GaN PA for 4G LTE-Advanced and 5G

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Abstract

This paper reviews the state-of-the-art of RF power amplifiers technologies in cellular base station for 4G and coming 5G mobile wireless communications. GaN device technologies enable various advanced power amplifiers architectures to offer high efficiency, and high power applications for wide band signal transmission. It summarize the system-level requirement posed by 5G new radios and outlooks the potential challenges and opportunities of advanced GaN PA developments.

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RUI MA, KOON HOO TEO, SHINTARO SHINJO, KOJI YAMANAKA AND PETER M. ASBECK

I. INTRODUCTION

The ever-increasing data rate and number of connections in mobile communication offer exciting user experience in our everyday lives. At this moment, wireless communication frontier is shifting from current 4G (fourth generation) to the forthcoming 5th generation (5G). Our society is expected to go through a revolutionized change within the coming 5G era. It will involve not only the telecommunication industry but also a wide range of different vertical sectors including automobile, robotics, health care, factory automation, agricultures, and education. This makes 5G fundamentally different from the previous generations of mobile communications. As shown in Fig. 1, the typical usage scenarios are outlined in the IMT-2020 whitepaper [1] describing the three categories of 5G that include enhanced mobile broadband (eMBB), ultra reliable and low-latency communications (uRLLC), and massive Machine Type of Communications (mMTC). Under the 5G umbrella, these scenarios certainly have quite different system-level performance requirements such as latency, mobility, number of users, and data rate. This will translate into different radio access network architectures and radio frontend performance requirement. In this article, we will particularly focus on the power amplifier technology required for 5G eMBB use case.

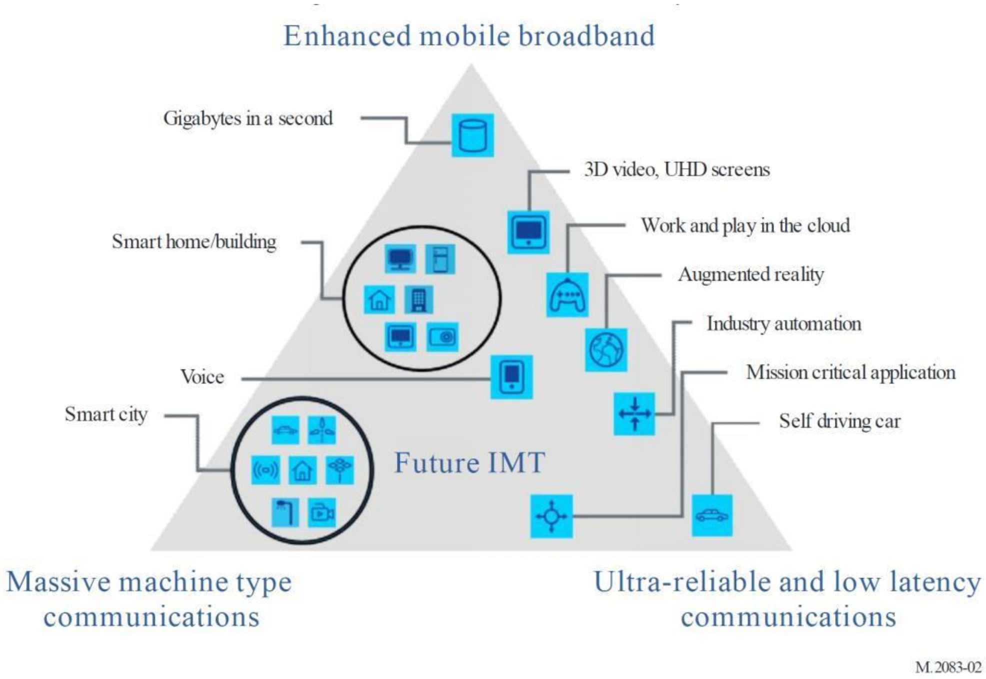


Figure 1. Usage scenarios of IMT 2020 and beyond [1].

In fact, Carrier Aggregation (CA) was one of the key features introduced in 4G LTE –Advanced in 3GPP Release 10 as an effective means to increase signal bandwidth within the existing spectrum [2], [3]. As shown in Fig. 2, there are non-contiguous and contiguous intra-band CA types depending on the aggregated component carrier (CC) whether are disjoint or not. In the other type of CA, namely, inter-band CA, the component carriers are located in two or more different frequency bands. In [3], the authors discussed the various transmitter architectures including multi-branch, multi-band PA, and digital transmitter. Radio transmitters with reduced hardware components are preferred, with more demanding performance on the RF PA design. Unique challenges from the quantization approaches such as delta-sigma are mentioned for the digital transmitter with multi-band capability. It was pointed out that the linearization scheme for concurrent transmission needs special attention due to the memory effect and intermodulation of cross-terms [3].

