In this article, I will cover various aspects of millimeter wave (mmW) beamforming and antenna technology with what I consider interesting and unique technical design examples.

**Beamforming**

Beamforming networks (BFN) are used to combine signals from small antennae into a pattern that is more directional than each individual antenna alone because of the array factor. Beamformers are used in radar and communications. A radar example is a linear array capable of four beams in azimuth for an automotive radar; a communications example is a two-dimensional beamformer used in a satellite to cover a broad ground area in multiple spots.

BFN can provide simultaneous beam coverage, such as in a satellite, or single-point coverage, like that of a classic phased array radar system. Beams can be fixed in a design or adaptive using beam-steering computer control.

There are two main kinds of phased array beamforming networks: passive electronically steerable antenna (PESA) and active electronically steerable antenna (AESA). See this video by Keysight’s Dr. Sangkyo Shin on beamforming:

**Brooklyn 5G Summit**

5G in user equipment (UE), such as any devices used by the end-user in communications with a network, is a really hot topic right now. Nokia and the NYU Wireless research center at NYU Tandon School of Engineering has just finished the 5th Brooklyn 5G Summit (B5GS) in late April and two of their key topics were 5G mmWave Phased Arrays by Intel and 5G UE Phased Array Design by Qualcomm.

Ozge Koymen, senior director of technology at Qualcomm, gave the 5G UE phased array design presentation and discussed challenges with that effort such as:

- fast switching and settling times
- minimizing post-PA loss with regard to efficiency and thermal performance
- minimizing pre-LNA loss for an improved link budget
- space constraints in UE
- minimizing cost
- spherical coverage for both polarizations
In this section, we will deal with UE device face or edge design options for spherical coverage for both polarizations. Qualcomm discussed a front and a back antenna module for a hand-held device (Figure 1).

Koymen suggested that using multiple modules would help reduce hand-blocking as well as lowering the impact of orientation (Figure 2).
In a hand-held UE device, there are two popular configurations, face design or edge design (Figure 3).

Koymen discussed proposed face designs which use two modules that have a 2×2 x-pol (cross-polarized) planar array, 1×2 and 2×1 dipole arrays and edge designs that use three modules which have a single 4×1 x-pol planar array.

Looking at multiple types of beamforming architectures, Koymen commented that a maximal ratio combining (MRC) design along all of the directions of the device was employed. He felt that this was the optimistic design, upper bound scheme; an RF/analog beam codebook-based 24 beams for all modules/corresponds to P-1/2/3 initial sweep and beam refinement—this was a suggested practical scheme; and best antenna selection (legacy/LTE design)—a pessimistic, lower bound scheme. We will discuss MRC and multi-resolution codebook in more detail on the following page.

Qualcomm developed an RFIC that supported several possible antennae designs and used this in a demo smartphone form-factor showcasing adaptive beamforming and beam tracking. Each of their 8 RF front end (RFFE) modules supports multiple selectable antenna arrays in the X, Y, and Z directions. Mobile OEMs now have the opportunity to get an early start to optimize their particular
Maximal ratio combining (MRC)

Let’s take a look at the MRC architecture. This is quite an easy and effective scheme for combining in adaptive antenna arrays which will help reduce the effects of noise, fading, and co-channel interference to some degree. This architecture does require estimation of the spatial signature, which is the channel gain and phase at each of the antenna elements, of the signal of interest across the array. See Figure 4 for a classical MRC receiver architecture.

The paper in Reference 1 presented a general analytical framework of maximal-ratio combining reception in which the desired signal’s spatial signature is estimated by correlation with a known training sequence.

