# 5G Radio Access Networks

## Centralized RAN, Cloud-RAN, and Virtualization of Small Cells

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# Preface

In the ever-evolving telecommunication industry, smart mobile computing devices have become increasingly affordable and powerful, leading to a significant growth in the number of advanced mobile users and their bandwidth demands. According to Cisco, high-end devices such as smartphones, iPhones, netbooks, and laptops will account for 24.3 EB per month of data traffic by 2019. In order to achieve this, alternate solutions are required wherein traditional base stations can be replaced by more generic, simple, and small-sized nodes that can carry out minimal tasks such as radiofrequency operations, while moving other computationally intensive tasks such as resource allocation, baseband processing, and so on to a centralized location. In this context, a centralized or cloud radio access network (C-RAN) offers many advantages over a traditional radio access network and the architectural design and techniques offered by C-RAN make it a strong candidate to be incorporated into the 5G wireless network standard. C-RAN would enable joint scheduling and processing between multiple cells, which would eventually enable a collaborative radio environment. Notably, C-RAN would enable a seamless integration between multiple operators and a multiproduct vendor design. On similar lines, small cells have also been looked at, for moving the computation from the user terminal/device to the network; either to the small cell node itself or to the core network. In this regard, the functionality of small cells resembles that offered by the C-RAN. In fact, with the rapid development of network function virtualization (NFV) in the telecommunication world, communication service providers and product vendors have been looking to offer virtualized small cells.

## Organization of the Book

Being at a very nascent stage, C-RAN and virtualized small cell technology poses several major research challenges. This book aims to provide a deeper insight into the next generation of RAN architecture; especially in the presence of virtualization and the cloud environment. The book will present a survey of the coexistence of software-defined networking (SDN), C-RAN, and small cell solutions proposed in the literature at different levels, for example, physical characteristics, open access, dynamic resource allocation, technology neutrality, coverage obligations, the minimization of interference problems, and so on.

The book is structured into two main sections. The first section on 5G RAN Architectures and Applications, describes the current challenges in the radio access network environment, which leads to the next generation of wireless networks. It includes important chapters written by researchers from prestigious laboratories in China, the Czech Republic, Germany, Spain, and the United Kingdom, which each present what is currently state of the art in the area of next-generation 5G networks, including possible architectures and solutions, performance evaluation and interference mitigation, resource allocation management, energy efficiency and cloud computing, and so on. The 5G RAN Architectures and Applications section consists of five chapters. The following offers a brief description of each of the chapters in this section:

Chapter 1 discusses a new kind of user-centric network architecture for the next generation of mobile systems (5G), referred to as a Frameless Network Architecture (FNA). The proposed FNA decomposes the functionality of the traditional base station into a centralized processing entity (CPE) and an antenna element (AE), such that the CPE will maintain the networking, implement the signal processing, handle the control plane and user place, manage the radio resources, and construct on-demand user-centric serving sets.

Chapter 2 identifies the need for a distributed architecture in 5G networks for efficient computation management in mobile edge computing. Importantly, it introduces two options for newly distributed deployments of the management unit. The chapter also discusses the integration of the proposed solution into 5G mobile networks based on C-RAN. Through an analysis and simulations of the proposed architectures, we prove that both signaling delay and signaling load could be significantly reduced compared with centralized solutions.

Chapter 3 provides a comprehensive survey of the latest developments and the use of nonorthogonal multiple access (NOMA) schemes for next-generation 5G networks. The survey first provides a comparison between orthogonal multiple access schemes and NOMA schemes, identifying the advantages and disadvantages of each of the technologies. The solutions offered by NOMA schemes for the uplink and downlink transmissions are discussed with an emphasis on the NOMA-based solutions for downlink transmissions.

Chapter 4 looks into the performance evaluation of a NOMA-based mechanism used within the wireless downlink cloud radio access network (WD-CRAN) environment. The mechanism makes use of successive interference cancellation (SIC) receivers in order to enhance the reception and to lay multiple base stations over each other in the power domain.

