大规模天线阵列波束赋形
的实现与演示

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摘 要

随着信息时代的发展，无线移动通信的应用需求现已从过去的人人通信，转变为人与物及物与物通信。在未来的移动通信系统中，物联网的勃发毫无疑问会使移动设备的吞吐量需求急剧增加。为了解决当前通信系统的需求，有限信道资源的重复充分利用将是当前通信的主要研究方向。

多天线技术（MIMO，multiple input multiple output）正是充分利用了空间信道资源思想解决系统需求。MIMO 是指无线链路的发射端和接收端（或者少一端）使用了多个天线的无线传输技术。使用了多天线后，无线信道可以被分解为若干个相互没有干扰的并行数据通道，从而可以在空间上实现信道利用效率的倍增。随着多天线的进一步发展以及基带处理能力与射频、天线技术的进步，大规模天线（Massive MIMO）技术成为满足更高用户数与业务量需求的主要途径。

大规模阵列天线可分为分布式和集中式两种部署形式。分布式天线即通过回传网络将接入点汇集至计算中心进行处理，利用天线间的协作实现高速传输与能量提升。集中式天线阵列则利用阵列天线间距小，相关性强的特点提升阵列天线的方向性，以实现更加灵活的空分多址，从而抑制用户之间的干扰，实现更高的频谱利用率。

在集中式阵列天线高方向性的基础之上，波束赋形技术是 Massive MIMO 的主要实现形式。在获取信道信息后，通讯系统利用该技术通过馈电等手段使波束聚集于用户位置，从而减少路径损耗，提升了能量效率。实际工程中波束赋形的设计需要结合精度和成本。在综合两者的考虑后，码本可作为波束赋形的重要参考。

本文将依据阵列天线的基础理论对阵列天线和波束赋形技术进行了分析，在此基础上讨论了码本的有效性及有限性，并根据设计原则生成一套新的码本进行仿真分析。此外，本文还基于上述内容做了一个用户交互界面进行理论上的演示，对研究阵列天线和波束赋形具有一定的参考意义。

关键词：大规模天线；波束赋形；阵列天线演示；天线增益；方向图

Abstract

With the development of the communication, the application requirements of wireless mobile communication have now changed from the past of everyone-to-person communication to human-to-thing communication and thing-to-thing communication. In the future mobile communication system, the explosion of the Internet of Things will undoubtedly increase the throughput requirements of mobile devices dramatically. In order to solve the needs of current communication systems, the full use of limited channel resources will be the main research direction of current communication.

MIMO (multiple input multiple output) makes full use of the idea of spatial channel resources to solve system requirements. MIMO refers to the wireless transmission technology that uses multiple antennas at the transmitter and receiver (or at least one end) of a wireless link. After using multiple antennas, the wireless channel can be decomposed into several parallel data channels that do not interfere with each other, so that the channel utilization efficiency can be doubled in space. With the further development of multiple antennas and the advancement of baseband processing capabilities and radio frequency and antenna technology, Massive MIMO technology has become the main way to meet the needs of higher user numbers and traffic

Large-scale array antennas can be divided into distributed and centralized deployment forms. Distributed antennas collect access points to the computing center for processing through the backhaul network and use collaboration between antennas to achieve high-speed transmission and energy improvement. The centralized antenna array uses the characteristics of small array antenna spacing and strong correlation to improve the directionality of the array antenna to achieve more flexible space division multiple access, thereby suppressing interference between users and achieving higher spectrum utilization.

Based on the high directivity of the centralized array antenna, beamforming is the main implementation form of Massive MIMO. After acquiring the channel information, the communication system uses this technology to focus the beam on the user's position through feeding and other means, thereby reducing path loss and improving energy efficiency. The design of beamforming in actual engineering needs to combine accuracy and cost. After considering the two, the codebook can be used as an important reference for beamforming.

This article will analyze the array antenna and beamforming technology based on the basic theory of array antennas. On this basis, the effectiveness and limitations of the codebook are discussed, and a new set of codebooks are generated according to the design principles for simulation analysis. In addition, based on the above content, this article also made a user interaction interface for theoretical demonstration, which has a certain reference significance for the study of array antennas and beamforming.

Keywords: massive mimo, beamforming, array-antenna demonstration, pattern

目　录

第 1 章 绪　论

1.1 课题背景及研究的目的和意义

随着信息时代的发展，无线移动通信的需求已从用户与用户间的通话和短讯，拓展到人与传感器，传感器与传感器的数据通信。面对各种新兴业务形态以及终端连接数和数据流量规模的爆炸式增长，未来移动通信系统对于无线传输链路的传输性能有着近乎无止境的需求。

对于移动系统，信道资源通常包括时间，频段，码字等。根据特定的多址方法，系统可以为不同的用户分配不同的时隙，频段和扩频码，以实现无线传输过程中用户信息的区分。实际上，只要可以合理地控制信号的辐射方向（空间）和功率，就可以在一定距离后重新使用信道资源。

多天线技术（MIMO, Multiple Input Multiple Output）技术正是充分利用空间信道资源的思想发挥到了极致。MIMO 是指无线链路的发射端和接收端（或者至少一端）使用了多个天线的无线传输技术。根据 MIMO 信道容量理论，使用了多天线之后，无线信道可以被分解为若干个相互没有干扰的并行数据通道。理论上，各个并行的数据通道都可以重复使用相同的时，频，码资源，从而可以在空间上实现信道资源利用效率的倍增。随着多天线技术理论的进一步发展以及物理材料技术的进步，多天线技术逐步向提升系统容量，支持更多并行信息流的方向发展。在 5G 的建设中，多达上百根天线的大规模天线技术（Massive MIMO）成为了主要研究途径。

大规模天线可以分为分布式和集中式两种天线部署形式，对于分布式大规模天线阵列，天线间距远大于 10 倍的波长，在热点地区或者室内部署的环境下，通过将多个天线分布在不同的地理位置，形成不同接入点，大量的接入点可以通过光纤或其他的回传网络汇集至基带处理节点或计算中心进行处理。利用分布式大规模天线阵列，天线间通过协作，以虚拟大规模天线系统的形式进行发送与接收，实现系统高速传输与容量提升。对于集中式大规模天线阵列，天线间采用小间距部署方式（小间距一般指天线间距为 1/2 波长的情况）。利用天线间隙小的，天线之间的相关性强的集中式大规模 MIMO 天线阵列的特性，可以形成具有高增益和高空间分辨率的窄波束，实现更灵活的空分多址以改善接收信号质量，并大幅降低用户间的干扰,从而实现更高的系统容量和频谱利用效率[1]。

波束赋形技术是 massive MIMO 的重要实现形式。通过部署 Massive MIMO 波束赋形技术所获得的空分复用增益可以使系统的容量获得大量的提升。同时波束赋形技术使能量的定向聚集于局部，减少了路径的损耗，提升了能量效率[2]。

波束赋形的目的是根据系统性能指标来形成基带（中频）信号的最佳组合或分布。它的主要目的是在减少同频用户之间的干扰的同时，补偿由于无线电传播期间空间损耗和多径效应等因素引起的信号衰落和失真。因此，有必要建立一个描述系统信号的系统模型，并根据系统的性能要求将信号的组合或分布表达为数学问题，找到最优解[4]。

由于采用了波束赋形的信号发送方式，集中式大规模天线又被称作大规模天线波束赋形技术（简称大规模天线）。同时，由于基于集中式小间距大规模天线阵列进行波束赋形的技术方案对于提升系统频带利用效率，改善覆盖，抑制干扰具有重要作用，集中式大规模天线式目前大规模天线系统设计和标准化最为关注的技术方向。

大规模天线波束赋形技术对于不同的应用频段都具有重要的作用。在 6GHz 以下频段，大规模天线波束赋形技术可以通过高增益窄细波以更高的空间分辨能力实现各用户的空域区分并有效地抑制干扰。而在 6GHz 以上频段，从设备成本，功耗及复杂度地角度考虑，一般会采用数模混合地两级波束赋形结构，即首先通过数字控制地模拟移相器在模拟域实现对信号空域特征地粗略匹配以客服路径损耗，进而在较低维度的数字域利用用户级和频率选择性的数字波束赋形技术精准匹配信道特性，最终实现提升传输质量及有效抑制干扰。在这种情况之下，波束赋形技术对于弥补非理想传播环境以保证系统覆盖的作用将更加关键。

1.2 MassiveMIMO 和波束赋形及其相关理论的发展概况

大规模天线阵列和波束赋形是当今 5G 移动通信中的关键技术，可以有效提高频谱效率和能效并减少小区间干扰。国内外进行的研究发现[11]，大型天线阵列将天线的数量增加了一个数量级以上，并且可以更有效地执行空间分集和复用。随着基站天线数量的增加，天线之间的相关性变小，有利于形成相互干扰很小的多个窄波束。因此，大型天线阵列在相同的时频资源上同时为大量终端服务，可以有效降低辐射功率，有效减少小区之间的干扰，提高系统容量，系统传输速度和频谱效率。从能源效率的角度来看，基站采用大型天线阵列来辐射窄波束，这有利于将波束指定打向特定用户，从而可以在基站中获得更高的信噪比，可节省接收端天线的功率。

除此之外，研究人员还在传统的波束赋形的算法基础上提出了 3D 波束赋形的算法模型。也就是说，垂直维度波束赋形技术被引入到传统的水平维度 Massive-

MIMO 中，可以有效地增加基站服务的用户数量并降低部署成本[13][14]。 3D 波束赋形技术可以在信道的垂直维度上充分利用信道信息，实现垂直面的小区分裂和波束切换，进一步提高整体传输效率和性能无线通信系统。

1.2.1 大规模天线阵列的技术研究的发展与研究现状

阵列天线是 Massive MIMO 的理论基础，它能够形成不同于一般单元天线的辐射特性，尤其是可以形成指向某部分空间的，比单元天线强得多的辐射，最根本的原因就是来自多个相干辐射单元的辐射电磁波在空间相互干涉并叠加，在某些空间区域加强，而在另一些空间区域减弱，从而使得不变的总辐射能量在空间重新分布[8]。

早在 2010 年，Massive MIMO（大规模天线）这一新技术在 2010 年被 Marzetta 等人提出后受到学术界的广泛关注。到了 2014 年，Andrews 等提出了 5G 三大关键技术：超密集组网技术，毫米波技术和 Massive MIMO 技术[17]。可以看出，Massive MIMO 技术是 5G 最重要的物理层技术之一。

通过利用适当的预编码（precoding）技术，例如迫零预编码，最大比合并预编码等算法[18]，利用多用户 MIMO 传输方式，可在不额外占用频谱资源的情况下同时向多个终端发送信号，成倍地提升频谱效率[19]。

1.2.2 波束赋形技术的发展趋势与研究现状

2010 年，贝尔实验室的 Marzetta 教授提出，可以在基站中使用大规模天线系统（Massive MIMO），以提高系统的容量。大规模 MIMO 是指使用大规模天线阵列的 MIMO 技术，其设计思想类似于扩频通信。在扩频通信技术中，发射机使用伪随机序列来使信号白化。随着基站天线数量的增加，每个用户的信道系数矢量逐渐趋于正交，高斯噪声和不相关的小区，干扰趋于可忽略，因此在系统中容纳的用户数量可急剧增加，分配给每个用户的功率可以任意减小。研究结果表明，如果基站配备 400 根天线，并且在相同频率上使用具有 20MHz 带宽的 TDD 系统，即使没有 MU-MIMO 模式，每个小区也可以为 42 个用户服务小区之间的协作，就算用 MRC/MRT（Maximum Ratio Combining/Maximum Ratio Transmission），每个小区的平均容量也可以高达 1800Mbit/s。从波束赋形的角度来看，随着天线阵列的尺寸增大，在基站侧形成的波束越来越窄，并且将具有极高的方向选择性和波束赋形增益。

Massive MIMO 出现后，立即成为学术界和工业界的热点。从 2010 年到 2013 年，贝尔实验室，瑞典隆德大学，美国莱斯大学和其他领先的学术界对基本的理论和技术问题进行了广泛的探索，例如庞大的 MIMO 信道容量， CSI 的传输，检测和获取。在理论研究的基础上，学术界还积极开展了验证 Massive MIMO 技术的主

要工作。隆德大学（Lund University）于 2011 年根据来自大型天线信道的测量数据发布了分析结果。实验系统的基站使用 128 个天线的二维阵列，包括 4 行 16 条微带天线双极化圆。单个天线实际信道测量结果显示，当天线总数超过用户数量的 10 倍时，即使使用线性 ZF 或 MMSE 预编码，也可以达到最佳 DPC（脏纸编码）容量的 98%）。该结果证实了当天线数量达到一定数量时，多用户信道是正交的，这可以保证在使用线性预编码时仍能达到最佳 DPC 容量，从而验证了实现大规模 MIMO 的可行性。 2012 年，莱斯大学，贝尔实验室和耶鲁大学联合建立了基于 64 套天线的远程验证平台（Argos），该平台可支持 15 个用于 MU-MIMO 的单天线终端。根据接收信号，波束赋形后的多用户干扰和噪声的实测数据，系统的容量可以达到 SISO 系统频谱效率的 6.7 倍，且总功率仅仅用了 1/64。

由于无线移动通信环境极其复杂，因此难以准确描述其输入输出关系。工程上，通常经过大量测量和理论研究构建出具有有限参数的信道模型进行分析。采用该方法后，可以获得噪声信号与原始信号的关系，从而可以在一定程度上恢复信号。

综上所述, 大规模 MIMO 波束赋形技术的研究是无线信号处理领域的关键研究点，也是 5G 应用的关键技术，近几年有大量显著的研究成果,具有较为广阔的研究前景和较高的研究价值。

1.3 本文的主要研究内容和文章结构安排

为了研究大规模 MIMO 系统的波束赋形的实现方式，本文首先将讨论阵列天线的主要天线参数，如天线元个数，天线元的空间分布，馈电相位等对于天线的辐射特性，其中包括方向图，天线的方向性，增益等的影响。这些是阵列天线的最核心的综合问题，也是 MIMO 工程中必须解决的基础问题。在此基础之上，引入波束赋形技术，通过部署相控天线阵实现波束赋形，所获得的空间复用增益使系统的容量获得大量的提升。

上述是阵列天线和波束赋形的基础理论研究，而实际上，由于信道的变化莫测，且考虑到硬件成本问题，天线的波束无法总是精准地打向每个用户终端。现有的波束赋形往往和码本搭配使用。因此本文的同样将对码本的选择方式和应用方式进行分析。

本课题除了对阵列天线和波束赋形进行研究分析，还有上述技术实现的演示。因此本课题的最后一步基于信号分析软件 MATLAB 做了一款 GUI(用户交互界面）进行天线分析，波束赋形和码本的演示。

本文具体的内容和论文的结构安排如下：

第一章为绪论，对本课题的研究背景和目的意义进行阐述，并介绍 Massive MIMO 和波束赋形的发展背景和研究现状，最后对本文结构和章节内容安排进行说明。

第二章主要介绍了大规模阵列天线系统的基础理论知识，对天线阵列结构分为均匀线阵和面阵结构进行分析。其中面阵根据不同的组成方式分为平面矩形阵列，平面均匀圆阵列和三角阵列等，不同的阵列对应不同的辐射叠加方式。其次介绍了波束赋形的基础理论，为后续的阵列分析和码本设计的进一步研究奠定了理论基础。

第三章根据前面的理论内容，对阵列天线的方向图，天线增益，副瓣电平，方向性系数进行推导并仿真绘图，分析改变阵列天线可变参数对于上述因变量的影响。

第四章详细地介绍了基于码本和非码本相控天线阵波束赋形技术。首先介绍了天线定向波束的形成方式，阐述如何通过相控阵列天线打向指定位置。其次说明了码本存在的必要性以及码本的形成方式，同时引入著名的 butler matrix 作为码本进行分析。最后根据码本进行波束赋形的仿真，讨论码本波束赋形的有效性和有限性。

第五章为前文内容的演示介绍，在前文理论的基础上做了一个用户图形交互界面（GUI）。主要对 GUI 模型的框架进行了说明，随后分别对 GUI 的四个模块进行演示介绍，最后对演示的输出结果对比分析，证明前文理论的正确性。

第 2 章 Massive MIMO 和波束赋形的基本理论

2.1 引言

Massive MIMO，即大规模多输入多输出技术，是 5G 时代最核心的技术之一。它通过在单个基站安置更多数量级的天线，从而提高天线系统的增益，提升吞吐量，提高天线效率，降低辐射损耗等，进而提升通讯系统的稳定性和可靠性。传统的单天线，例如各种线形天线，表面天线，反射性表面天线等。它们可能具有良好的性能，但是一旦选择了天线硬件，就无法更改，并且其所有辐射特性几乎都固定。只能沿特定方向辐射或机械扫描。且高性能的天线的成本较高，大大浪费了天线的辐射性能，若对于一些非特定的特殊应用场合，如要求方向性较高且具有扫描功能的雷达天线，单个电线性能完全无法满足。

在第五代移动通信系统中，为了追求更强的通信性能，工程师们开发了更高的频段提高通信带宽。5G 通信系统的数据传输速率可达到 Gbps 量级，但同时高频段信号意味着波长较小，信号的传播损耗严重。而阵列天线可通过提升天线增益对信号的损失进行补偿，且可通过馈电的手段，改变天线的相位，从而控制方向图，实现相控扫描。同时在理论上天线的尺寸和阵列天线的间距同信号波长大小呈正相关，往往为 0.5 倍波长，因此高频信号也大大降低了阵列天线的空间成本，证明了阵列应用的必要性。

与此同时，波束赋形技术随着阵列天线应运而生，波束赋形的本质是调整每个天线收发器单元的幅度和相位，以使特定方向上的信号相干重叠，而其他方向的信号互相抵消。本章将从基本理论出发，介绍不同天线组的结构和特性，并介绍波束赋形原理。

2.2 天线阵列结构

若干天线（辐射器）以某种方式排列和馈电。排列成阵列的多个天线可以视为一个单独的天线，并且根据不同的馈电方法，它具有自己独特的辐射特性。阵列天线一般按照各个天线元的排练方式分类，多个天线元若按照一条直线排列称其为线阵，如果每个天线元的中心排列在一个平面上，则称为平面矩阵。平面矩阵还可分为矩形和圆形矩阵等。其中矩形阵的天线元按照矩形栅格排列，而圆阵的天线元则是位于同心圆环或者椭圆环上。本文将分别按照线阵和面阵对阵列天线的辐射特性进行推导分析。

2.2.1 线天线阵列

来自天线在空间的辐射是由天线中的电流源产生的。如果空间中有多个满足相干关系的电流，来自多个电流的辐射电磁场形成干涉现象，则导致某些空间区域的场相位重叠并使得场增强；在某些空间区域中场反向重叠并使得场变弱。而在其他区域，场交叠在同相和反相之间，这形成了空间电磁场的强弱。类似地，如果电流以其他方式分布，则相应的辐射场分布量将相应改变。

如下图 2-1 所示，天线放置在每个小段 dl 的中心。这些单元天线都是相似的元素，因此视为 N 个连续相似的天线元，其方向图函数为 $F_e(\theta,\varphi)$。每一个单元的位置标记为 Z_{n} ，远场坐标可写作 (r,θ,φ)。在不失一般性的情况下，将每个当前段的复矢量设置为 I，可以将其视为放置在此小段中心的元素天线的激励电流。每个单元天线将在较远的区域中产生电磁波，并且场强与激励电流成正比。那么，第 n 个单元在远场观察点 $P(\theta,\varphi)$ 产生的电场为：

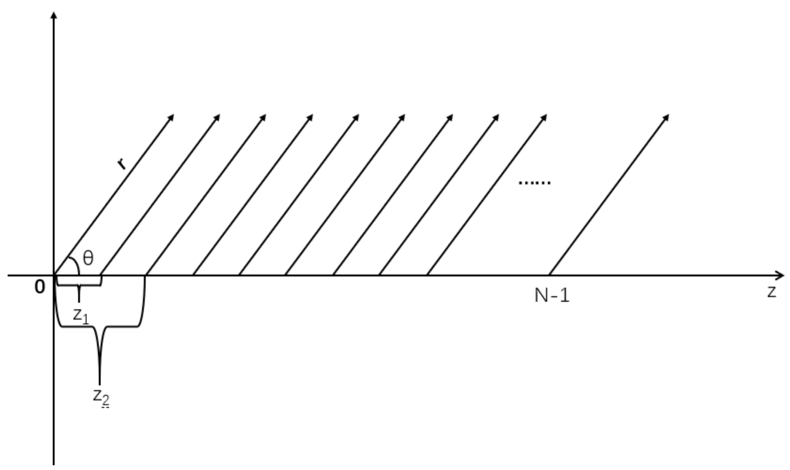


图 2-1 线天线阵列模型

$$\dot{E}_n = A\dot{I}_n \frac{e^{-jkR_n}}{4\pi R_n} F_{\mathrm{e}}(\theta,\varphi) \tag{2-1}$$

上式中，A 为比例系数，与单元形式有关。现代入远场条件：

$$\frac{1}{R_{\mathrm{n}}} \approx \frac{1}{r_{\mathrm{n}}} \tag{2-2}$$

$$R_n = r - z_n \cos\theta \tag{2-3}$$

可得到：

$$\dot{E}_n = A\frac{e^{-jkr}}{4\pi r}F_e(\theta,\varphi)\dot{I}_n e^{jkz_n\cos\theta} \tag{2-4}$$

式中，因子 $e^{jkz_n\cos\theta}$ 表示由于每个单元的空间位置不同而导致的电磁波在观察角 (θ,φ) 处的相对相位。根据叠加原理，此线矩阵在观察点处生成的场等于在观测点各个单元生成的场的矢量和:

$$\dot{E}_n = \sum_{n=0}^{N-1}\dot{E}_n = A\frac{e^{-jkr}}{4\pi r}F_e(\theta,\varphi)\sum_{n=0}^{N-1}\dot{I}_n e^{jkz_n\cos\theta} \tag{2-5}$$

故可以得到天线阵的方向图因子为：

$$F(\theta,\varphi) = F_e(\theta,\varphi)\sum_{n=0}^{N-1}\dot{I}_n e^{jkz_n\cos\theta} \tag{2-6}$$

由方向图乘积定理：

$$F(\theta,\varphi) = F_e(\theta,\varphi)S(\theta,\varphi) \tag{2-7}$$

可知上述线阵的阵因子为：

$$S(\theta,\varphi) = \sum_{n=0}^{N-1}\dot{I}_n e^{jkz_n\cos\theta} \tag{2-8}$$

因为单位因子 $F_e(\theta,\varphi)$ 仅代表构成矩阵天线的每个单元的辐射特性，它仅取决于单元的形状和方向，与矩阵的值无关，因此单位因子是位于坐标原点的单位天线的归一化方向图函数。矩阵因数仅取决于天线矩阵的形状，元件的间距，元件的激励电流的幅度和相位，而与天线元的形状和方向无关。故天线阵因子等于各向同性点源矩阵的辐射函数，单位因子和矩阵因子彼此独立。

由上式 2-5 可以看作是复平面上 N 个相量的叠加。此时阵因子的最大值发生在 $\cos\theta = 0$，即 $\theta = \frac{\pi}{2}$，此时所有的相位都位于实轴上。

设 L 为线阵的长度，则 $L=Nd$，故有：

$$kd\cos\theta = \frac{2\pi}{\lambda}\frac{L}{N}\cos\theta = \frac{2\pi}{N}\frac{L}{\lambda}\cos\theta \tag{2-9}$$

当 $kd\cos\theta = \frac{2\pi}{N}\frac{L}{\lambda}\cos\theta = \pm\frac{2\pi}{N}$ 时，各个向量是等角等间隔分布的，正好完全占据了 2π 的角域，其叠加和为 0，则此时的角度为：

$$\cos\theta_{NP} = \pm\frac{\lambda}{L} \tag{2-10}$$

可求得：

$$\theta_{NP} = \arccos(\pm\frac{\lambda}{L}) \tag{2-11}$$

当 $L<<\lambda$ 时，则从远处看各个向量非常接近，不可能出现零值。

当 $L=\lambda$ 时，此时 $\theta_{NP}=0$ 或 $\theta_{NP}=\pi$

当 $L>>\lambda$ 时，有 $\theta_{NP}=\frac{\pi}{2}\pm\frac{2\lambda}{L}$

通过上述分析可知，当角度 θ 变化偏离到 $\frac{\pi}{2}$ 以上时，则这些相量在复平面的分布要超出 2π，超出 2π 的部分即相当于多绕了一部分，此时相量除了相互抵消之外，还有一部分相互叠加了起来，此时，继续令角度 θ 偏离，当达到：$\theta_{NP2}=\arccos(\pm\frac{2\lambda}{L})\approx\frac{\pi}{2}\pm\frac{2\lambda}{L}$ 时，其向量叠加又会出现一个零点。同理，这一规律还会随着角度 θ 偏离下去，并交替出现最大值，据此可画出线阵的方向图。

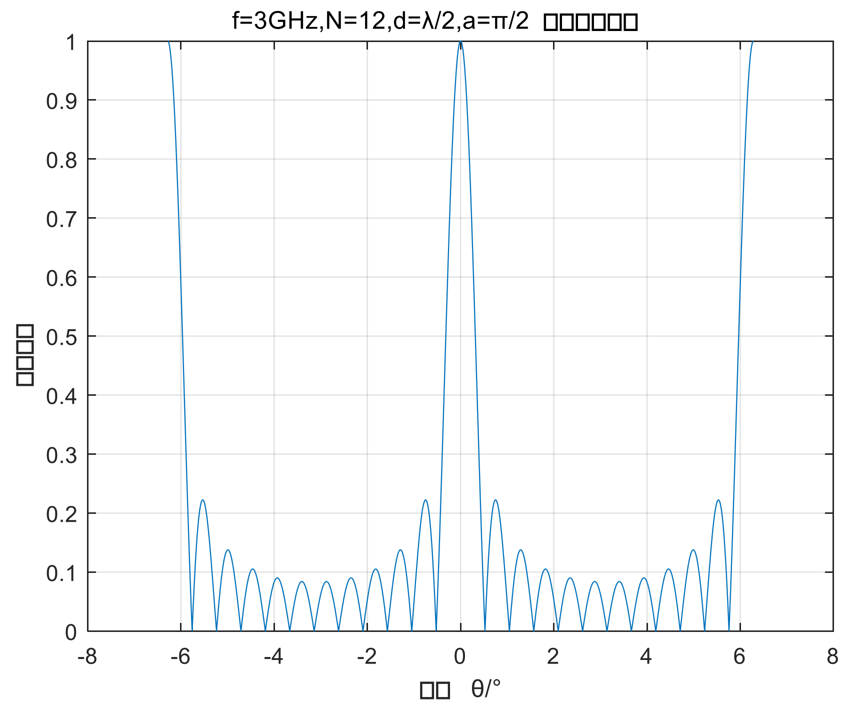


图 2-2 线天线阵因子方向图

从阵因子式可以看出，影响线阵的参数有频率（波长），线阵元个数，阵元间隔和馈电相位差等。

2.2.2 矩形平面天线阵列

面阵的研究方式和线阵相似，可以把面阵看作为线阵的扩展，仅需根据面阵的结构与坐标系统进行适应性调整即可。但是面阵有时不仅仅具有线阵简单扩展的特点，需要更为特殊的综合分析方法。