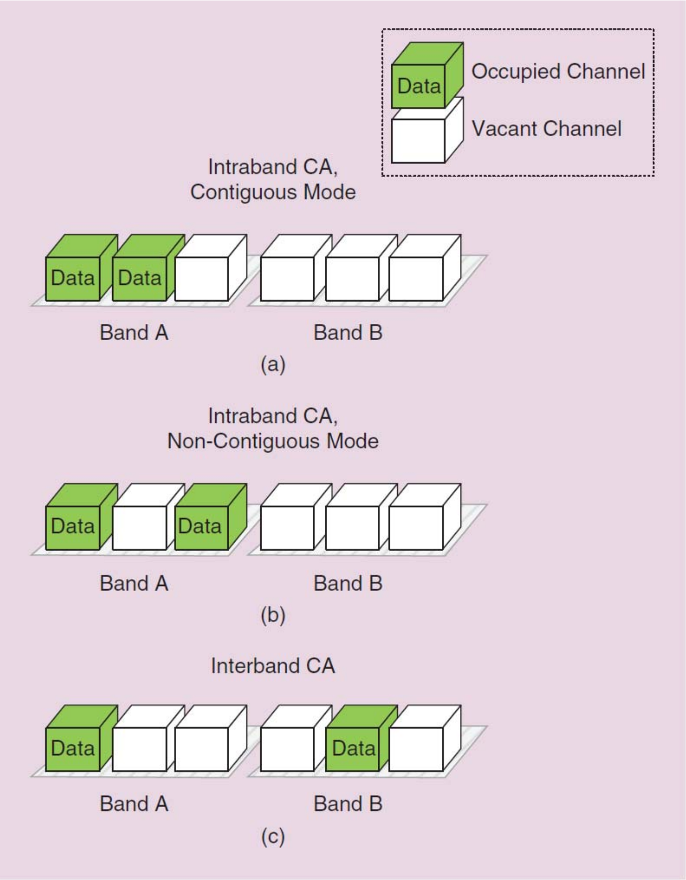


Figure 2 (a) and (b). Interband CA in contiguous and noncontiguous modes and (c) Interband CA in LTE-advanced systems. [3]

In comparison with current 4G LTE-advanced networks, future 5G network for eMBB is targeting 20Gbps peak data rate, which is a 10 times improvement. New waveforms, Massive-MIMO, beamforming, and millimeter wave technologies are considered as key features for 5G, to enable dramatic network performance in terms of both energy efficiency and spectrum efficiency. Advancement of radio front-end architecture is playing a critical role to achieve such goals in a cost-effective manner, facilitating network operators to improve their network efficiency.

In particular, wider modulation bandwidth of signal with higher spectral efficiency (bits/second/Hz) is needed to realize broadband mobile connection services for high speed data rate applications. So far, in 3GPP Release 10, carrier aggregation has been introduced and defined to enable wider bandwidth (up to 100MHz aggregated bandwidth). For 5G new radio, even wider bandwidth is proposed and under consideration, for example, above 1 GHz signal bandwidth for RF frequencies above 6GHz (millimeter wave bands) is targeted. Increasing signal peak to average power ratio of OFDM like signal make the efficient amplification at 5G millimeter wave extremely challenging, which demands both innovation in the power amplifier architecture as well as signal processing techniques to reduce signal PAPR [4].

5G radio base station in particular massive MIMO at millimeter wave frequency puts significant challenges on the hardware design, due to hardware component counts, extra dense physical footprint size for front-end module at millimeter wave to support beam-forming functionality. Thermal cooling becomes extremely critical for massive-MIMO antenna array design. This puts new challenges on designing high performance RF power amplifier for 5G new radio.

Power amplifiers (PA) have been always the working horse for RF front end in any radio transmitter. Together with the development of semiconductor technologies in particular, Gallium Nitride (GaN), advanced power amplifier architectures have evolved to deal with ever-increasing system level requirements mainly in terms of power levels, antenna number, and modulation bandwidth operating over wider RF frequency range, as shown in Fig. 3 from a whitepaper published by Qorvo. Compared with mainstream device technology of LDMOS at 3G base station, the recent advancement of GaN HEMT RF power device has enabled a number of successful demonstrations using a series of advanced PA topologies for 4G LTE and 5G systems. Compared with other transistor technologies, GaN has unique characteristics, which make it the ideal candidate for designing RF PA for cellular base station applications in both 4G and 5G wireless communication.

This paper mainly reviews the state-of-the art GaN power amplifier used for base station applications. In section II, we will first explain the underlying physical material properties of GaN, and in particular the widely used HEMT (High Electron Mobility Transistor) RF power devices. State-of-the-art device performance of GaN will be reviewed. Following that, wideband Doherty, envelop tracking, digital transmitters demonstrator and mmwave GaN PA will be discussed.

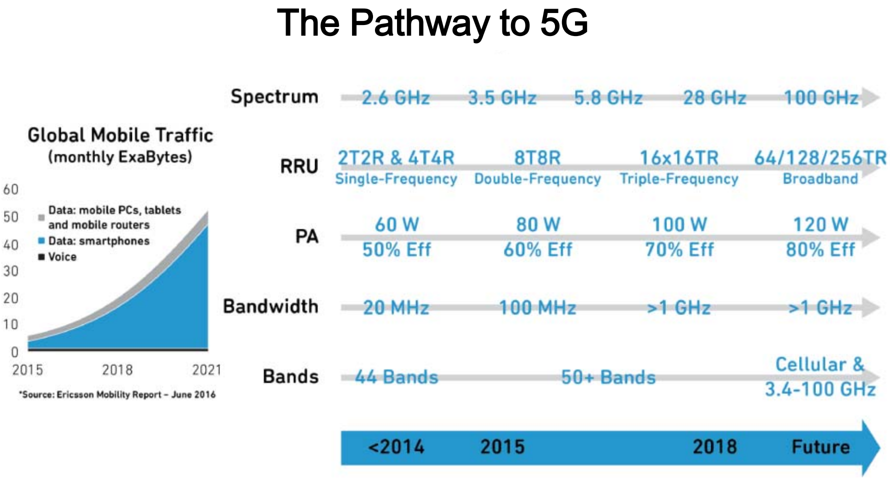


Figure 3. Qorvo, Gallium Nitride – A Critical Technology for 5G [5]

II. DEVICE SELECTION FOR NEW RADIO PA

To meet the complex requirements for PAs for 4G/5G applications, PA device technology selection as well as circuit configuration is important. Figure 4 and 5 show the PA device technology maps which is based on the latest literatures up to 400 GHz [6] and up to 30 GHz, respectively. As demonstrated, Si-based PAs such as CMOS SOI stacked PAs [7], [8] and power combining SiGe PAs [9], [10] can achieve higher power at higher frequency, and it means that they can be applied to applications where output power needs to be above a few Watts even at Ku-band. However, at very high frequency, Si-based PAs have difficulties in delivering the necessary output power due to its properties compared with GaN PAs. As shown in Fig. 5, the region of GaN PAs is expanding to “high power & high frequency” and “high integration & relative low power” [11]-[14]. We expect GaN PA can be most attractive devices for the 4G/5G markets that required output power of more than a few Watts [15], [16].

