1 Introduction

1.1 Overview

This book will provide state-of-the-art research on aerial communications coexisting with terrestrial networks from physical, MAC, network, and application layer perspectives. The book also includes the fundamental theories upon which aerial communication systems will be constructed. The book discusses in detail the issues of control, access techniques, and resource sharing (e.g., spectrum and energy) between cellular communication and aerial communications to accommodate larger volumes of traffic and to provide better service to users. Other challenges to be discussed in the book include identification of services for which aerial communications are useful, radio resource allocation and resource management for aerial links, self-organizing aerial networks, aerial offloading, and capacity and performance evaluation of aerial communications.

The key features of this book are

- a unified view of aerial access communications and networking;
- comprehensive review of the state-of-the-art research and key technologies for aerial communications networks;
- comprehensive of a wide range of techniques for the design, analysis, optimization, and applications of aerial communications networks;
- outlining the key research issues related to aerial communications and terrestrial networks; and
- standardization activities in the area of aerial communications.

The purpose of this book is to provide a systematical and comprehensive overview of the potentially promising models and methodologies in the era of aerial access network (AAN) empowering 6G from the perspective of the system architecture and networking design, enabling technologies, modeling and performance analysis, system performance optimization, and technical challenges and future directions. The book also presents techniques for analysis, design, optimization, and applications of aerial communications systems under given objectives and constraints.

1.1.1 Integrated System Architecture of AANs

With the development trend of AANs for the provision of wireless coverage extension and enhancement for 6G services, we first elaborate on the AAN architecture, which is designed to provide seamless and ubiquitous 6G services for more users and applications. The key functional components of the AAN system are presented to give flexibility and scalability to the management and control of the AANs. Notably, valuable suggestions and recommendations are proposed and analyzed in each part of the AAN architecture.

1.1.2 Modeling and Performance Analyses

We investigate the related modeling and performance analysis strategies of the combined multitiered systems in AANs to provide readers with a convenient reference. Specifically, we first analyze the complicated channel model in an aerial network of highly dynamic unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), and satellites the goal of which is to assist the terrestrial network to extend coverage. We then study modeling and performance analysis in UAV/HAP-terrestrial networks. We also explore the network models and performance analysis schemes in integrated satellite-terrestrial networks for service performance enhancement. Notably, we present some insight for the modeling and performance evaluation in future AANs with multinetwork tiers integration.

1.1.3 System Performance Optimization

To improve the system performance of AANs, we consider AANs with a single-tier network and multitiers heterogeneous network. Because the resources of the different components (i.e., HAP, UAV, and satellite tiers) are dynamic and have different characteristics, we study performance optimization strategies from the perspectives of single HAP, single UAV, single satellite, and integrated networks. Furthermore, regarding system performance improvement, we review technologies on four aspects: wireless communication services enhanced by applying UAV networks, user service performance optimization based on HAP networks, multiresource collaboration in satellite networks, and heterogeneous resource collaboration in AANs.

1.2 Motivation

The current development of 5G networks represents a breakthrough in the design of communication networks for their ability to provide a single platform enabling a variety of different services, such as enhanced mobile broadband communications, automated driving, and the huge number of connected Internet of Things (IoT) devices. Nevertheless, looking at the current development of technologies and new services, we can already envision the need to move beyond 5G (B5G) or sixth generation (6G) with a new architecture incorporating new services and technologies.

Providing "connectivity from the sky" is the new innovative trend in wireless communications for future communication systems. Benefitting from the inherent advantages in high throughput, large coverage, and resilience of satellite communications, more and more commercial companies and organizations have been working on satellite-related projects such as OneWeb [1] and SpaceX [2] in recent years. In addition, the third generation partnership project (3GPP) defines the deployment scenario of nonterrestrial network (NTN) and provides 6G commercial services for areas with an underdeveloped ground network infrastructure. The project is expected to achieve wide coverage by using aerospace access facilities such as UAVs and satellites. As a result, the AAN composed of low-altitude platforms (LAP), UAV, HAP, and satellites is an emerging architecture to support ubiquitous services. Thanks to the 3D wide service coverage capabilities and reduced vulnerability of space/airborne vehicles to physical attacks and natural disasters, NTNs have a number of benefits:

