipment such as power splitters. The locations for in-building antennas and their power levels are pre-calculated according to the coverage planning and capacity requirements. Then, IB-DAS planning is performed to connect the in-building antennas to the roof antenna with minimum cost, where the cost is dominated by the cable usage. Successful deployment of IB-DAS can, to a large extent, avoid coverage holes, help reduce the power consumption and deliver excellent user experiences for in-building subscribers.

3 Mathematical Modeling and Applied Optimization

The thesis has applied mathematical modeling and optimization methods as the main tool to approach the problems arising from planning and optimization of mobile broadband networks. Linear programming (LP) models, integer programming (IP) and mixed integer linear programming (MILP) models as well as various search algorithms have been developed.

3.1 Linear Programming

LP involves solving a problem of minimizing or maximizing a linear cost function subject to a number of linear equality and inequality constraints. All variables are continuous in LP. A general LP formulation can be written as,

$$\begin{aligned} max \quad & \mathbf{c^T x} \\ s.t. \quad & \mathbf{Ax} \geq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{aligned}$$

in which $\mathbf{c}$ is the vector of objective coefficients, $\mathbf{x}$ denotes the vector of non-negative variables and $\mathbf{b}$ is a column vector. $\mathbf{c^T}$ is the transposed vector of $\mathbf{c}$. $\mathbf{c^T}x$ defines the objective function, where $\mathbf{x}$ should be found within the polyhedron defined by constraints $\mathbf{Ax} \geq \mathbf{b}$, and $\mathbf{x} \geq \mathbf{0}$. Notice that converting the above maximization problem to a minimization problem is straightforward. A simple linear program with two variables and five inequality constraints is shown in Fig. 3.1. In general, one of the extreme points is optimal, if the LP has bounded optimum, as illustrated in the figure. For more detailed discussions of LP, the readers are referred to [64].

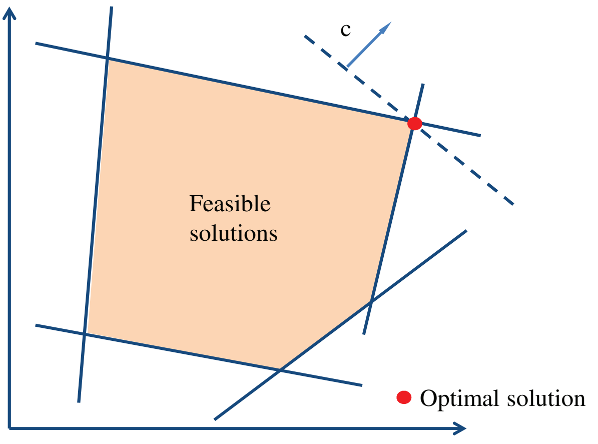

Figure 3.1: Illustration of a linear program.

3.2 Integer and Mixed Integer Linear Programming

In many of the practical problems, variables are required to have integer values. In such a case, the formulation of the problem is similar to LP, but with integer requirements on the variables. Those problems are referred to as IP problems. A general formulation of IP problems is shown below.

$$
\begin{aligned}
max \quad & \mathbf{c}^{\mathbf{T}}\mathbf{x} \\
s.t. \quad & \mathbf{A}\mathbf{x} \geq \mathbf{b} \\
& \mathbf{x} \geq \mathbf{0} \\
& \mathbf{x} \quad integer
\end{aligned}
$$

When all variables are required to be integer, the solution space becomes a discrete set of integer points, which is illustrated in Fig. 3.2. As can be seen, the optimal point changes from the extreme point of the continuous solution space in LP to the point where all the variables have integer values and the objective value is the best possible one. In the case where only some of the variables are required to have integer values, the problem is referred to as MIP. Interested readers are referred to literature of IP, in particular [65, 66, 67].

