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mmWave Semiconductor Industry Technologies: Status and Evolution

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Executive summary

A number of semiconductor technologies capable of operating at frequencies up to 90GHz are currently available. Each has particular strengths and weaknesses with respect to various applications identified for millimetre wave transmission systems. This document takes the use cases identified by the ETSI Millimetre Wave Transmission Industry Specification Group in ETSI GS mWT 002 [3] and examines the demands these make on semiconductor components in order to meet the system requirements.

First generation products based on single function GaAs pHEMT MMIC technology facilitated the demonstration of high performance communication links up to 86GHz. Subsequent generations have seen the introduction of highly integrated silicon based chips (SIGe, SIGEBICMOS, CMOS and in future FD-SOI) and the parallel development of multifunction GaAs chipsets offering similar levels of baseband to RF functionality. The potential of each semiconductor technology in terms of performance and integration levels must be balanced against the maturity of the process and the potential return on investment for chipset development in the context of the market size for each use case. It is shown that present volume forecasts for macro cell backhaul applications in the E-Band which are in the region of hundreds of thousands of units per year represent a small opportunity for high-volume silicon-based processes. This may present a significant commercial barrier for semiconductor manufacturers to develop chipsets for this specific application. Use of the E-Band spectrum for small-cell use cases could however provide the necessary commercial justification. Here, low-cost silicon chips providing frequency conversion functions and moderate levels of performance for small-cell applications may be supplemented with GaAs devices to provide the power and noise figure performance needed for the more demanding use cases.

V-band applications present a much stronger business case for silicon technology where adjacent applications such as WiGig and wireless HDMI drive very high underlying volumes to justify the initial investment.

Assembly and packaging techniques have a critical effect on module performance and manufacturability at millimetre wave frequencies, so while not strictly semiconductor technology it is essential to consider these aspects in the selection of components.

Future requirements for fronthaul and for backhaul of 5G will require capacities achievable only by using very large amounts of contiguous spectrum. This spectrum exists at frequencies above 90 GHz therefore the development of semiconductor technologies operating above 90GHz and up to 300GHz is becoming increasingly important. This document introduces these technologies briefly; however, further development of this topic is addressed in ETSI GR mWT 008 [9].

Since many of the semiconductor technologies suitable for millimetre wave applications were originally developed using defence research funding, export controls imposed in the manufacturing countries may limit the availability of certain technologies in some emerging markets.

Introduction

The key challenge for the semiconductor industry is to develop and supply technology that will enable next-generation transmission networks to:

- Increase throughput
- Increase range
- Improve service availability
- Increase spectral efficiency
- Reduced power consumption
- Reduce cost – both CAPEX and OPEX
- Exploit of frequencies above 90GHz

These translate to semiconductor device demands in terms of:

- Transmit power
- Linearity
- Phase noise
- Noise figure
- Bandwidth – RF and Baseband
- Baseband I-Q Phase and Amplitude errors
- Operating frequency
- Integration level
- Packaging
- Support beam steering

This document reviews the status of foundry processes, chipsets and packaging technology to address present and future demands in backhaul, fronthaul and enterprise applications in both macro cell and small cell scenarios.

Scope

The scope of this document is to provide information on semiconductor technologies applicable to millimetre-wave transmission systems operating in the frequency bands of 57 to 66GHz (V-Band) and 71 to 86GHz (E-band). It also considers evolution into new frequencies of greater than 90GHz, up to 300GHz.

The document covers the following topics:

- Present and future capabilities of the mainstream semiconductor technologies:
  - III-V, primarily GaAs pHEMT and InGaP HBT but also GaN and InP in the future
  - Silicon, primarily SiGe/BiCMOS and CMOS
- System requirements by use case and implications for RF analogue components
- Key RF analogue components and optimum technology according to figure 1
  - Power Amplifiers
  - Low Noise Amplifiers
  - Frequency generation and conversion
- Analog Baseband according to figure 1
  - ADC, DAC and PLL
- Packaging and assembly technologies
- Semiconductor technologies for frequencies of between 90GHz and 300GHz
- Export restrictions, which may affect worldwide availability of technology in emerging markets.

Not covered in this document:

- Baseband
  - Digital Baseband/Modem: - FPGA, DSP, ASIC

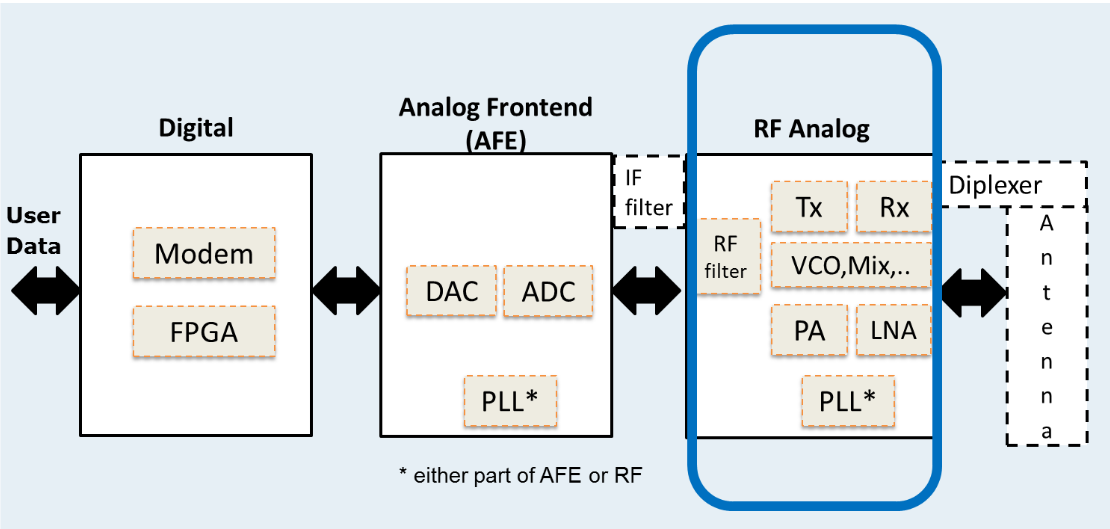


Figure 1: Semiconductor System Overview

Overview of semiconductor technology – status and evolution

Foundry processes which are available and in production for RF Analog components are: III-V (primarily GaAs) and silicon (primarily SiGe/BiCMOS and CMOS, used in WiGig 60GHz so far). New processes under development include GaN, InP and GaAs mHEMT, however none of these is currently available for commercial volume production.

The millimetre-wave (mmWave) application domain has historically been dominated by III-V MMIC semiconductor technologies (primarily GaAs). These are ideally suited for the RF front ends of mmWave systems such as power amplifiers and low noise amplifiers, as well as enabling oscillators with excellent phase noise characteristics (Figure 1 shows the generic system overview of a point-to-point radio).

More recently, SiGe:C HBT-based technologies, by addressing the automotive radar market, have gained increasing interest for emerging mmWave markets, as fT and/or fMAX of the HBT devices has exceeded 200GHz. The performance of SiGe HBT is no longer the limiting factor for a mmWave transceiver front end integration for small-cell applications with limited output power (usually intended to use V-band frequencies) but rather the quality factor of the on-chip passive devices, such as inductors, capacitors and transmission lines for matching and tuning and their accurate characterization in the mmWave frequency domain. However, the latest products on the market demonstrate sufficiently high quality which is a trade-off between performance and cost.

E-band applications for macro cells usually require high-order QAM modulation (>128), which can be achieved with GaAs components or a combination of SiGe/BiCMOS transmitter/receiver and GaAs PAs, LNAs and VCOs.

CMOS implementation promises higher levels of integration at reduced cost if volumes scale to several million parts per year, due to the higher speed of scaled technology. Several recent developments, especially chipsets available and targeting WiGig 60GHz, have shown that CMOS can be used to operate at mmWave frequencies, as the CMOS transistor fT goes close to 400GHz (http://electronics360.globalspec.com/article/4078/samsung-foundry-adds-rf-to-28-nm-cmos). However, the performance for point-to-point links is worse compared to SiGe or GaAs components in terms of phase noise and noise figure for the same distances (e.g. >100m). The status of various semiconductor foundry technologies and their application is summarized in Table 2.

In parallel with the usual CMOS planar bulk technologies, the Fully-Depleted SOI (FDSOI) technology is known to be very promising to provide high speed at low voltage. Several studies have demonstrated that competitive results can be achieved thanks to the Forward Body Biasing (FBB) technique, which is an extremely powerful and flexible concept that boosts performance, optimizes passive and dynamic power consumption, aided by the possibility to cancel out process variations and extract optimal behaviour from all parts. It is faster, provides better gain and better parasitic capacitance noise immunity. Moreover, this technology is fully compliant with designs already available for bulk CMOS technologies guaranteeing a successful IP porting.

SiGe-BiCMOS combines high-performance bipolar transistors and CMOS technology in a single chip. Bipolar transistors provide the high speed and gain that are critical for high-frequency analog sections, while CMOS technology is excellent for building simple, low-power logic gates. Solid know-how in design, architecture and process integration enables leading-edge SiGe BiCMOS technology that makes possible to integrate the RF, analog and digital parts on a single chip. This drastically reduces the number of external components while optimizing power consumption. BiCMOS process technology today offers a level of performance that was previously only attainable with more expensive technologies such as gallium arsenide (GaAs). Compared to bulk CMOS, BiCMOS with Silicon Germanium (SiGe) Heterojunction Bipolar Transistors (HBT) allows a much higher cut-off frequency at a given technology node together with a higher voltage capability. To reach similar frequencies, bulk CMOS designs have to use much smaller process nodes. This makes it necessary to compromise on the design and most of the time leads to lower overall power performance and higher cost.

The table below summarizes the main process features of the remaining SiGe Bipolar and BiCMOS technology industrial manufacturers.

Company[1]	Freescale		IBM			Infineon		TowerJazz		STMicroelectronics	
Name	HiP6MW	HiP6MW2	BiCMOS8HP	BiCMOS8XP	BiCMOS9HP	B7HF200	B11HFC	SBC18H3	SBC18H4	BiCMOS9MW	BiCMOS055
Status	Prod.	Dev	Prod.	Prod?	Dev.	Prod.	Dev.	Prod.	Dev.	Prod.	Dev.
CMOS node	180nm		130nm		90nm	Bipolar-only	130nm	180nm	180nm	130nm	55nm
Wafer Size	200mm		200mm			200mm		200mm		200mm	300mm
SiGe HBT structure	Self-aligned SEG epi.		Self-aligned NSEG epi.			Self-aligned SEG epi.		Self-aligned NSEG epi.		Self-aligned SEG epi.	
SiGe HBT f_T / f_{MAX} (GHz)	200 / 280	260 / 350	210 / 270	260 / 320	300 / 350	190 / 250	240 / 380	240 / 270	275 / 350 (tbc)	220 / 280	320 / 370
BEOL (w/o Alu cap)	5 Cu levels (0.8 µm top metal)		3 Cu+2 Al levels (1.25 µm + 4.0 µm)		NA	4 Cu levels (0.6/0.6/1.2/2.5 µm)	6 Cu levels (0.29/0.32/0.32/0.32/1.0/2.8 µm)	Up to 6 Al levels with at least 1 thick top metal		6 Cu levels (0.26/0.35/0.35/0.9/3.0/3.0µm)	8 Cu levels (0.16/0.2x4/0.9/3.0µm)
TL (µ-strip)	1.25 dB/mm @ 77GHz	<1 dB/mm @ 80GHz	0.9 dB/mm @ 60GHz		NA	NA	NA	NA	NA	0.5 dB/mm @ 60GHz	0.65 dB/mm @ 50GHz

[1] *IHP hasn't been listed because it is not an industrial company although it offers a prototyping line.*

Table 1: Main process features of SiGe Bipolar and BiCMOS technology industrial manufacturers

Packaging processes which are available and in production for RF analogue components are: QFN, eWLB, CSP and FlipChip. However today's mmWave RF components are mostly bare dies or modules.

The eWLB examples with SiP demonstrate that assembly and packaging using the eWLB technology offer outstanding system integration capabilities. This includes the integration of different chips and the design of integrated passives like resistors, inductors, transformers either in the RDL or using TEV. Antennas can be integrated into the package.

Other technologies where silicon wafer-level technology and backend merge are TSV and die embedding in laminate technologies. TSV technologies are typically combined with RDLs, e.g. for silicon interposer. They are presently investigated in worldwide consortia. A major hurdle for their broad integration is cost. The status of various semiconductor packaging technologies and their application is summarised in Table 3.

In terms of the evolution of future chip integration for RF analogue components, there are different approaches possible. They will depend mainly on several factors:

- allowed output power and EIRP of the system (incl. antenna)
- phase noise required for defined modulation scheme (BPSK, QPSK, QAM4, …, QAM256 etc.)
- noise figure
- power consumption
- size in terms of PCB area and related cost

Silicon transistors cannot compete with III-V compounds (GaAs, InP, GaN) for low noise performance, linearity and output power at frequencies above 20GHz. A GaAs mmWave LNA results in an average noise figure around 2.5dB, which is far lower than state-of-the art SiGe LNA of 5dB. Output power levels (Psat) of over 30dBm can be achieved with GaAs in E-Band, while SiGe-HBTs can reach 19dBm (Psat).

Silicon RF ICs do however allow the integration of multiple application specific functionalities on a single silicon chip (RF ASIC) with excellent yield and uniformity plus the possibility to integrate the different calibration schemes required to take into account RF impairments (not possible or much more complex to implement in GaAs).

The level of integration is a factor to be considered. A high level of integration makes the chip very specific and could increase development time in a first design but reduces production test and simplifies module assembly. A good compromise for high-end applications (e.g. E-band high power, QAM256) is to use compound semiconductors for the front-ends (LNA of the receiver input and power amplifier of the transmit output) and silicon semiconductors for the lower frequency mixed signal functions and control/digital elements. The outlook for semiconductor technologies at frequencies from 90GHz up to 300GHz is given below.

III-V compound devices can realize systems to expand the use of the electromagnetic spectrum above 90GHz. However improvements in the high-frequency capability of CMOS/BiCMOS technology have made it possible to consider it as a low-cost, lower performance alternative to III-V compound devices. An oscillator is usually the first high-frequency circuit demonstrated in a new technology. An example is given in this paper.

