

Realizing 5G network potential through mMIMO and precise beamforming technology

Bhavesh Rathod

Applications engineer
Wireless Infrastructure

Introduction

With every new wireless generation, the demand for higher data rates and lower latency increases substantially. 5G advances this trajectory by delivering tens of gigabits-per-second throughput and submillisecond latency, essential for applications such as augmented and virtual reality, industrial Internet of Things (IIoT), and autonomous systems. Achieving performance targets – especially in dense urban areas and high-mobility scenarios – requires two technologies: massive multiple-input multiple-output (mMIMO) and beamforming.

5G mMIMO systems use large antenna arrays, typically ranging from 16 transmit antennas and 16 receive antennas to 128 transmit antennas and 128 receive antennas. These antennas enable spatial multiplexing, transmitting multiple data streams simultaneously over the same frequency in order to enhance spectral efficiency and user capacity without additional bandwidth or power.

Beamforming, implemented through phased array antennas, enables spatial filtering to steer and focus radio-frequency (RF) energy toward intended users, mitigating interference and improving the signal-to-noise ratio. Beamforming requires consistent phase alignment across antennas. It enhances performance at higher RF frequencies (the FR1 and FR2 bands, for example), where free-space path loss and signal blockage are significant challenges.

To overcome these challenges, 5G mMIMO combined with beamforming enables high-throughput, low-latency communication and ensures scalability. These combined technologies empower network operators and developers to create innovative wireless applications for increased frequency bands through precise antenna control.

Realizing mMIMO and beamforming requires the use of RF transceivers to convert bits to RF and vice versa. Because both mMIMO and beamforming require spatial and timing accuracy, the bits-to-RF conversion process of the RF transceiver must have a precise time stamp and time synchronization across multiple antennas.

Radio equipment with a 5G-capable RF transceiver enables the radio to operate in both 4G and 5G. According to 3rd Generation Partnership Project (3GPP) specifications for 5G, 5G improves 4G in these specific areas:

- Enhanced mobile broadband (eMBB)
- Critical communication (CC) and ultra-reliable low-latency communication (URLLC) for industrial applications
- Massive Internet of Things (mIoT).
- Flexible network operations to enable adaptability and network optimizations while supporting diverse applications and end-user needs through network slicing, cloud-native infrastructures and software-defined networks.

What is 5G mMIMO?

5G MIMO is the wireless communication technology used in 5G network systems. A typical MIMO radio may have between 16 and 32 transmit and receive antennas compared to mMIMO's 64, 128 or even more antennas in a single radio unit. Packing these many antennas into a single radio unit helps serve more users with higher data rates.

mMIMO-based 5G network support for spatial multiplexing enables a substantial increase in channel capacity without adding any extra bandwidth or transmit power.

As the industry moves toward higher 5G frequencies such as millimeter wave (mmWave) (from 24GHz to 40GHz), beamforming becomes even more important. mmWave frequencies make it possible to have a high number of antennas in a constrained space because the antenna sizes are small. mMIMO proves to be a blessing in disguise, as it not only enhances throughput and coverage but also enables support for multiple users at the same time without having to add more resources (bandwidth, power, radios). This makes 5G mMIMO an essential technology required for achieving higher data rates, ultra-low latency and the massive connectivity targets defined by 3GPP for 5G networks.

5G mMIMO and beamforming

Beamforming is one of the primary technologies required for 5G wireless communication systems. 5G ultrawide-band frequencies operate in the sub-6GHz frequency range and mmWave frequency bands. This spectrum of frequencies is susceptible to higher signal attenuation and interference from objects in its path, and mmWave cannot penetrate walls as easily as 4G. Thus, 5G requires beamforming in order to focus power in a specific area to achieve high data rates, especially in dense urban deployments. See **Figure 1**.

Another benefit of beamforming is maintaining connectivity with mobile targets such as moving vehicles

using beamsteering and beamtracking as defined in the 3GPP releases. Beamforming can be either digital, analog or hybrid beamforming architectures. Let's look at the math behind this technology.

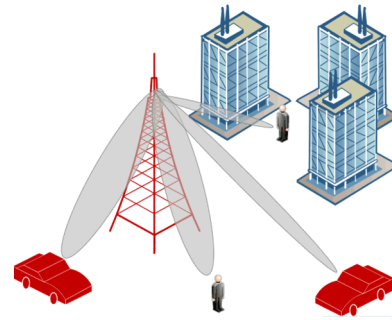


Figure 1. How beamforming helps connect more people over a 5G network in a densely populated urban area.

The math behind beamforming

Equation 1 models signal propagation over a channel, **Equation 2** shows the detailed H matrix. Each element h_{mn} in matrix H represents the complex gain from each transmit antenna n to each receive antenna m . where ρ is the signal at the receiver, τ is the transmitted signal and the matrix H is the channel characteristics matrix. Matrix H represents the gain and phase response of every channel.

$$\rho = H \times \tau \tag{1}$$

$$\rho = \begin{bmatrix} h_{11}h_{12} \cdots h_{1n} \\ \vdots \\ \vdots \\ \vdots \\ h_{m1}h_{m2} \cdots h_{mn} \end{bmatrix} \tau \tag{2}$$

Under linear precoding, **Equation 3** calculates the transmit signal τ as:

$$\tau = \Sigma w \times s \tag{3}$$

where s is the symbol being transmitted and w is the linear precoding vector.

