Technical Article

# Design Considerations: 5G Small Cell Radios

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## Introduction

5G benefits to consumers and enterprises include higher data throughputs, lower latency, and increased network reliability. On the radio side, this is enabled by use of wider RF bandwidths—beyond 100 MHz—in the sub-6 GHz bands (like the popular C-bands), as well as higher-order modulation schemes (256 QAM). Both factors, when combined with stringent 3GPP-defined RF spectral compliance requirements, put pressure on RF designers for system-level optimization.

Looking at RF requirements for FR1 (<6 GHz) base stations, we can consider two ways to define the system. First, the definition as standardized by 3GPP (in the 38.104 series of standards for 5G):

| Base Station Class | Distance (m) | Power |
|---|---|---|
| Local Area | >2 | ≤250 mW/24 dBm |
| Medium Range | >5 | ≤6.3 W/38 dBm |
| Wide Area | >35 | No upper limit |

Table 1 : 3GPP Base Station Classes (FR1)

The 3GPP-defined base station classes are important, because they define the minimum RF requirements that the product needs to support. Examples include error vector magnitude (EVM) of the transmitted signal (which translates to modulation order) and adjacent channel leakage ratio (ACLR) and other unwanted signal transmissions (say, RF spurs) that define unwanted transmissions outside of the intended transmitted spectrum. These minimum RF requirements differ per base station class, generally being more relaxed for lower-power product classes (e.g., Local Area).

In addition to 3GPP base station classes, we can define a market segmentation that outlines typical products that are deployed by managed network operators (MNOs) or private networks. There are no standardized definitions of these cell types, so keep in mind there is some fluidity in this definition.

**5G system design involves not only component-level optimization but also tradeoffs between energy consumption in different parts of the system**, such as the modem SoC and the RF front-end.

| Cell Type | Location | Users | Radius (m) | RF Power | MIMO |
|---|---|---|---|---|---|
| Femto | Indoor | 10s | 10s | 100 mW/20 dBm | 2R2T..4R4T |
| Pico | Indoor/Outdoor | <100 | 100 | 250 mW/24 dBm | 4R4T |
| Micro | Outdoor | 100..1000 | <1000 | <10 W/40 dBm | 4R4T..8R8T |
| Macro | Outdoor | <1000 | <5000 | 100 W/50 dBm | 4R4T |
| MMIMO | Outdoor | <1000 | <5000 | <200 W/53 dBm | 16R16T..64R64T |
| FR2 | Indoor/Outdoor | <100 | <1000 | <75 dBm | 100s |

Table 2: Marketing Segmentation

This paper considers relatively low-power base station classes (Femto, Pico, Micro), as shown in Table 2.

## RF Compliance Requirements

As mentioned above, the 3GPP 38.104 and related standards define key RF compliance requirements on a per power-class basis. There are separate sets of requirements for transmit and receive performance. Key requirements that impact the digital and analog transmit chain include error vector magnitude and adjacent channel leakage power ratio.

### *Error Vector Magnitude Requirements*

Error vector magnitude (EVM) is a measurement of distortion ("error" here is defined as the difference between intended and actual transmitted signal) of the transmission, defined in 3GPP 38.104, Chapter 6.5.

Adjacent channel leakage ratio (ACLR) (see following section), and EVM performance are related in that they both are a measure of distortion. Therefore, for completeness, we include the 3GPP minimum EVM performance for each modulation scheme:

| Modulation Scheme (PDSCH) | Required EVM |
|---|---|
| QPSK | 17.5% |
| 16 QAM | 12.5% |
| 64 QAM | 8% |
| 256 QAM | 3.5% |
| 1024 QAM | 2.5% (≤4.2 GHz)<br>2.8% (>4.2 GHz) |

Table 3: Transmitter (minimum) EVM requirements

### *Adjacent Channel Leakage Power Ratio*

ACLR is the ratio of (filtered, mean) power on the assigned channel to (filtered, mean) power on an adjacent channel frequency.