A major obstacle to investigate further is the state of regulation for the use of frequencies >90GHz for commercial backhaul/fronthaul applications. This will be a new subject of study for ETSI ISG mWT.

	Available	RF Analog	Available	Filter	Available	AFE	Available	Digital
Foundry Process	Yes	GaAs (PA, LNA, Mix, VCO,..)	Yes	GaAs				
	Yes	SiGe Bipolar	Yes	SiGe Bipolar				
	Yes	SiGe BiCMOS	Yes	SiGe BiCMOS	Yes	SiGe BiCMOS	Yes	SiGe BiCMOS
	Yes	CMOS & FD-SOI (WiGig 60GHz)	Yes	FD-SOI	Yes	FD-SOI	Yes	CMOS & FD-SOI
	Yes	GaN PAs, Limited availability	Yes	GaN				
	Yes	InP LNA, Limited Availability						

Table 2: Foundry processes of semiconductor components for mmWave

	Available	RF Analog	Available	Filter	Available	AFE	Available	Digital
Packaging Process	Yes	Bare die	Yes	SMT	Yes	QFN (PLL)	Yes	BGA
	Yes	QFN (PLL, VGA, Tx/Rx)			Yes	BGA (ADC, DAC)		
	Yes	eWLB (Tx/Rx)			Yes	CSP (ADC, DAC)		
	Yes	CSP (PA, VGA)						
	Yes	Flip Chip						

Table 3: Packaging processes of semiconductor components for mmWave

The market for mmWave backhaul (used here as synonym for other applications like fronthaul, enterprise etc.) is not yet developed in terms of higher volume deployments, defined as a few hundred thousand to millions of devices. This is relevant for advanced Silicon-based foundry processes like SiGe Bipolar/BiCMOS and CMOS.

Investments in new and advanced semiconductor technologies require reliable business cases. Therefore a more reliable market outlook for mmWave is required to stimulate evolution and improve the semiconductor contribution towards TCO (Total Cost of Ownership).

The mmWave backhaul/fronthaul market in 2015 is less than 100,000 units a year. Assuming each unit includes two transceivers, this equates to less than 200,000 RF chips. If we convert a maximum of 200,000 pieces in SiGe technology to the number of wafers, this is about 125 wafers per year or about 10 wafer starts per month. A standard foundry has about 100,000 wafer starts per month. Therefore this is just 0.01% of a standard fab. While GaAs chipsets are generally larger and fabs are lower capacity the equivalent number of GaAs wafers is still less than 500 which is about 0.2% of a high volume GaAs fab's capacity. The graph below compares GaAs and Si wafer numbers vs E-band chipset volumes.

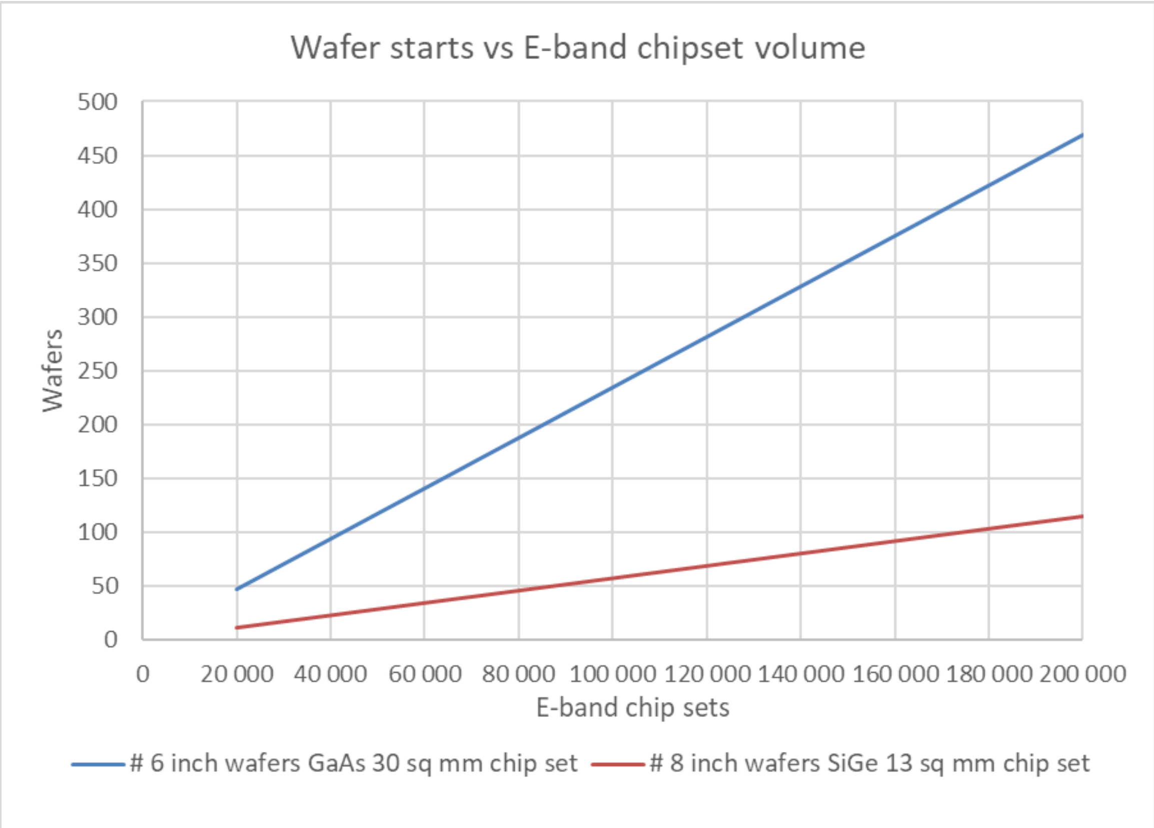


Figure 2: Wafer starts vs. E-band chipset volume

To conclude, the 2015 worldwide demand for mmWave systems is negligible even for a single wafer fab in terms of volumes.

System requirements by use case

mmWave transmission use cases

ETSI GS mWT 002 [3] has identified the following applications and use cases of mmWave transmission:

1. Macro-cell mobile backhaul application (mobile network upgrade, expansion)
2. Small-cell mobile backhaul application (rooftop-to-street / street-to-street connectivity, multi-hop)
3. Fronthaul for small cells application (rooftop-to-street / street-to-street connectivity, multi-hop)
4. Fronthaul for macro cells application (mobile network upgrade, expansion)
5. Next-generation mobile transmission application
6. Fixed broadband application (wireless to the home, wireless to the cabinet)
7. Temporary infrastructure application (special events, public safety)
8. Business-to-business application
9. Business-to-government application (broadband connectivity, public Wi-Fi hotspot backhaul)
10. Redundant network application
11. Video surveillance backhaul application
12. TV signal relay application

This paper focusses mainly on use cases #1 to #6 above, however use cases #8-11 are also considered as these "Enterprise applications" represent a substantial part of E-band shipments made since 2012 and will continue to see widespread deployment.

Macro-cell mobile backhaul application

(mobile network upgrade, expansion)

E-Band:

Assumption: FDD implementation due to frequency allocation (2 bands available high and low at 70GHz and 80GHz which enable FDD).

a. Typical output power that can be achieved:

- Current state of the art circuits operating in the E-band, especially PA, LNA are designed with III-IV compounds (GaAs). GaN has potential but is available only in research and academia but not commercially. SiGe/ BiCMOS and CMOS usually do not achieve required output power for distances >2km and high-order QAM (>QAM64). It usually has lower power efficiency and linearity compared to III-V compound semiconductors.
- Psat required is more than 23dBm, P1dB is more than 20dBm
- Output power achieved varies per modulation: QPSK is about 20dBm, higher-order modulations require more back-off, e.g. >= QAM256 can operate at around 10 to 12dBm.

b. Typical Noise Figure (NF)

- Typical NF achieved is around 7 to 10dB together with losses prior to LNA (diplexer, waveguide transitions etc.)
- State of the art LNAs are designed in GaAs. SiGe integrated LNAs are entering the market with performance of typical NF of 6-7dB
- NF measurement over temperature will vary for E-band (71 to 76GHz). An example of SiGe technology (Infineon) shows a variation depending on the temperature of 6 to 8dB@+55°C, 6 to 7dB@+25°C and 4.5 to 6dB@-40°C. As a comparison, NF variation over the same temperature range for GaAs is about 1.2 dB.

c. Phase Noise (PN) VCO

- Very few integrated solutions exist in the market (Infineon has commercially available products)
- External VCOs are operating at wanted RF frequency of f_rf/6 or f_rf/8
- VCO phase noise is a very important specification for the overall RF performance to allow higher-order QAM modulation. An example of SiGe technology (Infineon) shows better than -82dBc/Hz@100MHz offset, with a slope of -20dB per decade @ 1MHz and @100MHz offset for the 71 to 76GHz and the 81 to 86GHz band. As a comparison, multiplied InGaP HBT-based oscillators are about 10dB lower in phase noise at the same offsets.

d. Simulation of typical link budget and link distances

- The actual value of the maximum transceiver power (Ptx_out-max) at the antenna port depends on the modulation scheme used for the radio link. The output power back-off (= Psat – Ptx_out-max) is lower for simple modulation schemes like QPSK, QAM16 and higher for more efficient modulation schemes like QAM64, QAM128, QAM256.
- A typical link budget will depend on many parameters of the radio link such as:
    - antenna size, e.g. 30cm or 60cm diameter
    - RF Noise Figure, e.g. 7dB typical at antenna port
    - system gain, e.g. 61dB@QAM256 / 500MHz bandwidth
    - modulation scheme and bandwidth, e.g. QAM64 / 500MHz

System parameter	30 cm antenna	60 cm antenna
Tx power @ 256 QAM	+10 dBm typical at antenna port	
Tx power @ 64 QAM	+12 dBm typical at antenna port	
Tx power @ 4 QAM	+18 dBm typical at antenna port	
Rx noise figure NF	7 dB typical at antenna port	
10e-6 BER threshold @ 256QAM / 500MHz	-51 dBm typical at antenna port	
System gain @ 256QAM / 500MHz	61 dB	
Max link length @ 256QAM / 500MHz 99.99% link availability in K region	1.17 km	1.72 km
Max link length @ 64QAM / 500MHz 99.99% link availability in K region	1.35 km	1.99 km
Max link length @ 4QAM / 500MHz 99.99% link availability in K region	2.73 km	3.51 km
Max link length @ 256QAM / 500MHz 99.9% link availability in K region	2.09 km	3.52 km
Max link length @ 64QAM / 500MHz 99.9% link availability in K region	2.63 km	4.40 km
Max link length @ 4QAM / 500MHz 99.9% link availability in K region	6.47 km	10.29 km

Note: SNR for 10e-6 sensitivity level with 256QAM assumed to be equal to 30 dB.

K region: is equivalent to 42mm/hour or ~15dB/km for 99.99%, 12mm/hour or ~7dB/km for 99.9%

Table 4: Example of link coverage simulation for 73GHz at different system parameter conditions (source Infineon Technologies AG)

V-Band

Assumptions: Link distances are much smaller due to oxygen absorption at 60GHz – attenuation is roughly 16dB/km. Macro-cell mobile backhaul application is possible but lower distances are achieved. Both TDD and FDD implementations exist due to one band frequency allocation 57GHz to 64GHz. High attenuation allows frequency reuse therefore 60GHz is more popular for small cells.

a. Typical output power

- Similar to E-Band for SiGe

b. Noise Figure (LNA NF)

- Similar to E-Band for SiGe

c. Phase Noise (PN) VCO

- Similar to E-Band for SiGe

d. Simulation of typical link budget and link distances

- The following data have been used for a simulation of Infineon 60GHz transceiver
    - Link Availability: 99,99% with and without an additional external PA
    - Channel spacing: 50MHz or 250MHz
    - Modulation Format QPSK up to QAM64 (WiGig)

Modulation scheme	Channel BW	Antenna diameter	Radio ch. frequency	Additional PA	Link Availability	Max Link Distance (km)
4QAM	250MHz	30cm	64.0GHz	N	99.99%	1.32
4QAM	250MHz	30cm	64.0GHz	Y	99.99%	1.47
4QAM	50MHz	30cm	64.0GHz	N	99.99%	1.58
4QAM	50MHz	30cm	64.0GHz	Y	99.99%	1.73
16QAM	250MHz	30cm	60.0GHz	N	99.99%	0.85
16QAM	250MHz	30cm	60.0GHz	Y	99.99%	0.96
32QAM	250MHz	30cm	60.0GHz	N	99.99%	0.78
32QAM	250MHz	30cm	60.0GHz	Y	99.99%	0.88
64QAM	250MHz	30cm	60.0GHz	N	99.99%	0.61
64QAM	250MHz	30cm	60.0GHz	Y	99.99%	0.71
128QAM	250MHz	30cm	60.0GHz	N	99.99%	0.55
128QAM	250MHz	30cm	60.0GHz	Y	99.99%	0.62

Small-cell mobile backhaul application

(rooftop-to-street / street-to-street connectivity, multi-hop)

E-Band

Assumption: Typical output power required is lower since the distance required is lower. Typical distance 100m-500m.

a. Typical output power

- Typical output power required for E-Band is 10dBm or lower
- Achievable with GaAs, SiGe, BiCMOS and CMOS

b. Noise Figure (LNA NF)

- Similar to E-Band macro-cell backhaul for SiGe

c. Phase Noise (PN) VCO

- Similar to E-Band macro-cell backhaul for SiGe

d. Simulation of typical link budget and link distances

- Similar to E-Band macro-cell backhaul for SiGe

V-Band

Assumption: Link distances are much smaller due to oxygen absorption at 60GHz – attenuation is roughly 16dB/km

Small-Cell mobile backhaul application is possible. Both TDD and FDD implementations are possible.