The precoding vectors determine the direction of the beam by adjusting the relative phase difference of each transmit channel.

To calculate the precoding vectors, estimate the H matrix. It is important that each transmitter has a deterministic relative phase difference; otherwise the estimated H matrix and the calculated precoding vectors will not hold true. Beamforming relies on the phase accuracy of transmitted signals to constructively combine them at the receiver.

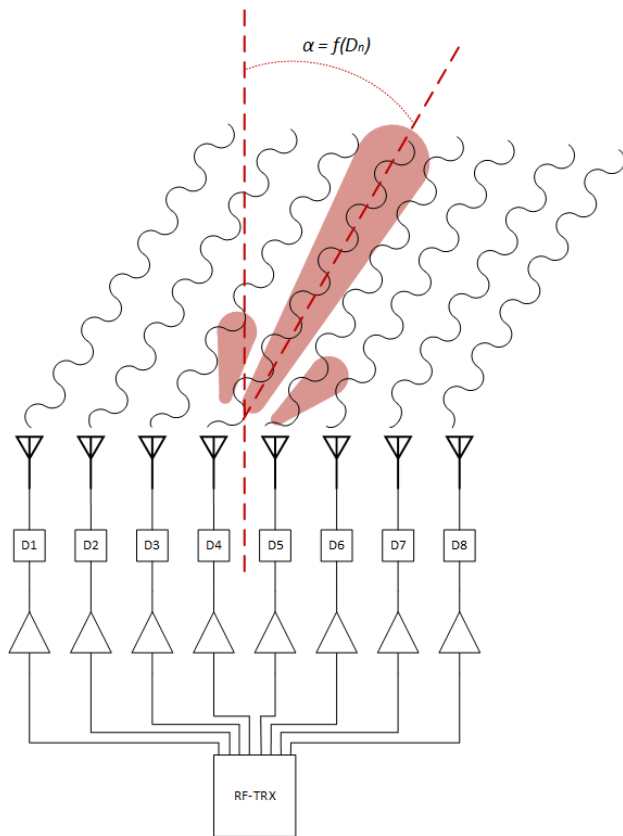


Figure 2. A beam formed (using an eight-channel transceiver) by adjusting the phase between time-synchronous antennas.

Synchronizing the output phases of multiple transmitters from one mMIMO becomes tricky when there are multiple analog front-end devices on the radio unit. A 128-antenna mMIMO system would have eight- to 16-channel analog front-end devices.

Current challenges for mMIMO systems

In a typical 5G mMIMO transceiver, a single board houses multiple RF transceivers. For a 64-channel configuration, the board can be populated with eight 8 channel transceivers or four 16-channel

transceivers. Reliable beamforming requires that all transmit and receive paths remain phase-synchronized throughout the entire system life cycle, including initial bring-up, subsequent JESD204B and JESD204C link reinitializations between the analog front end and application-specific integrated circuit (ASIC) or field-programmable gate array (FPGA), and power-on resets. This is a fundamental challenge that all radio system designers face. The deterministic relative phase relationship ensures that the composite antenna array forms and steers beams predictably.

Exploiting the internal phase-shift capability of the numerically controlled oscillator (NCO) embedded in the transceiver can compensate only for any residual static phase offset that exists across the multielement antenna array. Because this offset remains invariant across bring-up cycles, JESD relink events and power cycles, a one-time NCO calibration will align the phases of all channels and thereby preserve beamforming performance. But the fundamental need for all RF transceivers on the radio to be time-synchronized remains.

TI's AFE80xx and AFE81xx families of RF integrated circuits include several features to help designers achieve mMIMO requirements.

Using single-shot sysref mode

The default mode of operation in most systems is continuous sysref mode, where sysref is a periodic low-frequency signal. But it is possible to achieve multidevice synchronization using the “single-shot” system reference clock (sysref) mode in the AFE8092, AFE8030, AFE8128, AFE8190, AFE8192. In single-shot mode, the sysref signal is a single pulse, which is given simultaneously to all analog front ends on the board. When all of the analog front ends receive sysref at exactly the same instant with regards to the reference clock, they naturally become phase-synchronized.

One of the challenges in implementing this method is how to achieve differential routing of the sysref and reference clock to multiple devices on the board. At the

radio level within the printed circuit board, you need to preserve the timing of sysref and reference clock routing to the picosecond level with respect to the reference clock.

As shown in **Figure 3**, single-shot sysref mode using the AFE8092, AFE8030, AFE8128, AFE8190, and AFE8192 require a specific sequencing.