以图 2-3 为例，平面阵在沿 x 轴方向由 N_x 行，行间距为 dx，在沿 y 轴方向由 Ny 列，列间距均为 dy，全阵的阵元共有 $N=N_x\times N_y$ 个单元，每个阵元记为(m,n)，设单元(m,n)的激励电流为 $\dot{I}_{mn}$，根据电磁波的叠加原理，可以直接写出上述平面阵的阵因子为：

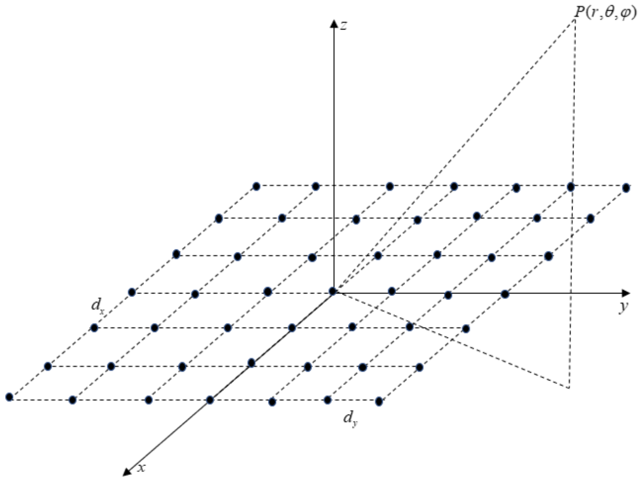


图 2-3 矩形均匀平面阵

$$S(\theta,\varphi)=\sum_{m=-M_x}^{M_x}\sum_{n=-M_x}^{M_y}(\frac{\dot{I}_{mn}}{\dot{I}_{00}})\exp[jk\sin\theta(md_x\cos\varphi+nd_y\sin\varphi)] \qquad (2\text{-}12)$$

归一化，令 $\dot{I}'_{mn}=\dfrac{\dot{I}_{mn}}{\dot{I}_{00}}$

上式可化简为：

$$S(\theta,\varphi)=\sum_{m=-M_x}^{M_x}\sum_{n=-M_x}^{M_y}\dot{I}'_{mn}\exp[jk\sin\theta(md_x\cos\varphi+nd_y\sin\varphi)] \qquad (2\text{-}13)$$

设 $\dot{I}'_{mn}$ 与中心单元电流 $\dot{I}'_{00}$ 的相位差为 a_{mn},则 $\dot{I}'_{mn}$ 可以表示为

$$\dot{I}'_{mn}=\dot{I}_{mn}\exp(ja_{mn}) \tag{2-14}$$

代入上式，则此时的阵因子可以写为：

$$S(\theta,\varphi)=\sum_{m=-M_x}^{M_x}\sum_{n=-M_x}^{M_y}\dot{I}'_{mn}\exp[jk\sin\theta(md_x\cos\varphi+nd_y\sin\varphi)+ja_{mn}] \tag{2-15}$$

由此式的变量可知，矩形平面天线阵的辐射特性与天线的空间排列方式，单位间隔大小，馈电相位相关。

因为平面上的天线元都视作相同的，即每行的各个单元电流与本行中心单元的电流之比都相等，即：

$$\frac{\dot{I}_{mn}}{\dot{I}_{m0}}=\frac{\dot{I}_{0n}}{\dot{I}_{00}} \tag{2-16}$$

则在远场观察点 $P(r,\theta,\varphi)$ 的阵因子可以表示为：

$$S(\theta,\varphi)=S_x(\theta,\varphi)S_y(\theta,\varphi) \tag{2-17}$$

其中

$$S_x(\theta,\varphi)=\sum_{m=-M_x}^{M_x}\dot{I}_m\exp(jmkd_x\sin\theta\cos\varphi) \tag{2-18}$$

$$S_y(\theta,\varphi)=\sum_{m=-M_y}^{M_x}\dot{I}_n\exp(jnkd_y\sin\theta\sin\varphi) \tag{2-19}$$

$\dot{I}_m$ 和 $\dot{I}_n$ 分别为 x 轴平行的列和与 y 轴平行的行中各单元的归一化电流分布，可表示为：

$$\dot{I}_m=\frac{\dot{I}_{m0}}{\dot{I}_{00}} \tag{2-20}$$

$$\dot{I}_n=\frac{\dot{I}_{0n}}{\dot{I}_{00}} \tag{2-21}$$

此时位于面阵第 m 行，第 n 列的单元电流为

$$\dot{I}_{mn}=\dot{I}_m\dot{I}_n \tag{2-22}$$

根据极坐标与直角坐标的转换关系

可以很容易地看出式 2-18 和式 2-19 分别为沿 x 轴和沿 y 轴排列线阵的阵因子，$\dot{I}_m$ 和 $\dot{I}_n$ 分别为这两个线阵的激励电流。故式 2-17 可再次证明方向图乘积定理，即矩形列阵的阵因子是沿 x 轴和 y 轴排列的两个线阵阵因子的乘积。

设 $\dot{I}_m$ 和 $\dot{I}_n$ 分别表示沿 x 轴和 y 轴排列的两个线阵的单元电流幅度，a_x 和 a_{y} 分别表示递变的相位，此时有

$$\dot{I}_{mn} = \dot{I}_m \dot{I}_n = I_m I_n \exp[j(ma_x + na_y)] = I_{mn} \exp[j(ma_x + na_y)] \tag{2-23}$$

此时可以看出单元激励电流 $\dot{I}_m$ 和 $\dot{I}_n$ 的相位差为

$$a_{mn} = (ma_x + na_y) \tag{2-24}$$

当均匀递变的相位不为 0 时，式 7 可写为：

$$S(\theta,\varphi) = S_x(\theta,\varphi) S_y(\theta,\varphi) =$$

$$\{\sum_{m=-M_x}^{M_{\mathrm{x}}} \dot{I}_m \exp(jm[kd_x \sin\theta\cos\varphi + a_x)]\} \cdot \{\sum_{m=-M_y}^{M_y} \dot{I}_n \exp(jn[kd_y \sin\theta\sin\varphi + a_y)]\} \tag{2-25}$$

据此式可对均匀矩形平面阵列的辐射特性进行仿真分析。

2.2.3 圆环天线阵列

均匀平面圆阵列是一种二维模型的天线阵列，其分布方式如图 4-1，N 个有各向同性单元沿着半径为 a 的圆周排列而构成了圆环阵，设位于 $\beta=\beta_n$ 处的单元电流为：

$$\dot{I}_{\mathrm{n}} = I_n e^{ja_n} \tag{2-26}$$

式中，I_n 表示第 n 个单元激励电流的幅度，a_n 是这一单元以阵列中心为参考点的激励相位。现把各天线元对远场电场的辐射叠加起来，就可以得到圆环阵的远场方向图函数：

$$S(\theta,\varphi) = \sum_{n=1}^{N} I_n \exp[jka\sin\theta\cos(\varphi-\beta_n) + ja_n] \tag{2-27}$$

如果主波瓣最大值指向为 (θ_0,φ_0)，则第 n 个单元的激励相位应选为：

$$a_n = -ka\sin\theta_0\cos(\varphi_0-\beta_n) \tag{2-28}$$

令：

$$\rho = a[(\sin\theta\cos\varphi - \sin\theta_0\cos\varphi_0)^2 + (\sin\theta\sin\varphi - \sin\theta_0\sin\varphi_0)^2]^{1/2} \tag{2-29}$$

$$\xi = \arctan(\frac{\sin\theta\sin\varphi - \sin\theta_0\sin\varphi_0}{\sin\theta\cos\varphi - \sin\theta_0\cos\varphi_0}) \tag{2-30}$$

则有

$$\sin\xi = \frac{\sin\theta\cos\varphi - \sin\theta_0\sin\varphi_0}{[(\sin\theta\cos\varphi - \sin\theta_0\cos\varphi_0)^2 + (\sin\theta\sin\varphi - \sin\theta_0\sin\varphi_0)^2]^{1/2}} \tag{2-31}$$

$$\cos\xi = \frac{\sin\theta\cos\varphi - \sin\theta_0\cos\varphi_0}{[(\sin\theta\cos\varphi - \sin\theta_0\cos\varphi_0)^2 + (\sin\theta\sin\varphi - \sin\theta_0\sin\varphi_0)^2]^{1/2}} \tag{2-32}$$

故式 2-27 可以写为更简洁的下式：

$$S(\theta,\varphi) = \sum_{n=1}^{N} I_n \exp[jk\rho\cos(\beta_n - \xi)] \tag{2-33}$$

由上式可知，只要知道了同性单元半径，天线元个数，单位电流幅度，主波瓣方向，即可简单地计算出天线方向图。如果圆环阵中的各天线元为等幅激励，并沿着等距排列成角对称，即 $I_n = I$，$\beta_n = \frac{2\pi n}{N}$ ，则式 2-33 可以改写为以下更简单的形式：

$$S(\theta,\varphi) = NI\sum_{m=-\infty}^{\infty} \exp[jmN(\tfrac{\pi}{2} - \xi)]J_{mN}(k\rho) \tag{2-34}$$

2.3 波束赋形原理

波束赋形是天线阵列的信号预处理技术。通过调节天线阵列中每个元件的加权系数，使阵列天线产生具有可控方向性的波束，从而提升天线矩阵的增益。波束赋形技术在扩大覆盖范围，改善边缘性能和抑制干扰方面具有巨大优势。波束赋形提供的空间选择性使波束赋形与 SDMA（空间分多址）紧密相关。实际工程中，波束赋形常常应用于不同的目标，如专注于提升链路质量（提升吞吐量性能）或多用户问题（例如干扰消除）。

波束赋形实际上利用了波的干涉原理，例如，单个振动源在水中引起的波纹在各个方向的振幅是各相同性衰减的，但是如果增加一个振动源，则两列波之间将发生干涉现象，某些方向振幅增强，某些方向振幅减弱（振幅增强部分的能量来自于

振幅减弱部分）。利用光波，同样可以观测到由于波之间的干涉而在不同方向产生的明暗条纹。

考虑到两个具有相同极化方向并保持一定距离的天线元件，矩阵的这两个元件发射的波之间将发生干涉，即振幅将在某些方向上增大，在某些方向上减小。下图解释了上述现象的原因。假设观察点远离天线元件，则到达观察点的两个波的角度可以被认为是相同的。此时，两个波列的相位差$\mathrm{d}\cdot\sin\theta$将随观察角$\theta$的变化而变化。在某些角度下，两个波列的同相叠加将增加幅度，而在某些方向上，相反相位的叠加将导致幅度减小。

因此，如果可以根据信道条件来适当地控制每个矩阵元素的加权系数，则可以在提高期望信号的增益的同时尽可能地减小对不想要的方向的干扰。波束赋形的效果是，通过调整每个阵列元素的加权系数，波束赋形后的等效通道具有可控的空间选择性。对于 TDD 系统，可以轻松地使用信道互易性从上行链路信号估计信道或 DOA（到达方向），并使用它来计算波束赋形矢量。对于 FDD 系统，则可以根据上行信号的估计对下行进行波束赋形。

在实际的多径传播环境中，由于信号到达接收机时要经过多次散射，反射，每次反射和散射还会引起极化的偏转。从接收机的角度考虑，每个散射，反射体也都可以被视为等效的虚拟天线阵元，而最终到达接收机的信号是多条路径的叠加，在这种情况下，可能不存在明确的波束到达方向，但是如果发射机能够获得充分的信道状态信息，则仍然有可能通过对加权向量的选择实现增强期望信号并抑制干扰的作用。

在波束赋形的技术中，阵元间距将对经过赋形后等效信道的选择性带来明显的影响，在图 2-4 所示的模型中，假设观测位置发生了一个较小的角度偏移$\Delta\theta$，则相位差将变为$\Delta\varphi = d\cdot\sin(\theta+\Delta\theta)$。阵元间距越大，相位差随角度偏转的变化就越大。或者说对于大间距天线阵，一个很小的角度偏转也能引起很大的相位差的变化，从而信号的功率随角度变化比小间距天线阵更为剧烈。如果两个阵元间距不同的阵列采用相同的赋形算法分别对同一角度赋形，那么在目标角度上得到的增益是相同的。不同的是，小间距天线阵的波瓣相对较宽，对于角度偏转不如大间距天线敏感，因此对信道的变化具有更高的鲁棒性。

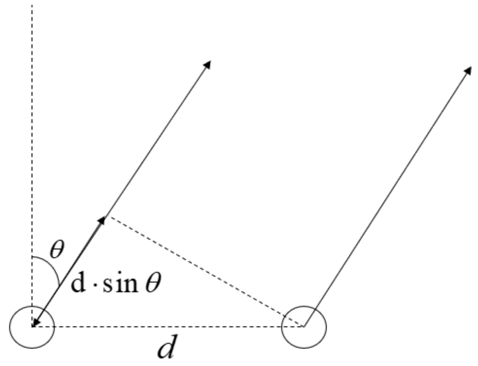


图 2-4 相邻天线的干涉模型

综上所述，波束赋形技术可以根据信道状态信息，选择传输质量最高的方向放松波束，并通过将能量集中到某个特定的方向提高提高接收信号的信噪比。

2.4 本章小结

本章主要对大规模天线阵列和波束赋形的基础理论进行了介绍。

首先进行基础天线结构的分析。分别对线天线阵，矩形面天线阵和圆环面天线阵的建立模型。然后从基础的天线电场分布进行天线的方向图的推导，探究影响阵列天线方向图的参数。为后文的天线参量的分析作好了理论基础。

其次在阵列天线的基础上引出波束赋形技术，并利用波的干涉性对波束赋形的原理进行介绍，指出其能够通过对加权向量的选择实现对期望信号的增强和干扰信号的抑制，从而实现直接提高接收信号的信噪比。最后说明了小间距天线的波束赋形由于波瓣较宽，对于角度的偏转的敏感性较小，对于信道变化具有鲁棒性。

本章的主要贡献是对阵列天线和波束赋形进行了简单的介绍和理论推导，为后文阵列天线参数的分析和演示奠定了理论基础。

第 3 章 阵列天线的辐射特性分析

3.1 引言

第二章对阵列天线的理论进行了介绍。通过天线的阵因子公式，本文能够看出天线阵列和天线的空间分布，天线元个数，馈电相位和信号频率相关。为了使对阵列天线的方向图更加直观，本章将对不同阵列天线进行仿真，直观地得到不同参数对天线辐射特性的影响。

3.2 线阵天线方向图分析（均匀）

通过第二章的理论，本文可知直线阵列天线的阵因子公式为：

$$S(\theta,\varphi)=\sum_{n=0}^{N-1}\dot{I}_n e^{jkz_n\cos\theta} \tag{3-1}$$

根据此式即可画出直线阵列的方向图，如图 3-1 所示，以天线元 N=8，仿真频率 300MHz，间距 0.5m（近半波长）为例：

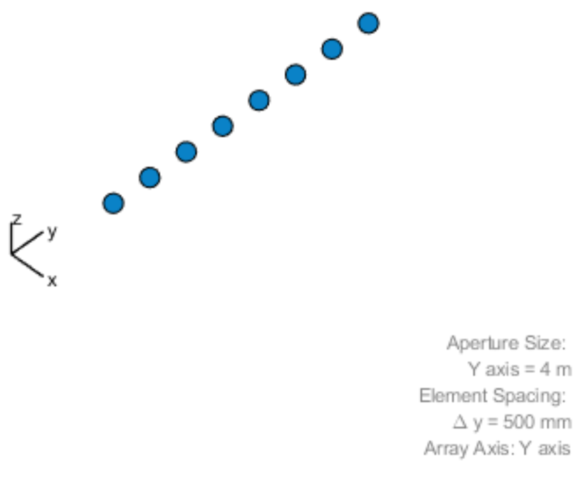
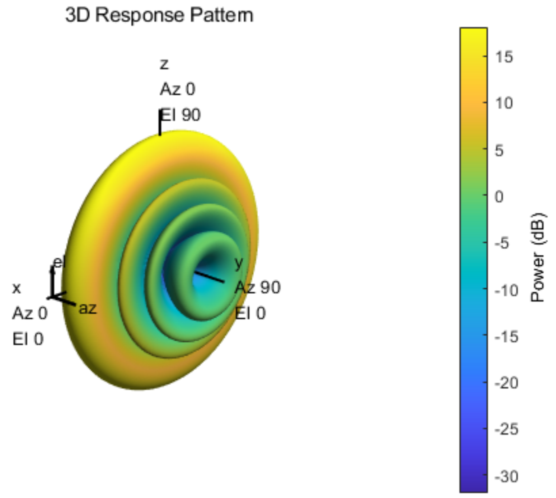


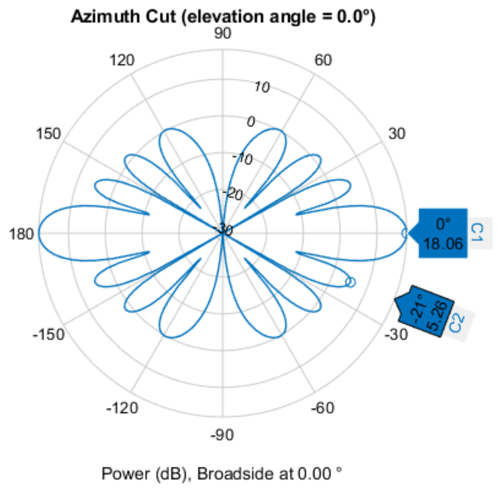
图 3-1 天线排列

通过计算可画出方向图：

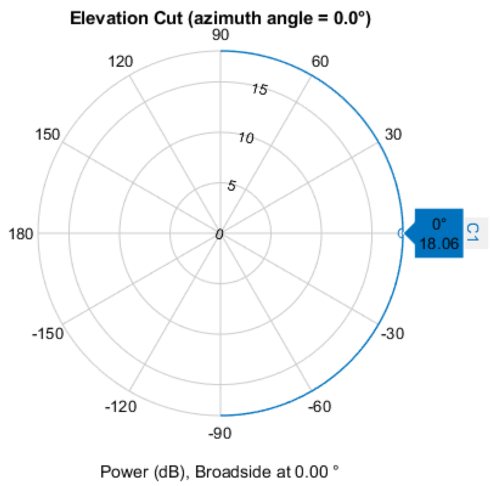


a) 3D 方向图

其 Azimuth 面和 Elevation 分别为：



b) Azimuth 面方向图



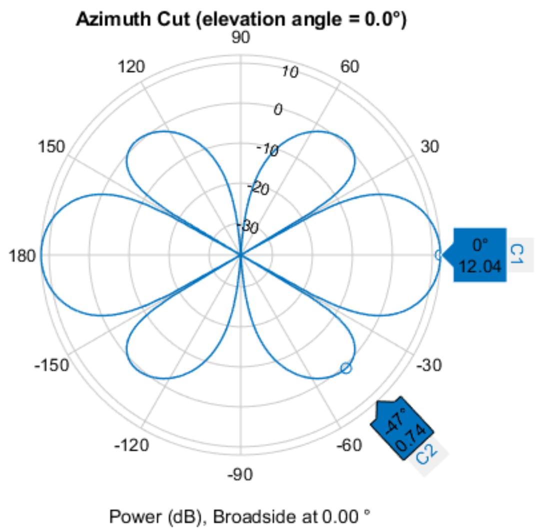
c) 3-5Elevation 面方向图

图 3-2 天线方向图

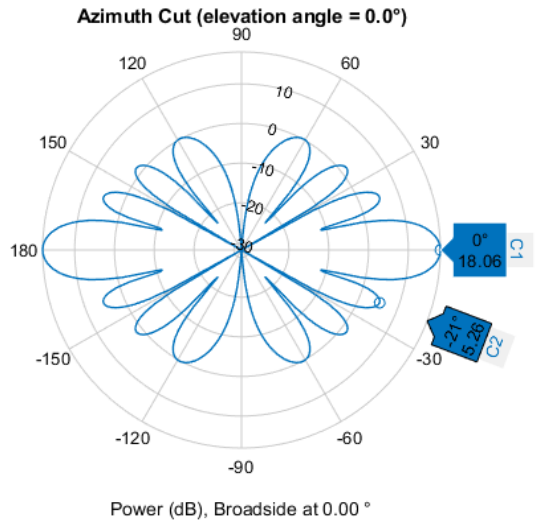
由此可以看出，经过计算，上述阵列的方向性系数为 9.0348，且主瓣和旁瓣相差 13dB，由此看以看出阵列天线具有较高性能的方向性。为分析方便，后文的分析主要以 azimuth 面为准。

3.2.1 天线元个数对均匀线阵天线辐射特性的影响

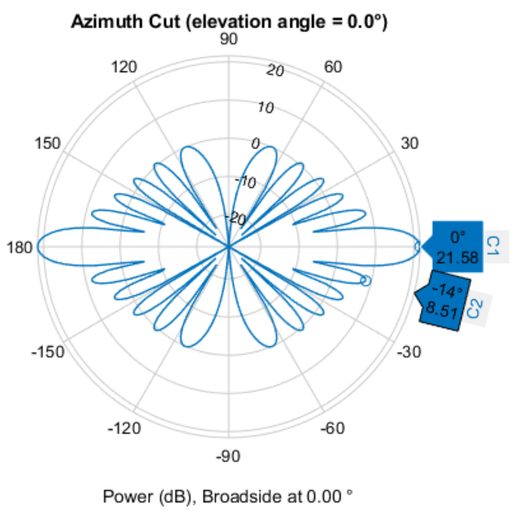
下图 3-3 为改变线天线阵的天线元个数画出的方向图对比，表 3-1 为天线元个数对辐射特性的影响：



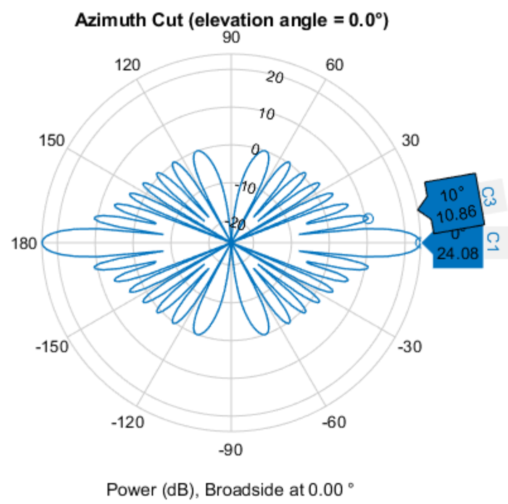
a) N=4



b) N=8



c) N=12



d) N=16

图 3-3 天线元个数对方向图的影响

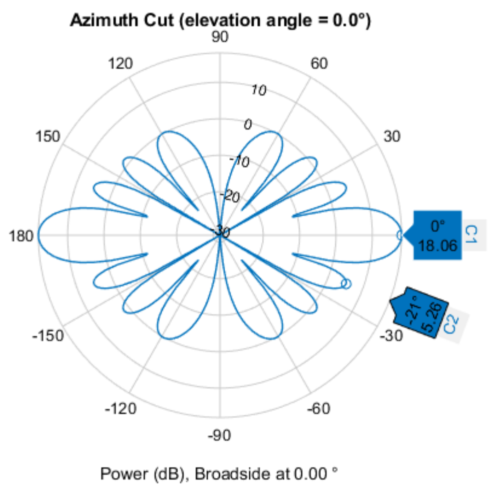
表 3-1 辐射特性与天线元个数的关系

天线元个数	方向图峰数	方向性系数	主瓣旁瓣差/dB	主瓣旁瓣角度差
4	3	6.024	11.3	47
8	7	9.0348	12.8	21
12	11	10.7961	13.07	14
16	15	12.046	13.2	10

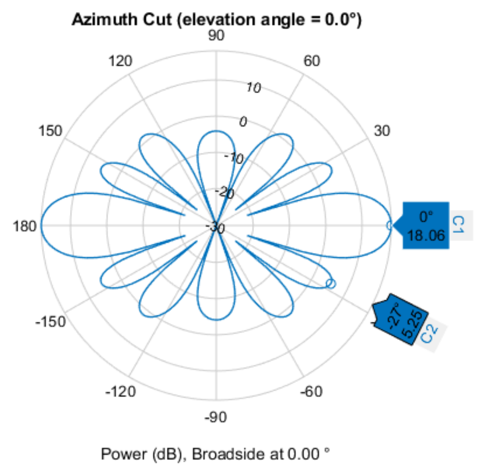
经过计算，方向图的峰数=天线数-1，其中主瓣是由两个峰合并在一起，可以得出结论：均匀线天线阵列随着天线元个数的增加，方向图的峰数增大，天线的波束更窄，方向性更强，对旁瓣的抑制作用更加有效。在成本综合下，增加线阵天线的天线元个数是增强天线性能的有效途径。

3.2.2 天线间距对线阵天线辐射特性的影响

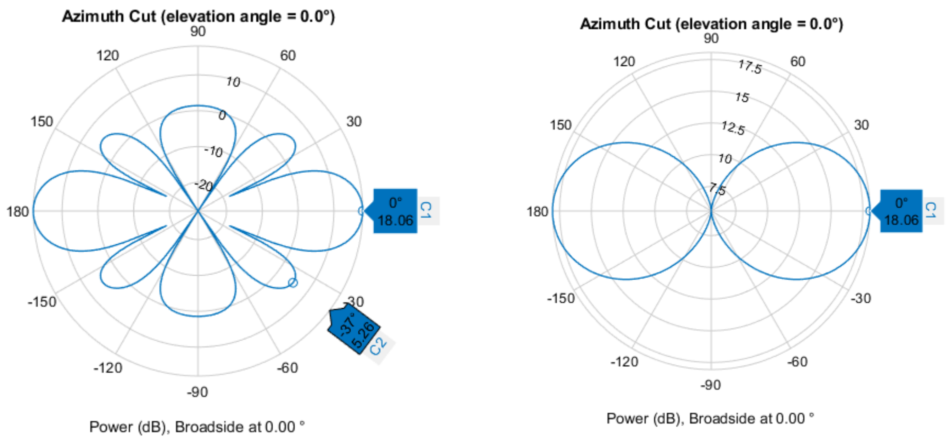
在式 3-1 中，本文也可以看出天线的方向因子和单位天线的间距 d 相关。在固定天线元个数的情况下，以上述天线元个数 N=8，信号频率=300Mhz 的均匀线阵天线为例，天线间隔分别设为 0.5m，0.4m，0.3m，0.1m 进行分析，下图 3-4 和下表 3-2 为对应方向图和辐射特性表：



a) 天线间隔 d=0.5m 时



b) 天线间隔 d=0.4m 时



c) 天线间隔 d=0.3m 时　　　　d) 天线间隔 d=0.1 时

图 3-4 天线间距对方向图的影响

表 3-2 幅射特性与天线元个数的关系

天线元间距	方向图峰数	方向性系数	主瓣增益	主瓣旁瓣差
0.5m	7	9.0103	18.06	12.8
0.4m	6	9.0106	18.06	12.8
0.3m	4	9.0108	18.06	12.8
0.1m	1	9.0108	18.06	None
1.2m	16	9.0101	18.06	12.8

