Integrated Transceiver Architectures for 5G Cellular Base Stations

Jaiganesh Balakrishnan & Sriram Murali

Texas Instruments, Bangalore

Feb 21, 2020

Outline

- Cellular Base Station – Trends
  - Driving Factors
- Cellular Base Stations – Overview
  - 5G Signal Structure
- Cellular Base Station – Integrated Transceivers
  - Overview
  - Key Parameters
  - Transceiver non-idealities
- Integrated Transceiver Architectures
  - IF Sampling Architecture
  - Zero IF Architecture
  - RF Sampling Architecture

Is this a Cellular Base Station?

A

4G Macro

B

Small Cell

C

WiFi & DAS

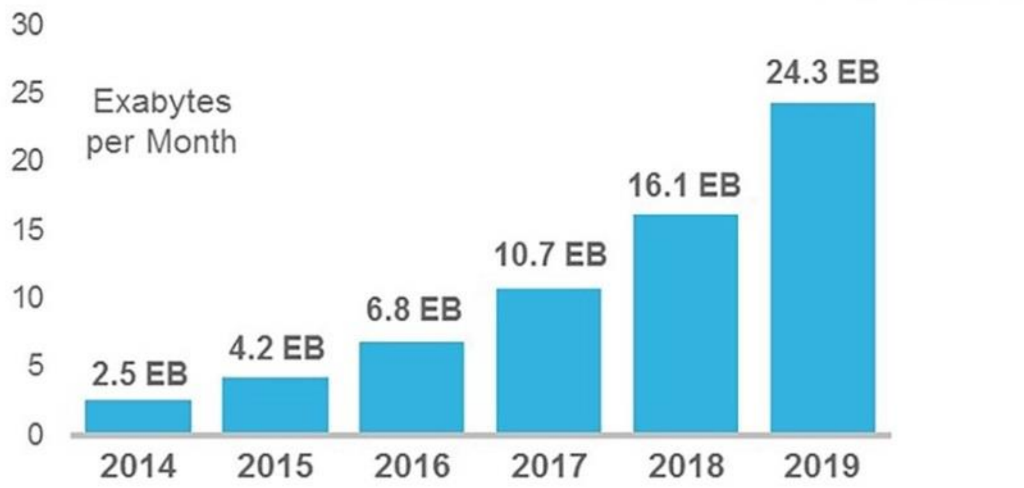
D

5G Massive MIMO

Cellular Base Station – Trends

Cellular Base Stations – Driving Factors (1)

Global Mobile Data Traffic Growth Trends



Source: Cisco VNI Global Mobile Data Traffic Forecast,

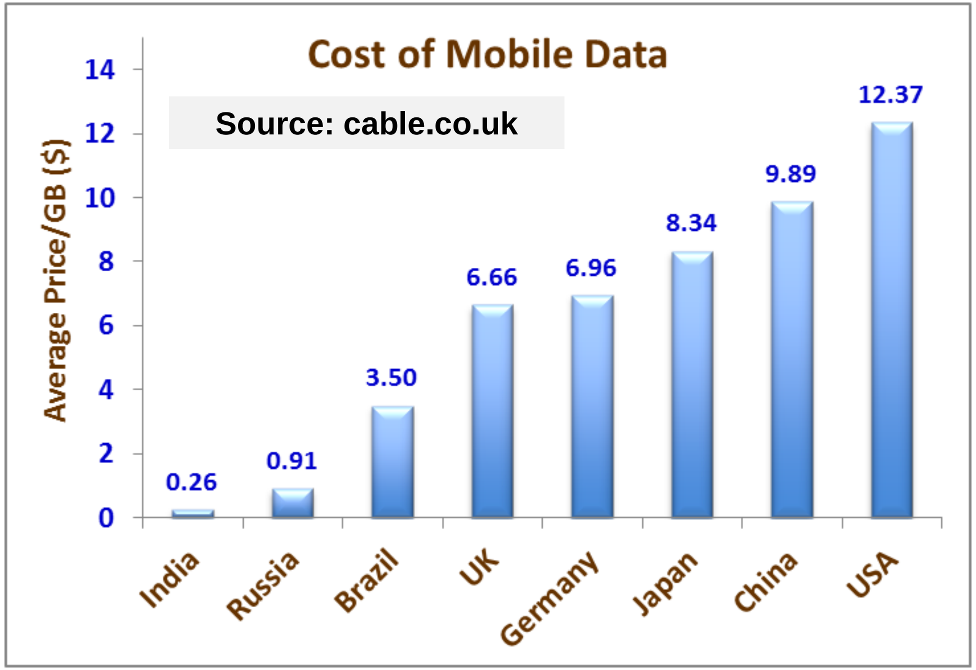
How to increase Channel Capacity?

- ↑ **Standards Evolution: 4G ⇒ 5G**
- ↑ **Bandwidth: 20 to 60 MHz ⇒ 200 to 800 MHz**
- ↑ **No. of Bands: Single ⇒ Dual**
- ↑ **No. of Antennas: 2 / 4 ⇒ 32 / 64**

$$\text{Capacity} = \text{BW}*\log_2(1+\text{SNR})$$

5G base stations achieve 5X – 8X higher channel capacity by using massive MIMO (64T64R)

Cellular Base Stations – Driving Factors (2)



Source: cable.co.uk

How to achieve lower cost/bit?

- **↑ Channel capacity**
- **↓ Cost per channel (or antenna)**
- **↓ Form Factor**
- **↓ Power per channel**

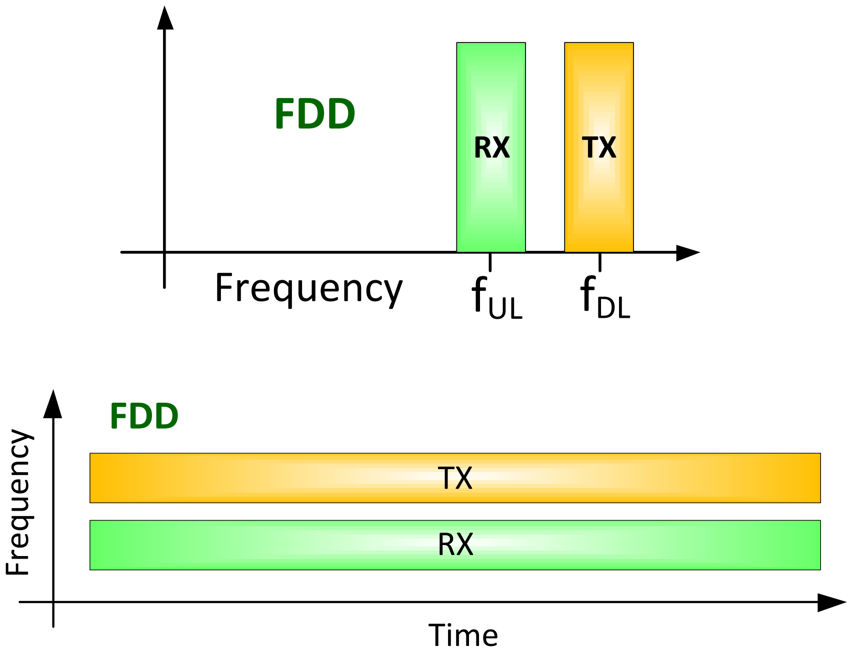
A base station is not battery operated. Hence, does its power consumption matter?