High attenuation allows frequency reuse and therefore 60GHz is more popular for small cells.

a. Typical output power

- Distances up to 500m, therefore > 0dBm to 10dBm is required

b. Noise Figure (LNA NF)

- Similar to V-band Macro-Cell backhaul for SiGe

c. Phase Noise (PN) VCO

- Similar to V-band Macro-Cell backhaul for SiGe

d. Simulation of typical link budget and link distances

- Similar to V-band Macro-Cell backhaul for SiGe

Fronthaul for small cells application

(rooftop-to-street / street-to-street connectivity, multi-hop)

Assumption: Application is similar to backhaul. Both E-Band and V-band can be used. Typically distances are short like in small cell backhaul.

The real difference is throughput requirement. Fronthaul needs to transmit CPRI standard digital signal – not optimized and requires higher throughput.

- No details available

Fronthaul for macro cells application

(mobile network upgrade, expansion)

Assumption: Application is similar to Backhaul. Both E-Band and V-band can be used but E-band is preferred. Typically distances are longer like in macro cell backhaul.

The real difference is throughput requirement. Fronthaul needs to transmit CPRI standard digital signal – not optimized and requires higher throughput

- No details available

Next-generation mobile transmission application

According to the use cases and statements of ETSI GS mWT 002 [3] as below:

The entire ecosystem of the mobile industry is now paving the way towards the standardization of the fifth generation of mobile telecommunications technology, in order to meet the demands of the next decade. The unprecedented growth of mobile traffic is going to be driven by established and new use cases, which will be delivered across a wide range of devices and across a fully heterogeneous environment. The potential attributes that would be unique to 5G are sub-1 ms latency and over 1 Gbps DL speed, while the data rate of 10 Gbps is the minimum theoretical upper limit speed discussed for 5G.

In-band backhauling solutions where the radio access shares the same spectrum with the backhaul links are considered as a cost effective solution for deploying a large number of small cells for 5G capacity solutions. In this context, millimetre wave bands are specifically mentioned as frequency bands of interest. The above indicates that 5G wireless transmission technologies, either as backhaul or front-haul, will also have to adapt significantly to these tremendous changes at both macro-cell and small-cell layers. It is logical that in order to achieve fibre-like performance, 5G wireless transmission technologies will require massive amounts of spectrum. Furthermore, as 5G mobile networks will display higher density to accomplish the 1000x capacity per unit area, a 5G wireless transmission application will benefit from high frequency re-use schemes, dense deployments, new licensed spectrum complemented by unlicensed spectrum according to the layer (small-/macro-cell) that is developed.

Semiconductor technology will need to adapt its performance and integration level accordingly. To implement the details, it is required to have a system requirement/ specification.

It is important to notice that semiconductor technologies for mmWave backhaul/fronthaul will require about 1 to 2 years development cycle, depending on integration level, to provide such new solutions. If new techniques are needed a longer term research (>3-5 years) is required.

Fixed broadband application

(wireless to the home, wireless to the cabinet)

Assumption: This could be a “WiGig type” of application using 60GHz backhaul or 802.11ad solutions for short distances.

Beamforming is already exploited due to PtP or PtMP links having LOS, nLOS and NLOS conditions.

BiCMOS and RF CMOS prevail due to lower BOM for high volumes and lower power consumption for beamforming.

Wireless to Home | **Wireless to the Cabinet**

RF Path Clearance	LOS/nLOS/NLOS	RF Path Clearance	LOS/nLOS/NLOS
Connectivity	PtP/PtMP	**Connectivity**	PtP
Capacity	≤ 1 Gbps	**Capacity**	≤ 10 Gbps
Range	≤ 100 m	**Range**	≤ 1 km (urban) ≤ 3 km (sub-urban)
Availability (at reference physical modulation)	99,9 % - 99,99 %	**Availability (at reference physical modulation)**	99,99 % - 99,999 %

Reference: ETSI GS mWT 002 [3]

Table 5: Fixed broadband application

Enterprise applications summary

This includes the following use cases: business-to-business application, business-to-government application, redundant network application, video surveillance backhaul application.

E-Band

Assumption: Typical antenna size is 30cm or 60cm and typical distance 0 - 2000m

- Throughput: 1Gbps
- Modulation modes: up to QAM64 maximum
- Channel sizes: 250MHz, 500MHz
- Typical output power required for E-Band is +10dB

There is a demand for links providing 1Gbps lines for enterprise / WISP / businesses / CCTV backhaul, and these need to be as low-BOM as possible, but still capable of up to 2km range. The low-BOM dictates that expensive PAs and LNAs are avoided if possible, using the SiGe chipsets alone, and using wider channel sizes and lower-order modulation modes to achieve the required link budget.

Use case requirements vs. RF semiconductor foundry technologies

Different use case requirements trigger different semiconductor technologies.

Table 6 and Table 7 give an overview of the advantages and disadvantages of each RF technology. The overall system performance and cost will depend on further components described in Figure 1 and the technical system specification.

RF Technology	**RF system BOM**	**RF Integration level**	**RF performance**	**Main RF products**
GaAs (PHEMT)	High for complete RF solution, multi-chip modules	Difficult to integrate logic	Very good performance	PA, LNA, RF Modules
GaN	Technology in early stage	Same as GaAs	Potentially better P_{sat} vs GaAs but linearity may be worse negating advantage for High QAM applications	Today mainly for non-mmWave, PA, LNA in future
InP-PHEMT	Higher than GaAs	Difficult to integrate logic and complex RF circuits	Better RF Performance (f_T, f_{MAX}) than GaAs PHEMT	Focus on military applications
SiGe	Lower than GaAs, GaN, InP and CMOS (depends on volume)	High level RF integration possible Not suitable for SOC integration with ADC, baseband	Optimized for MMW, due to high f_T and f_{MAX}, low phase noise and low loss BEOL metal/dielectric stacks.	MMW transceiver with medium/high Tx power (longer range)
SiGe BiCMOS	Lower than GaAs, GaN, InP and CMOS (depends on volume) - high production yield because of SoC	Excellent to integrate larger logic blocks like SPI, PLLs, ADCs, VGAs, …. Lower power required to move signals across chip boundaries (digital to analog, analog to RF)	Optimized for MMW, due to high f_T and f_{MAX}, low phase noise and low loss BEOL metal/dielectric stacks.	MMW transceiver with medium/high Tx power (longer range) + ADC, VGA, PLL possible
RF CMOS	Low cost and high volume fab sourcing . RF/MMW additions	Enables low power digital intensive RF architectures.	MMW capable transistors (f_T, f_{MAX}), thick top metals for low loss and high Q	RF Transceiver + ADC, VGA, PLL possible. Best choice for price

	to mainstream digital CMOS, but high NRE with advanced lithography.	SOC integration with RF,ADC, digital baseband, memory. Lower power required to move signals across chip boundaries (digital to analog, analog to RF)	but needs smaller process node and consequently gets lower breakdown voltage with respect to SiGe BiCMOS. Low Tx output power / efficiency at mmWave and poor device isolation.	sensitive lower performance (short-range) applications.
FD-SOI	Lowest voltage and lowest power operation with unique back-gate bias capability.	High-density SOC integration. Lower power required to move signals across chip boundaries (digital to analog, analog to RF)	High self-gain vs CMOS High f_T / f_{MAX} Substrate engineering for additional RF benefits Increased isolation and linearity	New capability in industry for novel architectures and reconfigurable operations. Mixed signal and high speed interfaces like serializers and deserializers

Table 6: Comparison of RF analogue semiconductor technologies for millimetre waves

Simplified comparison of RF technologies and related Use Cases

RF Technology	**RF system BOM [1)]**	**RF Integration level**	**RF performance**	**Preferred Use Cases [1)]**
GaAs (PHEMT)	**+**	**-**	**+++**(high order QAM)	• Macro-cell mobile backhaul • Fronthaul for Macro-cell • Fronthaul for Small-cell
GaN	**0**	**-**	**+++** (Psat)	• Macro-cell mobile backhaul • Fronthaul for Macro-cell • Fronthaul for Small-cell • Next-generation mobile transmission application
InP-PHEMT	**-**	**-**	**+++** (NF)	• Macro-cell mobile backhaul • Fronthaul for Macro-cell
SiGe	**++** (depends on volume)	**+**	**0**	• Small-cell mobile backhaul • Fronthaul for Small-cell • Fixed broadband application (WtH, WtC) • Enterprise applications

SiGe BiCMOS	++ (depends on volume)	+++	++	• Macro-cell mobile backhaul • Small-cell mobile backhaul • Fronthaul for Small-cell • Fixed broadband application (WtH, WtC) • Next-generation mobile transmission application • Enterprise applications
RF CMOS	++ (depends on volume)	+++	+	• WiGig/ 802.11ad • Small-cell mobile backhaul • Front haul for Small-cell • Fixed broadband application (WtH, WtC) • Next-generation mobile transmission application • Enterprise applications
FD-SOI	++ (depends on volume)	+++	++	• Small-cell mobile backhaul • Front haul for Small-cell • Fixed broadband application (WtH, WtC) • Next-generation mobile transmission application • Enterprise applications

1) Use cases defined in ETSI GS mWT 002 [3]

Symbols: "-"only part of the feature, "0" neutral, basic feature, "+" positive differentiator, "++" very positive differentiator; "+++" best in class

Table 7: Use Case and simplified comparison of RF analogue technologies for millimetre waves

The comparison of the use cases as defined in ETSI GS mWT 002 [3] versus foundry process technologies is based on the following assumptions:

- Modulation schemes: BPSK up to 256QAM; in the future a higher-order QAM might be required
- Channel Spacing (CS): The standard supports channel spacing down to 62.5MHz; minimum CS is 50MHz - this CS is supported in the V Band (60GHz) which is important for small-cell applications.
- Bit rate: several Mbps up to 10Gbps. In future data rates >10Gbps might be required, an important capability for fronthaul applications
- Semiconductor technologies like GaAs, SiGe/BICMOS, CMOS, FD-SOI and GaN are likely most important for mmWave applications, as InP might be more relevant for military applications due to cost
- Highly integrated single chip receivers and medium power transmitters available from several vendors in SiGe, SiGe/BiCMOS, CMOS and FD-SOI.

- Power amplifiers up to 30dBm demonstrated with commercial 0.1µm pHEMT Foundries
- GaAs mHEMT processes have demonstrated 2dB NF in E-band (50nm mHEMT).
- InP components demonstrate <2.5dB NF with 0.1µm InP HEMT
- GaN PAs with Psat > 30dBm to 100GHz have been demonstrated (0.14µm GaN on SiC)

Figure 3 summarizes the overview of current RF semiconductor technologies and trends towards developments in 2020. The RF semiconductor technology versus uses case shows a selection of typical system parameters relevant for semiconductors.

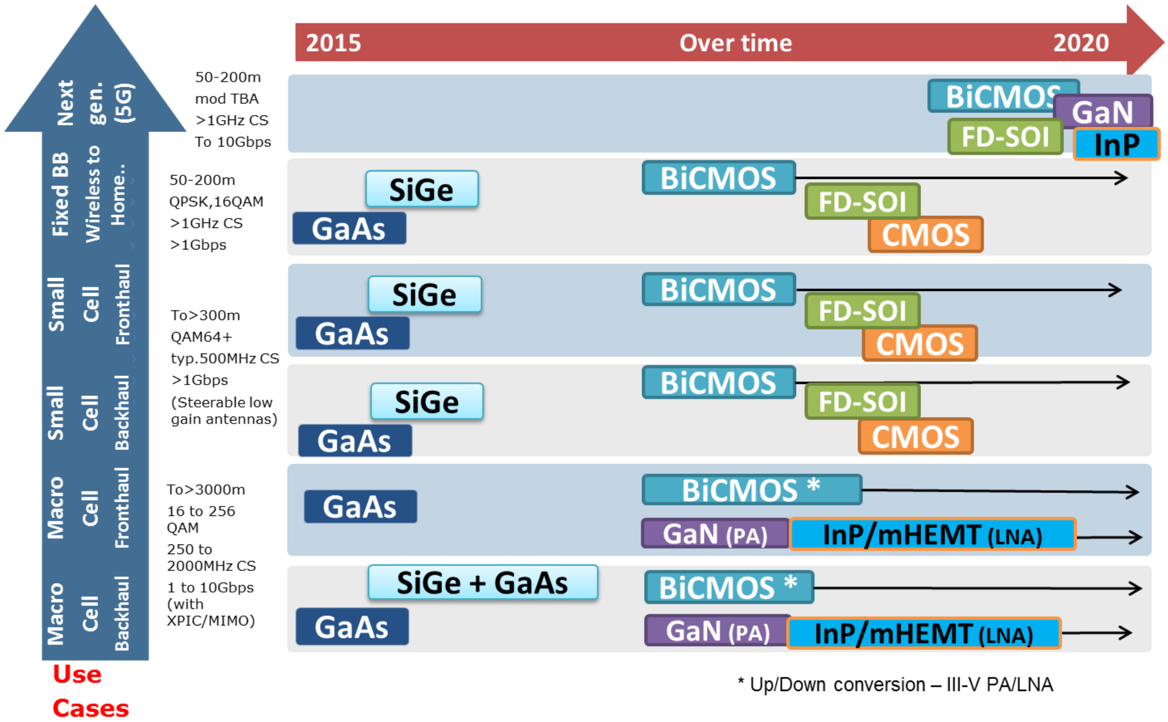


Figure 3: Semiconductor technology overview, trends towards 2020 and use cases

Baseband analogue frontend (AFE) technology overview

Introduction

Millimetre-wave modems utilise digital signal processing to perform complex (IQ) modulation and demodulation in order to transmit gigabit rate data streams onto radio carriers in V, E and other bands. Data rates range from 1 – 10 Gbps over channel bandwidths of 250, 500 MHz and more recently use of wider channel widths such 1 and 2 GHz. Modulation levels range from BPSK, QPSK, 16QAM and through to 256QAM for high-performance channel limited systems. Therefore, it is necessary to perform real time IQ ADC (receive) and IQ DAC (transmit) for the interface between the analogue and digital domains. Moreover, such conversions require low-jitter baseband clocks in order to minimize intersymbol interference. Grouped together, the combination of IQ ADC, IQ DAC and Baseband PLL is known as an Analogue Front End (AFE), refer to Figure 1. The performance of the AFE has a significant influence on the overall performance of the modem in terms of receiver dynamic range, transmitter spurious emissions and end to end BER/PER. This chapter therefore reviews key AFE technical requirements and provides a brief review of the state of the art of both discrete and chip level AFE technologies available today.

