

White Paper

RF MEMS based Passive Smart Antenna Array

Introduction	2
Sofant RF MEMS Technology	3
RF MEMS Phase Shifter	3
RF MEMS Step Attenuator	4
RF MEMS SPDT Switch	4
Phased Array Architectures	5
Digital Beam Forming.....	5
RF Beam Forming	6
Hybrid Beam Forming	6
RF Path Trade-offs.....	6
Power Dissipation	6
Phase Error.....	7
RF Filtering	7
Over-The-Air (OTA) Testing.....	8
Sofant Technologies Passive Smart Antenna Array Solution.....	8
Power Dissipation	8
Phase Error.....	10
RF Filtering	10
Conducted Testing	10
Cost Comparison	10
Conclusion.....	11
About Sofant Technologies	11
References	12

Introduction

This white paper describes Sofant Technologies' approach to developing a high-performance smart antenna system which is enabled through the use of low-loss, low cost, CMOS compatible RF MEMS (Micro-Electro-Mechanical System) device.

The use of smartphones to watch video caused mobile data traffic to rise 55% in 2016 and demand is expected to grow 13 times by 2021. Mobile World Live published a survey report in February 2017 called "The future of mobile video." (1) The report provides a summary of the views of 370 industry leaders on mobile video. It reveals a number of clear trends in consumer behavior and the amount of time spent watching video on smartphone platforms. Even inside the home, there is a clear trend towards watching more content on smartphones. In 2016 the smartphone was the 2nd most popular screen used to watch video in developed countries (behind the TV) and the most popular screen in developing countries. Across all countries, 82% of those surveyed agreed that smartphone video consumption will continue to increase over the next 5 years. Outside the home, the smartphone is the clear leader in mobile video. Twenty-nine percent of the survey respondents rated on-demand video as the largest growth driver over the next 5 years (live, user-generated content, was ranked as the 2nd).

The same survey asked respondents to list the barriers to watching video on the move. Seventy-four percent of those surveyed ranked battery life as the number one barrier followed by mobile data charges at 70% and network performance at 59%.

The growth of mobile data has caused radio spectrum for consumer applications in the sub-6 GHz frequency bands to become highly congested. A number of blocks of high frequency, millimeter wave (mmW) radio spectrum are currently under consideration by the International Telecommunication Union (ITU) for 5G networks and network operators already have firm plans to roll out networks at 28GHz in the US and South Korea. Millimeter wave spectrum is essential for servicing the exploding demand but there are a number of key technical challenges which must be addressed.

'Network densification' is a key component in the drive to increase capacity and improve radio performance. This will be accomplished through the deployment of small cells and consumer premise equipment (CPE) devices which are designed to serve areas that experience high demand from large numbers of wireless subscribers (i.e. sports arenas, airport departure lounges, train stations etc.) or to extend indoor coverage. In order to increase the range of devices which operate at mmW, phased array antenna systems, which direct transmitted radio energy, will replace conventional antenna systems.

