Stochastic Geometry For Wireless Networks

Stochastic geometry is a widely accepted mathematical tool used to analyze cellular networks, where the location of base stations are modeled by spatial point processes. It is used to derive closed-form or semi-closed-form expressions for the SINR or for the functions of the SINR which determine various network performance metrics such as coverage probability, "edge" capacity, 90% quantile rate, spectral efficiency, and connectivity without resorting to complicated simulation methods. Predominantly, it is used in deriving marginal distributions of SINR by considering a typical user assumed to be located anywhere on the plane. Models beyond the typical user approach have been proposed with the aim of analyzing QoS metrics of a population of users, and not just a single user. Most of which include considering networks at certain times by representing instances or snapshots of active users as realizations of spatial (usually Poisson) processes or users occurring at random locations that last for some random duration. Analyzing the performance of a typical mobile user on the move or that of a population of such mobile users is complicated since it requires studying not just the marginal but the spatial stochastic fields associated with wireless networks. In this thesis, we model and analyze the fields associated with wireless networks where the locations of base stations are distributed according to a homogeneous Poisson point process. We focus on characterizing the level crossings, extremes, and variability of the Shannon rate fields in noise limited (SNR based) environment by establishing a connection to queueing theory. In interference limited (SIR based) environments, we rely on the theory of Gaussian random fields which arise as natural limits of standardized interference under densification. Using this, we characterize the spatial correlations, and variability of the Shannon rate fields in the limiting regime. We leverage the spatial characterization of the fields to study the temporal variations and various Quality of Service (QoS) metrics seen by the users on the move. The quantification of such metrics as a function of a small number of network parameters, e.g., the density of base stations, path loss, should allow network operators to appropriately tune the density of the base stations to meet the demands of mobile users for a required performance level. In noise limited environments, we study the performance of mobile users in dense networks by incorporating the cost of handovers along with the temporal variability in the Shannon rate. We study the tradeoff between the cost of handover and the Shannon rate by proposing a new class of association policies. Associating with a base station that is farthest in the known users' direction of motion leads to fewer handovers but may lead to a decrease in the rate. Thus, we attribute a local association region to the mobile user to restrict the greediness in the association, which also models the constraint on the available information about the locations of the base stations. We propose a class of greedy association policies and once again leverage stochastic geometry to characterize the performance of such policies. We then optimize the shape and size of the association region by establishing a connection to the theory of Markov processes and compare the performance of this policy to traditional association policies

The new edition of Advanced Wireless Communications: 4G Cognitive and Cooperative Broadband Technology, 2nd Edition, including the latest developments In the evolution of wireless communications, the dominant challenges are in the areas of networking and their integration with the Future Internet. Even the classical concept of cellular networks is changing and new technologies are evolving to replace it. To reflect these new trends,Advanced Wireless Communications & INTERNET builds upon the previous volumes, enhancing the existing chapters, and including a number of new topics. Systematically guiding readers from the fundamentals through to advanced areas, each chapter begins with an introductory explanation of the basic problems and solutions followed with an analytical treatment in greater detail. The most important aspects of new emerging technologies in wireless communications are comprehensively covered including: next generation Internet; cloud computing and network virtualization; economics of utility computing and wireless grids and clouds. This gives readers an essential understanding of the overall environment in which future wireless networks will be operating. Furthermore, a number of methodologies for maintaining the network connectivity, by using tools ranging from genetic algorithms to stochastic geometry and random graphs theory, and a discussion on percolation and connectivity, are also offered. The book includes a chapter on network formation games, covering the general models, knowledge based network formation games, and coalition games in wireless ad hoc networks. Illustrates points throughout using real-life case studies drawn from the author's extensive international experience in the field of telecommunications Fully updated to include the latest developments, key topics covered include: Advanced routing and network coding; Network stability control; Relay-assisted Wireless Networks; Multicommodity flow optimization problems, flow optimization in heterogeneous networks, and dynamic resource allocation in computing clouds Methodically guides readers through each topic from basic to advanced areas Focuses on system elements that provide adaptability and re-configurability, and discusses how these features can improve wireless communications system performance

This book constitutes the proceedings of the 12th International Conference on Wireless Algorithms, Systems, and Applications, WASA 2017, held in Guilin, China, in June 2017.The 70 full papers and 9 short papers presented in this book werde carefully reviewed and selected from 238 submissions. The papers cover various topics such as cognitive radio networks; wireless sensor networks; cyber-physical systems; distributed and localized algorithm design and analysis; information and coding theory for wireless networks; localization; mobile cloud computing; topology control and coverage; security and privacy; underwater and underground networks; vehicular networks; internet of things; information processing and data management; programmable service interfaces; energy-efficient algorithms; system and protocol design; operating system and middle-ware support; and experimental test-beds, models and case studies.

This book constitutes the proceedings of the First International Conference on 5G for Future Wireless Networks, 5GWN 2017, held in Beijing, China, in April 2017. The 64 full papers were selected from 135 submissions and present the state of the art and practical applications of 5G technologies. The exponentially growing data traffic caused by the development of mobile Internet and smart phones requires powerful networks. The fifth generation (5G) techniques are promising to meet the requirements of this explosive data traffic in future mobile communications.