由此可以看出，天线间距在半波长以内的变动，会使得部分天线的辐射方向出现交叠，随着距离不断降低，阵列天线方向图的峰数减少，天线的方向性变差，当减小到一定程度时，如到上述绘制的间距为0.1λ的方向图，线阵天线的天线元不断重叠，相当于两个元辐射功率增大的二元阵。而若阵列天线的间距大于半波长时，如 d=1.2m 时，天线的 azimuth 下图 3-5，可以看出，天线的峰数增多，出现混叠现象，方向性变差。故避免天线间出现混频现象，因此工程上一般要求阵列天线之间的间距小于等于信号半波长。

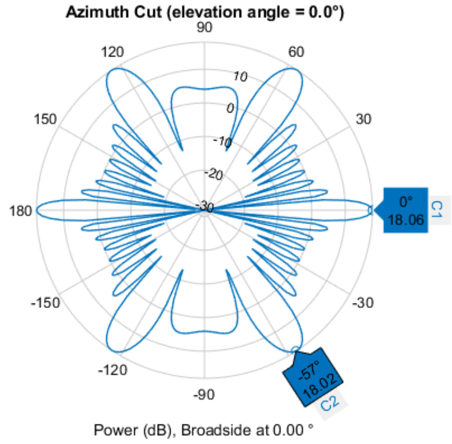


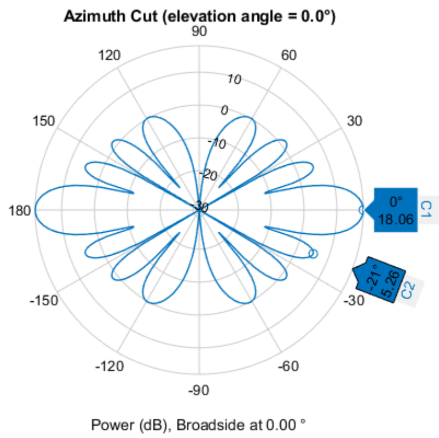
图 3-5 d=1.2m 时的天线方向阵

3.2.3 通信频率对线阵天线辐射特性的影响

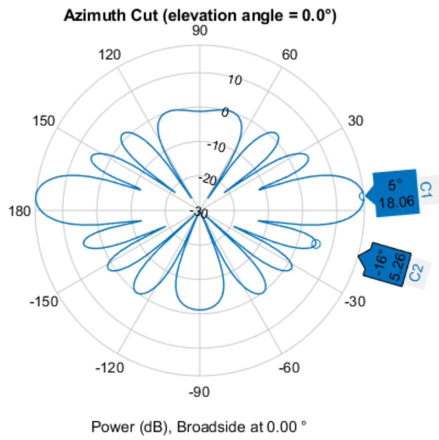
均匀直线阵列的阵因子公式中虽然没有频率分量，但是幂项中的 $kd\cos\theta = \frac{2\pi}{\lambda}\frac{L}{N}\cos\theta$，可见频率实际上决定了天线间距，故在大范围下分析频率对天线阵辐射特性的影响与分析天线间隔的结论相同。

3.2.4 均匀单元激励相位对线阵天线辐射特性的影响

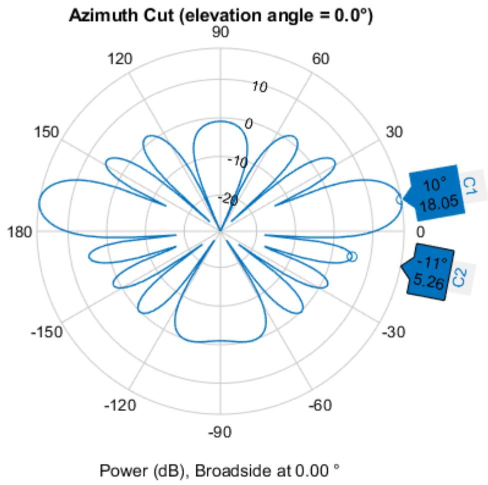
规律递变相位是均匀线天线阵列的重要特点之一，在此对比不同馈电相位差的天线阵辐射特性。以天线元个数 N=8，信号频率 300MHz，单位间距 d 为半波长为例。下图 3-6 为均匀改变馈电相位对应输出的方向图：



a) 当天线的馈电相位相同时



b) 当天线的馈电相位以 15° 均匀叠加时



c)当天线的馈电相位以 30° 均匀叠加时

图 3-6 馈电相位对方向图的影响

对于等幅渐变相位的线天线阵，可以写出其阵因子：

$$\begin{aligned} S(u) &= I_0 \frac{1-e^{jNu}}{1-e^{ju}} = I_0 \frac{e^{jNu/2}}{e^{ju/2}} \frac{e^{jNu/2}-e^{-jNu/2}}{e^{ju/2}-e^{-ju/2}} \\ &= I_0 e^{j(N-1)u/2} \frac{\sin(Nu/2)}{\sin(u/2)} \end{aligned} \qquad (3\text{-}2)$$

式中，相位因子 $e^{j(N-1)u/2}$ 因为坐标定位不同产生的相位差，若把阵列的相位中心设在原点，则上述相位因子将不再出现，此时可以把阵因子看作：

$$S(u) = I_0 \frac{\sin(Nu/2)}{\sin(u/2)} \qquad (3\text{-}3)$$

u=0 时，可得归一化阵因子：

$$S(u) = \frac{\sin(Nu/2)}{N\sin(u/2)} \qquad (3\text{-}4)$$

上式的最大值发生在

$$\frac{u_i}{2} = \frac{1}{2}(kd\cos\theta_i + a) = \pm i\pi (i = 0,1,2,3\cdots) \qquad (3\text{-}5)$$

可求得：

$$\theta_i = \arccos[\frac{1}{kd}(-a \pm 2i\pi)](i = 0,1,2\cdots) \qquad (3\text{-}6)$$

θ_i 表示各个波峰的位置，当 i=0 时，上述对应的是主瓣，即：

$$\theta_i = \arccos[\frac{-a}{kd}] \tag{3-7}$$

通过公式分析和理论推导可以看出，天线的方向性和波束宽度并没有明显变化，但主瓣出现的角度发生了改变，且方向图的旁瓣因为各天线馈电相位不同出现了叠加，合并为一个瓣。

3.2.5 对非均匀线阵的讨论

为分析方便，本文讨论和演示的主要是均匀线阵/面阵。但非均匀线阵因为具有其普适性，在实际工程中也有广泛的应用，甚至在某些环境下非均匀线阵是唯一解决方案。非均匀线阵和均匀线阵同理：包括天线元馈电幅度不均匀，天线元间距不均匀和馈电相位不均匀三种情况。

3.2.5.1 不等幅馈电线阵

不等幅激励线阵即各个天线元的激励电流幅度各不相同，按照某种某种函数规律分布，如三角形分布，V 形分布，正弦和余弦分布等。不同的分布自然也对应着不同的分布特性，在所有的单元激励幅度分布函数中，最常用的是幅度锥削，即馈电幅度边缘低，中心高。在此进行仿真绘图：

以天线元个数 N=8，单位天线元间隔 0.5m，信号频率为 300MHz 为例，单元激励相对幅度向量为[0.4 0.6 0.8 1.0 1.0 0.8 0.6 0.4]。幅度分布函数曲线如图 3-7 所示：

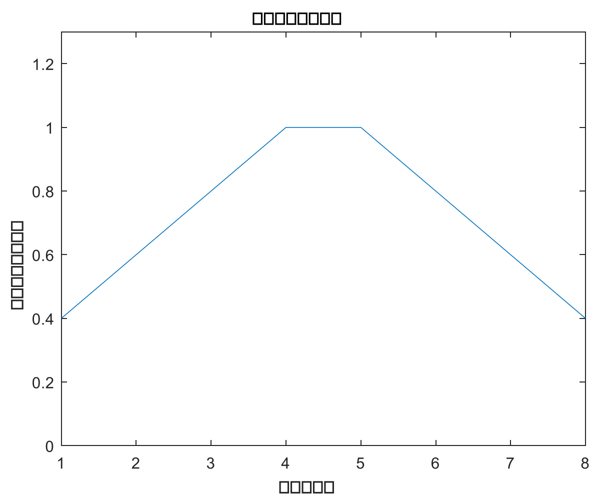
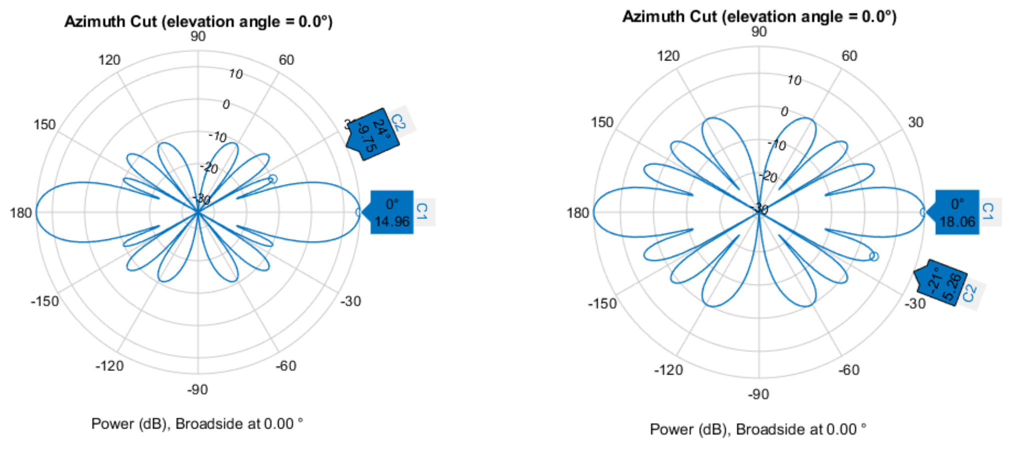


图 3-7 天线馈电幅度分布

经过计算，其方向图为：



a) 不等幅馈电方向图　　　　b) 对比方向图

图 3-8 不等幅馈电方向图对比

可以看出，由于部分天线的增益减小了，主波瓣的最大增益出现降低。但可以明显发现副瓣主瓣差增大，天线阵的方向性更好。在综合馈电幅值的成本下，使用非均匀阵列能够更好地适应部分环境。

3.2.5.2 不等间距天线阵

不等间距的天线阵一般分为两类，一类是阵列单元间距自阵中心向侧方向按比例增大，即天线密度锥削阵；另一类是将等间距天线阵按照规律抽调部分天线元构成的天线阵，即天线元之间的间距为单位天线元间距的整数倍。上述这两类希布阵列大大减少了所需单元数目，因而降低了馈电系统的复杂性和故障率，节省了制作和维护成本，在实际工程设计中也广泛使用。在此根据第二类希布天线排列进行仿真绘图：

以下图 3-9 为例，天线元个数 N=5，单元天线间隔为 0.5m，仿真频率 300MHz 的等幅激励为例：

图 3-9 不等距天线阵列模型

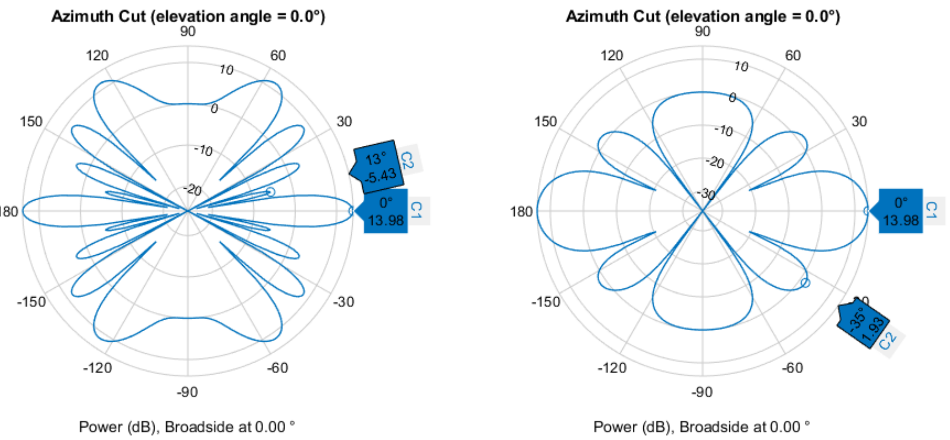


图 3-10 不等距天线阵方向图对比

可以看出，天线阵牺牲了空间成本，获得主波瓣的波束宽度变窄。因为部分天线间隔超过半波长甚至二倍波长，不等距天线的波束增多。天线阵的天线元个数不变，限制了阵列天线的增益。我们能够注意到，不等距天线阵和 URL 不同，即使利用加大间距的办法增加天线的总长度，但未必能很有效地改变天线方向性，因此工程上间距不均匀的天线阵的各单元位置还需要进行细致的选择。

3.2.5.3 不均匀相位递变阵列

上述讨论的两种非均匀线阵都建立在同一个基础之上——阵列天线的馈电相位是均匀变化的。而实际的应用中，天线阵的间距往往在基站安装时就已经确定了，各天线元的幅值的馈电成本较高，控制天线波束最有效最简单的途径往往是控制天线的相位。相控阵同样是波束赋形的核心技术，后面的章节将具体分析。

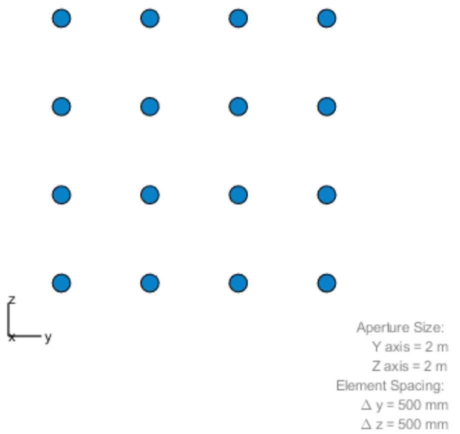
3.3 均匀平面阵列

相比于线天线阵，平面阵具有更高的辐射性能，精度更高，更容易控制波束方向。平面天线阵的辐射结果同样和天线元的个数，空间排列位置，以及馈电相位和幅值分布相关。在此就上述变量对均匀矩形平面阵进行分析。

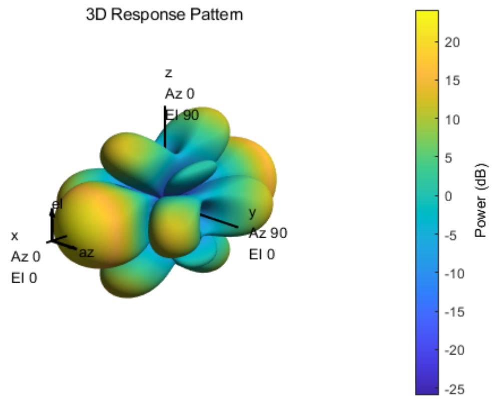
根据第二章的天线基础理论可知式：

$$S(\theta,\varphi)=\sum_{m=-M_x}^{M_x}\sum_{n=-M_x}^{M_y}(\frac{\dot{I}_{mn}}{\dot{I}_{00}})\exp[jk\sin\theta(md_x\cos\varphi+nd_y\sin\varphi)+ja_{mn}] \quad （3\text{-}8）$$

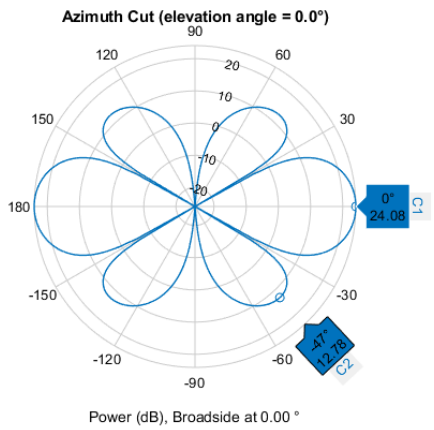
根据此式可以画出阵列天线的方向图，以4*4天线阵为例，信号频率为300MHz，天线元间距 d 设为半波长 0.5m，可绘制出天线阵的辐射特性：



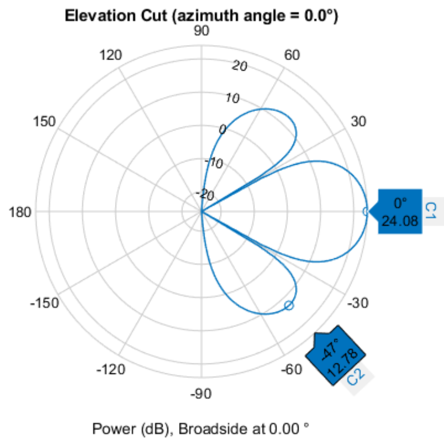
a) 天线排列分布



b) 3D 方向图



c) Azimuth 切面



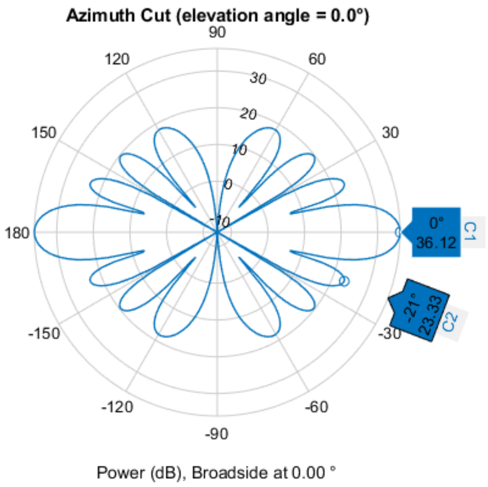
d) Elevation 切面

图 3-11 均匀平面阵列的辐射特性

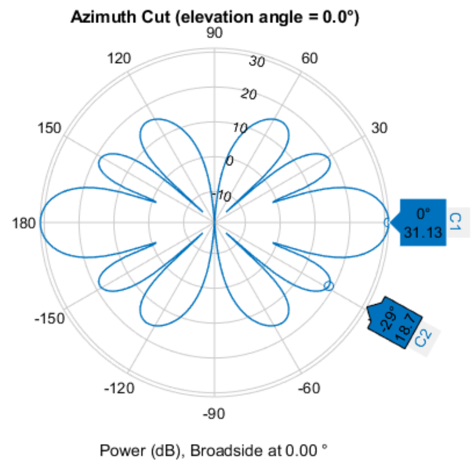
经过计算，天线的方向性系数输出为 13.5123。且主瓣和旁瓣相差约 11.3dB，可见面天线阵的方向性能更好。为分析方便，后文同样以分析 Azimuth 面为主。

3.3.1 天线元个数对辐射特性的影响

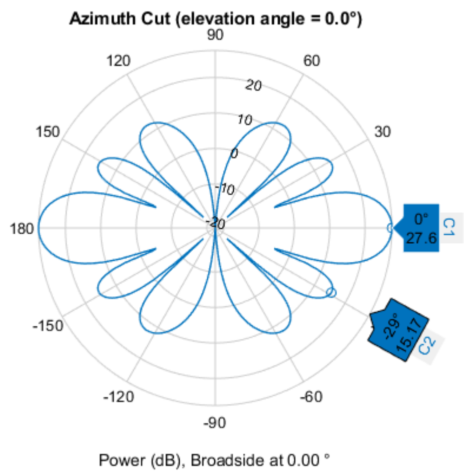
将天线元分别设为 6*6，8*8，4*6，4*8，分析其 Azimuth 的辐射分布情况，下图 3-12 为对应输出的方向图，表 3-3 为天线元与辐射特性的关系：



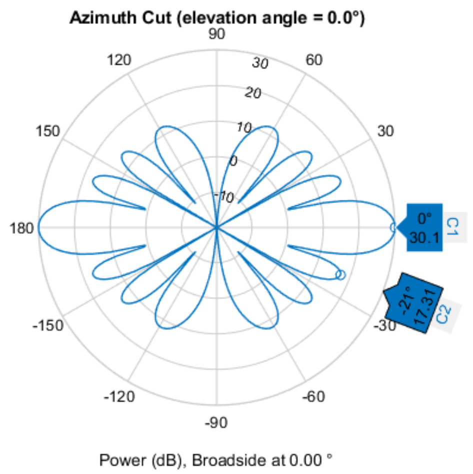
a) 8*8 天线元



b) 6*6 天线元



c) 4*6 天线元



d) 4*8 天线元

图 3-12 天线个数对面天线阵方向图的影响

表 3-3 幅射特性与天线元个数的关系

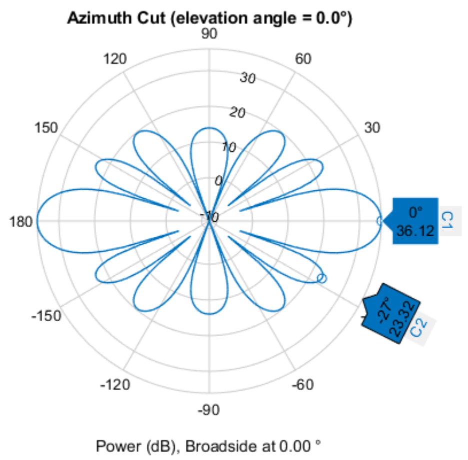
天线元个数	增益大小	方向图峰数（单边）	方向性系数	主瓣旁瓣差
4*4	24.8	3	13.5123	11.3dB
4*6	27.6	5	15.3390	12.43dB
4*8	30.1	7	16.6249	12.79dB
6*6	31.13	5	17.1645	12.43dB
8*8	36.12	7	19.7440	12.79dB

通过上述仿真验证可以看出，天线元总个数越多，天线的增益越大，方向性系数越高，天线的方向性越好。此处仅仅只针对 Azimuth 面的分析，可以发现天线阵的方向图的峰数实际上与天线阵的列天线元有关，方向图的峰数=列天线元个数-1，与此同时旁瓣的大小也仅与列天线元个数有关。而天线的辐射图实际上是三维的，通过上述相同的方法仿真分析方向图的 Elevation 面，可知 Elevation 的峰数和旁瓣是由行天线元个数决定。

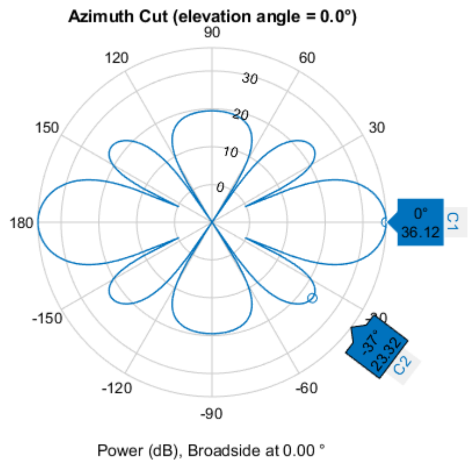
3.3.2 天线间距对阵列天线的辐射特性的影响

通过式 3-8 可以看出，天线的方向图同样与天线元间距相关，在此进行仿真分析：

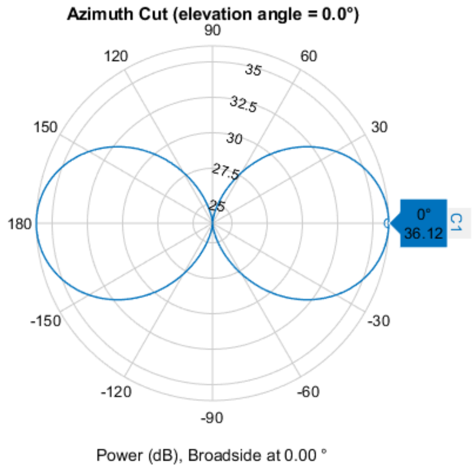
以天线元个数为 8*8，信号频率 300MHz 为例：分别设置天线间距为[0.5 0.5],[0.4 0.4],[0.3 0.3],[0.1 0.1],[0.3 0.5],[0.1 0.5],进行分析。图 3-13 为对应输出的方向图，表 3-4 反应了天线间距对辐射特性的影响。



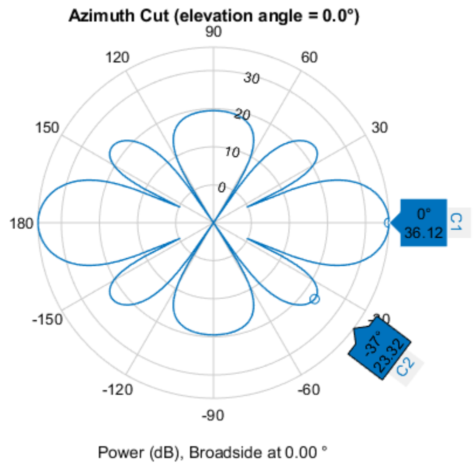
a) d=[0.4 0.4]



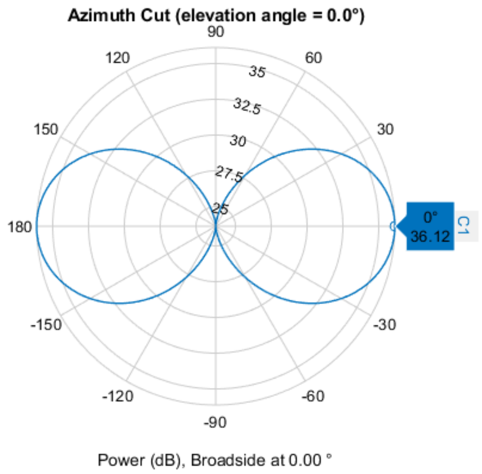
b) d=[0.3 0.3]



c) d=[0.1 0.1]



d) d=[0.5 0.3]



e) d=[0.1 0.5]