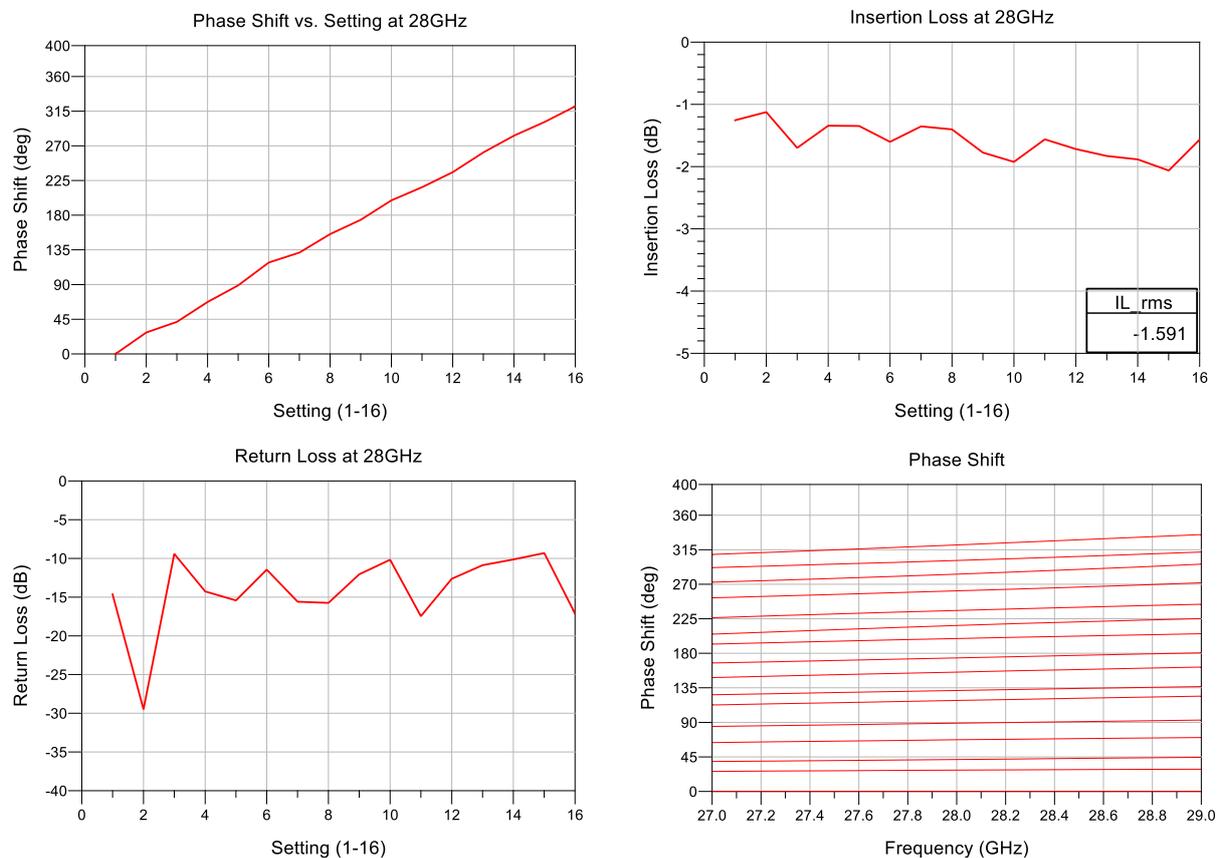
Phased array antenna systems enable one or more directed beams of radio energy to be sent to a mobile user. This approach reduces co-channel interference and enables the development of denser networks, through higher frequency reuse. Phased array antenna systems also promise the potential for a much higher quality of service and a better experience for the consumer.

Sofant RF MEMS Technology

Sofant has developed a capacitive RF MEMS device, optimized for use in the mmW spectrum, using a low cost CMOS compatible manufacturing process. Recognizing that RF MEMS reliability is as important as cost and performance, Sofant has designed the device and process to address the two primary elements which limit RF MEMS reliability: mechanical wear and charge based stiction. Sofant's RF MEMS intellectual property and technology is based on more than 10 years of research at the University of Edinburgh's Scottish Microelectronics Centre.

RF MEMS Phase Shifter

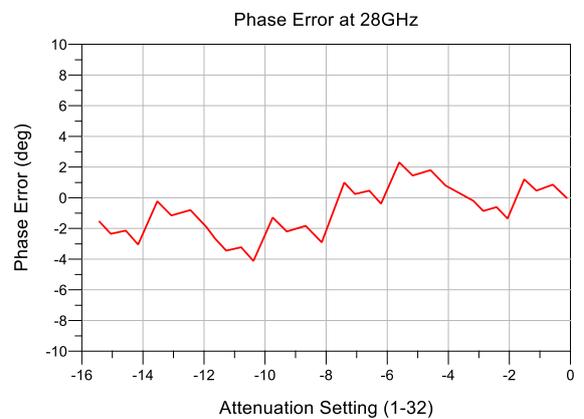
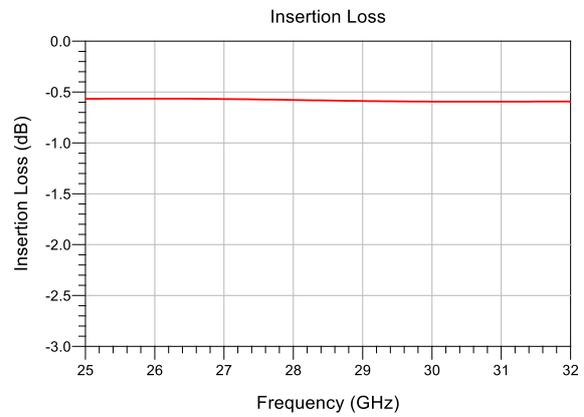
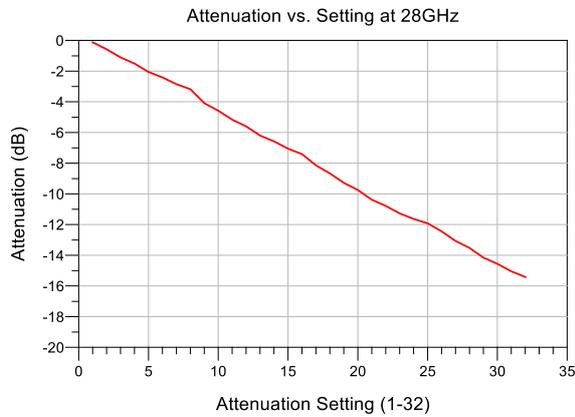
Sofant's technology has been used to design a very low-loss MEMS phase shifter which is initially targeted at 28GHz for 5G user equipment (UE) and CPE applications. In this paper, we present the simulated results from a 28GHz, 4-bit device. The design exhibits 22.5° phase shift per bit over a full 360° phase shift range. Crucially, the design achieves 1.6dB loss RMS (root mean square) across all states while maintaining a flat frequency response over the 27-29 GHz band. The expected performance for the product is shown below.