The use of stochastic geometry allows the analysis of the typical performance of a wireless network. Specifically, under a stationary framework, the network performance at a typical receiver represents the network performance spatially-averaged over all receivers. This approach has been applied to the Poisson point processes whose points are independently located in space. The Poisson point process expresses a total independence type randomness in network architectures. Its tractability leads to its wide use in modeling various wireless networks, e.g., cellular networks, ad hoc networks, and vehicular networks. However, a network analysis using the Poisson point process might be inaccurate when the network components are geometrically correlated or in motion, as in heterogeneous cellular networks, or vehicular networks. For instance, macro base stations are deployed far from each other. Vehicles are located on roads, i.e., lines, and they move on the lines. As a result, the analysis of these networks can be improved by new spatial models that capture these spatial and dynamic features. In my first contribution, I derive the signal-to-interference ratio (SIR) coverage probability of a typical user in heterogeneous cellular networks where base stations are modeled by the sum of a Poisson point process and a stationary square grid. In my second contribution, I develop a stationary framework based on the sum of a Cox point process and a Poisson point process to model random cellular networks with linear base stations and linear users on straight lines. I derive the SIR coverage probability of the typical user and characterize its association. In the third contribution, I investigate the statistical properties of the Cox point process, exploring the nearest distance distribution and the convergence of the Cox-Voronoi cell. In the above three contributions, I analyze the performance of wireless networks by focusing on their correlated structures, extracting results which cannot be obtained from models based only on Poisson point processes. In my fourth contribution, I propose a new technology for harvesting Internet-of-Things (IoT) data based on mesh relaying with vehicles as sinks. I derive the network capacity and compare it to the traditional approach, which is based on static base stations. In the fifth contribution, I derive the SIR distribution of direct communication from roadside devices to vehicles. By characterizing the evolution of the network snapshots, I derive the behavior of vehicles' service coverage area and the network latency. In my sixth contribution, I propose a data

harvesting technology for the ground-based data devices, based on the use of unmanned aerial vehicles (UAVs). I derive the total data transmitted from a typical device by characterizing the evolution of network geometry with respect to time. These last three contributions are built on a combination of network snapshot analysis and network evolution analysis
Stochastic Geometry for Wireless NetworksCambridge University Press
Achieve faster and more efficient network design and optimization with this comprehensive guide. Some of the most prominent researchers in the field explain the very latest analytic techniques and results from stochastic geometry for modelling the signal-to-interference-plus-noise ratio (SINR) distribution in heterogeneous cellular networks. This book will help readers to understand the effects of combining different system deployment parameters on key performance indicators such as coverage and capacity, enabling the efficient allocation of simulation resources. In addition to covering results for network models based on the Poisson point process, this book presents recent results for when non-Poisson base station configurations appear Poisson, due to random propagation effects such as fading and shadowing, as well as non-Poisson models for base station configurations, with a focus on determinantal point processes and tractable approximation methods. Theoretical results are illustrated with practical Long-Term Evolution (LTE) applications and compared with real-world deployment results.
Ultra dense networks (UDNs) allow for efficient spatial reuse of the spectrum, giving rise to substantial capacity and power gains. In order to exploit those gains, tractable mathematical models need to be derived, allowing for the analysis and optimization of the network operation. In this course, stochastic geometry has emerged as a powerful tool for large-scale analysis and modeling of wireless cellular networks. In particular, the employment of stochastic geometry has been proven instrumental for the characterization of the network performance and for providing significant insights into network densification. Fundamental issues, however, remain open in order to use stochastic geometry tools for the optimization of wireless networks, with the biggest challenge being the lack of tractable closed form expressions for the derived figures of merit. To this end, the present thesis revisits stochastic geometry and provides a novel stochastic geometry framework with a twofold contribution. The first part of the thesis focuses on the derivation of simple, albeit accurate closed form approximations for the ergodic rate of Poisson cellular networks under a noise limited, an interference limited and a general case scenario. The ergodic rate constitutes the most sensible figure of merit for characterizing the system performance, but due to the inherent intractability of the available stochastic geometry frameworks, had not been formulated in closed form hitherto. To demonstrate the potential of the aforementioned tractable expressions with respect to network optimization, the present thesis proposes a flexible connectivity paradigm and employs part of the developed expressions to optimize the network connectivity. The proposed flexible connectivity paradigm exploits the downlink