图 3-13 天线间距对面天线阵方向图的影响

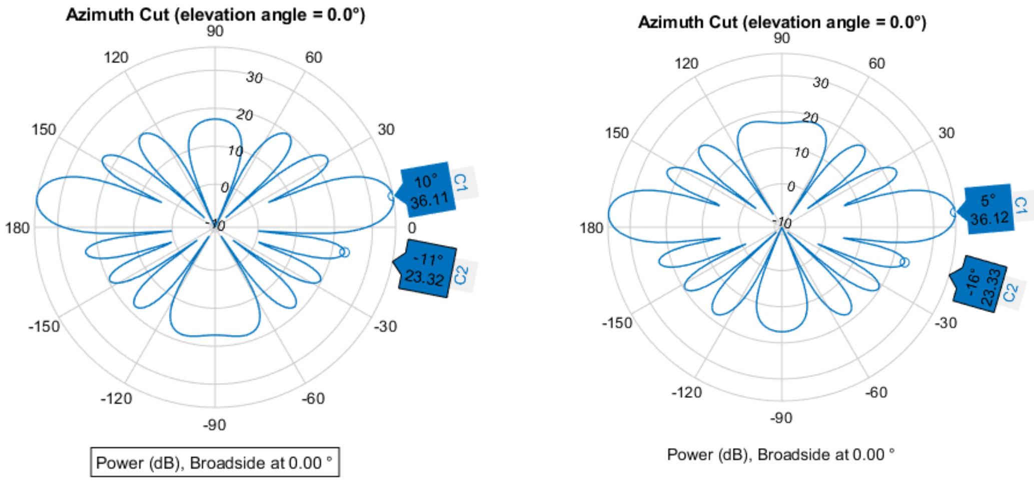
表 3-4 天线间距与辐射特性的关系

天线元间隔	增益大小	方向图峰数（单边）	方向性系数	主瓣旁瓣差
[0.5 0.5]	36.12	7	19.7440	12.79
[0.4 0.4]	36.12	6	17.9434	12.8
[0.3 0.3]	36.12	4	15.4339	12.8
[0.1 0.1]	36.12	1	5.6762	None
[0.5 0.3]	36.12	4	17.5808	12.8
[0.5 0.1]	36.12	1	12.6964	None

通过上表可以看出，天线的主瓣和旁瓣的增益与天线元的间距无关。但是天线元间距影响着天线的方向性，在间距小于半波长的范围内，天线元的间距越小，天线主瓣的波束就越宽，方向性越差。除此之外，天线元的间距影响方向图的峰数，间距缩小，方向图的峰数减少，当间距降低到 0.1 倍波长时，多个天线元分量叠加，相当于的二元阵。上述分析都是基于方向图的 Azimuth 切面结果，可以看出天线元的列间距才会影响 Azimuth，使用的方法进行 Elevation 面的仿真，会得到天线元的行间距影响 Elevation 的类似结论。

3.3.3 天线相位对阵列天线的辐射特性的影响

均匀平面天线阵的特点是平面阵每行或者每列的激励电流分布规律都相同，而激励电流的属性包括幅值和相位，在馈电成本的考虑下，调整天线相位来控制波束方向是工程上最常见最简单的手段。现在此分析沿着天线行/列均匀递变的相位馈电会对方向图有什么影响，以天线元个数 8*8，信号频率为 300MHz，间距为半波长 0.5m 为例，馈电相位分别设为沿列以 30° 均匀递变，沿列 15° 均匀递变，下图 3-14 为对应输出的方向图：



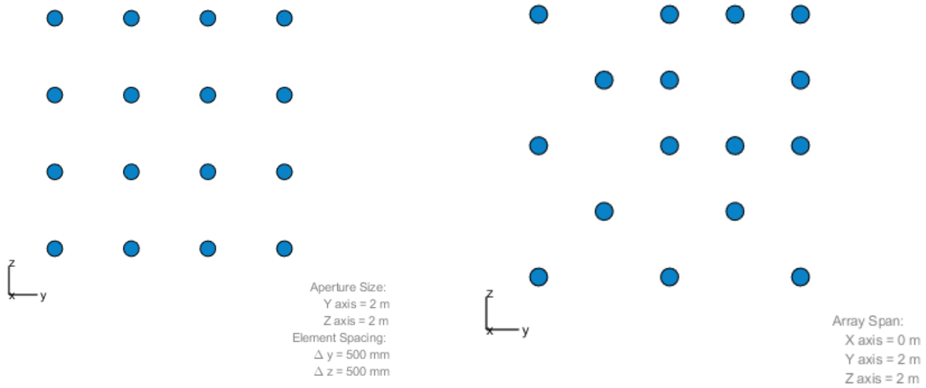
a) 30° 均匀递变　　b) 15° 均匀递变

图 3-14 均匀相移对面天线阵方向图的影响

经过分析，可以看出天线的方向性和波束宽度没有明显变化，但是主瓣的角度发生了改变，并出现天线图的旁瓣合并为一个瓣的现象。这个结论几乎和线阵相同，很容易预测。因为在第二章的式 2-14 获知，均匀矩形天线阵的辐射特性是可以看作是行线阵和列线阵分量相乘。通过仿真，同时也能说明改变相位是对波束方向进行控制的有效手段。上述分析是根据列对天线阵添加均匀递变相位的激励，故改变的是 Azimuth 切面的波束，若以行作为根据添加相位递变激励会得到 Elevation 切面的相同结论。

3.3.4 关于平面天线阵列的排列方式的讨论

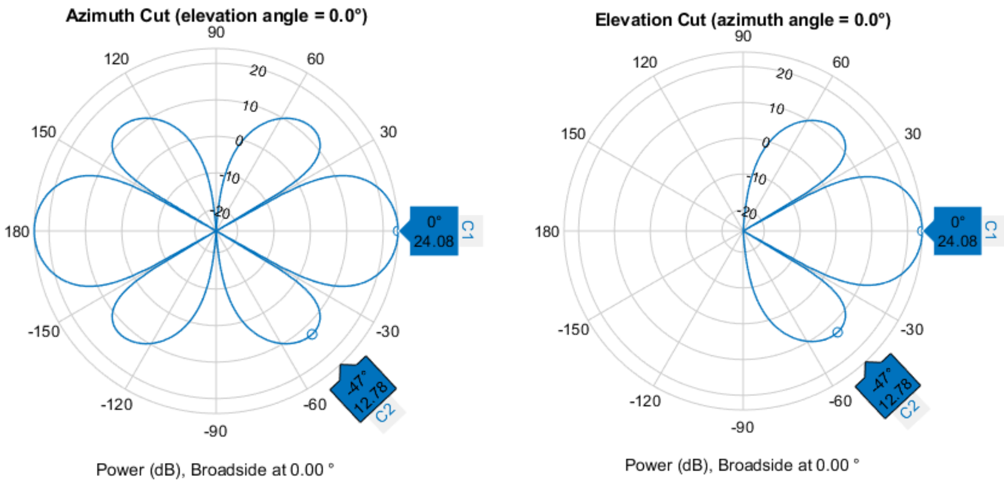
面阵天线不仅相比线天线或单个天线有更好的方向性和控制性，相同天线元个数不同天线阵的空间排列也会影响天线辐射特性。如下图 3-15 所示，两个天线阵的天线元个数都为 16，而右边的天线阵改变了天线的分布，使之分布在更大的平面上，现以信号频率为 300MHz，单元间距为半波长 0.5m 为例进行方向图仿真：



a) 4*4 均匀排布　　　　b) 变换排布方式后

图 3-15 天线空间排布变换

下图 3-16 为平面阵 a 画出的方向图：

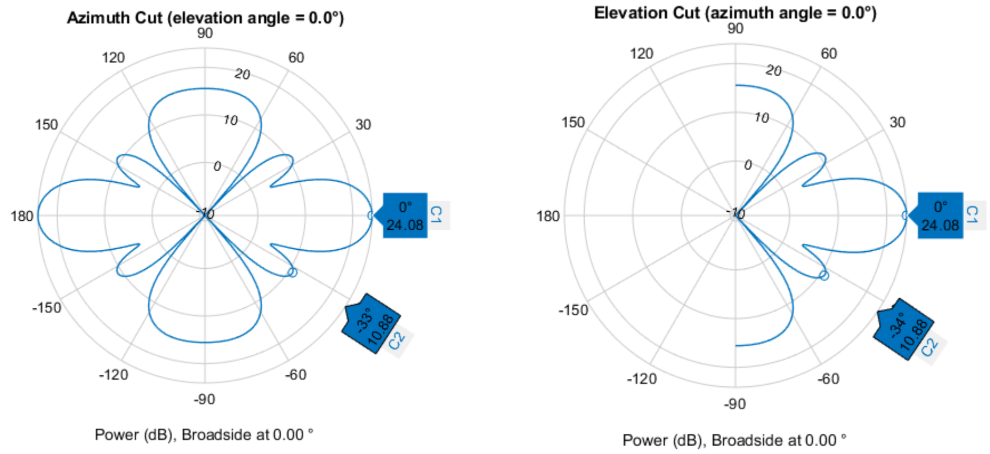


a) Azimuth 面方向图　　　　b) Elevation 面方向图

图 3-16 均匀排布阵列方向图

经过计算，其方向性系数为 13.5123。

改变天线元分布后画出方向图 3-17：



a) Azimuth 面方向图　　b) Elevation 面方向图

图 3-17 均匀排布阵列方向图

经过计算，其方向性系数为 15.31。

通过对比可以看出，主瓣的波束峰值的高低是和天线元天线元个数有关的。但经过新的空间排布后，阵列天线的主瓣波束明显变窄，副瓣变小，天线的方向性系数增大，方向性变好。上述空间说明了阵列天线可以通过牺牲空间来换取更高的天线增益和副瓣控制。

3.4 本章小结

本章主要对阵列天线的辐射特性进行了分析。

首先对基础的均匀线阵进行分析，通过画出方向图和得到方向性系数，得知天线元个数，天线间距和均匀相位变化对天线方向图的影响。并在此基础之上对非均匀线阵进行了讨论。

其次对均匀平面阵列进行了介绍，利用相似的方法分析了平面阵列对应参量对辐射特性的影响，得到平面阵具有更高的辐射性能，精度更高，更易控制波束方向的结论。此外还对平面天线阵列的排列方式进行了讨论，通过对两个同天线个数不同天线排列的天线阵的对比，提出了一种阵列变换可通过牺牲天线空间来换取天线增益和副瓣控制。

本章的主要贡献是帮助研究对阵列天线的方向图和增益等辐射特性有更深入的理解，并为后文阵列天线的导向矢量和码本设计提出进行理论铺垫，直观地证明了波束赋形的可行性。

第 4 章 导向矢量和码本设计

4.1 引言

波束赋形是一种基于天线阵列的信号预处理技术。通过调节天线阵列中每个元素的加权系数，以产生方向性可控的波束，可以获得天线阵列的处理增益

如果可以根据信道条件适当地控制每个矩阵元素的加权系数，就能够提高期望方向上的信号强度，并最大程度地减少不必要方向上的干扰。波束赋形的效果是，通过调整每个阵列元素的加权系数，使得经过处理后的等效信道具有可控的空间选择性。而波束赋形的实际作用手段是根据天线的空间位置设置控制矩阵，将预编码矩阵与天线自身的导向矢量相乘，得到理想的波束输出。本章将在此讨论码本的设计。

4.2 阵列天线的导向矢量

移动通信传输信号是一个非常复杂的过程。在建立数学模型时，本文需要分析相关参数，合理简化或参数化某些变量并分析以下参数。

信源信号：视距（LOS）传播环境和非视距环境（NLOS）的主要区别在于信源信号被看作是点信源或一个方向，本文将统一 LOS 传播环境为准，将信源模型视作点信源。

噪声：假设噪声为零均值的平稳高斯白噪声，不同天线元之间的噪声相互独立，与信源信号不相干。

基于以上的假设，本文在此建立模型。假设天线有 N 个天线元，K 个信源（N>K），信源的载波频率均为 ω，波长均为 λ，入射到天线阵列的角度为 ϕ_1，$\phi_2,\cdots\phi_{\mathrm{k}}$，其中 $\phi_{\mathrm{k}}=(\theta_k,\varphi_k)$ ，$K=1,2\cdots\cdots K$，θ_k 代表信号源序号为 k 的俯仰角，φ_{k} 则代表其对应的方位角，$0^\circ\le\theta_k\le 90^\circ$，$-180^\circ\le\theta_k\le 180$，则天线阵列中第 m 个阵元对应的信号如下：

$$x_m(t)=\sum_{k=1}^{K}s_k(t)e^{-=jw\tau_m(\phi_k)}+n_m(t) \tag{4-1}$$

其中，$s_k(t)$ 是信源 k 入射到阵元 m 上的信号，$\tau_m(\phi_k)$ 是指从入射信源信号与阵元之间的时延差，$n_m(t)$ 指高斯白噪声。在以上信号形式的基础上，本文可以得到整个天线的统计模型：

$$x(t)=A(\phi)s(t)+n(t) \tag{4-2}$$

其中,$x(t)$是列向量，维数为$M\times1$，$s(t)$也是列向量，维数为$K\times1$, $A(\phi)$表示导向矢量，维数为$M\times K$， $n(t)$是列向量，维数为$M\times1$。

$$x(t)=[x_1(t),x_2(t),\cdots,x_M(t)]^T \tag{4-3}$$

$$s(t)=[s_1(t),s_2(t),\cdots s_K(t)]^T \tag{4-4}$$

$$A(\phi)=[e^{-j\omega\tau_1(\phi_k)},e^{-j\omega\tau_2(\phi_k)},\cdots,e^{-j\omega\tau_M(\phi_k)}]^T \tag{4-5}$$

从上式可看出，导向矢量$A(\phi)$的主要影响因素是天线阵元的排布形式和来波的方向。后文将根据不同的天线阵列形式计算对应的导向矢量。

4.2.1 线天线阵的导向矢量

如第三章图 3-1，均匀线性阵列实际上是一维的天线阵列。假定线天线阵里有M个天线元，K个信源（$M\geq K$），每个阵元之间的间距为d，来波方向用方位角θ_k表示，$k=1,2,3,\cdots K$。分析阵列天线时一般以第一个天线元作为参考，故其相位设为 1，则其余的天线元与第一个天线之间的波程差可以表示为：

$$u_k=\frac{2\pi d}{\lambda}\bullet\sin\theta_k \tag{4-6}$$

由此，可以将线天线阵的导向矢量以及方向矩阵表示为：

$$a(\theta_k)=[1,e^{-j2\pi\frac{d}{\lambda}\sin(\theta_k)},e^{-j2\pi\frac{2d}{\lambda}\sin(\theta_k)},\cdots,e^{-j2\pi\frac{(M-1)d}{\lambda}\sin(\theta_k)}]^T \tag{4-7}$$

$$A(\theta)=[a(\theta_1),a(\theta_2),\cdots,a(\theta_k)] \tag{4-8}$$

线天线阵是一维阵列模型，因此只能分辨信号来波方向和阵列法线方向之间的夹角，其结构较为简单，馈电也较为简易。

4.2.2 均匀环形天线阵的导向矢量

不同于线天线阵，均匀圆形面天阵列是一种二位模型的天线阵列，其分布方式一般是由多个等距阵元放置在同一个圆周上，如图 4-1 所示。假设天线阵列中有M个阵元，K个信源（$M\geq K$），圆周的半径设为R，则可以将均匀圆阵列放置在球坐标系中，圆心在原点，入射方向与z轴之间形成的角度为俯仰角θ，入射方向在天线平面上的投影与x轴之间形成的角度则可以定义为方位角ϕ。

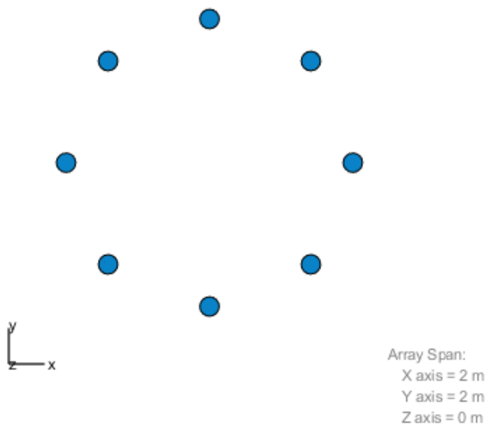


图 4-1 均匀环形天线阵模型

方向矩阵可以表示为 $A(\vartheta)$=[$\mathrm{a}(\vartheta_1), a(\vartheta_2), \cdots, a(\vartheta_k)$]，其中 $a(\vartheta)=a(\theta_k, \phi_k)$，表示第 k 个信源信号入射时对应的导向矢量，则对应圆阵列的导向矢量则可以表示为：

$$a(\theta_k, \phi_k)=[e^{-j2\pi\frac{R}{\lambda}\sin\phi_k\cos(\theta_k)}, e^{-j2\pi\frac{R}{\lambda}\sin\phi_k\cos(\theta_k-\frac{2\pi}{M})}, \cdots, e^{-j2\pi\frac{R}{\lambda}\sin\phi_k\cos(\theta_k-\frac{2(M-1)\pi}{M})}]^T \quad (4\text{-}9)$$

均匀圆周矩阵可以提供全方位的方位角估计，因为它可以将入射方向在水平与垂直方向之间划分，比均匀线性矩阵具有更好的方向性。此外，圆形天线阵的辐射覆盖面积更大，适合应用于用户分散的场景。

4.2.3 均匀平面矩形天线阵的导向矢量

平面矩形阵列实际也是一种二维天线阵模型，相比环形天线它的排列形式简单，馈电算法更加简洁。以第二章的图 2-3 为例进行分析：

x 轴上 M 个阵元以及 y 轴上的 N 个阵元对应的导向矢量为：

$$a_k(\theta_k, \varphi_k)=[1, \exp\{u\}, \cdots, \exp\{u(m-1)\}]^T \quad (4\text{-}10)$$

$$a_y(\theta_k, \varphi_k)=[1, \exp\{v\}, \cdots, \exp\{v(m-1)\}]^T \quad (4\text{-}11)$$

其中 x 轴以及 y 轴上的单位波程差可表示为：

$$u=\frac{-j2\pi}{\lambda}\bullet d\cos\varphi_k\sin\varphi_k \quad (4\text{-}12)$$

$$v=\frac{-j2\pi}{\lambda}\bullet d\cos\varphi_k\sin\varphi_k \quad (4\text{-}13)$$

整个均匀平面阵针对第 k 个信源的导向矢量为：

$$a(\theta_k,\varphi_k)=a_x(\theta_k,\varphi_k)\otimes a_y(\theta_k,\varphi_k) \tag{4-14}$$

其中$\otimes$表示克罗内克积，由此均匀平面阵针对 K 个信源的导向矩阵可以表示为：

$$A(\theta,\varphi)=[a(\theta_1,\varphi_1),\cdots a(\theta_k,\varphi_k),\cdots a(\theta_K,\varphi_K)] \tag{4-15}$$

以上分析可知，平面矩形阵列作为平面阵，有更高的方向性，且多了一个波束维度。除此之外，矩形平面阵和线天线阵结构十分相似，馈电形式简单，相比环形天线阵更加适合用户集中分布的环境。

4.3 码本和 butler 矩阵

预编码矩阵决定单个波束的控制信息，但是在考虑到成本的实际运用中，波束几乎不可能每次都精准地指向信源。因此需要舍弃部分不必要的精度，平衡信息传输方案的计算复杂度和系统性能。码本（codebook）作为预编码矩阵的集合，可提前设定期望波束希望指向的位置，并在实际应用中，在码本中找出与目标点方向最接近的预编码矩阵，再调整方向矢量发送波束得到匹配。

4.3.1 传统码本的设计方法

相控阵的控制核心是通过调整控制矩阵并使之与导向矢量相乘，从而得到理想的波束增益。即：

$$\left|C\cdot A(\phi)\right|=G(\phi) \tag{4-16}$$

其中，C 为阵列天线的预编码矩阵，即控制矩阵，A 为天线阵在ϕ方向的导向矢量，G 为在ϕ方向的波束增益。因此在设计预编码矩阵时，将期望的波束增益$G(\phi)$通过上式代数，即可得到 $m*n$ 元的方程组，$m*n$ 为阵列的总天线元的个数，解得的矩阵 C 即为天线的相位控制矩阵。

4.3.2 Butler 矩阵的应用

巴特勒矩阵（Butler Matrix）是一种波束赋形网络，用来馈电天线阵列的相位矩阵，从而达到调整波束方向的目的。Butler 矩阵只需要多个 3dB 定向耦合器组成的基本网络中加入固定相移的移相器即可实现阵列天线的点扫描。因为其结构简单，相比于传统的点扫描阵列能够极大程度地减少电路元件的数量，故在转换波束的形成网络中有着广泛的应用。

一个 $N\times N$ 的 Butler 矩阵，有 N 个输入端口和 N 个输出端口，使用它给 N 个天线组成的天线阵列馈电，将会产生 N 个不同的指向波束。在此以 4×4 的基本 Butler 矩阵为例，进行其波束指向的介绍。

如下图所示，即 4×4 Butler 矩阵的组成结构，其由定向器，90° 耦合器，交叉器和 45° 移相器组成。它由四个端口组成：*1R,2R,1L,2L* 和四个输出端口 *A,B,C,D*。基础的 Butler 矩阵每次只允许一个输入端口被激励，当一个端口被激励时，其余相邻的端口都会产生等幅等差的输出。此外，Butler 矩阵的输入端可以外接微波开关，在输出端外接天线阵列。当微波天线开关在其激励端口之间切换时，会改变相应输出端口的相差值，影响天线阵列的相位排布，导致天线波束指向的转换，完成对某区域的扫描，如图 4-2 所示

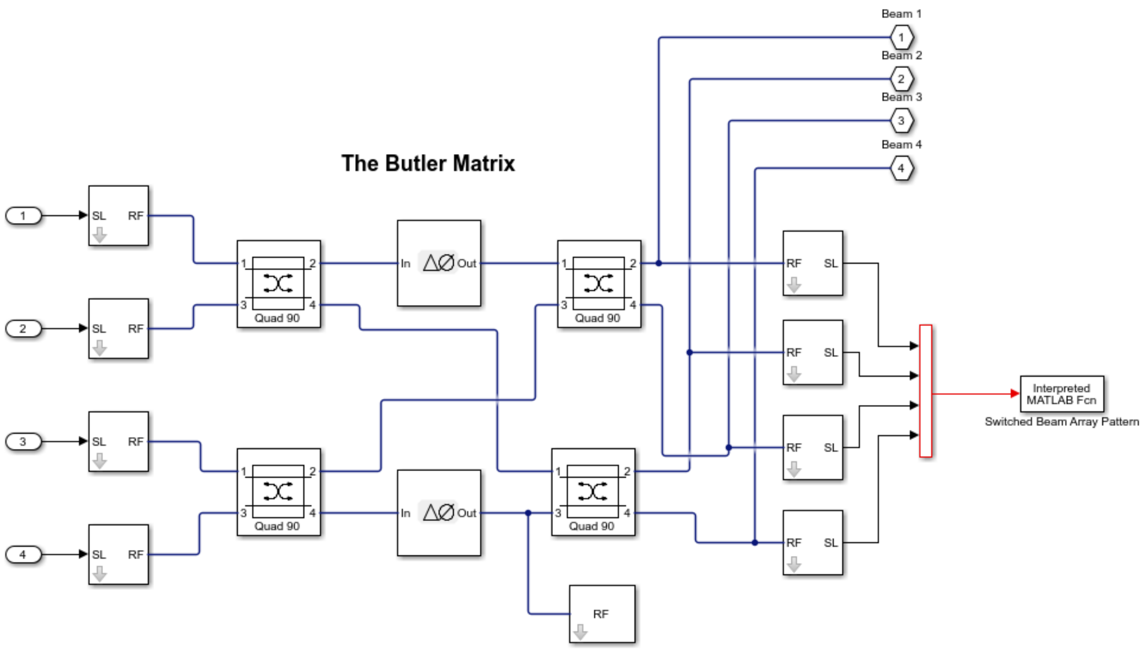


图 4-2 Butler 矩阵

表 4.1 是 butler matrix 的相位排布，可将其看作阵列天线波束赋形的码本。现将上述角度转化为相位矩阵，作为天线的导向矢量进行相控，输出结果如下图 4-3 所示：

表 4-1 4*4Butler 矩阵相位排布[10]

	A	B	C	D	$\Delta\varphi$
1R	-45	-90	-135	-180	-45
1L	-180	-135	-90	-45	45
2R	-90	-225	0	-135	-135
2L	-135	0	-225	-90	135

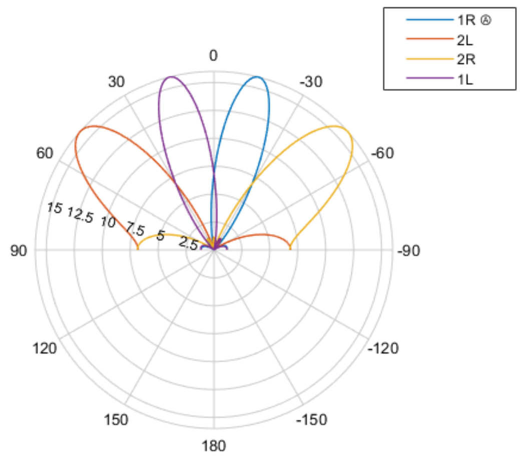


图 4-3 4*4butler 矩阵的波束

上图的四个波束分别对应 Butler 矩阵的四种输出模式，从此出可以理解 butler 矩阵实际上为一个已经集合了控制矩阵和天线阵列矩阵的黑盒，对于 4×4 的 butler 矩阵，共有 4 种不同输出波束，若是 8×8 的 butler 矩阵，则会有 8 个波束方向。如下图所示：

表 4-2 为相位排布矩阵：

表 4-2 8*8Butler 矩阵相位排布[25]

	A	B	C	D	E	F	G	H
Beam1	-112.5	45	-157.5	0	157.5	-45	112.5	-90
Beam2	-112.5	0	112.5	-135	-22.5	90	-157.5	-45
Beam3	-135	-67.5	0	67.5	135	-157.5	-90	-22.5
Beam4	-180	-157.5	-135	-112.5	-90	-67.5	-45	-22.5
Beam5	-22.5	-45	-67.5	-90	-112.5	-135	-157.5	-180
Beam6	-22.5	-90	-157.5	135	67.5	0	-67.5	-135
Beam7	-45	-157.5	90	-22.5	-135	112.5	0	-112.5
Beam8	-90	112.5	-45	157.5	0	-157.5	45	-112.5

对应的波束分布为：

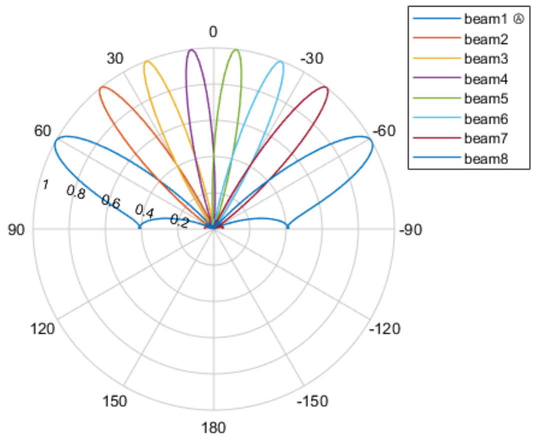


图 4-4 8*8butler 矩阵的波束

可见，波束方向越多，码本的精度就越高，同时矩阵的复杂性也就越高。基于上述的 butler 矩阵，文献有学者针对控制副瓣幅值提出了低旁瓣码本。这个矩阵的特殊之处在于每个方向矢量的模不一定为 1，意味着在进行馈电相位控制的同时也需要施加天线幅值控制。表 4-3 为其馈电矩阵：