Similar designs supporting up to 7 bits of phase shift (2.8° per bit) can be developed for the CPE market, as required. These designs will likely incorporate an integrated MEMS-based step attenuator as described below.

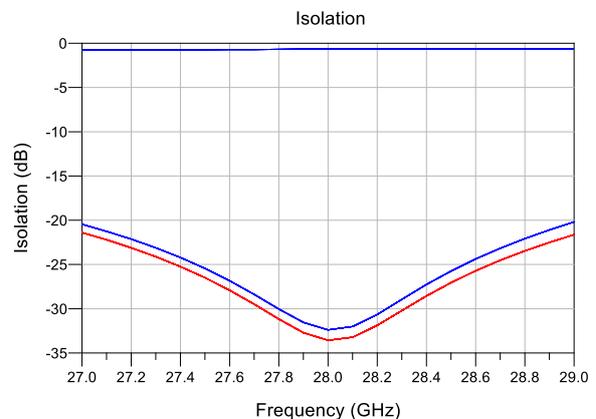
RF MEMS Step Attenuator

Sofant’s MEMS device can also be configured to create a step attenuator at 28GHz. The 5-bit design shown below uses 0.5dB steps for a total attenuation of 15.5dB. Expected performance is shown below. This design can be integrated with the phase shifter for a small, low-loss combination.



RF MEMS SPDT Switch

In addition to these functions, it is also possible to configure Sofant’s MEMS device to create a single-pole, double-throw switch at 28GHz. The switch is designed to obtain the required isolation between branches as shown in the plots below.