uplink decoupling (DUDe) configuration, which is a promising framework providing substantial capacity and outage gains in UDNs and introduces the DUDe connectivity gains into the 5G era and beyond.Subsequently, the last part of the thesis provides an analytical formulation of the probability density function (PDF) of the aggregate inter-cell interference in Poisson cellular networks. The introduced PDF is an accurate approximation of the exact PDF that could not be analytically formulated hitherto, even though it constituted a crucial tool for the analysis and optimization of cellular networks. The lack of an analytical expression for the PDF of the interference in Poisson cellular networks had imposed the use of intricate formulas, in order to derive sensible figures of merit by employing only the moment generating function (MGF). Hence, the present thesis introduces an innovative framework able to simplify the analysis of Poisson cellular networks to a great extent, while addressing fundamental issues related to network optimization and design.
The ability to exchange secret information is critical to many commercial, governmental, and military networks. Information-theoretic security - widely accepted as the strictest notion of security - relies on channel coding techniques that exploit the inherent randomness of the propagation channels to significantly strengthen the security of digital communications systems. Motivated by recent developments in the field, this thesis aims at a characterization of the fundamental secrecy limits of large-scale wireless networks. We start by introducing an information-theoretic definition of the intrinsically secure communications graph (iS-graph), based on the notion of strong secrecy. The iS-graph is a random geometric graph which captures the connections that can be securely established over a large-scale network, in the presence of spatially scattered eavesdroppers. Using fundamental tools from stochastic geometry, we analyze how the spatial densities of legitimate and eavesdropper nodes influence various properties of the Poisson iS-graph, such as the distribution of node degrees, the node isolation probabilities, and the achievable secrecy rates. We study how the wireless propagation effects (e.g., fading and shadowing) and eavesdropper collusion affect the secrecy properties of the network. We also explore the potential of sectorized transmission and eavesdropper neutralization as two techniques for enhancing the secrecy of communications. We then shift our focus to the global properties of the iS-graph, which concern secure connectivity over multiple hops. We first characterize percolation of the Poisson iS-graph on the infinite plane. We show that each of the four components of the iS-graph (in, out, weak, and strong component) experiences a phase transition at some nontrivial critical density of legitimate nodes. Operationally, this is important because it implies that long-range communication over multiple hops is still feasible when a security constraint is present. We then consider full-connectivity on a finite region of the Poisson iS-graph. Specifically, we derive simple, explicit expressions that closely approximate the probability of a node being securely connected to all other nodes inside the region. We also show that the iS-graph is asymptotically fully out-connected with probability one, but full in-connectivity remains bounded away from

one, no matter how large the density of legitimate nodes is made. Our results clarify how the spatial density of eavesdroppers can compromise the intrinsic security of wireless networks. We are hopeful that further efforts in combining stochastic geometry with information-theoretic principles will lead to a more comprehensive treatment of wireless security.

Recently, the location of the nodes in wireless networks has been modeled as point processes. In this dissertation, various scenarios of wireless communications in large-scale networks modeled as point processes are considered. The first part of the dissertation considers signal reception and detection problems with symmetric alpha stable noise which is from an interfering network modeled as a Poisson point process. For the signal reception problem, the performance of space-time coding (STC) over fading channels with alpha stable noise is studied. We derive pairwise error probability (PEP) of orthogonal STCs. For general STCs, we propose a maximum-likelihood (ML) receiver, and its approximation. The resulting asymptotically optimal receiver (AOR) does not depend on noise parameters and is computationally simple, and close to the ML performance. Then, signal detection in coexisting wireless sensor networks (WSNs) is considered. We define a binary hypothesis testing problem for the signal detection in coexisting WSNs. For the problem, we introduce the ML detector and simpler alternatives. The proposed mixed-fractional lower order moment (FLOM) detector is computationally simple and close to the ML performance. Stochastic orders are binary relations defined on probability. The second part of the dissertation introduces stochastic ordering of interferences in large-scale networks modeled as point processes. Since closed-form results for the interference distributions for such networks are only available in limited cases, it is of interest to compare network interferences using stochastic. In this dissertation, conditions on the fading distribution and path-loss model are given to establish stochastic ordering between interferences. Moreover, Laplace functional (LF) ordering is defined between point processes and applied for comparing interference. Then, the LF orderings of general classes of point processes are introduced. It is also shown that the LF ordering is preserved when independent operations such as marking, thinning, random translation, and superposition are applied. The LF ordering of point processes is a useful tool for comparing spatial deployments of wireless networks and can be used to establish comparisons of several performance metrics such as coverage probability, achievable rate, and resource allocation even when closed form expressions for such metrics are unavailable.

This book investigates key security issues in connection with the physical layer for random wireless cellular networks. It first introduces readers to the fundamentals of information theoretic security in the physical layer. By examining recently introduced security techniques for wireless point-to-point communications, the book proposes new solutions to physical layer security based on stochastic geometric frameworks for random cellular networks. It subsequently elaborates on physical-layer security in multi-tier heterogeneous networks. With the new modeled settings, the authors also verify the security performance with the impact of the full-duplex transceivers. The specific model design presented here offers a valuable point of reference for readers in related areas. In addition, the book highlights promising topics and proposes potential future research directions.

This book constitutes the refereed proceedings of the 10th International Conference on Communication Systems and Networks, COMSNETS 2018, held in Banaglore, India, in January 2018.The 12 revised full papers presented in this book were carefully reviewed and selected from 134 submissions. They cover various topics in networking and communications systems.