表 4-3 低旁瓣 Butler 矩阵相位排布[25]

	A	B	C	D	E	F	G	H
Beam1	0.138	0.393	0.588	0.693	0.693	0.588	0.393	0.138
Beam2	0.138∠-123.75°	0.393∠146.25°	0.588∠56.25°	0.693∠-33.75°	0.693∠-123.75°	0.588∠146.25°	0.393∠56.25°	0.138∠-33.75°
Beam3	0.138∠-33.75	0.393∠56.25	0.588∠146.25°	0.693∠-123.75°	0.693∠-33.75°	0.588∠56.25°	0.393∠146.25°	0.138∠-123.75°
Beam4	0.138∠-56.25	0.393∠-11.25	0.588∠33.75°	0.693∠78.75°	0.693∠-123.75°	0.588∠168.75°	0.393∠-146.25°	0.138∠-101.25°
Beam5	0.138∠-101.25	0.393∠-146.25	0.588∠168.75°	0.693∠-123.75°	0.693∠78.75°	0.588∠33.75°	0.393∠-11.25°	0.138∠-56.25°
Beam6	0.138∠-33.75	0.393∠101.25	0.588∠-123.75°	0.693∠11.25°	0.693∠146.65°	0.588∠-78.75°	0.393∠56.25°	0.138∠-168.75°
Beam7	0.138∠-168.75	0.393∠56.25	0.588∠-78.75°	0.693∠146.65°	0.693∠11.25°	0.588∠-123.75°	0.393∠-146.25°	0.138∠-33.75°

上述矩阵对应的波束分布为：

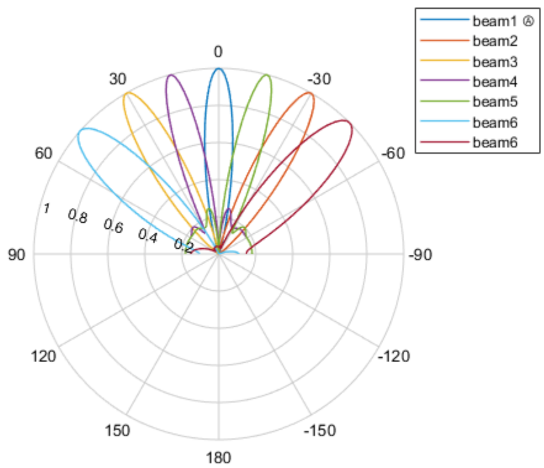


图 4-5 低旁瓣 butler 矩阵的波束

4.3.3 基于码本波束赋形的有限性

利用码本可以有效地节省波束赋形的馈电成本，仅需要根据 CSI 找出码本与目标信源最接近的预编码矩阵即可。但是低成本的简单算法同样会带来低性能，因为天线无法总是精准地指向地期望方向，带来波束赋形的精度降低，由此会降低通

讯系统的部分性能，其中一种重要的情况时信源出现在两个码本之间，形成贝壳现象（scalloping effect）：

如下图 4-6 所示，目标信源在两个方向的波束之间，因此无论使用这两个波束的哪个预编码矩阵都不能完全地覆盖对应波束。这样会导致目标用户接收到的信号信噪比降低，需要其它更多的算法匹配才能抵消对其的影响。

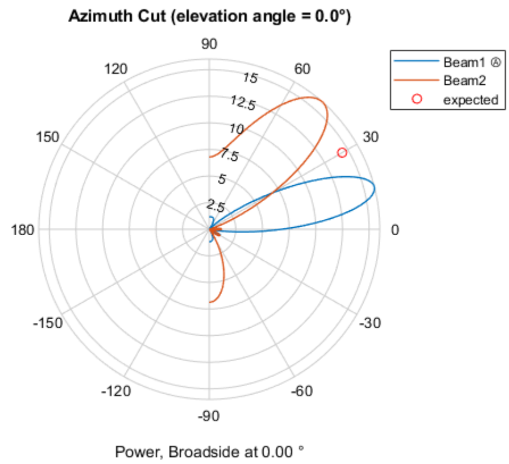


图 4-6 scalloping effect

由此可见，码本影响着信号的强弱，影响着最终误码率的高低。从最基本的设计思路来讲，码本应该尽量覆盖所有角度。可以通过增大码本数量的大小来提升波束赋形的性能，但是同时也会带来馈电成本的增大。因此设计和选择一个适当大小的码本至关重要。

4.4 本章小结

本章主要对阵列天线阵的导向矢量和预编码矩阵进行了介绍。

首先分别介绍了线天线阵，均匀环形面天线和均匀矩形面天线阵的导向矢量的建立。在此基础上，设定控制矩阵并与导向矢量相乘即可实现相控阵的波束赋形。

其次介绍了传统码本的设计方法和 Butler 矩阵的原理和应用，并根据文献上的 butler 矩阵的排布画出对应波束方向图。最后根据上述理论设计了一套新的相控码本。

最后由扇贝现象对码本的有限性进行了讨论，说明了码本在节省计算资源和馈电成本的同时，需要对天线扫描精度做出一定的牺牲。

第 5 章 交互界面的设计与演示

5.1 引言

本课题工作的其中一部分是完成大规模天线的辐射特性及波束赋形的演示，在此本人基于 MATLAB 设计了 GUI（Graphic User Interface）模型。该模型分为四个模块：基础规则天线阵列的仿真与方向图绘制；任意规则的天线阵列的仿真；波束赋形的实现；基于 Butler 矩阵的波束赋形仿真。GUI 的结构如框图 5-1 所示：

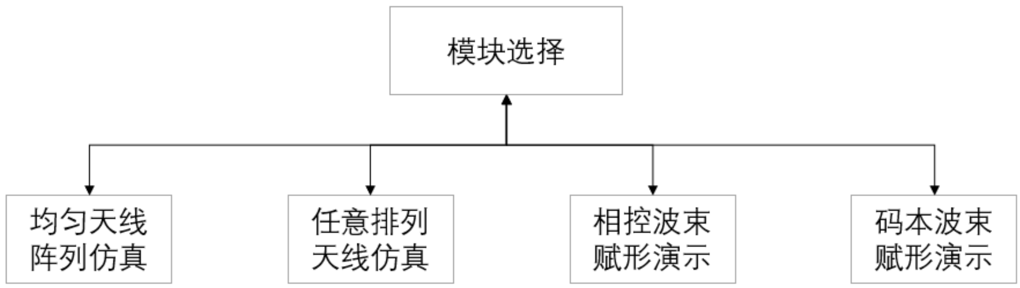


图 5-1 GUI 结构框图

下图为程序的模块选择界面，分别点按不同的按钮即可进入不同的仿真界面：

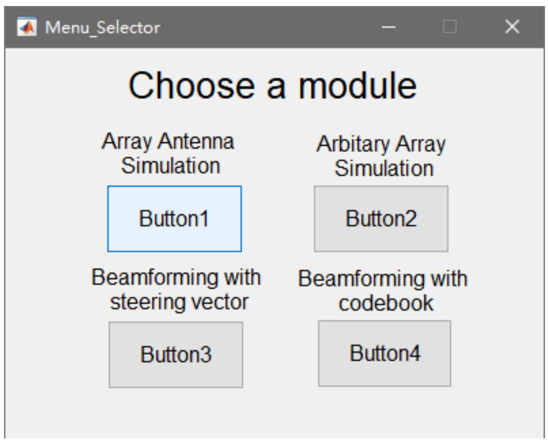


图 5-2 GUI 模块选择界面

5.2 基础规则阵列天线的仿真与方向图绘制

为了方便探究天线阵的相关参数对天线辐射特性的影响，我设计了最基础规则阵列天线界面，天线仿真的基础界面如下图所示，在选择天线阵列的规则形状

（线阵列或矩形面阵列）后，输入相应参数——天线元数量，天线间隔，信号频率等信息后即可仿真出对应方向图及方向性系数，以下图 5-3 为例：

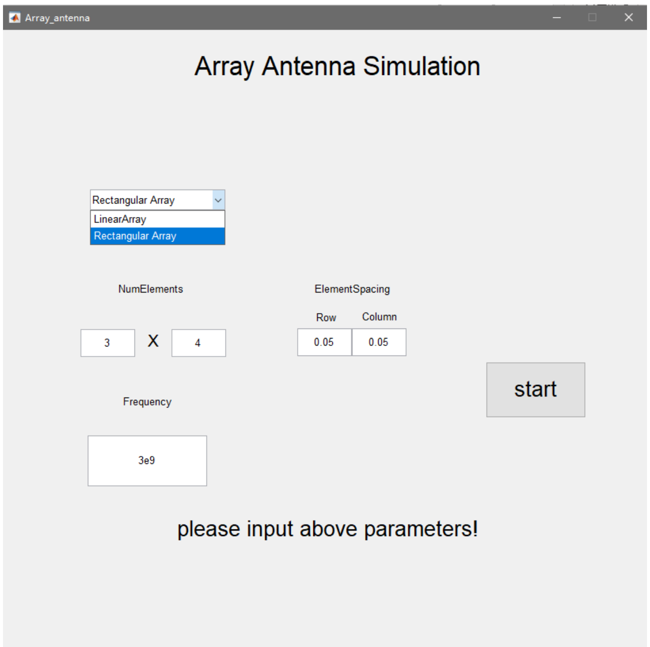
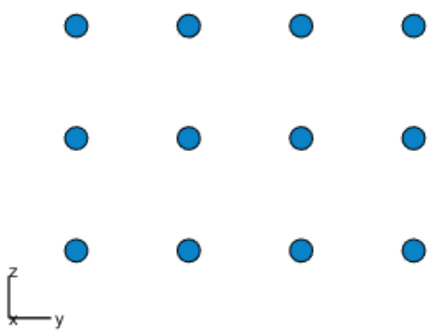
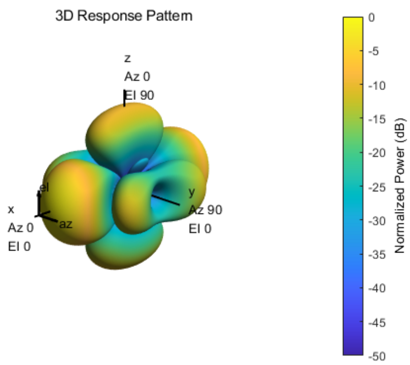


图 5-3 基础天线仿真

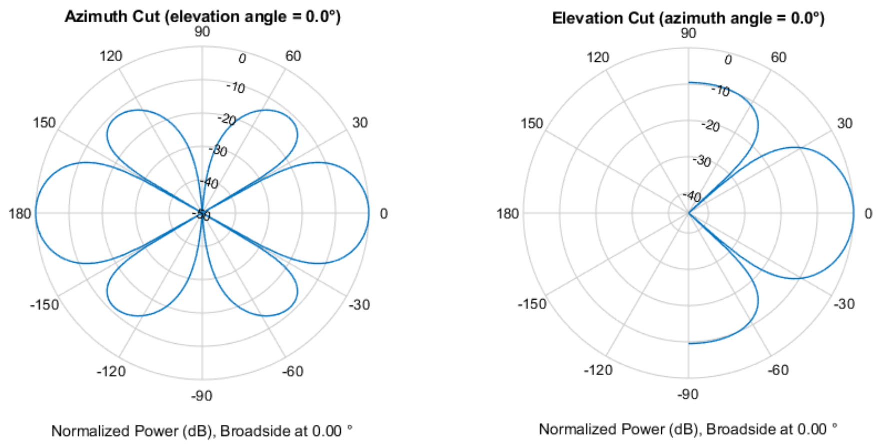
对应输出的结果：



（a）天线排布



(b)3D 方向图



（a）Azimuth 平面方向图　　(b)Elevation 平面方向图

图 5-4 基础天线演示输出

5.3 任意规则的天线阵列仿真

为了探究任意排列天线阵的辐射特性，GUI 的第二个模块是对任意形状的天线进行仿真。设计思路是先建立一个 16*16 的大的矩形面天线阵，然后通过馈电的手段对阵列中我们期望给予馈电的天线进行仿真，绘制出方向图，以下图 5-5 为例：

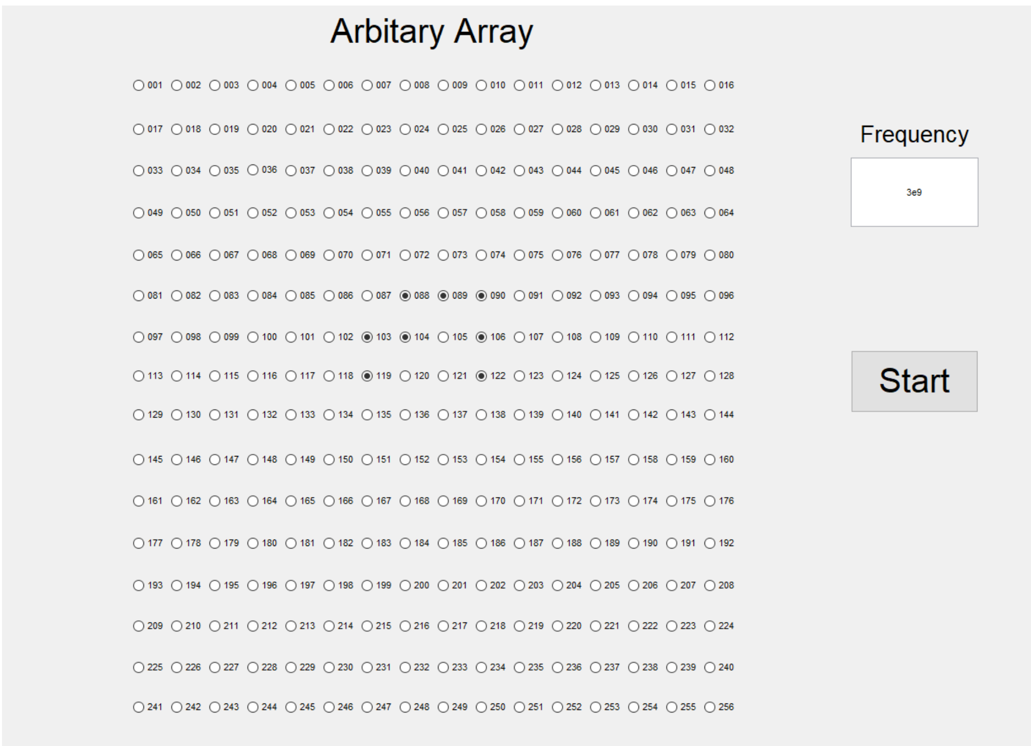
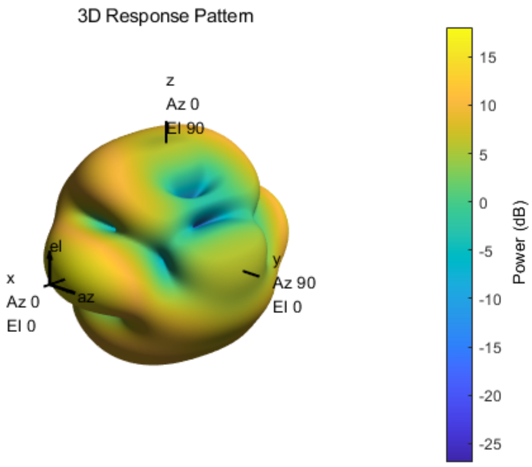
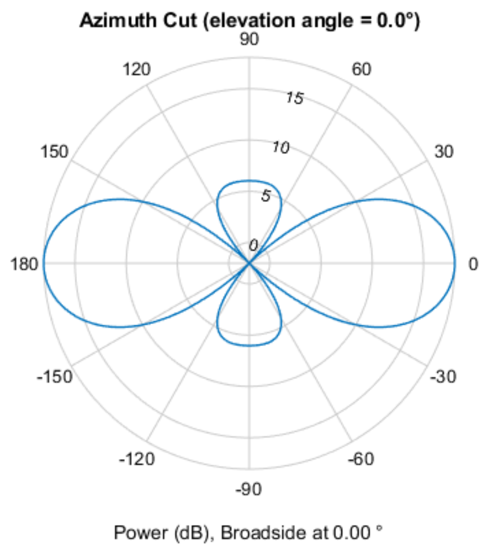


图 5-5 任意规则天线阵列仿真界面

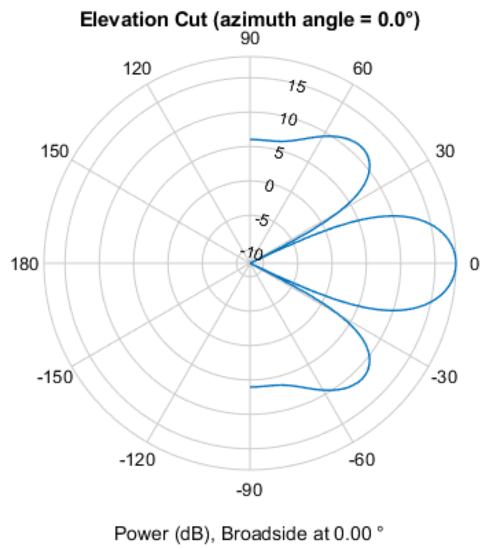
对应的仿真输出结果为：



a) 3D 方向图



b) Azimuth 面方向图



c) Elevation 面方向图

图 5-6 任意规则阵列天线演示输出

5.4 波束赋形的仿真实现

为模拟波束赋形的形成过程，GUI 的第三个模块的功能为根据信源方向进行波束赋形。首先在输入任意信源的俯仰角和方位角后，根据天线位置生成一个导向矢量（steering vector），并以此作为预编码矩阵，对天线阵的相位进行调整，从而波束赋形。以下图 5-7 输入为例：

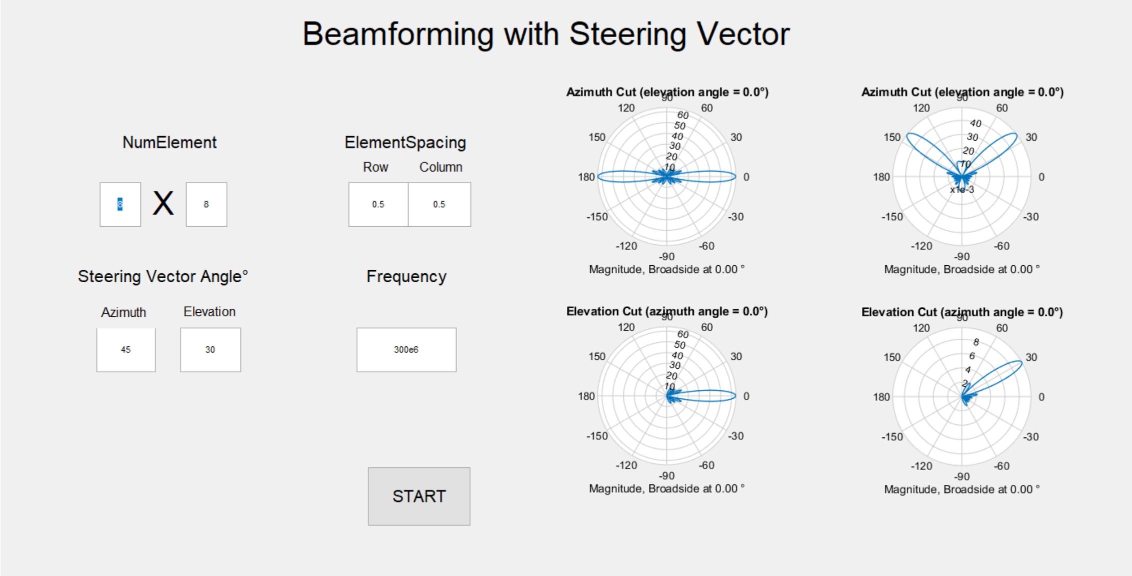


图 5-7 波束赋形演示输出

在输入信源的俯仰角 30° 和方位角 45° 后，可以看出右边的两幅方向图的波束分别打在近 30° 和 40° 上，导向矢量的精度设为 5bits。

5.5 基于 Butler 矩阵和自定义码本的波束赋形仿真

在阵列天线的实际应用中，相当一部分的波束赋形是基于码本实现的。GUI 的第四个模块的功能是基于 butler 矩阵或自定义码本作为波束方向参考，实现对信源的波束赋形。用户可选择码本作为波束方向的参考，随后随意输入信源的方向。系统会根据信源方向选择角度最接近的波束与之匹配。除了上述两种码本之外，此模块还根据文献 k 设计了一种基于 butler 矩阵的低旁瓣相位矩阵，实际相位排布和波束方向见下表：

以下图 5-8 输入为例进行模块演示：

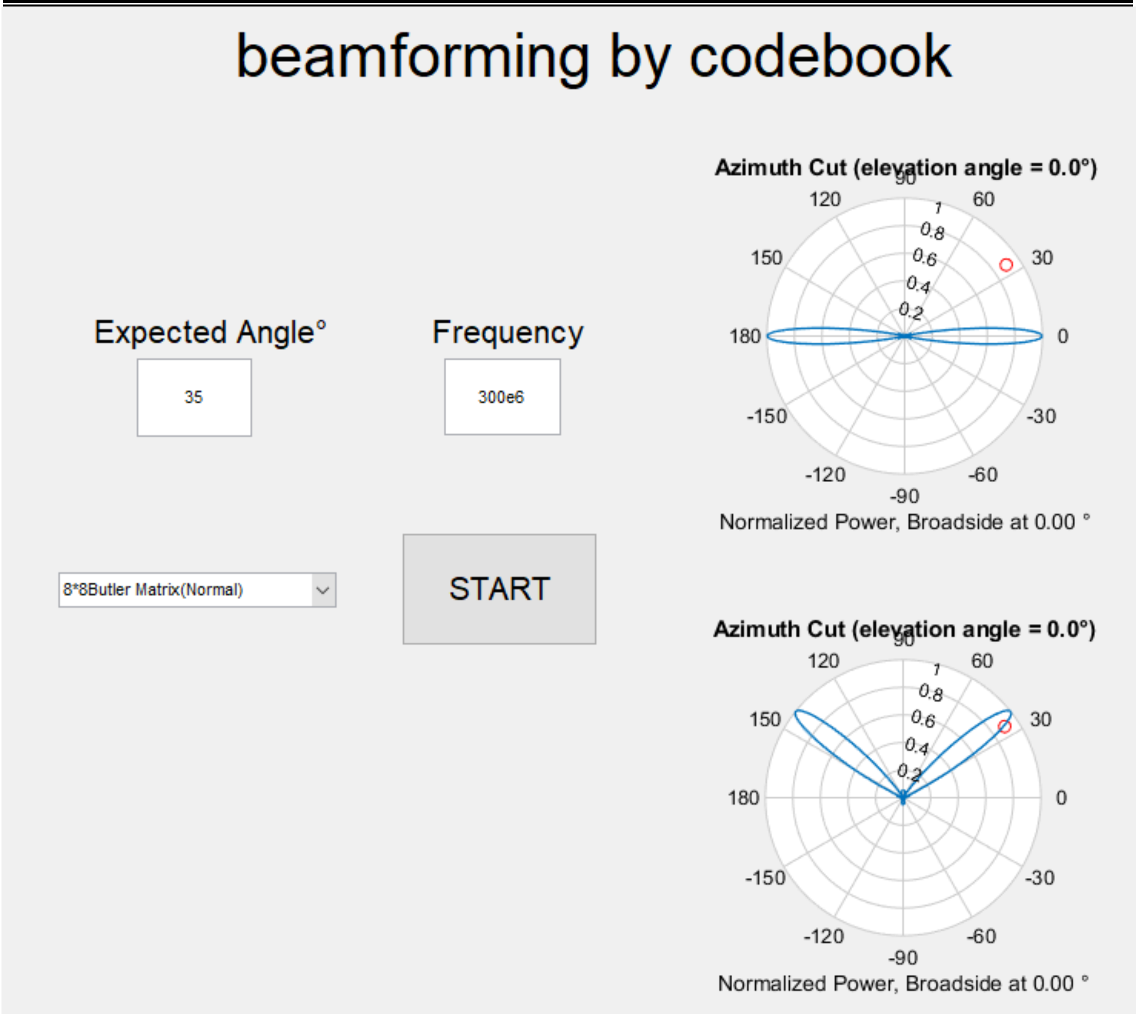


图 5-8 基于码本的波束赋形演示输出

可见经过波束赋形后，波束成功指向目标信源（红点）。因为参考了 butler 矩阵作为波束指向的目录，精度有限，实际指向仍存在着一定的误差。

5.6 本章小结

本章主要介绍了课题设计的用户交互界面对前文模型的演示。

首先对 GUI 模型的框架进行了说明，随后分别对 GUI 的四个模块——基础规则天线阵列的仿真与方向图绘制；任意规则的天线阵列的仿真；波束赋形的实现；基于 Butler 矩阵的波束赋形仿真的演示进行介绍，最后对演示的输出结果进行对比分析，证明前文理论的正确性。

结 论

大规模阵列和波束赋形技术作为第五代移动通信的核心技术，海内外的许多专家学者都对其进行了深层次的剖析和研究。无论是在理论研究，还是在工程实践应用中，通信的发展都是日新月异。且在未来的移动通信系统中，物联网的勃发毫无疑问会使移动设备的吞吐量需求急剧增加，且无线频段资源逐渐会变得短缺，为了解决日后的通信系统的需求，设计出能够有效提升通信资源的利用效率和降低通信成本的大规模阵列天线模型和波束赋形算法将是日后研究的核心。

本篇论文基于上述方向进行大规模天线和波束赋形的仿真和分析，并在此基础上对前文的理论进行演示，本文的主要工作如下：

（1）对大规模天线阵列和波束赋形的基础理论进行了梳理，从单个天线元入手，推导了不同天线的阵因子式，并从公式理论上分析了阵列天线和波束赋形技术应用的有效性和必要性。

（2）根据阵列天线的理论基础，针对阵列天线进行了整体的仿真与分析，分析阵列天线不同的变量对于天线辐射方向图，方向性，天线增益的影响。同时对相控阵的波束赋形技术进行了研究和仿真，并在此基础上对 butler 矩阵进行讨论，并自定义设计了一套码本。最后讨论基于码本波束赋形的有限性。