Figure 4 A classical pre-detection MRC receiver architecture (Image courtesy of Reference 1)

Figure 5a describes an architecture in which combining is performed at baseband, prior to detection. The authors also suggest a better possibility in Reference 1 that performs combining at the intermediate frequency (IF).
**Figure 5a** An MRC receiver with separate channel and carrier tracking. Here is a baseband-combining pre-detection MRC receiver using baseband compensation of carrier phase jitter (Image courtesy of Reference 1)

In **Figure 5b**, weighting is applied via adjustable delay elements or phase shifters. Then a single carrier recovery loop brings the combined signal to baseband before matched filtering is done. This method reduces RF hardware complexity by trading $N$ downconverters for only one downconverter and one upconverter.

The final results were the derivation of the pdf of the normalized SNR (its inverse is the training loss) conditioned on the ideal SNR. This was a foundation to obtain various performance results in nonfading environments and in uncorrelated Rayleigh-fading environments. It was found that the training loss has a much greater impact in fading environments on the outage probability than on the average bit error rate (BER).

These kinds of results are useful for system design in determining the required training sequence length and to realistically assess the performance of systems including the impact of imperfect estimation without resorting to simulation.

**The multi-resolution codebook**

A codebook is a kind of document used to gather and store codes. Originally codebooks were books, but today codebook is a byword for the complete record of a series of codes, regardless of the physical format.

In order to overcome the higher path loss at mmWave bands, highly directional beamforming using large-scale, or massive, multiple-input multiple-output (MIMO) systems is crucial. The problem of channel estimation becomes challenging due to the substantial training overhead needed to sound all possible beam directions using a high-resolution narrow beam. To resolve and improve the issue of beam search in a mmWave system, the paper in Reference 2 describes a design of multi-resolution beamforming sequences, which can quickly search out the dominant channel direction in a bisection manner. Given the multi-resolution codebook, the proposed multi-resolution beamforming sequence is designed to strike a balance between minimizing the training overhead and maximizing beamforming gain. The paper discusses how the multiresolution codebook can be designed using a phase-shifted version of a Discrete Fourier Transform (DFT) matrix.
5G mmWave phased arrays

During the 5th Brooklyn 5G Summit, Batjit Singh, director of advance technology at Intel, discussed his company’s mmWave arrays. One topic in particular intrigued me on 5G 28 GHz automotive mobility.

Intel has a design with four panels that provide 360° coverage with panel switching, beam selection, beam switching time-optimized and designed for mobility. Their multiple field trials have demonstrated and proven a mmW system (26.5 GHz to 29.5 GHz) (Figure 6).

![Figure 6 An Intel 5G 28 GHz automotive mobility system (Image courtesy of Intel)](image6)

Trials were performed in Japan and Korea as well as other countries. Tests helped evaluate such critical mmW parameters as modulation and coding scheme (MCS), received signal strength indicator (RSSI), biased received signal power (BRSP) performance, and intra/inter baseband unit (BBU) handover. See Figure 7 for the system deployed on the top rear roof of a vehicle.

![Figure 7 This is one of the Intel 5G automotive mobility system test cars with the 5G mmWave phased array system for automotive on the top rear of the vehicle. (Image courtesy of Intel)](image7)

I am all for V2X for improving safety in autonomous automotive driving in the future and 5G will enable that system.
Rotman Lens beamforming

Rotman Lens beamforming

Let’s take a look at this method of beamforming which is crucial to UAV collision avoidance, traffic monitoring, and intruder detection.

Radar can measure range of an object and radial velocity in addition to detecting the object. It works well any time of day or night and in most weather conditions. In collision avoidance, radar needs to have the capability of detecting the object angle of the target; the use of radar’s mechanically or electronically steerable, narrow antenna beam enables that capability.

Size, weight, and power (SWaP) necessitates tradeoffs in sensor simplicity and view angle estimation capability, so a front-end that can generate multiple, fixed narrow antenna beams that radiate out in different directions could be a good compromise. So, each beam will have its own discrete view angle--this can be accomplished by the planar Rotman Lens (RL)\(^4\).