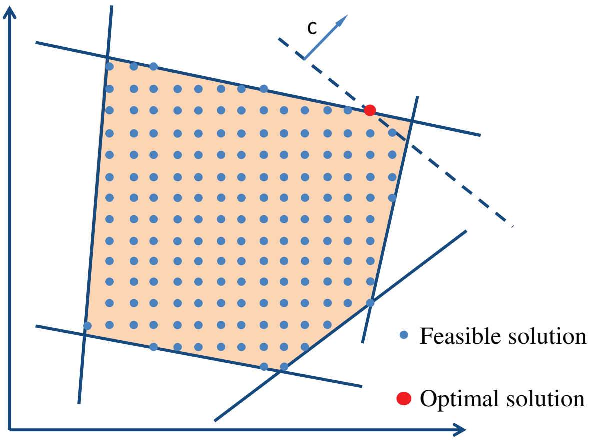

Figure 3.2: Illustration of a integer program.

3.3 Optimization Methods

LP problem can be solved to optimal by methods such as the simplex algorithm [68, 69] proposed by G. B. Dantzig and interior-point algorithms such as Karmarkar's algorithm [70]. IP and MILP problems in general are harder to solve because the solution space is non-convex due to the integrality requirement. So far, there is no general algorithm which can solve those problems efficiently. Many algorithms have been proposed to tackle those problems, mainly including exact algorithms, approximation algorithms, as well as heuristic algorithms. Optimization methods such as branch and bound, branch and cut as well as dynamic programming belongs to the exact algorithms. Those methods can guarantee the optimal solution, but might take an exponential number of iterations. Some of those methods have been integrated with the IP solvers such as CPLEX [71] and GUROBI [72]. Instead of targeting the optimal solution, approximation algorithms provide methods to find a suboptimal solution in polynomial time, and guarantee the quality of the solution in terms of the maximum amount of suboptimality. For exact algorithms and approximation algorithms for IP and MIP, interested readers are referred to [73, 74, 75, 76].

Another class of major methods for solving hard problems time efficiently is composed by heuristic and meta-heuristic algorithms. Meta-heuristic algorithms are algorithmic principles that can be used to derive specific heuristics for a large range of problem. These algorithms provide suboptimal solutions.

The solution quality can not be guaranteed in all cases. However, for most of the practical problems, delivering the solutions time efficiently outweighs the optimality of the solution. Obtaining close-optimal solution fast is in general sufficient for problems of large scale. Empirical application results of heuristic methods have demonstrated their applicability for practical problems. In this thesis, besides mathematical modeling, heuristic algorithms such as greedy algorithms, local search (LS) [77], as well as Tabu search (TS) [78, 79] have been applied. We give a brief introduction below to the concept of each of the heuristic algorithms.

- **Greedy algorithm**: Greedy algorithms are the most simple heuristic algorithms. Greedy algorithms attempt to construct feasible solutions by assigning new values to variables in an incremental fashion within each iteration. The assignment that currently performs best in the objective function is chosen. The algorithm stops once a feasible solution is found. Depending on the problem structure, greedy algorithms are usually very easy to design and implement. For some of the problems, greedy algorithms can actually provide high quality solutions. Moreover, greedy algorithms can also be part of the iterative procedures of more complicated algorithms such as local search and Tabu search.

- **Local search**: Local search involves finding the best solution within a neighborhood. The definition of the neighborhood depends on algorithm design, and is individualized according to the problem structure. In general, for a given feasible solution, a neighborhood is generated by introducing small changes on the solution, leading to a set of neighboring candidate solutions. Local search starts from a feasible solution, and goes through neighboring solutions to find a solution with a better objective value. The solution is then used to replace the current solution and the search continues until no better solutions can be found. The final solution is then referred to as a local optimum. Such a local optimum is not necessarily the global optimal solution, unless the neighboring solutions cover the entire solution space. Therefore, local search has the tendency to get stuck in suboptimal regions. In such cases, possible measures can be taken to lead the local search out of the suboptimal region, such as repeated local search in which local search is restarted with multiple initial solutions.