（3）在前文工作的基础上，本课题最后的工作对上述天线基础理论及波束赋形的实现进行演示。本文的演示方式是建立用户图形交互界面，对于天线基础理论部分，将希望探究的参数作为任意输入变量进行仿真，计算并画出对应的阵列天线方向图和方向性系数；GUI 的另两个模块分别演示基于码本和基于非码本的波束赋形处理。用户图形界面的建立是为了方便研究者或者初学者更直观地对天线方向图进行分析，通过对比码本和非码本的波束赋形技术可以更深入理解码本的优缺点。GUI 建立了一个演示框架，课题后续的研究者还可根据研究方向添加其它内容，如波束赋形的算法等。

尽管本文在研究阵列天线的辐射特性和波束赋形的演示等方面有一定的进展，但是限于时间和精力有限，本文的设计成果还有待进行进一步的完善，针对本课题还有以下展望：

（1）本文主要是在物理信号的层面上对阵列天线和波束赋形进行研究，并没有涉及到 CSI 层面上的仿真。而通信研究的核心的部分在于构建信道，因此希望后续的研究可以在本文的基础上进行信道仿真，并在此基础上进行波束赋形算法的研究。

（2）本课题约一半的工作在于波束赋形的GUI演示工作，目前能够勉强实现模型的基础演示功能，然而用户的演示界面较为粗糙，在此希望课题后面的工作者在添加算法演示功能的同时能够针对演示界面进行美化。

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哈尔滨工业大学本科毕业设计（论文）原创性声明

本人郑重声明：在哈尔滨工业大学攻读学士学位期间，所提交的毕业设计（论文）《大规模天线阵列波束赋形的实现与演示》，是本人在导师指导下独立进行研究工作所取得的成果。对本文的研究工作做出重要贡献的个人和集体，均已在文中以明确方式注明，其它未注明部分不包含他人已发表或撰写过的研究成果，不存在购买、由他人代写、剽窃和伪造数据等作假行为。

本人愿为此声明承担法律责任。

作者签名：　　　　　　　　　　　日期：　　　年　　月　　日

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大一的消极迷茫；大二的孤独彷徨；大三的锲而不舍；大四的放飞自我，大学里有开心，有失落，有遗憾，也有期待，它们都是人生画卷里靓丽的风景线。无论是明月当空，还是繁星点点，这就是我们四年的岁月。

附　录

附件一：相关外文文献

5g 大规模 MIMO 系统的波束赋形技术:概述、分类和未来研究趋势

作者：马来西亚国立大学电子和电气工程系
Ehab ALI；Mahamod ISMAIL

摘要:大规模多输入多输出(MIMO)系统结合波束赋形天线阵列技术有望在下一代无线通信系统(5G)中发挥关键作用,将于 2020 年及以后部署。这篇综述论文的主要目的是讨论最有利的波束赋形技术类型的最新研究，这些技术可以部署在大规模 MIMO 系统中，并阐明其重要性大规模 MIMO 系统中的波束赋形技术，用于消除和解决大规模 MIMO 系统实施面临的许多技术难题。详细回顾了无线通信系统中使用的最佳波束赋形技术的分类，以确定哪些技术更适合在大规模 MIMO 系统中部署，以提高系统吞吐量并减少内部和内部细胞干扰。为了克服文献中的局限性，本文提出了一种最佳波束赋形技术，该技术可以在大规模 MIMO 系统中提供最高性能，满足下一代无线通信系统的要求。

关键词：波束赋形分类；大规模 MIMO；混合波束赋形；毫米波波束赋形

1.绪论

下一代蜂窝通信系统，即 5G，将由能够显著提高吞吐量的技术提供帮助。近年来，各种研究集中于大规模多输入多输出(MIMO)系统,被认为在 5g 大规模 MIMO 系统中发挥重要作用的是 MIMO 系统，其中预编码器和/或检测器包含大量天线。如此多的天线使得更高的频谱效率和能量效率得以实现。几种类型的天线可用于此目的，其中一种称为智能天线。智能天线是在无线通信链路的基站(BSs)和移动站由众多天线元件组成的组织，其中信号被适当地管理,目的是改善无线移动链路，提高系统性能。

这种天线是用于无线通信系统的数字天线，为用户设备提供了增加多样性的好处。天线通过成功地减少多径衰落和信道干扰，提高了无线通信系统的容量,这

可以通过将信号辐射集中在预期的方向，并根据信号周围或使用波束赋形技术改变这种辐射来实现。

在无线通信系统中，发送和接收波束赋形用于从具有多个天线的 BS 到应覆盖的一个或多个用户设备的信号传输。发射波束赋形的目标是最大化每个用户的接收信号功率，同时最小化来自其他用户的干扰信号功率，从而增加容量。这可以通过从所有具有不同幅度和相位的发射器发送相同的信号来实现。这些发射信号的多个版本将通过不同的多输入多输出信道，从而在期望的用户处建设性地添加它们，在其他用户处破坏性地添加它们。

2.背景

2.1 大规模多输入多输出系统

由于服务用户的不断增长和对大量数据的需求不断增加，MIMO 系统受到了极大的关注。多用户 MIMO 系统可能为提高无线通信中的频谱效率提供突破性技术。随着无线服务请求数量的不断增加，频谱有限，MIMO 已成为未来通信系统的关键技术。最近，在多用户 MIMO 通信领域进行了大量深入的研究，其中相关系统被称为大规模 MIMO 或大规模 MIMO 系统。

大规模 MIMO 系统被定义为 MU-MIMO 系统的一种布置，其中在 BS 部署了大量天线元件，在终端部署了大量天线。在大规模多输入多输出系统中，大量连接到基站的天线(数百或数千)同时工作的时间要少得多(数十或数百)使用相似时间和载波频率资源的终端。大规模多输入多输出系统由于其特性和能效约为 100 倍，可以将无线通信系统的容量提高 10 倍或更多。大规模 MIMO 系统实现的容量增加是由于实施了大量天线。然而，使用大量天线会引起干扰问题，这可以通过部署波束赋形天线而不是常规天线来缓解。

2.2 大规模 MIMO 系统中波束赋形的好处

波束赋形是一个过程，通过在期望终端的方向上完全建立处理信号并取消干扰信号的波束，来产生天线的辐射波束图。这可以使用有限脉冲响应(FIR)滤波器来实现。FIR 滤波器是有益的，因为它们的权重可以自适应地改变，并应用于获得最佳波束赋形。波束赋形在大规模 MIMO 系统中的应用具有以下优点:增强能量效

率、提高频谱效率、提高系统安全性以及对毫米波段的适用性。

2.2.1 提高能源效率

波束赋形天线向预期用户发送信号的较低功率要求和成本降低导致大规模MIMO 系统的功耗和放大器成本降低。大规模 MIMO 系统通过波束赋形过程来辅助，通过计算满足操纵节能大规模 MIMO 系统的几个基本标准的天线元件的最佳数量来降低整个系统的功耗。对于每个 BS 的每个指定功耗，整体能效相对不受单元中工作天线元件数量的影响;因此,可以为系统中的整个单元实现通用数量的工作天线，以获得高成本效益和整体能效。为了满足终端吞吐量要求，必须考虑波束赋形技术的优化过程，如功率控制，以降低基站的功耗。

2.2.2 提高频谱效率

上行和下行信号的功率控制，训练序列信息的利用，以及通过波束赋形天线元件改善信号质量，可以提高容量。大规模 MIMO 系统具有提高无线通信系统频谱效率的潜力，通过在 BSs 上安装具有大量服务天线元件的波束赋形天线阵列，并进行相干预编码和检测器处理。蜂窝系统的频谱效率受到手机载频干扰比分布的影响。

2.2.3 毫米波段的适用性

波束赋形的另一个优点是它可以应用于毫米波段。因为大多数频谱适用于密集的城市蜂窝通信，获得许可，在频域中提高数据速率的唯一方法是利用毫米波范围附近未使用的频带。这些频段的主要优点是它们的高带宽可用性。然而，即使在短距离内，这些条带的传播特性也很差。

必须使用高度定向的天线来克服这一限制。幸运的是，由于高载波频率，在相当小的天线尺寸下可以实现高天线增益。这意味着这些定向天线也可以与移动单元一起使用。然而，固定窄波束系统不适合移动应用。这使得波束赋形成为此类应用的唯一可行的解决方案。

2.3 大规模 MIMO 预编码器和检测器

如上所述，Massive MIMO 系统具有以下优点:吞吐量性能增强、低成本组件、低功耗和高效能量辐射。发射信号的预编码或预均衡是 MIMO 系统中涉及的功能之一，并为依赖 CSI 可用性来纠正 BSs 信号错误的大规模 MIMO 系统开发。终端

的探测器随后应在下行阶段同时从 BS 的天线阵列元件中恢复所需的已建立信号。具有增强功耗和低估计复杂性的检测器设计很难获得，但极其重要，尤其是当天线数量增加时。

在大多数大规模 MIMO 系统的情况下，移动台可以精确地跟踪来自导频信号的信道的瞬时状态，导频信号被特征地插入到来自小区内各种终端的上行链路传输信号中;因此,接收到的信号可以表示如下:

$$\mathbf{y}_{j,u}(t)=\sqrt{P_{\mathrm{u}}}\sum_{k=1}^{K}\mathbf{h}_{j,k}(t)s_k(t)+\mathbf{n}_j(t) \tag{1}$$

这里$\mathbf{h}_{j,k}(t)\in\ ^{M\times1}$是从小区中第 k 个用户到 BS 的上行信道矢量，M 是 BS 中阵列天线的元素数量,$s_k(t)$是第 k 个用户在第 t 个时隙在单元格中传输的符号,P_{u}是平均信噪比(SNR)，$\mathbf{n}_j(t)\in\ ^{M\times1}$是加性噪声向量

在每个时隙，在 BS 处采用线性波束赋形来抑制干扰并增强信号。对于第 j 个单元中的第 k 个用户，接收到的信号向量,$\mathbf{y}_{j,\mathrm{u}}(t)$在式(1)中，由波束赋形处理，结果信号表示为

$$\tilde{s}_{j,k}(t)=\mathbf{w}_{j,k}^{\mathrm{H}}\mathbf{y}_j(t) \tag{2}$$

在下行链路阶段，BS 部署 N 个发射波束赋形天线单元，每个终端可以很好地配置多个波束赋形天线。$\mathbf{w}_{j,k}$表示第 j 个小区中第 k 个用户的发射下行波束赋形矢量。然后，第 j 个单元中第 k 个用户处的接收信号由

$$y_{j,k,\mathrm{d}}=\boldsymbol{h}_{j,j,k}^{\mathrm{H}}\boldsymbol{w}_{j,k}x_{j,k}+\sum_{n,t\neq j,k}\boldsymbol{h}_{n,j,k}^{H}\boldsymbol{w}_{n,l}x_{n,l}+n_{j,k} \tag{3}$$

这里$x_{j,k}$表示第 j 个单元中第 k 个用户的信息信号。用户 k 处的信噪比(SINR)为

$$\mathrm{SINR}_{j,k}=\frac{\left|\boldsymbol{h}_{j,j,k}^{\mathrm{H}}\boldsymbol{w}_{j,k}\right|^2}{\sum_{n,l\neq j,k}\left|\boldsymbol{h}_{n,j,k}^{\mathrm{H}}\boldsymbol{w}_{n,l}\right|^2+\sigma^2} \tag{4}$$

我们可以将这些预编码器/检测器分为两大类:线性预编码器/检测器和非线性预编码器/检测器。具有低复杂度的线性信号检测器考虑所有信号，这些信号通过排除指定发射天线中的期望流作为干扰来传输。因此，从其他天线传输的干扰信号

在从指定发射天线检测所需信号的过程中被减少或取消。众所周知的探测器，如最大比率合并(MRC)接收机(也称为匹配滤波器(MF)接收机)，强迫零接收机(ZFRs),和最小均方误差(MMSE)接收机是大规模多输入多输出系统的实用候选接收机。

线性检测器简单，但误码率性能较差。相比之下，非线性检测器提供了合理的误码率性能，但具有较高的计算复杂度。最著名的非线性预编码器/检测器技术可用于 MUMIMO 系统是脏纸编码(DPC)，矢量扰动(VP),和晶格辅助方法(Masouros 等人，2013)。与使用线性检测器相比，这种检测器可以以更高的估计复杂性为代价获得更好的性能。

3 波束赋形技术分类

波束赋形技术用于大规模多输入多输出系统中用于发射和接收信号的智能天线。智能天线是具有信号处理算法的天线阵列，该算法能够识别空间信号标识符，例如信号的到达方向(DOA)，并使用它们来评估波束赋形向量。这些矢量识别并跟踪从移动台发送的所需信号。智能天线技术特别用于声信号处理、射电天文学和射电望远镜、跟踪和扫描雷达。

根据波束赋形技术的特点对其进行分类。一些科学家根据波束赋形技术的物理特性对其进行分类。研究人员将技术分为模拟波束赋形、数字波束赋形和混合模拟/数字波束赋形。采用模拟波束赋形的好处是，与数字波束赋形相比，廉价的移相器用于大规模多输入多输出系统，具有提供更准确和快速的基础结果以获取用户信号的优势。然而，数字波束赋形具有高复杂性和昂贵的设计;因此，它没有被用于大规模多输入多输出系统。混合模拟/数字波束赋形已经为大规模 MIMO 系统开发，以获得模拟和数字波束赋形的优势。此外，许多算法为增加和优化自适应波束赋形天线的性能提供了技术进步。

这些算法可分为两大类:盲自适应算法和非盲自适应算法。非盲自适应算法查询传输信号的已知统计量，目标是确定加权旅行路径。这一目标通常可以通过通过通信链路传输到终端的训练信号来实现，以支持首选用户的检测。相比之下，盲自适应算法不需要训练任何统计知识;盲算法的重点是重新建立下行信号的某些类型的物理特性，目标是最大化信号到期望终端和最小化来自其他终端的干扰。可以提高波束赋形技术服务质量的另一个因素是，它们可以用于毫米波段(宽带)，而不是

传统波段(窄带)，也就是说,900MHz-5GHz。在毫米波段，由于波长和波束宽度的大小非常尖锐，天线阵列非常小,BS 和用户之间的最大范围是几百米。我们在图 1 中展示了这些分类。

3.1 宽带波束赋形与窄带波束赋形

波束赋形根据信号带宽可分为两类:窄带波束赋形和宽带波束赋形。窄带波束赋形是通过接收到的阵列信号的瞬时线性组合来实现的。然而，当所涉及的信号是宽带的，一个额外的处理维度必须采用有效的操作，如抽头延迟线(或 FIR/IIR 滤波器)或最近提出的传感器延迟线,这导致了一个宽带波束赋形系统(柳和 Weiss，2010)。

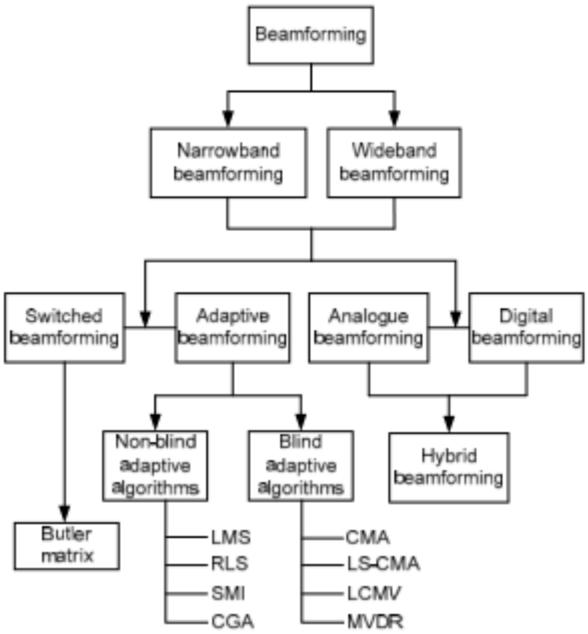


图 1 一般波束赋形分类

LMS:最小均方;RLS:递归最小二乘;SMI:样本矩阵反演;CGA:共轭梯度算法;CMA:恒模算法;LS-CMA:最小二乘恒模算法;LCMV:线性约束最小方差;MVDR:最小方差无失真响应

目前大多数无线通信应用仍然集中在窄带波束赋形上;然而,由于 5g 要求实现极高的数据速率，宽带波束赋形成为未来无线通信应用的重要课题。可以为 5g 实现的宽带波束赋形的最佳例子是毫米波波束赋形。

3.2 相控阵列波束赋形与自适应阵列波束赋形

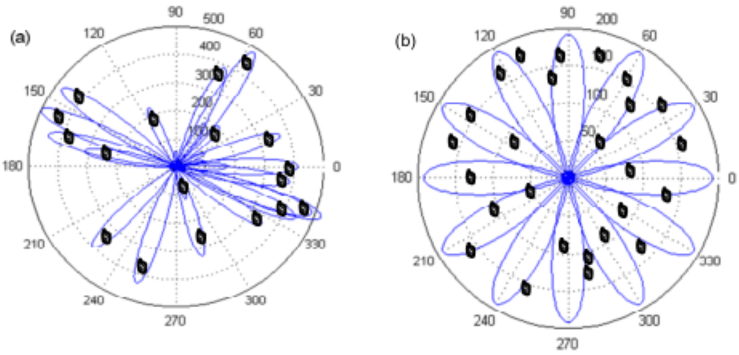
波束赋形方案通常分为相控阵列波束系统或自适应阵列系统。基于相控系统依赖于一个固定的波束赋形网络，该网络产生已建立的预调制光束。也许固定波束赋形最常见的解决方案是 Butler 矩阵。Butler 矩阵由混合耦合器、移相器和分频器组成。切换波束系统需要一个切换网络，目的是选择合适的波束来从特定的终端获得所需的信号。选择的大部分发射光束可能不会指向所需的方向。此外，光束通常服务于一个以上的移动台(图 2a)。相比之下，自适应阵列系统可以选择为每个用户制定一个特殊波束。该选项是通过权重向量实现的，权重向量通过自适应阵列处理器应用于检测信号，目的是控制天线阵列元件之间的相位变化及其幅度扩展。

自适应波束赋形假设 BS 使移动台的本地化现代化。然而，准确的定位是一项艰巨的任务，因为大量的实时移动站点可能会使这一过程过载。因此，估计入射到天线阵列上的接收信号的波达方向是无线通信系统的主要问题。将自适应波束赋形系统付诸实践比切换波束赋形系统要困难得多。

相比之下，完美的自适应光束试图减少用户之间的干扰，并实现显著改善提供的功率资源。无论如何，这两类都有优缺点，在大规模 MIMO 系统的实施中必须考虑这一点。这些优点和缺点如表 1 所示，这说明虽然自适应波束赋形很难实现，大多数最近与大规模多输入多输出相关的研究和仿真更喜欢这种技术，因为它对 5g 要求的可靠性。

表 1 两种方法在覆盖范围、容量、干扰抑制和复杂性方面的比较

参数	相控阵列波束赋形	自适应波束赋形
覆盖范围和容量	与常规天线系统相比，覆盖范围和容量更好。从 20%到 200%的改进中心	覆盖更大的区域，并且与在相同功率级别的切换波束赋形相比更加均匀
干扰消除	在区分所需信号和干扰信号时遇到问题	提供更全面的干涉喷射
复杂性和成本	-易于在现有蜂窝系统中实现 -便宜 -使用简单的算法选择光束	-难以实施 -昂贵 -需要更多时间和更准确(高度复杂)的算法来引导光束和空值



a) 自适应波束赋形　　　　b) 切换波束赋形

图 2

3.3 自适应波束赋形算法:盲算法与非盲算法

在波束赋形天线阵列中，在天线阵列的每个天线单元处接收的信号是自适应建立的，以提高无线通信系统的整体效率。在 BS 的不同天线上检测到的信号通过具有复杂权重的乘法过程。修改后的权重立即求和。在自适应波束赋形天线阵列中，根据 DOA，估计波束可以引导到所需的信号方向，并且对不需要的信号方向进行归零。智能天线可以很容易地估计输入信号的 DOA 和交互信号的方向。然后，使用波束赋形算法，天线的波束朝着期望的信号方向产生，空值朝着干扰信号方向形成。自适应波束赋形算法分为两种主要类型:非盲自适应算法和盲自适应算法。自适应阵列输出的一般方程 $y(t)$ 是

$$y(t)=\boldsymbol{w}^{\mathrm{H}}\boldsymbol{x}(t) \tag{5}$$

其中 w^{H} 表示权重向量的复共轭转置。权重以基于数组的迭代方式计算 $y(t)$。在非盲自适应算法中，参考信号用于不断调整阵列权值。随后，将每次迭代结束时权重的响应与参考信号进行比较，并实现产生的误差信号来调整算法中的权重。误差信号有

$$e(t)=d(t)-\boldsymbol{w}^{\mathrm{H}}\boldsymbol{x}(t), \tag{6}$$

这里 $d(t)$ 是参考信号，与原始信号相似,算法应尽量减小输出信号和参考信号之间的误差差异，使输出信号尽可能接近原始信号。然后，可以形成朝向所需信号的光束，并且始终可以跟踪用户。

非盲自适应算法的一些例子是最小均方(LMS)算法，递归最小二乘(RLS)算法。

相比之下，盲自适应算法不依赖于参考信号的实现，因此，不需要调整阵列的权重。

盲自适应算法的著名例子包括恒模算法(CMA)和最小二乘恒模算法。通过自适应地改变天线阵列方向图，零点被设计成朝向识别的干扰源方向;因此，自适应波束赋形技术可以在干扰条件下工作。

自适应波束赋形中的主要发生器是数字信号处理器，它推导接收信号，定义复权值，将产生的权值单独乘以每个元素响应，并修改阵列辐射模式。噪声信号和干扰信号的影响被天线阵列最小化，这也产生了朝着期望方向的最大增益。因此，智能天线的性能主要取决于用于数字波束赋形的自适应算法。自适应波束赋形算法的大多数性能标准取决于各种类型算法在评估时间(转换速度和迭代次数)和准确分辨率方面的比较,受多径和干扰信号的影响，从所需终端获得最大信噪比。

最近，基于零转向方法开发了两种著名的自适应算法，LCMV 波束赋形和 MVDR 波束赋形;这些算法使用零转向波束赋形思想来产生自适应波束赋形阵列。零转向天线在无线通信中至关重要，因为它们通过将零指向干扰方向，同时指向期望方向的主瓣来提高 SINR。天线方向图中的空位置是复权重的函数。它们的值是通过求解线性方程得到的。然而，干扰信号的方向必须精确知道。这在实践中导致了一个问题，因为在实时情况下，干扰信号的方向随着时间的推移而变化。采用可跟踪干扰方向的自适应零转向来解决这个问题。

3.3.1 线性约束最小方差波束赋形

大多数设计的波束赋形算法需要一些参考信号和所需信号强度的知识。这些限制可以通过对权重向量应用线性约束来克服。LCMV 的波束赋形器是基于功率约束选择最佳权重向量来降低滤波器响应的空间滤波器。该条件与其他约束一起，确保在所需位置的信号保护，同时减少来自其他方向的创建信号的方差效应。LCMV 是基于传统的 MMSE 开发的，用于简单地自动调整阵列权重。

LCMV 技术的主要缺点是其低收敛速度，这使得它不适合应用于大规模 MIMO 系统，即使它只需要 DOA 来最大化信噪比,这简化了过程估计。

3.3.2 最小方差无失真响应波束赋形

MVDR 波束赋形算法的主要概念是通过选择天线元件的权重来减少波束响应的方差，同时保持将波束引导到所需方向恒定的增益水平。该程序的主要目的是终

止来自不希望的方向的强干扰信号。

3.4 模拟、数字和混合模拟/数字波束赋形

波束赋形技术分为两种类型:模拟波束赋形和数字波束赋形。模拟波束赋形是 50 多年前提出的。模拟波束赋形天线由混合矩阵和固定移相器组成。模拟波束赋形背后的主要概念是使用低成本移相器控制每个发射信号的相位。选择性射频(RF)开关用于促进光束转向功能(转向角度)。

相比之下，数字波束赋形由许多实用程序组成，包括 DOA 估计、天线辐射模式的可编程控制以及波束和零点的自适应转向，以增强 SINR，只有使用数字技术才能获得这些优势。

数字波束赋形的实现不适用于大规模 MIMO 系统，因为传统的波束赋形是在基带实现的，这有助于控制信号的相位和幅度;因此,它要求处理信号的载波频率在交叉 RF 链后向上转换，其中包括数字到模拟(D/a)转换器、混频器和功率放大器。射频链的响应然后与天线元件结合。换句话说，每个天线阵列元件必须通过专用的 RF 链进行增强。这在大规模 MIMO 系统中实现是昂贵的，因为需要大量的天线元件。

如上所述，使用便宜的移相器以简单的方式实现模拟波束赋形。因此，模拟波束赋形比数字波束赋形更具成本效益。同样，与数字波束赋形相比，模拟波束赋形表现出更差的性能，因为移相器的振幅不灵活。为了获得更好的性能，提出了数字和模拟波束赋形之间的混合，称为混合波束赋形。

4 结论

本文全面概述了大规模 MIMO 系统中的波束赋形技术。回顾了最近关于波束赋形技术的各种分类的研究，并研究了哪些技术更适合在大规模多输入多输出系统中使用。

宽带波束赋形(毫米波段波束赋形)与窄带波束赋形相比，它更适用于大规模 MIMO 系统，因为它具有降低带宽问题的成本效益，并且在智能天线阵列设计中具有节能电路。自适应波束赋形比交换波束赋形更适合大规模 MIMO 系统，因为它具有消除干扰和降低功耗的能力。

最后，大规模 MIMO 系统的最佳波束赋形可以通过在毫米波段部署模拟和数字波束赋形(混合模拟/数字波束赋形)与最佳算法相结合来实现。这种最佳波束赋形的部署将在大规模多输入多输出系统中提供最高的性能，满足下一代无线通信系统的要求。

附件二：外文文献复印件

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Review:

Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research

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Abstract: Massive multiple-input multiple-output (MIMO) systems combined with beamforming antenna array technologies are expected to play a key role in next-generation wireless communication systems (5G), which will be deployed in 2020 and beyond. The main objective of this review paper is to discuss the state-of-the-art research on the most favourable types of beamforming techniques that can be deployed in massive MIMO systems and to clarify the importance of beamforming techniques in massive MIMO systems for eliminating and resolving the many technical hitches that massive MIMO system implementation faces. Classifications of optimal beamforming techniques that are used in wireless communication systems are reviewed in detail to determine which techniques are more suitable for deployment in massive MIMO systems to improve system throughput and reduce intra- and inter-cell interference. To overcome the limitations in the literature, we have suggested an optimal beamforming technique that can provide the highest performance in massive MIMO systems, satisfying the requirements of next-generation wireless communication systems.