Need innovations in transceiver design to reduce cost & power consumption, while supporting wider bandwidth and maintaining the high performance

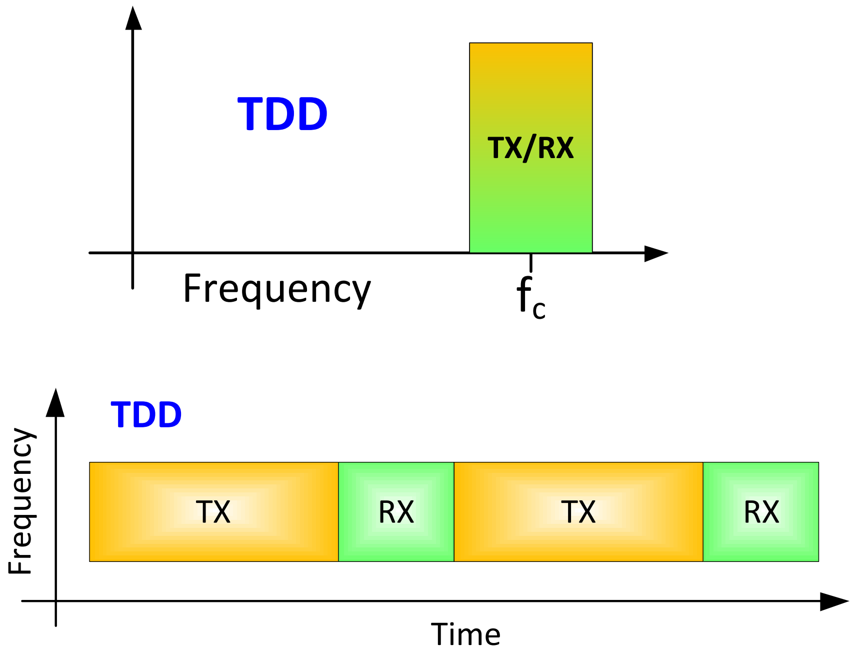
5G Cellular Base Stations – Overview

Cellular Base Station – Spectrum Usage

FDD – Frequency Division Duplex



TDD – Time Division Duplex



- **What happens when there is asymmetry between volume of uplink (UL) & downlink (DL) data?**

5G – Frequency Band Allocation

- **Initial 5G deployment is focused on sub-6 GHz frequency bands**
  - **3.3 GHz to 3.8 GHz are the more popular frequency bands, although 2.5 to 2.7 GHz & 4.4 to 5 GHz bands have also been allocated in some countries**
  - **Spectrum auction has been completed in many countries (China, South Korea, Japan, Germany, United Kingdom, Italy, Switzerland, etc.)**
- **mmWave (28 GHz) currently limited to fixed wireless access (e.g., Verizon, USA)**

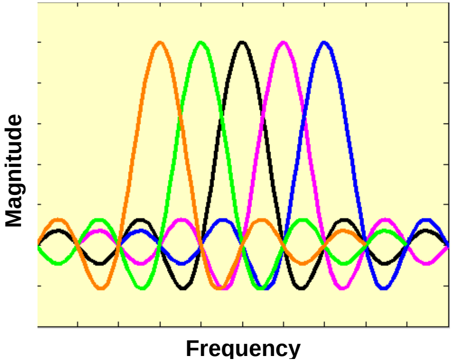
Service Provider	Spectrum (GHz)	Service Provider	Spectrum (GHz)
China Mobile	2.52 – 2.68 & 4.8 – 4.9	South Korea Telecom	3.6 – 3.8
China Telecom & Unicom	3.4 – 3.5 & 3.5 – 3.6	Korea Telecom	3.5 – 3.6 & 3.8 – 3.9
India (5G auction pending)	3.3 – 3.6	Europe	3.42 – 3.8
NTT Docomo, Japan	3.6 – 3.7 & 4.5 – 4.6	KDDI, Japan	3.7 – 3.8 & 4.0 – 4.1

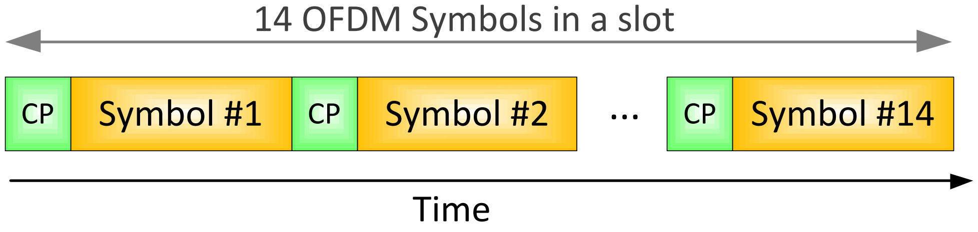
Integrated transceivers need to cater to a wide variety of frequency bands & signal BW

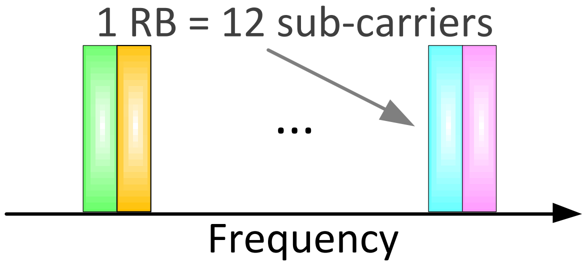
For the same transmit power, is cell coverage area similar for sub-6 GHz & mmWave bands?

Cellular Base Station – 5G Signal Structure

- Orthogonal Frequency Domain Multiplexing (OFDM) with Cyclic Prefix (CP) is used.
  - Signal band is partitioned in to sub-carriers in the frequency domain.
  - For instance, sub-carrier spacing can be 15 KHz / 30 KHz / … / 240 KHz.
  - A slot, typically has 14 OFDM symbols (slot duration of 1 ms / 500 µs / … / 62.5 µs).
  - A slot can be all DL, UL or mixed (combination of DL / UL)
- Users are allocated different physical resource blocks (RB)
  - Each RB is a group of contiguous 12 sub-carriers

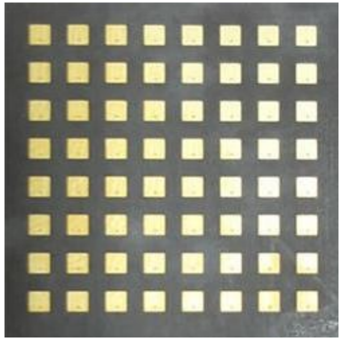




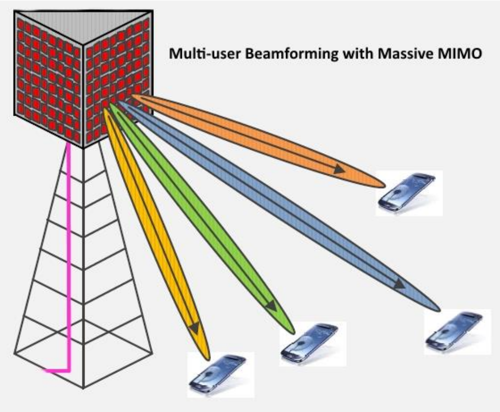


Massive MIMO – Introduction

- 5G uses massive # of base station antennas (e.g., 64 for sub-6 GHz; 256 for mmWave)
- Fully digital beamforming is employed in sub-6 GHz 5G bands
  - 3D beamforming improves SINR (Signal to Interference-&-noise ratio) of each user
  - Multi-user MIMO enables same time/freq. resource to be allocated to spatially separated users
  - Spatial multiplexing enables increase in data throughput
- Hybrid (mostly-analog) beamforming is employed in mmWave 5G bands



mmWave Antenna Array

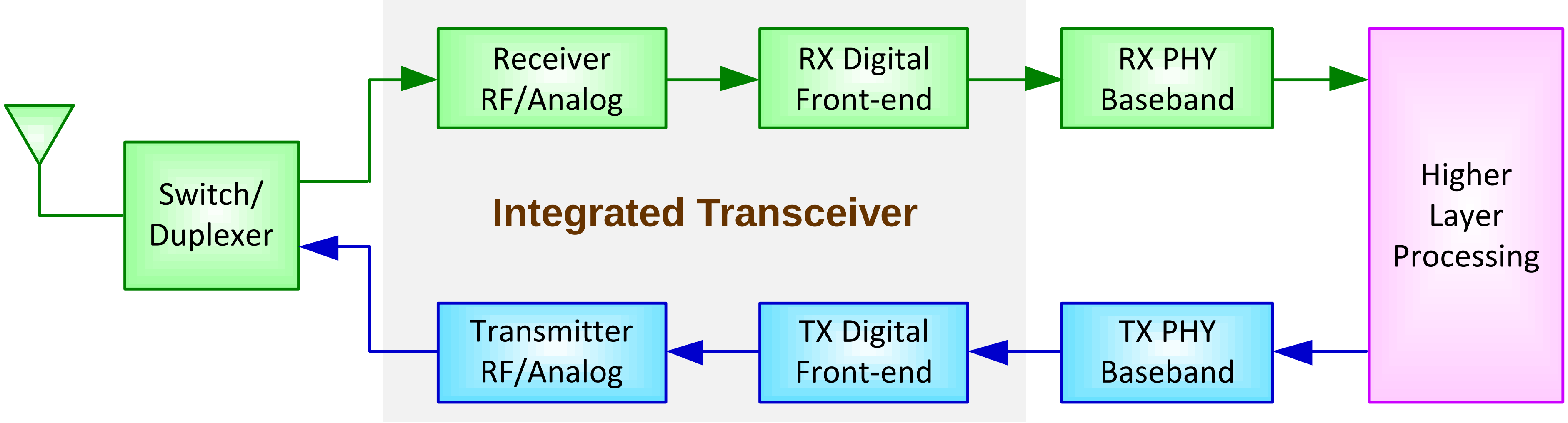


$$\underline{r}_{NR \times 1} = C_{NR \times NT} * \underline{s}_{NT \times 1}$$

Is independent beam steering of RBs (different frequency bins) possible with analog beamforming?