- Foster the roll out of wireless service in unserved areas where terrestrial networks are not available (such as in isolated/remote areas or on board aircrafts or vessels) or underserved (e.g., in suburban/rural areas) to upgrade the network performance in a cost-effective manner.
- Improve the wireless service reliability by providing service continuity for machine-to-machine (M2M) and IoT devices or for passengers on board moving platforms (e.g., aircraft, ships, high speed trains, and buses) or ensuring service availability anywhere especially for critical communications, future railway/maritime/aeronautical communications, and to.
- Enable cellular network scalability by providing efficient multicast/broadcast resources for data delivery at the network edges or user terminal.

These benefits relate to NTNs operating alone as well as integrated terrestrial and nonterrestrial networks. They will affect coverage, user bandwidth, system capacity, service reliability or availability, energy consumption, and connection density. For example, the incorporation of links with aerial access points placed on drones or very low-Earth-orbit (LEO) satellites is an effective way to provide coverage on demand and cope with the high variability of data rates as a function of space and time. These access points will most likely operate over lower frequency bands (up to tens of gigahertz). Their use, coupled with a dense deployment of terrestrial access points placed on locations such as lampposts and tall buildings, will allow future communication systems to enable true 3D connectivity.

Exploiting AANs to supplement terrestrial networks is a key approach to deal with massive data traffic demands and global ubiquitous communication in the future. There are about 30 satellite constellations around the world. The service capabilities of the system are gradually expanding from traditional mobile communication services to broadband interconnection services. Despite the fact that the number and size of satellite constellations are growing quickly, the link between constellation scale, structure, frequency usage guidelines, and constellation service in satellite constellation systems isn't fully understood. In addition, on-demand integration and movement of heterogeneous resources are critical technologies to enhancing network performance in a typical heterogeneous AAN upgraded for ground services. The limited and mobile network resources between different tiers, however, have a significant impact on the network performance because of the AAN's inherent self-organization, heterogeneity, and time-variability. For ensuring ubiquitous on-demand user services, it is crucial to consider the system architecture and design, resource management and frequency allocation, mobility management, networking protocol, and network performance analysis and optimization of heterogeneous AANs.

There have been state-of-the-art surveys on AANs. First, some surveys were conducted on single networks. Recent advances and future challenges of satellite and CubeSat communication were introduced in [3], respectively. In [4], the technology, standards, and open challenges of satellite IoT were introduced. The vision and framework of future HAP networks were provided and the unrealized potential of the HAP system was emphasized in [5]. The research status and future research directions of AANs including HAP and UAV cellular communications are detailed in [6]. In [7], the practical problems and security challenges in UAV cellular communications were discussed. Other works have focused on the integration of different kinds of networks. Satellite-ground communication networks were discussed from different aspects in [8] and [9]. In addition, some surveys of the AANs were carried out in [10] and [11], including recent research work, key technologies, application prospects, and requirements, architecture and challenges in 6G.

However, a full analysis of the aforementioned parts or all tiers of AANs for special applications is missing from the existing publications concerning AANs that are either constrained to or dedicated to particular topics. This indicates that the relevant studies in this subject are still dispersed and independent, and their connections are sporadic and asynchronous. As a result of AANs' inherent self-organization, heterogeneity, and time-variability, the objectives and methodology of the existing research has also varied substantially. In order to provide a concise guide, this book highlights the following crucial issues, including system architecture and networking design, network performance analysis, system optimization schemes, simulation evaluation, and system testing, in both single-tier and multitier AAN scenarios, which had not been well investigated. Conceptually, combining current systems to create a multitiered, hierarchical AAN is intended to give readers direction and a complete reference model for future topics.