Key words: Beamforming classifications; Massive MIMO; Hybrid beamforming; Millimetre-wave beamforming
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1 Introduction

Next-generation cellular communication systems, or 5G, will be assisted by technologies that produce significant improvements in cell throughput. In recent years, various studies have focused on massive multiple input multiple output (MIMO) systems, which are considered to play a significant role in 5G. Massive MIMO systems are MIMO systems wherein the precoders and/or detectors contain numerous antennas. Such a larger number of antennas enable higher spectral efficiency and energy efficiency to be achieved. Several types of antennas can be used for this purpose, one of which is called a smart antenna. Smart antennas are organizations of numerous antenna elements at base stations (BSs) and mobile stations of wireless communication links, in which signals are appropriately managed, with the purpose of improving the wireless mobile link and increasing the performance of the system.

Such an antenna is a digital antenna used in wireless communication systems and provides the benefit of increased diversity for the BS and/or user equipment. The antenna enables increase of capacity in wireless communication systems by successfully reducing multipath fading and channel interference, which can be realised by concentrating signal radiation only in the anticipated direction and modifying such radiation according to the signal surroundings or varying traffic situations using beamforming techniques.

In wireless communication systems, transmit and receive beamforming is used for signal transmission from BSs with multiple antennas to one or multiple pieces of user equipment that should be covered. The objective of transmit beamforming is to

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maximise each user's received signal power while minimising the interference signal power from the other users, hence increasing capacity. This can be achieved by transmitting the same signal from all transmitters with different amplitudes and phases. These multiple versions of the transmitted signal will pass through different MIMO channels such that they are added constructively at the desired users and destructively at other users.

Several other review papers, such as Vouyioukas (2013) and Murray and Zaghloul (2014), have focused on beamforming techniques for MIMO. Vouyioukas (2013) investigated beamforming techniques in MIMO relay networks and procedures that were recently developed for interference mitigation under various network performance challenges, such as complexity and power consumption reduction and capacity improvements. Murray and Zaghloul (2014) reviewed various cognitive beamforming techniques that can be used in MIMO systems. Several algorithms were proposed based on constraints or idealizations of channel state information (CSI) and quality-of-service metrics. The authors evaluated the cognitive beamforming techniques using distributed, joint, and cooperative beamforming strategies based on game theory, genetic algorithms, and neural networks.

Kutty and Sen (2016) concentrated on the use of beamforming techniques for millimetre wave (mm-wave) communications. They provided a significant survey on the evolution and advancements in antenna beamforming for mm-wave communications in the setting of the different requirements for indoor and outdoor communication scenarios, and introduced beamforming techniques generally by announcing some basic concepts of beamforming, including typical beamforming architectures and approaches.

Heath *et al.* (2016) provided an overview of signal processing for mm-wave wireless communication systems and described the main mm-wave-MIMO architectures including analogue and hybrid beamforming for different types of propagation models. Furthermore, channel estimation algorithms and beam training protocols were reviewed in detail for mm-wave communications. Although the aforementioned surveys and many other surveys have investigated the importance of beamforming for MIMO systems in detail, they did not discuss which types of beamforming techniques can be deployed for massive MIMO systems according to 5G requirements. Thus, this paper is focused on beamforming technique classifications for wireless communication systems and investigation of their effects on massive MIMO systems to determine which optimal categories can be adopted with massive MIMO system requirements.

This paper provides an in-depth overview of up-to-date research on classifications of beamforming techniques that can be deployed for massive MIMO systems. Several key elements are discussed to show the importance of beamforming techniques in reducing and resolving many technical complications that disallow massive MIMO implementation.

In Section 2, a background of massive MIMO systems and the benefits of applying beamforming techniques for massive MIMO systems are presented. In addition, various types of transmitters (precoders) and receivers (detectors) that can be implemented in massive MIMO systems are introduced. Section 3 provides comprehensive details about beamforming approaches and their classifications in physical terms. Switched and adaptive beamforming algorithms and their possessions are discussed in detail to establish which types of techniques are more affordable for massive MIMO systems. In addition, adaptive beamforming optimization algorithms based on azimuth and elevation angles, such as linearly constrained minimum variance (LCMV) and minimum variance distortionless response (MVDR), are presented. Furthermore, hybrid digital/analogue beamforming clarification that can be implemented in massive MIMO systems is discussed in detail. Section 4 is focused on mm-wave bands and their advantages for beamforming techniques in massive MIMO systems as a type of broadband beamforming. Unresolved issues and trends for the future are addressed in Section 5. Finally, conclusions are provided in Section 6.

2 Background

2.1 Massive MIMO systems

MIMO systems have received significant attention owing to the growing number of served users and the increasing demand for large amounts of data. Multi-user MIMO systems might provide a breakthrough technique for improving spectral efficiency in wireless communications. MIMO has become a key technology for future communication systems as the number of requests for wireless services continues to increase, with the spectrum being finite. Recently, numerous in-depth studies have been conducted in the field of multi-user MIMO communication, in which relevant systems are referred to as massive MIMO or large-scale MIMO systems.

Massive MIMO systems are defined as an arrangement of MU-MIMO systems wherein large quantities of antenna elements at BSs and large quantities of antennas at terminals are deployed. In massive MIMO systems, large quantities of antennas (hundreds or thousands) connected to a BS simultaneously work for considerably fewer (tens or hundreds) terminals using similar time and carrier frequency resources (Larsson *et al.*, 2014). Massive MIMO systems can improve the capacity of wireless communication systems 10-fold or more owing to their characteristics and the energy efficiency by approximately 100-fold. The capacity increase enabled by massive MIMO systems is due to the large number of antennas that are implemented. However, using a large number of antennas causes interference problems, which can be mitigated by deploying beamforming antennas instead of conventional antennas.

The definition of beamforming in massive MIMO systems differs slightly from the aforementioned definitions. Beamforming is a signal processing procedure used with multiple arrays of antennas at the transmitter side and/or receiver side to simultaneously send or detect multiple signals from multiple desired terminals to increase system capacity and performance. Beamforming can be realised by assembling the elements in an organised array, in which beams steered toward a specific direction are added and the other beams neglected. Although this technique is not new, it remains reinforced by developed wireless communication system organizations, namely, long-term evolution (LTE) and LTE advanced operators. These operators focus on integrating beamforming techniques into wireless communication systems. The energy efficiency of massive MIMO systems could be increased dramatically by deploying a large quantity of beamforming antenna elements at the BS (Rusek *et al.*, 2013; Larsson *et al.*, 2014; Lu *et al.*, 2014). Recent studies related to 5G wireless systems have largely focused on massive MIMO systems and beamforming solutions. However, beamforming techniques can still contribute to further enhancements of future wireless communication systems.

2.2 Benefits of beamforming in massive MIMO systems

Beamforming is a process formulated to produce the radiated beam patterns of the antennas by completely building up the processed signals in the direction of the desired terminals and cancelling beams of interfering signals. This can be accomplished using a finite impulse response (FIR) filter. FIR filters are beneficial in that their weights can be varied adaptively and applied to obtain the optimum beamforming. The application of beamforming in massive MIMO systems has the following advantages: enhanced energy efficiency, improved spectral efficiency, increased system security, and applicability for mm-wave bands.

2.2.1 Enhanced energy efficiency

The lower power requirements of beamforming antennas for transmitting signals to the intended user and cost reductions result in the lower power consumption and amplifier costs of massive MIMO systems. The significance of overall energy efficiency for upcoming wireless communication systems was discussed by Yang and Marzetta (2013b; 2015), Björnson *et al.* (2014), Chen *et al.* (2015), He *et al.* (2015), and Gozalves (2016). Massive MIMO systems are assisted by beamforming processes to reduce the power consumption of the entire system by computing the optimal quantity of antenna elements that meet several essential criteria for manipulating energy-efficient massive MIMO systems. For each specified power consumption of each BS, the overall energy efficiency is relatively unaffected by the number of working antenna elements in the cell; thus, a common number of working antennas can be implemented for the entire cells in the system to obtain high cost-effectiveness and overall energy efficiency. To meet the terminal throughput requirements, optimization processes for beamforming techniques, such as power control, must be considered to reduce the power consumption at the BS.

2.2.2 Improved spectral efficiency

Power controlling of the uplink and downlink signals, utilization of the information of the training sequence, and improvement of the signal quality by beamforming antenna elements enable capacity improvements. Massive MIMO systems have potential for improving the spectral efficiency of wireless communication systems by installing beamforming antenna arrays with large numbers of serving antenna elements at BSs with coherent precoding and detector processing (Huh *et al.*, 2012; Kim *et al.*, 2013; Ngo and Larsson, 2013; Behjati *et al.*, 2015; Jin *et al.*, 2016; Noh *et al.*, 2016). The spectral efficiencies of cellular systems are influenced by the carrier-to-interference ratio distributions at the mobiles.

A comparison of the performances of an omnidirectional BS and sectored antennas with beamforming in the presence of traffic was presented by Ismail *et al.* (1999). The performance of traffic in wireless system constructions has been effectively enhanced via the replacement of conventional omnidirectional antenna arrays with dynamic cell sectored construction and beam steering antenna arrays using time division duplex (TDD) procedures. Simulations have shown that the efficiency of dynamic cell sectoring is improved by using beamforming techniques rather than omnidirectional antennas at BSs. Moreover, average beamforming gains increase the power of the downlink signal at the precoder because of the coherent combination of the received signals at all antenna elements. The gain is relative to the download speed; therefore, the data rate can be increased using massive MIMO systems (Pradhan and Roy, 2014; WWRF, 2014; Yan *et al.*, 2014; Liu GY *et al.*, 2016).

2.2.3 Increased system security

The concept of beamforming is to steer the transmitted signal toward the intended user; therefore, the receiver will be the only party to recover the wanted signal from the overlay signal. Physical security can be achieved because the probability of an eavesdropper receiving the transmitted signal will be smaller than when using conventional antennas (Liao *et al.*, 2011; Guo *et al.*, 2015).

2.2.4 Applicability for mm-wave bands

Another advantage of beamforming is that it can be applied to mm-wave bands. Because the majority of the frequency spectrum that is suitable for dense urban cellular communication (e.g., below 5 GHz) is licensed, the only way to increase data rates in the frequency domain is by leveraging the unused frequency bands near the mm-wave range (e.g., 60 GHz and above), as discussed by Cudak *et al.* (2013), Rappaport *et al.* (2013), Medbo *et al.* (2014), and Carton *et al.* (2015). The main advantage of these frequency bands is their high bandwidth availability. However, the propagation characteristics of these bands are poor, even for short distances.

Highly directive antennas must be used to overcome this limitation. Fortunately, high antenna gains can be achieved at a considerably smaller antenna size because of the high carrier frequency. This means that these directional antennas can also be used with mobile units. However, a fixed narrow beam system is not suitable for mobile applications. This makes beamforming the only viable solution for such applications (Andrews *et al.*, 2014; Roh *et al.*, 2014; Swindlehurst *et al.*, 2014).

2.3 Massive MIMO precoders and detectors

As noted above, massive MIMO systems have the following benefits: enhancement in throughput performance, low-cost components, low power, and efficient energy radiation. Precoding, or pre-equalization of the transmitted signals, is one of the functions involved in MIMO systems and developed for massive MIMO systems that depend on CSI availability to correct the signal errors at BSs. Detectors at terminals (mobile stations) should subsequently recover the desired established signal from antenna array elements at the BS simultaneously in the downlink stage. Detector designs with enhanced power consumption and low estimation complexity are difficult to obtain but extremely important, particularly when the number of antennas increases.

In most cases of massive MIMO systems, mobile stations can precisely follow the instantaneous state of the channel from pilot signals that are characteristically inserted into uplink-transmitted signals from various terminals within the cell; therefore, at the tth (t=1, 2, …, T) time slot, the signals received at the jth BS can be expressed as follows (Hu, 2016):

$$\boldsymbol{y}_{j,\mathrm{u}}(t)=\sqrt{P_{\mathrm{u}}}\sum_{k=1}^{K}\boldsymbol{h}_{j,k}(t)s_k(t)+\boldsymbol{n}_j(t), \tag{1}$$

where $\boldsymbol{h}_{j,k}(t)\in\mathbb{C}^{M\times 1}$ is the uplink channel vector from the kth user in the cell to the BS, M is the number of elements of the array antenna in the BS, $s_k(t)$ is the symbol transmitted by the kth user in the cell at the tth time slot, P_u is the average signal-to-noise ratio (SNR), and $n_j(t)\in\mathbb{C}^{M\times 1}$ is an additive noise vector received at the tth time slot. At each time slot, linear beamforming is employed at the BS to suppress the interference and enhance the signal. For the kth user in the jth cell, the received signal vector, $y_{j,u}(t)$ in Eq. (1), is processed by the jth BS with beamforming, and the resulting signal is expressed as

$$\tilde{s}_{j,k}(t)=\boldsymbol{w}_{j,k}^{\mathrm{H}}\boldsymbol{y}_j(t). \tag{2}$$

In the downlink stage, the BS deploys N transmitting beamforming antenna elements, and each terminal can be well appointed with multiple beamforming antennas. $\boldsymbol{w}_{j,k}$ denotes the transmit downlink beamforming vector for the kth user in the jth cell. Then, the received signal at the kth user in the jth cell is given by

$$y_{j,k,\mathrm{d}}=\boldsymbol{h}_{j,j,k}^{\mathrm{H}}\boldsymbol{w}_{j,k}x_{j,k}+\sum_{n,l\neq j,k}\boldsymbol{h}_{n,j,k}^{\mathrm{H}}\boldsymbol{w}_{n,l}x_{n,l}+n_{j,k}, \tag{3}$$

where $x_{j,k}$ represents the information signal for the kth user in the jth cell. The signal-to-interference-plus-noise ratio (SINR) at user k is

$$\mathrm{SINR}_{j,k}=\frac{\left|\boldsymbol{h}_{j,j,k}^{\mathrm{H}}\boldsymbol{w}_{j,k}\right|^2}{\sum_{n,l\neq j,k}\left|\boldsymbol{h}_{n,j,k}^{\mathrm{H}}\boldsymbol{w}_{n,l}\right|^2+\sigma^2}. \tag{4}$$

Recently, detection algorithms with low complexity and high optimal performance have received significant attention from researchers seeking to upgrade conventional wireless communication systems to 5G. We can categorise these precoders/detectors into two main categories: linear precoders/detectors and nonlinear precoders/detectors. Linear signal detectors with low complexity consider all signals, which are transmitted by excluding the desired stream from the specified transmit antenna as interference (Wagner *et al.*, 2012; Kammoun *et al.*, 2014). Thus, interfering signals, which are transmitted from other antennas, are reduced or nullified in the process of detecting desired signals from the specified transmit antenna. Well-known detectors, such as maximum ratio combining (MRC) receivers (also called matched-filter (MF) receivers), zero-forcing receivers (ZFRs), and minimum mean-square-error (MMSE) receivers, are practical candidates for massive MIMO systems.

Using MRC receivers, BSs attempt to obtain the highest SNR (maximum SNR) for every stream and ignore the influence of other multiuser interference. MRC receivers are advantageous in that they simplify signal processing; however, MRCs perform poorly in interference-limited scenarios because they do not address the effects of multiuser interference. In comparison to MRC receivers, ZFRs consider multiuser interference in their calculations; however, they do not consider noise effects.

Through zero-forcing (ZF), multiuser interference can be completely nullified by estimating the orthogonal complement of each stream of the multiuser interference. Yang and Marzetta (2013a) compared the two most well-known linear precoding schemes for massive MIMO (conjugate beamforming precoding and ZF precoding) in terms of power consumption and capacity efficiency. They found that by optimising the management of transmitted power, conjugate beamforming could obtain better overall computational measures compared to ZF precoding because of the larger number of served terminals. Regardless of the computational aspects, conjugate beamforming is more robust than ZF and may thus be preferable. Another advantage of conjugate beamforming is that it results in a situation characterised by decentralised planning, in which each antenna independently possesses its channel estimates.

The main objective of a linear MMSE receiver is reducing the mean-square error of the estimated signal versus the transmitted signal. The performance of massive MIMO systems has been examined and studied from several viewpoints based on the characteristics of various linear receivers. A comparison of the performances of MMSE receivers and MF receivers in realistic system settings was presented by Ju *et al.* (2013). The results indicated that the MMSE receiver can perform similarly as MF receivers with fewer antennas, particularly under interference conditions. The final formulations for various receivers according to Eqs. (3) and (4) are as follows:

$$W = H^*, \text{ for MF},$$
$$W = H^*(H^{\mathrm{T}}H^*)^{-1}, \text{ for ZF},$$
$$W = H^*\left(H^{\mathrm{T}}H^* + \frac{1}{\mathrm{SINR}}I_k\right)^{-1}, \text{ for MMSE},$$

where H^* is the Hermitian operation of the channel matrix and I_k is the identity matrix for the kth user. MMSE receivers have performed slightly better than ZFR receivers, but the noise variance must be known at the MMSE receiver. This drawback does not affect conventional MIMO systems but will induce a high complexity for systems with many antennas. Thus, the majority of recent studies have concentrated on ZFRs for massive MIMO systems rather than MMSE receivers (Li and Leung, 2013; He *et al.*, 2014; Jin *et al.*, 2014; Liu DL *et al.*, 2016). Li *et al.* (2016) evaluated the average sum rate of coordinated scheduling and beamforming of users in a multicell model, and the authors developed low-complexity, multicell, coordinated user scheduling policies for massive MIMO systems. In Le and Kim (2015), spectral efficiency under power scaling laws of massive MIMO systems was analysed, where the authors engaged ZF beamforming and ZF relay for a multipair, massive antenna relaying system.

As noted above, linear detectors are simple but provide poor BER performance. By contrast, nonlinear detectors provide a reasonable BER performance but have a high computational complexity. The best-known nonlinear precoder/detector techniques that can be used for MU MIMO systems are dirty-paper-coding (DPC), vector perturbation (VP), and lattice-aided methods (Masouros *et al.*, 2013). Such detectors can be used to obtain better performances compared to using linear detectors at the cost of higher estimation complexity. The improvement of complexity for nonlinear detectors is the key issue in massive MIMO systems (Mazrouei-Sebdani *et al.*, 2016).

3 Beamforming technique classifications

The beamforming technique is used in smart antennas for transmitting and receiving signals in massive MIMO systems. Smart antennas are antenna arrays with signal processing algorithms that are aware of spatial signal identifiers, such as the direction of arrival (DOA) of the signal, and employ them to evaluate beamforming vectors. These vectors identify and consequently track the desired signal sent from mobile stations. Smart antenna techniques are used particularly in acoustic signal processing, radio astronomy and radio telescopes, track-and-scan radar, as well as in wireless communication systems, such as W-CDMA, UMTS, LTE, and LTE Advanced.

Several methods, such as the multiple signal classification (MUSIC) technique, estimation of signal parameters via rotational invariance techniques (ESPRIT), and the matrix pencil method and its derivatives, have been elaborated as a part of the beamforming technique to predict the DOA of incoming signals and have been implemented via smart antenna systems. Such methods take in spatial spectrum results of the antenna array and compute the DOA based on the peaks of the spectrum (Yang *et al.*, 2010; Liao and Chan, 2011; Oumar *et al.*, 2012; Chuang *et al.*, 2015). Smart antennas can be categorised into three types: diversity, spatial multiplexing, and beamforming. Diversity is used at the transmitting and receiving sides to reduce multipath fading and improve link reliability, whereas spatial multiplexing involves transferring multiple streams of data in parallel to increase the transmission rate.

Several works have been conducted to classify beamforming techniques according to their characteristics. Some scientists classified beamforming techniques in terms of their physical characteristics. Gotsis and Sahalos (2011) classified beamforming techniques into two main categories: switched beamforming and adaptive beamforming. Moreover, they categorised the techniques into various types of array antennas, that is, linear arrays, circular arrays, and rectangular arrays. Another classification of beamforming techniques based on signal processing was presented by Hur *et al.* (2013) and Bogale and Le (2014), wherein the researchers classified the techniques into analogue beamforming, digital beamforming, and hybrid analogue/digital beamforming. The benefit of employing analogue beamforming is that inexpensive phase shifters are used for massive MIMO systems compared to digital beamforming, which has the advantage of providing more accurate and rapid foundation results to obtain user signals. However, digital beamforming suffers from high complexity and an expensive design; thus, it is not adopted in massive MIMO systems. Hybrid analogue/digital beamforming has been developed for massive MIMO systems to obtain the advantages of analogue and digital beamforming. In addition, many algorithms have provided technological advancements for increasing and optimising the performance of adaptive beamforming antennas.

These algorithms can be classified into two main types: blind adaptive algorithms and non-blind adaptive algorithms. Non-blind adaptive algorithms require known statistics of the transmitted signal, with the objective of determining a weighted path of travel. This objective can typically be achieved using a training signal that is transmitted through the communication link to the terminals to support the detection of the preferred user. By contrast, blind adaptive algorithms do not require any statistical knowledge to be trained; this is clearly expressed by the term 'blind'. The focus of blind algorithms is on re-establishing some types of physical characteristics of the downlink signal with the goals of maximising the signal to the desired terminal and minimising interference from other terminals. Another factor that can improve the quality-of-service of beamforming techniques is that they can be used for mm-wave bands (wideband) instead of conventional bands (narrowband), that is, 900 MHz–5 GHz. In mm-wave bands, the antenna array is extremely small owing to the size of the wavelength and beam width being extremely sharp, and the maximum range between the BS and the users is a few hundred metres. We present these classifications in Fig. 1.

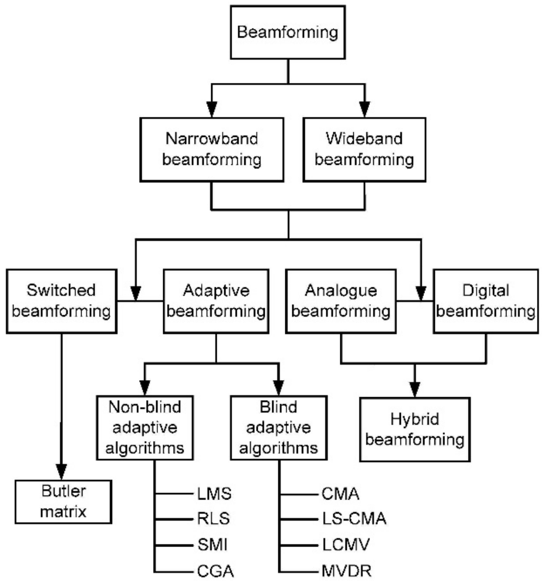

Fig. 1 General beamforming classification

LMS: least-mean-square; RLS: recursive-least-square; SMI: sample matrix inversion; CGA: conjugate gradient algorithm; CMA: constant modulus algorithm; LS-CMA: least square constant modulus algorithm; LCMV: linearly constrained minimum variance; MVDR: minimum variance distortionless response

3.1 Wideband beamforming versus narrowband beamforming

Beamforming can be divided into two categories depending on the signal bandwidth: narrowband beamforming and wideband beamforming. Narrowband beamforming is achieved by an instantaneous linear combination of the received array signals. However, when the involved signals are wideband, an additional processing dimension must be employed for effective operation, such as tapped delay lines (or FIR/IIR filters) or the recently proposed sensor delay lines, which lead to a wideband beamforming system (Liu and Weiss, 2010).

The majority of current wireless communication applications are still focused on narrowband beamforming; however, wideband beamforming becomes an important topic for future wireless communication applications owing to 5G requirements concerning high-frequency band signals for achieving an extremely high data rate. The best example of wideband beamforming that can be implemented for 5G for establishing extremely high speeds and high capacities is mm-wave beamforming. An extensive review of mm-wave (wideband) beamforming is provided in Section 5.

3.2 Switched array beamforming versus adaptive array beamforming

Beamforming schemes are generally classified as either switched-beam systems or adaptive array systems. A switched-beam system depends on a fixed beamforming network that yields established predefined beams. Perhaps the most common solution for fixed beamforming is the Butler matrix, which was developed by Butler and Ralph (1961). A Butler matrix is composed of hybrid couplers, phase shifters, and crossovers. In Ren *et al.* (2016), the reader can find an all-inclusive review of the Butler matrix functionality and its operation subjects. A switched-beam system requires a switching network, with the objective of choosing a suitable beam to obtain the desired signal from a specific terminal. The majority of the chosen emitted beam might not point to the desired direction. Bae *et al.* (2014), Huang and Pan (2015), and Tiwari and Rao (2015) addressed these issues (Table 1). Furthermore, a beam typically serves more than one mobile station (Fig. 2a). By contrast, adaptive array systems have the option to formulate a singular beam for each user. This option is realised by weight vectors that are applied via adaptive array processors to detected signals with the objective of controlling phase changes between the elements of the antenna array and their amplitude spreading (Fig. 2b). In this technique, specific beam shapes can be formed, and the directions toward a preferred mobile station are given by the main lobe remote sensing and consequently null toward the interfering sequences.

Adaptive beamforming assumes that the BS modernizes the localization of the mobile station. However, accurate localization is a difficult task because a large number of real-time mobile stations may overload the process. Therefore, estimating the DOA of received signals impinging on an antenna array is a main issue for wireless communication systems. It is considerably more difficult to put an adaptive beamforming system into practice than a switched-beamforming system.

By contrast, perfect adaptive beams attempt to reduce the interference between users and achieve considerably improved offered power resources (Huang *et al.*, 2015; Sivasundarapandian, 2015; Wu *et al.*, 2015). Regardless, there are advantages and disadvantages to both categories, which must be considered in implementation for massive MIMO systems. These advantages and disadvantages are shown in Table 1, which illustrates that although adaptive beamforming is difficult to implement, the majority of recent studies and simulations related to massive MIMO prefer this technique to switched beamforming because of its reliability for 5G requirements.