Cellular Base Station – Integrated Transceiver

Cellular Base Station – Signal Chain Architecture (1)

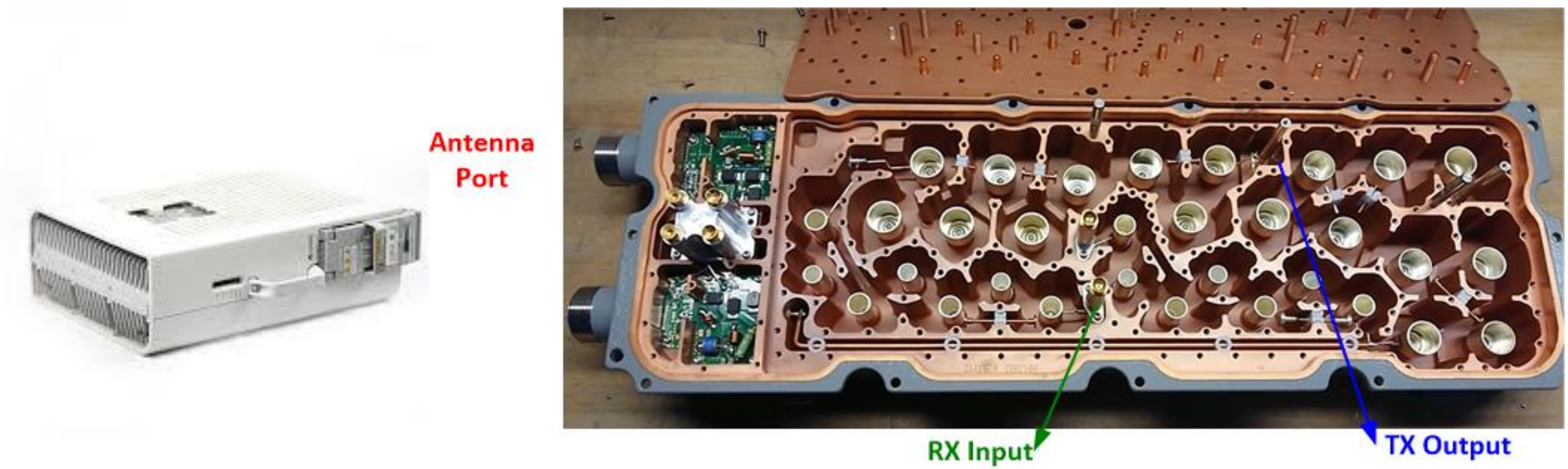


- **How many TX/RX channels should a single “integrated transceiver” chip support?**
  - **Need to consider Signal routing on board, Scalability and Power consumption**

Transceiver design needs to handle various non-idealities

Thermal Noise	**PLL Phase Noise**	**Flicker Noise**
Amplifier Non-linearity	**IQ Mismatch & LO Leakage**	**ADC Quantization**

Cellular Base Station – FDD Example

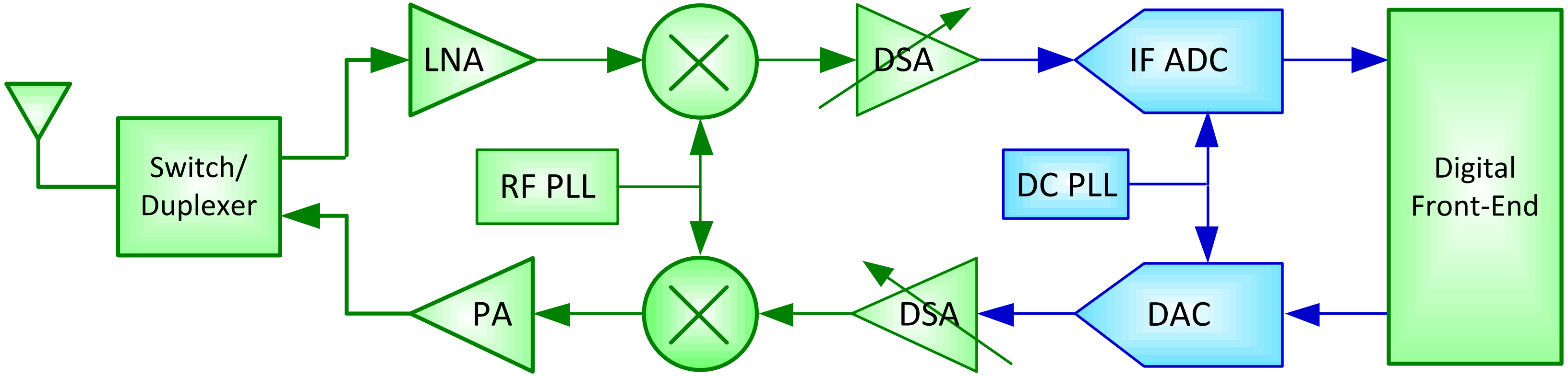


Metal Cavity Duplexer in an FDD base station (Huawei, 1.8 GHz band) with 2 antennas

Source: Kaizer Power Electronics

Base Station – Integrated Transceiver Architecture

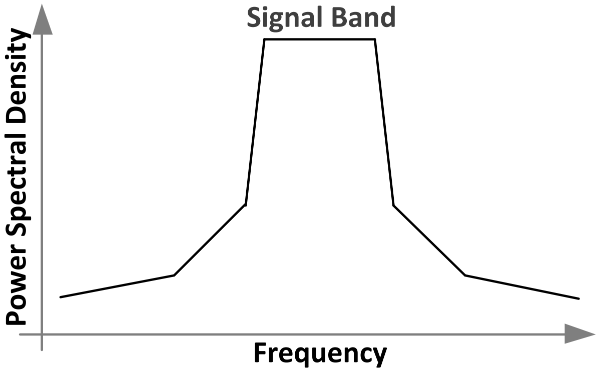
- **Receiver**
  - **Desired Signal is down-converted from the pass-band using RF mixers**
  - **Down-converted analog base-band signal is sampled using ADCs**
- **Transmitter**
  - **Sampled signal is converted to continuous time domain using DACs**
  - **Analog baseband signal is up-converted to its pass-band using RF mixers**



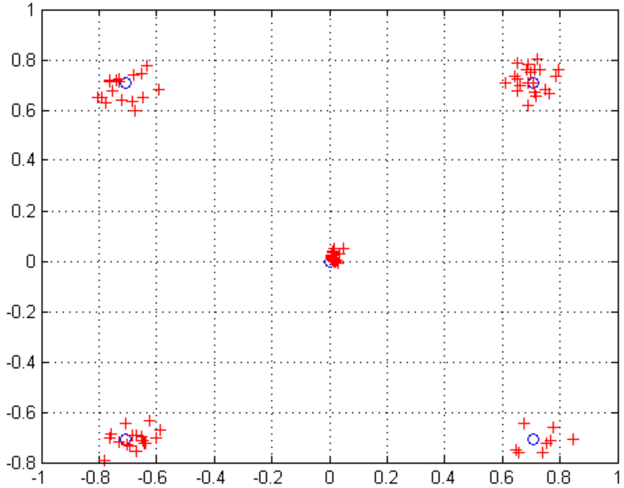
Cellular Base Stations – Key Transmitter Parameters

- **Transmitter needs to comply with spectral emission mask.**
  - **Steep drop in emissions required in adjacent bands.**
  - **ACLR (Adjacent channel Leakage ratio) is a key parameter.**
  - $\Rightarrow$ **In FDD system, TX emissions in to the UL band would limit base station performance.**
- **TX EVM (Error Vector Magnitude)**
  - **Measure of deviation in the transmitted signal from the ideal “symbol constellation”.**
  - **EVM** $= \|x(n) - s(n)\|^2 / \|s(n)\|^2$
  - **TX EVM reduces the noise margin available at the receiver $\Rightarrow$ Limits the largest symbol constellation that can be used.**

Would there be any additional care-about on TX emissions for FDD?