- **Tabu search**: Tabu search is meta-heuristic algorithm that extends local search. Tabu search has the ability to lead the local search out of the suboptimal regions. It employs different memory mechanisms including a short-term memory mechanism and a long-term memory mechanism. A short-term memory mechanism marks the recently visited solutions and stores the attributes of those solutions in a list, referred to as Tabu list. A solution having any attribute in the Tabu list cannot be revisited until an expiration point (e.g., a certain time or iteration steps) is reached. The short-term memory mechanism helps avoid cycling between certain solutions. However, even with the short-term memory mechanism, the search may still get stuck in suboptimal regions. To tackle this issue, Tabu search also utilizes diversification methods based on a long-term memory mechanism. The long-term memory records the frequency (for example, number of iterations from the algorithm start) of some attributes which have been encountered in the visited solutions. In case the search gets stuck, it will be forced to visit solutions whose attributes have seldom appeared in the long-term memory, thus making it possible to explore more interesting regions with potentially better solutions. Because of the above memory mechanisms, Tabu search has the potential of achieving high-quality solutions for hard problems, where simple local search procedures might be insufficient.

Besides the methods mentioned above, there are various types of heuristics and meta-heuristics such as simulated annealing [80, 81], genetic algorithms [82], greedy randomized adaptive search procedure (GRASP) [83], etc. In practice, the choice of heuristics is not trivial and has to be adapted to the structure of the problem.

4 The Thesis

This thesis focuses on performance engineering of mobile broadband. The main topics cover capacity analysis, resource planning and optimization of broadband cellular networks and design of in-building solutions. This chapter present the objectives, contributions along with summaries of the seven papers. A discussion of future research is also presented.

4.1 Objectives

The main objective of the thesis is to address major issues arising from the rapid development of mobile broadband technology and to provide efficient algorithms for network planning and optimization. One line of research focuses on capacity analysis of wireless communications where the capacity is limited by interference. The objective is two fold. The first is to develop algorithms for maximum LA with high scalability. The second is to study the performance gains brought by IC methods for maximum LA. The next line of research focuses on practical network planning and optimization related to power and frequency allocation in GSM, UMTS and LTE networks. The planning elements in the optimization problems range from the power consumption for coverage, the power requirement for achieving the performance threshold for HSDPA service, to LTE network capacity in terms of cell-edge throughput. The research objective is to develop optimization models and time-efficient methods that are capable of delivering high-quality solutions. The research is also aimed to use realistic planning scenarios to demonstrate the benefit of the optimization approaches. The third line of research contributes to mathematical modeling for IB-DAS deployment. The objective is to deliver compact integer models that enable optimality for IB-DAS scenarios of which the size is of practical relevance.

4.2 Contributions

This thesis makes the following scientific contributions:

- A new integer programming algorithm has been developed based on an effective representation of the SINR constraints for the maximum link activation problem. The algorithm performs significant better in proving optimality than the conventional model.

- An integer programming model has been developed to integrate the single stage single link IC (SLIC) and single stage parallel IC (PIC) in maximizing the collaborative transmission rate in wireless networks. Both complexity analysis and numerical simulation have been presented. The results indicate significant performance gains for IC in the low SINR regime.

- Link activation, with weights, has been studied with SLIC, PIC, as well as multi-stage successive IC (SIC). Compact integer programming models have been developed to maximize the total weight of active links. Extensive complexity analysis on the problems and thorough numerical analysis have been performed. The results show significant performance gains for low to medium SINR thresholds, indicating the benefits to integrate IC in future wireless networks.

- Two integer linear models have been developed for coverage planning in cellular networks where overlaps between cell pairs are required. The strengths of the continuous relaxations of the two models have been analyzed in detail. A Tabu search algorithm has been developed to deliver suboptimal results for large scale networks time-efficiently.

- For power planning in HSDPA networks, a method is proposed to minimize the coverage power and reallocate the power to data services of cell-edge users. Meanwhile, soft handover in UMTS networks is also considered. An integer linear model has been developed and applied to smaller planning scenarios for performance benchmarking. Algorithms based on local search and repeated local search have been developed for large scale network planning.

- Towards the next generation OFDMA-based networks, a generalization of the FFR scheme has been proposed to improve the spectrum efficiency, especially for cell-edge users. The proposed method allows flexibility in the total number of sub-bands as well as the number of sub-bands in each cell-edge zone, thus enabling a network-adaptive FFR scheme. The complexity of the problem has been analyzed and an optimization algorithm based on local search has been proposed to maximize the cell-edge user throughput.