Undeniably, the progress in wireless networks during the last two decades is extraordinary. However, the ever-increasing upward trend in the numbers of wireless devices that will overwhelm every field of our everyday life, e.g., building automation, traffic management, health-care, etc., will introduce several issues in terms of communication and energy provision that need to be handled in advance. Regarding the communication issues, it is imperative to ensure the correct operation of the vast collection of nodes, especially for life-critical applications. Two well-known metrics that can characterize sufficiently the network reliability are the coverage and the connectivity probability that are derived by taking into account the network topology, the channel conditions between every transmitter-receiver pair, and the interference from other nodes. Nevertheless, considering all those factors is not straightforward. Lately, stochastic geometry has come into prominence, which is a mathematical tool to study the average network performance over many spatial realizations, while considering all aforementioned factors. Moreover, the other crucial issue for the large-scale dense network deployments of the future is their energy supply. Traditional battery charging or swapping for the wireless devices is both inconvenient and harms the environment, especially if we take into account the enormous numbers of nodes. Therefore, novel solutions have to be found using renewable energy sources to zero down the significant electricity consumption. Wireless energy harvesting is a convenient and environmentally-friendly approach to prolong the lifetime of networks by harvesting the energy from radio-frequency (RF) signals and converting it to direct current electricity through specialized hardware. The RF energy could be harvested from signals generated in the same or other networks. However, if the amount of harvested energy is not sufficient, solar-powered dedicated transmitters could be employed. In this way, we can achieve a favorable outcome by having both a zero-energy network operation and convenience in the charging of the wireless devices. Still, extensive investigation should be done in order to ensure that the communication performance is not affected. To that end, in this thesis, we study the communication performance in large-scale networks using tools from stochastic geometry. The networks that we study comprise wireless devices that are able to harvest the energy of RF signals. In the first part of the thesis, we present the effects of wireless energy harvesting from the transmissions of the cooperative network on the coverage probability and the network lifetime. In the second part of the thesis, we first employ batteryless nodes that are powered by dedicated RF energy transmitters to study the connectivity probability. Then, we assume that the dedicated transmitters are powered by solar energy to study the connectivity in a clustered network and investigate, for the first time, the reliability of zero-energy networks. Finally, we conclude the thesis by providing insightful research challenges for future works.

This thesis takes as its objective quantifying, comparing, and optimizing multiple-antenna (MIMO) physical layer techniques in dense ad hoc wireless networks. A framework is developed from the spatial shot noise interference model for packet radio network analysis. The framework captures the behavior of a wide variety of signal and interference distributions, which permit inspection of a number of signal processing methods including representatives from most of the major MIMO techniques. Multi-antenna systems for point-to-point are becoming mature and being developed and deployed in many wireless communication systems due to their potential to combat fading, increase spectral efficiency, and overcome interference. The framework permits an algorithm or system designer to view the network from the perspective of a typical user, to optimize performance in the midst of a given environment, or to view the network as a whole, to determine behavior that maximizes network performance. In particular, it enables questions to be answered quantitatively, such as which MIMO techniques perform best in a given environment? Or what rate and power settings should be used across the available spatial modes? Or what is the maximum benefit of channel state information? Or what gain should an individual device, or the network as a whole expect to see given a particular physical layer strategy? The dissertation begins by developing the framework for a generic set of assumptions on network behavior and signal and interference distributions. It then presents a progression of applications to representative MIMO techniques. Broad and intuitive scaling laws are developed as well as detailed exact results for careful comparison. Capacity scaling with the number of antennas is given for systems employing beamforming, selection combining, space-time block coding, and spatial multiplexing. These applications are used as the basis for developing simple distributed algorithms for optimizing MIMO settings with QoS constraints and in heterogeneous networks. Lastly, the framework is expanded to permit comparison and optimization of MIMO performance under alternative medium access strategies. In general it is found that significant performance gains can be reaped with multi-antenna physical layers, provided the proper techniques are employed. It is also shown that the availability of multiple spatial channels impacts the inherent tradeoff between per-link throughput and spatial reuse.

The third edition of this popular reference covers enabling technologies for building up 5G wireless networks. Due to extensive research and complexity of the incoming solutions for the next generation of wireless networks it is anticipated that the industry will select a subset of these results and leave some advanced technologies to be implemented later,. This new edition presents a carefully chosen combination of the candidate network architectures and the required tools for their analysis. Due to the complexity of the technology, the discussion on 5G will be extensive and it will be difficult to reach consensus on the new global standard. The discussion will have to include the vendors, operators, regulators as well as the research and academic community in the field. Having a comprehensive book will help many participants to join actively the discussion and make meaningful contribution to shaping the new standard.

Wireless -- Stochastic -- Cellular -- Networks.

This book presents a unified framework for the tractable analysis of large-scale, multi-antenna wireless networks using stochastic geometry. This mathematical analysis is essential for assessing and understanding the performance of complicated multi-antenna networks, which are one of the foundations of 5G and beyond networks to meet the ever-increasing demands for network capacity. Describing the salient properties of the framework, which makes the analysis of multi-antenna networks comparable to that of their single-antenna counterparts, the book discusses effective design approaches that do not require complex system-level simulations. It also includes various application examples with different multi-antenna network models to illustrate the framework's effectiveness. .

Interference creates a fundamental barrier in attempting to improve throughput in wireless networks, especially when multiple concurrent transmissions share the wireless medium. In recent years, significant progress has been made on characterizing the capacity limits of wireless networks under the premise of global and instantaneous channel state information at transmitter (CSIT). In practice, however, the acquisition of such instantaneous and global CSIT as a means toward cooperation is highly challenging due to the distributed nature of transmitters and dynamic wireless propagation environments. In many limited CSIT scenarios, the promising gains from interference management strategies using instantaneous and global CSIT disappear, often providing the same result as cases where there is no CSIT. Is it possible to obtain substantial performance gains with limited CSIT in wireless networks, given previous evidence that there is marginal or no gain over the case with no CSIT? To shed light on the answer to this question, in this dissertation, I present several achievable sum of degrees of freedom (sum-DoF) characterizations of wireless networks. The sum-DoF is a coarse sum-capacity approximation of the networks, deemphasizing noise effects. These characterizations rely on a set of proposed and existing interference management strategies that exploit limited CSIT. I begin with the classical multi-user multiple-input-single-output (MISO) broadcast channel with delayed CSIT and show how CSI feedback delays change sum-capacity scaling law by proposing an innovative interference alignment technique called space-time

