AALBORG UNIVERSITY

DENMARK

An Empirical Study on Radio Propagation in Heterogeneous Networks

with Focus on Mobile Broadband Networks and Small Cell Deployment

Rodriguez, Ignacio

AN EMPIRICAL STUDY ON RADIO PROPAGATION IN HETEROGENEOUS NETWORKS

WITH FOCUS ON MOBILE BROADBAND NETWORKS AND SMALL CELL DEPLOYMENT

BY
IGNACIO RODRIGUEZ LARRAD

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Ph.D. Dissertation
Ignacio Rodriguez Larrad

Biography

Ignacio Rodriguez Larrad

He was born in Oviedo, Spain, on July 7, 1984. He holds a 5-year degree (B.Sc+M.Sc) in Telecommunication Engineering from University of Oviedo, Spain. In 2011, he received the M.Sc. degree in Mobile Communications from Aalborg University, Denmark, where he is currently working toward the Ph.D. degree in Wireless Communications. He is also an External Research Engineer within Nokia - Bell Labs. From 2014, he is a board member of the Society of Spanish Scientists in Denmark (CED/SFD), institution at which he also acts as local coordinator of the Aalborg branch.

In 2015, he was a visiting researcher at the Institute of Technology Development (INDT), Brazil. In 2015-2016, during the final stage of his Ph.D., he carried out several external research consultancy works for INDT, Brazil, and Business Region North (BRN), Denmark.

He has authored or co-authored over 25 technical papers in the field of wireless communications. His research interests are mainly related to radio propagation, measurements and field trials, channel modeling, radio network planning and optimization of heterogeneous networks; slightly moving into 5G, M2M, industrial automation, and ultra-reliable and low-latency communications.

Biography

Abstract

The growing demand for mobile services represents a challenge for the existing networks. In order to cope with the increasing coverage and capacity requirements, operators have shifted the focus of their network evolution strategies from the densification and optimization of the macro layer to the deployment of heterogeneous networks (HetNets), where multiple radio access technologies and cell deployment options will coexist. These networks may be enhanced in the future by the use of higher frequency bands, which can help in supporting larger data rates as well as in coping with capacity problems in ultra-dense deployments. In order to plan and deploy such networks, radio propagation must be studied and properly modeled. The combination of different cell types and new frequencies have shaped a large set of yet unexplored propagation scenarios, which is further enlarged by the atypical use cases that will exist in the future cellular networks.

With the aim of providing insight into some of these unexplored propagation scenarios, this thesis investigates, through experimental work and simulation analysis, different deployment configurations. The evaluation of the empirical data, together with the simulation results, is used to provide deployment guidelines and simple models useful for both radio planning and optimization; as well as for standardization purposes.

The first part of the work addresses outdoor propagation. In the initial part of the analysis, the applicability of existing large-scale path loss models is validated, based on measurements, for selected frequencies, distances ranges and base station configurations outside of their original range of application. A lower accuracy of the models in the short range is observed, caused by the difficulty in predicting the antenna patterns effects in the close vicinity of the base station antenna. A geometrical extension of the models is proposed and the base station antenna pattern distortion effects are further analyzed in detail by means of simulations. With particular focus on relay node scenarios, a set of deployment guidelines is given based on empirical observations and performance evaluations. The propagation at higher frequencies is explored through several dedicated measurement campaigns for both the urban macro and micro cell scenarios with different base station

antenna heights. The parametrization of the scenarios is given for selected statistical models, observing similar trends at both cm-wave and low frequencies below 6 GHz, which suggests no substantial differences in the overall outdoor propagation, despite of the change in main propagation mechanisms observed in some of the other presented investigations.

In the second part, outdoor-to-indoor propagation is addressed. Based on the results from different sets of dedicated measurements, the observed frequency and building construction material dependencies of the penetration loss are modeled. The different models cover up to cm-wave frequency bands and account for the high and very frequency-dependent attenuation experienced in modern buildings, as compared to the lower and less frequency-dependent attenuation experienced in old constructions. The indoor part of the overall outdoor-to-indoor propagation is also addressed, finding no substantial frequency dependence in neither the indoor open space propagation nor the attenuation of the indoor walls. The different models are combined to provide a large-scale frequency-dependent model for the overall outdoor-to-indoor propagation, and geometrically-extended for accounting for the different incident angles in both he horizontal an vertical domains for frequencies below 6 GHz.

Resumé

Det stadigt stigende behov for mobil bredbåndsservice repræsenterer en udfordring for de eksisterende netværk. For at kunne følge med de stigende krav til dækning og kapacitet har mobiloperatørerne skiftet fokus i deres netværksevolutionsstrategi fra øget densitet og optimering af macro-laget til udrulning af heterogene netværk (HetNets) hvor multiple radio access teknologier og optioner for udrulning af celler vil koeksistere. Disse netværk kan forbedres ved brug af højere frekvensbånd, som giver mulighed for større datarater og afhjælpning af kapacitetsproblemer i ultra-tætte netværk. For at kunne planlægge og udrulle mobile netværk er det nødvendigt at undersøge og modellere radioudbredelsen. Kombinationen af forskellige celletyper og nye frekvenser har formet et nyt uudforsket område for radioudbredelse, som er yderligere kompliceret af de atypiske anvendelsesscenarier man vil se i fremtidige netværk.

Med det formål at få indblik i nogle af disse uudforskede radioudbredelsesscenarier, undersøger denne afhandling gennem eksperimentelt arbejde og simuleringsanalyse forskellige cellekonfigurationer. Evalueringen af de eksperimentelle data, sammen med simuleringsanalyser, benyttes til at give praktiske retningslinjer for celleudrulning og simple modeller der er nyttige til radioplanlægning og optimering. Tilsvarende er de anvendelige for standardiseringsformål.

Den første del af arbejdet adresserer udendørs radioudbredelse. Indledningsvis er anvendeligheden af eksisterende udbredelsesmodeller for udbredelsestabet valideret, baseret på målinger, for udvalgte frekvenser, afstande og basestationskonfigurationer ulig deres oprindelige anvendelsesområde. En reduceret nøjagtighed af modellerne er observeret for korte afstande, forårsaget af problemerne med at prædiktere effekten af antenneudstrålingen tæt på basestationen. Der er foreslået en geometrisk udvidelse af modellerne, og betydningen af forstyrrelser i antenneudstrålingen er yderligere analyseret ved hjælp af simulering. Med særligt fokus på anvendelsen af relæbasestationer er der givet et sæt retningslinjer for cellekonfiguration baseret på empiriske observationer og performanceevalueringer. Radioudbredelsen ved højere frekvenser er undersøgt gennem adskillige dedikerede målekam-

pagner for både bynære macro- og micro-celle scenarier med forskellige antennehøjder. Parametriseringen af disse scenarier er givet for udvalgte modeller. Der er observeret tilsvarende afhængigheder ved både cm-bølge og frekvenser under 6 GHz, hvilet indikerer at der ikke er væsentlige forskelligheder i den overordnede udendørs radioudbredelse på trods af den observerede ændring i udbredelsesmekaniske der er observeret i nogle af de andre foretagne undersøgelser.

I den anden del er der fokuseret på udendørs-til-indendørs udbredelse. Baseret på resultater fra forskellige dedikerede målinger er der lavet modeller for den observerede afhængighed af frekvens og bygningsmateriale for indtrængningstabet. De forskellige modeller dækker op til cm-bølge båndet, og tager højde for den høje og meget frekvensafhængige dæmpning observeret i moderne bygninger, i sammenligning med den lavere og mindre afhængige dæmpning i ældre konstruktioner. Den indendørs relaterede del af udendørs-til-indendørs udbredelse er også adresseret. Der er her konstateret en uvæsentlig frekvensafhængighed for både åbne områder samt ved dæmpning gennem vægge. De forskellige modeller er kombineret til en frekvensafhængig model for den samlede udendørs-til-indendørs dæmpning, og udvidet til også at tage højde for forskellige indtrængningsvinkler, vertikalt som horisontalt, for frekvenser under 6 GHz.

Preface and Acknowledgments

This thesis presents the outcomes of the research that I have performed since September 2011, initially at the Radio Access Technology Section (RATE), and now at the Wireless Communication Networks Section (WCN), Department of Electronic Systems, Aalborg University, Denmark; in close collaboration with Nokia - Bell Labs. Parallel to the work presented in the thesis, all the mandatory courses required to obtain the Ph.D. degree were completed.

The study has been completed under the supervision and guidance of Associate Professor Troels B. Sørensen, Associate Professor Huan C. Nguyen, and Professor Preben Mogensen; and it has been co-financed by Aalborg University and Nokia - Bell Labs. The thesis is comprised by 11 published conference articles, 1 submitted journal paper and 1 more journal paper in preparation (13 technical contributions in total), summarizing various of the radio propagation studies performed along the years. The results of the different investigations, in the form of propagation models and deployment guidelines, are useful for radio network planning and optimization activities, as well as for standardization purposes.

I would like to express my gratitude to my supervisors for their constant guidance and assistance over the years. Troels and Preben, many thanks for giving me my first professional opportunity within the field of wireless communications. That initial year and a half as Research Assistant, right after finalizing my M.Sc. when I was a bit lost in life, turned later into this Ph.D. work; and now I feel that I have done something relevant which makes me extremely happy and self-fulfilled. Many thanks to you Huan as well, I have learned a lot during all our discussions and crazy measurement adventures together. The measurements in the cold and in the snow, our tour around all the "tall" buildings in Aalborg, the measurements inside Salling and Friis, the long summer days during the mm-wave trial,... they all constitute unforgettable moments. If one day trolley-pushing becomes an Olympic discipline,

I think that we are ready to participate after these 5 years of training.

I would like to thank to our neighbor Antennas, Propagation and Radio Networking Section (APNet) for lending us their equipment for some of our measurement campaigns. More in particular, I thank Kim Olesen and Kristian Bank for their continuous help and fantastic measurement setups. Without them this Ph.D. study would have never been possible.

Thanks to the Institute of Development and Technology (INDT) and the Foundation Center for Analysis, Research and Technological Innovation (FU-CAPI), Brazil, for the financial, logistical and technical support during my research stay there.

Thanks to all the external co-authors of my publications, mainly from Nokia - Bell Labs, Telenor, INDT, Vale and NYU. It has been a wonderful experience collaborating together in so many different projects and topics.

I would also like to thank all my friends, and current and former colleagues from the RATE and WCN sections and Nokia - Bell Labs, Research Center, Aalborg. It is a luck to work always surrounded by talented and inspiring people. I will not cite all their names here, not risking the sin of leaving anyone out by accident. Special thanks to Claudio for being an excellent Mentor, to Luis for the Wi-Fi lessons and the mine research activities, to Oscar and Niels for the measurement campaigns and the football, to Erika for all the help during my stay in Manaus and for choosing me as her Ph.D. Mentor, to Jakob for all the crazy conversations about our potential joint startup company, and finally, to Mads for all the collaborations, discussions and trips together (and for all the help with the Danish language! - tusind tak!).

Thanks to all the friends that I have made along these 7 years living in Aalborg. Particularly to Isa, Carlos Y., Pablo F., and Thibaut.

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Last but not least, I would like to thank my family, in particular my parents Cruz and Jose, my sister Begoña and my brothers Jorge and Victor. Being a large family has not always been easy, but getting over the different situations has made us stronger. This thesis is the fruit of that strength and the hard-working attitude that I learned from you. As part of my family, I should also include my lovely girlfriend M♡ni, whose love and affection makes me happy at every second. This Ph.D. thesis is entirely dedicated to you all.

Ignacio Rodriguez Larrad
Aalborg University, September, 2016

Thesis Details

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Ph.D. Student: Ignacio Rodriguez Larrad

Ph.D. Supervisor: Assoc. Prof. Troels Bungaard Sørensen
Aalborg University

Ph.D. Co-Supervisor 1: Assoc. Prof. Huan Cong Nguyen
Aalborg University

Ph.D. Co-Supervisor 2: Prof. Preben Mogensen
Aalborg University, Nokia - Bell Labs

The main body of this thesis consist of the following papers:

[A] **I. Rodriguez**, H. C. Nguyen, T. B. Sørensen, J. Elling, M. B. Gentsch, M. Sørensen, L. Kuru, and P. Mogensen, "A Geometrical-based Vertical Gain Correction for Signal Strength Prediction of Downtilted Base Station Antennas in Urban Areas", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2012.

[B] **I. Rodriguez**, H. C. Nguyen, T. B. Sørensen, and O. Franek, "Base Station Antenna Pattern Distortion in Practical Urban Deployment Scenarios", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2014.

[C] **I. Rodriguez**, C. Coletti, and T. B. Sørensen, "Evaluation of Potential Relay Locations in a Urban Macro-Cell Scenario with Applicability to LTE-A", *IEEE Vehicular Technology Conference (VTC Spring)*, May 2012.

[D] **I. Rodriguez**, H. C. Nguyen, N. T. K. Jørgensen, T. B. Sørensen, J. Elling, M. B. Gentsch, and P. Mogensen "Path Loss Validation for Urban Micro Cell Scenarios at 3.5 GHz Compared to 1.9 GHz", *IEEE Global Communications Conference (GLOBECOM)*, December 2013.

[E] **I. Rodriguez**, H. C. Nguyen, I. Z. Kovács, T. B. Sørensen, and P. Mogensen, "Considerations on Shadow Fading Modeling for 5G Urban Micro Cell Scenarios", <u>in preparation for submission to</u> *IEEE Transactions on Antennas and Propagation*.

[F] H. C. Nguyen, **I. Rodriguez**, T. B. Sørensen, L. L. Sanchez, I. Z. Kovács, and P. Mogensen, "An Empirical Study of Urban Macro Propagation at 10, 18 and 28 GHz", *IEEE Vehicular Technology Conference (VTC Spring)*, May 2016.

[G] **I. Rodriguez**, E. P. L. Almeida, R. Abreu, M. Lauridsen, A. Loureiro, and P. Mogensen, "Analysis and Comparison of 24 GHz cmWave Radio Propagation in Urban and Suburban Scenarios", *IEEE Wireless Communications and Networking Conference (WCNC)*, April 2016.

[H] **I. Rodriguez**, R. Abreu, E. P. L. Almeida, M. Lauridsen, A. Loureiro, and P. Mogensen, "24 GHz cmWave Radio Propagation Through Vegetation: Suburban Tree Clutter Attenuation", *European Conference on Antennas and Propagation (EuCAP)*, April 2016.

[I] **I. Rodriguez**, H. C. Nguyen, T. B. Sørensen, J. Elling, J. Å. Holm, P. Mogensen, and B. Vejlgaard, "Analysis of 38 GHz mmWave Propagation Characteristics of Urban Scenarios", *European Wireless Conference (EW)*, May 2015.

[J] **I. Rodriguez**, E. P. L. Almeida, M. Lauridsen, D. A. Wassie, L. Chavarria Gimenez, H. C. Nguyen, T. B. Sørensen, and P. Mogensen, "Measurement-based Evaluation of the Impact of Large Vehicle Shadowing on V2X Communications", *European Wireless Conference (EW)*, May 2016.

[K] **I. Rodriguez**, H. C. Nguyen, N. T. K. Jørgensen, T. B. Sørensen, and P. Mogensen "Radio Propagation into Modern Buildings: Attenuation Measurements in the Range from 800 MHz to 18 GHz", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2014.

[L] **I. Rodriguez**, H. C. Nguyen, I. Z. Kovács, T. B. Sørensen, and P. Mogensen, "An Empirical Outdoor-to-Indoor Path Loss Model from below 6 GHz to cm-Wave Frequency Bands", <u>submitted to</u> *IEEE Antennas and Wireless Propagation Letters*.