Technical requirements

The AFE requirements can be divided into three functional areas as follows:

Receiver ADC requirements analysis

A quadrature IQ ADC is required in order to sample the baseband IQ analogue signals downconverted from the millimetre wave receiver. Typical channel widths range from 250/500 MHz for traditional backhaul systems to 1.76 GHz or higher for 802.11ad ‘WiGig’ systems. Required sample rates therefore track from 500 MHz to 2.6 GHz or higher depending on the required over-sample ratio for a given modem implementation. Required resolution or effective number of bits (ENOB) is primarily a function of modulation level from QPSK requiring 4bits, 16QAM - 5bits, 64QAM - 6bits. Also noteworthy is the need for additional dynamic range to support OFDM modulation modes as compared to Single Carrier (SC) modulation modes because of their increased peak to average power ratio (PAPR) due to power summation over multiple sub-carriers (Crest Factor). This may increase the effective resolution requirement for another 5-6dB for OFDM modes as compared to SC modes for a given modulation index. In order to determine the dynamic range of the ADC for a given modulation level and receiver, the following factors at least must be considered:

The noise floor of the ADC range is defined by the power level of the (quantization) noise produced by the ADC itself when referred back to the receiver input i.e. the actual ADC noise power divided by the gain of the front end. Conventionally, this is set to a level approximately 10 dB below the total effective noise power at the input to the receiver so that the effect of the ADC is to increase the frontend noise figure by at most 0.5 dB. The receiver noise power is just the thermal noise power (i.e. kTB, with k being the constant of Boltzmann, T the absolute temperature and B the bandwidth) raised by the receiver noise figure in dB.

Above the receiver noise, an interval must be added for the signal-to-noise-ratio (SNR) requirement at the input to the demodulator. This must be followed by an extra interval related to the crest factor of the signal. Both these intervals vary with the modulation and error coding mode (MCS index). What is left at the top of the range is then referred to as headroom, which is the amount by which the average signal power can be allowed to increase before any gain reduction needs to be applied with the receiver automatic gain control (AGC). Hence, the headroom determines the minimum AGC step requirement for any given mode. The larger the headroom, the larger the value that can be assigned to the AGC step size. In short, the ADC dynamic range is given by:

$$DR_{ADC} = 9.636 + SNR_{dB} + CF_{dB} + Hr_{dB} \quad \text{dB} \tag{1}$$

where SNR_{dB} is the minimum signal-to-noise ratio required at the demodulator, CF_{dB} is the crest factor and Hr_{dB} is the ADC headroom. A typical dynamic range from an example QPSK modulation (MCS7 from 802.11ad) would be approximately 36 dB if the headroom is restricted to 14 dB. This analysis may be extended to higher order modulation MCS modes in order to determine the optimum ADC dynamic range and resolution for the support for 16QAM, 64QAM or 256QAM and then relate this back to ADC ENOB (Effective Number of Bits) from the equation below.

$$ENOB = \left\{ DR_{ADC} - 10\log_{10}\left(1.5x\frac{f_{samp}}{f_{chan}}\right)\right\} \div 6 \quad bits \tag{2}$$

where f_{samp} and f_{chan} are the sampling frequency and channel bandwidth respectively. In general we can observe that each doubling of I or Q resolution (being 4x in modulation domain) requires an additional 6 dB or 1 additional bit of ENOB. Hence we may imagine QPSK would require ~4bits, 16QAM ~5bits, 64QAM ~6bits. OFDM modulation could require additional dynamic range due to its increased PAPR. This may add the requirement for another 5-6dB for OFDM modes compared to SC modes for a given modulation index.

DAC dynamic range requirement analysis

A quadrature IQ DAC is required to generate the baseband IQ analogue signals for upconversion, filtering and amplification for the millimetre wave transmitter. Typical bandwidths and sample rates are the same as those needed for the IQ ADC. However, the key technical parameter for the transmitter relates to the spurious emissions requirement. Spurious emissions requirement refers to IEEE 802.11ad transmit spurious spectrum mask. As will be seen in the analysis presented below, resolution requirements of 7 bits or higher are typically required.

The dynamic range requirement of the DACs is largely determined by the spurious emissions requirement of the transmitter, for example, as given in the IEEE 802.11ad specification. The dynamic range requirement is also dependent on the headroom deemed necessary to cope with both gain variations in the millimetre wave transmitter chain along and with the provision of digital power control. The IEEE specification on spurious emissions presently states that the noise power density at a carrier-offset frequency of 3.06 GHz shall not be greater than 30 dB below the power density of the wanted signal itself.

The DAC dynamic range requirement can be calculated with reference to equation (4) below where S_{pdB} is the spurious emissions requirement (i.e. -30dBr), L_{dB} is the IF filter attenuation at 3.06 GHz carrier offset, CF_{dB} is the crest factor of the wanted signal and HR_{dB} is the required DAC headroom. This equation applies for all MCS modes and hence, if the headroom is fixed, the dynamic range becomes dependent on only the crest factor. Taking the same modulation index as used in calculating the ADC dynamic range –

namely 802.11ad MCS7 – a dynamic range of 43.7 dB is required assuming that the headroom is set to 10 dB and there is only limited IF filter rejection of the order of 3 dB.

$$DAC_{drdB} = -S_{pdB} - L_{dB} + CF_{dB} + HR_{dB} \quad \text{dB} \tag{3}$$

Baseband PLL requirement analysis

A baseband PLL is required to generate the local IQ sample clocks required for the IQ ADC and DAC. Depending on the channel bandwidth this sample clock may range from 500 MHz through to 3 GHz or higher. The phase noise of this baseband clock may therefore have an impact on overall system performance. To evaluate this issue consider the SSB phase-noise characteristics of a commercial ADC clock PLL from Analog Devices – part number ADF 4360-1 – which, with a 40 MHz crystal reference, achieves an rms phase noise of 1.57° in the bandwidth 100 Hz to 4.5 GHz.

Using equation (4) below, this phase noise converts into an equivalent value of SNR of 31.24 dB in the Nyquist band between +/- fs/2, where fs is the sampling frequency.

$$SNR_{\theta dB} = 20\log_{10}\left[\frac{180}{\pi\theta_j}\right] \quad \text{dB} \tag{4}$$

The phase noise performance needed of the ADC clock PLL can be further estimated from an analysis of the receiver SNR at reference sensitivity for all modulation modes and then defining the acceptable further reduction in SNR that could be tolerated as a consequence of the additional phase-noise contribution of the sampling clock. If the further reduction of SNR is set to 0.1 dB, it can be shown that the corresponding rms phase noise of the PLL will be 2.08° and the rms time jitter for a typical 802.11ad sample clock of 2.64 GHz will be 2.2ps. Hence a reasonable jitter requirement for the baseband PLL can be set to be less than 2ps.

Power consumption

For WiGig style consumer electronics applications the AFE function is required to be integrated onto the same silicon baseband die as the PHY+MAC digital processing functions. This gives a typical target power consumption in the region of 200 – 400mW for the entire AFE. For discrete IQ ADC, DAC and PLLs, power consumption in the region of 2W is more typical. However much less power consumption can be obtained by fully exploiting the technology features of the FD-SOI process, as demonstrated in the ADC shown below.

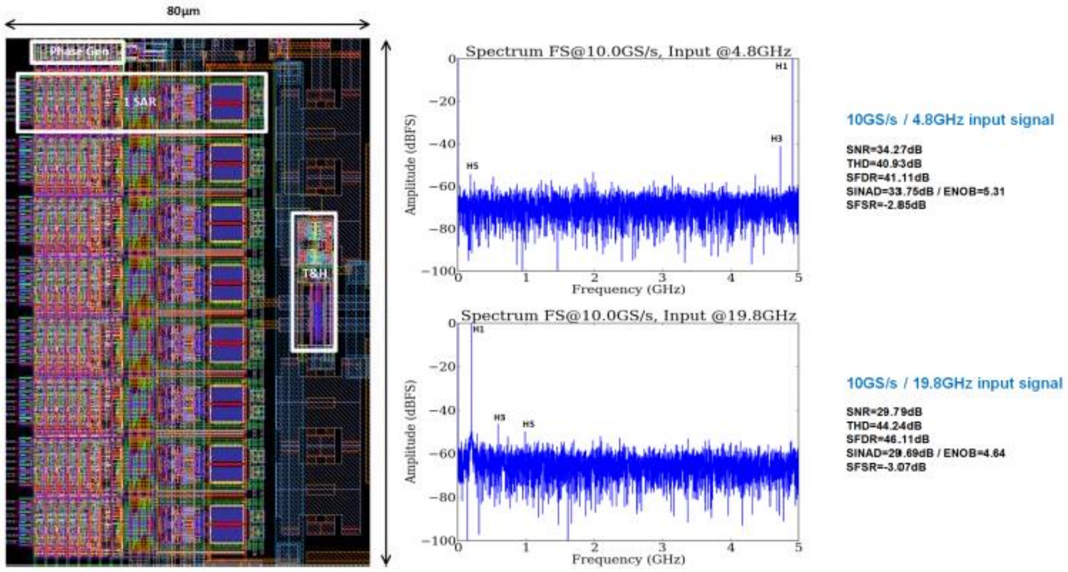


Figure 4: STMicroelectronics high speed ADC: 6b 10Gsps 50mW power consumption in 28nm FD-SOI process

Technology review: discrete AFE components

Discrete ADC and DACs are typically used with digital modems implemented in FPGA technology although Xilinx Inc recently announced their RFSoC family of devices with integrated DACs and ADCs.[2] Several examples of backhaul modems utilising up to 256QAM modulation in a 500 MHz channel and delivering 3 Gbps data rate are available, for example from Escape Communications[1]. Such modems typically use discrete IQ ADC and IQ DAC devices such as those examples listed below.

- Texas Instruments Dual ADC ADC08D500 dual 8b 500 Msps at 1.4W power consumption
- Texas Instruments Dual DAC : DAC3154: 10b 500 Msps at 0.5W power consumption
- Analog Devices AD9625 12b 2.5 Gsps 4W power consumption
- E2V Single ADC : EV12DS130ACZPY 12b 3.0 Gsps 1.3W power consumption

Typical ENOB figures are in the region of 0.5 – 1.0b less than quoted resolution and hence can be compared to the dynamic range requirements as defined above.

Technology review: integrated AFE sub-systems

A very useful summary of the state of the art in published performance figures for high performance semiconductor implementations of ADCs and DACs is updated annually by Stanford University.[2] An example of a commercially available integrated AFE comprising IQ ADC, IQ DAC and PLL with 7bit resolution at a sample rate of 3.5 GHz and power consumption of ~200 mW is available from Cadence as a silicon proven IP macro block implemented in 28nm CMOS.[3] Such a macro is therefore well suited for

[1] http://www.escapecom.com/products-2/products.php
[2] http://web.stanford.edu/~murmann/adcsurvey.html
[3] http://ip.cadence.com/ipportfolio/ip-portfolio-overview/analog-ip/

integration within a larger baseband SoC for cost and power efficient implementation of a complete gigabit rate PHY/MAC modem.

Recently, Xilinx Inc. announced their Zynq® UltraScale+™ RFSoC family of devices with integrated multi-giga-sample RF data convertors.[4] These SoC devices integrate among other things a quad-core ARM® Cortex-A53 processor subsystem, programmable logic, multiple 6.4GSPS 14bit DACs and 4GSPS 12bit ADCs in a TSMC 16nm FinFet+ technology node. The integrated data convertors save power dissipation by removing the need for transceivers and the JESD204 protocol required in discrete implementations to connect from the modem to the data convertors. There is also a significant reduction in the overall footprint and cost of the system due to a much smaller number of components. With power dissipation <1W for a pair of Direct-RF DAC and ADC [7] these devices represent an attractive platform to develop mmWave backhaul modems, 28GHz-39GHz fixed wireless access and other recent 5G developments in the mmWave bands, such as converged access and backhaul modems.

Summary

The AFE function, comprising IQ ADC, IQ DAC and local low jitter sample clock generation is a critical gateway between the RF analogue domain and the digital processing PHY and MAC functions within a gigabit rate millimetre wave modem. Data rates of 1 – 10 Gbps over channel bandwidths of 250, 500 MHz and more recently wider channel widths such 1 and 2 GHz are required utilising modulation levels ranging from BPSK, QPSK, QAM16, QAM64 and through to QAM256 and also QAM1024 for high performance channel limited systems. The performance of the AFE has a significant influence on the overall performance of the modem in terms of receiver dynamic range, transmitter spurious emissions and end to end BER/PER and therefore can be viewed as a critical link between the RF analogue and digital domains. State of the art in discrete and integrated IQ ADC/DAC devices is the region of 6-9 GSPS/12-14b resolution whereas AFE macros suitable for integration onto modem CMOS digital SoCs typically achieve 3.5 Gsps/7b resolution. Considerable scope for improved performance to support increased sample rates, channel bandwidths and therefore increased data rates remains for AFE developers and suppliers.

[4] https://www.xilinx.com/products/silicon-devices/soc/rfsoc.html

Overview of possible chip integration evolution of semiconductor technologies

RF analogue foundry process technologies considerations

GaAs, InP, GaN, SiGe BiCMOS

GaAs is well suited to mmWave analogue circuit integration and chips have been produced with many high-performance elements combined in multifunction chips.

Figure 5 is a generic block diagram of a typical E-band transceiver chip set. This comprises a single Rx chip containing an LNA with gain control, an attenuator, a frequency multiplier, an LO amplifier and a demodulator with full quadrature baseband outputs. The Tx is partitioned into two chips, a variable gain PA with integrated power detector and an up converter chip comprising a modulator, LO amplifier, LO multiplier, envelope detector and variable gain medium power amplifier (an example is shown in Figure 6). Separate low phase noise VCOs complete the line-up. This architecture allows the most appropriate process technology to be used for each function. For example the VCOs may employ InGaP HBT technology while the Rx and Tx convertor chips may employ a low noise pHEMP or mHEMT process. The PA could use a pHEMT process optimized for high power. Separating the chips provides an upgrade route allowing the possibility for GaN PAs or InP LNAs to be employed in the future.