- To provide sufficient coverage and capacity for indoor users, IB-DAS optimization has been studied. Integer linear models have been developed for the optimal design of IB-DAS. Applications of the models for realistic planning scenarios have been performed to demonstrate the applicability and efficiency of the proposed approach.

4.3 Summary of papers

This thesis consists of seven research papers. The author of the thesis has contributed to papers I-III as a co-author, in performing the modeling and simulation work, and analysis of the results, along with the writing of these parts. The author of the thesis has contributed to papers IV-VII as the first author, by making a major role in the research planning, the modeling and simulation work, result analysis, as well as a majority part of writing. We give a brief summary for each paper in the following part.

Paper I: A New Computational Approach for Maximum Link Activation in Wireless Networks under the SINR Model

This paper deals with the capacity aspect of maximizing the number of simultaneous transmissions in wireless communications. The wireless environment is typically interference-limited, where concurrent transmissions pose interference to each other. In such an environment, whether a transmission can be established depends on both the signal of interest and the interference, expressed by the SINR requirement. The conventional approach to guarantee global optimality is to solve an integer linear model with explicit SINR constraints. However, due to the magnitude variation of the wireless propagation gains, the SINR constraints are numerically very difficult to solve.

In this paper, a new exact algorithm is developed. The algorithm reformulates the SINR constraints using effective inequalities, leading to a numerically equivalent but much more effective representation of those constraints. Based on the new representation, the problem can be solved time efficiently for large scenarios. Comparisons with the conventional algorithm show that the new exact algorithm performs significantly better in proving optimality.

The paper is co-authored with Antonio Capone, Stefano Gualandi, and Di Yuan, and has been published in *IEEE Transactions on Wireless Communications*.

Paper II: Optimal and Collaborative Rate Selection for Interference Cancellation in Wireless Networks

This paper deals with utilizing IC by collaborative rate selection for maximizing the transmission rate in wireless networks. Capacity analysis for wireless networks usually assumes single-user decoding at the receivers, where interference is treated as noise. IC explores the possibility for a receiver to cancel interference provided that the interference is strong enough to be decoded. Successful IC eliminates the interference from the composite received signal, thus a better SINR and transmission rate can be achieved.

In this paper, we consider single stage IC for the problem of optimal rate selection. Both SLIC and PIC are studied. For each receiver, SLIC allows only one interference to be cancelled while PIC allows multiple transmissions to be cancelled simultaneously. The complexity of the problem has been analyzed. An integer programming formulation is developed for benchmarking the performance. We show that up to 30% throughput improvement can be achieved for the low SINR regime with the introduction of IC, indicating the effectiveness of IC in boosting the throughput.

The paper is co-authored with Vangelis Angelakis and Di Yuan, and has been published in *IEEE Communications Letters*.

Paper III: On Optimal Link Activation with Interference Cancellation in Wireless Networking

This paper deals with maximum weighted LA in wireless networking, with the consideration of multi-user decoding (MUD). In MUD, receivers have the ability to decode and cancel strong interferences before decoding the signal of interest, enabling a better SINR and data rate. MUD can be done with single-stage IC, such as SLIC and PIC, and multi-stage IC such as successive

IC (SIC). Compared with SLIC and PIC, SIC performs the cancellation with multiple stages, where one cancellation is done in each of the stages. This allows more performance gains, but also introduces extra complexity. Due to that the ordering for the interference cancellation operations is of significance, the problem size is magnitude larger than single stage IC.

In this paper, we study the complexity of maximum weighted LA with SLIC, PIC, and SIC, and develop compact integer linear programming formulations. The numerical studies show that for low to medium SINR threshold, IC delivers a significant performance improvement.

The paper is co-authored with Di Yuan, Vangelis Angelakis, Eleftherious Karipidis, and Erik G. Larsson, and has been published in *IEEE Transactions on Vehicular Technology*.