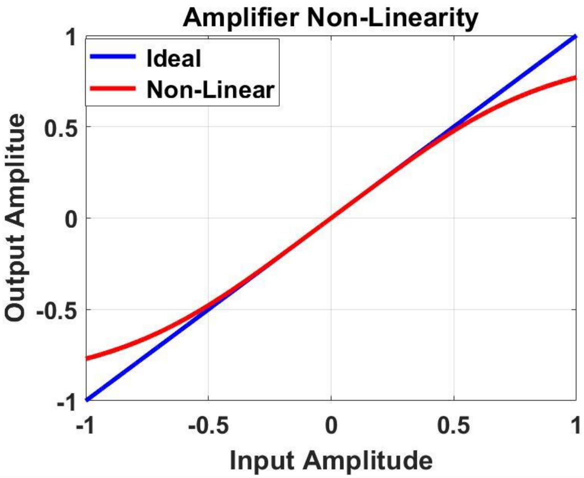


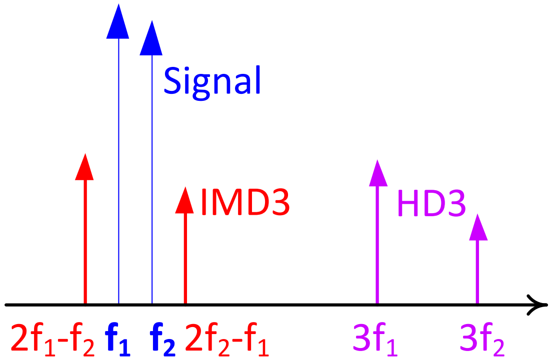
Sample TX Emission Mask



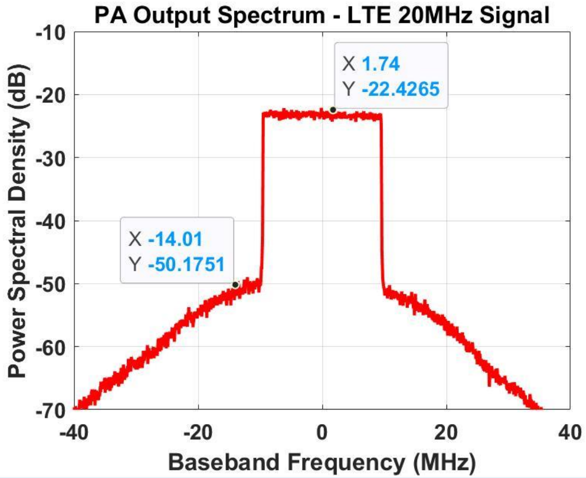
Transmit Power Amplifier Non-linearity

- **Transmit PA (power amplifier) is highly non-linear.**
  - **⇒ Creates harmonic distortion (HD) and inter-modulation (IMD) spectral components.**
  - **⇒ Would degrade ACLR, resulting in violation of TX emission mask specification.**
  - **– Signal power can be backed-off to operate in the linear region ⇒ Loss in power efficiency.**
- **The PA non-linearity can be compensated by pre-distorting the transmit signal.**





3^{rd} Order Non-linearity

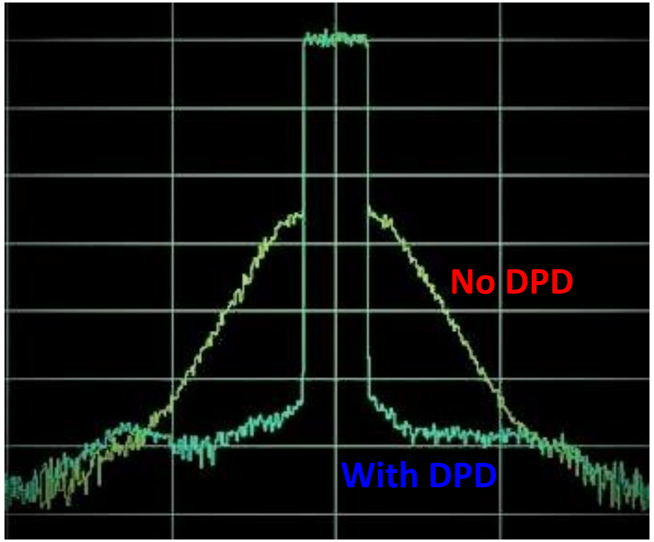


What happens to the output spectrum, if PA non-linearity is of the form : $f(x) = x - \propto x^3$?

Transmit Power Amplifier – Digital Pre Distortion (DPD)

- **Non-linearity can be estimated, if the signal at the PA output is observable, by comparing it against the desired transmit signal.**
  - **Once the non-linearity is estimated, it can be pre-compensated in digital ⇒ Referred to as DPD**
  - **Fairly complex problem, as PA's are highly non-linear and experience memory artifacts.**
- **A Feedback (FB) Receiver (also known as auxiliary receiver) chain can be used to observe the "non-linear" PA output signal.**
  - **Need to observe a wider BW than that of the inherent signal (anywhere from 3X to 5X) ⇒ FB cannot be same as RX**

PA Output Spectrum – LTE 20MHz SIgnal

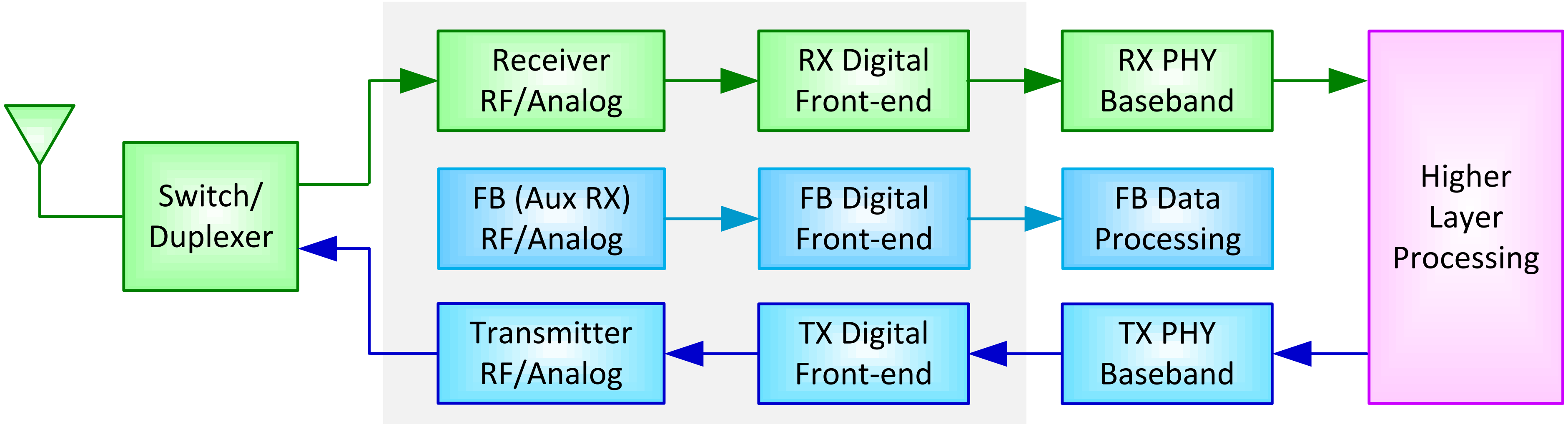


PA Output Spectrum without DPD and, with DPD enabled

Courtesy: Goutham Ramesh & Jawaharlal Tangudu

What bandwidth should the Feedback receiver have to support, assuming signal has a BW of X?

Cellular Base Station – Signal Chain Architecture (2)



Feedback (FB) or Auxiliary Receiver chain is used to monitor the "on-air" transmit signal, estimate its characteristics and compensate for non-idealities in the TX.