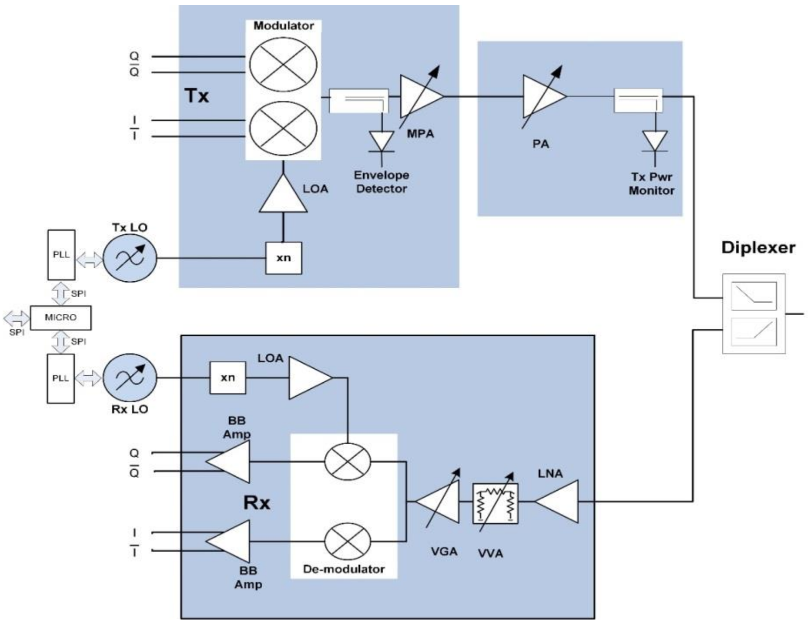


Figure 5: Typical GaAs Transceiver chip set

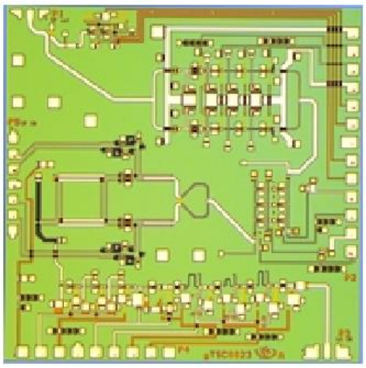


Figure 6: GaAs Transmitter chip*

*Courtesy *gotMIC* AB

The relatively lower level of integration for III-V compound devices has limited their mainstream use at lower frequencies where silicon is superior in terms of integration density, yield and functionality on a single chip. mmWave analogue front end applications are today dominated by the area consumed by passive components which is similar in size for both technologies. Lumped element circuit design techniques employed at lower frequencies on silicon cannot be used at mmWave frequencies due to the impact of parasitics at these frequencies and the use of transmission line structure is essential. Fortunately these are more easily accommodated at mmWave frequencies due to their very small dimensions.

Silicon RFICs do however allow the integration of multiple application specific functionalities on a single silicon chip (RF ASIC) with excellent yield and uniformity plus the possibility to integrate the different calibration schemes required to take into account RF impairments (not possible or much more complex to implement by GaAs).

The level of integration is a factor to be considered. A high level makes the chip very specific and could increase development time at first design but reduces production test and simplifies module assembly. A good compromise is to use compound semiconductors for the front ends (LNA of the receiver input and power amplifier of the transmit output) and silicon semiconductors for the lower frequency mixed signal functions and control/digital elements.

mmWave phased array - RF beam forming and steering

SiGe BiCMOS technology is well suited for highly integrated mmWave systems, especially, mmWave phased array transceivers. The phased array based on electronic beam forming and steering provides increased range, higher EIRP and high resolution antenna scanning. Beam forming transceivers can be used in many applications like multi-Gbps communications, industrial and automotive radars and both active and passive mmWave imaging systems. Phase shifting for antenna beam steering and beam forming could be implemented both in the base band domain (analogue or digital) or in the analogue RF domain or in the analogue LO domain. In both the cases, BiCMOS will exploit its integration capabilities, not only reducing the number of chips to be assembled in the phased array but also greatly simplifying the control routing in large arrays. Today techniques for phased array semiconductor implementations are analogue RF phase shifting, RF LO phase shifting and digital phase shifting. The pros and cons needs to be evaluated to clarify the impact on system performance in terms of noise figure, linearity and gain and system BOM.

Phased-array transmitters feature multiple transmit chains driving multiple antennas, which together are used to realize a directive beam with high effective isotropic radiated power (EIRP), as pictured in the simplified diagram in Figure 7.

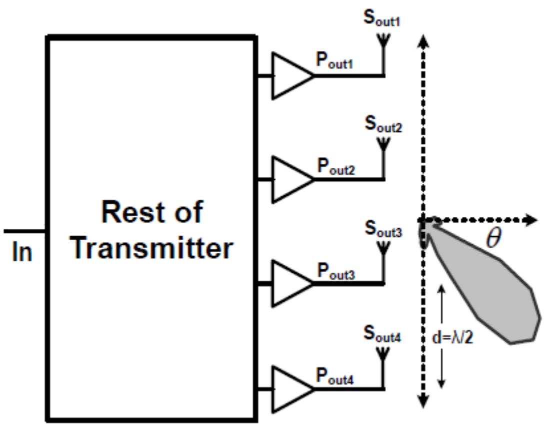


Figure 7: General diagram of an N-element phased array transmitter

The EIRP can be directly related to the array dc power consumption (P_{DC}), the array number of elements (N), the antenna array unit element gain (G_a) and the power efficiency at back-off (η_{bo}), as follows:

$$EIRP = G_a N P_{DC} \eta_{bo}$$

From this expression, we see that there is a direct trade-off between η_{bo} and N, meaning that as the back-off efficiency improves, fewer antenna elements realize the same EIRP for the same dc power consumption. Moreover, there is a direct cost benefit associated with improved back-off efficiency. Typical efficiencies demonstrated for silicon beam formers (including full chains of PAs, preamplifiers and phase shifters) range between 1% and 3% for 6-dB back off, with array sizes between 16 and 32 elements [8].

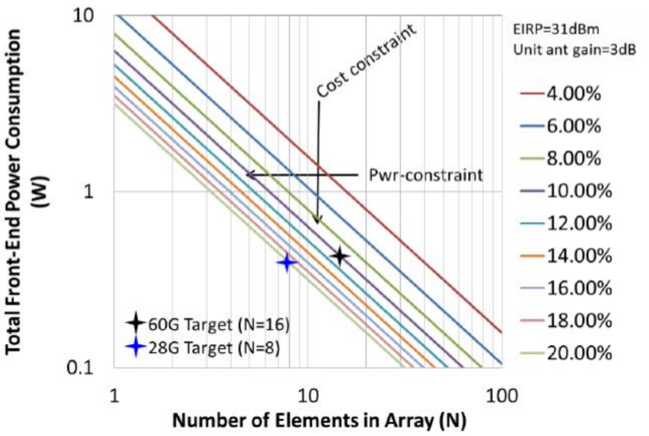


Figure 8: trade-off of phased-array DC power consumption versus system cost

In ST Microelectronics and Infineon Technologies AG, an active antenna system with an integrated 60GHz transceiver front end for each antenna element has been investigated in order to provide RF beam forming and steering for a small-cell backhauling application demonstrator and a feasibility study is currently in progress. The ST Microelectronics building block composition and the layout screen shot of the SiGe: C BiCMOS active part of the antenna is shown in Figure 9.

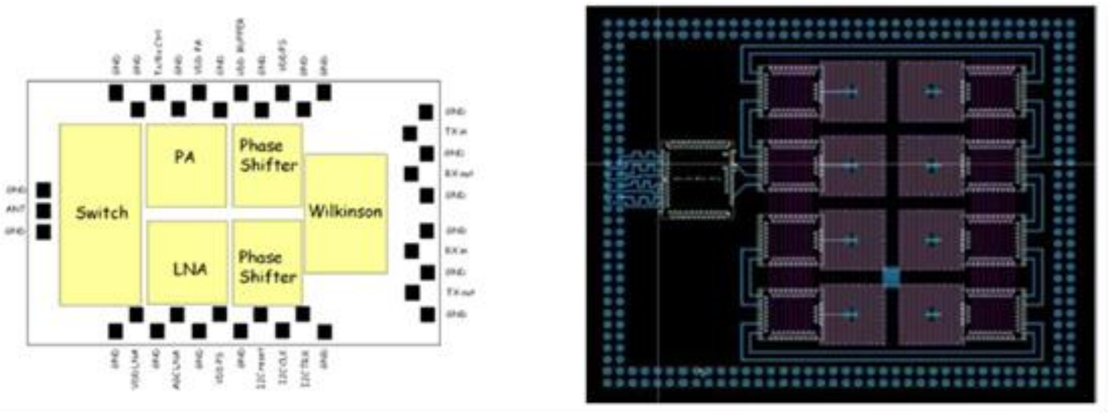


Figure 9: ST Microelectronics example transceiver front end companion chip for each single 60GHz active antenna element

The Infineon layout for the 60GHz case study shows the application board of the SiGe: C active part with integrated antenna in Figure 10.

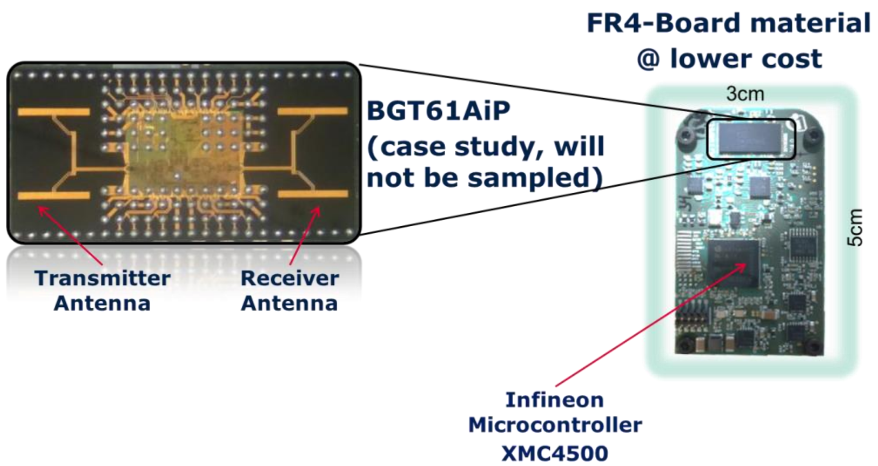


Figure 10: Infineon case study transceiver front end companion chip with integrated single 60GHz active antenna element and application board

Possible integration options using SiGe BiCMOS foundry technology

SiGe technology with cutoff frequencies in the range of 200 to 300 GHz has enabled the realization of radar systems in silicon based technologies for the first time. However, these frequencies are still only a factor of 3 higher than the application frequency in the 80 GHz range.

More recently, SiGe: C HBT-based technologies, by addressing the automotive radar market, have gained increasing interest for emerging millimetre-wave markets, as f_T and/or f_{MAX} of the HBT devices has exceeded 200GHz. The performance of the SiGe HBT is no longer the limit for a mmWave transceiver front end integration for small cell applications with limited output power (usually intended to use V-band frequencies) but rather the quality factor of the on-chip passive devices, such as inductor, capacitor and transmission lines for matching and tuning and their accurate characterization in the mmWave frequency domain.

Better performance of the SiGe HBTs in SiGe BiCMOS will improve the overall performance of radar MMICs. Additionally, next generation radar sensors will require a lot of digital functionality to enable the frequency generation on chip, functions like temperature sensors, power sensing, and high data rate interfaces or AD conversion and the integration of base band functionality. A lot of computational power is also needed for self-surveillance functions which are needed to achieve the ASIL classes (automotive) needed for safety critical functions like autonomous emergency braking. Therefore, in the future, SiGe technologies with superior RF performance have to be combined with advanced CMOS devices on the same chip.

To address this, Infineon has developed the SiGe BiCMOS technology B11HFc. This technology integrates 130nm MOS devices from Infineon´s CMOS platform C11 with state-of-the-art SiGe devices pre-developed in the EU funded projects DOTFIVE and DOTSEVEN.

In summary, SiGe BiCMOS technology and eWLB package technology have enabled the realization of 76-81 GHz radar sensors in low-cost technology. Bare-die GaAs solutions needing 8 MMICs for the RF part of radars can now be replaced by only two chips which can be assembled using standard soldering techniques. The availability of SiGe BiCMOS technology will further improve RF performance and enable highly-integrated single chip radars with superior performance at low power consumption (refer to Figure 11).

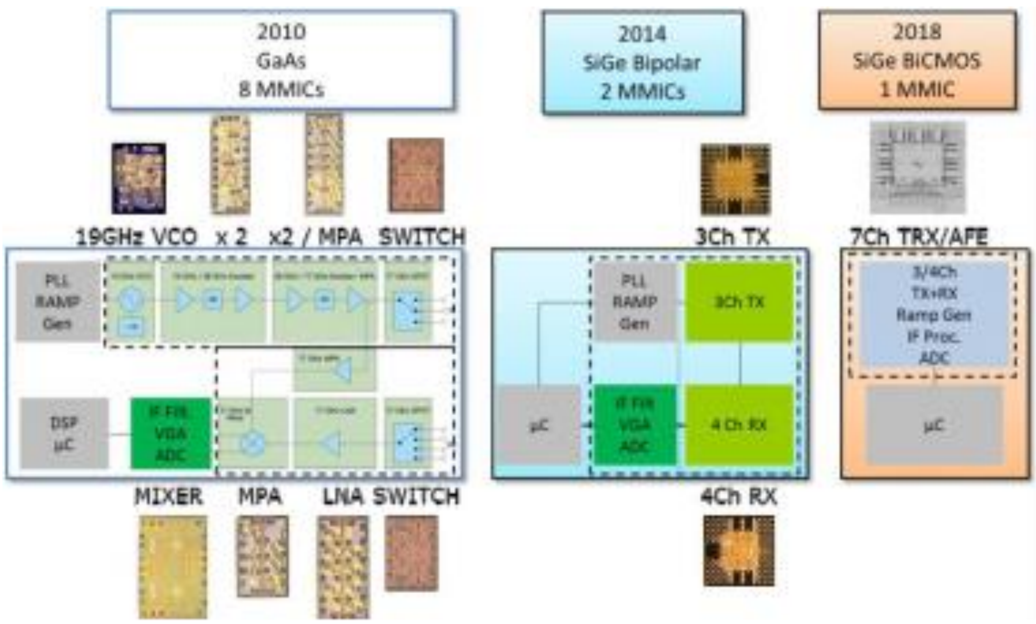


Figure 11 : Evolution of the RF part of automotive radars from multi-chip bare-die GaAs MMICs (left) to actual eWLB packaged 2 chip SiGe solution (middle) to future highly integrated BiCMOS single chip transceivers (right)

However E-band applications for macro cells usually require a high order of QAM (e.g. 256) which requires GaAs (future GaN,) components or a combination of SiGe/BiCMOS transmitter/receiver and GaAs (GaN,) PAs and LNAs.