[M] **I. Rodriguez**, H. C. Nguyen, T. B. Sørensen, Z. Zhao, H. Guan, and P. Mogensen, "A Novel Geometrical Height Gain Model for Line-of-Sight Urban Micro Cells Below 6 GHz", *International Symposium on Wireless Communication Systems (ISWCS)*, September 2016.

In addition to the main papers, the following publications have also been made:

[a] H. C. Nguyen, **I. Rodriguez**, T. B. Sørensen, J. Elling, M. B. Gentsch, M. Sørensen, L. Kuru, and P. Mogensen, "Validation of Tilt Gain under Realistic Path Loss Model and Network Scenario", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2013.

[b] L. G. U. Garcia, **I. Rodriguez**, D. Catania, and P. Mogensen "IEEE 802.11 Networks: A Simple Model Geared Towards Offloading Studies and Considerations on Future Small Cells", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2013.

[c] O. Tonelli, **I. Rodriguez**, G. Berardinelli, A. F. Cattoni, J. L. Buthler, T. B. Sørensen, and P. Mogensen, "Validation of an Inter-Cell Interference Coordination Solution in Real-World Deployment Conditions", *IEEE Vehicular Technology Conference (VTC Spring)*, May 2014.

[d] N. T. K. Jørgensen, **I. Rodriguez**, J. Elling, and P. Mogensen "3G Femto or 802.11g WiFi: Which is the Best Indoor Data Solution Today?", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2014.

[e] S. Sun, T. Thomas, T. S. Rappaport, H. C. Nguyen, I. Z. Kovács, and **I. Rodriguez**, "Path Loss, Shadow Fading, and Line-Of-Sight Probability Models for 5G Urban Macro-Cellular Scenarios", *IEEE Globecom Workshop on Mobile Communications in Higher Frequency Bands (MCHFB)*, December 2015.

[f] M. Lauridsen, **I. Rodriguez**, L. M. Mikkelsen, L. Chavarria, and P. Mogensen, "Verification of 3G and 4G Received Power Measurements in a Crowdsourcing Android App", *IEEE Wireless Communications and Networking Conference (WCNC)*, April 2016.

[g] L. G. U. Garcia, E. P. L. Almeida, V. Barbosa, G. Caldwell, **I. Rodriguez**, H. Lima, T. B. Sørensen, and P. Mogensen, "Mission-Critical Mobile Broadband Communications in Open-Pit Mines", *IEEE Communications Magazine*, Vol. 54, No. 4, April 2016.

[h] T. Thomas, M. Rybakowski, S. Sun, T. S. Rappaport, H. C. Nguyen, I. Z. Kovács, and **I. Rodriguez**, "Prediction Study of Path Loss Models from 2-73.5 GHz in an Urban-Macro Environment", *IEEE Vehicular Technology Conference (VTC Spring)*, May 2016.

[i] S. Sun, T. S. Rappaport, S. Rangan, T. Thomas, A. Ghosh, I. Z. Kovács, **I. Rodriguez**, O. Koymen , A. Partyka, and J. Järveläinen, "Propagation Path Loss Models for 5G Urban Micro- and Macro-Cellular Scenarios", *IEEE Vehicular Technology Conference (VTC Spring)*, May 2016.

[j] S. Sun, T. S. Rappaport, T. Thomas, A. Ghosh, H. C. Nguyen, I. Z. Kovács, **I. Rodriguez**, O. Koymen, and A. Partyka "Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications", *IEEE Transactions on Vehicular Technology*, Vol. 65, No. 5, May 2016.

[k] A. N. Barreto, B. Faria, E. P. L. Almeida, **I. Rodriguez**, M. Lauridsen, R. Amorim and R. Vieira, "5G – Wireless Communications for 2020", *Journal of Communication and Information Systems (JCIS)*, Vol. 31, No. 1, June 2016.

[l] H. C. Nguyen, L. Chavarria, I. Z. Kovács, **I. Rodriguez**, T. B. Sørensen, and P. Mogensen, "A Simple Statistical Signal Loss Model for Deep Underground Garage", *IEEE Vehicular Technology Conference (VTC Fall)*, September 2016.

[m] V. S. B. Barbosa, L. G. U. Garcia, E. P. L. Almeida, G. Caldwell, **I. Rodriguez**, T. B. Sørensen, P. Mogensen, and H. M. Lima, "The Challenge of Wireless Connectivity to Support Intelligent Mines", accepted in *World Mining Congress (WMC)*, October 2016.

Moreover, throughout the collaboration with Nokia - Bell Labs, a number of contributions have been submitted and considered in different standardization activities, technical reports and white papers, based on some of the material presented in this thesis:

[r1] 3GPP TSG RAN WG1, R1-131233, Nokia Siemens Networks and Nokia, "Field Measurement Results at 1.9 GHz and 3.5 GHz", April 2013.

[r2] 3GPP TSG RAN WG1, R1-144188, Nokia Networks, and Nokia Corporation, "Simulation Scenarios for LTE Licensed Assisted Access", October 2014.

[r3] ITU-R WP5D-AR 626, Nokia Solutions and Networks, "Path Loss Measurements on 10 and 20 GHz for M.[IMT.ABOVE.6GHZ]", January 2015.

[r4] 3GPP TSG RAN WG1, R1-160708, Nokia Networks, Alcatel-Lucent Shanghai Bell, and Alcatel-Lucent, "UMa Measurement and Ray Tracing Results for the Study on Channel Model for Frequency Spectrum above 6 GHz", February 2016.

[r5] 3GPP TSG RAN WG1, R1-161641, Nokia Networks, Alcatel-Lucent Shanghai Bell, and Alcatel-Lucent, "Path Loss Modeling for Channels above 6 GHz", March 2016.

[r6] Aalto University, AT&T, BUPT, CMCC, Ericsson, Huawei, Intel, KT Corporation, Nokia, NTT DOCOMO, New York University, Qualcomm, Samsung, University of Bristol, and University of Southern California, White Paper on "5G Channel Model for bands up to 100 GHz", May 2016.

[r7] 3GPP TR 38.900 v14.0.0, Study on Channel Model for Frequency Spectrum above 6 GHz, June 2016.

And, 1 patent application has been filed:

[p1] L. G. U. Garcia, E. P. L. Almeida, **I. Rodriguez**, V. S. B. Barbosa, and G. Caldwell, "Método de Planejamento de Rede e Método de Planejamento de Mina", BR Patent 10 2016 005371 4, issued date 10 March 2016.

This thesis has been submitted for assessment in partial fulfillment of the Ph.D. degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

List of Acronyms

2G 2nd Generation

3G 3rd Generation

3GPP 3rd Generation Partnership Project

4G 4th Generation

5G 5th Generation

AB Alpha-Beta

BS Base Station

CDF Cumulative Distribution Function

CI Close-In

CIR Channel Impulse Response

CW Continuous Wave

DCM Directional Channel Model

DG Deployment Guidelines

FBR Front-to-Back Ratio

FF Far-Field

FS Free Space

FSPL Free Space Path Loss

FWA Fixed Wireless Access

GO Geometrical Optics

GTD General Theory of Diffraction

HetNet Heterogeneous Network

HG Height Gain

IoT Internet-of-Things

ISM Industrial, Scientific and Medical

ITU-R International Telecommunication Union Radiocommunication Sector

KED Knife-Edge Diffraction

KEDL Knife-Edge Diffraction Loss

LOS Line-of-Sight

M2M Machine-to-Machine

MBB Mobile Broadband

METIS Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society

NF Near-Field

NLOS Non-Line-of-Sight

PL Path Loss

PLE Path Loss Exponent

RAT Radio Access Technology

RMSE Root Mean Square Error

RQ Research Question

RT Ray Tracing

RX Receiver

SbS Street-by-Street

SCM Spatial Channel Model

SCME Spatial Channel Model Extended

SF Shadow Fading

SIR Signal-to-Interference Ratio

STD Standard Deviation

List of Acronyms

TX Transmitter

UDHN Ultra-Dense HetNet

UE User Equipment

URLL Ultra-Reliable and Low-Latency

UTD Uniform Theory of Diffraction

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

V2X Vehicle-to-Everything

WINNER Wireless World Initiative New Radio

WLAN Wireless Local Area Network

Contents

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Chapter 1

Introduction

In recent years, Mobile Broadband (MBB) data traffic has experienced an enormous growth. As illustrated in Fig. 1.1, the mobile data traffic was increased by a 7-fold factor from 2010 to 2013 [1]. The increasing trend has not changed, and reported data and forecasts indicate that by 2020 the monthly traffic would reach up to 30.6 EB/month in 2020 (i.e. approximately 22 times more data traffic than in 2013, or 8 times more than in 2015) [1].
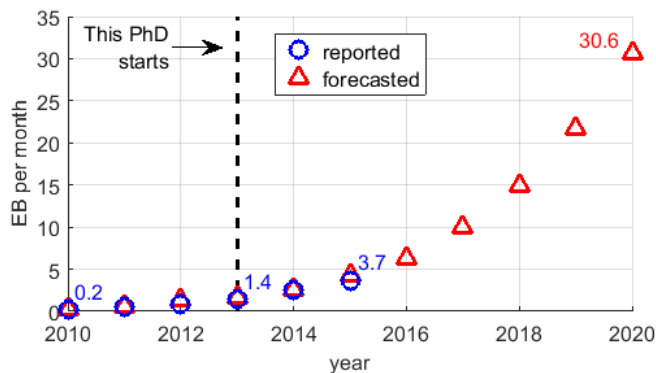
Fig. 1.1: Monthly global mobile data traffic 2010-2020 [1].

In the beginning, this growth was coped with by the evolution of the 2nd Generation (2G) and 3rd Generation (3G) mobile networks, together with the development and initial roll-outs of the 4th Generation (4G). However, the massive penetration of MBB data-enabled devices, together with the increasing number of subscriptions and generated traffic volume per subscriber, have pushed telecommunication operators into the search for solutions that help them to further boost their networks.

In order to provide ubiquitous coverage and cope with this massive growing traffic demand, simultaneously with the legacy of existing Base Stations (BSs) and User Equipments (UEs), operators have increasingly focus on the development and deployment of of Heterogeneous Networks (HetNets).

1.1 HetNet Definitions

HetNets can be defined as networks where multiple Radio Access Technologies (RATs) (such as 2G, 3G, 4G, Wi-Fi, or even the forthcoming 5th Generation (5G)) and cell deployment options (macro, micro, pico and relays) coexist together. These multi-RAT multi-cell networks are typically disposed in a multi-layer topology [2], where a main macro cell layer is used for wide area coverage and mobility, and secondary layers of low-power small cells target particular areas where coverage holes are present or extra capacity is needed [3,4].

Typically, the different types of cells that are part of a HetNet are classified by the size of the area covered or the number of connected users. From larger area (or higher number of users) to smaller area (or lower number of users), the following types can be distinguished: macro, micro and pico; being the last two categories small cell types [2,3]. HetNets are to be mainly deployed in urban areas where most of the mobile traffic is generated [4]. Therefore, a more specific classification can be done from a radio propagation perspective, according mainly to the position of the BS antennas in the urban scenario:

- **Macro cells** are typically deployed with BS antennas in elevated outdoor positions, above rooftop level.

- **Small cells** are deployed with BS antennas below rooftop level, closer to the end users, in outdoor or indoor positions.

  - **Micro cells** are deployed in outdoor positions with BS antennas close to street level (e.g. mounted on lampposts or traffic lights).

  - **Relay nodes** are a type of outdoor small cell deployed with wireless backhaul [5] and BS antennas at similar positions to a micro cell. In the very particular case of the relay nodes, and always from a radio propagation perspective, the backhaul link can be seen as a macro cell, while the access link between the relay and the UE resembles a micro cell.

  - **Pico cells** are deployed with BS antennas at lamppost level or lower, typically at indoor positions [6].

A multi-layer HetNet topology considering the different types of cells defined is illustrated in Fig. 1.2.

Fig. 1.2: Overview of the different types of cells in a multi-layer HetNet [4].

1.2 HetNet Evolution: Strategies and Challenges

In the past, mobile networks were mainly composed of a macro layer operating at low frequency bands (below 3 GHz) with the main target of providing outdoor coverage. In order to meet the coverage requirements, it was sufficient to apply network evolution strategies consisting of densification and optimization of the macro layer [7]. However, as wireless communications evolved and became more widespread, the mobile data traffic demands increased, and meeting the coverage and capacity requirements turned into a big challenge for network operators.

With respect to **coverage**, the actual needs of exchanging data everywhere and anytime have made in-building (indoor) coverage an extra issue that operators need to address together with the outdoor coverage holes. As the previous macro-centric strategies are not always sufficient to provide the targeted coverage levels, and further densification of the macro layer may not always be feasible, mobile operators can choose to deploy instead outdoor or indoor small cells in particular areas where they are needed. The small cell deployment may also solve initial **capacity** problems in areas where mobile traffic is concentrated (hotspots).

However, as a result of the deployment of small cells and the further densification of the network layers in general, inter-site distances are reduced and co-channel interference may compromise capacity in Ultra-Dense HetNet (UDHN) deployments [8]. In order to limit and control the interference from the network side, and be able to meet the capacity requirements, network operators would unavoidably need to explore different spectrum allocation combinations. More allocated bandwidth or out-band deployments, where

the macro and the small cell layers are deployed at different carrier frequencies, are part of the solution.

Up to today, apart from at the typical cellular carriers frequencies below 3 GHz used for the macro layer (which are used by operators in initial small cell deployments), small cells are being operated mainly at the Industrial, Scientific and Medical (ISM) bands at 2.4 and 5.8 GHz, and more recently, at the 3.5 GHz band [9]. The lack of cellular spectrum available in the below 6 GHz region has already triggered the exploration of higher frequencies in the cm-wave (3-30 GHz) and mm-wave (30-300 GHz) bands in the search of free spectrum and larger continuous bandwidth allocations [10].

In order to plan, deploy and optimize HetNets, radio propagation must be studied and properly modeled. Along the years, the focus of the studies has typically been aligned with existing deployment needs. While in the past the focus was on macro cells operated at low frequencies over large distance ranges, the development of UDHNs has changed the focus to short distances and new frequency bands for both macro and small cells. The different combinations of cell types, BS antenna positions and frequency bands have shaped a new set of yet unexplored propagation scenarios, which need to be addressed and modeled in order to create adequate network deployment guidelines and harvest the best out of the HetNets.

The exponential mobile traffic growth, together with the evolution towards a global connected Internet-of-Things (IoT) world [11], is triggering the development of new cellular technologies. These new wireless technologies will need to integrate MBB connectivity with new use cases such as Machine-to-Machine (M2M) or Ultra-Reliable and Low-Latency (URLL) communications. These new disruptive use cases, where the typical human-operated UEs are substituted with automated machines, will result in very different deployment configurations as compared to the existing HetNets scenarios and, therefore, radio propagation issues need to be assessed in advance.

1.3 A Survey of Radio Propagation Modeling

A vast amount of radio propagation studies and models has been reported in the literature. This section, that should serve as a motivation for the work presented in this thesis, aims at summarizing the modeling evolution with focus on the main trends and models.