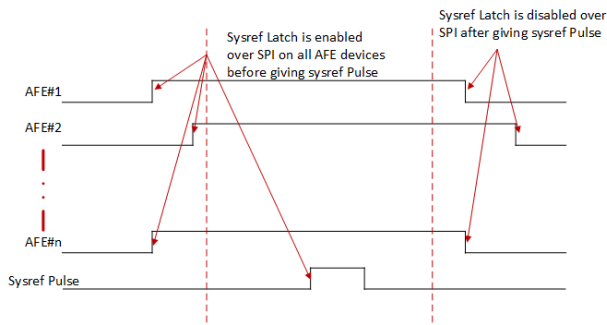


Figure 3. Timing diagram for single-shot sysref mode.

Using a common time-stamp signal through GPIO to time-align the RF integrated circuit

It is also possible to use general-purpose input/output (GPIO)-based control to enable sysref latch. In this mode, the sysref can operate in continuous sysref mode. All analog front-end devices will latch to the first reference clock rising edge after receiving a GPIO-based latch enable signal. All subsequent pulses will be ignored.

This approach only requires routing a CMOS GPIO signal to all of the analog front ends, which makes this method relatively simpler to implement compared to the single-shot sysref method, as it can be challenging to route a differential signal to multiple analog front-end devices on the board with matched lengths. At the same time, this approach requires synchronizing one GPIO per device from the host’s ASIC. The method is not suitable if the host ASIC or FPGA does not have enough GPIOs.

As shown in **Figure 4**, using GPIO-based control to enable sysref latch with the AFE8092, AFE8030, AFE8128 AFE8190, AFE8192 require a specific sequencing.

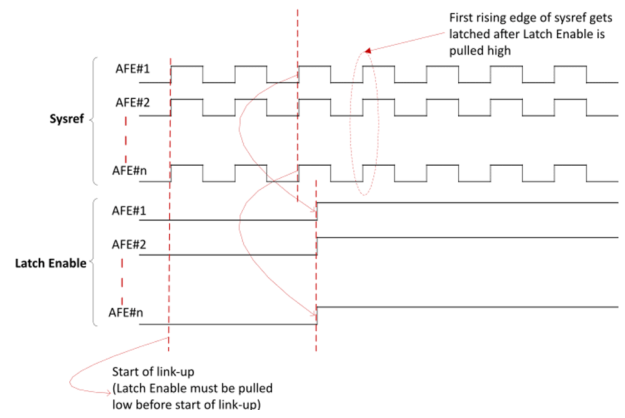


Figure 4. Timing diagram of using GPIO-based control to enable sysref latch mode.

NCO selection

The simplest way to achieve phase synchronization is to choose transmitter and receiver NCOs that are integer multiples of the sysref frequency. This method works even for continuous sysref modes, as it does not need any extra mechanism to synchronize the NCOs for transmit and receive across multiple analog front-end devices.

This method is most suitable if the restriction put on NCO frequency is acceptable for the end application, as you can achieve phase synchronization with no change to existing hardware. You will need to follow a specific software sequence in the case of a relink or power cycle of the analog front-end devices. **Figure 5** shows how in this mode, it would not matter even if all analog front ends latched to different sysref edges.

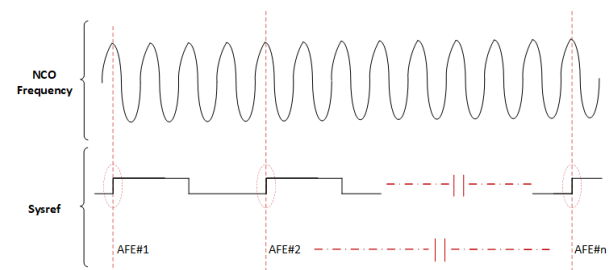


Figure 5. Example illustrating how the NCO frequency equals four times the sysref frequency.

Conclusion

The integration of mMIMO and beamforming technologies is pivotal to unlocking the full potential

of 5G networks, enabling unprecedented data rates and ultra-low latency. By leveraging large antenna arrays and precise spatial filtering, these technologies overcome the challenges of high-frequency signal propagation, ensuring reliable and high-throughput communication in diverse scenarios. As outlined in the 3GPP specifications, 5G's enhanced capabilities in eMBB, CC, URLLC, mMTC and flexible network operations are largely attributed to the synergistic effects of mMIMO and beamforming.

TI's AFE8092, AFE8030, AFE8128 and AFE8190, AFE8192 transceivers can help network operators support a range of wireless applications, from augmented and virtual reality and IIoT to autonomous systems and beyond.

About the Author

Bhavesh Rathod is an applications engineer at Texas Instruments, specializing in RF applications and wireless infrastructure solutions. Bhavesh brings hands-on expertise in post-silicon validation and embedded systems to support the development of cutting-edge wireless infrastructure technologies. He received an M.S. in electrical and computer engineering from Purdue University, and a bachelor's degree in electrical engineering from the College of Engineering Pune. Bhavesh was recognized with the Gandhian Young Technological Innovation Award in 2017 for his work on Swayam, a passively stabilized communication satellite.

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Last updated 10/2025