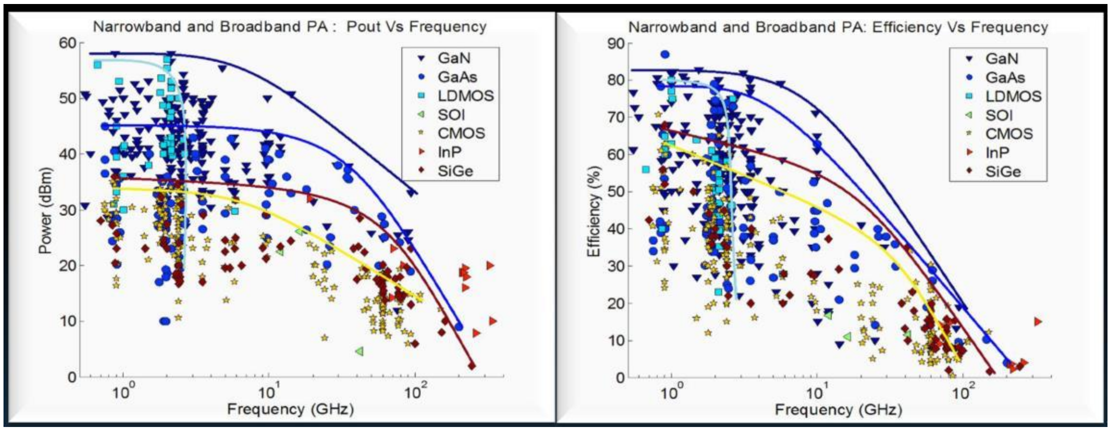


Figure 4. PA device technology map with based on the latest literatures up to 400 GHz [6].

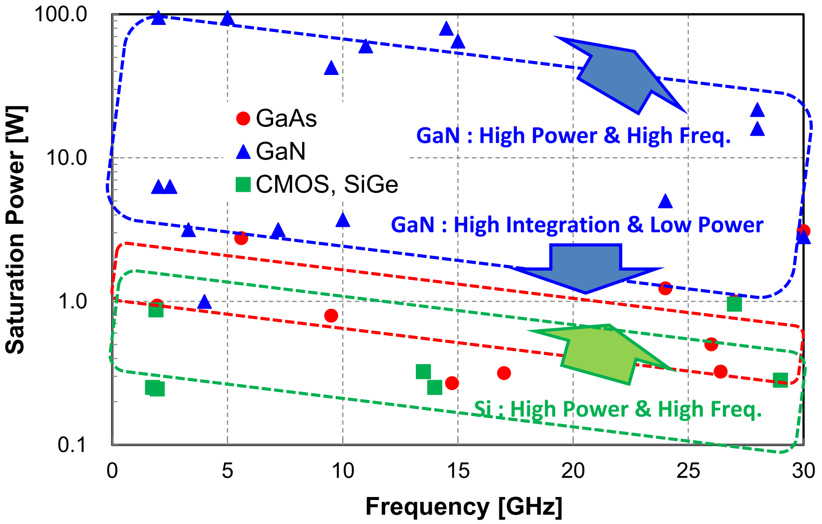


Figure 5. PA device technology map with based on the latest literatures up to 30 GHz

In the coming years, massive connection will be provided for novel and various applications in the 5G system. In order to realize that, massive MIMO is one of the promising technologies because more than hundreds of antenna elements can achieve much efficient frequency spectrum usage with multi-beam multiplexing transmission. Figure 6 shows the estimated Effective Isotropic Radiated Power (EIRP) versus a number of radiators. The parameter is the average power per ONE PA, and it set to be 5, 20, 50, and 200 mW. For a given net EIRP, it shows that increasing array size dramatically reduces the required individual PA output power. In case of 64 radiators that means 8 x 8 array, CMOS or SiGe PA would be able to realize the application with EIRP of 45 dBm. On the other hand, GaN or GaAs technology would be appropriate for application with EIRP of 60 dBm or higher. That is, device technology for PAs is selected with depending on a number of radiators in massive MIMO system as well as the required output power.

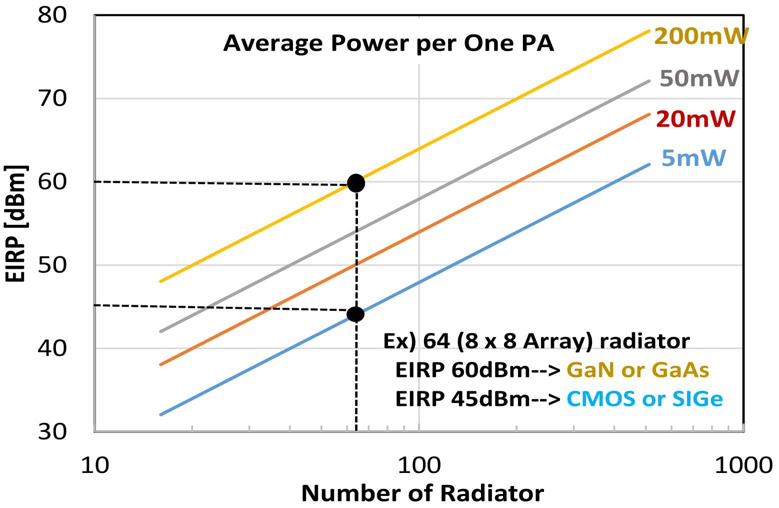


Figure 6. Estimated EIRP versus a number of radiators.