Paper IV: Solving a Minimum-power Covering Problem with Overlap Constraint for Cellular Network Design

This paper deals with coverage planning in cellular network design. Given the locations of BSs, the problem amounts to determining cell coverage at minimum cost in terms of power usage. Minimum-power coverage tends to make cell size as small as possible; such a solution may have negative impact on handover performance. To tackle this issue, the objective is to perform power minimization with the requirement of having sufficient overlap between cells.

Two integer linear models are presented. The strength of their respective continuous relaxations as well as the numerical performance of the two models are thoroughly investigated. For large-scale networks, a tabu search (TS) algorithm is developed. The algorithm is able to obtain close-to-optimal results with short computation time. Simulation results are reported for both synthesized networks and networks originating from real planning scenarios.

The paper is co-authored with Di Yuan, and has been published in *European Journal of Operational Research*.

Paper V: Coverage Planning for Optimizing HSDPA Performance and Controlling R99 Soft Handover

This paper deals with a coverage planning problem for the currently common network deployment scenario of having co-existing HSDPA and R99 services. By utilizing the power saving resulted from power minimization in coverage planning, the throughput of HSDPA can be improved. The focus is to bring up the HSDPA performance at cell edge, for which improved data throughput is more perceived in comparison to cell center. At the same time, the level of soft handover (SHO) for R99 is taken into account in determining the coverage pattern.

An integer linear model is developed for the problem. The model can be used to find global optimum for small-sized networks. For large-scale planning scenarios, a heuristic algorithm is developed. The algorithm is based on local search and repeated local search. Performance benchmarking on small test networks shows that the algorithm gives close-to-optimality results. In addition, simulation results from the model and the use of the heuristic algorithm demonstrate significant power saving and HSDPA performance improvement in comparison to the reference solution.

The paper is co-authored with Di Yuan, and has been published in *Telecommunication Systems*. Parts of the paper have been published in the following conferences:

- L. Chen and D. Yuan. Automated planning of CPICH power for enhancing HSDPA performance at cell edges with preserved control of R99 soft handover. In *Proc. of IEEE International Conference on Communications (ICC '08)*, 2008.
- L. Chen and D. Yuan. Achieving higher HSDPA performance and preserving R99 soft handover control by large scale optimization in CPICH coverage planning. In *Proc. of IEEE Wireless Telecommunications Symposium (WTS '09)*, 2009.

Paper VI: Generalizing and Optimizing Fractional Frequency Reuse in Broadband Cellular Radio Access Networks

This paper deals with resource allocation and inter-cell interference mitigation in OFDMA-based networks. With OFDMA, inter-cell interference is the main performance-limiting factor for cell-edge users due to their high level of sensitivity to interference. FFR is one of the schemes used for inter-cell interference mitigation by frequency separation. Standard FFR uses a fixed number of sub-bands and a fixed reuse factor. This works well for a regular, hexagonal cell layout. However, for networks with irregular cell patterns, standard FFR can not be directly applied, and the performance is far from being optimal.

In the paper, the standard FFR is generalized to enable a high flexibility in the total number of OFDMA sub-bands and the number of sub-bands allocated in the cells' edge areas. Two power assignment strategies are considered in sub-band allocation. Solution algorithms using local search are developed to optimize sub-band allocation for generalized FFR. Performance evaluations are conducted for large-scale networks with realistic radio propagation conditions. The results demonstrate the applicability and benefit of applying and optimizing generalized FFR in performance engineering of OFDMA networks.

The paper is co-authored with Di Yuan, and has been published in *EURASIP Journal on Wireless Communications and Networking*. Parts of the paper have been published in the following conferences:

- L. Chen and D. Yuan. Soft frequency reuse in large networks with irregular cell pattern: how much gain to expect? In *Proc. of the IEEE 20th International Personal, Indoor and Mobile Radio Communications Symposium (PIMRC '09)*, pages 1467-1471, 2009.
- L. Chen and D. Yuan. Generalized frequency reuse schemes for OFDMA networks: optimization and comparison. In *Proc. of IEEE Vehicular Technology Conference (VTC '10-Spring)*, 2010.
- L. Chen and D. Yuan. Generalizing FFR by flexible sub-band allocation in OFDMA networks with irregular cell layout. In *Proc. of IEEE Wireless Communications and Networking Conference (WCNC '10) Workshops*, 2010.