3GPP defines two limits on ACLR: base station ACLR limit and base station ACLR absolute basic limit. Per the "Minimum Requirement for BS type 1-C" chapter, whichever (limit) is less stringent shall apply for each antenna connector.

ACLR limits are defined as offsets from the carrier frequency, as a function of frequency, as shown in Figure 1, below, for the base station ACLR limit:

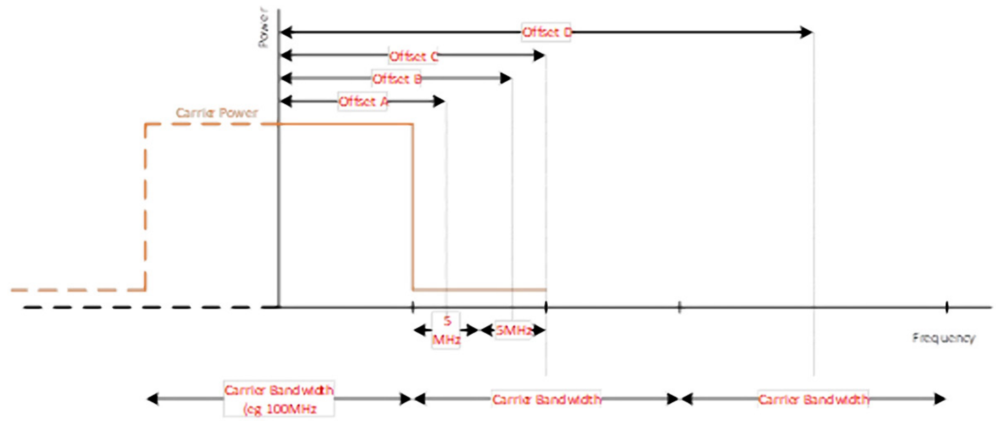


Figure 1: ACLR Frequency Definitions

The base station ACLR Limit is defined by a square filter with the passband bandwidth equal to the bandwidth of the transmitted signal (BWConfig) centered on the assigned channel frequency and rejection specified on the adjacent channels' frequency according to the tables (refer to Figure 1, above, for a graphical representation). ACLR in general is defined in dB (relative) distance to the channel frequency.

| $BW_{Channel}$ | ACLR Basic Limit | Adjacent channel carrier | Adjacent channel filter | ACLR limit |
|---|---|---|---|---|
| 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100 | $BW_{Channel}$ | NR of same BW | Square ($BW_{config}$) | 45 dB |
| | 2× $BW_{Channel}$ | NR of same BW | Square ($BW_{config}$) | 45 dB |
| | $BW_{Channel}/2 + 2.5$ MHz | 5 MHz E-UTRA | Square (4.5 MHz) | 45 dB |
| | $BW_{Channel}/2 + 7.5$ MHz | 5 MHz E-UTRA | Square (4.5 MHz) | 45 dB |

Table 4: Base Station ACLR Basic Limit

Base station ACLR absolute basic limits are shown in Table 5, below, and are defined in dBm/MHz (therefore over a much smaller slice of bandwidth than the base station ACLR basic limit, which is defined over a 3GPP channel bandwidth).

| BS Class | ACLR Basic Limit | Power | Tolerance (normal) | Tolerance (extreme) |
|---|---|---|---|---|
| Cat A Wide Area | -13 dBm/MHz | Not defined | +/- 2 dB | +/- 2.5 dB |
| Cat B Wide Area | -15 dBm/MHz | Not defined | +/- 2 dB | +/- 2.5 dB |
| Medium Range | -25 dBm/MHz | ≤38 dBm | +/- 2 dB | +/- 2.5 dB |
| Local Area | -32 dBm/MHz | ≤24 dBm | +/- 2 dB | +/- 2.5 dB |

Table 5: Base Station ACLR Absolute Basic Limit

As an example, consider a local area (picocell) base station with a rated output power of 24 dBm and a single 100 MHz 5G NR carrier. For now, ignore RF losses / inefficiencies and look only at the antenna connector output as per 3GPP specifications.