interference alignment. Next, I consider interference networks with distributed and delayed CSIT and show how to optimally use distributed and moderately-delayed CSIT to yield the same sum-DoF as instantaneous and global CSIT using the idea of distributed space-time interference alignment. I also consider a two-hop layered multiple-input-multiple-output (MIMO) interference channel, where I show that two cascaded interfering links can be decomposed into two independent parallel relay channels without using CSIT at source nodes through the proposed interference-free relaying technique. Then I go beyond one-way and layered to multi-way and fully-connected wireless networks where I characterize the achievable sum-DoF of networks where no CSIT is available at source nodes using the proposed space-time physical-layer network coding. Lastly, I characterize analytical expressions for the sum spectral efficiency in a large-scale single-input-multiple- output (SIMO) interference network where the spatial locations of nodes are modeled by means of stochastic geometry. I derive analytical expressions for the ergodic sum spectral efficiency and the scaling laws as functions of relevant system parameters depending on different channel knowledge assumptions at receivers.
Spatially proximal devices wanting to exchange information are expected to become more prevalent in wireless networks, rendering the option for direct device-to-device (D2D) communication increasingly important. On the one hand, within networks where communication via infrastructure has been the convention, enabling such an option for short-range and single-hop communication between co-located devices might potentially bring about performance benefits on several accounts. On the other hand, in the realm of networks where direct interaction between devices has been an obvious option, there is a growing demand for supporting extreme-data-rate applications and much denser deployments of simultaneous transmissions. This dissertation explores these aspects by addressing two main problems: (i) analyzing the performance benefits of D2D communication integrated into cellular mobile networks, and (ii) investigating the feasibility of mmWave (millimeter wave) frequencies for personal networks of wearable (body-born) devices in enclosed settings. Under sufficient spatial locality in wireless traffic within cellular networks, the D2D mode of communication can be leveraged to employ a denser spectral reuse, thereby achieving very high area spectral efficiencies (bits/s/Hz per unit area). Enabling D2D entails a reshaping of the network topology comprising the sources of useful signal and harmful interference from the vantage of each receiver, which is a factor that delimits network performance fundamentally. Therefore, to gauge the performance gains of D2D and to identify the challenges thereof, it is essential to model D2D communication in a large multicellular setting, without missing key features of the ensuing interference environment. In this regard, we develop a robust analytical framework, utilizing tools from stochastic geometry. The dissertation propounds a novel approach to the application of stochastic geometry that is shown to improve the simplicity, accuracy, and generality of wireless network analysis. The performance evaluation conducted using the framework, while

demonstrating the potential of D2D, also indicates the need for managing the interference surge. Prompted by this, and to illustrate the flexibility of the framework, we further extended it to incorporate interference protection schemes based on exclusion regions and the benefits thereof are assessed. The presence of multiple wearable networks—each comprising several on-body device-pairs worn by people—in proximity might result in an extreme density of simultaneous wireless transmissions. Such a scenario is expected to become commonplace in enclosed settings, e.g., commuter trains, subways, airplanes, airports or offices, and be further challenging due to an increasing demand for data-rate-intensive wireless applications in wearable technology. This combination of very-short-range communication, high-data-rate applications, and dense spectral reuse seems to render operation at mmWave frequencies a suitable candidate; add to that the possibility of accommodating antenna arrays within devices for directional beamforming. Hence, we investigate the feasibility of enclosed mmWave wearable networks, with a particular focus on appropriately modeling the impact of propagation mechanisms at these frequencies. In the propagation modeling, specular reflections off surfaces are explicitly accounted for, as they are expected to contribute useful signal power while, at the same time, intensify the interference. Recognizing the increased prominence of blocking by obstacles, body-blockages in the direct and reflected propagation paths are also modeled. The impact of these mechanisms on the spectral efficiency of the network is evaluated, aided by the application of stochastic geometry and random shape theory. Under relevant indoor settings, and in the plausible absence of strong direct signal, the reliability of surface reflections in providing useful signal power for efficient communication is investigated and the need for directional antennas is established.
The shared medium of wireless communication networks presents many technical challenges that offer a rich modeling and design space across both physical and scheduling protocol layers. This dissertation is organized into tasks that characterize the throughput performance in such networks, with a secondary focus on the interference models employed therein. We examine the throughput ratio of greedy maximal scheduling (GMS) in wireless communication networks modeled as random graphs. A throughput ratio is a single-parameter characterization of the largest achievable fraction of the network capacity region. The throughput ratio of GMS is generally very difficult to obtain; however, it may be evaluated or bounded based on specific topology structures. We analyze the GMS throughput ratio in previously unexplored random graph families under the assumption of primary interference. Critical edge densities are shown to yield bounds on the range and expected GMS throughput ratio as the network grows large. We next focus on the increasing interest in the use of directional antennas to improve throughput in wireless networks. We propose a model for capturing the effects of antenna misdirection on coverage and throughput in large-scale directional networks within a stochastic geometry framework. We provide explicit expressions for communication outage as a function of network

density and antenna beamwidth for idealized sector antenna patterns. These expressions are then employed in optimizations to maximize the spatial density of successful transmissions under ideal sector antennas. We supplement our analytical findings with numerical trends across more realistic antenna patterns. Finally, we characterize trade-offs between the protocol and physical interference models, each used in the prior tasks. A transmission is successful under the protocol model if the receiver is free of any single, significant interferer, while physical model feasibility accounts for multiple interference sources. The protocol model, parameterized by a guard zone radius, naturally forms a decision rule for estimating physical model feasibility. We combine binary hypothesis testing with stochastic geometry and characterize the guard zone achieving minimum protocol model prediction error. We conclude with guidelines for identifying environmental parameter regimes for which the protocol model is well suited as a proxy for the physical model.

