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Preface

Owing to advances in wireless communication, networking, and data analysis technologies, the generation, dissemination, and acquisition of data are more frequent and accessible than ever. Consequently, data services, which *move* data from its generator(s) to its consumer(s) through individual connections, are quickly migrating to the edge of networks. Such wireless systems are composed of numerous devices that are different in many aspects, e.g., communication technology, mobility pattern, and so on. Though service latency can be greatly reduced at the network edge, emerging data services at the edge create new challenges to the network: heterogeneity of individuals adds to the complexity of system design, management, and performance evaluation, while proliferating end devices impose an ever-increasing demand on resources, that are already scarce at the edge. To exploit the full potential of data services, it is essential to understand the cause, governing rules, and impact of data's *mobility* in such heterogeneous wireless networks, for the benefit of data owners, service providers, and network operators.

Therefore, this book is dedicated to study *mobile data dynamics*, that is, dynamic processes of mobile data. Specifically, we identify three dynamic processes, of *information*, *coverage*, and *spectrum*, as the cause, manifestation, and impact of mobile data, respectively. Then we examine these dynamic processes and the governing rule of data movements, through a modeling and analysis approach to answer the following questions: *When* data move and stop? *Where* data are? *How* data move? *What* impact mobile data induce on network resources?

In particular, we first study conflicting information propagation with a novel *Susceptible-Infected-Cured (SIC)* model to answer the *when* question. Our results reveal the impact of network topology on the lifetime of the undesired information, which provides bounds, scaling laws, and guidelines for practical information control measures. For the *where* question, we quantify the whereabouts of data, that is, data coverage, with a data-strength metric, and find that the change of data coverage depends heavily on user mobility, by which prediction is possible. Then, we consider dissemination processes of multiple data blocks in the emerging DSA-enabled fog paradigm, to answer the *how* and *what* questions. We propose a *gravity model* to describe how data move in an offloading process, based on which we find the amount of storage and communication resource needed for data offloading scales linearly with the network size. Particularly for the spectrum resource, a scarce resource in wireless networks, we study *spectrum activity surveillance (SAS)* to observe the impact of mobile data, and propose multi-monitor deployment strategies with guaranteed performances for both the dedicated and crowdsourcing SAS scenarios. Finally, we recapitulate the key findings with regard to mobile data dynamics, and outline the open research questions in the context of Edge Intelligence (EI). We hope this book helps advance understanding on mobile data and provides design guidelines for future data services in heterogeneous wireless networks.

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Acronyms

AI	Artificial Intelligence
AP	Access Point
AR	Augmented Reality
BS	Base Station
CDF	Cumulative (probability) Density Function
CDN	Content Delivery Network
CR	Cognitive Radio
D2D	Device-to-Device Communication
DSA	Dynamic Spectrum Access
EI	Edge Intelligence
ER	Erdös-Rényi random graph
ETC	Electric Toll Collecting
GFT	Graph Fourier Transform
GSP	Graph Signal Processing
IoT	Internet-of-Things
ITS	Intelligent Transportation System
LAN	Local Area Network
LBS	Location-Based Service
LTE	Long-Term Evolution
MACC	Mobile Ad hoc Cloud Computing
MCC	Mobile Cloud Computing
MEC	Mobile Edge Computing
MFA	Mean-Field Approximation
MGF	Moment Generating Function
OBU	On-Board Unit
OSN	Online Social Network
PDF	Probability Density Function
PMF	Probability Mass Function
PU	Primary User
QoS	Quality-of-Service
RAT	Radio Access Technology

REM	Radio Environment Map
RSU	RoadSide Unit
SAS	Spectrum Activity Surveillance
SI	Susceptible-Infected
SIC	Susceptible-Infected-Cured
SIR	Susceptible-Infected-Recovered
SIS	Susceptible-Infected-Susceptible
SU	Secondary User
VR	Virtual Reality
r.v.	random variable

Chapter 1
Introduction

1.1 Motivation

Data, which refers to *transmittable and storable computer information*, has been an integral part of modern society ever since the invention of computers. Especially in the past decade, its indispensable role in various applications, ranging from marketing [26] to scientific researches [7], has been re-enforced by advances in data mining, machine learning, and artificial intelligence (AI) studies. As the proliferation of smart devices that can interconnect with each other on-the-go, the creation, collection, and analysis of data are much easier and more accessible than before, leading to huge amounts of data being generated in both wired and wireless networks almost every second. For instance, the online social network (OSN) giant Facebook (now Meta) has 1.6 billion daily active users, who generate more than 4 PetaBytes new data every single day [27]. Meanwhile, the delivery networks of data are evolving into large and complex systems, due to the explosive growth of wireless devices, e.g., the number of Internet-of-Things (IoT) devices is expected to exceed 500 billion by 2030 [4], imposing a tangible impact on mobile data traffic. Consequently, recent years are witnessing the transition of data from a commodity owned by big companies, to a *service* that can be provided/acquired by practically anyone, just like the transition of computing resource in the cloud infrastructure a decade ago [22]. The principal course of such service is to *move* data from its generator(s) to its consumer(s) through a network of data carriers. In this data dissemination process, *data is mobile*, in the sense that both the traffic volume and whereabouts are constantly changing due to user movements and data forwarding actions.