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Calculate the power spectral density (PSD) in dBm/MHz:

**PSD[dBm/MHz] = 24 dBm – 10log10(BW[Hz]/1 MHz) = 24 – 20 = 4 dBm/MHz**

Now, define the performance limits:

- ACLR basic limit, common across offsets A,B,C,D
    - Relative to carrier and measured over carrier bandwidth: **45 dBc**
- ACLR absolute basic limit
    - In PSD terms = **-32 dBm/MHz**
    - Relative to carrier: 4 dBm/MHz – -32 dBm/MHz or **36 dB offset from carrier**

Given that the least stringent applies, the ACLR absolute basic limit is the limit to aim for most aggressively. Note how the absolute basic limit is specified with a narrower filter than the basic limit ACLR specification—presumably to catch a higher level close to the desired signal. If the noise floor is relatively flat, and spurs are limited, the absolute basic limit is most often applied.

## Radio Front End Architecture

Digital baseband processing (layer 1 or physical/PHY layer) and layers 2 and 3 (medium access control/MAC, radio link control/RLC, packet data convergence protocol/PDCP) are typically implemented on a combination of digital signal processor (DSP), hardware accelerator (for forward error correction, ciphering and other compute-intensive functions) and general-purpose processor (GPP).

The digital front-end (DFE) prepares and multiplexes the signals created by the baseband processing subsystem and sends them to the RF power amplifier for transmission.

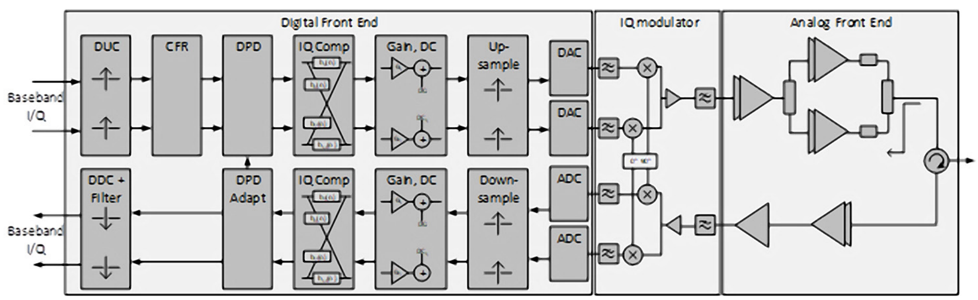


Figure 2: Typical Small Cell Radio Front-End Architecture

A digital upconverter receives the carriers created by the baseband and then pulse-shapes and sums them according to the carrier's specified pattern, using oversampling and filtering. The DFE can employ crest factor reduction (CFR) for limiting peak-to-average power ratio (PAPR) and signal linearization using digital pre-distortion (DPD), both of which can increase power amplifier efficiency, as discussed below. After digital up-conversion, RF filtering (to remove out-of-band unwanted emissions), and amplification (including the final stage PA), there are often other components that can impact RF performance, 3GPP compliance, and the RF output power level. These components include the antenna transmit/receive switch, coupler for power measurements and DPD feedback path implementation, and RF bandpass filter. Expect the output power at the antenna to be ~2-3 dB below the power at the PA output pin due to these losses.

### *Peak-to-Average Power Ratio and Crest Factor*

The peak-to-average power ratio (PAPR) of a signal is the ratio between the peak and the average amplitude of the signal—measured either as peak amplitude squared (peak-to-average power) or as peak amplitude of a waveform divided by the RMS value of the waveform (crest factor). Multicarrier applications (5G uses orthogonal frequency division multiplexing (OFDM) signals in the downlink direction – or transmit from base station to user equipment) exhibit a very high PAPR, typically in the 8-15 dB range, depending on the number of OFDM carriers in the signal (and therefore of the signal bandwidth), and modulation format (QPSK, 16QAM, 64QAM, 256QAM).

PAPR/crest factor measurements are typically plotted in a complementary cumulative distribution function (CCDF) plot, with percentage numbers on the vertical axis indicating how much of the time the signal power is above the power specified on the horizontal access. The horizontal axis shows the amount of dB that the actual power is above average power.