This book focuses on the design and analysis of protocols for cooperative wireless networks, especially at the medium access control (MAC) layer and for crosslayer design between the MAC layer and the physical layer. It highlights two main points that are often neglected in other books: energy-efficiency and spatial random distribution of wireless devices. Effective methods in stochastic geometry for the design and analysis of wireless networks are also explored. After providing a comprehensive review of existing studies in the literature, the authors point out the challenges that are worth further investigation. Then, they introduce several novel solutions for cooperative wireless network protocols that reduce energy consumption and address spatial random distribution of wireless nodes. For each solution, the book offers a clear system model and problem formulation, details of the proposed cooperative schemes, comprehensive performance analysis, and extensive numerical and simulation results that validate the analysis and examine the performance under various conditions. The last section of this book reveals several potential directions for the research on cooperative wireless networks that deserve future exploration. Researchers, professionals, engineers, and consultants in wireless communication and mobile networks will find this book valuable. It is also helpful for technical staff in mobile network operations, wireless equipment manufacturers, wireless communication standardization bodies, and governmental regulation agencies.

Energy harvesting technology is essential for enabling green, sustainable and autonomous wireless networks. In this report, a large-scale wireless network with energy harvesting transmitters is considered, where a group of transmitters forms a cluster to cooperatively serve a desired user in the presence of co-channel interference and noise. Using stochastic geometry, simple closed-form expressions are derived to characterize the outage performance at the user as a function of important parameters such as the energy harvesting rate, the energy buffer size and the cluster size for a given cluster geometry. The analysis is further extended to characterize the delay due to transmission failure. The developed framework is flexible in that it allows the in-cluster transmitters to have possibly different energy harvesting capabilities. The analytical expressions are first validated using simulations and then used for investigating the impact of different parameters such as cluster and buffer size on outage performance. The results suggest that substantial outage performance can in fact be extracted with a relatively small energy buffer. Moreover, the utility of having a large energy buffer increases with the cluster size as well as with the energy harvesting rate.

This book presents a unified framework for the tractable analysis of large-scale, multi-antenna wireless networks using stochastic geometry. This mathematical analysis is essential for assessing and understanding the performance of complicated multi-antenna networks, which are one of the foundations of 5G and beyond networks to meet the ever-increasing demands for network capacity. Describing the salient properties of the framework, which makes the analysis of multi-antenna networks comparable to that of their single-antenna counterparts, the book discusses effective design approaches that do not require complex system-level simulations. It also includes various application examples with different multi-antenna network models to illustrate the framework's effectiveness.

This volume bears on wireless network modeling and performance analysis. The aim is to show how stochastic geometry can be used in a more or less systematic way to analyze the phenomena that arise in this context. It first focuses on medium access control mechanisms used in ad hoc networks and in cellular networks. It then discusses the use of stochastic geometry for the quantitative analysis of routing algorithms in mobile ad hoc networks. The appendix also contains a concise summary of wireless communication principles and of the network architectures considered in the two volumes.

Over the past decade, stochastic geometric models, and most notably the planar Poisson point process (PPP) model, have become popular for the analysis of spectral efficiency in wireless networks, in both the D2D and the cellular contexts [1]. By modeling base station (BS) and user locations as spatial point processes, stochastic geometry has recently been recognized as a tractable and efficient analytical tool to quantify key performance metrics. This tool provides a natural way of defining and computing macroscopic properties of multiuser information theory. These properties are obtained by averaging over all node patterns found in a large random network of the Euclidean plane. For example, some key performance metrics such as signal to interference and noise ratio and data rate depend on the network geometric configurations. This tool has thus been widely adopted for analyzing the network performance and broadening network design. This thesis proposes new models to represent several new scenarios. Three main scenarios are considered: 3-D inbuilding networks, MIMO adhoc networks, and multihop communication under mmWave networks. To do so, mathematical tools such as Poisson point processes, Poisson line processes, Boolean models and Poisson bipolar models are used. Each model is 1) generative in that it has a clear physical interpretation, 2) leads to explicit analytical representations of important wireless performance metrics, and 3) highly parametric, with parameters expressing the geometric characteristic of the elements of networks. Physical interpretations from these models are quite different from previous results. The core of this thesis is focused on the effects of correlated shadowing. Shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path. By introducing an independent shadowing term over links, it is possible to model the effect of shadow fading. Most previous papers analyzing urban networks assume that shadowing fields are independent over links. With this assumption, it is possible to derive simple closed-form expressions of important network performance metrics. However, this assumption cannot capture that shadowing fields are spatially correlated. This thesis goes beyond the independent shadowing approximation and analyzes the effects of correlated shadowing on various performance metrics

Providing an extensive overview of the radio resource management problem in femtocell networks, this invaluable book considers both code division multiple access femtocells and orthogonal frequency-division multiple access femtocells. In addition to incorporating current research on this topic, the book also covers technical challenges in femtocell deployment, provides readers with a variety of approaches to resource allocation and a comparison of their effectiveness, explains how to model various networks using Stochastic geometry and shot noise theory, and much more.