1.3.1 Outdoor Macro Cell Propagation Models

As it was briefly mentioned in the previous section, radio propagation has been typically addressed in parallel with existing deployment needs. This means that, in the past, when mainly sparse macro-only networks existed

with the aim of providing large outdoor coverage; the focus of the propagation studies was on scenarios with elevated BS antenna positions, long distance ranges (up to several km) and low frequencies (below 3 GHz). For these scenarios, the empirical Hata model [12], and its later evolution based on Okumura frequency corrections [13], the COST-Hata model [14] is the most commonly used Path Loss (PL) model for signal strength prediction in large and small macro cell scenarios in both urban and rural areas. The model is applicable over flat terrains, with BS antennas above rooftop level at heights in the range between 20 and 300 m, distances over 1 km, and frequencies up to 2 GHz. More specifically for urban macro cells, the semi-deterministic COST-Walfisch-Ikegami model [14], based on a combination of the models from Walfisch [15] and Ikegami [16], allows for improved PL estimation by parameterizing some of the characteristics of the urban scenario such as the average building height and separation or street width and orientation. In this case, the model is applicable for frequencies from 800 MHz to 2 GHz, BS antenna heights from 4 to 50 m, and distances between 20 m and 5 km. The accuracy of these urban models has generally been reported to be in the order of 8-9 dB Root Mean Square Error (RMSE) [17].

The impact of vegetation and terrain profile in large macro cell scenarios operating at low frequency bands has also been addressed in the past. The influence of vegetation has typically been modeled as additional PL to the Hata model [18], or by means of empirical exponential models like the one proposed by Weissberger [19], that accounts for the overall attenuation as a function of the distance inside the vegetated area. Other more theoretical approaches, like the one presented by Blaunstein in [20], combine statistical models and multiple diffraction and scattering deterministic approximations. With respect to the impact of irregular terrain profiles, the effect of the large-scale variations has typically been addressed through semi-empirical models like the one in [21], that combines the Hata model with deterministic Knife-Edge Diffraction (KED) factors. Other main models considering terrain variations are based on fully deterministic Geometrical Optics (GO) approaches such as the General Theory of Diffraction (GTD) [22] or the Uniform Theory of Diffraction (UTD) [23]. These models do not have a clearly defined application range and, as they rely on topographic information, their accuracy is subject to the resolution of the maps and number of interactions of the rays with the terrain.

For suburban areas, the Erceg model [24] and its subsequent evolution, the SUI model [25], are two of the most commonly used empirical PL models for macro cells in hilly terrain scenarios. They present an application range with frequencies up to 2 GHz, BS antenna height between 15 and 40 m, and distance ranges up to 10 km, achieving a similar accuracy to that from the urban models [17].

All the previous literature aimed at modeling large-scale propagation effects, mainly PL, in macro cell scenarios. However, some models with focus on small-scale propagation effects have also been reported. For example, the statistical Turin model [26], that can be used to predict multipath in urban scenarios, by assuming the presence of random intermediate scatterers within the wireless path between the BS and the UE.

1.3.2 Outdoor Micro Cell Propagation Models

Even though macro cells were the main deployment option, researchers already explored in the past the possibility of bringing the BS antennas closer to the street level. PL in urban micro cell scenarios has been typically modeled, considering the different Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions, by means of statistical dual slope models [27, 28] and other site-specific semi-deterministic recursive methods considering consecutive street directions and orientations [29]. These short-range models are typically applied in terms of a breakpoint distance that fixes the range at which the change in slope should happen.

With respect to the impact of irregular terrain profiles and vegetation on the radio propagation in this type of scenarios, generally, both effects were not specifically addressed in the past. As micro cells aim to cover small areas, these were assumed to be flat. And, in the case of the presence of vegetation in the scenario, its effect was likely to be captured by the different slopes of the models.

Bringing the micro cell BS antennas below rooftop level results in a more complex propagation environment compared to the macro cell case. The exact geometry of the urban scenario greatly impacts the short range propagation turning it into site-specific, and also the expected accuracy is higher than in the macro cell case. Thus, fully deterministic Ray Tracing (RT) modeling approaches [30] were developed based mainly on detailed 2D or 3D maps of the scenarios.

1.3.3 Outdoor-to-Indoor Propagation Models

In order to estimate the coverage provided by an outdoor macro or micro cell inside a building, the transition between outdoor and indoor needs to be carefully considered. Common building penetration models split the overall PL into outdoor, outdoor-to-indoor and indoor [14]. Following this approach, the most famous model is the one proposed by Berg [31], which applies to urban micro cells in LOS conditions. It accounts for the external wall loss and the dynamics in the horizontal domain by empirically modeling the dependence on the interaction angle between the BS position and the facade of the target building.

In the case of macro cells, or micro cells in NLOS, where actual building illumination conditions are difficult to be estimated in real-world deployments, the typical approach has been to apply a constant 'effective' penetration loss factor on top of the estimated outdoor PL [32]. This factor has usually been computed empirically by comparing the indoor signal strength with an outdoor reference level, generally measured at street level.

With respect to modeling of the vertical domain, not much work was done in the past. The most common approach applied to estimate coverage at different floors has been to compensate the outdoor street level PL predictions by a linear Height Gain (HG) compensation factor [33] accounting for the loss/gain per floor. This approach applies to both macro and micro cell scenarios. A gain is applied until reaching the floor at BS antenna height, while above, a loss should be applied.

1.3.4 Indoor Propagation Models

In relation to indoor propagation, different models oriented to the design and evaluation of wireless systems with indoor BSs (pico cells) have been reported in the literature. Typical approaches include mainly empirical models such as the single-slope, multi-wall/floor and linear attenuation models reported in [14] for frequencies below 2 GHz. They are all said to have a similar application range, with no limitations as long as they are applied to indoor environments. However, their accuracy depends on the scenario. If propagation is evaluated inside the same compartment, without trespassing any wall, the single-slope model presents a better accuracy with less than 3 dB mean error. In the case the models are applied to a scenario with multiple floors and compartments, where signals penetrate through indoor walls/ceilings, the multi-wall/floor applies better with an average mean error of 6 dB (decreasing with distance). All the models present a Standard Deviation (STD) of the error in the order of 7-10 dB [14].

As propagation in indoor scenarios differs considerably from the outdoor case, with a stronger influence of surrounding obstacles such as walls or furnitures due to the shorter distances, local shadowing variations are stronger that in the outdoor case, and therefore multipath needs to be more carefully considered. At this respect, the initial Saleh-Valenzuela model [34] is a small-scale statistical propagation model that assumes that in indoor scenarios the multipath components arrives in clusters to the UE.

Indoor scenarios were the first over which fully deterministic RT approaches were taken, due to the early availability of the geometrical indoor information. Some of the initial models reported in the literature [35], are shown to outperform other models when the application scenario is correctly parametrized and calibrated.

1.3.5 New Frequencies and Model Extensions

The presented propagation models were developed and validated mainly at low frequency bands, generally below 3 GHz. With the years, the evolution of the different wireless systems resulted in yet unexplored propagation scenarios, where the different types of cells were operated at higher frequency bands outside the application range of the models. This was the case of, for example, the Fixed Wireless Access (FWA) macro cell deployments in urban and suburban areas operating at 3.5 GHz; or the micro and pico cell Wireless Local Area Network (WLAN) deployments operating at 5.4 GHz. In order to plan and deploy the networks at the new frequency bands, a re-evaluation of the existing propagation models was needed. Therefore, several studies reported in the literature focused on validating the applicability to those new particular bands, or proposing extension to the existing models [36–38].

The evolution towards denser HetNets with more cells and shorter inter-site distances, made the characterization of co-channel interference a key issue for propagation modeling. Due to the need for accurate 3D predictions, RT tools become an increasing trend in radio propagation prediction and network planning [39, 40]. From the mixture of cell types, new frequency bands and also the variety of propagation environments, one of the first approaches to a joint modeling of large and small-scale effects was born with aim of evaluating the performance of adaptive antennas or systems with multiple antennas. The COST259 Directional Channel Model (DCM) [41] is a wide-band mixed deterministic/statistical aimed at modeling directional Channel Impulse Response (CIR) in both spatial and temporal domains. The frequency application range of the model is limited to a maximum bandwidth of 10 MHz and frequencies from 450 MHz to 5 GHz. This model was later extended by the COST273 [42] and COST2100 [43] models, which included correlation between large and small scale parameters and were applicable on the same frequency range up to 5 GHz, but with extended bandwidths up to 20 MHz.

1.3.6 Standardized and Simulation-oriented Models

Some of the presented models are part of the recommendations from the International Telecommunication Union Radiocommunication Sector (ITU-R) standardization body [44]. These documents constitute a set of international technical standards that have been developed by administrations, industry and network operators dealing with radio communications. The propagation models included in the recommendations are typically very detailed and can be used to perform propagation predictions in very particular scenarios. However, the ITU-R also provides documents with guidelines for evaluating specific technologies over a set of reference deployment scenarios.

These guidelines generally include references to simplified propagation models suitable for implementation in system and link level simulators, and they are used by other standardization bodies like the 3rd Generation Partnership Project (3GPP) [45]. The exact same simplified propagation models are used by the different contributing parties in order to ensure that the provided performance studies are comparable among them. The 3GPP models are simple, but they still capture the essence of the different propagation environments and they are, in most cases, based on the modeling approaches presented up to now.

The currently used 3GPP models are hybrid large and small-scale models originated in the 3GPP Spatial Channel Model (SCM) [46] and its further evolution, the 3GPP Spatial Channel Model Extended (SCME). This model was the outcome of the Wireless World Initiative New Radio (WINNER) [47] projects, and it is a geometry-based stochastic channel applicable to single and multi-antenna wireless systems operating in the frequency range from 2 to 6 GHz with up to 100 MHz bandwidth. This 2D channel model introduced several simplifications as compared to the COST2100 in order to facilitate its implementation in system level simulators, and is the current one recommended by the ITU-R as a baseline for evaluating different radio interface technologies [48].

1.3.7 Current Modeling Trends

Nowadays, the different radio propagation modeling efforts keep trying to accommodate actual and future deployment needs. In order to design and plan UDHN for the existing wireless technologies, and prepare the terrain for the future 5G systems which are intended to cope with more diverse requirements than current cellular necessities, accurate models are needed [49,50]. Some of the main requirements for the new channel models are [49]:

- Extended frequency range from around 500 MHz up to 100 GHz, with support of large channel bandwidths, up to 2 GHz.

- Assurance of 3D spatial/temporal and frequency consistency.

- Suitability for implementation in system and link-level simulators with practical computational complexity.

- Accuracy, validation and consistency with models below 6 GHz.

- Accommodation of new use cases with disparate requirements such as M2M or vehicular and URLL communications.

Addressing some of these modeling requirements, several measurement results and models have been recently reported by Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society

(METIS) [51]. Based on extensive measurement campaigns, covering frequencies up to 86 GHz with large bandwidths in the order of hundreds of MHz, three different models were developed: a map-based model, a stochastic model, and a scalable hybrid model based on the two previous.

These works serve as a basis for the future radio propagation modeling efforts. Future works will, at the moment, continue in the direction fixed by the 3GPP standardization body, that has proposed the 3GPP 3D channel model [52] as a baseline. This model was inspired by the different existing SCMs and the extension from 2D to 3D defined as part as the WINNER+ [47]. It is a hybrid large and small-scale model applicable to urban macro and micro cell scenarios with outdoor BS antennas. The key aspect is that the UE position is dynamic, and modeled at different heights, not only at the street level as it was done in the previous models.

1.4 Scope, Objectives and Research Questions

This thesis is based on a collection of empirical radio propagation studies addressing different deployment configurations. As in the historical evolution of radio propagation literature, the different studies have been performed according to some of the more immediate needs and demands from existing network deployments. From macro-only networks to small cell HetNet scenarios. From outdoor coverage to in-building coverage. From low frequencies below 3 GHz, to slightly higher frequencies below 6 GHz, addressing later up to cm-wave and mm-wave frequency bands.

The different studies aim at complementing previous works by providing **accurate and simple large-scale propagation models** in diverse areas where there is still a lack of them, or extension and generalization of existing models is needed. These areas are mainly related to the outdoor propagation at frequencies above 6 GHz, the multi-frequency behavior of penetration loss and the 3D outdoor-to-indoor propagation at low frequency bands.

Besides that, based on the different observed behavior, this thesis provides a set of **HetNet small cell Deployment Guidelines (DG)**. Furthermore, it is expected that the proposed models and guidelines are useful for radio network simulation, radio network planning and optimization activities, as well as for 5G standardization purposes.

In connection to the overall objectives, this thesis aims at addressing the following scientific **Research Questions (RQ)**:

RQ.1 To which extent are the existing large-scale macro cell outdoor propagation models applicable to the new HetNet deployment scenarios? Are they accurate in the short distance range (i.e. less than 200 m)? Are they suitable for the new frequency bands (i.e. above 2 GHz)?

RQ.2 To which extent are the existing small cell large-scale outdoor propaga-
tion models applicable to the new HetNet deployment scenarios? Are
they suitable for the new frequency bands (i.e. above 2 GHz)?

RQ.3 How different is the outdoor propagation at high frequency bands (e.g.
cm-wave and mm-wave) and at low frequency bands (e.g. 2 GHz)? Are
the main outdoor propagation mechanisms the same at higher frequen-
cies than at lower frequencies?

RQ.4 Is outdoor-to-indoor propagation frequency-dependent? If so, how sig-
nificant is this dependence?

1.5   Applied Methods

When it comes to understanding and characterizing radio propagation, there
are always two possible approaches: the theoretical and the empirical one.
All the models reported in the literature are based on one of these approaches
or a combination of both. The theoretical approach is based on physical
laws and concepts that have been verified. However, when the underlying
mechanisms are not fully understood or estimated, this modeling approach is
not appropriate. Most of the propagation scenarios investigated in this thesis
are complex and they have not been explored for the higher frequencies yet.
Therefore, the empirical approach is more convenient.

In order to fulfill the aforementioned objectives and provide answers to
the various research questions presented, this thesis investigates, through
experimental and analytical work, different deployment configurations.

The **experimental work** is based on different measurement campaigns
independently planned for each particular objective and type of cell under
study. The measurements have been performed on **realistic/actual deploy-
ments** in order to include the relevant propagation conditions. The exact
details on the different campaigns (setups, scenarios, calibration,...) are given
in each of the individual papers that comprise this thesis.

The **analytical work** performed comprises mainly measurement data pro-
cessing and interpretation. As the main focus is on large-scale propagation,
average path loss is characterized. From the analysis of the different measure-
ment results, empirical statistical models and network planning observations
are derived. In some cases, the modeling is complemented by simulation and
theoretical analysis, in order to provide further explanation to the empirical
observations.

1.6   Thesis Contributions and Outline

The work and contributions presented in this thesis are extensive and cover a broad area of interests. In order to put them in perspective, Fig. 1.3 illustrates a thesis map including contextual information, relating the different topics and publications done during the Ph.D. Note that not only the papers that made up the main body of the thesis (A-M), but all the publications (a-m) and the contributions to ITU-R and 3GPP standardization, previously detailed in the Thesis Details, are included in the figure.

