Top-Side Cooling Enables 5G Active Antenna Systems

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Since the first 5G services were launched at the end of 2018, mobile network operators (MNOs) around the world have been busily deploying 5G networks and, according to the Global mobile Suppliers Association (GSA), the number of global subscribers reached 1.15 billion at the end of 2022.¹ This represented a year-on-year growth of 85.9 percent. It is still early days for 5G and MNOs globally are continuing to invest heavily in their 5G networks, primarily in the C-Band or mid-range spectrum, around 3.8 GHz.

Due to the specific propagation characteristics of higher frequency 5G signals, concerns about the end-user experience are driving MNOs to increase the density of their networks. This is particularly true in crowded urban areas where connection densities are high and the spectrum is crowded. The specifics of these urban environments bring constraints on space and access to power, meaning operators must comply with increasingly strict planning regulations when deploying 5G base stations (gNB).

Massive MIMO (mMIMO) systems are key components of the gNB and the pressures of network densification have driven a dramatic reduction in the size of the radios and antenna systems that comprise these systems. Increased levels of on-chip integration have enabled significant levels of miniaturization, contributing to this reduction in form factor, but pressure remains to continue this trend. Semiconductor manufacturers are now looking at innovations in packaging technology to achieve further reductions.

This article discusses these trends in more detail. It will explore how top-side cooling (TSC) techniques can result in smaller and lighter semiconductor devices. TSC packages are already found in several applications, such as electric motor control, but this article examines a top-side arrangement for RF radio modules, which are at the heart of mMIMO solutions.

MEETING THE 5G CHALLENGE DEMANDS INNOVATIVE TECHNOLOGIES

The design specification for 5G was drafted in response to the relentless growth in demand for wireless bandwidth and throughput. The specification contains some challenging requirements, including a step change in transmission speeds and sub-millisecond levels of latency. While previous cellular networks evolved between generations, the challenging demands of 5G require designers to adopt a transformational approach, incorporating a range of innovative techniques. These techniques include wider spectrum utilization, mMIMO and beamforming.

Wider Spectrum Utilization

5G uses much more spectrum than previous cellular generations. It operates in two distinct frequency bands known as FR1 and FR2. A graphical representation of these two bands is shown in Figure 1.
• FR1 (sub-6 GHz): 410 to 7125 MHz
• FR2 (mmWave): 24.25 to 52.6 GHz

The majority of 5G network rollouts to date have offered services in the midband region shown in Figure 1. This region, which includes the C-Band spectrum around 3.8 GHz, is becoming known as the “coverage and capacity” layer because operation in this band delivers an attractive capacity-coverage compromise. MNOs are beginning to consider the deployment of mmWave infrastructure, however, as demand grows for the higher throughput and lower latencies supported by this portion of the spectrum.

**mMIMO and Beamforming**

Figure 2 shows a diagram of massive MIMO combined with beamforming techniques. These are core components of 5G NR and together they enable 5G to support many more devices per square meter than 4G. These techniques also allow faster data transmission to more users with high precision and low latency.

Beamforming enables the beam from the 5G base station to be directed toward the end-user mobile device, increasing special efficiency and ensuring optimum transmission levels while minimizing interference to other nearby mobile devices. mMIMO increases the number of transmit and receive paths as well as the antenna count, enabling spatial multiplexing to transmit independent and separately phased data signals, or “streams,” reusing the same time and frequency resource. At higher frequencies, the spacing between antenna elements reduces and these tightly-located antennas generate narrow beams that can be precisely focused, strengthening the received power, reducing interference and significantly increasing throughput. Spectral efficiency and capacity can be improved by adding more streams or layers until the point where power sharing and interference between users results in diminishing gains and, eventually, losses. MIMO antennas are designated by the number of transmit and receive antennas, with the most common mMIMO antenna sizes today being 32T32R and 64T64R.

**NETWORK DENSIFICATION DRIVES THE MINIATURIZATION CHALLENGE**

The 5G rollout is fundamentally changing the configuration of cellular networks since the higher transmission frequencies of 5G signals require denser networks. The traditional macrocells, responsible for providing wireless coverage over large areas, are being supplemented by increasing numbers of gNB. These base stations use mMIMO techniques to support higher numbers of connections while making more effective use of the spectrum.

The gNB are progressively appearing in urban areas where demand is high. These base stations are mounted in locations, like buildings and street furniture, which impose constraints on the base station design. Size and weight become important to avoid overloading of the mounting structures and to facilitate low installation costs. Low power consumption is also key since forced air cooling is not usually an option and access to local power may be limited.

The architecture of the gNB is evolving rapidly as 5G networks are rolled out with these base stations incorporating increasing levels of mMIMO to achieve the design requirements. A mMIMO deployment
integrates an active transceiver array and a passive antenna array into a single hardware unit. The mMIMO system also includes the hardware and software required for the signal processing and the algorithms to support the execution of the mMIMO features. Shrinking transmission wavelengths are increasingly allowing the use of patch antennas and these smaller geometries enable antenna arrays with a higher number of elements.

The developments in antenna design have been enabled by significant advancements in semiconductor technology. Miniaturization techniques enable electronic components such as RF transceivers, power amplifiers (PAs), analog-to-digital converters, filters and switches to be packed into smaller ICs. These devices can fit on the back of the antenna board, significantly reducing the depth of the antenna.

THE SEMICONDUCTOR INDUSTRY RESPONDS WITH TSC

The need to fit more power into smaller spaces is not unique to the 5G gNB, as an examination of most sectors will confirm. Applications such as complex automobile control systems, wearable medical devices or the small CubeSats that increasingly support IoT connectivity, all demand more computing power in smaller and lighter enclosures. In response to this demand, the electronics industry continues to innovate. Increasing levels of on-chip integration are key enablers of small form factors and MMICs. MMICs integrate RF and digital functionality, including microwave mixing, power amplification, low noise amplification and high frequency switching onto single chips with 50 Ω inputs and outputs.

To support increasing levels of integration, circuit board and packaging techniques have also evolved rapidly. In component manufacturing, surface-mount technology has largely replaced traditional through-hole printed circuit boards (PCBs). Surface-mount devices (SMDs) enable increased manufacturing automation, which reduces cost and improves quality while enabling more components to fit on a given substrate area.

However, more components generate more heat. The RF PA is typically the most power-hungry device in a radio and an mMIMO system will contain many of these devices. Forced air cooling is often not an option in many systems, including the gNB, so thermal management is a key design consideration when packaging electronic devices. With bottom-side cooling (BSC), thermal conduction paths transfer heat from high-power components into the PCB, which is bonded to a cold plate or heat sink. However, BSC is a compromise between thermal performance and PCB utilization since components can only be placed on one side. This constraint can significantly reduce the functional density of the board.

In response to these space and weight challenges, semiconductor manufacturers are developing packaging for their components that utilizes TSC. Different TSC implementations have been developed to meet the requirements of specific industries.

With TSC, the semiconductor chip is connected to a direct-bonded copper ceramic substrate on the top side of the package. The chip is mounted on the surface of the PCB, making a direct connection to the external heat sink. This ensures maximum power dissipation and optimizes thermal performance while eliminating the board density issues inherent in BSC mounting techniques. Semiconductor devices in SMD packages that implement TSC provide enhanced thermal performance, enable smaller form factors and increase design flexibility.

The exact implementation of TSC varies by manufacturer, driven by the needs of the application and other factors. The next section takes a closer look at the implementation of this packaging technology to better understand the benefits. Designed for 32T32R radios, this section will explore RF power modules that utilize TSC.

TSC SOLUTION REDUCES DEVICE SIZE

In 2018, NXP began producing integrated, multi-chip RF radio modules to meet customer demands for smaller and lighter RF equipment. As the 5G rollout has gathered pace, the company has responded to the requirement for even smaller radios with a new packaging technology that leverages TSC to reduce the size of a high frequency radio module. **Figure 3a** shows the packaging layout of a conventional radio module, using BSC. **Figure 3b** shows an implementation of the same radio architecture using NXP’s TSC packaging technology.
On the conventional, bottom-side cooled device, the heat from the PA is conducted through a coin in the PCB to the heat sink mounted on the underside of the PCB. The RF components are mounted on the top side of the PCB and are enclosed by an electromagnetic (EM) shield. The antenna array is connected to a dielectric filter that is connected to the PCB.

To reduce the size of the radio module, the first step was to integrate the coin into the PA. This enables the coin to be moved to the other side of the PCB where it can be connected directly to the heat sink. Improvements to the circulator and the dielectric filter enable them to be mounted on this side of the PCB as well. This brings all the RF components to the same side of the PCB, creating an improved thermal path through the module. Next, integrating the EM shield into the heat sink allows the shield on the top side of the PCB to be removed, bringing the antenna array much closer to the PCB. This configuration change reduces the length of the connectors, saving cost and reducing RF losses. We estimate that the removal of the shield is responsible for much of the reduction in the thickness and weight of the new radio module.

These thinner and lighter radio units contribute to improved base station radio equipment design. Theoretically, any size reduction reduces installation cost and complexity since only one installer is required for the deployment in most cases. The goal is for the gNB to be small enough to allow a self-install process. In addition, smaller base stations are less likely to meet objections from building landlords and planning authorities and they are well-suited to indoor deployments. All these factors should be advantageous to MNOs as they add small cells to their networks.

The gNB is just one of many applications that can benefit from packaging using TSC techniques. Other verticals, such as automotive and aerospace, face similar challenges as more power is packed into smaller spaces. NXP expects that a growing range of packaging utilizing TSC will emerge to enable all these market applications.

References