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1.1.1 Data Is Alive and Mobile

From the data owner or disseminator's perspective, it is their natural rights to know who have taken (temporary) possession of their data, where those data blocks have traveled to, and when a data block of interest stops circulating in a certain region. All of these questions are tied closely to movements of data during dissemination.

From the delivery network's perspective, data is *alive*, that is, interacting with individuals in the network, only when it is *mobile*. In other words, the *lifetime* of data begins at the time instant when it is first injected into the network, and stops when none of its copies is circulating in the network of interest any more. During its lifetime, every move of a data block induces dynamical changes in the network, with respect to both resources and network status. In the former aspect, mobile data utilizes various kinds of network resources, for example: storage resource is consumed at a device, when the data block is temporarily stored by intermediate data carriers (for later forwarding); bandwidth/spectrum resource is consumed, when it is transmitted between data carriers; computation resource is also consumed, when the data block needs to be fragmented, processed, or routed. On the other hand, operating status of both individuals and the networked system as a whole, e.g., capacity and system integrity, are in turn impacted by mobile data. For example, a computer malware, e.g., the SMS Trojan [8] that spreads over emails and messages, can hide in data blocks, piggyback on their dissemination processes, and attack multiple users in an institutional computer network. As such a process unfolds in time, normal operations of the networked system may no longer be sustained.

Therefore, it is both primitive and essential to understand data's *mobility*, for the design, management, and recovery of data-delivery networks, as well as the provision of service transparency to data owners. Specifically, we identify the following open questions to understand the dynamic processes with respect to mobile data:

1. *When* does a data block start and stop moving in a network?
2. *Where* is the data block of interest accessible during dissemination?
3. *How* do data blocks move in the heterogeneous wireless network?
4. *What* is the observable impact of mobile data on data-delivery networks?

Among these, the first and second questions focus on the dissemination process of a single data block, while the rest two questions are for cases of multiple blocks. Particularly, the first question focuses on the time domain, in which the cause, or the driving force of mobile data, dictates the start and stop of the dissemination process, i.e., the *lifetime* of a data block in a network. The second question focuses on the space domain, in which the *whereabouts* of data refer to the time-varying locations, where the data block (and its copies) is accessible. The third question asks for the *governing rule* of mobile data, taking interactions of multiple data dissemination processes into consideration. The last question focuses on the consequence and *impact* of data being mobile, especially on shared network resources.

Considering that movements of a single data block already create a dynamic process in the space that spans over time, geographical location, and spectrum domains, the sheer complexity of multiple data blocks being replicated, piggybacked and transmitted in the same network prohibits these questions to be answered with a single model, nor a simple solution. Therefore, we first specify and analyze the scenario of mobile data, and then introduce our solution that tackles the aforementioned problem in different domains.

1.1.2 Mobile Data Dynamics in Heterogeneous Wireless Networks

Thanks to developments in wireless communication and networking technologies, including 5G [24], dynamic spectrum access (DSA) [17], IoT [1], fog computing [25], and so on, wireless network has become the primary choice of many data disseminators, and the common practice of content delivery services as well. This phenomenon can be observed by the ever-increasing volume of wireless (especially mobile) traffic [5] and spectrum demand. For instance, ever since 2015, over 80% of social media traffic in the U.S. comes from wireless mobile devices, as well as over 50% of all website traffic worldwide [11]. Such a wireless data-delivery paradigm is adopted by various application scenarios, including data sharing/forwarding [13, 14] in Long Term Evolution (LTE) device-to-device communication (D2D) networks, mobile advertisement [21] in WiFi-LTE networks, safety message dissemination [14, 30] in vehicular networks, IoT provisioning by LTE-based fog [1], and many more. Motivated by its extensive applications, this book is devoted to *mobile data in heterogeneous wireless networks*, which are composed of both wireless end devices, such as mobile phones, smart vehicles, and sensory devices, and network elements of the wireless access network, such as base station (BS) in cellular networks, access point (AP) in wireless LAN, and roadside unit (RSU) in vehicular networks.

Such wireless data-delivery networks exhibit distinct characteristics, bringing new challenges to the field of networking: First, data carrying individuals (users) themselves are mobile, resulting in intermittent data transmission links and changing network topologies. Moreover, user mobility introduces the notion of ‘where’, i.e., geographical location, which further complicates the problem. Second, individuals in such networks can be highly diverse in many aspects, including communication protocol, radio access technology (RAT), data forwarding preference, mobility pattern, etc., creating a dynamic and heterogeneous environment, which is difficult to model and experiment on. Last but not least, the data-delivery network can be formed in a spontaneous manner, lacking possible control of any form, which further complicates the design, maintenance, and operation of such systems.