- **How many FB receivers are needed in an integrated transceiver with 4 transmit channels?**
  - **Less than 4, as FB receiver can be time-multiplexed across TX channels.**

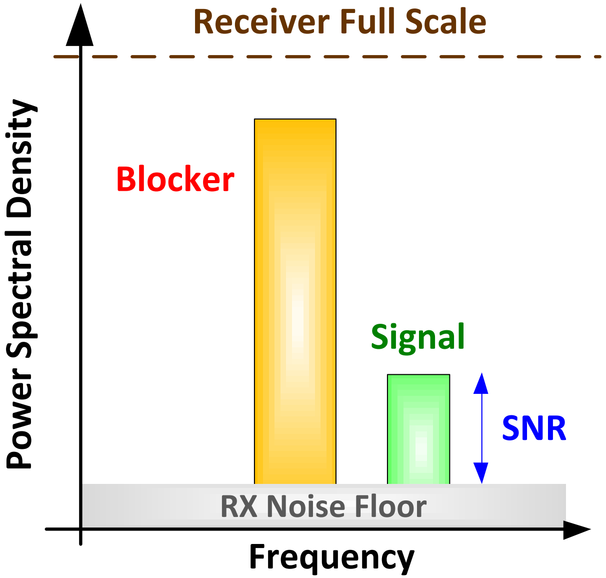
Cellular Base Stations – Key Receiver Parameters

- **Receiver Sensitivity**
  - Indicates the lowest power signal that can be successfully demodulated and decoded at the receiver.

  ⇒ Determines the UL cell coverage.
- **Blocker tolerance**
  - Indicates the highest level of out-of-band interferer that can be tolerated at the receiver.

  ⇒ Determines the attenuation spec for the external filters ⇒ Direct impact on cost.

  ⇒ In FDD system, TX signal is always present and would be the strongest blocker.



Would there be any additional care-about on blockers for FDD?

What performance aspect would non-linearity in RX chain impact?

Integrated Transceiver Non-Idealities (1)

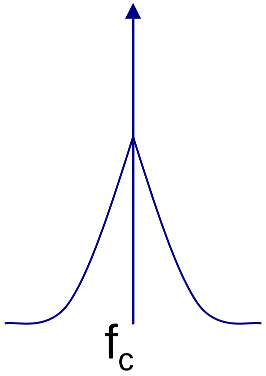
- **Phase Noise**
  - **Ideal down-conversion involves mixing with a sinusoid.**
  - **In practice, this operation is far from ideal.**
  - $y(t) = r(t) * exp\{j2\pi f_c t + j\theta(t)\}$

  $\Rightarrow$ **Impacts TX EVM, TX Emission mask & RX blocker tolerance.**
- **Sampling Jitter**
  - **Sampling instances of the data converters (DAC & ADC) would be non-uniform.**
  - $r(n) = r(t)|_{t=nT+\tau(n)} = r_{unif}(n) + \tau(n) * r'(t)|_{t=nT}$

  $\Rightarrow$ **Impacts TX EVM, TX Emission mask & RX blocker tolerance.**

- **What system parameters would phase noise impact?**

- **What attribute of the input signal, does the relative magnitude of sampling jitter depend on?**



PLL Phase Noise – PSD

Integrated Transceiver Non-Idealities (2)

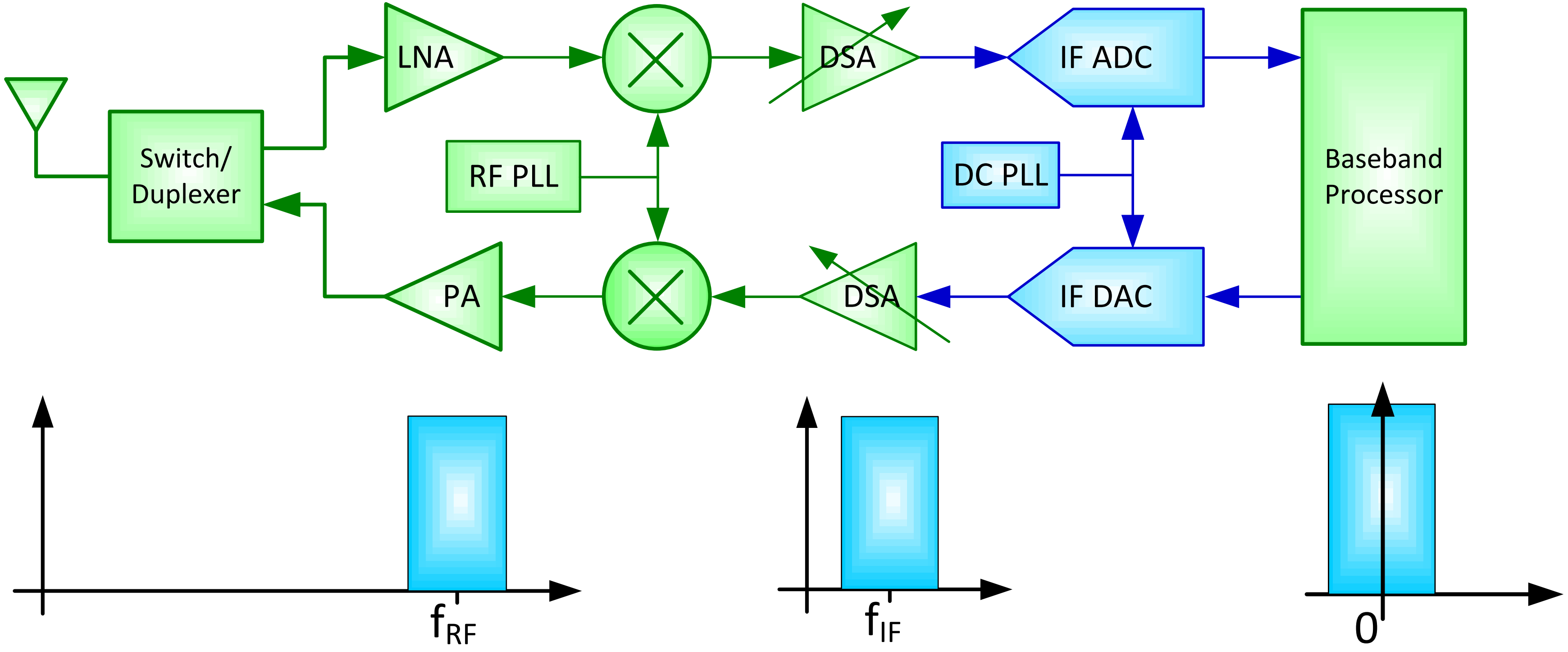
- **TX LO Leakage**
  - **The carrier used in the RF mixer can leak-through to the Transmit output.**
  - ⇒ **Impacts TX emission mask & TX EVM.**
- **Flicker Noise**
  - **Low frequency noise with a PSD inversely proportional to frequency (1/f)**
- **ADC Quantization Noise**
  - **Additional contributor to RX noise floor.**
  - $\mathrm{ADC\ SQNR} = 6.02 * Nbits + 10 * \log_{10}(3)$
  - ⇒ **ADC over-sampling factor improves the PSD of the quantization noise floor**
  - **Quantization noise can be shaped, if the desired BW is much smaller than the Nyquist BW ⇒ Fewer ADC bits are sufficient.**
  - **Digital decimation filters are used to suppress shaped out-of-band noise**

- **What happens if ADC has an over-sampling factor?**

IF Sampling (Heterodyne) Architecture

Wireless Base Stations – IF Sampling Architecture

- **Desired Signal is down-converted to an intermediate frequency (IF) using RF mixers**
- **IF signal is sampled using wider bandwidth IF data converters**



IF Sampling Architecture – Advantages & Limitations

- **Requires only an in-phase (I) signal chain**
  - **⇒ Potential cost savings**
- **TX LO leakage is far away from signal band and can be filtered out**
  - **⇒ Easy to comply with emission mask**
- **Flicker noise has less impact on TX/RX performance**
  - **⇒ Relaxes analog baseband design**

- **Image band will alias, if it is not filtered out**
  - **⇒ Increases complexity of the external filter**
- **Analog base-band has to process wider BW than that of the signal (BW + 2f$_{IF}$)**
  - **⇒ Increases cost & power consumption**
- **Dual band support need chain duplication**
  - **⇒ Doubling of cost & power consumption**