This book discusses the smooth integration of optical and RF networks in 5G and beyond (5G+) heterogeneous networks (HetNets), covering both planning and operational aspects. The integration of high-frequency air interfaces into 5G+ wireless networks can relieve the congested radio frequency (RF) bands. Visible light communication (VLC) is now emerging as a promising candidate for future generations of HetNets. Heterogeneous RF-optical networks combine the high throughput of visible light and the high reliability of RF. However, when implementing these HetNets in mobile scenarios, several challenges arise from both planning and operational perspectives. Since the mmWave, terahertz, and visible light bands share similar wave propagation characteristics, the concepts presented here can be broadly applied in all such bands. To facilitate the planning of RF-optical HetNets, the authors present an algorithm that specifies the joint optimal densities of the base stations by drawing on stochastic geometry in order to satisfy the users' quality-of-service (QoS) demands with minimum network power consumption. From an operational perspective, the book explores vertical handovers and multi-homing using a cooperative framework. For vertical handovers, it employs a data-driven approach based on deep neural networks to predict abrupt optical outages; and, on the basis of this prediction, proposes a reinforcement learning strategy that ensures minimal network latency during handovers. In terms of multi-homing support, the authors examine the aggregation of the resources from both optical and RF networks, adopting a two-

timescale multi-agent reinforcement learning strategy for optimal power allocation. Presenting comprehensive planning and operational strategies, the book allows readers to gain an in-depth grasp of how to integrate future coexisting networks at high-frequency bands in a cooperative manner, yielding reliable and high-speed 5G+ HetNets.
"The past few years witnessed a major revolution in the area of unmanned aerial vehicles (UAVs), commonly known as drones, due to significant technological advances across various drone-related fields ranging from embedded systems to autonomy, control, security, and communications. These unprecedented recent advances in UAV technology have made it possible to widely deploy drones across a plethora of application domains ranging from delivery of goods to surveillance, environmental monitoring, track control, remote sensing, and search and rescue. In fact, recent reports from the Federal Aviation Administration (FAA) anticipate that sales of UAVs may exceed 7 million in 2020 and many industries are currently investing in innovative drone-centric applications and research. To enable all such applications, it is imperative to address a plethora of research challenges pertaining to drone systems, ranging from navigation to autonomy, control, sensing, navigation, and communications. In particular, the deployment of UAVs in tomorrow's smart cities, is largely contingent upon equipping them with effective means for communications and networking. To this end, in this book, we provide a comprehensive treatment of the wireless communications and networking research challenges and opportunities associated with UAV technology. This treatment begins in this chapter which provides an introduction to UAV technology and an in-depth discussion on the wireless communication and networking challenges associated with the introduction of UAVs"--
Physical layer security has recently become an emerging technique to complement and significantly improve the communication security of wireless networks. Compared to cryptographic approaches, physical layer security is a fundamentally different paradigm where secrecy is achieved by exploiting the physical layer properties of the communication system, such as thermal noise, interference, and the time-varying nature of fading channels. Written by pioneering researchers, Physical Layer Security in Wireless Communications supplies a systematic overview of the basic concepts, recent advancements, and open issues in providing communication security at the physical layer. It introduces the key concepts, design issues, and solutions to physical layer security in single-user and multi-user communication systems, as well as large-scale wireless networks. The book starts with a brief introduction to physical layer security. The rest of the book is organized into four parts based on the different approaches used for the design and analysis of physical layer security techniques: Information Theoretic Approaches: introduces capacity-achieving methods and coding schemes for secure communication, as well as secret key generation and agreement over wireless channels Signal Processing Approaches: covers recent progress in applying signal processing techniques to design physical layer security enhancements Game Theoretic Approaches: discusses the applications of game theory to analyze and design wireless networks with physical layer security considerations Graph Theoretic Approaches: presents the use of tools from graph theory and stochastic geometry to analyze and design large-scale wireless networks with physical layer security constraints Presenting high-level discussions along with specific examples, illustrations, and references to conference and journal articles, this is an ideal reference for

postgraduate students, researchers, and engineers that need to obtain a macro-level understanding of physical layer security and its role in future wireless communication systems.

"This book brings together advanced research on diverse topics in wireless communications and networking, including the latest developments in broadband technologies, mobile communications, wireless sensor networks, network security, and cognitive radio networks"--