To address these challenges, we identify three dynamic processes, each of which describes the behavior of mobile data in one of the three domains, namely, *time*, *geographical space*, and *spectrum*, such that their properties are tractable to be analyzed individually, and collectively they are comprehensive enough to understand mobile data in heterogeneous wireless networks. These dynamic processes reflect the cause, manifestation, and result of data's mobility, respectively, and are hence referred to as *mobile data dynamics*.

1.1.2.1 Information Dynamics: The Driving Force of Mobile Data

Any data-delivery network is designed to facilitate the flow of *information*, in the form of moving data blocks, so the beginning and the end of information propagation decide the start and stop time of data movements. However, as networks evolve into more complex systems, increasing users of diverse backgrounds introduce information of different aspects, even *conflicting information*, e.g. rumor vs. truth, into delivery networks. Similar phenomena can also be observed in various forms of networked systems, if the information concept is generalized to include virus/malware, system operation status, and adoption of new products.

Despite different manifestations, we observe that all the conflicting information propagation instances share some common characteristics: the later-injected desired information targets at an existing undesired information, stops its propagation, and terminates a potential/ongoing *epidemic* of the latter. In this way, the undesired information resembles an infectious *virus* that can infect susceptible individuals, while the desired information functions as an *antidote* that can permanently immune susceptible individuals or cure infected individuals. Due to this asymmetry, the propagation process is *transient*, in the sense that its asymptotic behavior at time t goes to infinity is known (virus-free), and the two epidemic processes co-exist only for a short period of time, as opposed to the long-term coexistence (and equilibrium) in existing models on competing epidemics, e.g., [2, 6, 19].

Accordingly, a natural question is, how such propagation process evolves in *finite* time. In other words, there is little knowledge on the aftermath of conflicting information propagation via individual spreading, especially *when* the undesired information (virus) dies out, *how fast* the number of victims of the virus decreases below a predetermined level, and how to design effective information (antidote) distribution strategy to reduce the lifetime of undesired information in a network.

These questions have a broad impact on the design, operation, and management of networks, because information propagation is the driving force of mobile data, and the extinction of the undesired information marks the end of its propagation (generation of data traffic), while the impact of the propagation reveals requirements of data delivery services.

1.1.2.2 Coverage Dynamics: The Whereabouts of Mobile Data

In a wireless data-delivery network that includes mobile devices, a data dissemination process is actually a sequence of data relocation actions, which are the superposition of data transmissions and entity (data-carrying individuals) movements. In this scenario, data's mobility is manifested in its time-varying *coverage*, that is, the geographical location where the data block of interest can be accessed (legally by its consumers or monitors, and illegally by malicious attackers).

Then the direct question of mobile data follows: *where* is the data during a dissemination process? If such a dissemination process is viewed as a cause-and-effect phenomenon, existing researches mainly focus on single factors from the cause-direction, e.g., from the network topology and communication aspects. While most literature [14, 18, 21, 30] do not carry the notion of 'where', the ones that do [12, 36] assume entities are homogeneous in every aspect. To answer the *where* question for a heterogeneous scenario, a new model is needed to describe data's current whereabouts/coverage.

Knowing the dynamically changing data coverage is important to both the data owner(s) and the delivery network. To the former, data dissemination should be transparent to the customer (data owner/disseminator) as a service, while to the later, particularly network elements, including AP, BS, RSU, and gateways, changing coverage translates to traffic load and is hence relevant to resource management, as well as policy and charging plan design.

1.1.2.3 Spectrum Dynamics: Impact of Mobile Data in the Spectrum Domain

Due to the natural gap between its scarcity and high communication demand, radio *spectrum* is one of the most important resources in current wireless systems. Any data transmission in a wireless network will result in a spectrum *activity*, i.e., occupancy of a spectrum slice for a certain period of time (typically several milliseconds) at a geographical location, so that no other individual in this region can utilize the same slice simultaneously. In other words, *spectrum dynamics*, that is, time-varying spectrum activities over a geographical region, are the *outcome* of mobile data, as well as an impact to the system capacity.

To observe and evaluate such impact, it is necessary to have a spectrum surveillance system, which carries out continuous scans of spectrum activities on the frequencies of interest, for the purpose of usage data collection, including temporal and spatial patterns of spectrum occupancy, user mobility, as well as traffic patterns. Spectrum surveillance is particularly crucial to dynamic spectrum access (DSA)-enabled systems, because of the risks introduced by the open and opportunistic nature of DSA. In prior studies of spectrum surveillance strategies (e.g., [10, 15, 23]), an implicit assumption is that spectrum monitors are sufficiently powerful, such that they can watch over the entire geographical region of interest and tune/move without any limit. The fact is that most spectrum activities, including communications, attacks/jamming and monitoring/sniffing, are *local*, i.e., confined in both the spectrum domain and the space domain during a fixed-length time interval. This discrepancy is especially pronounced in wide-band wide-area spectrum