Recently, various GaN PAs have been reported for 4G/5G applications as well as satellite/space applications. Figure 7 shows the simplified GaN's characteristics and benefits. GaN is well known as device with low output capacitance, high output impedance as well as high breakdown voltage. These features lead to high efficiency and high power PA performances over a wide frequency range, and they contribute to the realization of low cost, large bandwidth and small size base station system.

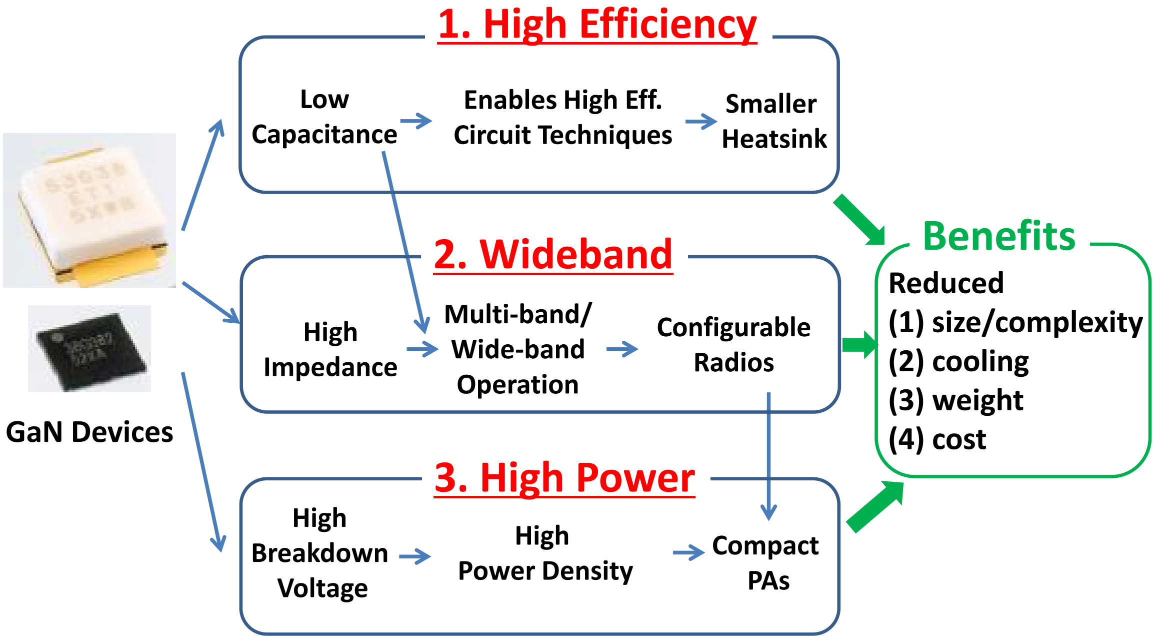


Figure 7. Simplified GaN's characteristics and benefits

III. PROTOTYPED RESULTS OF ADVANCED GAN POWER AMPLIFIERS

III -1 *Back-off Efficiency Enhancement PA*

Wireless communication systems require signals with high peak to average power ratio (PAPR) and wide modulation bandwidth. High PAPR signals usually degrade the PA efficiency because it has to operate at a large back-off. Especially, in 4G/5G systems, as mentioned before, the modulated signals with higher bandwidth and more complex scheme are used to realize higher data rate, and the demand for flexibility under the multi-band multi-mode operation is increasing. Figure 8 shows the back-off efficiency enhancement GaN PA architecture road map. To efficiently amplify the signals with flexibility, various approaches such as envelope tracking amplifier, analog/digital based Doherty Amplifier, and digital transmitter with superior property GaN have been investigated. In this section, some of them are described and discussed.