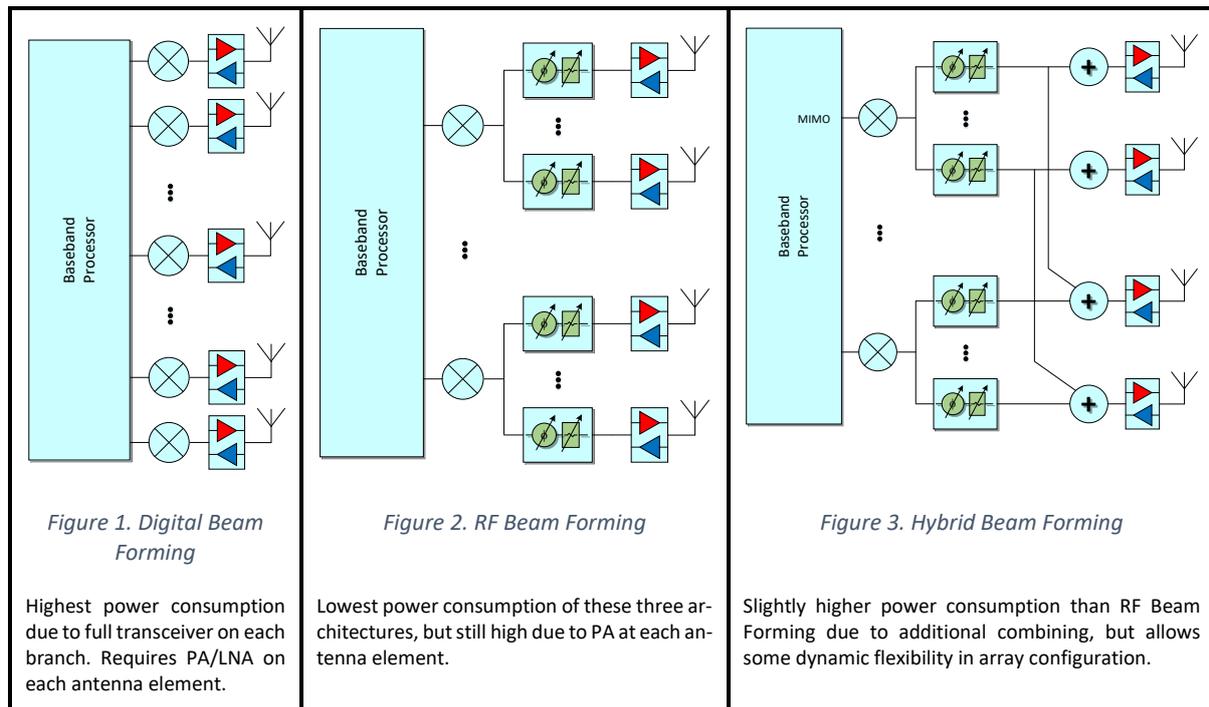
The MEMS phase shifter, with the optional attenuator and/or the switch, will be packaged in a low-cost, chip-scale package, with an integrated CMOS controller and a surface-mount LGA (Land Grid

Array) interface. A SPI (serial-parallel interface) or RFFE (RF Front-End) interface is used to control the device.

Sofant’s low-loss MEMS phase shifter device is a key enabling technology for mmW applications. It enables a passive antenna array architecture which is low cost and much lower power than other approaches. This passive array architecture is presented later in this paper.

Phased Array Architectures

Phased array antennas electronically steer radio ‘beams’ rather than using mechanical movement. For beam steering to occur, the phase, and optionally the amplitude, must be adjustable at each antenna element. There are three commonly accepted beam-forming architectures which are being considered for 5G phased array applications: digital, RF and hybrid.



Reference: Peregrine Semiconductor

Digital Beam Forming

In digital beam forming, each antenna element utilizes independent transceivers, data converters, and upconverters as shown in Figure 1. Phase shifting occurs at baseband; thus, this method enables a significant level of flexibility because it dynamically allows the array to be subdivided into sub-arrays or configured as a single array. However, this approach employs complex hardware, is computationally intense and dissipates a significant amount of power. The mixer in each channel must have a synchronous local oscillator, or the phase will not be coherent and the phase shift will be uncontrolled. The power consumption is high because a full RF chain is required for each antenna element in the array. Because this approach requires each path to have a PA and LNA, thermal management is a major challenge due to the high levels of dissipated power. It is likely that a heat sink will be required to manage the temperature at the array so this approach will not work for user equipment (UE) or applications where power consumption and thermal management are important.

RF Beam Forming

RF beam forming is a traditional approach where the beam is formed in the analog/RF domain close to the antenna element. Typically, one transceiver provides a single signal source for the entire array. Only one upconverter is utilized (dual-conversion notwithstanding, all upconversion occurs in a single channel); thus, the RF signal will be coherent on each channel and can be phase shifted as needed for beam-steering. High-loss components (i.e. semiconductor-based phase shifters and attenuators) push the PA, LNA and T/R switch function to each antenna element. This approach requires the phase shift to occur before the PA and is illustrated in Figure 2. This option can be cost effective but it is the least flexible approach. In the configuration shown, a PA/LNA is required at each antenna element which consumes a significant amount of power and will likely not be acceptable for UE designs.