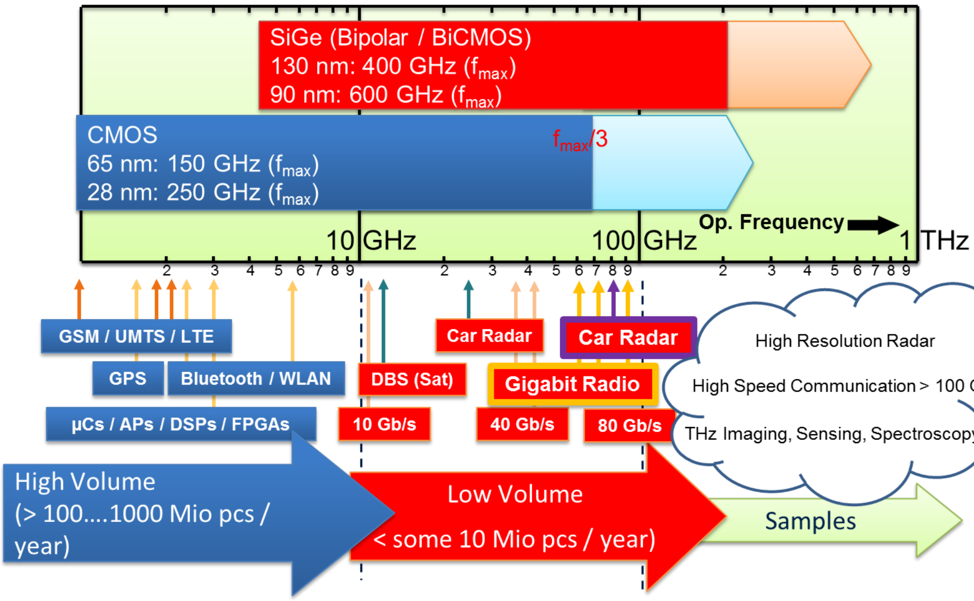


Figure 12: The DOTSEVEN Project [5] using Infineon Technologies SiGe/BiCMOS technology

Referring to Figure 12, currently all major high volume markets use CMOS foundry technology. These include markets with volumes >10m pieces per year such as mobile phones (2G/3G/4G), WLAN/Wi-Fi, GPS/GNSS, Bluetooth and any kind of microcontroller or DSP. CMOS wafer technology requires higher investment upfront to produce semiconductor devices compared to SiGe or GaAs. On the other hand it gives an economy of scale if high volume is required. Therefore from a purely economic point of view the choice of CMOS or SiGe Bipolar/BiCMOS is always based on the expected volume versus investment.

Today's applications in mmWave for backhaul, fronthaul and enterprise applications are far below such high volume. Other attractive mmWave applications, such as automotive radar at 24GHz and 77/79GHz and WiGig at 60GHz, have some high volume potential.

The technical assessment is of utmost importance to achieve the required RF performance. Today CMOS in an RF product has not demonstrated the required analogue performance at operating frequencies above 50 GHz for backhaul PtP. This situation is likely to change over time with specific RF CMOS technologies. The III-V MMIC semiconductor technologies (primarily GaAs) as said before, have low integration level options. SiGe: C silicon-based, is in the meantime a mature and volume proven mm ave technology in automotive radar applications.

One technical assessment of SiGe vs CMOS is done in a European Commission-funded research project of 4 partners from 6 countries: "Towards 0.7 THz SiGe Technology, The DOTSEVEN Project" [5]. It targets a development of Silicon-Germanium HBT technology with f_{MAX} = 0.7 THz. The project duration is from October 2012 until March 2016.

Figure 13 gives a comparison of CMOS technology nodes from 65nm to 28nm (gate length/effective emitter width) versus SiGe HBT in terms of fmax (maximum oscillation frequency).

f_{MAX} is a good indicator and higher f_{MAX} implies:

- Larger design margins, easier achievement of design to RF performance

- Lower power consumption, CMOS lower nodes will require less power consumption than comparable SiGe HBT
- Less sensitive to temperature variation, especially for low (-40 to -20 deg. Celsius) and high (+60 to +85 deg. Celsius) temperature

Main RF performance parameters are:

- Phase Noise
- Noise Figure

Comparable foundry technology nodes are (refer to Figure 13) SiGe HBT, e.g. ST's BiCMOS55, Infineon's BICMOS B11HFc and CMOS foundry technology, e.g. 65nm, 40nm, 45nm, 28nm …

The initial results indicate that CMOS nodes <28nm will not improve the RF capabilities due to max. frequency (f_{MAX}).

Cut-off frequency (f_T) might decrease and therefore will not reach SiGe BiCMOS and CMOS >28nm RF performance (refer to Figure 13).

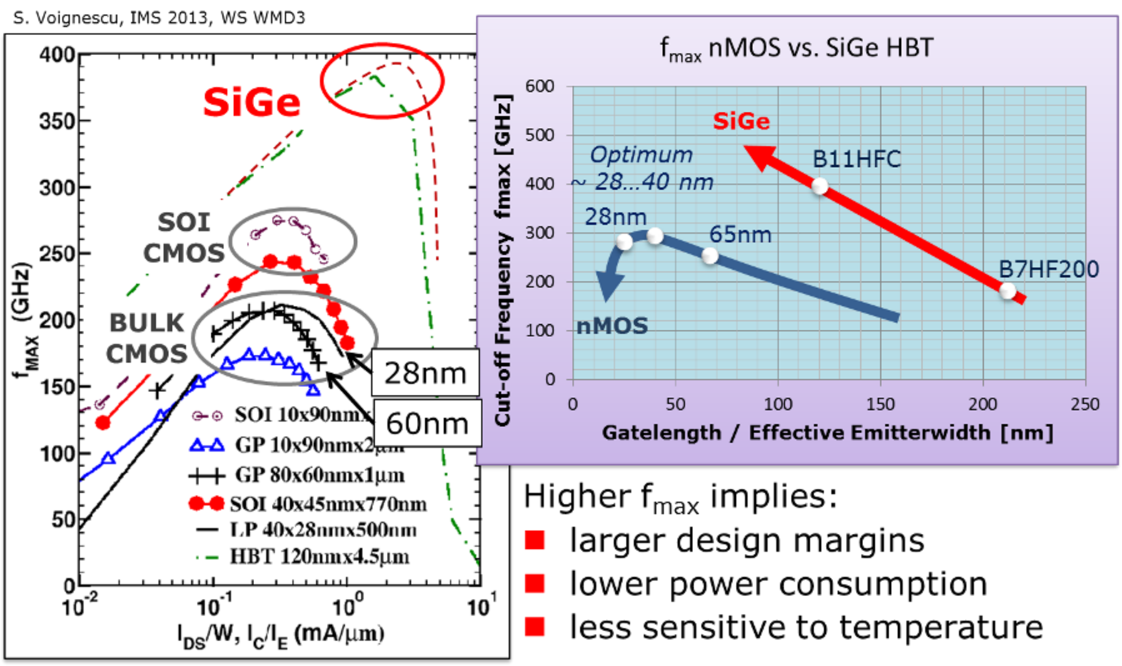


Figure 13: fmax nMOS versus SiGe HBT comparison

So the main reasons for the interest in SiGe: C Bipolar/BiCMOS and CMOS for future mmWave RF design and implementation are:

1. Transition frequency (fT), frequency value at which the transistor current gain becomes unity, close to 300GHz (Figure 14for ST's BiCMOS55 and similar for Infineon´s BICMOS B11HFc technology).
2. Maximum oscillation frequency (fMAX), frequency value at which the transistor power gain becomes unity, higher than 300GHz (Figure 14).

3. Digital and analog mixed signal circuits, as calibration and control functions, could be easily integrated in the same die
4. Low cost of manufacture and integration scale typical of the semiconductor technologies on silicon substrate.
5. Low phase noise of integrated solution (like VCO) on the same die for the complete transceiver (Figure 15)

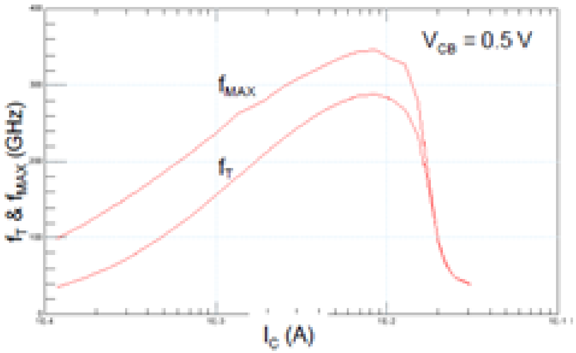


Figure 14: f_T and f_{MAX} versus collector current of ST's BiCMOS055 process (npn high speed transistor: Wdrawn= 0.2µm, Ldrawn=5.56µm, T=25°C)

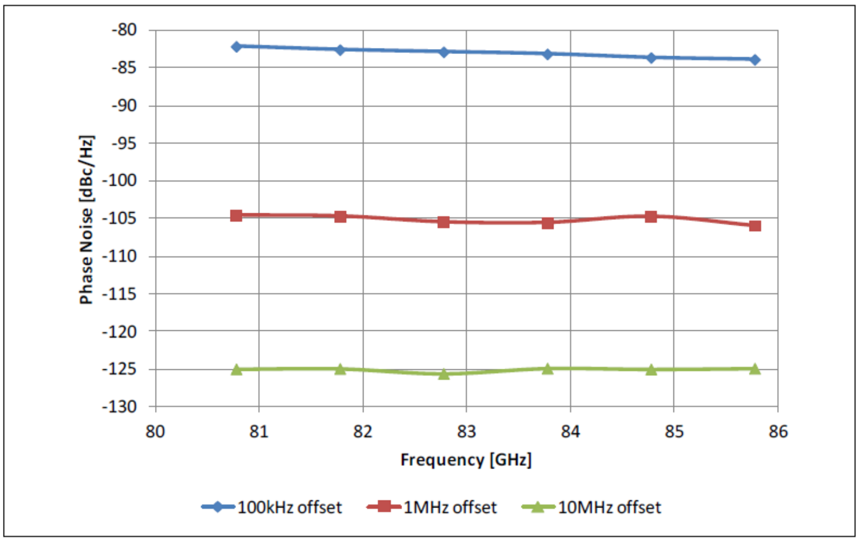


Figure 44 Phase Noise over Frequency for BGT80

Figure 15: Phase Noise ssb (single side band) at several frequency offsets from 100kHz to 10MHz for 60GHz (V-band) transmitter from Infineon Technologies

However, due to the higher speed of scaled technology, a CMOS implementation also promises higher levels of integration at reduced cost. Several recent developments have combined to enable CMOS circuit blocks to operate at mmWave frequencies, as the CMOS transistor f_T goes to >200GHz [4]. A successful R&D demonstrator of a multi-gigabit super-heterodyne transceiver for 60GHz frequency carrier, implemented in bulk CMOS technology, is shown in Figure 16. The transmit power amplifier (PA), the local oscillator (LO) buffering and the receiver low noise amplifier (LNA) draw most of the current in the RF front-end, so they need to be minimized for broadband link portable applications. The single-ended LNA input / PA output simplify antenna interfacing (important for antenna beam forming) and require less current than a differential circuit.

Two important disadvantages of a silicon metal–oxide–semiconductor field-effect transistor (MOSFET) compared to a GaAs field-effect transistor (FET) are:

1. low-resistivity substrate
2. High sheet resistance of the polysilicon gates.

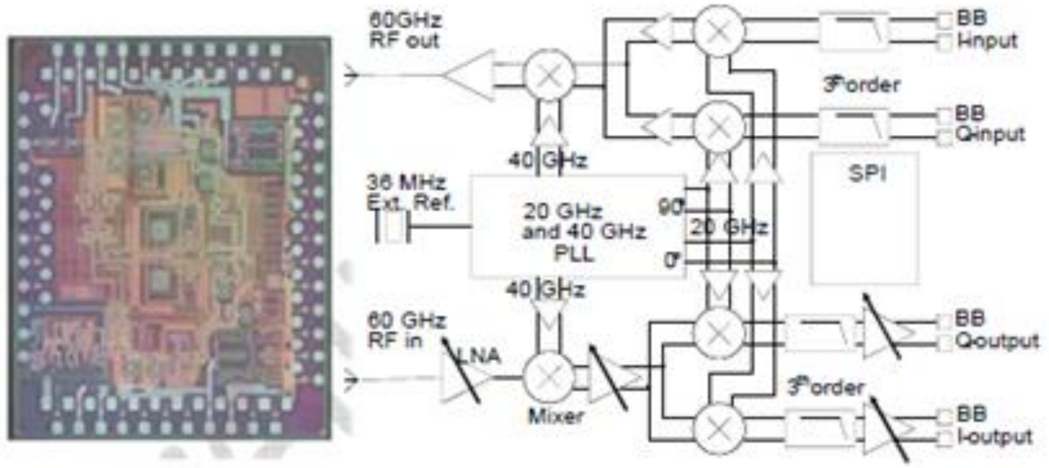
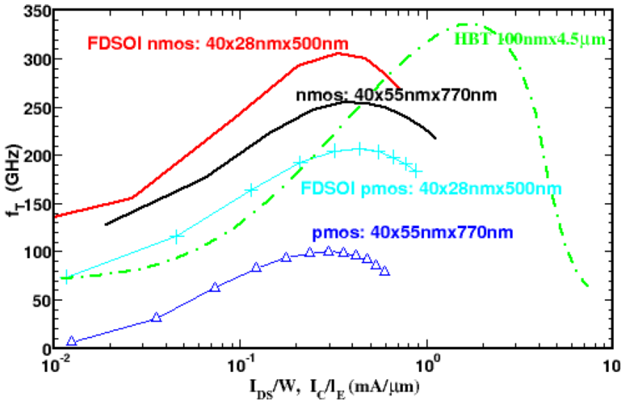


Figure 16: low cost 60GHz RFIC transceiver front end in ST CMOS065RF technology [1]

The substrate resistivity of most modern standard silicon processes is ~10Ω•cm , which is many orders of magnitude lower than that of GaAs (~10^7 – 10^9 Ω•cm). Signals through the low-resistivity silicon substrate incur significant losses, especially at mmWave frequencies. Furthermore, whereas a GaAs FET can effectively be treated as a three-terminal device, the existence of the bulk terminal and the body-effect complicate matters for MOS designers. Wherever simple layout techniques can be used to minimize the detrimental effects of the polysilicon gate higher sheet resistance, the low resistivity silicon substrate effects could be mitigated by the silicon-on-insulator (SOI) process technology. Then future realizations of such transceivers, towards mature and reliable product development, should be more compact and consume minimal power, by exploiting the improved performance and efficiency of the CMOS-SOI technology well suited for very large volume portable applications (WiGig/IEEE802.11.ad). Figure 17 shows that the ST's BiCMOS055 SiGe HBT f_T and F_{MAX} are comparable to the corresponding parameters of the ST's 28nm FDSOI n-MOSFET.