Each of the publications contains different standalone specific contributions such as proposals or validations of propagation models, deployment guidelines or statistical observations. However, all of them can be grouped in three more general categories, which can be considered as the **main contributions of the thesis**:

- **Characterization of the outdoor propagation in urban micro and macro cell scenarios, considering different base station antenna positions, for the cm-wave frequency bands in comparison with the frequency bands below 6 GHz.**

- **Identification of the change in main outdoor propagation mechanisms at cm-wave and mm-wave frequency bands, and evidence of substantially unchanged outdoor large-scale propagation trends at the different frequencies due to the complex propagation in urban scenarios.**

- **Characterization of the frequency and building composition dependencies of the outdoor-to-indoor propagation, and evidence of the frequency independence of the indoor part of the overall outdoor-to-indoor large-scale propagation.**

The remainder of the thesis is organized as follows:

Chapter 2: provides an brief overview of the different investigations with focus on exploration and characterization of **outdoor propagation**. The main discussion revolves around the two first main contributions, where the frequency behavior of the large-scale radio propagation in urban scenarios is discussed, not only in terms of overall path loss but also in terms of frequency-specific main propagation mechanisms. Paper-specific contributions:

- Paper A: validation of the applicability of the COST-Hata and COST-Walfisch-Ikegami models at 2.6 GHz in urban macro cell scenarios and proposal of a geometrical extension to improve downtilt prediction accuracy.
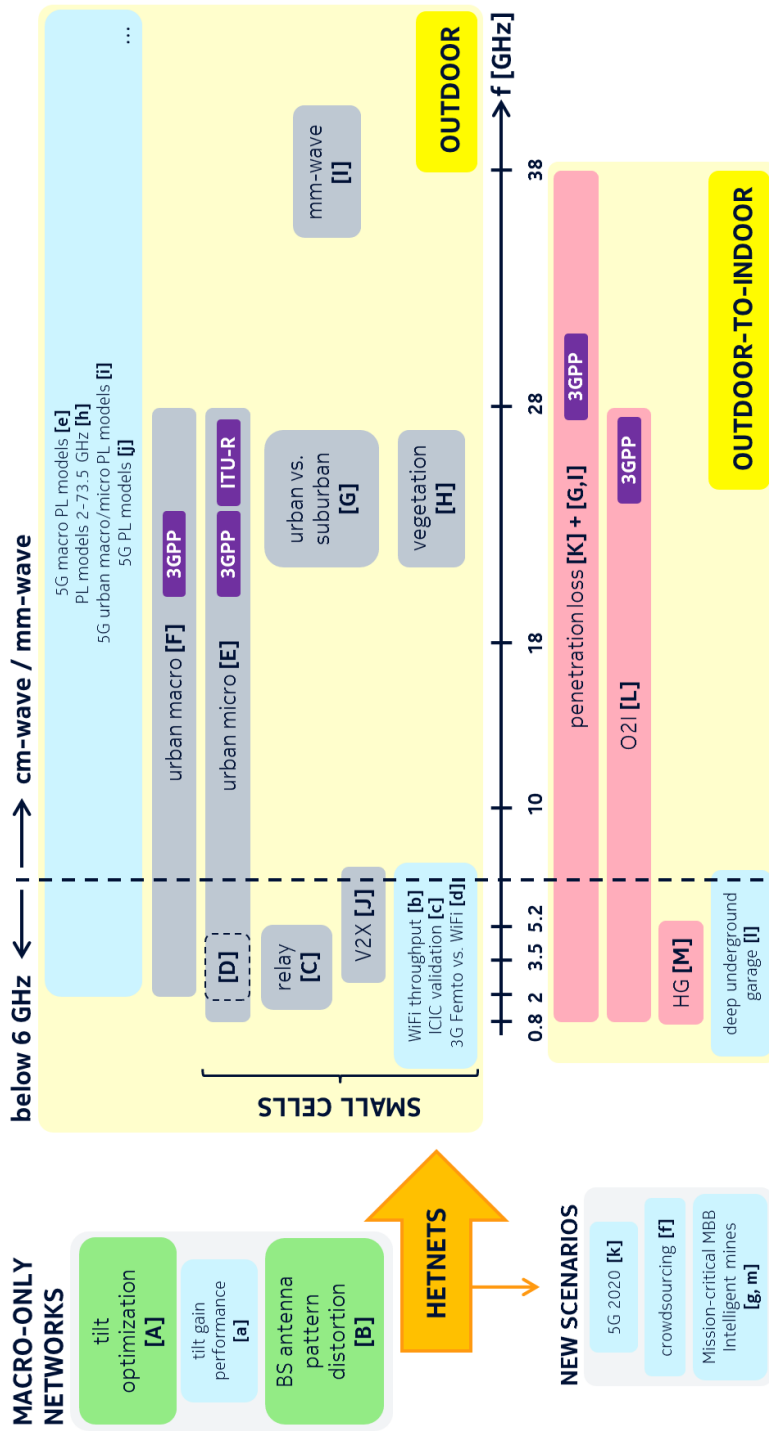
Fig. 1.3: Overview of the thesis outline.

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- Paper B: simulation-based quantification of the magnitude of macro BS antenna pattern distortion in practical urban deployment scenarios.

- Paper C: analysis of the sensitivity of the backhaul link in terms of relay receive antenna type and position, and development of guidelines for relay node deployment in urban macro cell scenarios.

- Paper D: LOS/NLOS statistical path loss model proposal and validation of the applicability of the COST-Hata, WINNER, ITU-R and 3GPP models for urban micro cells at 3.5 GHz.

- Paper E (in preparation): parametrization of different statistical path loss models and characterization of shadow fading for urban micro cells at below 6 GHz and 10, 18 and 28 GHz cm-wave frequency bands.

- Paper F: parametrization of different statistical path loss models for urban macro cells at 2 GHz and 10, 18 and 28 GHz cm-wave frequency bands, for different BS antenna heights.

- Paper G: statistical analysis and comparison of the directional propagation characteristics at 24 GHz cm-wave in urban and suburban scenarios.

- Paper H: computation of the tree-induced and vegetation clutter linear attenuation, and parametrization of the vegetation-induced attenuation ITU-R Terrestrial model at 24 GHz cm-wave.

- Paper I: proposal of a set of simple semi-deterministic models for ray-based characterization of basic urban propagation mechanisms at 38 GHz mm-wave.

- Paper J: statistical characterization of the shadow fading induced by large vehicles in vehicular scenarios at 5.8 GHz with different BS antenna heights, considering a large number of different scenario geometries.

Chapter 3: serves as insight into the topic listed as the third main contribution, presenting a discussion on **outdoor-to-indoor propagation**, where the frequency-dependence and the impact of the modern materials over the effective penetration loss are analyzed. The 3D dynamics of the outdoor-to-indoor propagation are also examined with focus on providing in-building coverage. Paper-specific contributions:

- Paper K: characterization of the outdoor-to-indoor attenuation experienced in different types of constructions. Quantification of the impact of modern construction materials.

- Paper L (submitted): proposal of a set of multi-frequency statistical extension to the existing 3GPP and ITU-R outdoor-to-indoor propagation models at below 6 GHz and cm-wave frequency bands.

- Paper M: proposal of a geometrical KED-based HG model for LOS urban micro cells operating at frequencies below 6 GHz.

Chapter 4: Conclusions. Provides a summary of the main results of the presented investigations with focus on the explored research questions, as well as an outline for future work.

Appendices. Each of the 13 appendices (A-M) contains one of the papers providing support to the different discussions and findings detailed along the main body of the thesis in Chapters 2 and 3.

Chapter 2

Outdoor Propagation

In this chapter, a discussion on several outdoor propagation-related topics is given. The analysis introduces, in first place, a couple of studies related to macro cell propagation with focus on low frequency bands. Later, the study moves toward investigations related to outdoor small cell deployments (i.e. relay nodes and micro cells). The use of higher frequency bands (above 6 GHz) is also explored in this chapter for both micro and macro cell urban scenarios. In line with this, not only overall propagation, but mechanism-specific investigations are reported with focus on cm-wave and mm-wave frequency bands. To conclude the chapter, a small investigation related to small cell vehicular communication systems is presented.

2.1   Macro-only Networks

As stated in section 1.2, optimization of the macro layer is a very important step in network evolution. One of the most common techniques applied by network operators in order to optimize coverage and capacity is BS antenna downtilting [53]. By adjusting the antenna downtilt, the macro cell domi-nance area and the inter-site interference towards surrounding cells can be simultaneously adapted. In order to correctly plan the level of downtilt for the different BSs in the network, accurate predictions are needed. In this context, the first study presented in **paper A**, investigates how the predic-tions from typical empirical path loss models such as the COST-Hata [14] or the COST-Walfisch-Ikegami [14] can be compensated to correctly account for different antenna tilts. The signal strength comparisons between model pre-dictions and measurements performed over selected urban macro sectors at different downtilt angles in a fully operational network show how antenna patterns should be considered differently in each of the models. COST-Hata gives a more accurate prediction when the antenna gain is geometrically

accounted for in the street level height (average RMSE of 9.3 dB). On the other hand, the combined LOS/NLOS COST-Walfisch-Ikegami performs better when it is compensated by the antenna gain calculated at average rooftop level (average RMSE of 5.9 dB). This level of accuracy is in the range of the one achieved by a semi-deterministic calibrated RT model, which was also compared to the measurements (average RMSE of 6.3 dB). The predictions are evaluated for a carrier frequency (2.6 GHz) outside the application range of the empirical models and different distance ranges, thus it is possible to provide some insight into **RQ.1**. With respect to the frequency, the fact that the overall RMSE fall in the typically reported range of 8-9 dB accuracy of the models [17], brings evidence of the valid applicability of these models at this frequency, slightly higher than 2 GHz. With respect to the short distance ranges (distances shorter than 200 m), all the proposed approaches present 4-6 dB higher RMSE than for intermediate and long ranges with distances above 200 m. It is observed from the analysis that, in general, predicting the effects close to the BS is difficult due to the multiple vertical sidelobes of the antennas and the complex mixed LOS and NLOS propagation conditions of the urban scenario.

As a follow up on the short range analysis, **paper B** presents a simulation-based analysis of the distortion experienced by BS antenna patterns in practical urban deployments. The study considers deterministic approaches in order to quantify the effect of the different Near-Field (NF) and Far-Field (FF) potential sources of distortion for two deployment configurations: rooftop and telecommunications tower. The analysis of the results show how, in general, the distortion induced by elements placed in the close vicinity of the BS antenna (such as mounting structures or nearby obstacles) is small in comparison with the distortion caused by the urban propagation mechanisms. In practice, antenna pattern distortion is often translated into a reduction of the expected Front-to-Back Ratio (FBR) [54]. For the simulated deployments, a significant 10 dB FBR reduction from the theoretical Free Space (FS) reference pattern was observed. From the total reduction, 1/3 was caused by NF distortion, and the other 2/3 by FF distortion (shadowing and multipath induced by the intrinsic urban propagation mechanisms, i.e. diffraction and reflection). These observations are also relevant for **RQ.1** as they provide further insight into what is causing the lower accuracy of the empirical prediction models in urban macro cell scenarios when applied combined with theoretical antenna patterns taken directly from the specifications of the manufacturer.

2.2 Outdoor Small Cells

With focus on heterogeneous deployments, **paper C** addresses a mixed macro-relay urban scenario. The backhaul link between macro cell and relay node is evaluated by means of measurements in an operational cellular network. The study evaluates different configurations in order to understand the sensitivity of this type of deployments with respect to relay node receive antenna and position. The measurement results show that, with omnidirectional antennas, the received signal strength from the donor macro BS can be increased by 1.8 dB, on average, by elevating the relay antennas from 2.4 to 5 m. However, the same combination of omnidirectional antenna and elevated position, results in a proportional increase of the amount of interference seen from other surrounding macro BSs, which translates into an average 1.8 dB decrease in terms of Signal-to-Interference Ratio (SIR). The use of directional antennas at the relay side to filter some of the interference, in order to improve the overall backhaul link quality, was also explored. From the evaluation of the measurements performed at different potential relay locations (at macro cell-edge), it was observed that, as expected, in LOS conditions there is a clear benefit in using directional antennas (6 dB higher interference reduction than with omnidirectional antennas). However, in NLOS conditions, where most of the relays are expected to be deployed, the benefit in terms of SIR is smaller (only 4 dB) or even inexistent due to the lack of a very clear dominant donor BS and the high amount of interference arriving from a number of directions. From these observations, some practical **relay node DG** can be extrapolated:

- Relay nodes are not as deploy-where-you-want-and-play devices as it was thought at the beginning. Careful radio planning might be necessary to ensure a high quality in the backhaul link and guarantee a correct service to the user connected to the relay node.

- Directional receive antennas are preferred at the relay node backhaul side.

- The deployment of relay nodes is easy in LOS conditions as the relay node receive antenna can be accurately pointed towards the desired donor macro BS without difficulty.

- In NLOS conditions, the correct deployment of relay nodes is more challenging. Due to the lack of direct visibility, the direction of arrival of the desired signal from the donor BS must be identified by applying a systematic approach: 1) explore the direction of arrival of potential first or second order reflections from the donor macro BS (e.g. pointing the receive antenna towards a building located in opposite direction

to the BS, or along a street canyon). 2) if no clear donor was found, sweep the entire azimuth by rotating the antenna in steps of a maximum size equal to half the antenna horizontal beamwidth until finding a dominant desired direction. 3) in the case that still no clear donor was detected, increase the height of the receive antenna and repeat the procedure.

As explained in section 1.1, from a radio propagation perspective, the relay node access link is similar to that from the other type of outdoor small cells (e.g. micro cells). Therefore, the results and observations from the following studies with focus on micro cells apply to relay node access links as well.

Urban micro cell propagation was initially addressed in the measurement-based study presented in **paper D**. The aim of the study was to provide an understanding on how different the propagation at the 3.5 GHz band (which at that point was about to be announced as an official candidate to support cellular short range communications [9]) is, in comparison with a more well-known and extendedly used frequency band at or below 2 GHz. A simplified micro cell deployment based on narrow-band Continuous Wave (CW) equipment and omnidirectional antennas at both the Transmitter (TX) and Receiver (RX) sides was used in the measurements. Different urban LOS and NLOS locations were selected, allowing to explore simultaneously the propagation at 2 and 3.5 GHz in short range distances up to approximately 200 m from the BS. Following the approach previously reported in the literature, the outdoor PL was fitted to a dual-slope model. In LOS, the PL was found to be very close to the Free Space Path Loss (FSPL) at both frequencies, with an offset of approximately 4 dB at 3.5 GHz over 2 GHz. In NLOS, the slopes were close to 40 dB/decade, finding an approximately 6 dB higher PL at 3.5 GHZ compared to 2 GHz. An inverse exponential probability of LOS function was defined in order to provide a joint LOS/NLOS formulation of the PL model. In connection with **RQ.2**, this model was compared to other selected state-of-the art models, finding that small cell-oriented models such as the 3GPP, ITU-R and WINNER, typically derived at 2 GHz, would predict correctly the trends of the PL at 3.5 GHz, with small deviations of maximum 2-3 dB at 200 m. Surprisingly, despite the COST-Hata model is defined for elevated BS antennas and minimum application distances over 1 km, it was found that its prediction matches closely (± 2 dB difference) the NLOS PL at both 2 and 3.5 GHz. On the other hand, the COST-Walfisch-Ikegami was found to clearly overestimate the PL in NLOS conditions by up to 20 dB at 2 GHz and 30 dB at 3.5 GHz.

2.3 Higher Frequency Bands

2.3.1 Micro Cells

Even though the previous study only presented the analysis of urban micro cell propagation at 2 and 3.5 GHz, the same measurement campaign considered simultaneously yet another two frequencies: 800 MHz and 5.2 GHz. In order to provide some insight into micro cell propagation for higher cm-wave frequency bands, another three different campaigns were performed afterwards considering 10, 18 and 28 GHz. A 2 GHz signal was used as a common reference throughout all the measurement campaigns to verify the correct alignment of the results and detect potential calibration errors. A measurement setup consisting in a simplified micro cell BS deployment with omnidirectional antennas at both the TX and the RX, similar to the one used in the first measurement campaign, was used. Also the measurement procedures and locations explored were exactly the same as in the first measurement campaign. The outcome of the different measurements was combined in **paper E** to provide a complete statistical overview of the propagation in urban micro cell scenarios from frequencies below 6 GHz up to cm-wave frequency bands. The analysis includes the parametrization of two of the most referenced statistical large-scale PL models considered as a baseline for comparison of the propagation in different scenarios [49]. These models are namely the Alpha-Beta (AB) model and the Close-In (CI) model, and their formulation can be found in Table 2.3.

Table 2.1: Formulation of the different statistical models evaluated for urban micro and macro cell scenarios paper [E,F].