Chapter 5 begins with a detailed background and terminologies to set a common understanding of cloud computing, toward a flexible networking future. The chapter will detail future network clouds and the need for efficient frameworks for cloud management and control. Furthermore, the chapter will outline OpenStack in order to offer the reader the tools for experimenting.

The second section, entitled 5G RAN Virtualization Solutions, presents various solutions proposed by world-known researchers in different areas of software-defined networks and virtualization. It includes important chapters written by researchers from prestigious laboratories in Belgium, Germany, Greece, India, Italy, and the United Kingdom, presenting results in the areas of software-defined networks, mobility management, the Internet of things (IoT), sensor applications, and so on. The 5G RAN virtualization solutions section consists of six chapters; the following offers a brief description of each of these.

Chapter 6 discusses two enabling technologies for C-RAN that allow decoupling beyond baseband and radio, that is, SDN and NFV. Importantly, the pros and cons of these enabling technologies are thoroughly discussed.

Chapter 7 begins with an introduction on the need for SDN. The new SDN paradigm is then briefly explained and compared with traditional networks. Furthermore, following a bottom-up approach, an in-depth overview of SDN architecture is provided.

Chapter 8 is a detailed chapter that provides a comprehensive yet practical walkthrough for managing the mobility of next-generation wireless networks with SDN.

Chapter 9 provides a detailed description of self-x network management, beginning with autonomic and cognitive networking and then goes on to describe in detail the proposed next-generation self-configurable and self-optimized framework.

Chapter 10 discusses different distributed data aggregation mechanisms and compression techniques for the 5G virtual RAN IoT-based sensor applications. It shows the mechanism for combining a centralized C-RAN architecture for the mobile cloud and a cluster head–based architecture for the wireless sensor network. Also, it demonstrates the importance of their approach in two application domains—the *distributed aggregation of temperature measurements* and *distributed video coding of visual data* obtained with wireless visual sensors.

Chapter 11 explains the 5G C-RAN uplink cross-layer optimization mechanism to support massive traffic in sensor network services. Importantly, the chapter investigates and studies the planning difficulties and restrictions that are related to interference, throughput, accessibility, and uplink connectivity, proposing solutions and rules to be followed. Furthermore, it explains why C-RAN planners should fulfill the proposed recommendations when optimizing the 5G IoT's network performance.

The prospective audiences for this book are mainly undergraduate students, postgraduate students, and researchers who are interested in learning more about the latest developments in the areas of mobile and wireless communications. It also targets industry professionals who are working or are interested in this area, providing them with a reference to the latest efforts that advance the research further by addressing some of the shortcomings of the existing solutions.

The editors wish you a pleasant reading.

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*5G Radio Access Networks: Centralized RAN, Cloud-RAN, and Virtualization of Small Cells* would not exist without the efforts of many people whose names may not appear on the cover of the book. However, their hard work, cooperation, friendship, and understanding were very important to the preparation and production of the book. The editors would like to sincerely thank the entire team at CRC Press for their support and help in the publication of this book. As in general, the work associated with the chapter review is underestimated and forgotten, the editors would like to thank the team of reviewers for the generous commitment of time and effort that they have put into the reviewing process and for providing their expertise to ensure a high-quality review process. Last but not least, the editors would like to thank their families for their continuous support along the way.

In particular, Hrishikesh Venkataraman would like to thank both of his parents for instilling a confidence in learning new topics and the ability to produce the learning in proper form to an audience. Also, he would like to thank his wife and his mother-in-law for their patience and dedication to other aspects of personal life while writing the chapters and editing this book. Importantly, he would like to thank his institution for their support for allowing him to focus on his research and allowing him to write/edit the book.

Furthermore, Ramona Trestian would like to thank her wonderful and loving parents, Maria and Vasile, for their unconditional love and care and for being an immense source of inspiration throughout her life. Her special gratitude goes toward her husband Kumar, for his immense love and continual patience and support, both of which were essential to this project, as well as toward her little bundle of joy, Noah Anthony, for making her life worth living.