Table 1 Comparison between the two approaches in terms of coverage area, capacity, interference suppression, and complexity

Parameter	Switched beamforming	Adaptive beamforming
Coverage and capacity	Better coverage and capacity compared to conventional antenna systems. The improvement ranges from 20% to 200%	Covering a larger area and being more uniform compared to switched beamforming at the same power level
Interference elimination	Suffering from a problem in differentiating between the desired signal and an interferer signal	Offering more comprehensive interference rejection
Complexity and cost	- Easy to implement in existing cellular systems - Inexpensive - Using simple algorithms for beam selection	- Difficult to implement - Expensive - Requiring more time and more accurate (highly complex) algorithms to steer the beam and nulls

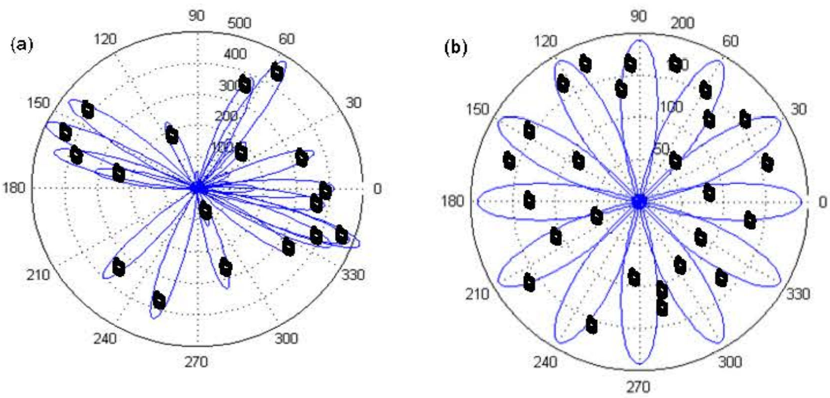

Fig. 2 Adaptive beamforming (a) and switched beamforming (b)

3.3 Adaptive beamforming algorithms: blind algorithms versus non-blind algorithms

In beamforming antenna arrays, signals received at each antenna element of the antenna array are adaptively built up to enhance the overall efficiency of the wireless communication system. The signals detected at the different antennas at the BS pass through multiplication processes with complex weights. The modified weights are immediately summed. In adaptive beamforming antenna arrays, according to the DOA, the estimation beam can be steered to the wanted signal direction, and nullification is applied to unwanted signal directions. The DOA of incoming signals and the direction of interfering signals can be easily estimated by smart antennas. Then, using a beamforming algorithm, the beam of the antenna is created toward the desired signal direction, and the null is formed toward the interfering signal directions. Adaptive beamforming algorithms are categorised into two main types: non-blind adaptive algorithms and blind adaptive algorithms (Arunitha *et al.*, 2015). The general equation for adaptive array output $y(t)$ is given by

$$y(t) = \boldsymbol{w}^{\mathrm{H}} \boldsymbol{x}(t), \tag{5}$$

where $\boldsymbol{w}^{\mathrm{H}}$ denotes the complex conjugate transpose of the weight vector. The weights are computed in an iterative manner based on the array $y(t)$. In non-blind adaptive algorithms, a reference signal is used to adapt the array weights continually. Subsequently, the response of the weights at the end of every iteration is compared to the reference signal, and the produced error signal is implemented to adjust the weights in the algorithms. The error signal is given by

$$e(t) = d(t) - \boldsymbol{w}^{\mathrm{H}} \boldsymbol{x}(t), \tag{6}$$

where $d(t)$ is the reference signal, which is similar to the original signal, and the algorithm should minimise the error difference between the output signal and reference signal such that the output signal is as close to the original signal as possible. Then, a beam can be formed toward the desired signal and the user can always be tracked.

Some examples of non-blind adaptive algorithms are the least-mean-square (LMS) algorithm, the recursive-least-square (RLS) algorithm (Arablouei and Dogancay, 2012), sample matrix inversion (SMI) (Liu J *et al.*, 2016), and conjugate gradient (CG) (Jamel, 2015). By contrast, blind adaptive algorithms are not dependent on the implementation of a reference signal and, therefore, there is no requirement to adjust the weights of the array.

Famous examples of blind adaptive algorithms include the constant modulus algorithm (CMA) and least square constant modulus algorithm (LS-CMA) (Bhotto and Bajić, 2015). Nulls are designed toward identified interference source directions by adaptively varying the antenna array pattern; hence, the adaptive beamforming technique can operate under interference conditions.

The main generator in adaptive beamforming is the digital signal processor, which deduces the received signals, defines the complex weights, multiplies the produced weights by every element response individually, and modifies the array radiation pattern. The effects of noise signals and interference signals are minimised by the antenna array, which also produces the maximum gain toward the desired direction. Thus, the performance of smart antennas is dependent mainly on the adaptive algorithms that are used for digital beamforming. Most performance criteria of adaptive beamforming algorithms depend on comparisons between various types of algorithms in terms of time of evaluation (speed of conversions and number of iterations) and accurate resolution, which is affected by multipath and interfering signals, to obtain the maximum SNR from a desired terminal.

Recently, two well-known adaptive algorithms were developed based on the null steering approach, LCMV beamforming (Rasekh and Seydnejad, 2014) and MVDR beamforming (Zou and He, 2013); these algorithms use null steering beamforming ideas to produce an adaptive beamforming array. Null steering antennas are critical in wireless communications because they improve the SINR by placing the null in the interference direction while pointing to the main lobe in the desired direction. The null positions in the antenna pattern are functions of the complex weights. Their values are obtained by solving a linear equation. Nevertheless, the direction of the interference signals must be precisely known. This causes a problem in practice because the directions of interference signals vary over time in real-time situations. Adaptive null steering, which can track the interference direction, is adopted to resolve this issue.

Many algorithms have been applied to the adaptive null steering problem. An efficient method based on the bees algorithm was presented by Guney and Onay (2007). One of the main algorithms used for adaptive null steering is the genetic algorithm (GA) (Khan and Tuzlukov, 2011). GAs represent a powerful searching method. The GA proposed in previous works was based on minimising the array output power. The direction of the main lobe must remain in the desired direction during the process.

3.3.1 Linearly constrained minimum variance beamforming

The majority of designed beamforming algorithms require some knowledge of the reference signal and the strength of the desired signal. These limits can be overcome by applying linear constraints to the weight vector. The principal concept of the LCMV beamformer was proposed by Frost (1972), where beamformers of LCMV are spatial filters that select optimum weight vectors to reduce the filter's response based on power constraints. This condition, together with other constraints, ensures signal protection at the desired location while reducing the variance effects of created signals from other directions. LCMV was developed based on the conventional MMSE for the automatic adjustment of array weights for simplicity.

The main disadvantage of the LCMV technique is its low convergence rate, which makes it inappropriate for application to massive MIMO systems even though it requires only the DOA to maximise the SNR, which simplifies the process estimation. Many different studies have sought to improve the capabilities of LCMV beamforming. Particle swarm optimization, dynamic mutated artificial immune systems, and gravitational search algorithms were incorporated into current LCMV techniques to improve LCMV weights (Darzi *et al.*, 2014). The simulation results proved that the detected SINR of the desired terminals can be improved through the combination of particle swarm optimization (PSO), DM-AIS, and GSA in LCMV based on interference mitigation.

3.3.2 Minimum variance distortionless response beamforming

The main concept of the MVDR beamforming algorithm is to reduce the variance of beam responses by selecting the weights of the antenna element while keeping the gain level that steers the beam to a desired direction constant. The main purpose of the procedure is to terminate strong interference signals from undesired directions. Several methods have been suggested to enhance the validity of the MVDR beamformer, with the most famous and widely used being diagonal loading and its extensions. The initial diagonal loading method was developed by Carlson (1988).

Although many methods based on loading factor evaluation have been proposed, the loading factor remains an issue, and some of these methods suffer from increased algorithm complexity. Vincent and Besson (2004) selected a negative loading level with the objective of maximising the SINR even though steering vector errors were found. A method that depends on the notion of uncertainty sets was recently proposed. Vorobyov *et al.* (2002) forced the steering vector magnitude responses into a sphere to obtain unity under a non-convex constraint. Gross (2005) proved that this algorithm is from the family of diagonal loading beamformers. Darzi *et al.* (2016) focused on solving the optimization problem of MVDR. The simulation attempted to demonstrate the cooperation of PSO and gravitational search algorithms to assist MVDR in improving its performance and reducing the effects of interference.

The new algorithm achieved significant improvements over conventional adaptive antennas. Based on 5G requirements that include no latency or accuracy, blind adaptive algorithms are more convenient than non-blind adaptive algorithms for massive MIMO systems. Huang *et al.* (2015), Sivasundarapandian (2015), and Wu *et al.* (2015) proposed some blind and semi-blind adaptive algorithms for massive MIMO systems.

However, the aforementioned properties of LCMV and MVDR indicate that MVDR is more suitable for massive MIMO systems than LCMV. Researchers have evaluated the DOA for the aforementioned algorithms in terms of the azimuth angle and elevation angle (2D-DOA), which increases the accuracy of the results, thus reducing inter-cell interference and increasing the performance of the massive MIMO system (Barua *et al.*, 2015; Kiani and Pezeshk, 2015; Shang and Li, 2015; Zhang *et al.*, 2016). In Kiani and Pezeshk (2015), a comparison between several array geometries, including planar arrays and volume arrays, for 2D-DOA estimation using MUSIC is presented. For each geometry, various criteria are taken into consideration and a comparative study of the performance of geometries is carried out. It has been shown that all the proposed geometries have to fit the system performance. However, the accuracy of the estimations reaches its peak by using planar geometries.

Zhang *et al.* (2016) proposed a new scheme for measuring and estimating the 2D-DOA of propagation paths, called multipath angular estimation, using the array response of PN-sequences (MAPS) in full-dimensional MIMO (FD-MIMO) systems. MAPS has been compared with other algorithms such as MUSIC, ESPRIT, and SAGE by simulations. The results have shown that MAPS outperforms the conventional methods in terms of estimation accuracy and capacity for various SNRs, antenna array sizes, numbers of paths, and delay differences.

3.4 Analogue, digital, and hybrid analogue/digital beamforming

Another classification of beamforming techniques is shown in Fig. 1, where they are categorised into two types: analogue beamforming and digital beamforming. Analogue beamforming was proposed more than 50 years ago. Analogue beamforming antennas are composed of hybrid matrices and fixed phase shifters. The main concept behind analogue beamforming is controlling the phase of each transmitted signal using low-cost phase shifters. A selective radio frequency (RF) switch is used to facilitate the beam steering function (steering angle).

Some modern analogue beamforming antennas have been proposed and offer continuous beamforming. Venkateswaran and van der Veen (2010) proposed analogue beamforming in MIMO communications with phase shift networks. They attempted to cancel interfering signals in the analogue domain and minimise the required ADC resolution. Unfortunately, it is difficult to control the direction of their nulls.

By contrast, digital beamforming consists of many utilities, including DOA estimation, programmable control of antenna radiation patterns, and adaptive steering of its beam and nulls to enhance the SINR (Gross, 2005; Liang *et al.*, 2014; Darzi *et al.*, 2016). These advantages can be obtained only by using digital technology.

The implementation of digital beamforming is not suitable for massive MIMO systems because traditional beamforming is implemented at the baseband, which helps to control the phase and amplitude of the signal; therefore, it requires the carrier frequency of the processed signal be up-converted after a crossover RF chain, which includes digital-to-analogue (D/A) converters, mixers, and power amplifiers. The responses of the RF chain are then combined with the antenna elements. In other words, each antenna array element must be reinforced by a dedicated RF chain. This is expensive to realise in massive MIMO systems because a large number of antenna elements is necessary.

As noted above, analogue beamforming is applied in a simple manner using inexpensive phase shifters. For that reason, analogue beamforming is more cost-effective than digital beamforming. Conversely, analogue beamforming exhibits poorer performance compared to digital beamforming because the amplitudes of the phase shifter are not flexible. To achieve better performance, mixing between digital and analogue beamforming has been proposed and is referred to as hybrid beamforming.

Kim *et al.* (2013), Haghighat (2014), Bogale *et al.* (2015), Ying *et al.* (2015), and Noh *et al.* (2016) demonstrated that hybrid beamforming concepts, which are a mixture of digital and analogue beamforming, are widely applied to massive MIMO systems. The digital beamforming portion creates baseband signals, whereas the analogue beamforming portion addresses RF chain effects by reducing the number of ADCs/DACs, which improves the outputs of power amplifiers or changes the architecture of the mixers and hence provides cost savings.

Different types of hybrid beamforming systems have been designed and suggested by many researchers. Hur *et al.* (2013) designed a hybrid beamformer and compared hybrid and digital beamforming in the case of downlink multiuser massive MIMO systems. They investigated the relationship between both digital and hybrid beamforming statistically by varying such factors as the RF chain parameters (ADCs and the number of multiplexed symbols). The simulation results showed that for a certain number of RF chains and ADCs, the difference in performance between digital and hybrid beamforming can be improved by reducing the number of multiplexed symbols. Furthermore, for a particular number of multiplexed symbols, increasing the number of RF chains and ADCs will increase the sum rate of hybrid beamforming that can be obtained.

Recently, researchers have concentrated on designing and developing hybrid beamforming that can operate in mm-wave bands for massive MIMO systems. Chen (2015), Dai *et al.* (2015a; 2015b), and Ghauch *et al.* (2016) designed hybrid mm-wave precoding for multiple objectives, such as reducing the weighted sum of squared residuals between the optimal digital beamforming design and hybrid beamforming design. Dai *et al.* (2015a; 2015b) addressed the problem of channel estimation and hybrid precoding/detectors, and Chen (2015) and Ghauch *et al.* (2016) reduced the complexity of hybrid beamforming.

4 Millimetre-wave beamforming for massive MIMO systems

Global bandwidth has reached a state of unavailability owing to the rapid growth of wireless communication system requirements. The carrier frequencies of wireless communication systems have ranged between 800 MHz and 5.8 GHz. There is great interest in replacing conventional global bandwidth by wireless mm-wave frequencies because conventional bandwidth currently surpasses the combined bandwidths of all wireless communication systems when it is heavily used.

Millimetre-wave frequencies found some use early on, such as in local multipoint distribution systems (LMDSs) and backhaul services at 20 and 40 GHz, in the 1990s; however, these applications were commercially impractical owing to the high costs of hardware characterising these mm-wave devices.

CMOS production technologies have been developed to obtain substantial reductions in cost and size, thereby creating attractive reasons for mm-wave frequencies to be considered as cost-effective means of mitigating bandwidth issues. Power-efficient circuits, smart antenna arrays, and mm-wave spectrum devices will be established to continue improving the abilities to use mm-wave frequencies as a highly effective solution for future technological development of wireless communication systems.

There are several benefits to using mm-wave frequencies in future 5G networks:

1. A broad spectrum exists at mm-wave frequencies that can be used for current cellular communication systems, including service bandwidth from 28 to 40 GHz, frequency band from 60 to 63 GHz, bandwidths from 71 to 76 GHz, 81 to 86 GHz, and 92 to 95 GHz. However, existing bandwidth has already been fully used and represents a restricted spectrum.

2. At mm-wave wireless communication bands, carrier frequencies can be reused within short distances because of the high debility of signals (attenuation) in free space and penetration.

3. Owing to the small wavelength of mm-wave frequencies, the antennas are sufficiently small, so it becomes practical to construct and implement multipart antenna arrays and integrate them onto boards and chip circuits.

4. Owing to transmission range limitations, in addition to the relatively narrow beam widths of mm-wave communication systems, significant improvements in security and privacy can be obtained.

Although mm-wave systems benefit from a wide range of spectra that can be used, they are power limited because of the large path loss accompanying mm-wave wavelengths because of the high carrier frequency. In addition, such systems are interference limited because of co-channel interference. With the goals of overcoming the uncomplimentary path loss and avoiding co-channel interference, an applicable beamforming scheme for concentrating the transmitted signals into a desired direction is one of the key enablers for wireless mobile communications at mm-wave frequency bands.

However, the small wavelengths of mm-wave bands enable the implementation of a large number of beamforming antenna elements in a compact form to create directional beams that can address the maximum number of terminals. As mm-wave systems have been developed, there has been significant work on beamforming techniques to enhance both spectral efficiency and energy efficiency for massive MIMO systems. The deployment of mm-waves in massive MIMO systems depending on beamforming techniques was explained in detail by Swindlehurst *et al.*

(2014) and Bogale and Le (2015), which discussed mainly the integration of mm-waves and massive MIMO technologies in 5G.

Extensive work is currently being done by researchers to develop an inclusive statistical mm-wave propagation model for channel modelling that can assist in reinforcing next-generation cellular system development. The mm-wave spectrum exhibits strong potential as a compulsory spectrum for 5G wireless systems.

The combination of mm-wave bands and beamforming techniques is of concern in the development of hybrid beamforming techniques and beamforming antenna array design. Roh *et al.* (2014) developed an mm-wave adaptive beamforming prototype that consists of 32 antenna elements organised in an arrangement of an identical planar array using eight horizontal elements by four vertical elements compressed inside a 60 mm×30 mm prototype. This minor prototype operates at a carrier frequency of 28 GHz. The created beam specifications, which are exclusively based on the full horizontal and vertical width at half maximum of the overall beamforming gain, have been significantly improved.

With the advanced adaptive beamforming system, researchers successfully proved that the mm-wave spectrum can support cells with a coverage radius of a few hundred metres for outdoor and indoor systems with transmit data rates of greater than 500 Mb/s, even in non-line of sight (non-LOS) environments. Sun *et al.* (2014) proposed principles for adopting the MIMO spatial multiplexing concept in addition to the beamforming concept for upcoming mm-wave wireless communication systems by exploring when either, or both, are most likely to be convenient. Among the contributions of their simulation, they evaluated the performance of general urban steering channel measurements at bandwidths of 28–38 GHz and 73–76 GHz and demonstrated that steering beams regularly occur in the presence of low path loss and slight multipath time dispersion. This means that high link power could be received using beamforming with a simple equalization process. In addition, they proved that digital beamforming is not suitable for mm-wave massive MIMO systems because of RF chains that follow each antenna array element in the system.

Thus, it will be extremely expensive and complex to address digital beamforming with the implementation of large numbers of antennas. Therefore, addressing hybrid beamforming approaches, which are combinations of digital beamforming and analogue beamforming, as shown above, promises to provide enhancements in terms of both power consumption and performance. Li *et al.* (2014), Huang *et al.* (2015), Bogale *et al.* (2016), and Dai and Clerckx (2016) have discussed briefly hybrid beamforming (Table 2). They drew the same conclusion that digital beamforming is not suitable for massive MIMO and proposed some schemes of hybrid beamforming that can avoid digital beamforming implementation problems and improve system performance.

5 Unresolved issues and future trends

Although several research works have focused on beamforming techniques and their applications in massive MIMO systems as a basic concept and realization for 5G systems, there are several issues that have received considerable attention in recent years and must be addressed before implementing massive MIMO systems in practice.

5.1 Pilot contamination

In a massive MIMO system, each terminal specifies an independent pilot sequence to be uplinked. However, the number of these independent pilot sequences is limited; therefore, they must be reused. The effect of reusing the same pilots between different cells will produce a conflict in the antenna array of a BS once they have correlated the desired received pilot signal with the pilot sequence associated with a particular terminal. These associated sequences are referred to as pilot contamination. The array antenna at the BS obtains a channel estimate that is corrupted by a combination of signals from other terminals using the same pilot sequence. These contaminated pilots affect downlink beamforming and result in interference directed toward those terminals, which are using similar pilot sequences. This undesired interference increases with an increasing number of antennas used.

The problem of pilot contamination was defined many years ago; however, its influence on massive

Table 2 Taxonomy of articles based on beamforming classifications

(a) Hybrid beamforming

Reference	Objective	Bandwidth	Methodology
Bogale *et al.* (2016)	Performance of the scheduling and sub-carrier allocation algorithm is analysed	Microwave and mm-wave bands	Comparison between the proposed hybrid beamforming and digital beamforming in terms of the average sum rate of the selected existing antenna beamforming, wherein approaches under ZF precoding and equal power allocation are evaluated
Dai and Clerckx (2016)	Study of the max-min fairness of multicasting driven by a limited number of RF chains	Microwave and mm-wave bands	Investigation of a hybrid precoding method for multicasting with a limited number of RF chains to propose a low-complexity search algorithm to determine the RF precoder and validate its near optimality in terms of the max-min rate
Li *et al.* (2014)	The performance of hybrid beamforming with fixed analogue beamforming weights in terms of average max-min SINR is evaluated	mm-wave	Investigation of the maximization of the minimal SINR over all of the considered subcarriers under total power constraints, which are considered as a typical optimization problem for 60 GHz multiuser hybrid beamforming
Sohrabi and Yu (2016)	Design of hybrid combiners that maximise the overall spectral efficiency	mm-wave	Proposing heuristic algorithms to solve the problem of overall spectral efficiency maximization for the transmission scenario under multi-user MIMO. The simulation results demonstrate that the proposed approaches achieve a performance similar to that of the fully digital beamforming schemes

(b) Adaptive beamforming

Reference	Objective	Algorithm type	Methodology
Huang *et al.* (2015)	Comparison of the convergence speed and sensitivity of steering vector errors between certain adaptive beamforming algorithms	Robust adaptive beamforming (RAB) technique	Proposing an algorithm based on projection matrices, called robust adaptive beamforming, to achieve robustness against the steering vector error. Instead of the eigenvalues, eigenvectors of the sample covariance matrix are used to determine whether the applicant is the base vector of the signal subspace
Wu *et al.* (2015)	The convergence performance of the developed algorithm is analysed and compared with those of conventional algorithms	Blind adaptive beamforming	Improving the reduced-rank beamformer via the development of a recursive least squares algorithm in relation to the constrained constant modulus standard
Sivasundarapandian (2015)	Comparison of newly combined algorithms with conventional algorithms in terms of convergence time and interference capability	Combined adaptive beamforming	Proposing a combination method that includes merging a pure conjugate gradient method (CGM) into pure normalised least mean square (NLMS) algorithms to improve the capabilities of fast convergence and high interference suppression

(c) Switched beamforming

Reference	Objective	Bandwidth	Methodology
Huang and Pan (2015)	Analyzing radiation patterns for dissimilar frequencies with a variety of port excitations, which are tabulated and demonstrate beamforming in unlike directions	Microwave band	Switched beam 4×4 Butler matrix array antennas are planned and simulated to operate at 2, 6.4, and 8.5 GHz to achieve beamforming in different directions for triple band frequencies
Bae *et al.* (2014)	The capacity estimation of beam patterns and proper selections of beams in a macroscope to meet guaranteed traffic demands among sectors	Microwave band	Implementing a coordinative switch beamforming scheduler over an area of 500 m×500 m. The scheduler effectively packs more guaranteed traffic into fewer resource blocks
Tiwari and Rao (2015)	Evaluating return losses and peak gains for switched beam antenna arrays at 60 GHz	mm-wave band	Designing a switched beam antenna array served by a 4×4 planar Butler matrix network with the goal of achieving switched beam characteristics in the 60 GHz bands

MIMO systems appears to be substantially greater owing to the large number of antennas in its construction compared to previous systems (Ngo *et al.*, 2011; Ashikhmin and Marzetta, 2012; Hu *et al.*, 2013; Wang *et al.*, 2013; Yin *et al.*, 2013; de Carvalho *et al.*, 2016).

Various methods have been proposed to alleviate pilot contamination and can be classified into two schemes. One scheme is based on the development of the pilot itself, such as by reducing pilot overhead, or using different frequency reuse factors in multicell systems instead of using a frequency reuse factor of one. This issue was clearly illustrated by Wang *et al.* (2013), who analysed the effects of pilot contamination using different reuse factors. They performed comparisons of area throughput for different reuse factors, and their results demonstrated that the performance of massive MIMO systems was improved.

By contrast, the other scheme concentrates on the development of precoding at the BS by adjusting the precoding matrix at one BS, which can mitigate the pilot contamination effect. Ahmadi *et al.* (2016) proposed open-loop power control (OLPC) and pilot sequence reuse schemes that avoid pilot contamination within a group of cells. Scientists compared the performance of a simple least-squares channel estimator with that of the higher-complexity minimum mean square error estimator, and evaluated the performance of the recently proposed coordinated pilot allocation (CPA) technique. They found that for moving users in vehicles, pilot contamination could be efficiently mitigated using both the OLPC and pilot reuse schemes.

Other proposals can also be suggested to mitigate pilot contamination effects without changes in pilot construction and depending on beamforming techniques, such as beamforming optimization methods, which can nullify the effects of inter-cell interference by discriminating the desired channel from the interfered channel in the uplink stage using the 2D angle of arrival (AOA) (Shang and Li, 2015) or based on joint angle and power domain discrimination (Yin *et al.*, 2016).

5.2 Millimetre-wave hybrid beamforming

New categories of hybrid beamforming that are compatible with mm-wave bands for massive MIMO systems are required for the design of beamforming weights compared to lower frequency-band MIMO systems and attempt to reduce the complexity and performance gap between hybrid beamforming and digital beamforming.

5.3 Channel correlation of beamforming array antennas for millimetre-waves

Channel correlation issues represent critical issues in mm-wave applications, particularly when propagation has a habit of being LOS or near LOS and when integrating with massive MIMO systems. Although this would likely avoid the use of maximum ratio combination and maximum ratio transmit precoding for interference suppression, other methods based on beamforming optimizations can be employed and could be extensively studied to mitigate this factor.

5.4 Sparsity of beams

Although cooperation between beamforming techniques and mm-wave systems mitigates many problems and enhances system performance, investigations that have focused on multiuser transmission schemes for mm-wave massive MIMO systems discovered that mm-wave channels exhibit strong sparse propagation after being converted into the angular space because of high path losses. Several studies have been conducted to solve this issue (Yang and Marzetta, 2013b; Lee *et al.*, 2015). A method that depends on a beamforming technique, referred to as beam overlapping, can be used to resolve the sparsity issue. The overlap between the beam patterns intensifies the amount of information carried by the channel outputs, and thus a path can be identified using a combination of multiple channel outputs instead of simply a single channel output.

5.5 Beamforming localization for massive MIMO systems

Although studies on massive MIMO systems have focused extensively on communications, they have also examined the high-accuracy localization. AOA estimation-based beamforming can be used for this purpose. Typically, a source emits a signal, and the AOAs are measured at all BSs using a two-step localization approach; hence, the source location is found by triangulation (Guerra *et al.*, 2015; Garcia *et al.*, 2017). However, the AOA estimates are affected by dense multipath environments, such as urban regions or inside buildings. Novel schemes to incorporate accurate localization based on beamforming techniques must be further developed to realise the benefits of beamforming.

6 Conclusions

This paper presents a comprehensive overview of beamforming techniques in massive MIMO systems. It critically reviews the recent research on various classifications of beamforming techniques and investigates which techniques are more appropriate for use in massive MIMO systems.

Broadband beamforming (mm-wave band beamforming) is more applicable in massive MIMO systems than narrowband beamforming owing to its cost-effective means of mitigating bandwidth issues and its power-efficient circuits in smart antenna array design. Adaptive beamforming is more suitable for massive MIMO systems than switched beamforming because of its ability to eliminate interference and reduce power consumption.

Finally, an optimal beamforming for massive MIMO systems can be achieved by deploying a combination of analogue and digital beamforming (hybrid analogue/digital beamforming) in mm-wave bands combined with optimal algorithms. The optimal algorithms can be one of the adaptive algorithms, such as MVDR, or a combination of two algorithms, to estimate accurately the DOA in terms of the azimuth and elevation angles (2D-DOA). The deployment of such optimal beamforming will provide the highest performance in massive MIMO systems, satisfying the requirements of next-generation wireless communication systems.

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