Hybrid Beam Forming

The hybrid architecture combines elements of the digital and RF approach as shown in Figure 3. This approach allows for some level of dynamic configuration. In this architecture, sub-arrays can be configured in the baseband, while the beamforming occurs closer to the antenna in the RF domain. The RF upconversion occurs in a single branch, as with RF beam forming, for a given sub-array. The partial beamforming at the baseband uses sub-arrays to suppress grating lobes and reinforce the main beam. Sub-arrays may carry adjacent messages or can be used for MIMO. This is less complex than the digital architecture and signal combining at RF can provide multiple signals per array. This approach uses only one transceiver per sub-array, enabling lower-cost and lower-power consumption. As with RF beam forming, existing high loss components require a PA, LNA and T/R switch function to be placed at each antenna element. This negates some of the power consumption and cost advantages and makes this approach very challenging for the UE.

RF Path Trade-offs

Regardless of the chosen architecture, the RF path trade-offs must be carefully considered because each approach impacts power dissipation, phase accuracy, production testing and total system cost to varying degrees.

Power Dissipation

Existing phase shifters and attenuators use semiconductor switches and (typically) integrated reactive elements like inductors and capacitors to implement the phase shift function. The switches and reactive elements used to implement the phase shifter exhibit high loss at mmW frequencies. Today's solutions exhibit between 6dB and 13dB of insertion loss at these frequencies. This level of loss adds significant noise to the receiver and drives output power requirements on the transmitter to unacceptably high levels. To mitigate these challenges, the PA, LNA and T/R function must be placed near the antenna.

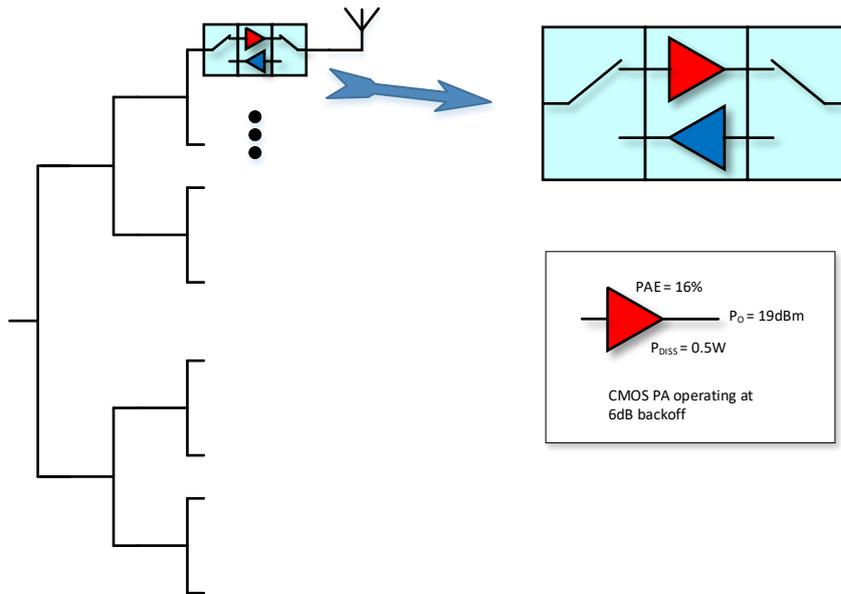


Figure 4. Traditional array configuration with T/R function at the antenna. PA designs with 30% PAE at saturated power, and 16% PAE at 6dB backoff are typical at 28GHz. The PA in this approach dissipates 0.5W per element, or 4W total for an 8-element array.

At mmW frequencies, power dissipation from the PA can be quite high. At 28GHz, the optimum element spacing of roughly half-wavelength makes the array compact (roughly 6mm antenna element spacing for a typical antenna substrate). Figure 4 shows a traditional array configuration with the T/R function near the antenna. The presence of high-power amplifiers at each antenna element leads to significant, possibly unacceptable, levels of power dissipation which generates a substantial amount of heat. For example, assume each power amplifier has a maximum average linear output power of 19dBm with 16% Power-Added Efficiency. This will lead to 0.5W of dissipated power per antenna element. Therefore, power dissipation in a 1x8 linear array for a UE device at 28GHz would be in the range of 4W. Managing the heat at the antenna element is difficult, at best.

Phase Error

Group delay distortion variation between the antenna elements, which is caused by the active components in the RF path, becomes significant at mmW frequencies. Non-uniformities across the array caused by component tolerances in the PA and LNA, variation in the assembly process and variation in temperature will all contribute to phase error. These errors lead to inaccuracies in beam-forming and cause sidelobe generation which affects total spurious emissions as well as array gain, directivity, and efficiency.