Paper VII: Mathematical Modeling for Optimal Design of In-Building Distributed Antenna Systems

This paper deals with one of the in-building solutions, the IB-DAS system. In-building mobile traffic has already dominated the total traffic and will continue to grow. It is vital to provide satisfactory user experiences for in-building customers. However, in-building scenarios are challenging in nature because of the wall penetration loss and multi-path propagation. To overcome the difficulties, a dedicated in-building system is needed. IB-DAS is among the in-building solutions, and is proved to be promising for in-building mobile broadband services. IB-DAS uses a number of distributed antennas within the building to provide line-of-sight connections to users. The distributed antennas will connect to the base station through cables and power equipment. Because of the fact that the impact of wall penetration and multi-path reflections are eliminated or reduced, significant better coverage and capacity can be achieved.

This paper focuses on the optimal deployment of IB-DAS systems. Deployment of IB-DAS involves the installation of cables and power equipment to connect all distributed antennas to the base station. Meanwhile, a predefined level of output signal power should be satisfied at each of the antennas, so that the coverage and capacity requirements can be fulfilled. We develop mixed integer programming models to tackle the problem. In order to comply to common practice for cable and power equipment installation, we integrate the building structures within the modeling approach. We apply the models on realistic building scenarios with different sizes and study the trade-offs between solution optimality and computation efficiency. The results show the effectiveness of our models in dealing with scenarios of practical interest and give indications on how to balancing the performance trade-offs.

The paper is co-authored with Di Yuan, and has been submitted for journal publication. Parts of the paper have been published in the following conference:

- L. Chen, D. Yuan, H. Song and J. Zhang. Mathematical modeling for optimal deployment of in-building distributed antenna systems. In *Proc. of the first International Conference on Communications in China (IEEE-ICCC)*, 2012.

4.4 Future Research

With the fast development of wireless technology and the rapid deployment of broadband access networks, mobile broadband has become a reality. Together with the technology evolution, mobile data has been exploding and the service demand has been increasing. However, because of the scarcity of the frequency band and the fact that the spectral efficiency per Hz is approaching the theoretical limit, planning and optimization methods are critical to achieve further performance improvement for mobile broadband networks.

- Capacity optimization for interference limited wireless environment, such as maximum LA, remains challenging. Solving the problem is crucial for improving the spectrum efficiency in wireless network engineering.

- The constant evolution of radio access networks, especially the full integration of different radio access technologies into a heterogeneous network, offers various opportunities for efficient radio resource utilization, and at the same time, poses new challenges. Advanced methods are necessary for efficient and automatic network planning and optimization with minimum human intervention.

- The dominate in-building traffic indicates a very uneven future mobile traffic pattern, which calls for efficient in-building solutions.

The work presented in the thesis contributes to dealing with capacity analysis in wireless communications, planning and optimization problems in broadband radio networks, as well as in-building mobile broadband solutions. One natural follow-up to this thesis is to implement the models and algorithms in practical mobile broadband networks. In addition, there are many potential lines for future research. First, new scheduling algorithms integrating the advanced IC methods for future networks require extensive research. Second, network optimization problems accounting for the latest technological advances such as MIMO, relay stations, and heterogeneous networks, warrant thorough investigations. Third, to catch the characteristics of a highly self-organized heterogenous mobile broadband network, developing distributed resource allocation algorithms and integrating them with system level simulation form a major topic for automatic network planning and optimization. Fourth, in-building solutions based on DAS require both advanced modeling and efficient algorithms for deployment, especially for large scale scenarios. To conclude, mobile broadband network planning and optimization require many complex processes involving various resource types, network elements as well as economic and social concerns. There are many problems that are beyond the scope of the thesis, but highly relevant to the research field. Topics such as green communications, mobile backhauling for heterogenous networks, and so on, are of great interest for future research.

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