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# I

# 5G RAN ARCHITECTURES AND APPLICATIONS

# Chapter 1

# Frameless Network Architecture for User-Centric 5G Radio Access Networks

Xiaodong Xu, Zhao Sun, and Jiaxiang Liu

## Contents



The system capacity for future mobile communication needs to be increased to fulfill the emerging requirements of mobile services and innumerable applications. For a long time, the cellular network topology and networking strategies have been regarded as the most promising way to provide the required capacity increase. However, with the emerging densification of cell deployments, the traditional cellular structure limits resource efficiency, and the coordination between different types of base stations is more complicated and entails heavy cost.

Consequently, this chapter discusses a new kind of user-centric network architecture for the 5th generation mobile system (5G), known as *frameless network architecture* (FNA). As there have been several studies on the network architectural evolution required for 5G, we first make a general introduction about current work.

For FNA, by decomposing the traditional Base Station (BS) into a Centralized Processing Entity (CPE) and Antenna Element (AE), the Radio Access Network (RAN) of FNA consists of two new network elements. The function of the CPE is to maintain the networking, implement the signal processing, handle the Control Plane (CP) and User Plane (UP), manage the radio resources including the connected AEs, and construct an on-demand user-centric serving set for specific users. The AEs are selected to construct a serving set for the specific user according to its quality of service (QoS) requirement.

Based on FNA, each user is always focused as being the coverage center of the serving AE set, which means that the cell boundary or the traditional cellular structure will no longer exist. The CP and UP are separated based on the FNA. The designated controlling AE implements the function of the CPE, which is handling and maintaining the control plane. The Data-AEs maintain their own User Plane under the control of Controlling-AEs.

In addition, based on FNA, the Control Plane and User Plane adaptation strategy is discussed in this chapter to improve the system Energy Efficiency (EE). A three-step system EE optimization with constraints on the CP/UP adaptation is given. We optimize the system EE via CP and UP construction and adaptation while guaranteeing the user QoS. The system-level simulation results show that, with constraints on the QoS of the users, the system EE performances are improved.

Finally, in order to further improve resource efficiency, especially the AE usage efficiency in the coordination-based user-centric RAN, we discuss the routing strategy in FNA. Based on the decoupling of CP and UP, the network virtualization is explored through Software Defined Network (SDN) approaches. We virtualize the wireless resources into a shared Resource Pool. In the User Plane, we use the *flow* to support different service slices. There can be multiple coordinated flows selected to meet the requirement of central user–specific QoS. In the Control Plane, we maintain an access route table to support the flow-selecting strategy. By choosing a flexible and appropriate routing strategy, we can prevent performance degradation due to the randomness and variance of mobile channels. Through this approach, relatively more stable services can be provided to users and the resource efficiency can be improved. On the aspect of routing algorithms, with reference to the wireless mesh network routing algorithms, we define a utility function–based routing selection algorithm, which achieves better performance.

Those highlighted aspects discussed in this chapter within FNA depict the way forward for the user-centric RAN of the 5G evolution. It is believed that, with the breakthroughs of the fundamental cellular network architecture, the future mobile network will surely have new performance improvements.

## 1.1 Related Works

Currently, mobile Internet applications and versatile mobile services are affecting every aspect of our daily life. Specifically, the dramatic increase in data traffic poses a great challenge to the network capacity and forces the mobile operators to make revolutionary changes. Besides expanding the spectrum and improving radio transmission, the mobile network architecture is considered as another potential way of further increasing the capacity of the 5G system [1,2].

Along with the evolutionary efforts for the 5G system, the cellular network topology and modeling are faced with urgent requirements for further evolution. The traditional hexagonal grid cellular network topology is believed not to be suited to centralized processing but rather to distributed deployments of RAN architecture [1], featuring as multi-tier Heterogeneous Networks (HetNet), ultra-dense small cells, and user-centric service-providing environments. The evolved network architecture should accommodate the separation of the central control entity and a large amount of distributed remote antenna elements. The BS and user association should also be evolved for on-demand service provision for users with specific QoS requirements, which are typical user-centric requirements. Moreover, an accurate depiction of the network topology modeling needs to be found for future network deployments, which will provide the operators with instructions for future network planning and optimization.