PAPR is important because in order to transmit (near) 100% of the signal correctly, the transmit chain needs to be able to accommodate not only the bulk/average signal level, but also the signal level that is exhibited by the fraction of a signal that exhibits the peak values. This means that the transmit chain needs to be dimensioned for by the PAPR amount of dB of margin. If building, for example, a 24 dBm average transmit chain targeting a 5G signal with 10 dB of PAPR, you need to dimension for (24+10=) 34 dB peak power. This peak power is the level at which the PA needs to transmit without significant impact on signal quality.

This obviously is a big topic in system design, as well as a cause of inefficiency in designs. For this reason, in handsets (uplink) transmitters, the waveform is modified to single carrier FDMA (SC-FDMA), which exhibits about 3 dB less PAPR compared to OFDMA. Alternatively, the crest factor of the OFDMA signal of the base station can be reduced through a technique called crest factor reduction (CFR). Multiple CFR techniques are described in literature. One example is "clipping" the OFDMA signal, such that all peaks that are above a certain PAPR/CR level are simply chopped off the transmitted signal, followed by some filtering functions to smooth out the resulting signal. Independent of which CFR technique is applied, the result is always the same—the PAPR of the signal is reduced by several (typically 3..7) dB, thus reducing the linearity requirements on the transmit chain, including the PA. Keep in mind that CFR has negative effects as well, such as impacting EVM.

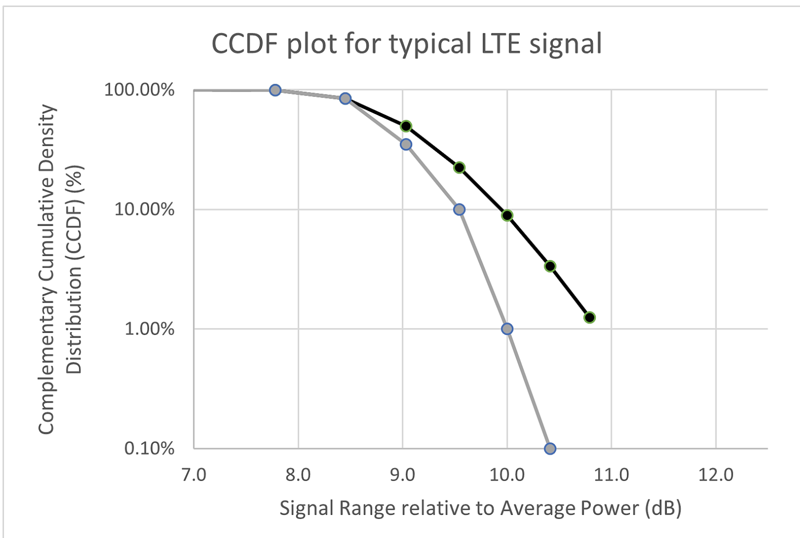


Figure 3: CCDF Plot for a Typical LTE Signal, Without (black) and With (grey) CFR Applied

## System Level Optimization

The issues here are: (1) what tradeoffs to consider in an RF system, and (2) how to go about optimization efforts. The answers always depends on the optimization goals. This paper focuses on building a system that is 3GPP RF-compliant, as well as optimized for the lowest total DC power budget, because power consumption relates to customer deployment cost, power supply and cooling costs, in addition to environmental impacts.

Given this optimization towards DC power consumption, the power amplifier is identified as the most power-consuming part in the system, so it should be made as low-power as possible. If DC power consumption of the PA is viewed as a function of its output power, it can be noted that the higher the output power, the more DC current it will consume, with efficiency being the main metric. Efficiency is defined as the amount of DC power consumed for a particular output power. The higher the efficiency, the lower the DC power is for a particular PA output.

Figure 4, below, is purely theoretical and included to save the user from having to calculate efficiency tradeoffs manually. The DC power consumed by a radio/PA is on the vertical axis, and the power at the PA output is on the horizontal axis. The lines in the chart represent different PA efficiency operating points. For example, a 27 dBm output power with a 20% efficient PA would require about

2.5 W DC at the DC supply line (typically, a 5 V DC supply for these low power levels). Keep in mind that 5G systems are typically operating in time division duplexing (TDD) mode, which implies that ~70% of the time, transmit is operating. Or said conversely, that 30% of the time, the PA can be disabled.