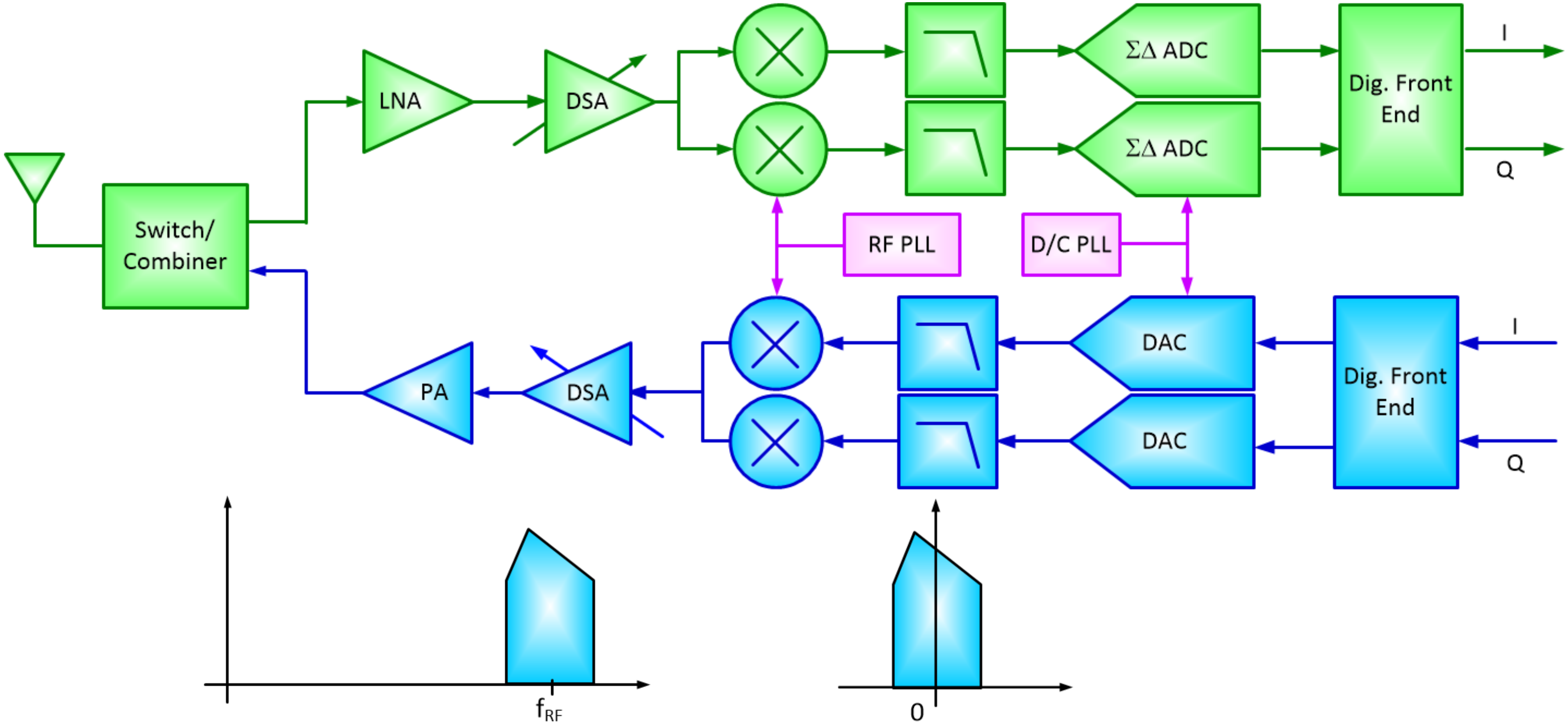
- **What are possible RX mixer frequencies for Band 1 (UL: 1920 – 1980 MHz & DL: 2110 – 2170 MHz), if the desired intermediate frequency (f$_{IF}$) is 100 MHz?**
  - **Is one of them desirable over the other?**

Lately, base station vendors have been moving away from “legacy” IF sampling architecture

Zero-IF Architecture

Zero-IF Architecture

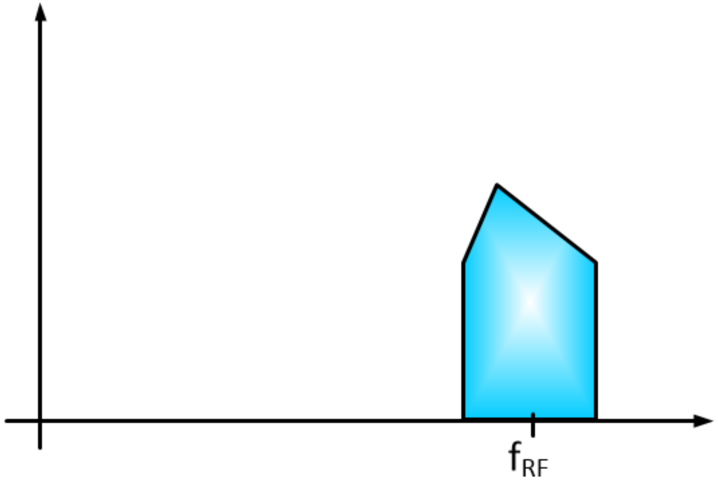
- **The RF signal is down-converted to Zero-IF using Quadrature (sin/cos) RF mixers, followed by base-band ADC I/Q sampling**



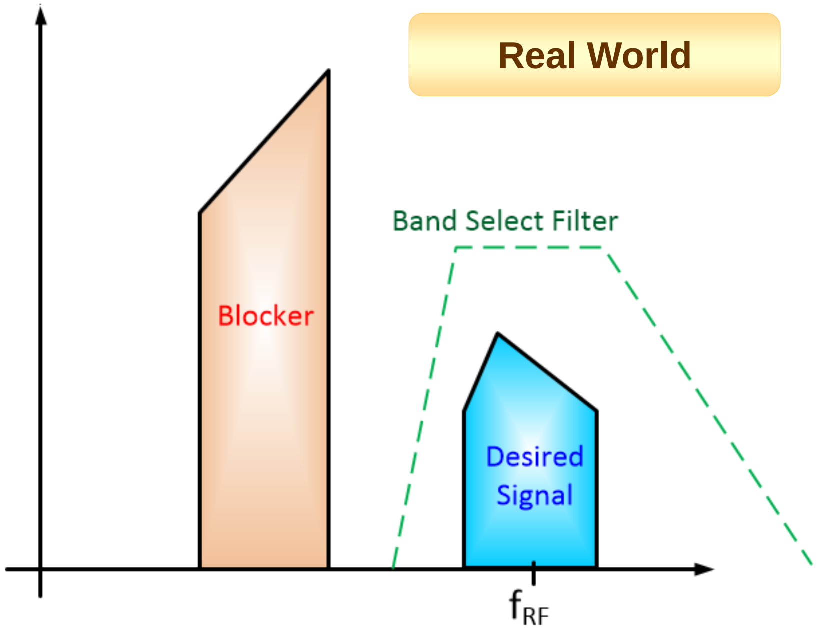
Zero-IF – Advantages over Heterodyne Architecture

- **No image-band filtering needed**
  - **Relaxes RF filter requirements, hence cost.**
- ***Architecturally*, in ZIF, NO input filtering is required … but is that practical?**
  - **Without filtering, there could be front-end saturation due to strong blockers**

Ideal World



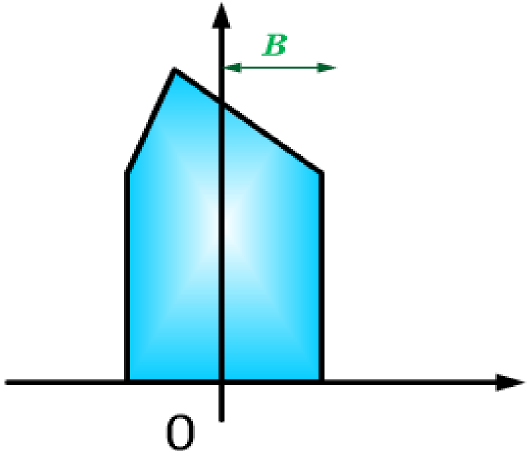
Real World



Zero-IF – Advantages over Heterodyne Architecture

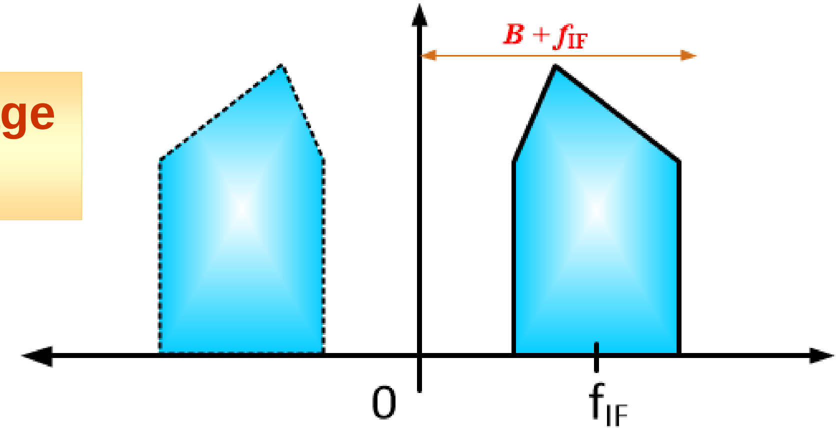
- **Analog base-band needs to process only the signal band**
  - **⇒ Cost savings & Power reduction**
- **I/Q processing actually requires <u>two</u> chains**
  - **– Yet, overall cost/power is lower because of significantly lower bandwidth to be supported**
- **Also easier to integrate DSA within the device**