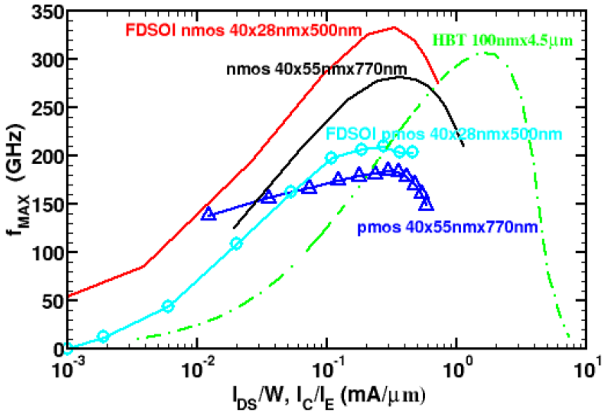


Figure 17: ST-s BiCMOS55 vs. ST's 28nm FDSOI: f_T and f_{MAX}

However, the thickness of the top metal(s) and the metal distance to the undergoing silicon substrate make the metal and the height of the dielectric stack (BEOL) of the SiGe BiCMOS process more suited in order to get higher quality factor values of the passive devices, as inductors and transmission lines operating in the mmw frequency regime. RF additions with thick Cu levels help to increase the lower passive device quality factors gettable in standard bulk CMOS process.

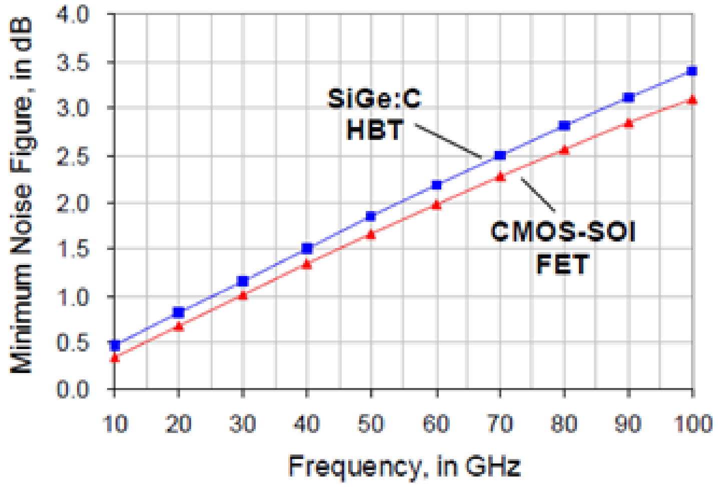


Figure 18: simulated NFmin for SiGe:C HBT and 65nm CMOS-SOI FET [2]

The practical noise figure for a MMW LNA is of the order of 5dB with around few mA of current consumption. Simulated minimum noise figure for transistors in BiCMOS and CMOS-SOI technologies are plotted in Figure 18, where the minimum noise figure (NF_{min}) behaves similarly for HBT and MOSFET with increasing frequency, although the source impedance required to get NFmin is generally lower and easier to design and implement to get the input impedance matching of BiCMOS HBT. Semiconductor technology noise performances have also a strong impact on the local oscillator (LO) phase noise and then on the MMW transceiver spectral efficiency. A phase noise benchmarking on a 60GHz LO by comparing BiCMOS and CMOS technologies, has been analysed and the result is in Figure 19.

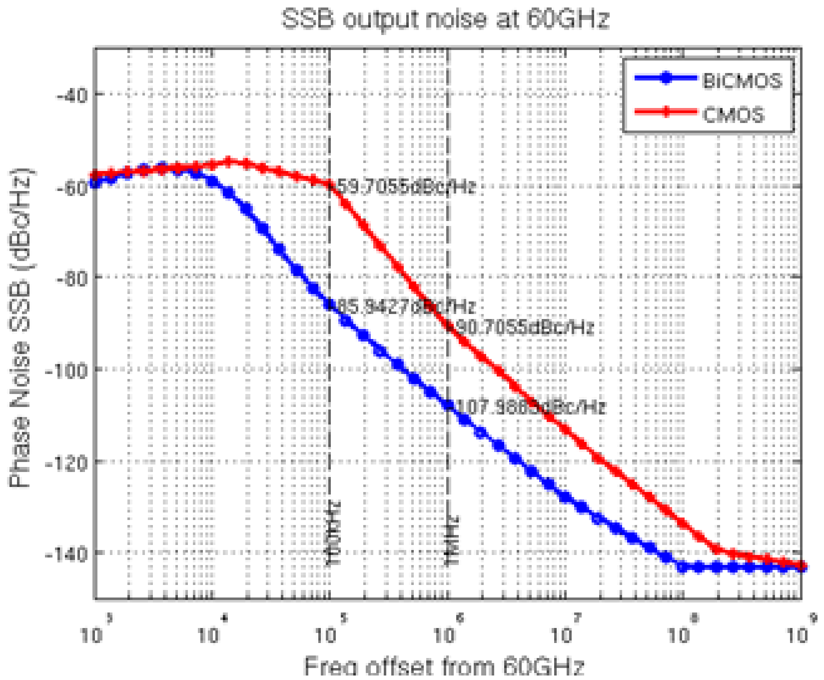


Figure 19: 60GHz LO SSB phase noise comparison of SiGe: C HBT and CMOS nFET

Future eWLB packaging technology options

eWLB technology offers interesting opportunities for future radar system in package solutions. As an example Figure 20 shows a four channel transceiver with in-package integrated antennas in 8 x 8 mm^2 eWLB. The antennas are realized as metal structures in the RDL layer. Due to the small wavelength at 77 GHz, antenna structures can be integrated in packages of some mm^2 edge dimensions. The antennas can be placed on the low-cost mould compound which also has very low losses compared to silicon. By integration of the antennas into the package, no RF transition from the MMIC to the PCB is needed any more. This allows the use of standard low-cost PCB materials compared to the expensive special RF top layers used in the PCBs of actual radar systems. eWLB technology also offers the possibility of integrating multiple structures into one package. An example is a waveguide which is formed by Cu filled vias produced in standard PCB technology. These via bars are placed together with a SiGe chip in an eWLB package. Together with the RDL layer and a backside metallization on the package, 3D waveguides are formed which can be used to directly transform the RF signal generated on the chip to an electromagnetic wave which can be transmitted. Using this technique a contact-less RF transition with a loss of < 2 dB could be demonstrated. Such structures can be used to overcome classical 2D patch antenna arrays used today and to pave the way to 3D signal distribution in radar systems. Multilevel metallization, backside metallization or integrated 3D structures can also be used for innovative cooling concepts which can be used to simplify the thermal management of the radar sensor.

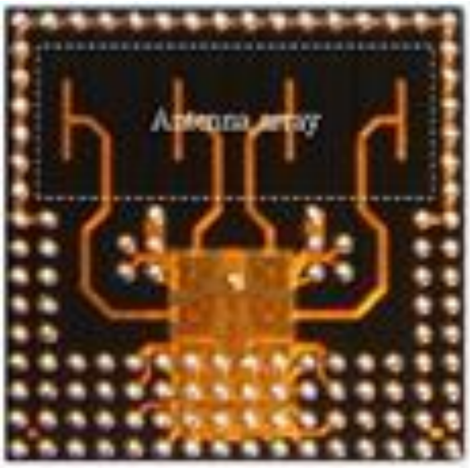


Figure 20: Four channel transceiver with in package integrated antennas

Outlook: semiconductor technology considerations for frequencies >90GHz up to 300GHz or higher

Group Report - Analysis of Spectrum, License Schemes and Network Scenarios in the D-band

Future requirements for fronthaul and for backhaul of 5G will require capacities achievable only by using very large amounts of contiguous spectrum. This spectrum exists at frequencies above 90 GHz therefore the development of semiconductor technologies operating above 90GHz and up to 300GHz is becoming increasingly important. This document introduces these technologies briefly; however, further development of this topic is addressed in ETSI Group Report GR mWT 008 [9].

RF analog - example of VCO

Improvements in the high-frequency capability of CMOS/BiCMOS technology have made it possible to consider it as a low-cost alternative to the III-V compound devices for realizing systems that can greatly expand the use of the electromagnetic spectrum above 90GHz. An oscillator is usually the high frequency circuit demonstrated in a new technology. In Figure 21, a 140GHz VCO microphotograph is shown, together with a photo of the test bench by DC and RF probing set up.

Figure 21: 140GHz VCO microphotograph and the measurements on wafer set up at IEMN, France

The VCO performances are summarized in the two graphs below (refer to Figure 22), where measured and simulated VCO tuning range and output power comparison has been reported.

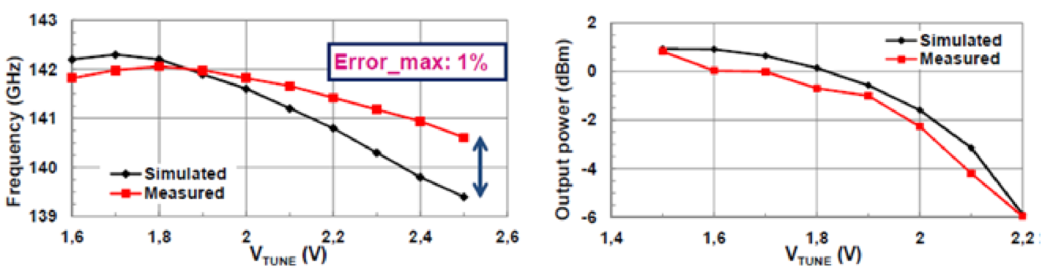


Figure 22: Measured and simulated comparison of 140GHz VCO tuning interval and output power

M3TERA - Micromachined TERAhertz systems - project

Source: http://www.m3tera.eu/

This project envisions the wide-spread use of low-cost THz technology in our society, enabled by the proposed micromachined heterogeneous integration platform, which provides an unprecedented way to highly-integrated, volume-manufacturable, reliable, reconfigurable and cost- and energy-efficient submillimetre-wave and terahertz (THz) systems.

The proposed THz integration platform is envisioned to initiate an important transition in industrial microwave systems manufacturing and is expected to finally enable the large-scale commercialization of the heavily sought-after frequency space between 100 GHz and 1 THz. In line with technology convergence of advancing microwave semiconductor technology according to internal and external roadmaps, the proposed THz microsystem platform is envisioned to accommodate multiple generations of future THz products in different application fields.

The concrete business and lead application case is THz microsystems enabling compact, low-cost point-to-point high-speed communication links in the frequency space between 100 GHz and 500 GHz, to be deployed in a scenario of a high-density small-cell base-station network providing ubiquitous high-speed internet access to mobile communication devices in an urban environment.

The key technology end-user driving the primary prototype development and demonstration of a complete THz communication link is Ericsson AB. A secondary prototype developed in M3TERA is on a multi-function adaptive THz sensor platform for different millimetre-wave sensing applications in society including food quality control, food safety monitoring, medical diagnosis and industrial sensing.

The key manufacturing partner in this industry-driven proposal is the high-volume semiconductor and microsystems manufacturer Infineon Technologies Austria, who also provides system packaging concepts. This 3-year project has 7 participants: Technikon Forschungs- und Planungsgesellschaft mbH, Kungliga Tekniska Hoegskolan, Anteral SL, Chalmers Tekniska Hoegskola AB, CSEM Centre Suisse D'Electronique Et De Microtechnique SA – Recherche et Developpement, and above mentioned Ericsson AB and Infineon Technologies Austria.

The M3TERA project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 644039.

This work is supported (also) by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 15.0059.

140GHz Transmitter chip prototype

The EETimes Europe reported on 22 October 2014 that a Chalmers University research group linked to Ericsson Research has successfully transmitted data wirelessly at 40Gbps using wireless transmit and receive circuits that operate at 140GHz, more than twice the previous record at the equivalent carrier frequency. The circuits were reported to be fabricated in indium phosphide. For further information please see the original story entitled "InP circuits set 40Gbps wireless data record" written by Peter Clarke at: http://www.electronics-eetimes.com/news/inp-circuits-set-40gbps-wireless-data-record.

DOTSEVEN: Towards 0.7 Terahertz Silicon Germanium Heterojunction Bipolar Technology

Source: http://www.dotseven.eu/

DOTSEVEN is a very ambitious 3.5 year R&D project targeting the development of silicon germanium (SiGe) heterojunction bipolar transistor (HBT) technologies with cut-off frequencies (fmax) up to 700 GHz. Special attention will be paid to clearly demonstrate the manufacturability and integration with CMOS as well as the capabilities and benefits of 0.7 THz SiGe HBT technology by benchmark circuits and system applications in the 0.1 to 1 THz range.