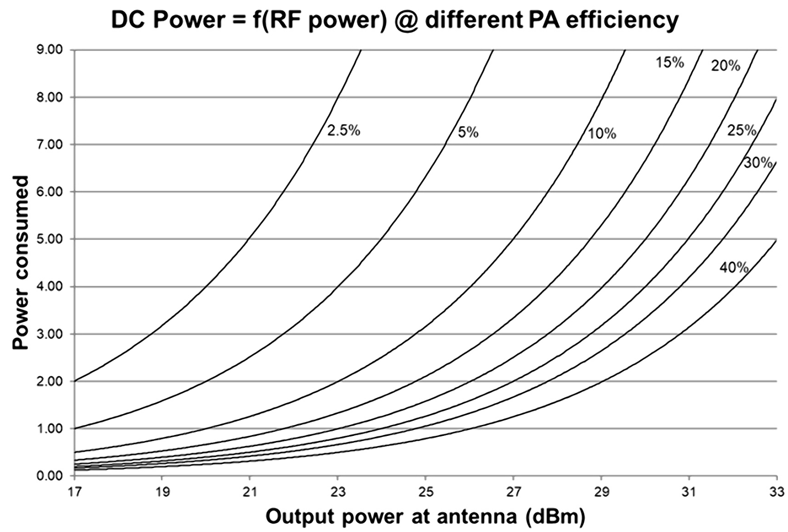


Figure 4: DC Power = f(RF power) @ Different PA Efficiency

There are a few points to note. First, RF efficiency levels depend on the operating band, with the rule of thumb being that lower frequency bands typically have higher efficiency levels. FR2/mmWave efficiency levels are a few %, whereas modern low-band PAs are operating at or near 50% efficiency (partially due to processes available at the particular frequency). Second, the (low) efficiency levels shown in Figure 4 are not binding. The RF signal can be made more efficient for transmission by tweaking it to lower the PAPR, allowing the PA to operate closer to its peak capabilities. This is done through crest factor reduction (CFR), as discussed above. Third, the performance of the PA can be stretched by compensating its non-linearity though linearization or digital pre-distortion (DPD), as presented in more detail below.

## Pre-distortion

As presented previously, the peak-to-average power ratio (PAPR) dictates the minimum output backoff (OBO) from saturated power at which the amplifier usually operates and directly impacts amplifier efficiency, because power amplifier efficiency (PAE) decreases as OBO increases. Consequently, reducing the PAPR helps to reduce the size (and thus cost) of the devices used in the RF PA and the amplifier's power consumption. This is obviously of major interest in small cell design and drives the need for crest factor reduction. Whilst this technique allows the PA performance to be stretched in terms of output power (at the cost of EVM and CFR complexity – tradeoffs, remember!), it does not solve another problem with PAs, which is limitations in linearity.

An ideal PA has a linear relationship between input and output, with a given gain (say, 30 dB) between the two. In reality, the gain is not linear. It changes as a function of signal amplitude, frequency, previous signals transmitted, temperature, and many other parameters. This poses challenges for the amplifier, as its non-linear behavior creates in-band distortion that increases error vector magnitude (EVM) and out-of-band distortion (spectral regrowth).

To meet increasingly stringent linearity and efficiency requirements, the power amplifier must be linearized using pre-distortion. This consists of approximating (the inverse of) amplifier characteristics using a behavioral model, as well as following the amplifier's behavior over changes in temperature, carrier frequency, and RF output power. Linearization also compensates for "memory effects" that are changes in the amplitude or phase (or both) of distortion components as a function of input signal frequency. These tend to be extremely difficult to model using standard steady-state characterization techniques. The less the contribution of memory effects, the easier linearization will be.