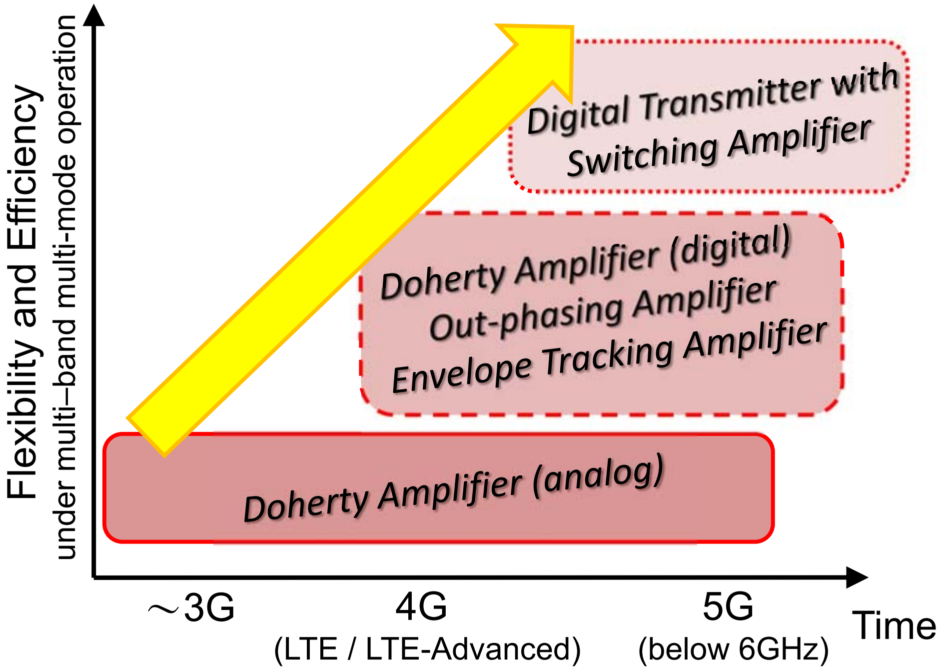
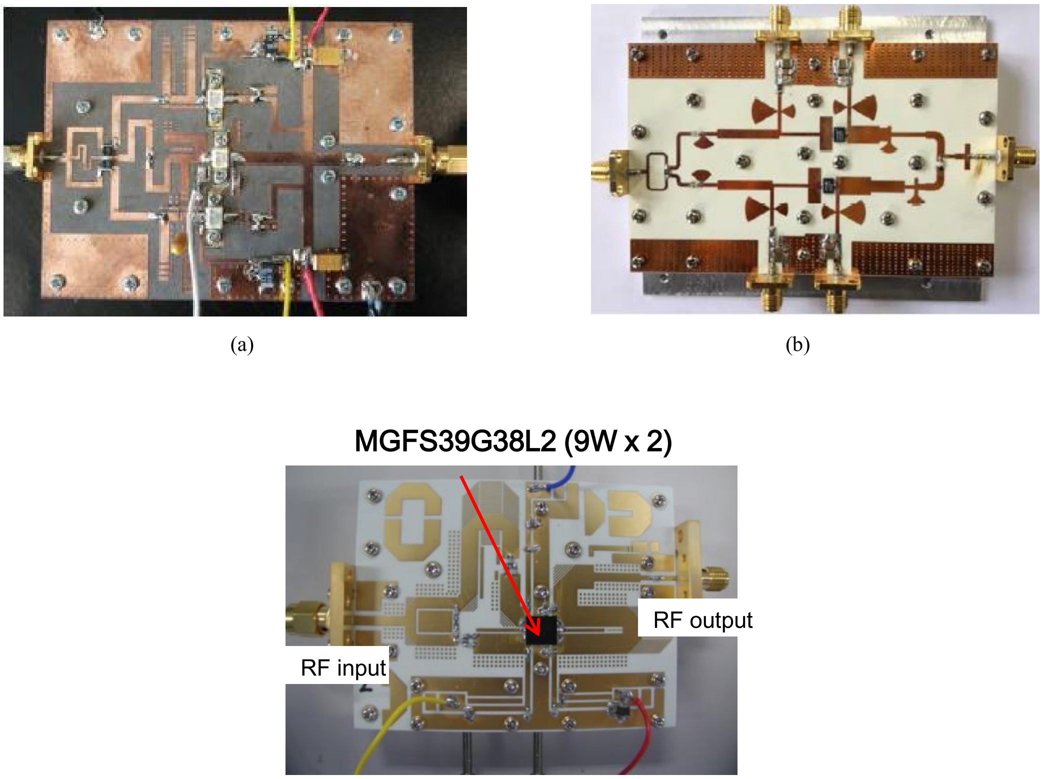


Figure 8. Back-off efficiency enhancement GaN PA architecture roadmap.

A. GaN Doherty Amplifier (analog)

A Doherty amplifier is well-known PA circuitry to enhance efficiency under high PAPR signals for base stations, and it is inherently narrow band due to the frequency-dependent impedance transformer. To overcome it, Doherty amplifiers employing GaN with low capacitance property have been proposed as shown in Fig.9 [17]-[19], and they present wideband performances which cover multi-band frequency range for 4G/5G systems.

First, in the GaN Doherty amplifier [17], a new load modulation network with a shunt quarter-wavelength short stub was proposed and implemented for bandwidth extension. The measurement results showed a drain efficiency (DE) of more than 40 % from 2.0 to 2.6 GHz. Next, in the GaN Doherty amplifier [18], the second harmonic impedances conditions caused by active load modulation were taken care of in the design. The measurement results using 40 MHz LTE modulated signal showed a DE of 40.9-55.1 % at 3.3 to 3.6 GHz. Finally, in the GaN Doherty amplifier [19], a “Frequency Dependency Compensating Circuit (FDCC)” was proposed and implemented at the output of the auxiliary amplifier to realize wideband operation. The FDCC works as an inductive reactance at lower frequency, and assumes as a capacitive reactance at higher frequency. Notably, the electric length from the equivalent current source plane of the transistor should be 180 × N degree (N = 1, 2, 3…), and N and the characteristic impedance are designed to dramatically reduce the frequency dependence. As a result, with an adjacent channel leakage ratio (ACLR) of -50dBc and DPD applied from 3.0-3.6 GHz, a DE of45.9-50.2 % was achieved. The advantages of both GaN’s low output capacitance and the proposed circuitry are clearly demonstrated in the realization of the ultra-wideband Doherty amplifier which will find its applications in the 4G/5G systems with simple and compact solution.



(a) (b)

(c)

Figure 9. Examples of prototyped broadband GaN Doherty amplifiers [17]-[19].

B. *GaN Envelope Tracking Amplifier*

Envelope Tracking (ET) is also a very competitive solution compared with Doherty architecture to boost PA efficiency. An ET amplifier mainly consists of a RF-PA and an envelope amplifier/modulator (EA) to track the envelope of the signal. In the ET amplifiers, supply voltage of the RF-PA is dynamically modulated by the EA, so that the RF-PA operates near saturation, resulting in high average efficiency even with high PAPR signals. One of the key components for high efficiency ET amplifiers towards 4G/5G systems is an efficient broadband EA, which is often a combination of a linear stage and a CMOS switcher stage. To realize efficient broadband EA, GaN having features of both higher speed operation and higher voltage is an attractive device, and an ET amplifier with GaN was already demonstrated [20].