Additionally, the antenna elements within the array are likely to have ~10dB isolation. This will lead to cross-talk during transmit, whereby the signal output from one element couples into an adjacent element. The resulting interference at the PA output is characterized by “Output Intermodulation Distortion” (IMD), which is a distortion product affecting spurious signal generation and phase error.

RF Filtering

The mmW 5G bands will require filtering to ensure radiated signal integrity. Spurious signals such as Power Amplifier harmonics, LO image frequencies, adjacent band interference, and others, will need to be filtered prior to transmission, and from the Rx input to the LNA prior to processing within the

baseband. Having the active components at each antenna element complicates this requirement. Harmonic filters might be integrated into each PA module, but a bandpass or lowpass/highpass filter would be too large to integrate into each module in the array. Without relaxed specifications, it is difficult to see how this requirement will be met with this topology.

Over-The-Air (OTA) Testing

Typical portable wireless devices have a 50Ω test port (the “conducted” port), both for certification and production testing. Certification requires a test of spurious emissions, output power levels, receive sensitivity, and a host of other system-level tests. Connecting the test equipment with a coaxial cable is a convenient way to ensure compliance. In addition, many system-level parameters can be tested on the production line through the conducted port to ensure unit-to-unit compliance.

Array architectures with active elements near the antenna cannot be tested through a conducted port, as the active elements are effectively part of the antenna array. The same is true for the digital architecture, which also integrates active components at each antenna element. This requires OTA testing at a certification facility which is complex and expensive. This means equipment will likely require radiated testing in an antenna chamber to ensure spurious emissions from the power amplifier are being met. Furthermore, the OEM has little insight into the portable device’s performance without radiated testing in a chamber. OTA testing is not conducive to the manufacture of low cost UE or CPE devices.

Sofant Technologies Passive Smart Antenna Array Solution

Figure 5 shows Sofant Technologies’ proposed configuration with a single T/R function on the system board at the single feed point to the antenna array. This approach is enabled by Sofant’s mmW optimized, low-loss RF MEMS technology. This configuration enables a **lower system level cost**, as only one T/R function is required. It also enables **lower power dissipation** which can be managed at the system board rather than at the antenna elements. **Better phase accuracy** is also maintained because there are no active components following the phase shifters. Finally, this approach is very similar to existing RF architectures which means it is possible to use **conducted system testing** in production versus radiated OTA testing. This will save UE and CPE manufacturers a significant amount of time and money.

Power Dissipation

Table 2 compares the power consumption and dissipation for each approach. A significant advantage of Sofant’s approach is that it enables a single, higher power PA which can be produced in an optimized semiconductor technology. The higher power output allows the PA to be optimized for Power Added Efficiency (Class AB, or even possibly Doherty, to maintain high efficiency at power backoff) at mmW frequencies. For example, the single PA could use GaN and be driven by a DC/DC converter or envelope tracking efficiency improvement techniques, similar to those used in today’s 4G PA systems. In any case, a single PA gives designers more flexibility to develop solutions which are optimized for performance and thermal management while providing a more stable phase shift response.