Model	Formulation
AB	$PL_{out,AB} = 10 \cdot \alpha \cdot log_{10}(d) + \beta + X_{SF}(0, \sigma_{out})$ [dB]
CI	$PL_{out,CI} = 10 \cdot n \cdot log_{10}(d_m) + FSPL(1m) + X_{SF}(0, \sigma_{out})$ [dB]

The AB model is a floating-intercept model with free linear fit to the data based on two coefficients: α, and β accounting for the slope and the offset, respectively. On the other hand, the CI model considers the fixed reference of the FSPL at 1 m as an anchor point for the frequency offset, and a single coefficient (n), derived from the data, accounting for the slope. In both cases, the models include the random Shadow Fading (SF) variations around the mean PL by means of a zero-mean Gaussian random variable (X_{SF}) with STD σ_{out}.

Table 2.2 provides the parametrization for the aforementioned models for the different frequencies explored. As it can be seen, in LOS conditions, the estimated propagation Path Loss Exponent (PLE) for the AB model (α) is slightly different for the each of the considered frequencies, with an average

Table 2.2: Parametrization of the different statistical models considered for the urban micro cell scenario for the different frequency bands explored [E].

f [GHz]	AB LOS			CI LOS		FS LOS	AB NLOS			CI NLOS	
	α	β [dB]	σ_{out} [dB]	n	σ_{out} [dB]	σ_{out} [dB]	α	β [dB]	σ_{out} [dB]	n	σ_{out} [dB]
0.8	2.1	28.5	4.2	2.0	4.2	4.2	4.0	11.0	7.7	3.0	7.6
2	2.3	32.9	3.8	1.9	4.0	4.0	3.6	27.2	7.9	3.0	8.0
3.5	2.5	34.6	3.7	2.0	3.9	3.9	3.7	31.4	8.3	3.1	8.3
5.2	2.0	46.9	5.4	2.0	5.5	5.4	3.5	38.7	9.2	3.1	9.2
10	1.9	52.5	3.1	2.0	3.1	3.2	4.0	33.0	8.7	3.0	8.7
18	2.3	52.7	4.1	2.0	4.1	4.1	4.1	36.6	8.7	3.0	8.8
28	1.8	63.3	3.2	2.0	3.3	3.3	3.8	46.4	7.7	3.0	7.7
AVG	2.1		3.9	2.0	4.0	4.0	3.8		8.3	3.0	8.3

value of 2.1. Differently, the PLE for the CI model (n), exhibits more stability PLE-wise, with values equal or very close to 2 in all cases. Despite of the slightly different predicted trends by the AB and CI models, they are in all cases very close to the FSPL for all frequencies. As it can be seen, for each particular frequency, the fit to the models, including the FSPL, exhibit a very similar STD (σ_{out}), which indicates a comparable level of fitting accuracy for all the models. Even being different the obtained STD values at each of the frequencies (mainly due to the different antenna radiation patterns), they present comparable levels, with an average of approximately 4 dB in the LOS case.

In NLOS conditions, the PLEs are higher than in LOS. Similarly to the LOS case, the trends predicted by the AB model present some variability across frequencies, with an average α of 3.8 in this case. On the other hand, for the CI model, n results in more-stable values about 3 for all frequencies. Once again, despite of the slightly different resultant trends, both the AB and CI approaches are very close to each other, exhibiting both a very similar σ_{out}. The variability of the STD in NLOS across frequencies is smaller than in the LOS, as in this case, the antenna pattern imperfections are smoothed out due to the multiple interactions suffered by the propagated signal within the surrounding environment. However, precisely due to the multiple interactions, the absolute value of the STD in NLOS is larger than in LOS. On average, it was found to be approximately 8 dB in NLOS.

A closer analysis of the SF at the different frequencies was presented in the paper. This analysis includes the decorrelation distances (representing the similarity of the SF at different RX locations from the same TX) and the inter-frequency correlation (quantifying the frequency-to-frequency similarity between the SF from the same TX at different frequencies at the same RX location). The results show that statistically, the decorrelation distance is invariable with the frequency, similar to the recent findings in [55]. Moreover, applying the calculations over the AB or CI resulted in similar decorrelation distances in the order of 5 m in LOS and slightly larger, 6-7 m, in NLOS. From the inter-frequency analysis, it was found that the SF presents no clear correlation between frequencies in LOS conditions, while in NLOS, a strong correlation (above 0.7) was found in approximately 75% of the cases.

The study also points out that the empirical distributions of the SF in LOS conditions fit well to the zero-mean Gaussian distribution considered by the AB and CI models. However in NLOS conditions, the resulting SF distributions are not Gaussian (despite the models typically consider them as such). This is due to the fact that the experienced PL in NLOS urban micro cell scenarios is very dependent on the different street canyons orientations and, thus the SF from dominant orientations bias the overall SF distributions.

In perspective of future large-scale propagation modeling approaches, which could improve the limited spatial consistency of the AB and CI statis-

tical models for urban micro cell scenarios, the study also reports the statistical SF distributions and basic correlation relationships applicable to potential Street-by-Street (SbS) PL models [56] accounting for the site-specific propagation. The measurement-based results confirm that, in comparison with the AB and CI models, more homogeneous zero-mean Gaussian SF distributions, with a lower average STD of approximately 3 dB, may be obtained in both LOS and NLOS conditions by applying the SbS modeling approaches. With respect to correlation statistics, shorter SF decorrelation distances of approximately 4 m were found in both LOS and NLOS by applying the SbS approach. The inter-frequency SF correlation presents similar characteristics to the one obtained with the AB and CI models.

2.3.2 Macro Cells

The higher frequencies were also explored for the urban macro cell scenario, as reported in **paper F**. In this case, measurements were performed, for several cm-wave bands (10, 18 and 28 GHz) in comparison with 2 GHz, by using a customized macro cell setup. A macro BS sector was emulated by using directional horn TX antennas located at several stationary elevated locations. The analysis considered three different BS antenna heights: 15 m (below average rooftop level), 25 m (slightly above average rooftop level) and 54 m (clearly above average rooftop level). The measurements were performed with RX omnidirectional antennas mounted on a van covering distances up to approximately 1.4 km from the BSs in LOS and NLOS conditions. A similar PL analysis to the one performed for the micro cell scenario, considering the parametrization of statistical models, was done. The original paper only presented the parametrization of the AB model. However, in order to provide a complete overview, also the parameterization of the CI model is detailed in this report. The details for both models are provided in Table 2.3, in which, as it can be seen, there are some values in italics and marked with an asterisk. These values were obtained from data sets in which, due to the more limited measurement dynamic range at the higher frequencies, a large portion of the data exceeded the RX sensitivity. Despite the results from these noise-limited measurements might be less representative than the others, they were considered in the original paper and in this report for the sake of completeness of the study, but they have not been considered in the computation of the average numbers at the bottom of each column.

In LOS, the macro cell PL is independent of the BS antenna height and therefore, the data from different TX antenna heights were combined in the analysis. Similarly to the micro cell case, the PLEs about 2 indicate that the PL is close to the FSPL at all frequencies. Also σ_{out} exhibit comparable levels across frequencies as in the micro cell analysis. On average, the STD is approximately 4 dB. Despite of the very similar trends, when fitting the

2.3. Higher Frequency Bands

Table 2.3: Parametrization of the different statistical models considered for the urban macro cell scenario for the different frequency bands and BS antenna heights explored [F].

f [GHz]	h_{TX} [m]	AB LOS			CI LOS		FS LOS	AB NLOS			CI NLOS	
		α	β [dB]	σ_{out} [dB]	n	σ_{out} [dB]	σ_{out} [dB]	α	β [dB]	σ_{out} [dB]	n	σ_{out} [dB]
2	15	2.1	37.9	3.1	2.1	3.1	3.8	3.9	14.4	8.0	3.0	8.3
	25							3.1	31.5	5.9	2.9	5.4
	54							3.2	18.0	5.4	2.5	5.7
10	15	2.0	55.8	5.1	2.1	5.1	5.9	3.4	52.5	7.8	3.4	7.8
	25							3.5	42.4	5.6	3.1	5.6
	54							3.9	17.1	6.2	2.6	7.0
18	15	2.1	57.5	4.7	2.1	4.7	5.4	4.9*	6.0*	4.5*	3.0*	5.2*
	25							3.3	51.9	5.9	3.1	6.0
	54							3.7	25.3	6.0	2.6	6.7
28	15	2.1	61.5	4.2	2.1	4.2	4.9	2.5*	63.8*	6.4*	2.6*	6.4*
	25							1.9*	79.3*	6.5*	2.6*	6.5*
AVG		2.1		4.3	2.1	4.3	5.0	3.5		6.4	2.9	6.4

FSPL to the data, the resulting σ_{out} is slightly larger (less than 1 dB) than for the AB and CI models. This is simply due to the noticeable ground reflection effect present in the measured LOS route, which provokes certain ripples over distance, slightly biasing the linear regression coefficients from the AB and the CI models and the STD of the FSPL.

The NLOS PLEs of the AB and CI models are, in general, smaller than in the micro cell case. The AB model predicts, in general, comparable slopes for all the different heights and frequencies, with an average α of 3.5. On the other hand, the slopes predicted by the CI models decrease with increasing BS antenna height, with an average n of 3.2, 3.1 and 2.6 at 15, 25 and 54 m, respectively. By comparing the σ_{out} of both modeling approaches, it can be seen how the STD is smaller for the AB model than for the CI model. This fact indicates that, in the NLOS macro cell case, the free linear fit of the AB model is able to capture better the dynamics of the scenario (e.g. predicted HG), which the artificially induced slope of the CI model would be overestimating or underestimating at short or long distances ranges, respectively. The average STD in NLOS was found to be, at all frequencies, approximately 8 dB for antennas below rooftop, and 6 dB for antennas above rooftop.

Based on the results from the AB model, an average HG of 4, 11.8 and 15.7 dB was found at 2 GHz by elevating the BS antenna from 15 to 25 m, from 25 to 54 m, and from 15 to 54 m, respectively. It is worth to point out that, in the particular case that considers BSs above rooftop (25 and 54 m), the HG value matches with the prediction from the COST-Walfisch-Ikegami macro cell-specific PL model (11.2 dB), which further validates the AB modeling approach as more suitable for the macro cell scenario. From the measurements at 10 GHz, the estimated HG values were 7.5, 14.2, and 23.4 dB, for the height ranges 15-25 m, 25-54 m and 15-54 m, respectively. These values are larger than at 2 GHz as, due to higher diffraction loss experienced at 10 GHz, elevating the BS antenna from 25 to 54 m, results in a relaxation of the diffraction interaction angle between BS and rooftop, which translates into a higher gain as compared to 2 GHz. In this case, the COST-Walfisch-Ikegami, which predicts the same HG independently of the frequency, would be underestimating the gain at 10 GHz by 3 dB. This should serve as a small extra input to **RQ.1**, which suggest that the error of the COST-Walfisch-Ikegami would increase with frequency, and thus would not be applicable at frequencies far outside the original range of applicability.

2.3.3   Dynamics of the Models

Fig. 2.1 helps to put in perspective the different observations derived in the previous subsections for the urban micro and macro cell scenarios. In a) the offsets of the AB model (β) for the different scenarios are displayed. As it can be seen, for both the micro and macro cell scenarios, in LOS, β is close to the
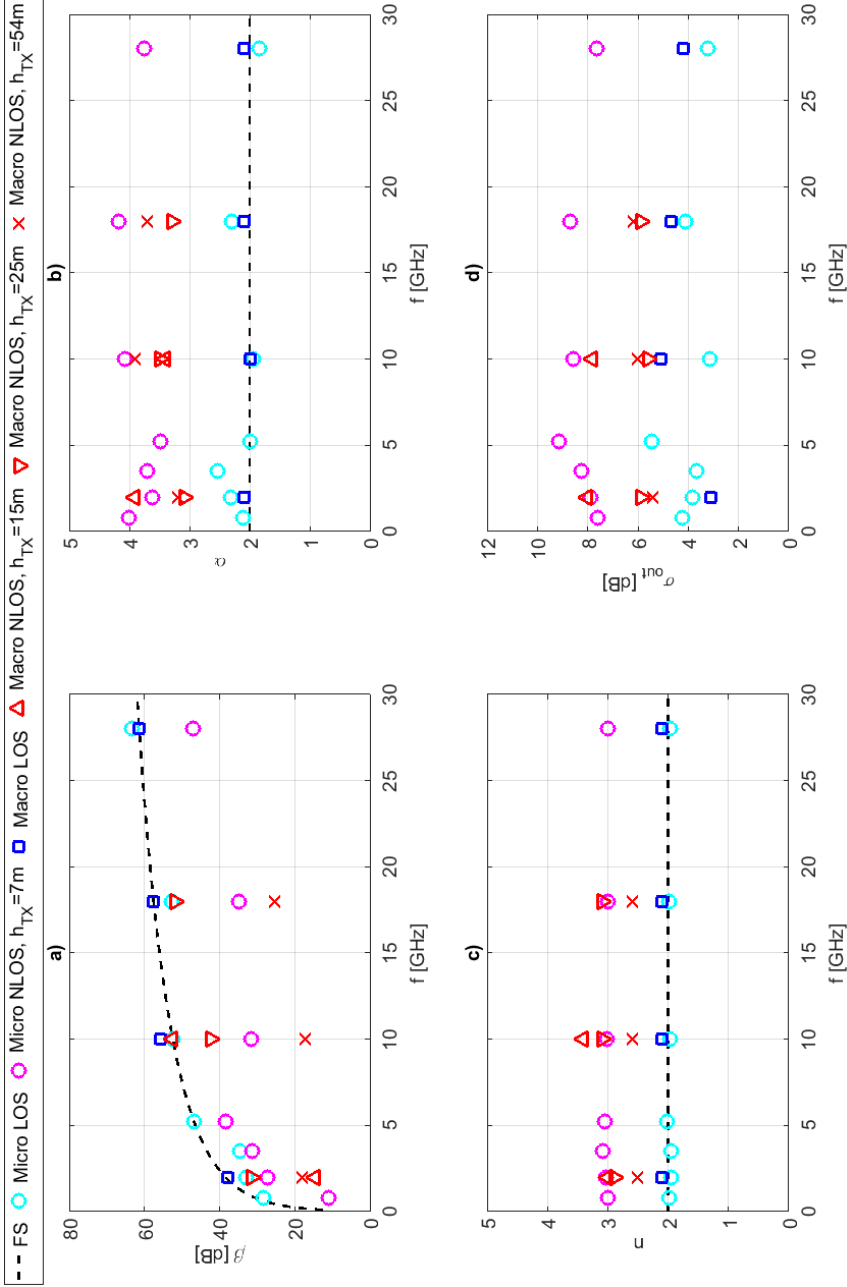
Fig. 2.1: Comparison between the different micro and macro cell parameters for the different models: a) slope (α) of the AB model, b) offset (β) of the AB model, c) slope (n) of the CI model, d) standard deviation of shadow fading (σ_{out}).

FSPL reference at all frequencies. In NLOS, a similar scaling with higher β for higher frequency generally applies as well, but in this case, the values are lower than the FSPL in NLOS. As it can be observed in b) the slopes of the AB model (α) are larger in NLOS than in LOS for both the micro and macro cell scenario. The physical interpretation of the higher α and smaller β of the AB model in NLOS is simply that the breakpoint distance at which the PL prediction would change from LOS to NLOS condition would happen at distances larger than 0 m. This is something that the CI model would never be able to account for without further input from, for example, a LOS probability function as, even though the slopes of the model (n) are larger in NLOS than in LOS (displayed in c)), the fixed FSPL reference offset would never allow that the predicted NLOS PL crosses below the LOS PL at any distance. Even with these theoretical differences, both the AB and CI modeling approaches lead to very similar predictions, due to the inherit short range nature of the micro cell scenario where NLOS conditions would be dominant at relatively close distances from the BS antenna.