The simplest pre-distortion scheme is open-loop correction without memory effect compensation and is based on static AM/AM and

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AM/PM power amplifier behavior. Closed-loop DPD includes memory effect correction and requires a demodulation path to sample the output signal and compare it with the desired transmitted signal. Given that 3GPP standards define out-of-band/unintended RF transmissions to be below a given level for both adjacent and second-adjacent carriers, the pre-distortion bandwidth needs to be 5× (intended, adjacent and second-adjacent in lower band, adjacent and second-adjacent in higher band) the intended bandwidth. For a typical 100 MHz 5G carrier, this means the pre-distortion bandwidth needs to cover up to 500 MHz in the transmit direction as well as the feedback path.

Pre-distortion can be implemented in both the analog (for example, Analog Devices carries a range of RF PA Linearizer ICs, doing analog pre-distortion/APD, in addition to their digital pre-distortion/DPD product range) and digital domain ( DPD), with the latter being the most used option in 5G systems. DPD implementations rely on brute force compute to modify the transmitted signal before it is fed to the DAC in the front-end architecture Figure 2, shown above, to cancel out the distortion added later in the system. Note how both APD and DPD come at a cost in terms of consumed DC power; take 1-2 W of DC power for implementation of the pre-distortion function as a "fixed cost" associated with the function. This cost is offset by allowing for a less linear, and therefore lower DC power-consuming, PA in the system. This is the tradeoff decision to be made by the system designer—invest in APD/DPD complexity or just design-in a "linear" PA that does not need its functionality.

## The Balancing Act

To demonstrate the various effects of CFR and DPD, and to estimate the RF power amplifier DC power budget for various types of small cells, an analysis was performed using 3 transmit power scenarios, covering the femto, pico and micro base station classes defined at the beginning of this paper. The following assumes a popular deployment with 100 MHz of occupied spectrum in band n78 (3.3 to 3.8 GHz).

### *Femto – 20dBm with GRF5536*

In the lower output power categories, the trade-off between power efficiency and linearity goes towards linearity—the added complexity in the digital domain to extract more performance from the system does not balance against the potential benefit of getting more performance at the RF output.

Take, for example, the Guerrilla RF GRF5536. This is a multi-stage, high gain, high-linearity HBT device that targets a relatively modest output power. It is rated at 22 dBm or 160 mW transmit power with a 100 MHz (LTE) OFDMA signal with 9.8 dB PAPR applied at the input. Assuming ~2 dB loss between the PA and the antenna connector, the RF performance for a design with this PA will likely hit the 20 dBm mark associated with a femto class system. In addition, note that to get to a PAPR of 9.8 dB for a 100 MHz wide signal, a basic CFR must be applied to the transmitted signal—a typical OFDMA signal is ~12 dB. The power consumption of this device is 290 mA @ 5V or 1.45 W or (160 mW/1445 mW=) 11% PA efficiency.

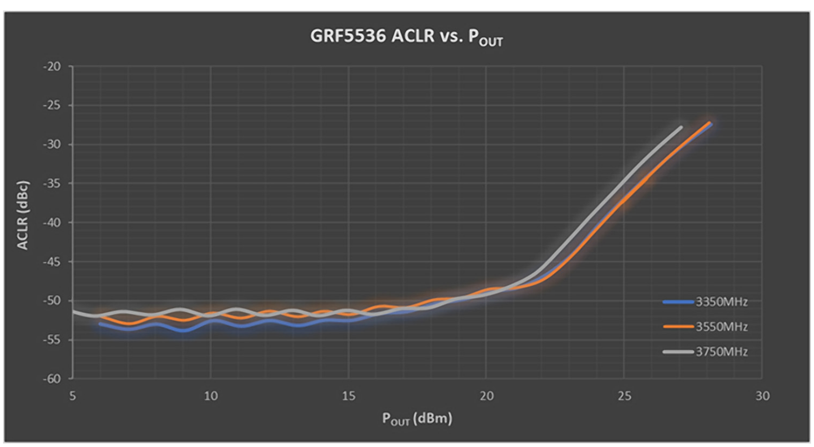


Figure 5 : Guerilla RF GRF5536 ACLR vs. POUT Performance

This device is designed to be a "linear PA," as it does not need pre-distortion to hit EVM and ACLR requirements. This makes system design easy by reducing the needed compute resources and other complexities, such as the implementation of a DPD feedback path with high transmit sampling rates often associated with DPD loops. These compute resources now become available for use with alternative functions, or designs can save even more power by removing the computations altogether. The device was benchmarked on the NXP modem test bench, which confirmed the claimed numbers.