Focusing on the aforementioned requirements, there has been some research on OpenRAN, Soft Cell, and C-RAN [3–5]. The authors of [3] propose a software-defined RAN architecture, which is implemented through virtualization. For the Soft Cell concept proposed in [4], the transparent sets of BSs are provided for users. Based on the baseband pool, China Mobile Research Institute proposes C-RAN with features such as a centralized baseband unit, coordination, and cloud computing [5]. In order to solve the key challenges with regard to the way forward for C-RAN, much attention has been paid to evolved network architectures and promising key technologies [6–10]. To overcome the disadvantages of C-RANs with fronthaul constraints, heterogeneous cloud radio access networks (H-CRANs) have been proposed in [6] as a cost-effective potential solution to alleviate intertier interference and improve cooperative processing gains in HetNets in combination with cloud computing. While in [7], a fog computing–based radio access network (F-RAN) is presented, which can take full advantage of local radio signal processing, cooperative radio resource management, and the distributed storing capabilities in edge devices. These features could effectively decrease the heavy burden on fronthaul and avoid large-scale radio signal processing in the centralized baseband unit pool. In addition, some key technologies for C-RAN and H-CRAN have been proposed, including remote radio head (RRH) association strategies, inter-tier interference cancellation, and the performance optimization of a constrained fronthaul. In [8], the single nearest and $N$-nearest RRH association strategies are presented. Closed-form expressions for the ergodic capacity of the proposed RRH association strategies are also derived. Lately, in [9], a contract-based interference coordination framework is proposed to mitigate the inter-tier interference between RRHs and macro BSs in H-CRANs. A hybrid coordinated multipoint transmission scheme is designed for the downlink scenario of C-RAN in [10], which fulfills flexible tradeoffs between cooperation gains and fronthaul constraints.

## 1.2 FNA for User-Centric Radio Access Networks

Apart from the promising evolved RAN architecture mentioned in Section 1.1, the FNA was proposed lately as an evolved user-centric architecture for the radio access network of 5G, which aims to provide a set of concepts and principles to guide the development of the centralized processing network architecture and the topology for RAN evolution [11–13]. The evolved implementation scenario of FNA is shown in Figure 1.1, including the Core Network (CN), RAN deployments, and serving User Equipment (UE).

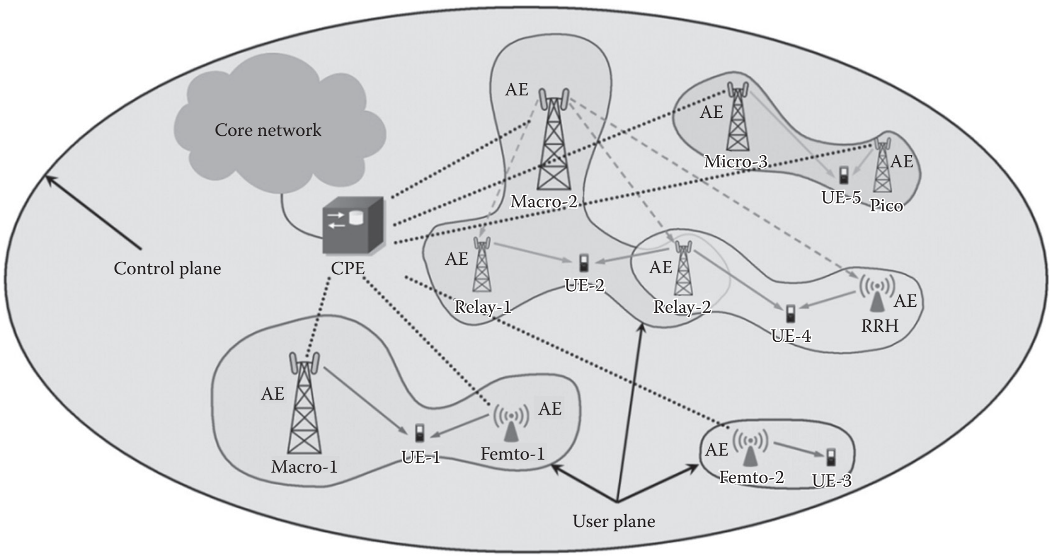


**Figure 1.1 FNA with typical deployment scenarios.**

The RAN of FNA consists of two main network elements. By decomposing the traditional BS into CPE and AE, FNA develops in an evolved manner. The main functions of the CPE are to maintain networking strategy, implement the signal processing, handle the CP and UP, manage all of the radio resources including the connected AEs, cope with the mobility management, and construct the on-demand user-centric service-providing environments. The CPE can be located with a macro BS or any other kinds of BSs that have the required processing ability, by which the CPE mainly functions as a logical node.