The prototyped GaN chip photo of the buck-converter (BC) for EA and the measurement setup of the GaN ET amplifier are shown in Fig. 10 [20]. The BC was fabricated using a 0.15 μm GaN HEMT process. This circuit employs a boot-strap technique for the high-side driver in order to improve the driver stage's efficiency. Measured efficiency was 78% with 50 ohm load for 20MHz modulation signal with 6.5dB PAPR. In Fig.10, the original baseband signal for 20-80MHz LTE was generated through Matlab in a remote computer and stored in the memory of a Real-time DPD system. Based on the baseband signals, the input signals for the BC and RF-PA were generated. Figure 11 shows measured spectra of the ET amplifier, and it includes both with and without DPD at 2.15 GHz operating under 80MHz LTE signal with 6.5dB PAPR (after Crest Factor Reduction). As shown in Fig. 11, that ACLR was improved from -37.6 dBc to -45.1 dBc even under an 80MHz LTE signal. Output power and power added efficiency (PAE) of the ET PA were 30.7dBm and 35.3%, respectively. Table I shows the state-of-the art performance of ET PAs. Compared with others, the ET-PA reported here has highest efficiency and widest modulation bandwidth while meeting the 3GPP requirement (less than -45dBc) for a broadband range. It means the ET-PA is one of the useful architectures for 4G/5G systems which requires multi-band multi-mode operations.

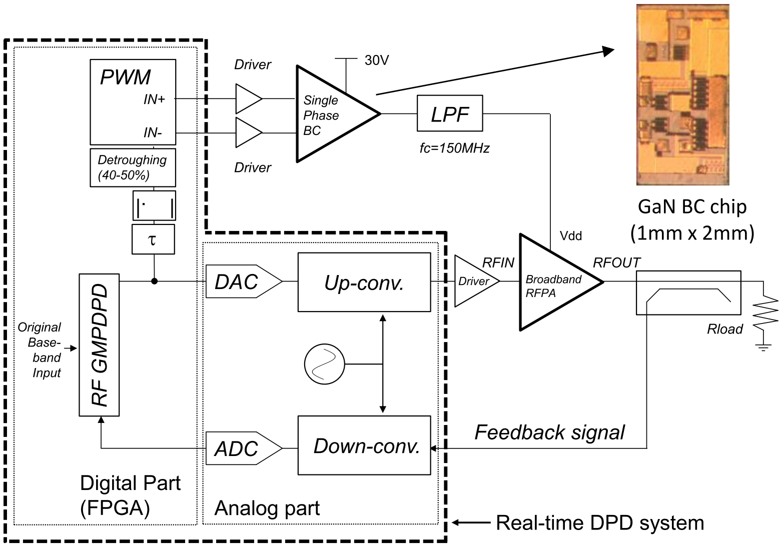
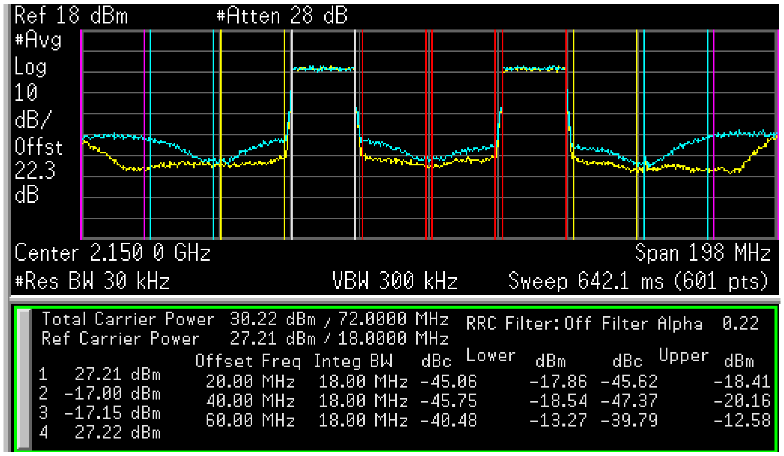


Figure 10. Measurement setup including the RT-DPD system [20]



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Ref 18 dBm          #Atten 28 dB
#Avg
Log
10
dB/
Offst
22.3
dB
Center 2.150 0 GHz                               Span 198 MHz
#Res BW 30 kHz             VBW 300 kHz     Sweep 642.1 ms (601 pts)