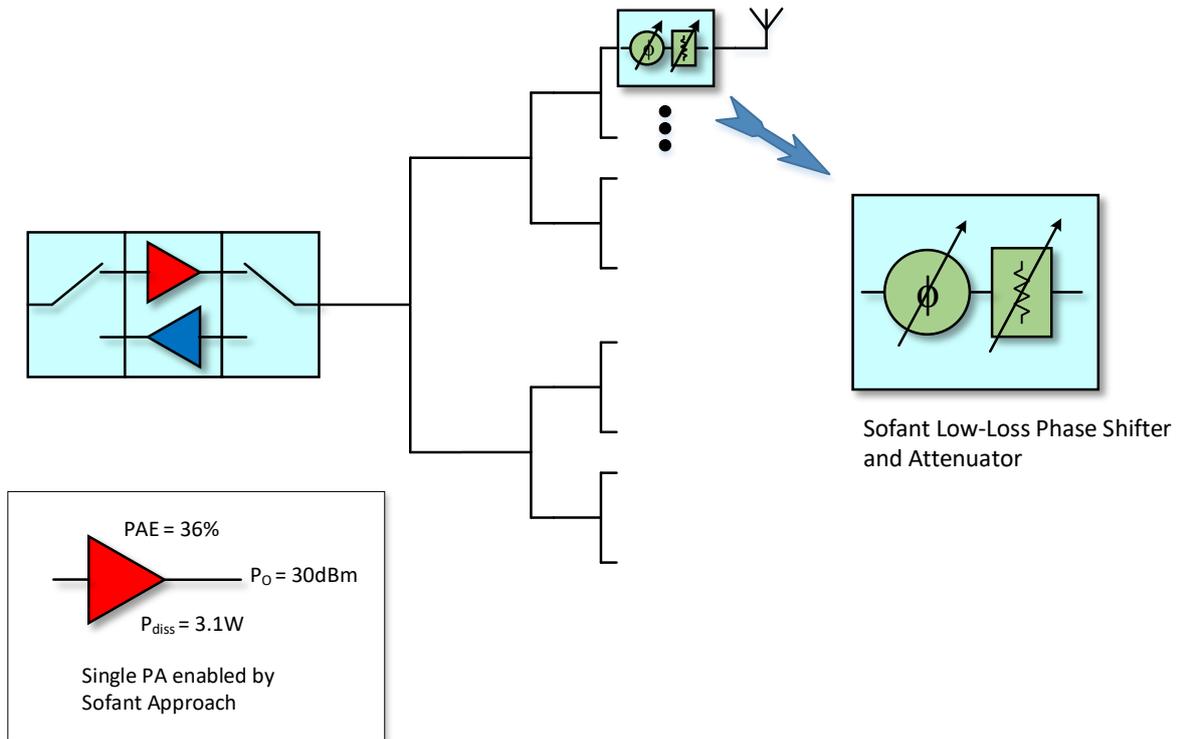


Figure 5. Proposed array configuration with T/R function on system board. The low-loss passive components allow a single PA/LNA to be placed on the system board at the transceiver output where power dissipation is much more easily managed. Power dissipation for a single, technology-optimized PA could be 3.1W for an 8-element array.

The loss budget which sets the power requirement for the PA assuming 19dBm will be transmitted at each antenna element is shown in Table 1 below.

Table 1. Loss budget for PA to Antenna using Sofant's proposed single-PA approach.

Array Size	Phase Shifter loss	Distribution Line loss	Ideal Power Division	Power Required
8	1.6dB	0.5dB	9dB	30.1 dBm
16	1.6dB	1dB	12dB	33.6 dBm

Table 2. Power calculations for the two scenarios.

Approach	Output Power (dBm)	DC Power (W)	Power-Added Efficiency (%)	Dissipated Power (W)	Dissipated Power for 8-element array (W)
Traditional	19	0.6	16%	0.5	4.0
Sofant	30	4.1	32%	3.1	3.1

Note: Sofant's low-loss phase shifter enables the PA to be placed on the system board. Other approaches integrate the PAs into the antenna array board.

Using Sofant's approach, the estimated power dissipation for an 8-element array will be 3.1W, significantly less than other approaches. Additionally, the PA will be integrated on the system board, rather than embedded in the antenna array. This approach helps the system designer to better manage thermal dissipation.

Phase Error

By utilizing a single PA, as shown in Figure 5, there are no active components at each antenna element other than the MEMS phase shifter. Group delay distortion and AM/PM distortion which can affect phase delay, while still possibly present in the PA, will not affect the operation of the phased array antenna. Since the antenna will have a single feed from the PA, all branches will be symmetric. The passive phase shifter at the antenna element is desired because the only phase error will be due to inaccuracies in that component. Since the phase shifter is fully tested prior to assembly into the array, the potential for phase error is minimized.

RF Filtering

With a single feed point to the passive array, a mmW bandpass filter (BPF) can be integrated into the array, providing the required signal conditioning and ensuring a high quality radiated signal.

Conducted Testing

Since the single-PA solution shown in Figure 6 is effectively a passive antenna array, it closely resembles conventional portable wireless systems. As such, the active components are contained to a system board, with a 50Ω point between the output of the Front-End Module (PA, LNA, switch) and the single feed point of the antenna. This provides a convenient place for a conducted test port, allowing greatly simplified and low-cost certification testing as well as production test opportunity for the UE and CPE devices, avoiding the complex and expensive OTA testing requirement.