1.3 Objectives and Organization

Utilizing modern information network technologies and interconnecting space, air, and ground network segments, the AANs have attracted much attention from academia and industry and have been recognized as a potential solution for the future communication systems. Such heterogeneous networks that are engineered to utilize satellites, HAPs, and UAVs to build communication access platforms. Compared to

https://doi.org/10.1017/9781108936538.002 Published online by Cambridge University Press

terrestrial wireless networks, AANs are characterized by frequently changing network topologies and vulnerable communication connections. Furthermore, AANs demand the seamless integration of heterogeneous networks such that the network quality of service (QoS) can be improved. Thus, designing mechanisms and protocols for AANs poses many challenges. To solve these challenges, extensive research has been conducted.

Note that AANs are not intended to replace existing technologies, but instead to work with them in a complementary and integrated fashion. Thus, AAN design, analysis, and optimization requires multidisciplinary knowledge – namely, knowledge of wireless communications and networking, signal processing, artificial intelligence (e.g., for learning), decision theory, optimization, and economic theory.

The three main objectives of this book are to (1) provide a general introduction to integrated AANs, (2) introduce key components and their corresponding techniques to enable AANs communications systems, and (3) present the state-of-the-art AANs and possible applications. To achieve these objectives (outlined in more detail in the Preface), this book is organized as follows:

1.3.1 Part I: Basics of Aerial Access Networks

We start with an introduction to wireless communications (including radio propagation and channel models) and by reviewing different wireless access technologies. To provide global connectivity for terrestrial users, AANs can work as a complementary component. The requirements of aerial services and the system architecture will also be discussed. A three-tier aerial access network consisting of UAVs, HAPs, and satellites will be introduced. In this chapter, we highlight the characteristics of each tier respectively and discuss the possible integrations and applications of these three tiers.

1.3.2 Part II: UAV Communication Networks

Emerging UAVs have been playing an increasing role in the military, public, and civil applications. Dedicated UAVs, also called drones, can be used as communication platforms (e.g., as wireless access points or relays nodes) to further assist the terrestrial communications. This type of application can be referred to as UAV-assisted cellular communications, which we describe in this part.

The key techniques to support the UAV communication networks will also be presented. For example, it is challenging to plan the time-variant placements/trajectories of the UAVs served as base station (BS)/relay due to complicated 3D propagation environments as well as many other practical constraints such as power and flying speed. In addition, spectrum sharing with existing cellular networks and user associations are other interesting topics to investigate.

1.3.3 Part III: HAP Communication Networks

High-altitude-platforms (HAPs) have the potential to deliver a range of communications services and other applications cost effectively due to their ability to carry a heavy payload. In addition, HAPs can provide larger coverage than UAVs and have a lower propagation delay with more controllable wireless links compared with satellite communications. This chapter explains a step change in performance and availability and the advantages of being able to deliver high capacity similar to that available from terrestrial systems and wide area type coverage similar to that available from satellites.

To integrate seamlessly with existing communication networks and achieve wide adoption among potential users, the HAP network has to be based on the most suitable existing or developing communication standards with necessary adaptations that take into consideration some specific requirements and the particular operating environment. Some applications such as data/computation offloading will be investigated. Specific emphasis is place on how this technology will integrate within a terrestrial/satellite infrastructure. Here we also describe the broadband services and the investigation into broadband architectures.

1.3.4 Part IV: Satellite Communication Networks

With recent significant advances in ultra-dense LEO satellite constellations, satellite access networks (SANs) have shown their significant potential to integrate with 5G and beyond to support ubiquitous global wireless access. This chapter proposes an enabling network architecture for a dense LEO-SAN in which the terrestrial and satellite communications are integrated to offer more reliable and flexible access.

Many key techniques such as effective interference management, diversity techniques, and cognitive radio schemes will be further elaborated on. An integrated architecture for satellite-terrestrial network will be proposed, where all types of satellites and aerial components play different roles given a software defined network (SDN) framework. Various applications of satellites for aerial-terrestrial integrated services are also studied.

1.3.5 Part V: Integration of UAVs, HAPs, and Satellites

The integration issue is another important aspect of providing seamless and high-rate wireless links for wireless devices with different QoS requirements. In this chapter, we further discuss the key problems in the integration of UAVs, HAPs, and satellites, including association, data/computation offloading, and routing, involved in providing seamless connectivity from the sky.