The AE is responsible for the radio signal transmission/reception. The backhaul links between the CPE and AE could be the optical fiber, wireless backhaul, wired connections, or other kinds of links. The capacity and latency features for different types of backhaul links are different, which will also be included in the consideration of resource allocations.

The AEs are selected to construct a serving set for the specific user according to its QoS requirement, which also forms the UP for the above user. The serving set may contain one or several AEs. The AE can also be a single antenna or an antenna array. According to the different transmission power limitations of their radio frequency (RF) abilities, the AEs are classified into several types that have different coverage abilities, such as the Macro AE, Micro AE, Pico AE, Femto AE, RRH AE, and so on. The AE in the serving set can also be different types, with coordination techniques supported between AEs and CPEs to provide a more flexible construction of the serving set for the specific users.

As shown in Figure 1.1, there are Macro, Pico, Femto, Relay and RRH AEs that are deployed as an underlay Scenario. UE-1 is served with a coordinated transmission mode with AEs Macro-1 and Femto-1 as the corresponding serving set according to the UE-1 QoS requirement. UE-2 is served by AEs Macro-2, Relay-1, and Relay-2. Femto-2 serves the UE-3 as the only corresponding AE. The AE Relay-2 in the serving set for UE-4 is the common node for the serving set of UE-2. For the UE-5, the AEs Micro-3 and Pico AE construct the serving set. The coordinated transmission scheme can be joint processing schemes based on the CoMP [14,15] or enhanced coordinated transmission schemes with precoding techniques applied in the transmission nodes.

The coverage area for the serving set of each UE will be amorphous because of the dynamically adaptive updated serving-set construction.

In FNA, the coordinated transmission is managed by one CPE with an arbitrary deployment of AEs within the coverage area. Similar to the phantom cells [16,17], the CP and UP are separated based on the FNA. The designated Controlling-AE implements the function of the CPE, which is handling and maintaining the Control Plane. The Data-AEs maintain their own User Plane under the control of Controlling-AEs. The Data-AEs distributed within the coverage area of a Controlling-AE are supposed to be managed by the Controlling-AE through the CPE.

According to the FNA deployments, network topology modeling will be the most fundamental research topic. For the network topology modeling, the traditional single-tier hexagonal grid network deployment model has been implemented for a long time. But with increasing deployments of HetNet and small cells, the multi-tier and ultra-dense HetNet topology cannot be depicted by the traditional hexagonal grids. The actual locations of the small cell BSs inside the future network will be more randomized, especially when the femtocells are randomly deployed in the network and the user can also have the ability to determine the ON/OFF state of their femtocells. The stochastic geometry method with the Poisson point process (PPP) model has been proposed for the aforementioned network topology [18,19], which provides good tractability for multi-tier HetNet and ultra-dense small cell deployments. The system outage capacity, mobility management, and interference management can be analyzed with closed-form solutions for many scenarios, which provide valuable theoretical instructions for the actual network planning and performance analyses.

But with more and more research focused on the PPP model, there are also some limitations found with the PPP model and the most important problem lies in the random features of the PPP. There is not a state of complete independency for the intratier and even intertier BS deployments in the actual network, which are the typical characters of field network planning and optimization. The PPP model is conservative because it deploys the BSs arbitrarily close to each other, which limits its suitability for the actual network. Recently, another model, Ginibre point process (GPP) has been proposed for depicting the multitier ultra-dense HetNet deployment topology with supporting the repulsion for deploying the BSs [20], which will be a promising tool for network topology modeling. Although the research about the GPP model is just beginning, the key challenges for RAN evolution in terms of its network topology and modeling are believed to have more breakthroughs based on deeper research about the FNA topology and Stochastic Geometry approaches. Further theoretical support will also be expected to be achieved for the centralized processing but distributed deployment architecture of 5G user-centric networks.