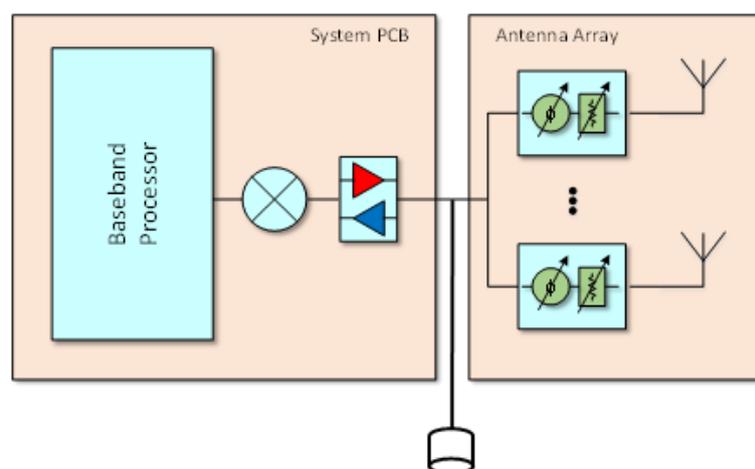


Figure 6. Using a “Passive Antenna Array” allows the 50Ω test port to be utilized, avoiding costly OTA test requirements.

Cost Comparison

A traditional 8-element array for a UE device requires 8 separate transmit and receive functions, with a PA, LNA, and switch for each antenna element. In addition to the performance disadvantages of this approach discussed earlier, adding 8 modules to each UE adds significant cost and complexity as well as the cost and complexity of OTA testing.

Conversely, the approach shown in Figure 5, requires a single, higher power PA, which can be designed for optimal power added efficiency. The required power levels shown above means that this PA can be designed for very low cost (>2W power amplifiers are currently used in high volume handset/UE applications). A 1W PA for 5G applications at 28GHz might use an optimized technology like GaN for

improved performance. The approach in Figure 5 assumes a phase shifter/attenuator is placed at each of the 8 elements without the need for active components.

If the antenna array, as shown in Figure 6, is supplied as a separate component it allows for testing and characterization of the antenna array prior to shipment. This reduces the OEM’s development expense and improves time-to-market. It also reduces production test cost because the OEM can use a pre-tested, fully yielded antenna component and conducted testing methodologies.

We assume an 8 element antenna array for the estimates in Table 3. The estimate shows the total number of functions (whether individual components or integrated) as a proxy for the cost of implementing the solution.

Table 3. Component savings due to proposed architecture.

Approach	Functional Component	Quantity
Traditional	19dBm Power Amp	8
	Low Noise Amp	8
	SPDT switches	16
	Filter (harmonic, other?)	8
	Phase shifter/attenuator	0 or 8 ^{Note 1}
	Total Components	40 to 48
Sofant	30dBm Power Amp	1
	Low Noise Amp	1
	SPDT switches	1 or 2 ^{Note 2}
	Filter (bandpass)	1
	Phase shifter/attenuator	8
	Total Components	12 or 13

Note 1. A digital beamformer would not require external phase shifters – this would be accomplished at baseband.

Note 2. The PA and LNA could be interfaced directly to the Tx and Rx ports of the transceiver, eliminating the need for a dual-switched T/R function.

Conclusion

In order for mmW 5G to be adopted for high volume consumer applications, phased array antennas must be low power and low cost without compromising performance. They must also be easy to integrate and simple to test in production using conventional high volume methods. Array architectures which integrate the PA and LNA function at each antenna element are costly and very power hungry. They also generate a substantial amount of heat and create other performance and production test challenges. Sofant’s low loss RF MEMS technology enables a passive smart antenna array which fundamentally changes the mmW radio architecture. It allows a single optimized PA, LNA and switch to be integrated onto the system board where device performance can be optimized and thermal management solutions are more easily engineered.

About Sofant Technologies

Sofant Technologies is based in Edinburgh, Scotland where it was spun out of the University of Edinburgh in 2011. Sofant’s mmW-optimized RF MEMS technology was developed at the Scottish Microelectronics Centre where it also developed intellectual property on integrated Phased Array Antenna

systems. Sofant's IP describes the combination of high performance MEMS devices with phased array antenna systems. Sofant technology is well positioned to enable low cost, high performance mmW 5G cellular systems.

References

1. *The future of mobile video, Cartesian and Mobile World Live. 2017.*