By observing once again the different NLOS PLEs in b) and c), the AB model predicts quite similar α per scenario across all frequencies (e.g. 4 for micro cells, and 3.5 for macro cells at all heights). Differently, the CI model predicts similar n (approximately 3) for micro cells and macro cells with BS antennas below and slightly above average rooftop level, and smaller (2.6) for macro cells with BS antennas clearly above average rooftop level. The CI model presents difficulties at discriminating the different BS antenna positions. This could be fine in the micro cell scenario, where it is proven that the change in antenna height does not have a very significant impact in PL meanwhile the BS antennas are located clearly below rooftop level [57]. However, as mentioned in the previous subsection, it might not be realistic in the macro cell scenario in relation to HG prediction.

Finally, in d) the STD of the residuals (σ_{out}) was illustrated in order to get some indications on the SF variability. The plot considers the values obtained based on the AB model, but the same observations apply to the CI as the values obtained were quite similar. From the illustration, it is very easy to see how, the SF variability is close to constant across frequencies. It is also possible to see that the results are consistent with respect to the BS antenna position. In LOS σ_{out} is approximately 4 dB for both micro and macro cell scenarios, slightly higher for NLOS scenarios with elevated macro cells (6 dB), and even higher (8 dB) for NLOS micro cells and low macro cells with BS antennas below rooftop level. The variability of the SF clearly steps up with lower antenna heights as the number of interactions increases. This is related to the main propagation mechanism in each of the scenarios. While in the macro cell case with elevated BS antenna positions, the radio signal propagates above rooftops and gets diffracted from rooftop to street level; in the micro cell case, the signal is mainly driven by street canyon guiding (reflec-

tions) and corner diffractions, suffering, in general, more interactions with the environment than in the macro cell case.

2.4 Propagation Mechanisms at Higher Frequencies

The previous investigations focused on the overall PL experienced at the different frequencies in the particular micro and macro cell urban scenarios. However, from them, it was not possible to derive any clear conclusion on the potential variation in main propagation mechanisms at the higher frequencies in comparison to the lower frequencies. With particular focus on the analysis of the propagation mechanisms at higher frequency bands, the study presented in **paper G** compares the radio propagation in urban and a suburban small macro cell scenarios at 24 GHz cm-wave. A dedicated CW-based measurement setup with directional antennas was used to perform the measurements. Differently from the previous studies, where on-route measurements were collected with omnidirectional antennas, in this case, a static measurement procedure with a rotating horn RX antenna was used. At each of the selected measurement positions, located inside of the area illuminated by the fixed elevated TX antenna, the rotating RX antenna explored the entire azimuth from 0 to 360 degrees with a resolution of 9 degrees, and the elevation range between -30 and +30 degrees with a resolution of 10 degrees. Based on the 280 (40x7) directional power samples available per measurement position, an extensive analysis was performed, comparing the different directional characteristics (multipath) in the urban and the suburban scenario by means of the evaluation of several statistical indicators (e.g. angle spread, angle of arrival or number of multipaths per particular location). From the analysis, it is concluded that, at 24 GHz, outdoor propagation in urban and suburban scenarios can be quite different, especially in NLOS conditions. In both cases, it was observed that propagation at this frequency is mainly driven by reflections. However, due to the presence of vegetation in the suburban area, the average number of directional multipath components received is higher than in the urban scenario. While in the urban case, the impact of the street canyon guiding effects condenses the received energy at a particular location around a main direction of arrival, in the suburban scenario, the strongest received components come from more random directions as a result of the strong scattering originated in the trees.

As a follow up, the multipath-rich behavior observed in the suburban scenario due to the presence of vegetation was analyzed in detail in paper **paper H**. Following the same measurement procedure as in the previous study, a number of measurement locations inside a dense-vegetated area were explored. The directional measurement analysis provided insight on the limited

existing knowledge about the interactions in the radio channel at higher frequencies in presence of vegetation. The results confirmed the observations from the previous study, finding that the radio signal arrives to the RX, on average, from up to 5 different directions inside the vegetation clutter. It was noticeable, that in some cases, the foliage-originated contributions were comparable or even stronger than the reflections from closer buildings. The analysis was complemented by a small PL characterization, estimating a linear attenuation 2.6-3.8 dB/m for the few first meters inside the vegetated area, and an average single-tree attenuation of approximately 20 dB. Based on the results, a parametrization of the ITU-R terrestrial model for 24 GHz was also given.

Within the same line of investigation of the last two studies, in paper **paper I** a measurement-based analysis of urban propagation mechanisms at 38 GHz mm-wave was presented. In this case, different sets of controlled measurements were performed with ultra narrow-beam antennas located close to street level in order to geometrically characterize the contributions from reflection, scattering and diffraction in practical scenarios. A maximum building reflection loss of 20 dB was found at close to normal incidence, decreasing with non-perpendicular grazing incident angles. In the case of non-specular reflection, scattered components were found to spread with certain strength in an interval of ± 30 degrees around the maximum (normal incidence). Diffraction loss was found to be predictable by applying KED calculations, increasing rapidly with increasing interaction angles. Based on these results, a set of simple geometrical models, able to capture the essential angular relationships intrinsic to each of the mechanisms at this frequency, was derived from the measurements. From the observations extrapolated from the comparison between the different diffraction and reflection contributions in the corner scenario, it was confirmed that in street canyons, in NLOS conditions, reflection becomes dominant over diffraction just after a few meters inside of the perpendicular canyon.

As from the findings and observations reported in section 2.3 and in this section, and in relation to **RQ.3**, it seems that even though the propagation at lower and higher frequencies is dominated by different main propagation mechanisms (diffraction and reflection, respectively), in practice, in the urban scenario, the combination of all the contributions from all the different mechanisms result in comparable variations of overall experienced PL at all the different frequencies explored, suggesting no frequency dependence beyond the intrinsic frequency scaling of the PL in FS conditions.

2.5   New Propagation Scenarios

Not only new frequencies, but also new technologies, use cases and deployment scenarios demand a better radio propagation understanding, as it was seen in section 1.2. This is the case in the investigation presented in **paper J**, addressing a particular issue in vehicular communications, where due to the stringent latency and ultra-reliability requirements, even the shortest disruption of the communication link could be an issue. Therefore, having observed the lack of references reporting realistic shadowing values suitable for the many different vehicular scenarios, a dedicated measurement campaign was designed, addressing the shadowing caused by a large vehicle obstacle in vehicular scenarios at 5.8 GHz. Several Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), combined termed as Vehicle-to-Everything (V2X) scenarios, with different geometries and BS antenna heights were explored simultaneously in a practical controlled measurement environment. The statistical analysis of the results show that, on average, the impact of shadowing is 3-6 dB higher in V2V scenarios with low antenna heights (e.g. 1.5 m) than in V2I scenarios with elevated BS antenna heights (e.g. 5 or 7 m). The study also examines maximum shadowing levels experienced in each of the scenarios, finding a maximum of 27 dB in the V2V case, that is reduced to 23 and 21 dB in the V2I scenario with BS antennas at 5 and 7 m, respectively. The impact of the non-asymmetries of the obstacle truck on the shadow levels were also quantified, finding small variations in the order approximately 2 dB. The investigation was completed with a comparison with standard 3D RT simulations, reproducing the measurement scenario and the different geometrical combinations explored in the measurements, with the aim of understanding how good the simple un-calibrated predictions from the tool are in predicting shadowing in this type of scenarios. A good agreement between measurement and simulations was found in general, suggesting, that this tool could be potentially use to partly substitute the tedious measurements and explore accurately more complicated geometrical combinations at a minimum effort. The paper also sets the base for future work oriented to the development of a dynamic scalable shadowing model for system level simulation of V2X communications systems.

Chapter 3

Outdoor-to-Indoor Propagation

This chapter addresses outdoor-to-indoor propagation. First, the impact of different building external facade compositions is discussed. Later, the analysis focus on the characterization of the overall end-to-end propagation, where also indoor propagation is included, for low frequencies below 6 GHz up to cm-wave frequency bands. Finally, a study exploring the outdoor-to-indoor propagation in the vertical domain for frequencies below 6 GHz is presented. The chapter is concluded with a practical outdoor-to-indoor application example.

3.1 Impact of the External Building Composition

Nowadays, most of the mobile data traffic (approximately 80%) is produced indoors [58]. Operators have two main options to provide in-building coverage: rely on the outdoor network infrastructure (macro and micro cells), or deploy dedicated indoor solutions (e.g. pico cells).

In the case that indoor coverage is provided from outdoor cells, the radio signals need to penetrate into the buildings. Thus, the external facade of the different constructions may have a major impact in outdoor-to-indoor propagation depending on its composition [31]. As the new (modern) construction techniques and materials, that are being used nowadays in order to comply with the energy-efficiency regulations [59], may be quite different from the ones applied in the existing (old) constructions, the attenuation experienced by the radio signals in each of the cases may be quite different. This issue was addressed in the measurement-based study presented in **paper K**. In order to estimate the attenuation experienced in different practical

scenarios a dedicated CW measurement setup with directional antennas was used. The analysis explored the penetration loss at normal incidence for the frequency range from 800 MHz up to 18 GHz for several modern constructions in comparison with an old building. From the measurement results, it was observed that the attenuation experienced in all the different scenarios is material-dependent. Due to the use of reinforced and metal-coated construction materials, modern buildings present additional shielding in comparison to the old constructions. On average, the attenuation experienced in modern buildings is 20-25 dB higher than the attenuation measured in the old building, which is lower than 10 dB throughout all the considered frequency range. The study verifies that, in modern constructions, the propagation into the building occurs mainly through the windows. This is due to the fact that the attenuation introduced by the external walls increases rapidly with frequency, while the windows exhibit a very irregular but more moderate frequency dependence, caused by their complex multi-layer and metal-coated structure. Moreover, this irregular behavior can be quite different depending on the type and composition of the energy-efficient glass.

Similar penetration loss measurements were performed at 38 GHz at two of the modern buildings. The results, presented in I, were combined with the ones obtained in the 0.8-18 GHz range to provide frequency-dependent penetration loss models for different external facade elements at normal incidence ($PL_{ext,norm}$). These models, derived as fitted linear dependencies in frequency, are summarized in Table 3.1.

Table 3.1: Summary of frequency-dependent penetration loss models obtained with directional antennas at normal incidence, and omnidirectional antennas at diverse grazing angles.

	Normal incidence [I]	'Effective' [L]
	$PL_{ext,norm}(f)$ [dB]	$PL_{ext,eff}(f)$ [dB]
Old	$PL_{ext,norm,old} = 3 + 0.2 \cdot f$	$PL_{ext,eff,old} = 5 + 0.2 \cdot f$
Modern	$PL_{ext,norm,wall} = 15 + 3.2 \cdot f$ $PL_{ext,norm,window} = 26 + 0.25 \cdot f$	$PL_{ext,eff,modern} = 23.9 + 0.35 \cdot f$
Shop	-	$PL_{ext,eff,shop} = 7.8 + 0.3 \cdot f$
	$f = \{0.8 - 18,\ 38\}$ [GHz]	$f = \{0.8 - 28\}$ [GHz]

A different approach was used in the investigation presented in **paper L**. In that case, the 'effective' penetration loss was measured in several different scenarios: the exact same old building than in the previous study, two of the exact same modern buildings as in the previous study, and various street shops and shopping malls. The measurements were performed with the same dedicated micro cell setups and at the same below 6 GHz (0.8, 2, 3.5, and 5.2 GHz) and cm-wave (10, 18 and 28 GHz) frequency bands, used

in the previous investigations reported in **papers D and E**. Differently from the previous outdoor-to-indoor analysis, omnidirectional antennas were used and the measurements were predominately performed at non-perpendicular horizontal grazing angles. The impact of the diverse grazing angles is observed in the measurement results as a dispersion of the data at each of the considered frequencies, obtaining penetration loss values that are generally larger than the ones previously obtained at normal incidence. This can be appreciated in Fig. 3.1, where a selection of penetration loss measurement results and models from **papers I, K and L** has been illustrated in order to provide visual support to the forthcoming remarks.
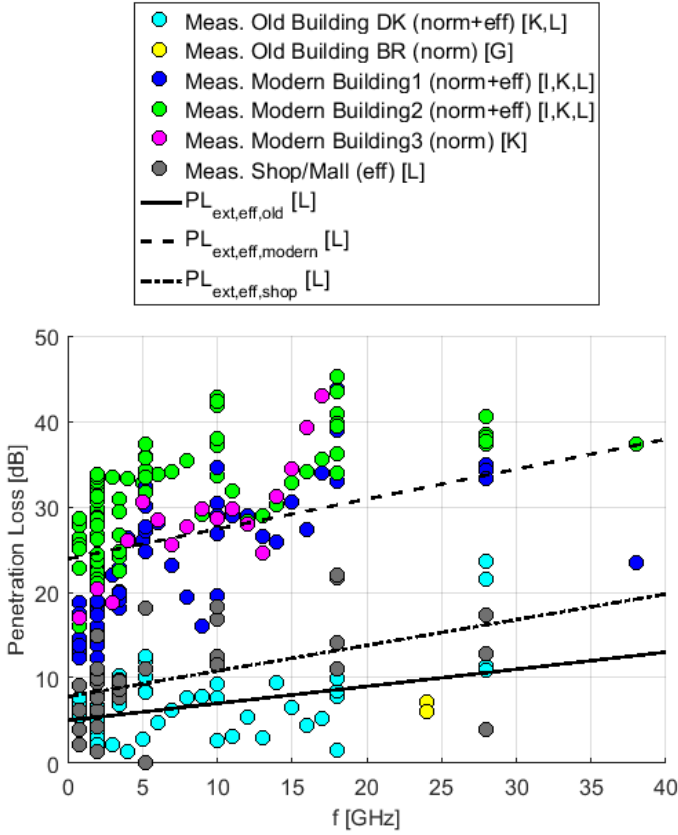

Fig. 3.1: Overview of different outdoor-to-indoor penetration loss measurements and models for the different old/modern buildings and shop/mall scenarios.

By looking at the data from the modern building 2, which is a composite of both the data sets at normal incidence (norm) and at grazing angles (eff), at, for example, 18 GHz, it can be seen how the measurements at grazing angles (cloud of green points) spread from approximately 35 dB (measured

at normal incidence) up to approximately 45 dB. Similarly at 5 GHz, the dispersion of the 'effective' penetration loss ranges from 32 dB up to 38 dB. By looking to the modern building 1 data, also at 5 GHz, the measurement at normal incidence resulted in a penetration loss value of 25 dB, while the maximum 'effective' penetration loss measured at a grazing angle was approximately 34 dB. Based on the clouds of points obtained for the different scenarios (grouped into old and modern buildings and shops/mall) at all the available frequencies, a set of simple linear multi-frequency effective penetration loss ($PL_{ext,eff}$) models was derived. These models are also detailed in Table 3.1. For further clarification, a visual overview of the different scenarios is also provided in Fig. 3.2.

Fig. 3.2: Overview of the different penetration loss measurement scenarios [K,L]: a) modern building 1, b) modern building 2, c) modern building 3, d) old building DK, e) old building BR, f) shop.

In Fig. 3.1, it can also be observed how the 'effective' penetration loss in modern constructions is considerably higher (15-30 dB) than in old buildings, while the shopping areas present an intermediate condition between them. With particular focus on the modern buildings, the irregular and distinct frequency behavior among the different buildings can also be observed. As captured in the 'effective' penetration loss models reported in Table 3.1 and plotted in the figure, which capture the overall behavior across frequencies, the general trend of the penetration loss is to increase with frequency at a rate of 0.2-0.35 dB/GHz. With respect to the dispersion, on average, the STD of the 'effective' penetration loss in the old building is approximately 3 dB, while in the shops and the modern buildings is larger (approximately 4.5 dB).