The main objective of the DOTSEVEN consortium is therefore to reinforce and further strengthen Europe's leading edge position in SiGe HBT technology and modelling as well as SiGe enabled mm-wave applications so as to stay significantly ahead of non-European competition. A highly qualified and success-proven consortium has been set-up to achieve these goals.

Road map & ambition

THz technology is an emerging field which has demonstrated a wide ranging potential. Extensive research during the last years has identified many attractive application areas, and paved the technological paths towards broadly usable THz systems. THz technology is currently in a pivotal phase and will soon be in a position to radically expand our analytical capabilities via its intrinsic benefits. One of the most pressing challenges of THz applications is the development of cost effective, compact & efficient THz signal sources and receivers for everyday applications. In this context, DOTSEVEN is planned to continue the push for fully integrated cost efficient electronic THz solutions. The deployment of the associated high-performance circuits and systems in commercial and other non-military markets is driven mainly by cost, form-factor and energy-efficiency.

A schematic overview on some of the application areas identified is depicted in Figure 23:. One of the most pressing challenges of THz applications is the development of cost-effective, compact and efficient THz signal sources and receivers for everyday applications.

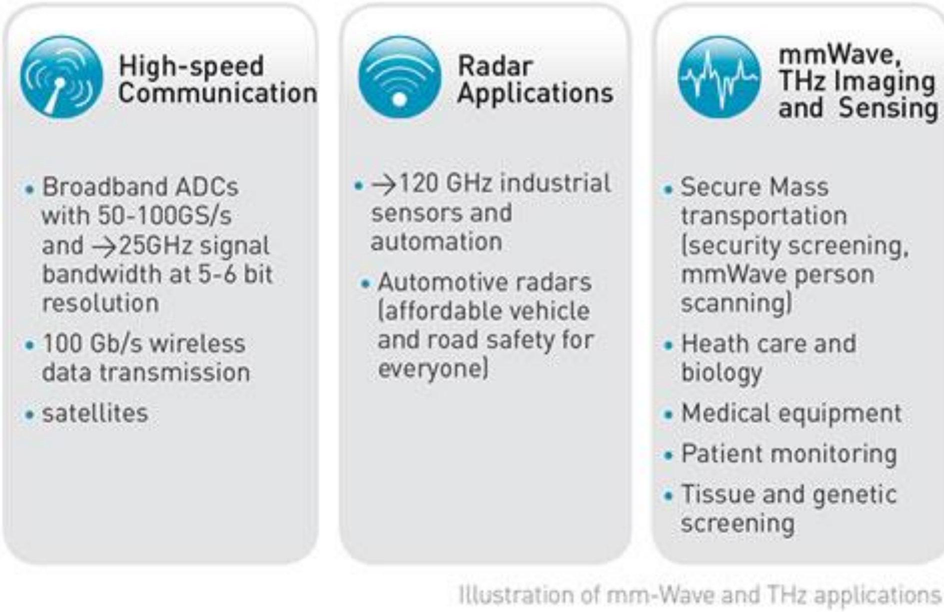


Figure 23: Illustration of mm-Wave and THz applications

Abbreviations

For the purposes of the present document, the following terms and abbreviations apply:

III-V	Compound Semiconductors including GaAs, InP, GaN, InGaP etc.
ADC	Analog to Digital Converter
AFE	Analogue Front End
AGC	Automatic Gain Control
ASIC	Application Specific Integrated Circuit
ASIL	Automotive Safety Integrity Level
ATPC	Automatic Transmit Power Control
BE	Backend (package production)
BER	Bit Error Rate
BiCMOS	Bipolar Complementary Metal-Oxide-Semiconductor (foundry technology)
BGA	BallGridArray Package (FCBGA – Flip Chip BGA)
BOM	Bill Of Material
BPSK	Binary Phase Shift Keying
CAPEX	Capital Expenditure or Capital Expense
CMOS	Complementary Metal-Oxide-Semiconductor (foundry technology)
CS	Channel Spacing
CSP	Customer Specific Package
CTE	Coefficient of Thermal Expansion
Cu	Copper, chemical element
DAC	Digital to Analog Converter
DHBT	Double Heterojunction Bipolar Transistor
DSP	Digital Signal Processor
EIRP	Equivalent Isotropically Radiated Power
ENOB	Effective Number of Bits
eWLB	embedded WaferLevelBallGridArray Package (Infineon)
FCBGA	FlipChipBallGridArray
FCoB	Flip Chip on Board

FCC	Federal Communication Commission
FE	Frontend (wafer production)
FET	Field-Effect Transistor
fMAX	maximum frequency (of semiconductor wafer technologies)
FPGA	Field Programmable Gate Array
frf	radio frequnecy
fT	Transit frequency (of semiconductor wafer technologies)
Flip Chip	flip-chip pin grid array (FC-PGA)
GaAs	Gallium Arsenide (foundry technology)
GaN	Gallium Nitride (foundry technology)
GHz	Gigahertz
GS	ETSI Group Specification
Gsps	Gigabit samples per second
HBT	Heterojunction Bipolar Transistor, a type of bipolar junction transistor (BJT) which uses differing semiconductor materials for the emitter and base regions, creating a heterojunction.
HDMI	High-Definition Multimedia Interface
HEMT	High-Electron-Mobility Transistor
Het Net	Heterogeneous Network
IF	Intermediate Frequency
InGaP	Indium Gallium Phosphide (semiconductor wafer technology)
InP	Indium phosphide (InP) is a binary semiconductor composed of indium and phosphorus
IO	Input Output (here: number of pins for semiconductor device)
IP	Intellectual Property
I-Q	In phase-Quadrature phase (amplitude modulated sinusoids known components)
ISG	Industry Specification Group
KTB	measure of thermal noise in bandwith B at Temperature T and with Kelvin’s Constant = -114 dBm per MHz at 300deg K (room temperature)
LOS	Line-Of-Sight
LNA	Low Noise Amplifier
LF-CSP	Customized lead frame-based CSP Package;
LO	Local Oscillator

MEMS	Microelectromechanical Systems
mHEMT	metamorphic HEMT (High-Electron-Mobility Transistor)
MOS	Metal–Oxide–Semiconductor
MMIC	Monolithic Microwave Integrated Circuit
mmWave	Millimetre Wave: >50GHz
Msps	Mega Samples per second
MW	Microwave: 6-42GHz
mWT	Millimetre Wave Transmission
Mix	Mixer circuitry
NF	Noise Figure
nFET	n-type Field Effect Transistor as Channel type (MOS capacitor)
nLOS	near Line-Of-Sight
NLOS	Non Line-Of-Sight
nMOS	n-type as Channel type (MOS capacitor)
npn	npn is one of the two types of bipolar transistors, consisting of a layer of P-doped semiconductor (the "base") between two N-doped layers
OPEX	Operating Expenditure or Operating Expense
PA	Power Amplifier
PCB	Printed Circuit Board
PER	Packet Error Ratio
pHEMT	pseudomorphic HEMT (High-Electron-Mobility Transistor)
PLL	Phased Looked Loop
Psat	Saturated output power
PtP	Point to Point (connection)
PtMP	Point to Multipoint (connection)
QAM	Quadrature Amplitude Modulation
QFN	Quad Flat No Leads Package
QPSK	Quadrature Phase-Shift Keying
RDL	ReDistributionLayer
RF	Radio Frequency

RFIC	Radio Frequency Integrated Circuit
rms	root mean square
Rx	Receiver
SC	Single Carrier
SiGe(:C)	Silicon Germanium carbon (SiGe: C) - foundry technology
SiP	System in Package
SMT	Surface-mount technology (SMT) is a method for producing electronic circuits in which the components are mounted or placed directly onto the surface of printed circuit boards (PCBs).
SNR	Signal-to-Noise-Ratio
SoC	System-on-Chip
SOI	Silicon on insulator technology refers to the use of a layered silicon-insulator-silicon substrate
SSB	Single Side Band
Sub6	defined as frequencies below 6GHz
TCO	Total Cost of Ownership
TEV	Through Encapsulate Via technology (interconnect technology process)
TSV	Through Silicon Via technology (interconnect technology process)
TSLP	Thin Small Leadless Package
Tx	Transmitter
VCO	Voltage Controlled Oscillator circuitry
VQFN	Very Thin Quad Flat No-Lead package
WiGig	Wireless Gigabit Alliance
WISP	Wireless Internet Service Provider
WL-CSP	Wafer-level redistribution CSP Package

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Appendix 1 – Export restrictions on mmWave

Export restrictions on mmWave, especially for frequencies >90GHz

An international arrangement on export controls for conventional arms as well as dual-use goods and technologies exists; this is known as the The Wassenaar Arrangement. https://www.wassenaar.org

The Participating States of the Wassenaar Arrangement are: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Republic of Korea, Romania, Russian Federation, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States (refer to Figure 24).

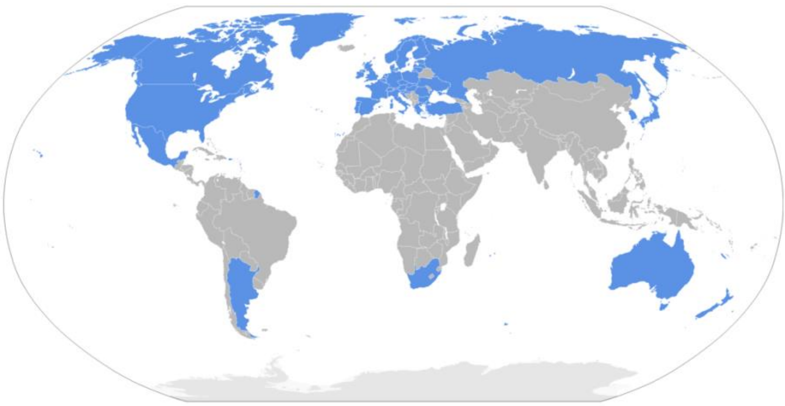

Figure 24: Participating States of the Wassenaar Arrangement

Participating States have agreed to control all items set forth in a set of control lists: the "Dual-Use Goods and Technologies List" (also known as the Basic List) and the "Munitions List". The Basic List is composed of ten categories:

- Category 1 – Special Materials and Related Equipment
- Category 2 – Materials Processing
- Category 3 – Electronics
- Category 4 – Computers
- Category 5 – Part 1 – Telecommunications
- Category 5 – Part 2 – "Information Security"
- Category 6 – Sensors and "Lasers"
- Category 7 – Navigation and Avionics
- Category 8 – Marine
- Category 9 – Aerospace and Propulsion

The lists relevant to mmWave semiconductors are given in category 3 and Category 5 – part 1.

3. A.1.b. Covers Microwave or millimetre wave components and 3.A.1.b.2. Lists Microwave "Monolithic Integrated Circuits" (MMIC) power amplifiers that are any of the following:

- 3.A.1.b.2.f. Rated for operation with a peak saturated power output greater than 31.62 mW (15 dBm) at any frequency exceeding 43.5 GHz up to and including 75 GHz, and with a "fractional bandwidth" of greater than 10%;
- 3.A.1.b.2g. Rated for operation with a peak saturated power output greater than 10 mW (10 dBm) at any frequency exceeding 75 GHz up to and including 90 GHz, and with a "fractional bandwidth" of greater than 5%; or 3.A.1.b.2h. Rated for operation with a peak saturated power output greater than 0.1 nW (-70 dBm) at any frequency exceeding 90 GHz;
- 3.A.1.b.3.e. Discrete microwave transistors that are rated for operation with a peak saturated power output greater than 0.1 nW (-70 dBm) at any frequency exceeding 43.5 GHz; includes bare dice, dice mounted on carriers, or dice mounted in packages.
- 3.A.1.b.4.e. Microwave solid state amplifiers and microwave assemblies/modules containing microwave solid state amplifiers, that are rated for operation at frequencies exceeding 43.5 GHz and having any of the following:
    - A peak saturated power output greater than 0.2 W (23 dBm) at any frequency exceeding 43.5 GHz up to and including 75 GHz, and with a "fractional bandwidth" of greater than 10%;
    - A peak saturated power output greater than 20 mW (13 dBm) at any frequency exceeding 75 GHz up to and including 90 GHz, and with a "fractional bandwidth" of greater than 5%; or
    - A peak saturated power output greater than 0.1 nW (-70 dBm) at any frequency exceeding 90 GHz;

The same restrictions are applied to "Technology" for the "development" or "production" of Microwave Monolithic Integrated Circuit (MMIC) power amplifiers specially designed for telecommunications in the category 5 lists (5.E.1.d.)

5.E.1.c. covers radio equipment and restrictions apply to equipment having any of the following:

- 5.E.1.c.4.a. Quadrature-Amplitude-Modulation (QAM) techniques above level 256;
- 5.E.1.c.4.b. Operating at input or output frequencies exceeding 31.8 GHz; (does not apply to equipment designed or modified for operation in any frequency band which is "allocated by the ITU" for radio communications services.

There is no mention of mmWave technology or components in the Wassenaar Munitions List.

The decision to transfer or deny transfer of any item is the sole responsibility of each Participating State. All measures with respect to the Arrangement are taken in accordance with national legislation and policies and are implemented on the basis of national discretion. Therefore, for specifics on Export Controls in Participating States it is necessary to contact the National Authorities in that country.

For EU see http://ec.europa.eu/trade/import-and-export-rules/export-from-eu/dual-use-controls/. There is no restriction on mmWave technology or components in the EU Dual-Use List; Annex I to Council Regulation (EC) No. 428/2009.

Since many of the semiconductor technologies suitable for mmWave applications were developed originally using U.S. defence research funding it is worth looking in more detail at the US export controls.

Summary of US Export Control Laws

The U.S. government maintains two primary sets of export control regulations that may impact the availability of mmWave technology. The Export Administration Regulations ("EAR") regulate exports of commercial items with potential military applications (so called "dual-use" items). The International Traffic in Arms Regulations ("ITAR") regulate exports of items and services specifically designed for military applications.

Full details are available at: https://www.pmddtc.state.gov/?id=ddtc_public_portal_compliance_landing.

A useful overview of US export control laws is provided by the Office of Compliance of the University of Southern California (USC) at https://ooc.usc.edu/international-activity/research/.

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