Total Carrier Power  30.22 dBm / 72.0000 MHz  RRC Filter:Off Filter Alpha  0.22
Ref Carrier Power    27.21 dBm / 18.0000 MHz
                     Offset Freq  Integ BW   dBc  Lower  dBm     dBc  Upper  dBm
1   27.21 dBm         20.00 MHz  18.00 MHz -45.06      -17.86 -45.62      -18.41
2  -17.00 dBm         40.00 MHz  18.00 MHz -45.75      -18.54 -47.37      -20.16
3  -17.15 dBm         60.00 MHz  18.00 MHz -40.48      -13.27 -39.79      -12.58
4   27.22 dBm
```

Figure 11. Measured spectra with and without DPD at 2.15GHz under 80MHz LTE signal with 6.5dB PAPR [20].

Table I. Performance comparison of ET PA.

Ref	Device for EA	Input Signal			Measurement Results		
		Freq [GHz]	Mod. BW [MHz]	PAPR [dB]	Pout dBm]	Total Effi [%]	ACLR [dBc]
[21]	CMOS	0.5-1.75	5	6.6	33-36	25-31	-47.5
[22]	GaN	1.84	10	11.7	32.8	23.9	-38.7
[20]	GaN	0.9-2.15	80	6.5	30-30.7	32.1-35.5	-45

C. Digital Transmitter with Switching Amplifier

All-digital architecture replaces RF/analog front-ends, which drive the PA in Class-S operation, with high-speed digital circuits, allowing a small and low-cost implementation. In addition, it is an attractive architecture for 4G/5G systems because of its strong potential to provide multi-band multi-mode operation and high average power efficiency.

In the paper [23], a digital Class-S out-phasing transmitter using two GaN Class-D PAs were proposed. Figure 12 shows the circuit schematic and chip photo of the GaN Class-D PA with the Chireix power combiner. The PAs have a 3-dB bandwidth of 1-GHz, and each PA has two internal pre-driver stages. Considering the 1-GHz bandwidth of the GaN PAs, 244 MHz and 500 MHz carriers are chosen for the designing of the digital transmitter. The prototyped digital transmitter achieved -37 dBc and -30 dBc ACPR at 244 MHz and 500 MHz, respectively. Also, the transmitted peak power and peak efficiency were 35.2dBm and 56.0 %, respectively for both frequencies. In the paper [24], single-bit high efficiency watt-class digital transmitter for the 450 MHz band was presented. It includes a GaN voltage-mode class-S (VMCS) PA and a CMOS envelope $\Delta \Sigma$ modulator. Figure 13 shows the block diagram of the complete digital transmitter with VMCS-PA and an envelope-$\Delta\Sigma$ modulator, and chip photo of the VMCS-PA module. The transmitter achieved 1.1 W output power and achieved 69 % DE for a 400 MHz WCDMA uplink signal, thus meeting the 3GPP specifications for ACLR.

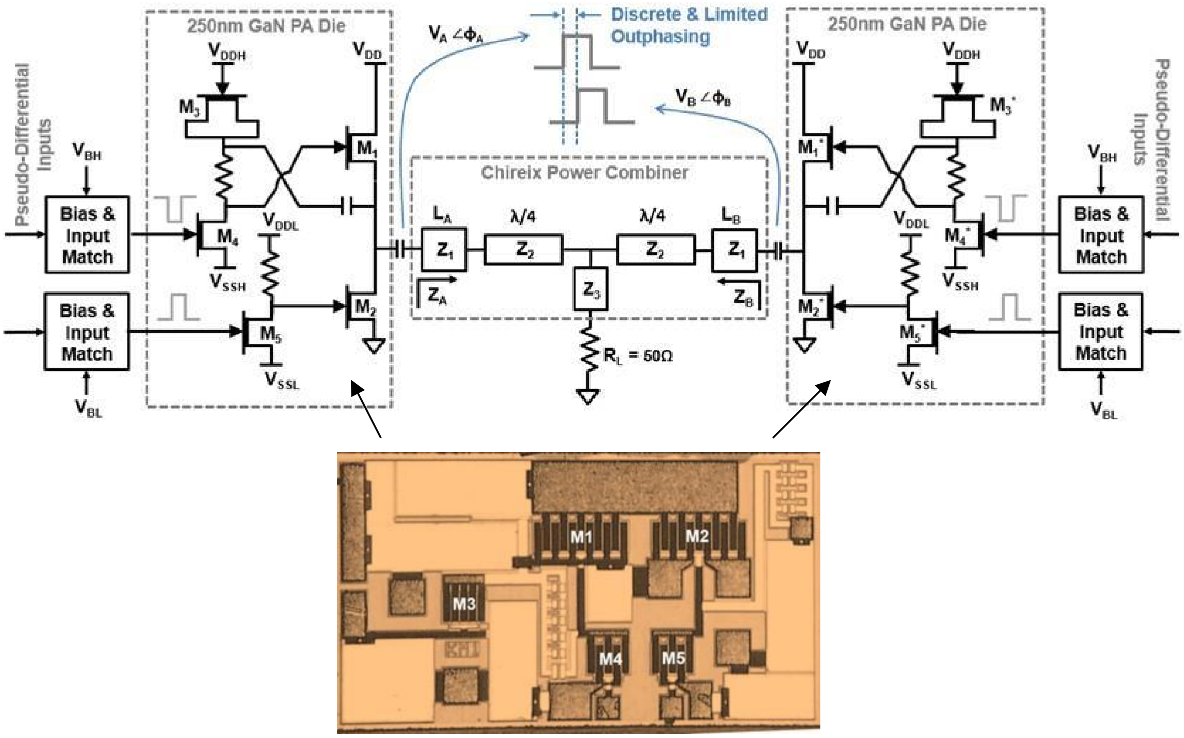


Figure 12. Circuit schematic and chip photo of the GaN Class-D PAs with the Chireix power combiner [23]

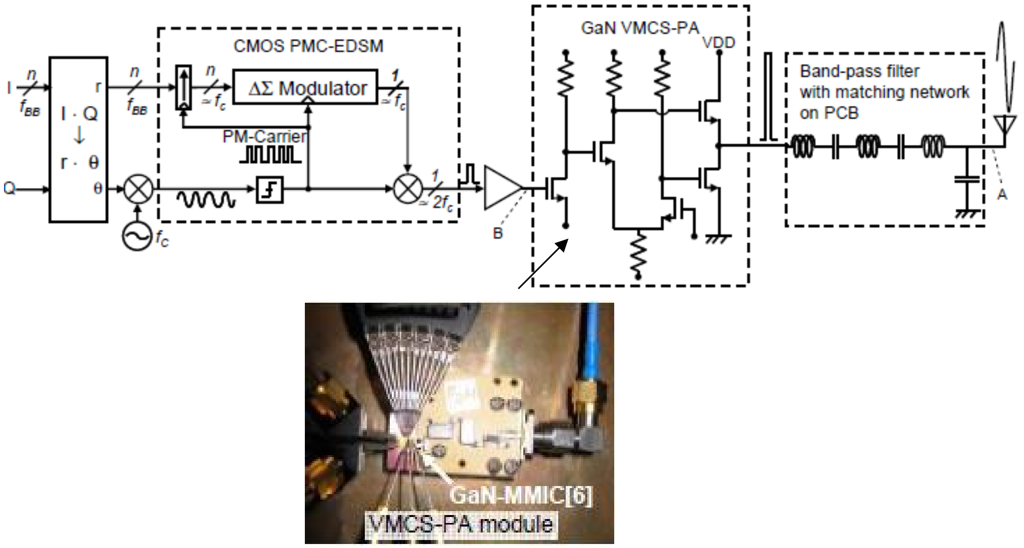
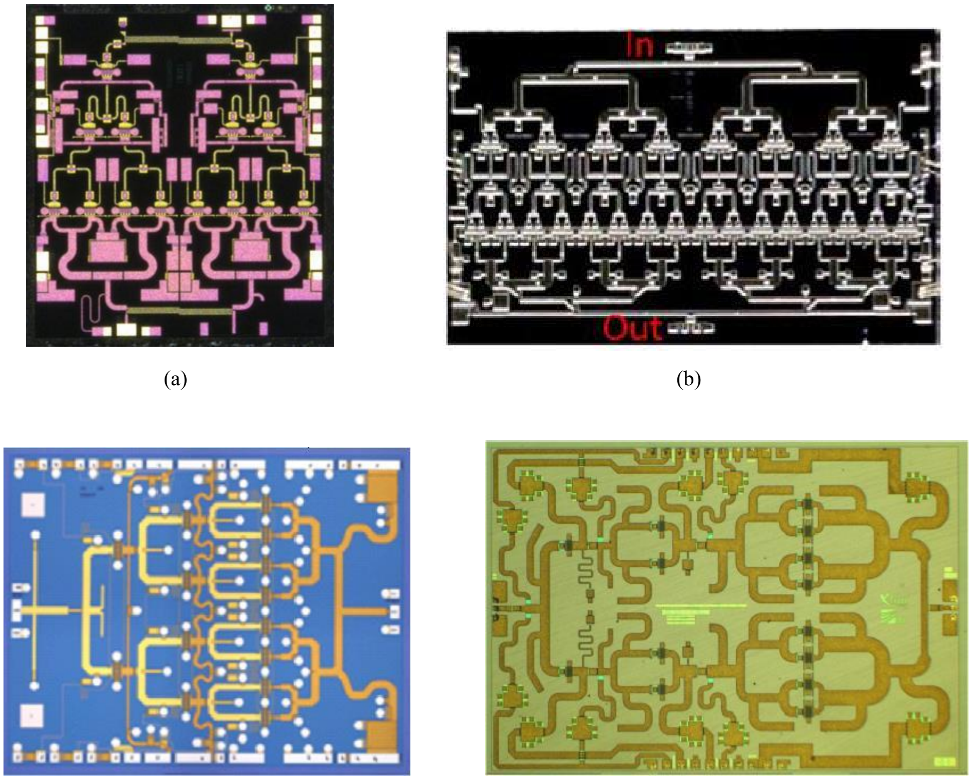


Figure 13. Block diagram of the complete digital transmitter with VMCS-PA and an envelope-ΔΣ modulator, and chip photo of the VMCS-PA module. [24]

III -2 High efficiency *PA MMICs at Ka-band*

Ka-band GaN MMIC PAs are critical components for applications such as space/satellite communication, and recently they attract attention to application to 5G communication.