## 1.3 Energy-Efficient Control Plane and User Plane Adaptation

As described in Section 1.1, CP/UP separation and adaption is one of the most significant features of FNA. In this section, we will give the CP/UP adaptation scheme for improving the system EE performance in the downlink scenario of the FNA networks. A three-step EE optimization process is designed as follows.

### *1.3.1 CP Construction and Adaptation with Voronoi Diagram*

As depicted in Section 1.1, there is a master–slave relationship between the controlling AE and the data AE. To quantify the relationship, we focus on a simplified scenario that includes a single Controlling-AE and multiple related Data-AEs. For notational simplicity, the controlling AE is denoted as $AE_0$ while the data AEs are denoted as AE$i$ ($i=1, \ldots, N$). We denote $P_i$ as the maximum transmission power of the $i$th AE, $p_c$, $p_0$ as the allocated transmission power for the CP and UP of the controlling AE, which satisfy the constraints that $p_c \leq P_0$, $p_0 \leq P_0$. For the Data-AE, the constraints should be $p_i \leq P_i$ ($i=1, \ldots, N$), where $p_i$ denotes the allocated transmission power of the $i$th data AE for the UP. Since the CP transmits the necessary signaling for the UP, additional coverage constraints should be made for the UP. That is, the whole coverage of all the UPs constructed by the data AEs should not surpass the coverage of the CP. Then, this constraint can be transformed as the coverage radius of data AE:

$$d_i + r_i \leq r_0 \tag{1.1}$$

where:

- $d_i$ is the distance between the controlling AE and $i$th data AE
- $r_i$ is the coverage radius of the $i$th data AE
- $r_0$ is the coverage radius of the controlling AE

The coverage radius of the $i$th data AE $r_i$ is actually determined by its transmission power $p_i$, while the coverage radius of the controlling AE $r_0$ is determined by its CP transmission power $p_c$. Then, Equation 1.1 can be further transformed into a power constraint of the $i$th data AE:

$$p_i \leq p_c - P(d_i), i \in \{1, \ldots, N\} \tag{1.2}$$

where $P(d_i)$ is the power attenuation from the $i$th data AE to the controlling AE. The power constraint just given still guarantees that the coverage of the UPs doesn't surpass the CP coverage, which will be used in the UP construction step of Section 1.3.2.

In order to formulate the constraints mentioned in the preceding paragraphs, a basic signal propagation model capturing pathloss as well as shadowing is defined as [21]

$$P_{rx} = K\left(\frac{r}{r_0}\right)^{-\alpha} \cdot \varphi \cdot P_{tx} \tag{1.3}$$

where:

- $P_{rx}$ is the receiving power
- $P_{tx}$ is the transmission power
- $r$ is the propagation distance
- $\alpha$ is the pathloss exponent

The random variable $\varphi$ is used to model slow-fading effects and commonly follows a log-normal distribution. $K$ is set to the free-space path gain at distance $r_0$ with the assumption of omnidirectional antennas. Here, the coverage is defined as the maximum coverage range, which satisfies the UE's minimum required received power $P_{\min}$. The effect of shadowing will be averaged out for the network planning of the CP's construction and adaptation. The coverage radius can be expressed as $r_i = r_0 \sqrt[\alpha]{KP_i / P_{\min}}$ .

In order to achieve EE optimization for CP/UP adaptation, the first step aims at constructing a seamless deployment of the CP with minimum transmission power. The Voronoi diagram, a geometric structure in computational geometry, divides the space into a number of regions consisting of all the points closer to a specific site than to any other. As energy consumption is proportional to distance, the Voronoi diagram also defines regions where less energy consumption is required. In order to achieve better EE in the CP's construction and adaptation, we construct a Voronoi coverage area for the Controlling-AEs. The Data-AEs located within the Voronoi coverage area are controlled by the corresponding Controlling-AE.