A multi-channel frequency modulated continuous wave (FMCW) radar, which operates in the ISM band at 24 GHz can do the job. The receive (RX) antenna is based upon a RL and a patch antenna array designed with microstrip technology. The transmit (TX) antenna uses a BFN and a patch antenna array.

The system used is based upon the IMST 24 GHz multifunctional radar product, Sentire sR-1200e.

The radar system

![Figure 8](Image) A block diagram of the radar system proposed in Reference 3 (Image courtesy of Reference 3)

The main component of this radar front end is a 9×14 RL realized in a planar microstrip technology. This method was first mentioned in 1963 when Walter Rotman presented a Microwave-Lens\(^4\) for beamforming methods. This lens can be either constructed as parallel-plate, waveguide, or substrate integrated waveguide (SIW) structure for linear beam arrays of antenna elements. The mathematical framework for the ground calculation of the RL design is referenced to a paper\(^5\) by Peter S. Simon (Figure 9).
Integrated phased array IC solutions: Practical solutions for the designer

Phased array radar systems are headed toward flat panel arrays with improved SWaP. Digital integration in silicon makes the next-generation of beamforming possible. GaN devices can deliver high power and excellent power added efficiency (PAE) which is (RF power to the load – RF power at the device input) DC power from the supply.

I absolutely love the Plank architecture that Analog Devices suggests in creating an excellent evaluation system using their new ADAR1000, a very unique Tile X/Ku-band time-division duplexing (TDD) analog beamformer. The paper in Reference 6 looked at frequency-division duplexing (FDD) vs. TDD and found that if robust operation across a wide variety of propagation conditions is required, reciprocity-based TDD beamforming is the only feasible alternative. Figure 10 shows the block diagram of the device.
The best part of this new product is not just in the high level of integration, which is amazing, but in the evaluation boards available to designers for constructing a phased array antennae board using a Plank architecture in which the ICs sit on a board that is perpendicular to the antennae board. In this manner, the sizes of the ICs are not too important since they do not need to fit into the lattice spacing of the antennae design. These tools will shorten design time to market for developers (Figure 11).
Flat panel arrays can also be created with antennae elements on one side of the board and the ICs on the back side—it is in this type of configuration that antennae lattice spacing and the size of the ICs become critical in order to prevent grating lobes (Figure 12).

Analog/digital beamforming in a phased array signal flow

Designers have the option of setting the analog/digital beamforming phased array signal flow depending upon their overall system goals. There are always compromises and tradeoffs in every type of electronic design. See Figure 13 for a generic example of a signal design flow.
**Figure 13** A generic signal flow design for an analog/digital beamforming phased array design architecture (Image courtesy of Analog Devices)

A complete X/Ku-band array with analog/digital (hybrid) beamforming

**Figure 14** X/Ku-band array with analog/digital (hybrid) beamforming (Image courtesy of Analog Devices)

Here is where Analog Devices really shines with their Hittite microwave and Linear Technology power and high-speed acquisitions.
I look forward to seeing more innovations like those mentioned in this article as we approach the implementation of 5G in our lives. I expect many more applications in spaces outside of the 5G space as well.

References

6. "Massive MIMO Performance—TDD Versus FDD: What Do Measurements Say?," Jose Flordelis, Student Member, IEEE, Fredrik Rusek, Member, IEEE, Fredrik Tufvesson, Fellow, IEEE, Erik G. Larsson, Fellow, IEEE, and Ove Edfors, Senior Member, IEEE, 2017

Steve Taranovich is a senior technical editor at EDN with 45 years of experience in the electronics industry.

Related articles:
• Hybrid beamforming for 5G MIMO arrays
• You, personally, are a nightmare for 5G
• The unmanned aircraft system (UAS) Part two: The electronics inside
• IMS: Phased-array antennas and beamforming
• A technical view into modern mil/aero radar systems
• Finding Malaysian Flight MH370: Deep sea electronics search challenges
• Millimeter-Wave Beamforming: Antenna Array Design Choices
• MIMO and beamforming: Papers tell the story