Zero IF



f_{IF} >> B, to ease image band filtering

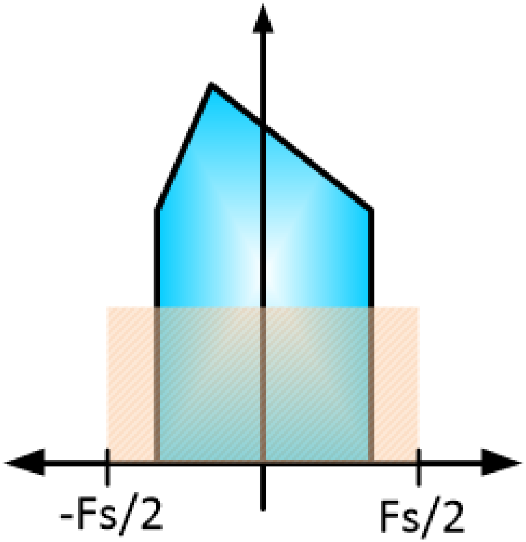
Heterodyne



Zero-IF – Advantages over Heterodyne Architecture

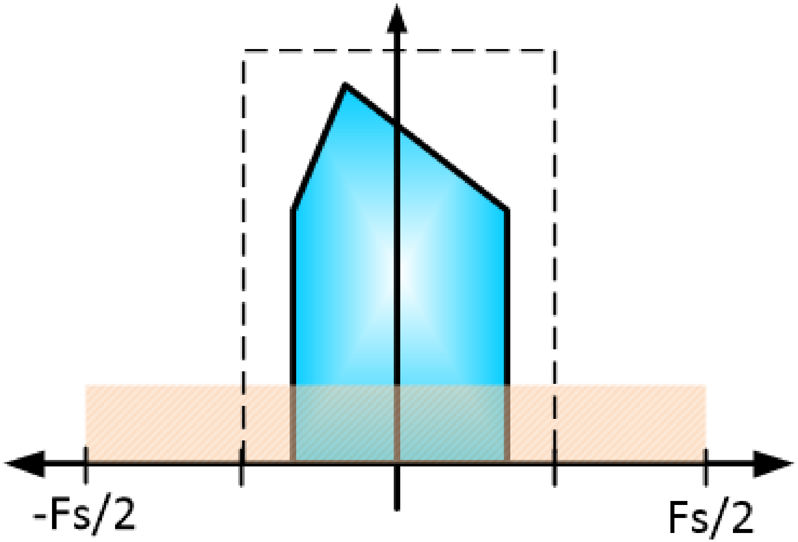
- **ADC need not support wide bandwidth**
  - ⇒ **Enables use of an oversampled ΣΔ ADC architecture**
  - ⇒ **Reduces ADC power consumption, relaxes anti-alias filtering requirement**

Nyquist Sampling



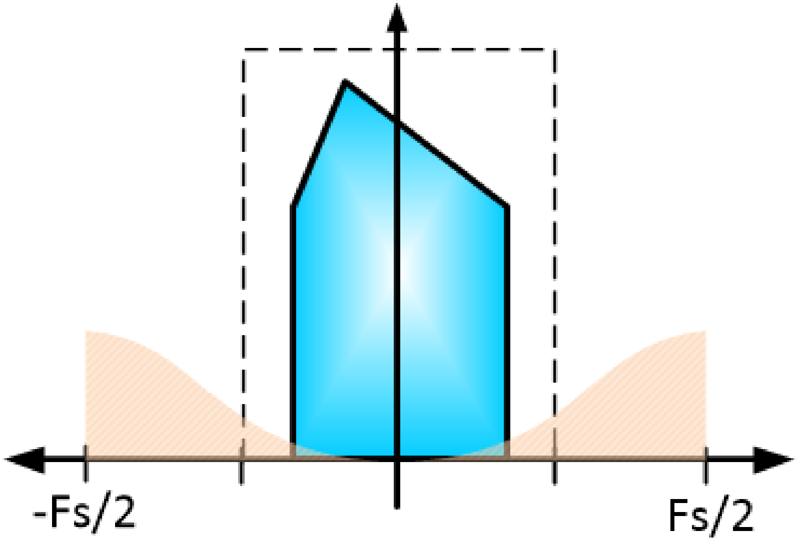
$SQNR \sim (6N + 2)\ dB$

Oversampling



$SQNR_{in} \sim [(6N + 2) + 10log10(OSR)]\ dB$

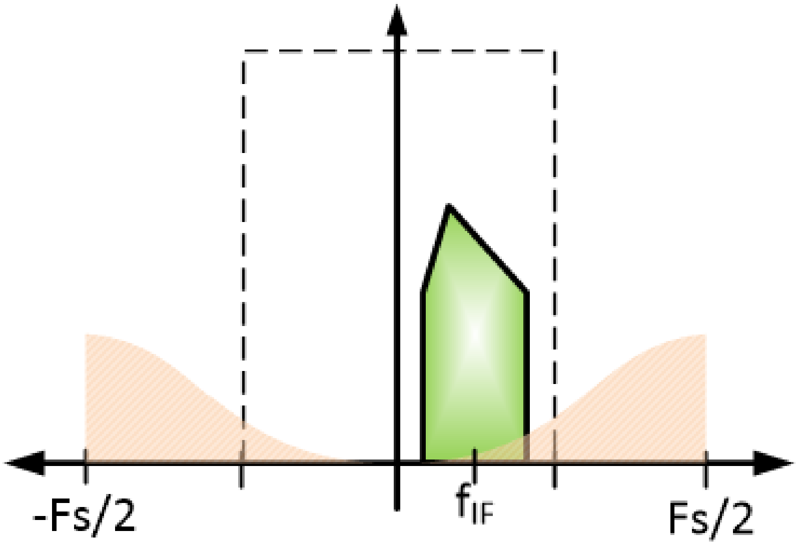
Oversampling + Noise Shaping



$SQNR_{in} \gg [(6N + 2) + 10log10(OSR)]\ dB$

Zero-IF and (complex) Low IF

- **In practice, a ZIF receiver designed for a certain bandwidth might actually get deployed as a complex Low IF receiver for a signal of slightly lower bandwidth**
  - Provides immunity from low-frequency flicker noise and LO-leakage based DC offset



- **Although we focused on the RX, analogous arguments work for the TX**
  - **Zero IF / (complex) Low IF is an efficient choice for single-band systems**

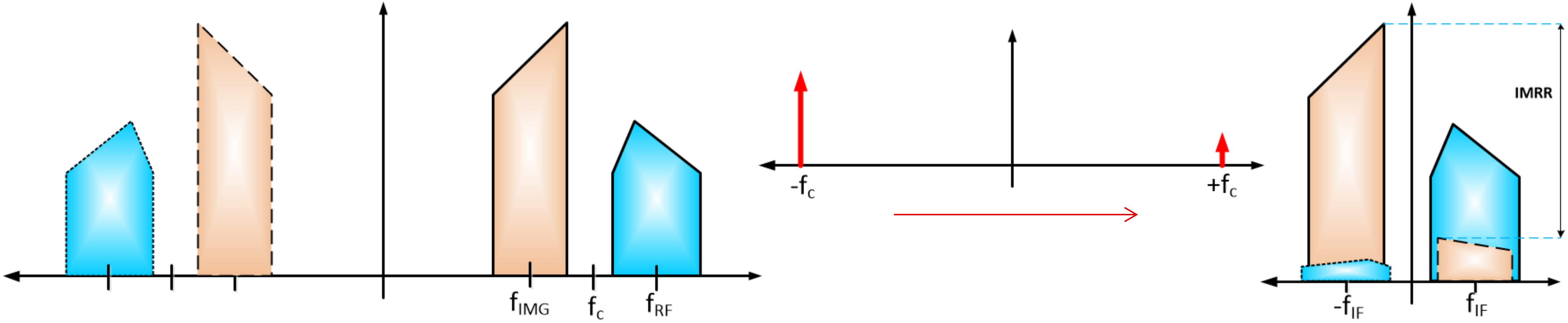
Zero IF / (complex) Low IF Challenges – RX IQ Mismatch