### *Pico – 24 dBm with SKY66520*

Going up the performance curve, the next category in output power category is ±24 dBm or ~0.25 W at the antenna. A well-known PA targeting this market is the Skyworks SKY66520, which is a high-efficiency, wide-bandwidth, 50 Ohm MMIC designed for 3.3 to 3.8 GHz operation. At these output power levels, the DC power consumption (and associated cooling cost) becomes important, and PA efficiency targets are higher (~25%). Note how a 25% efficiency implies a ~2W DC power consumption for the PA. At these levels, the cost of pre-distortion (even with a well-established analog pre-distorter chip like the SC1894, with about 1 W of DC power consumption) is very quickly worth the investment. On top of this, the SKY66520 requires pre-distortion to be applied to the system for it to achieve the 3GPP-dictated ACLR and EVM requirements.

### *Micro – 36 dBm with A3M36SL039*

At even higher output power levels, the DC power consumption associated with the PA dominates the system power. The NXP A3M36SL039, a fully-integrated, 50 Ohm PA module with Doherty configuration and automatic bias control, provides the appropriate output power and operates at ~35% efficiency level. To achieve this and meet 3GPP requirements, the PA relies on DPD, similar to the Pico use-case with the SKY66520 PA, but at a higher DPD complexity. This reflects the tradeoff where compute power invested in DPD is outweighed by the benefit in terms of getting a more efficient PA. In, for example, a 4-antenna small-cell application with 70% transmit activity, the PA-associated DC power consumption is 4 (antenna) x 4 W (36 dBm) x 70% (transmit activity) / 35% (efficiency) = 32 W. At this power level, the cost of implementation associated with both DPD and CFR is clearly offset by the benefit in terms of efficiency.

On the NXP testbench, when connected to the LA1200 modem and a partner RFIC, the performance for such a setup using a 100 MHz IBW signal, centered at 3.6 GHz can be seen. In the benchmarked configuration, the transmit sample rate is 491.52 MSPS for both I and Q, and CFR and DPD are implemented.


Figure 6: Performance Benchmarking of the NXP A3M36SL039

## Architecture

NXP's baseband architecture is based on its vector signal processing accelerator (VSPA), DSP cores and Arm host processors. One of the product markets targeted with this baseband architecture is the integrated small cell (ISC) or radio unit (RU)—the difference between these two being integration of upper PHY and MAC/RLC/PDCP/RRC stacks in the ISC. These types of products are typically implemented with devices like NXP's LS1046A host processor and LA1200 DSP.

## Summary

5G system design involves not only component-level optimization but also tradeoffs between energy consumption in different parts of the system, such as the modem SoC and the RF front-end (including the power amplifier). Establishing the boundaries of the use case helps the system designer making these tradeoffs.

Having a broad portfolio of devices in the system design toolbox is helpful and allows designers to address a diverse range of use cases. Typically, low-power transmitters (less than 15 dBm), do not require CFR or DPD and are targeted to systems that are cost-sensitive, not allowing for associated system complexity.

As power increases (15 to 24 dBm), CFR provides an improvement in transmit power at a modest system complexity increase. In most cases, the PAs used at these power levels do not require DPD for RF compliance. For power levels of 24 dBm and more, DPD is required to achieve 3GPP RF compliance with the PA architectures that are used in these systems. At higher power levels, the digital complexity associated with CFR and DPD is almost always worth the benefit with regards to DC power efficiency.

NXP is well-positioned to support different system challenges by providing a software-centric modem solution that gives flexibility to trade compute-complexity between different blocks in the digital processing chain. When combined with an "ecosystem" approach to RF component choice, as opposed to only supporting a small subset of PA options, a much wider solution space can be addressed.

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More information is available online at richardsonrfpd.com.

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