Offers comprehensive insight into the theory, models, and techniques of ultra-dense networks and applications in 5G and other emerging wireless networks The need for speed—and power—in wireless communications is growing exponentially. Data rates are projected to increase by a factor of ten every five years—and with the emerging Internet of Things (IoT) predicted to wirelessly connect trillions of devices across the globe, future mobile networks (5G) will grind to a halt unless more capacity is created. This book presents new research related to the theory and practice of all aspects of ultra-dense networks, covering recent advances in ultra-dense networks for 5G networks and beyond, including cognitive radio networks, massive multiple-input multiple-output (MIMO), device-to-device (D2D) communications, millimeter-wave communications, and energy harvesting communications. Clear and concise throughout, Ultra-Dense Networks for 5G and Beyond - Modelling, Analysis, and Applications offers a comprehensive coverage on such topics as network optimization; mobility, handoff control, and interference management; and load balancing schemes and energy saving techniques. It delves into the backhaul traffic aspects in ultra-dense networks and studies transceiver hardware impairments and power consumption models in ultra-dense networks. The book also examines new IoT, smart-grid, and smart-city applications, as well as novel modulation, coding, and waveform designs. One of the first books to focus solely on ultra-dense networks for 5G in a complete presentation Covers advanced architectures, self-organizing protocols, resource allocation, user-base station association, synchronization, and signaling Examines the current state of cell-free massive MIMO, distributed massive MIMO, and heterogeneous small cell architectures Offers network measurements, implementations, and demos Looks at wireless caching techniques, physical layer security, cognitive radio, energy harvesting, and D2D communications in ultra-dense networks Ultra-Dense Networks for 5G and Beyond - Modelling, Analysis, and Applications is an ideal reference for those who want to design high-speed, high-capacity communications in advanced networks, and will appeal to postgraduate students, researchers, and engineers in the field.

This authoritative resource offers a comprehensive overview of heterogeneous wireless networks, small cells, and device-to-device (D2D) communications. The book provides insight into network modeling and performance analysis of heterogeneous wireless networks. Interference management framework and design issues are covered as well as details about resource mobility, channel models, and typical and statistical interference modeling. This resource explains leveraging resource heterogeneity in interference mitigation and presents the challenges and feasible solutions for concurrent transmission. Moreover, complete coverage of interference alignment in MIMO heterogeneous networks for both downlink and uplink is presented. This book provides performance results for an ideal partially connected interference network as well as a practical heterogeneous network. Readers find practical guidance for LTE and LTE-Advanced as well as 5G in this resource. New techniques and designs for heterogeneous wireless networks are included.

This book introduces the Vienna Simulator Suite for 3rd-Generation Partnership Project (3GPP)-compatible Long Term Evolution-Advanced (LTE-A) simulators and presents applications to demonstrate their uses for describing, designing, and optimizing wireless cellular LTE-A networks. Part One addresses LTE and LTE-A link level techniques. As there has been high demand for the downlink (DL) simulator, it constitutes the central focus of the majority of the chapters. This part of the book reports on relevant highlights, including single-user (SU), multi-user (MU) and single-input-single-output (SISO) as well as multiple-input-multiple-output (MIMO) transmissions. Furthermore, it summarizes the optimal pilot pattern for high-speed communications as well as different synchronization issues. One chapter is devoted to experiments that show how the link level simulator can provide input to a testbed. This section also uses measurements to present and validate fundamental results on orthogonal frequency division multiplexing (OFDM) transmissions that are not limited to LTE-A. One chapter exclusively deals with the newest tool, the uplink (UL) link level simulator, and presents cutting-edge results. In turn, Part Two focuses on system-level simulations. From early on, system-level simulations have been in high demand, as people are naturally seeking answers when scenarios with numerous base stations and hundreds of users are investigated. This part not only explains how mathematical abstraction can be employed to speed up simulations by several hundred times without sacrificing precision, but also illustrates new theories on how to abstract large urban heterogeneous networks with indoor small cells. It also reports on advanced applications such as train and car transmissions to demonstrate the tools' capabilities.

Cognitive radio is a novel approach for better utilization of the scarce, already packed but highly underutilized radio spectrum. To this end, environment-aware unlicensed secondary wireless devices are envisioned to share the spectrum with the primary licensed network, provided that their operation does not impose unmanageable interference on the primary nodes. To achieve this coexistence goal, interference modeling is of great significance. Interference, in general, has a stochastic nature not only due to randomness in the propagation channel, but also due to the random geographic dispersion of nodes. A statistical representation for interference, in which the power levels of the secondary nodes influence the parameters of the model, is, thus, of considerable interest in analysis and design of cognitive wireless network. Stochastic geometry and spatial point processes are used for modeling the coexisting primary and secondary networks. In particular, we model these networks using spatial bivariate Poisson processes. We obtain statistical properties of the distances in these processes and use them for modeling the interference from secondary network on the primary nodes. We first consider an approximate Gaussian model for interference assuming that Central Limit Theorem (C.L.T) can be applied. We, then, show that a more accurate model for interference is the sum of a Normal and a Log-normal random variables. The power levels of secondary nodes can be adjusted to obtain desirable values for the parameters in both of these models. Having this characterization of interference, we propose power control strategies for the secondary network which assure the satisfaction of interference constraint at the primary nodes. We show that these strategies are very easy to implement with little coordination requirement. Nodes either need to know where they are located in the sequence of nodes ordered according to their Euclidean distance to a primary node or need no location information, based on which strategy is being used. Given that secondary nodes have imposed power control strategies to coexist with the primary nodes, we find the lower bound of achievable throughput for the secondary nodes. We use the statistical properties of distances between secondary nodes and find an upper bound for the interference of secondary network on an arbitrary secondary node and thereby a lower bound for its throughput. We show that the approach is applicable to finding the throughput in a general power-constrained random network.

Analyse wireless network performance and improve design choices for future architectures and protocols with this rigorous introduction to stochastic geometry.