The illustration in Fig. 3.1 is completed with a couple of penetration loss measurement values reported in **paper G** for an old building in Brazil at 24 GHz. As it can be seen, the values are well aligned with the results ob-

tained for the old building in Denmark, further validating the low frequency dependence and consistency of the penetration loss in this type of constructions.

The increased penetration loss in modern building scenarios can be seen as both an advantage or a disadvantage. It is a disadvantage when in-building coverage should be provided with outdoor BSs. However, if indoor deployments are used, the external walls with increased penetration loss can act as a natural barrier for containing the signals inside/outside the building, which can be exploited in outdoor/indoor heterogeneous co-channel deployments in terms of frequency reuse. These considerations can be translated into a small set of simple **DG for heterogeneous outdoor and indoor deployment scenarios**:

- Old buildings/shopping areas: non-co-channel outdoor and indoor deployments are preferred.

- Modern buildings: co-channel outdoor and indoor deployments can be used, especially at higher frequency bands. There is a great potential of exploiting cm-wave spectrum for co-channel deployment of outdoor and indoor small cells, under the umbrella of the macro layer operating at traditional low cellular frequencies.

3.2 Overall Outdoor-to-Indoor Propagation

In **paper L**, not only penetration loss but the overall outdoor-to-indoor propagation is modeled. A set of dedicated measurements were performed along several corridors in shopping malls and modern and old constructions in order to characterize the different indoor propagation contributions. It was found that the contributions from the propagation across open indoor spaces present no strong frequency dependence. Similarly, the attenuation from the indoor walls was found to present very small frequency dependence. This happened with both the old and modern building indoor walls, which presented estimated comparable low average attenuation values in the order of approximately 4-6 dB for the entire frequency range explored. This similarity can be explained from the very similar interior composition of both modern and old construction scenarios, with plaster walls and wooden doors.

The formulation and multi-frequency parametrization of the overall outdoor-to-indoor propagation model, which serves as an extension of the 3GPP [45, 60] and ITU-R models [48], is provided in Table 3.2. The model separates the overall PL into the different independent natural contributions from the outdoor PL (PL_{out}), the outdoor-to-indoor PL (PL_{ext}), and the indoor PL (PL_{in}). The modeling of the outdoor and outdoor-to-indoor contributions was already addressed in sections 2.3 and 3.1, respectively. As detailed in the

table, indoor propagation is formulated as a linear attenuation (α_{in}) model applied over the total indoor distance measured from the external wall (d_{in}), accounting for the attenuation ($PL_{wall,int}$) of the overall number of penetrated indoor walls ($n_{wall,int}$). The model can also account for the variability of the indoor SF, by means of a zero-mean Gaussian random variable (X_{SF}) with STD σ_{in}.

Table 3.2: Formulation of the overall outdoor-to-indoor frequency-dependent path loss model [L].

$PL = PL_{out} + PL_{ext} + PL_{in}$ [dB]
PL_{out} (see Table 2.1) [dB]
$PL_{ext} = PL_{ext,eff}$ (see Table 3.1) [dB]
$PL_{in} = \alpha_{in} \cdot d_{in} + n_{wall,int} \cdot PL_{wall,int} + X_{SF}(0, \sigma_{in})$ [dB] $\alpha_{in} = 0.49$ [dB/m] $PL_{wall,int}(f) = 4.9 + 0.05 \cdot f$ [dB] $\sigma_{in} = 2.6$ [dB]
$f = \{0.8 - 28\}$ [GHz]

From the complete multi-frequency outdoor-to-indoor characterization presented, a brief summary highlighting the main points can be given as an answer to **RQ.4**: according to the observations, the indoor part of the overall outdoor-to-indoor propagation is frequency-independent. However, the overall outdoor-to-indoor propagation is frequency-dependent due to the frequency-dependent behavior of the penetration loss, which is also external building composition-dependent.

3.3 Height Gain

The previous sections addressed outdoor-to-indoor propagation at normal incidence, and provided some insight into the variations in the horizontal domain by means of the 'effective' penetration loss. However, none of the previously presented studies explored the variations in the vertical domain. This was the main focus in **paper M**, which reports a geometrical height gain model that considers simultaneously the variability in the vertical and the horizontal domains. The model, with physical foundation, assumes that radio signals penetrate the external facade of the building through windows. It adopts a similar basic formulation to the one presented in the previous section, as it can be see in Table 3.3, splitting the overall outdoor-to-indoor propagation into three PL components: outdoor PL, outdoor-to-indoor PL and indoor PL.

Table 3.3: Formulation of the geometrical height gain path loss model for LOS urban micro cells [M].

$PL = PL_{out} + PL_{ext} + PL_{in}$ [dB]
$PL_{out} = FSPL(d_{3d,out})$ [dB]
$PL_{ext} = PL_{ext,norm,window} + L_{diff}$ [dB] $PL_{ext,norm,window}$ (see Table 3.1) [dB] $L_{diff} = 0.5 \cdot L_{diff,elev} + 0.5 \cdot L_{diff,azim}$ [dB] $L_{diff,elev}$ based on KED (see paper M) [dB] $L_{diff,azim}$ based on KED (see paper M) [dB]
$PL_{in} = 0.5 \cdot d_{3d,in}$ [dB]
$f = \{0.8 - 5.2\}$ [GHz]

The model is applicable to outdoor cells in LOS with the building and therefore, the outdoor PL is modeled as FSPL over the 3D distance between the BS and the window closer to the UE. The model assumes that propagation at low frequencies is diffraction-driven, and therefore the outdoor-to-indoor PL accounts for the attenuation of the window ($PL_{ext,norm,window}$) but also for the diffraction on the frame of the window (L_{diff}). This diffraction is variable and frequency-dependent, and drives the HG dynamics of the model, dependent on both the vertical and horizontal grazing angles, which are subsequently dependent on the BS and UE 3D positions relative to the window frames that act as diffraction edges. The total diffraction loss is computed as the average between the independent Knife-Edge Diffraction Loss (KEDL) experienced in the vertical ($L_{diff,elev}$) and the horizontal ($L_{diff,azim}$) domains. The indoor propagation is considered as a linear attenuation over the 3D distance between the frame of the window and the UE ($d_{3d,in}$), in a similar manner as in the previous model.

The realistic dynamics of the model, validated against an extensive set of measurements performed at 3.5 GHz considering different geometries of the scenario, are able to capture indoor situations that other models are not able to predict, which results in an overall RMSE accuracy of 6-7 dB, 1-3 dB better than current existing models such as the 3GPP [45] and ITU-R [48]. The frequency-behavior of the model, that is automatically driven by the KED, was also validated against measurements performed at 0.8, 2, 3.5 and 5.2 GHz, achieving a similar range of accuracy.

The vertical and horizontal KED computations considered in the model account for the extra loss experienced above the lower bound set by the normal incidence penetration loss, providing a geometrical characterization of the 'effective' experienced penetration loss. In relation to **RQ.4**, and gen-

eralizing only for the frequencies below 6 GHz, it can be said that the frequency dependence of the overall outdoor-to-indoor-propagation is mainly driven by the frequency dependence of the penetration loss with normal incidence (which, as seen before, is material-dependent). According to the dynamics described in the model, that match to real-world situations, the overall diffraction loss (dispersion of the data) is more geometry-dependent than frequency-dependent. Further validation would be needed to consider the applicability of the model to higher frequencies, as it could be that the main outdoor-to-indoor propagation mechanism vary.

3.4   A Practical Application Example

In order to illustrate the applicability of this HG model and the indoor multi-wall model presented in the previous sections, they are combined together in a practical example that explores and compares the PL predictions inside a building for different LOS micro cell BS configurations. The target building, with overall dimensions 50x50x90 m, is a 30 storey-building with 3 m/floor. Each of the 50x50 m floor layouts consist in 25 compartments of 10x10 m, uniformly distributed across the floor. As indoor propagation typically occurs in the direction perpendicular to the external facade, once the radio signal penetrates inside the building, it still needs to propagate indoor across 4 extra internal walls before reaching the deepest indoor positions.

The three different LOS micro cell deployment configurations depicted in Fig. 3.3 are explored:

a) BS operating at 800 MHz, deployed at 10 m height, 10 m perpendicular distance from the building, and 15 m away from the center of the facade.

b) similar configuration to a) but at 3.5 GHz.

c) BS operating at 3.5 GHz, re-deployed at 20 m height, 10 m higher than in a) and b), 50 m perpendicular distance from the building, 40 m further away than a) and b), and aligned with the center of the facade.

The building is considered as type modern, with a normal incidence window penetration loss of 24.1 and 25.2 dB for 800 MHz and at 3.5 GHz, respectively, according to the model in Table 3.1. The indoor linear attenuation is 0.49 dB/m for both frequencies and the attenuation of the indoor walls is 4.9 dB for 800 MHz and 5.0 dB for 3.5 GHz, also according to the models in Table 3.2.

The 3D heatmaps of the predicted PL for each of the three selected configurations, assuming UEs located 1.5 m above each floor level, are illustrated in Fig. 3.3. The BSs are included in the figure at position (0,0) in each of the subplots as a reference for an easier visual interpretation of the results.
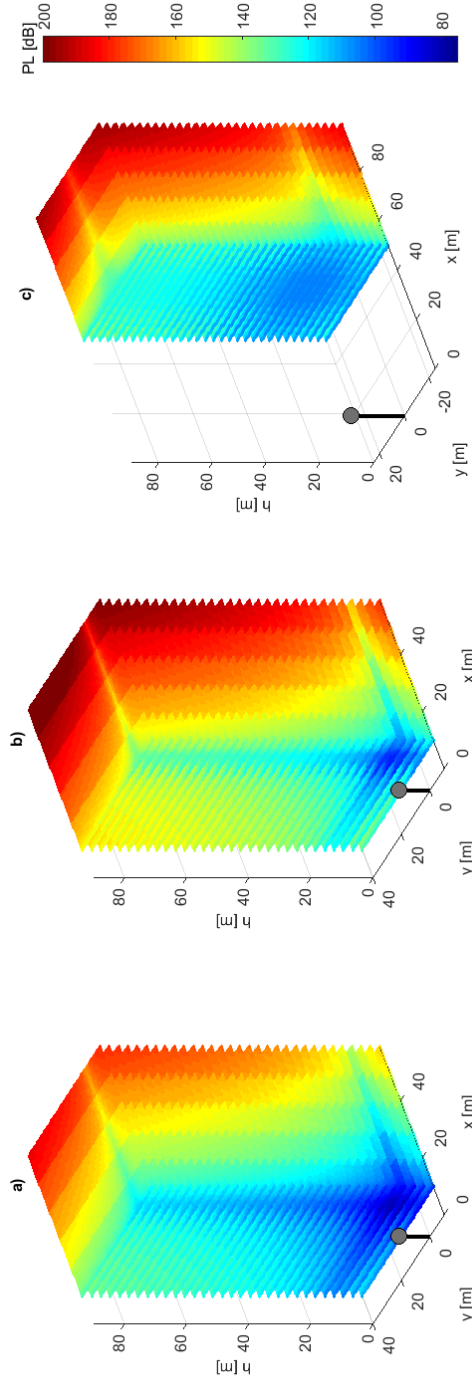
3.4. A Practical Application Example

Fig. 3.3: High-rise indoor PL prediction for different LOS micro cell configurations: a) $f = 800MHz$, $h_{BS} = 10m$, $d_{x,out} = 10m$, b) $f = 3.5GHz$, $h_{BS} = 10m$, and c) $f = 3.5GHz$, $h_{BS} = 20m$, $d_{x,out} = 50m$.

First, comparing a) and b), the impact of the change in carrier frequency can be observed. In b), at higher frequency, the upper floors suffer extra loss due to the higher diffraction loss. The effect is especially noticeable for the deep indoor users. Similarly, due to the higher diffraction in the horizontal domain, even users at the same height level of the BS but far from it, suffer some extra loss as compared with a). By maintaining the carrier frequency at 3.5 GHz, the overall indoor coverage can be improved by repositioning the BS as it is shown in c). In this case, the more centered and elevated position of the BS, induces geometrically more homogeneous and lower diffraction situations with respect to b).

In order to quantify the impact of the observed effects, the Cumulative Distribution Functions (CDF) of the different predicted PL contributions are presented in Fig. 3.4 for the three different configurations. It can be observed how in d), the change in frequency carrier from 800 MHz to 3.5 GHz results in an average indoor coverage loss of 20 dB. This is caused partly by the outdoor PL (approximately 13 dB) and partly by the outdoor-to-indoor PL (approximately 7 dB), as it can be seen in a) and b), respectively. By repositioning the BS to a better illumination position, the previous loss can be compensated. Despite of the higher outdoor PL (approximately 3 dB higher) due to the larger distance to the building as compared to the previous position, the overall outdoor-to-indoor PL is improved up to 12 dB, resulting in an overall compensation of approximately 9 dB.

This was only a small example to illustrate the practical application and the dynamics of the proposed models. The presented predictions are done in terms of PL, which would be proportional to the received signal strength in dBm in the ideal case of using isotropic antennas at both the BS and UE sides. As this is generally not the case in real systems, it would be possible to improve the indoor coverage by, for example, deploying directional BS antennas, which higher gains would help to overcome the indoor losses in certain directions. By following the same principle, uptilting techniques could actually be used to vary the illumination conditions and improve the coverage in upper floors of other particular areas of interest of the building [61,62].

The presented example and the different observations provided with respect to carrier frequency, positioning and radiation pattern of the BS antenna or applicability of uptilting techniques, can be seen as a practical set of **DG for the provisioning of in-building coverage from outdoor cells**. No particular formulation of the guidelines is given simply because it is too scenario-specific, but by using the proposed models, as shown, quick evaluations and straightforward comparisons can be done.
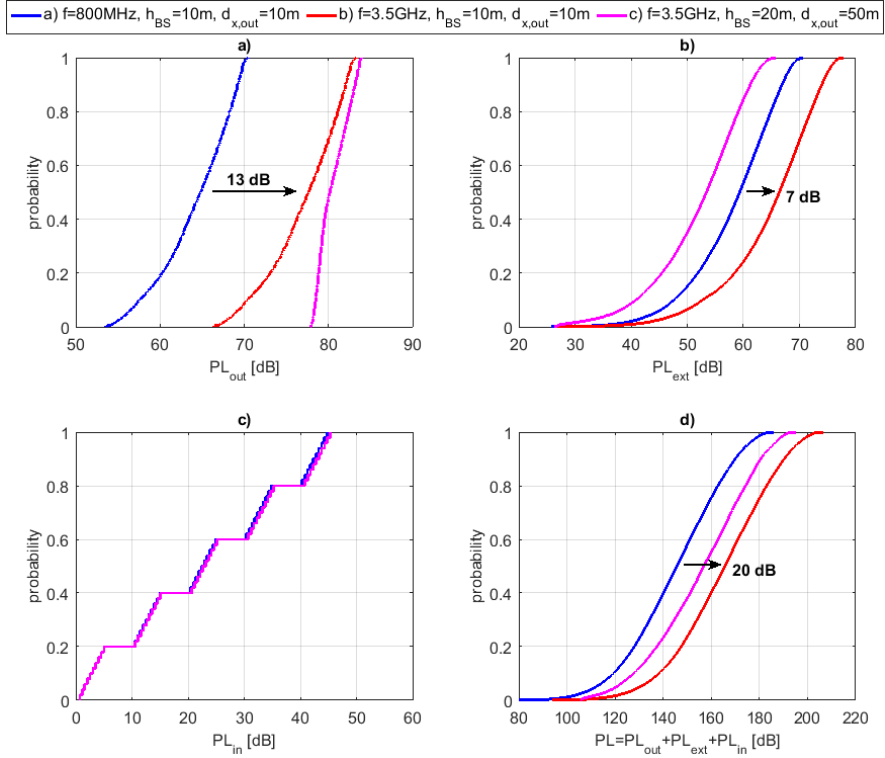
3.4. A Practical Application Example

Fig. 3.4: CDF of each of the predicted PL contributions for each of the configurations: a) outdoor PL (*PL_out*), b) outdoor-to-indoor PL (*PL_ext*), c) indoor PL (*PL_in*), and d) overall experienced in-building PL.