The CP construction can be well represented by Figure 1.2, in which a Voronoi tessellation is created by the deployment of Controlling-AEs. Assuming that $C$ represents the set of $n$ controlling AEs in 2D Euclidean space, $d_E(c_i, x)$ denotes the Euclidean distance between the $i$th controlling AE and a position $x$. Therefore, the Voronoi coverage of the $i$th controlling AE is defined as

$$Vor(c_i) = \left\{x \in R^2 \mid\mid \forall j \neq i, d_E\left(c_j, x\right)\right\} \tag{1.4}$$

In order to further adapt the transmission power of a controlling AE with an updated AE deployment or coverage area, the Voronoi coverage can be redefined based on the path loss between the controlling AE and point $x$. Let $\alpha(c_i, x)_t$ be the path loss between the $i$th controlling AE and the position $x$ at time slot $t$, the Voronoi coverage will be revised as

$$Vor(c_i)_t = \left\{x \in R^2 \mid\mid \forall j \neq i, \alpha\left(c_i, x\right)_t < \alpha\left(c_j, x\right)_t\right\} \tag{1.5}$$

Then, the whole CP can be formed in the expression as $U_{1 \leq i < n} Vor(c_i)$. This definition makes any position in the Voronoi coverage area closer to its Voronoi Controlling-AE than any others, which yields less power consumption. As a consequence, the required transmission power for the controlling AE is minimized. The simulation evaluation of the proposed CP construction and adaptation can be found in Section 1.3.4.

### *1.3.2 User-Centric UP Construction with Joint AE and Subchannel Allocation*

The initial deployment of the UP should be constructed right after the CP construction and each user should be allocated available system resources with the user's QoS requirement. Based

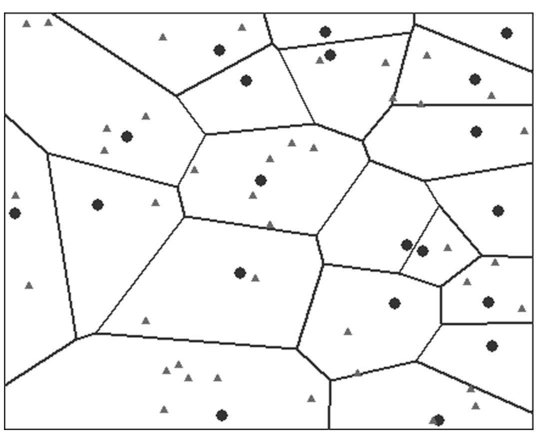

**Figure 1.2 Voronoi tessellation of the CP construction. (Spots represent the locations of the controlling AEs and triangles are data AEs.)**

on FNA, AE is released as a new dimensional radio resource for allocation and scheduling. By jointly allocating the AE and subchannel resources, the on-demand user-centric UP is constructed with the user's QoS requirements. The AE's transmission powers are allocated equally in this step. Moreover, the transmission power will be further adjusted based on Game theory in the third step.

### 1.3.2.1 Joint Resource Allocation Model for UP Construction

Considering a network with two types of Data-AEs, i.e., the Macro AE and Small cell AE, each AE has the same bandwidth and is divided into $M$ subchannels. We set $P_i$ as the maximum transmission power of the $i$th data AE. Meanwhile, $K$ users are randomly distributed in the coverage area of the FNA, including $K_1$ users with guaranteed bit rate (GBR) service and $K_2$ users with non-GBR service. The space division multiple access scenario is considered, in which each subchannel of an AE can only be allocated to one user.

In order to quantify the different QoS requirements of users, the utility theory in economics is introduced to describe the characteristics of service by mapping the data rate to the user satisfaction level [22]. According to the user service QoS constraints, the utility functions of the GBR and non-GBR service are verified as the $S$-shaped function and convex function correspondingly [22,23]. Based on the conclusions in [24], the utility function that satisfies both types of services is obtained as Equation 1.6.

$$U(r) = \frac{E}{A + Be^{-C(r-d)}} + D \tag{1.6}$$

where:

| | |
|---|---|
| $r$ | is the data rate allocated to the user |
| $R$ | is the total resource of the system |
| $C$ | mainly influences the slope of the curve |
| $A, B, D, E$ | mainly effect the range of the utility value |
| $d$ | is the inflection point of the utility function, which indicates the user requirement of the resource |

By setting different parameter values, the utility function can present different characteristics, both the $S$-shaped function and the convex function. The utility functions of the GBR service $U_{real}(r)$ and non-GBR service $U_{non\,real}(r)$ are obtained from Equation 1.6 [24].