Figure 14 shows the examples of prototyped Ka-band GaN MMICs with short gate length. Fig. 14 (a) shows the fabricated balanced-type GaN MMIC utilizing 0.15um technology [11], and its size is 3.24 x 3.60mm^2. The measured in-fixture results for CW output power and PAE shows greater than 9.5W and 26 % from 28GHz to 31GHz, respectively. Figure 14 (b) shows the photo of the fabricated single-ended-type GaN MMIC utilizing 0.15um technology [14], and its size is 4 x 6 mm^2. To realize high power high efficiency amplifier under CW operation at Ka-band, the gate pitch length was designed to obtain the maximum output power of FET cells in MMIC by using the new model. The amplifier achieved output power of 20W and PAE at 19% under CW operation at 26.5GHz. In addition, output power of more than 15W with PAE of more than 13% across 26GHz to 28GHz were demonstrated. Figure 14 (c) shows the power amplifier with a millimeter wave 100 nm GaN on Silicon process [25], and its size is 4.5 x 3.5 mm^2. The measured results shows the output power of 6W and PAE at 30% under pulsed condition. Moreover, Fig. 14 (d) shows a high-efficiency power amplifier MMICs utilizing a 100 nm AlGaN/GaN HEMT MMIC technology [26]. The PA provides 8.1 W of output power and 30% of PAE at 30 GHz, and chip size of 5 x 3 mm^2.



(a) (b)

(c) (d)

Figure 14. Examples of prototyped Ka-band GaN MMICs [11], [14], [25], [26].

IV. Future Outlooks

It is expected that with spectrum re-farming, low frequency band in the range of 600MHz-700MHz used for digital TV will be gradually used for cellular base station. Due to its low propagation loss in the space, these bands are better suited for increasing network coverage, compared with higher frequency (>3GHz). Therefore, wideband PA covers multi bands could significantly reduce the base station radio complexity and footprint. Also, due to the tower space limitation, it is also possible that different operators would share the radio front end including power amplifier. This will also increase the demand of multi-band /wideband PA to support various signal transmissions.

Network densification, in particular, small cell has been considered as an effective approach to address the capacity issue of the network, at the hot spot zone. Low cost packaged device will reduce the hardware CPEX of small cell deployment, and efficient amplification with natural air cooling could result in a faster deployment. GaN device on Si substrate with plastic packaging could results in a faster delivery of GaN devices, though many challenges still remain to be addressed. The progress in the digital signal processing power such as FPGA can be an excellent platform for implementing an all-digital transmitter architectures. Linearization of GaN PA becomes a significant challenge for Massive-MIMO, either in digital and/or analog, and this remains a hot research topics [27], [28]. Due to the constraint of RF front-end module size at millimeterwave, integrated circuits (IC) of RF Front End module is normally the preferred solution. With the advancement in both III-V and Silicon technology, heterogonous integration of baseband processing and RF power on a signal chip would be very attractive, thought there remains many challenges to be solved [29].

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