Chapter 4

Conclusions

This thesis focused on the various radio propagation challenges faced in Het-Net scenarios, derived from the combination of different cell types, BS antenna positions and new frequency bands. As an input to the planning, deployment and optimization of the future HetNets, a number of simple large-scale propagation models and deployment guidelines were provided along the main body of this thesis. This chapter summarizes the main findings of the PhD study, with main focus on the general frequency behavior of the outdoor and outdoor-to-indoor macro cell and small cell scenarios. The future potential research directions, that could help to complement or extend the presented findings, are also introduced.

4.1   Main Findings

The study brought empirical evidence of the valid applicability of typical large-scale macro cell propagation models, such as the COST-Hata and the COST-Walkfisch-Ikegami, at slightly higher frequencies (2.6 GHz) than the frequencies at which they were initially developed (below 2 GHz). Even though the average behavior predicted across the full distance range was within expected values (average RMSE of 8-9 dB), for shorter distances (below 200 m), it was detected that the accuracy diminishes (4-6 dB higher RMSE) as compared to the long range. In connection, from the observations derived at 10 GHz, some indications were given about the potential deviations of the COST-Walfisch-Ikegami at predicting correctly the height gain (HG) behavior at higher frequencies, suggesting the non-applicability of the model at this and higher frequency bands.

The reduced accuracy of the different models in the short range was identified to be caused by the general difficulty in predicting the exact behavior in areas close to the BS due to the multiple vertical sidelobes of the antennas and

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the complex mixed line-of-sight (LOS) and non-line-of-sight (NLOS) propagation conditions of the urban scenario. The roots of this higher uncertainty in the close macro cell range were quantified by means of simulations in terms of BS antenna distortion. The simulation results show that the overall deviation from the expected antenna pattern behavior experienced in reality are caused by approximately one third due to near-field (NF) distortion, and for the remaining approximately two thirds by the urban propagation itself.

With respect to existing small cell-specific large-scale outdoor propagation models, it was found that models such as the 3GPP, ITU-R and WINNER, typically derived at 2 GHz, would predict correctly the trends of the path loss (PL) at 3.5 GHz. So in principle, as the micro cell scenario was shown to exhibit a similar behavior up to cm-wave frequencies, a simple proportional frequency scaling of the models would fit to the higher frequency bands.

The existing large-scale macro cell models were also tested against the small cell scenarios. Despite the COST-Hata model is defined for elevated BS antennas and minimum application distances over 1 km, it was found that its prediction matches closely the NLOS PL experienced at both 2 and 3.5 GHz in micro cell scenarios with BS antennas below rooftop level. As the COST-Hata predicts an average path loss exponent (PLE) of 3.6-4 for BS antenna heights below 20 m, similar to the one exhibited by the micro cell scenarios at all the explored frequencies (according to the free linear fit from the alpha-beta (AB) modeling approach), there is indication that, in principle, a reasonably good match would be observed if the model is applied at the higher frequency bands. On the other hand, as the COST-Walfisch-Ikegami assumes propagation above rooftops, which is very different from the street-canyon propagation, it clearly overestimates the PL experienced in micro cell scenarios, with deviations larger than 20 dB that increase with frequency.

From the analysis of the dedicated micro and macro cell measurement campaigns performed exploring frequency bands below 6 GHz (with 2 GHz always a reference) and cm-wave frequency bands (10, 18 and 28 GHz), it was possible to identify that a modeling approach based on free linear fit to the data would be more representative than other with a fixed reference offset, as the latter may not be able to discriminate the position of the BS antenna with respect to the rooftop level. By sticking to the free linear fit approach, the measurements results show that in LOS, the PL in both micro and macro cell scenarios is close to the free space path loss (FSPL) with a PLE of 2. In NLOS, the situation is different depending on the BS antenna location. In the micro cell scenario, with BS antennas below rooftop level, an average PLE of 3.8 was found. By elevating the BS antennas above rooftop level, as in the macro cell scenario, the PLE was reduced to approximately 3.5, in average. The position of the BS antennas has a secondary effect on the experienced PL. The standard deviation (STD) of the PL dispersion increases with lower BS antenna heights. While with BS antennas located above rooftop, the dis-

persion presented a STD of approximately 6 dB, bringing the antennas below rooftop incremented that STD of the dispersion up to 8 dB, due to the higher number of interactions of the signal with the urban environment. In LOS, this dispersion, independent of the BS antenna height, was found to be in the order of 4 dB STD.

No substantial differences were observed in the outdoor propagation trends at higher frequencies in comparison with the low frequencies. Even though some of the presented investigations suggest a change in the main propagation mechanisms from diffraction-based at the low frequencies to reflection and scattering-based at cm-wave frequencies; **in practice, the complex propagation inside the urban scenario transforms the combination of all the contributions from different mechanisms into comparable variations of overall experienced PL at all frequencies, suggesting no frequency dependence beyond the intrinsic frequency scaling of the PL in free space (FS) conditions**.

The situation is different for the outdoor-to-indoor propagation. The indoor part of the outdoor-to-indoor propagation was found to be frequency-independent, with an experienced average indoor linear attenuation of approximately 0.49 dB/m at all frequencies, with a smaller STD (2.6 dB) than in outdoor scenarios. Indoor walls were also found to present a very similar attenuation at al frequencies in the order of 5 dB. However, **the overall outdoor-to-indoor propagation itself was found to be frequency-dependent due to the observed frequency-dependent behavior of the penetration loss, which is moreover external building composition-dependent**. Assuming, as observed in the study, that radio signals penetrate into the buildings through the windows (as they in general present lower attenuation than the external walls of the constructions); the average frequency dependence found for the so-classified as old buildings was lower (0.2 dB/GHz) than for the so-classified as modern constructions (0.35 dB/GHz). The higher frequency dependence experienced is the average obtained from various modern buildings, which all exhibited different (but irregular all of them) frequency behaviors due to the different types of high-isolation multi-layer windows, which furthermore presented very high attenuation in the order of up to 30-40 dB. On the other hand, the old buildings presented lower attenuation, below 10 dB, in general.

4.2 Future Work

The study provided empirical insight into the outdoor and outdoor-to-indoor propagation at higher frequencies in comparison with lower more well-examined frequencies. However, there is still plenty of room for further validation or extension along the lines suggested by the presented work.

First, it would be interesting to perform further dedicated directional measurements for other frequencies different from 24 GHz and 38 GHz, in order to obtain further insight to the change in propagation from diffraction-based to reflection-based, including the more precise range of frequencies at which this occur. This would facilitate the development of simple accurate frequency-dependent geometrical propagation models, such as, for example, an extension of the proposed height gain model for higher frequencies, where maybe diffraction is less dominant.

The presented work focused on outdoor and outdoor-to-indoor propagation, therefore, similar indoor-specific investigations for pico cells and frequencies above 6 GHz could be considered as an extension of the study, with focus on potential hotspot scenarios such as office buildings, shopping malls, or sport arenas.

Similarly, as this study focused on large-scale propagation, the wideband characterization of the exact same set of scenarios would serve as an extension of the work. Despite it could constitute altogether another different line of research, it would contribute to a more unified view of the propagation, specifically in view of the postulated change in main propagation mechanisms at higher frequencies, which may have an impact on the development of future hybrid large-scale small-scale spatial channel models (SCM).

With respect to more specific investigations with focus on scenarios that will be of big importance in future mobile communications, the shadowing analysis for V2X scenarios could be completed by considering vegetation, cars or other vehicles. Similar detailed studies at higher, for example, e.g. mm-wave frequency bands, could also be considered, as the short wavelengths at these frequencies makes propagation very sensitivity to blockage.

In the M2M communication regime there are other specific scenarios of interest where a proper understanding of the overall propagation conditions is essential due to the critical communications taking place, e.g. for autonomous and intelligent mining systems in open pit mines.

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Paper A

A Geometrical-based Vertical Gain Correction for Signal Strength Prediction of Downtilted Base Station Antennas in Urban Areas

Ignacio Rodriguez[1], Huan C. Nguyen[1], Troels B. Sørensen[1], Jan Elling[2], Morten B. Gentsch[2], Mads Sørensen[2], Lauri Kuru[3], and Preben Mogensen[1,3]

[1]Department of Electronic Systems, Aalborg University, Denmark
[2]Telenor, Aalborg, Denmark
[3]Nokia Siemens Networks, Research Center

Available online at:

Paper B

Base Station Antenna Pattern Distortion in Practical Urban Deployment Scenarios

Ignacio Rodriguez[1], Huan C. Nguyen[1], Troels B. Sørensen[1], and Ondrej Franek[2]

[1]Radio Access Technology Section (RATE),
 Department of Electronic Systems, Aalborg University, Denmark
[2]Antennas, Propagation and Radio Networking Section (APNET),
 Department of Electronic Systems, Aalborg University, Denmark

Available online at:

Paper C

Evaluation of Potential Relay Locations in a LTE-Advanced Urban Macro-cell Scenario

Ignacio Rodriguez[1], Claudio Coletti[1], and Troels B. Sørensen[1]

[1]Radio Access Technology Section (RATE),
  Department of Electronic Systems, Aalborg University, Denmark

Paper D

Path Loss Validation for Urban Micro Cell Scenarios at 3.5 GHz Compared to 1.9 GHz

Ignacio Rodriguez[1], Huan C. Nguyen[1], Niels T. K. Jørgensen[1], Troels B. Sørensen[1], Jan Elling[2], Morten B. Gentsch[2], and Preben Mogensen[1,3]

[1]Department of Electronic Systems, Aalborg University, Denmark
[2]Telenor A/S, Aalborg, Denmark
[3]Nokia Siemens Networks, Research Center Aalborg, Denmark

Available online at:

Paper E

Considerations on Shadow Fading Modeling for 5G Urban Micro Cell Scenarios

Ignacio Rodriguez, Huan. C. Nguyen, Troels B. Sørensen, István Z. Kovács, and Preben Mogensen

I. Rodriguez, H. C. Nguyen, T. B. Sørensen and P. Mogensen are with the Wireless Communication Networks Section, Department of Electronic Systems, Aalborg University, Aalborg Øst 9220, Denmark (email: irl@es.aau.dk; hcn@es.aau.dk; tbs@es.aau.dk; pm@es.aau.dk).
I. Z. Kovács is with Nokia - Bell Labs, Research Center Aalborg, Aalborg Øst 9220, Denmark (email: istvan.kovacs@nokia-bell-labs.com).
P. Mogensen is also with Nokia - Bell Labs, Research Center Aalborg, Aalborg Øst 9220, Denmark (email: preben.mogensen@nokia-bell-labs.com).

Not Available

Paper F

An Empirical Study of Urban Macro Propagation at 10, 18 and 28 GHz

Huan C. Nguyen[1], Ignacio Rodriguez[1], Troels B. Sørensen[1], Laura L. Sanchez[1], István Z. Kovács[2], and Preben Mogensen[1,2]

[1]Department of Electronic Systems, Aalborg University, Denmark
[2]Nokia, Research Center Aalborg, Denmark

Available online at:

Paper G

Analysis and Comparison of 24 GHz cmWave Radio Propagation in Urban and Suburban Scenarios

Ignacio Rodriguez[1], Erika P. L. Almeida[1,2], Renato Abreu[2], Mads Lauridsen[1], Alexandre Loureiro[2], and Preben Mogensen[1]

[1]Wireless Communication Networks Section,
  Department of Electronic Systems, Aalborg University, Denmark
[2]Instituto de Desenvolvimento Tecnológico (INDT), Manaus/Brasília, Brazil

Available online at:

Paper H

24 GHz cmWave Radio Propagation Through Vegetation: Suburban Tree Clutter Attenuation

Ignacio Rodriguez[1], Renato Abreu[2], Erika P. L. Almeida[1,2], Mads Lauridsen[1], Alexandre Loureiro[2], and Preben Mogensen[1]

[1]Wireless Communication Networks Section,
  Department of Electronic Systems, Aalborg University, Denmark
[2]Instituto de Desenvolvimento Tecnológico (INDT), Manaus/Brasília, Brazil

Available online at:

Paper I

Analysis of 38 GHz mmWave Propagation Characteristics of Urban Scenarios

Ignacio Rodriguez[1], Huan C. Nguyen[1], Troels B. Sørensen[1], Jan Elling[2], Jens Åge Holm[2], Preben Mogensen[1,3], and Benny Vejlgaard[3]

[1]Department of Electronic Systems, Aalborg University, Denmark
[2]Telenor A/S, Aalborg, Denmark
[3]Nokia Networks, Research Center Aalborg, Denmark

Available online at:

Paper J

Measurement-based Evaluation of the Impact of Large Vehicle Shadowing on V2X Communications

Ignacio Rodriguez[1], Erika P. L. Almeida[1,2], Mads Lauridsen[1], Dereje A. Wassie[1], Lucas Chavarria Gimenez[1], Huan C. Nguyen[1], Troels B. Sørensen[1], and Preben Mogensen[1,3]

[1]Department of Electronic Systems, Aalborg University, Denmark
[2]Instituto de Desenvolvimento Tecnológico (INDT), Manaus/Brasília, Brazil
[3]Nokia - Bell Labs, Research Center Aalborg, Denmark

Available online at:

Paper K

Radio Propagation into Modern Buildings: Attenuation Measurements in the Range from 800 MHz to 18 GHz

Ignacio Rodriguez[1], Huan C. Nguyen[1], Niels T. K. Jørgensen[1], Troels B. Sørensen[1], and Preben Mogensen[1,2]

[1]Department of Electronic Systems, Aalborg University, Denmark
[2]Nokia Networks, Research Center Aalborg, Denmark

Available online at:

Paper L

An Empirical Outdoor-to-Indoor Path Loss Model from Below 6 GHz to cm-Wave Frequency Bands

Ignacio Rodriguez, Huan. C. Nguyen, Troels B. Sørensen, István Z. Kovács, and Preben Mogensen

I. Rodriguez, H. C. Nguyen, T. B. Sørensen and P. Mogensen are with the Wireless Communication Networks Section, Department of Electronic Systems, Aalborg University, Aalborg Øst 9220, Denmark (email: irl@es.aau.dk; hcn@es.aau.dk; tbs@es.aau.dk; pm@es.aau.dk).
I. Z. Kovács is with Nokia - Bell Labs, Research Center Aalborg, Aalborg Øst 9220, Denmark (email: istvan.kovacs@nokia-bell-labs.com).
P. Mogensen is also with Nokia - Bell Labs, Research Center Aalborg, Aalborg Øst 9220, Denmark (email: preben.mogensen@nokia-bell-labs.com).

Available online at:

Paper M

A Novel Geometrical Height Gain Model for Line-of-Sight Urban Micro Cells Below 6 GHz

Ignacio Rodriguez[1], Huan. C. Nguyen[1], Troels B. Sørensen[1], Zhuyan Zhao[2], Hao Guan[2], and Preben Mogensen[1,3]

[1]Wireless Communication Networks Section,
  Department of Electronic Systems, Aalborg University, Denmark
[2]Nokia - Bell Labs, Beijing, China
[3]Nokia - Bell Labs, Research Center, Aalborg, Denmark

Available online at: