5G NR

Antenna-in-Package (AiP) Technology

White Paper

TMYTEK

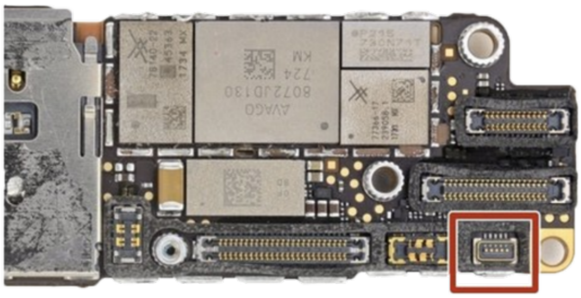
WWW.TMYTEK.COM

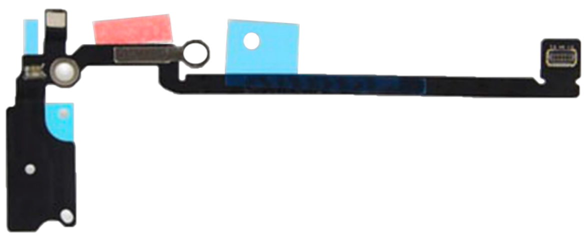
Introduction

Antenna-in-Package (AiP) is a technology that integrates antenna or antennas along with transceiver dies into a standard surface-mounted device. It has been widely used in 60 GHz for gesture sensors, 77 GHz for automobile radars, 94 GHz for phased array and even frequency as high as 122 GHz for imaging sensors and 300 GHz for wireless links. 5G mmWave spectrum has promised sufficient bandwidth to provide the next generation of user experiences and industry applications by using millimeter-wave (mmWave) as the carrier frequencies.

In sub-6 GHz

Compared to mmWave, sub-6 GHz technology had been used for decades and losses due to lengthy cable had never been an issue. Using iPhone 8 Plus as an example, the loss of the long cables with connectors between the Wi-Fi and the cellular module can be easily neglected providing smartphone ID designer the freedom to place the module almost anywhere within the design space. As such, repair on the main PCB board and the antenna module is easy and straightforward. On the other hand, mmWave antenna cannot be placed far away from the main circuitry, such as amplifiers, hence integrating the antenna into SiP module naturally becomes the only path.



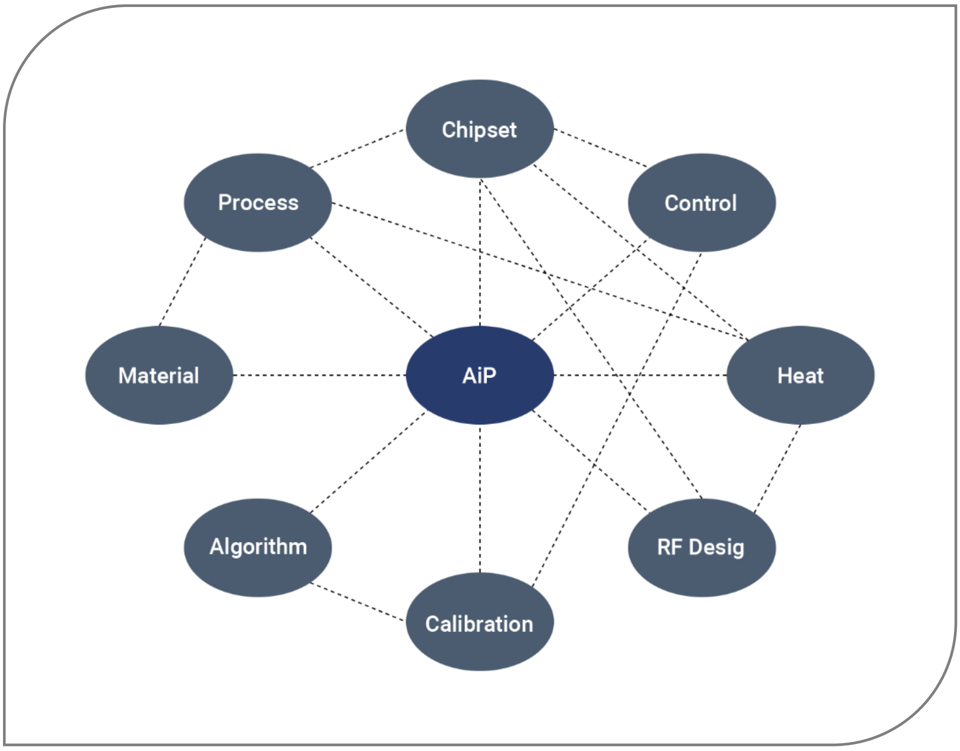


Opportunities and challenges

To fulfill the increasing demands in mmWave Frond-End Module (FEM), AiP turns into the most promising and suitable technology to achieve the phased arrays cost-effectively. At the same time, the material and process choices involving tradeoffs among engineering constraints are also considered, such as heat management, control design, RF performance, calibrations, and more.

The solution to multiple dimensional engineering problems is not straightforward and needs a lot of experience and creativity to realize the products. In addition to design, mass production is also a significant challenge, especially in Over-the-Air (OTA) testing.

In short, AiP is a promising technology for 5G mmWave and even for 6G LEO industry. In this whitepaper, we will breakdown the capability of TMYTEK's AiP technology and what we can do for the 5G NR mmWave industry. The first section will cover the design capability, while the second section will elaborate on the kind of processes we have used to build AiP modules. The third section will then follow with the introduction on our OTA solution (XBeam). Finally, we will wrap up the paper by sharing a few success stories that TMYTEK has engineered with our customers.



From design to production

Making an AiP product successful, many details need to be considered. In the design phase, we need to ensure that the design rules coincide with the fabrication technology to be used. During fabrication, evaluating the performance of a module quickly and accurately is very critical and directly affects the cost and the production rate. This whitepaper is meant to provide values that TMYTEK can contribute to the 5G industry and mmWave applications. The following sections will address each topic in greater depth.

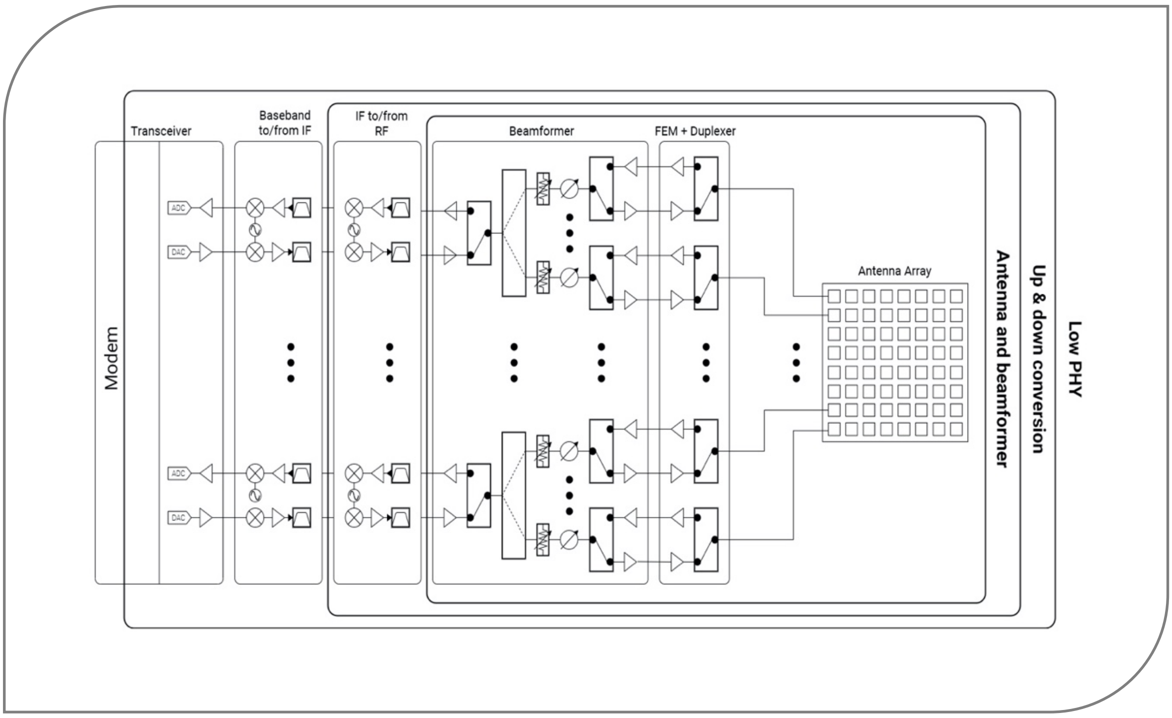
Design Capability

5G mmWave FEM architectures overview

The architecture of mmWave FEM is similar to the sub-6 GHz wireless system, including antenna, amplifiers, duplexers, and switches. Notable differences in the mmWave FEM are the antenna array and the beamformer. The antenna array is necessary to overcome the low antenna gain due to the short wavelength of the millimeter-wave. The array antenna results in beamforming. The beamformer is introduced to control the phase and the amplitude of each element of the array.

Refer to the diagram below, three different architectures for the 5G phased array are introduced. In the antenna and the beamformer architecture, the block shows a RF FEM with analog beamformer which includes antenna array, duplexer, and beamformer. Nowadays, a couple of beamformer chip makers have announced beamformer chips optimized for 5G millimeter-wave bands.

The second architecture integrates IF-RF conversion into the module as indicated in the rectangular block labeled with up & down conversion. Given that frequency converters dramatically affect the quality of communication, embedding it into the system increases system performance, and reduces the complication of integration. Integrating mixers and filters in the package is not a trivial job, and LO signal distribution is another concern, especially in large and tiled up array.



The third architecture is based on ORAN's (Open RAN's) split option 7.2 to integrate the low physical (Low PHY) layer into the module to offload the front-haul network on the Radio Access Network (RAN). In this architecture, digital components are included, which raise the challenges to a new level.

MMIC: Beamformer IC and up/down converter chips

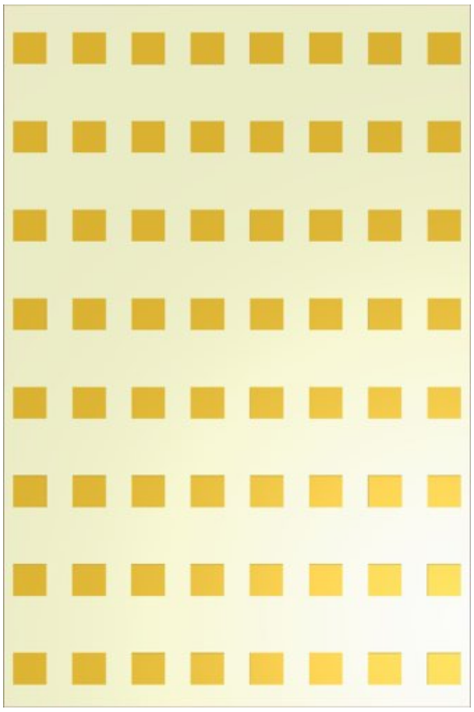
A modern beamformer chip integrates power amplifiers (PAs), low noise amplifiers (LNAs), phase shifters (PSs), variable attenuators, and T/R switches. CMOS or BiCMOS technologies are preferred due to the benefit of digital circuit integration; even if the output power is not as good as the counterpart in GaAs and GaN III-V compound processes.

TMYTEK is experienced in many beamformer chips. We know how to fulfill the specification of the AiP module by selecting the right chips to be used in our design. The chipsets are one of the important parts in this multi-dimensional engineering considerations. In a 5G mmWave phased array, the output power is not the only concern. Due to the feature of Orthogonal Frequency Division Multiplexing (OFDM) in 5G, PA back-off operation is necessary. It is considered along with antenna array gain to form a system with targeted equivalent isotropically radiated power (EIRP) and reasonable power efficiency.

Index	Consideration	TMYTEK capability
Tx Power	The output power of each element.	18 dBm for 28 GHz. 15 dBm for 39 GHz.
Frequency	Meet operator's frequency bands.	n257, n258, n260, n261. Ranges from 24 to 41 GHz.
Rx NF	Lower noise floor provides better system sensitivity.	4.5 dBm in 28 GHz. 6.5 dBm for 39 GHz.
Phase	Phase difference is the basic of beamforming. Step size and error are the key considerations.	6-bit phase shifter. +/-3 deg RMS phase error.

Antenna designs

The basic antenna is not good enough for AiP. Package-specific characteristics should be considered as well. TMYTEK's team held more than ten antenna patents and more than 15 years of experience in antenna design. Different antenna types were extensively investigated and modeled by the team, including patch, dipole, and SIW antennas. The prominent figures of merit are bandwidth, polarizations, and boresight beam width at 3dB and 10 dB, steering coverage in both X and Y directions, isolation, return loss, easy to implement or not, etc. Specific consideration for AiP includes Dk value, uniformity, thickness of the material, etc.



Transition & interconnection design

AiP has the advantage of minimizing the entire wireless system with the cost of a larger vertical dimension since MMIC is packaged. However, this can be improved by using die instead of IC and this is one of the benefits of TMYTEK's technology: Our processes are prepared to use bare-dies, given that we have experienced with some of the key mounting technologies such as wire bonding and flip-chip packaging. The distance from the antenna to the RFIC is much shorter in the AiP approach than a conventional discrete antenna. This implies smaller path losses, so the transmitter efficiency and receiver noise figure can be improved simultaneously.
We have managed transitions in 16 PCB stack-up layers and 26 layers of LTCC interconnections with excellent results.

Filters and feed networks

The BPF design is limited to the board area available for passive components. The larger the room for filters, the better the rejection performance can be achieved. At the same time, thermal stability and repeatability are also challenging for designers to reduce the tuning effort to achieve an SMT-capable device. As an example of the microstrip structure, the tolerance of substrate thickness, etching size and even dielectric constant should be considered and calculated carefully to achieve the best performance at 28/39 GHz.

A discrete filter on another board (e.g., the motherboard of SMT-able AiP modules) is an alternative architecture, but this will suffer from high losses. Another challenge is about the thermal stability. The performance of filters should be maintained to have similar spectral efficiency over operating temperatures.

Building a feed network is critical to AiP modules as the component cannot be placed off-board. Size and complexity are important figures of merit for measuring feed network performance. Typically, there are two strategies to address the design issue. The first approach is to implement the feed network in the PCB or the Low Temperature Cofiring Ceramic (LTCC) layers to save rooms. This approach increases the challenge of processing and thermal complexity. Another method is to build a network between beamformer ICs, but the space challenge is higher in this case. To achieve the best EIRP, it is important to guide the design of the feed network and TMYTEK practices the rules well.

Manufacture & Fabrication

As indicated in the preceding section, material and processing technologies affect the performance, cost, and size of AiP module. TMYTEK has explored how AiP can be manufactured in the past few years. The technology we have used includes high-frequency PCB and Low Temperature Cofiring Ceramic (LTCC).

PCB-based

Taiwan has a strong PCB supply chain. TMYTEK has implemented AiP modules with multi-layer PCB and achieved 1x8 to 8x8 array products. Two architectures have been made: with and without a frequency converter. With the 16-layer high-frequency PCB, we can construct a fairly complex module, and also be able to customize the thickness of the PCB board to maximize the design freedom.

LTCC-based

LTCC has been considered a highly suitable processing technique for mmWave AiP designs. The great electrical and packaging properties make this technology very attractive for high frequency applications. With the technology, up to a dozen layers can be stacked up to accommodate plenty of components to achieve a very compact design. The low-loss tangent of LTCC tapes maintains low loss even at very high-frequency. The dielectric constant of LTCC tapes can help reduce the size of passive components. We have worked with the world’s leading LTCC company to realize the 4x4 AiP module incorporated with mixers to make the module IF-ready.

OTA Testing

Conductive testing is no longer an option for mmWave module implemented by AiP technology. There are no more connectors or testing points available for the purpose. The only way to characterize the module is through the Over-The-Air (OTA) method.

History

Traditionally, a bulky chamber along with one or more mechanical positioners is necessary to ensure the DUT's radiation pattern is measured correctly and precisely. More recently, Compact Antenna Test Ranges (CATR) technology has reduced the size of the chamber but still retains the same concept of mechanical parts and testing items based on radiation patterns. The approach used for decades became an industry standard for research and design. But in the coming 5G and LEO era, the number of devices to be tested on the production line will overwhelm this old technology.

Problems in traditional approach

A big chamber or CATR is an excellent tool for R&D purposes, but it is too slow and bulky for production lines. For example, the latest technology in the industry can get a pattern in about a few minutes, which is already impressive if we compare it to our predecessors with a half-hour or longer testing cycle. But achieving the level in seconds is still not guaranteed. Furthermore, the nature of mechanical positioners makes automation integration in the product line not a straightforward task.

The innovation: XBeam

XBeam is a production line OTA testing solution built for 5G mmWave manufacturers. It adopts different approaches to meet the production demands of mmWave devices. We have abandoned the mechanical positioner to speed up the OTA testing process. We have used our own BBox technology to measure the RF performance of mmWave modules or devices, including EVM, power, phase, and more. We have also developed OTACali technology to help customers calibrate the phased array in an OTA manner: fast and accurate.

Success Story: LTCC Phased Array

TMYTEK has worked with NGK/NTK, the top three LTCC technology company in Japan, and achieved a 4x4 LTCC unit AiP module for the 5G FR2 n261 band (27.5-28.35 GHz). A larger array (8x8) is also demonstrated by tiling up four unit modules on one single motherboard. The module shows great integration of various technology domains and the partnership that TMYTEK has formed.

For 5G NR millimeter wave front-end design, the dimension of the antenna array could be very different, i.e. 2x4, 4x4, 16x16, or even larger, due to different applications. Therefore, the modularized design method provides a better way to configure a phased array system for adapting different dimensions of antenna arrays.

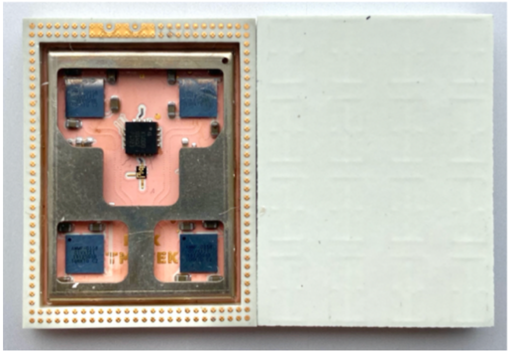
The 4x4 LTCC antenna-in-package frontend module (AiP FEM) is presented in this paper along with the 28 GHz 8x8 phased array system, which is fully integrated with four 4x4 AiP FEMs, power regulators and phase-locked oscillator (PLO) designs. Finally, the beamforming capability and results are presented using constellation diagrams and EVM results.

Unit 4x4 module

The AiP FEMs were fabricated with a 26-layer LTCC process by our LTCC partner. It is then fully integrated with four 4-channel beamformer chipsets, power combiner, mixer, frequency doubler and sixteen SIW antennas by TMYTEK. The main inputs and outputs are the transmitting/receiving IF signal, LO source, digital control signal, and DC power supply.

The phase and the power amplitude of each antenna channel can be controlled independently for beam steering and beam shaping capabilities. The SPI control interface is used for fast beamforming characteristics control, and the highest SPI clock rate achieved is 50 MHz.

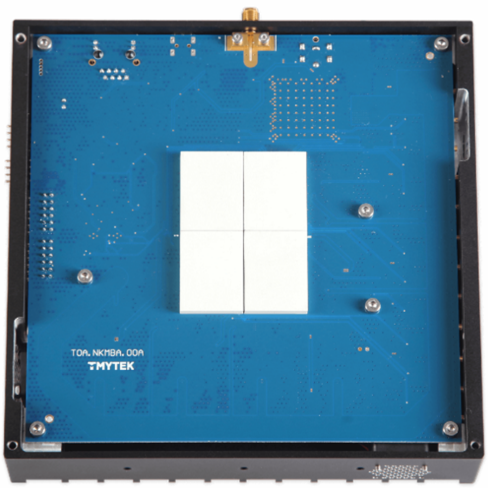
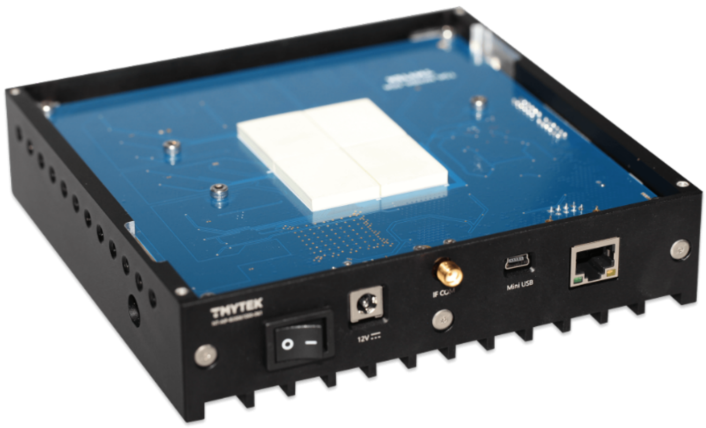
The dimension of the AiP FEM is 29.3 x 22.1 x 4.1 mm^3 as shown in the below figure. The cavity showing on the back side is designed for easy mounting of the device to form different dimensions of the phased array using these modulized AiP FEM.



8x8 array

The integration of the 8x8 phased array system is using four AiP FEM with the mother board. For better phase noise consideration, the local oscillator source was not embedded in the AiP FEMs, instead, they are integrated in the motherboard using TMYTEK's PLOs.

The integrated system can be seen in the following photos.

Test result

The following figure shows the OTA measurement results with different modulation scheme using NI's USRP. The calculated transmission gain is around 26.5 dB on average. Both the SNR and the throughput are in great agreement with the expectation.