The *system utility* is defined as the linear weighted sum of all users' utility values. In Equation 1.7, $\lambda$ represents the priority of GBR service and $\mu$ represent the priority of non-GBR service. These two weights are constrained by $\lambda,\mu \in [0,1]$ and $\lambda + \mu = 1$.

$$U_{System} = \lambda \sum_{k=1}^{K_1} U_{real}(r_k) + \mu \sum_{k=K_1+1}^{K_1+K_2} U_{non-real}(r_k) \tag{1.7}$$

The system utility can be further extended to include more types of service. Since the utility value represents the satisfaction level of the user, the system utility indeed represents all users' satisfaction levels, which can provide a better reflection of system performance than throughput.

### *1.3.2.2 Genetic Algorithm–Based Centralized Resource Allocation*

As described above, in the FNA, AE will be allocated as a new dimension of radio resource. Consequently, in the UP construction process, users with different QoS requirements are allocated with AEs and subchannels jointly. Such a multidimensional resource allocation problem can be solved by using the resource pooling–based centralized radio resources management (RRM) scheme [11]. This scheme is processed by the CPE to manage all of the available resources uniformly. Since the optimization problem of the centralized resource allocation has a large and complex search space, the genetic algorithm (GA) is implemented to obtain near-optimal solutions with a relatively fast convergence speed.

Based on the GA, a chromosome, which is a two-dimension-integer matrix, is used to represent the potential resource allocation solution. Each row of the matrix represents the resource allocation strategy for the specific user. Moreover, each row can be further divided into several parts. Each part lists the allocated elements of a particular dimension of resources. In particular, the chromosome $G$ in the following GA process is given by

$$G = \begin{cases} a_{1,1}, a_{1,2}, \cdots, a_{1,N_a}; b_{1,1}, b_{1,2}, \cdots, b_{1,N_s}; \\ \cdots\cdots \\ a_{K_1,1}, a_{K_1,2}, \cdots, a_{K_1,N_a}; b_{K_1,1}, b_{K_1,2}, \cdots, b_{K_1,N_s}; \\ a_{K_1+1,1}, a_{K_1+1,2}, \cdots, a_{K_1+1,N_a}; b_{K_1+1,1}, b_{K_1+1,2}, \cdots, b_{K_1+1,N_s}; \\ \cdots\cdots \\ a_{K_1+K_2,1}, a_{K_1+K_2,2}, \cdots, a_{K_1+K_2,N_a}; b_{K_1+K_2,1}, b_{K_1+K_2,2}, \cdots, b_{K_1+K_2,N_s}; \end{cases} \tag{1.8}$$

where the first $K_1$ rows represent the resource allocation strategies of the $K_1$ users with GBR service, and the remaining $K_2$ rows represent the resource allocation strategies of the users with the non-GBR services. Each row is further divided into two parts. The first part containing $N_a$ integers indicates the allocated AEs, while the second part containing $N_s$ integers lists the allocated subchannels. The initial population, which includes $N_p$ chromosomes, is generated by a random process.

In order to evaluate the chromosomes, fitness function needs to be constructed by the system utility function mentioned above. The larger the fitness value, the better the solution. Thus, the optimized objective is to maximize the fitness value, that is, to maximize the system utility. Since the utility value represents the satisfaction level of the user, the proposed algorithm tends to meet the requirements of two types of services simultaneously under the three constraints in the user-centric UP construction process. Specifically, we assume that at most $N_a$ out of $N$ AEs and $N_s$ out of $M$ subchannels can be allocated to the user $k$. In addition to AE and subchannel limitations, we also apply the constraint derived from Equation 1.2 in the power limitation, where we choose the minimum value between the two power constraints $P_i$ (maximum transmission power limitation) and $p_c - P(d_i)$. By