- **Gain/phase mismatch between the I & Q chains is referred to as IQ Mismatch (IQMM)**
  - **I/Q signals are not separated by 90 degrees & experience different gains.**

LO without IQ Mismatch $\cos\omega_c t \ - j\sin\omega_c t = e^{-j\omega_c t}$

LO with IQ Mismatch $\alpha\cos(\omega_c t) \ - j\sin(\omega_c t - \theta) = \left(\frac{\alpha + e^{-j\theta}}{2}\right) e^{-j\omega_c t} + \left(\frac{\alpha - e^{+j\theta}}{2}\right) e^{j\omega_c t}$

$\Rightarrow$ Causes mixing of positive/negative frequency components in base-band



Zero IF / (complex) Low IF Challenges – RX IQ Mismatch

- **The time-domain interpretation of IQMM is a matrix transformation of I and Q signals**

$$\begin{bmatrix} z_I \\ z_Q \end{bmatrix} = M \begin{bmatrix} y_I \\ y_Q \end{bmatrix} = \begin{bmatrix} \alpha & 0 \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} y_I \\ y_Q \end{bmatrix}$$

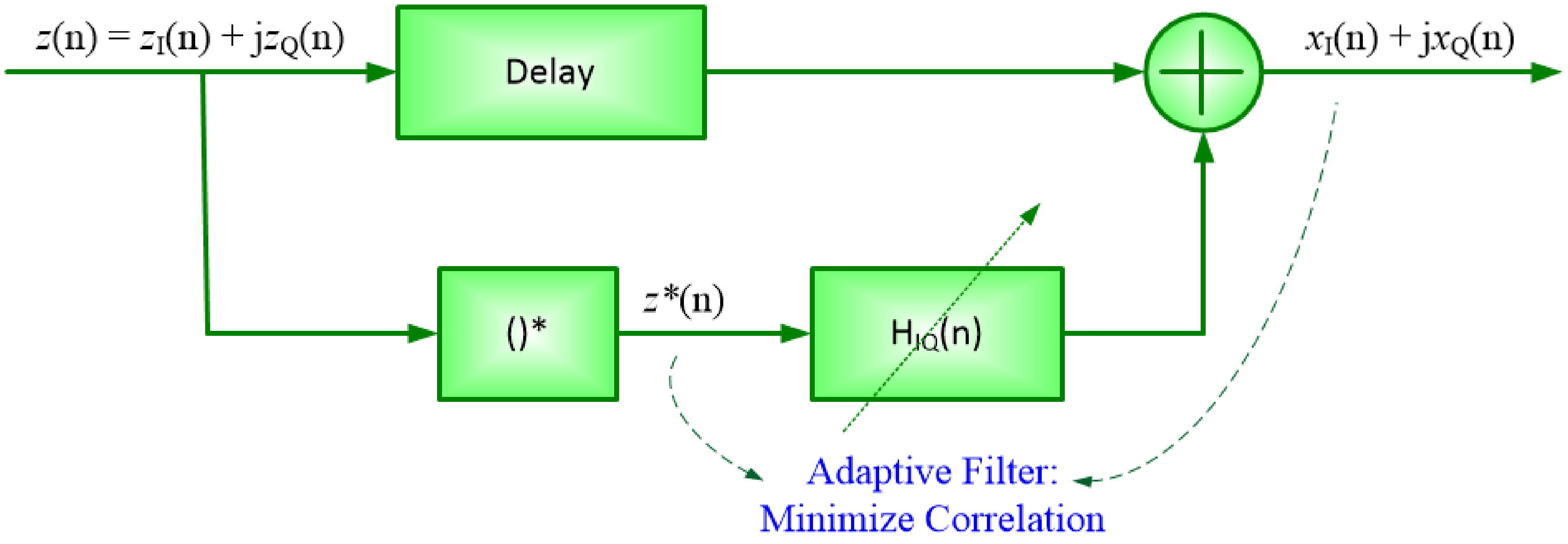
- **Assuming received I and Q signals are uncorrelated and of equal power, estimation can be done using self and cross correlations. Correction is with M^{-1}**

$$\hat{\alpha} = \sqrt{\frac{R_{II}}{R_{QQ}}} = \sqrt{\frac{E(|z_I(n)|^2)}{E(\left|z_Q(n)\right|^2)}} \qquad \hat{\theta} = \arcsin\left(\frac{R_{IQ}}{\hat{\alpha} R_{QQ}}\right) = \sqrt{\frac{E(z_I(n) z_Q(n))}{E(\left|z_Q(n)\right|^2)}}$$

- **Such approaches yield an IMRR (image rejection ratio) of ~40 dB; useful (e.g.) in WLAN RX**
- **70 dB performance required in base station transceivers. A key challenge is to estimate and correct a frequency dependent gain/phase mismatch between the I & Q chains**

Zero IF / (complex) Low IF Challenges – RX IQ Mismatch

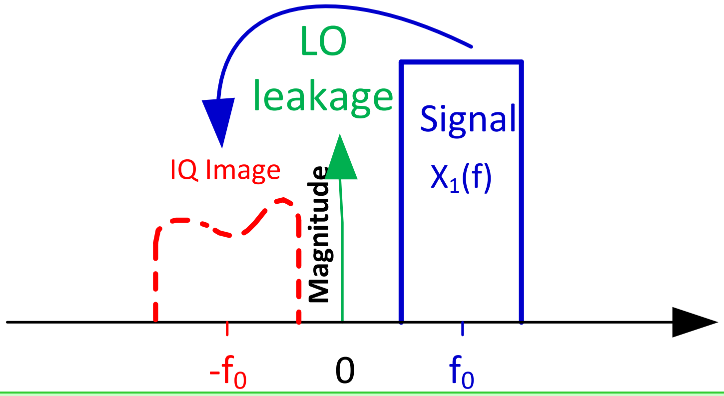
- **Core structure for IQMM estimation / correction is shown below, uses an adaptive filter**
- **Need to track time / temperature variations**
  - Has to be a blind algorithm running in the background

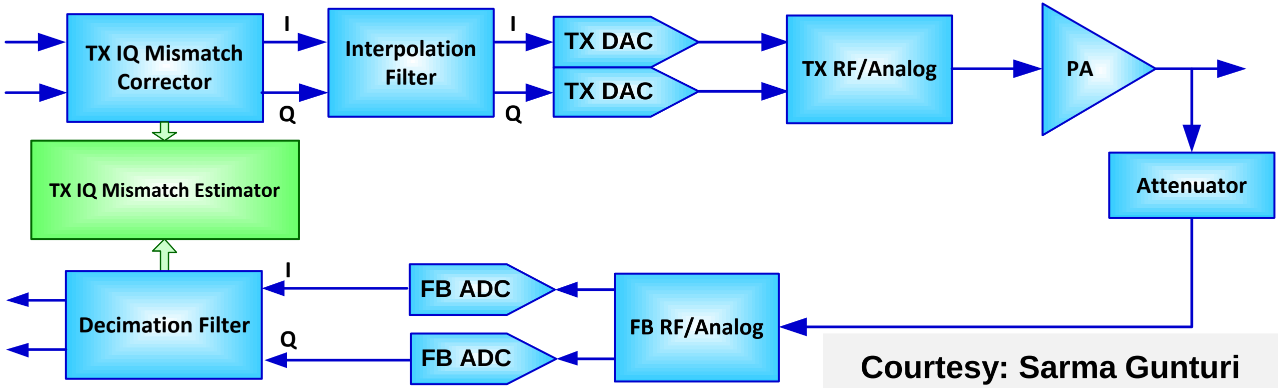


Zero IF / (complex) Low IF Challenges – TX IQ Mismatch

- **Frequency selective gain/phase mismatch between the I & Q chains in TX as well**

  ⇒ **Transceiver algorithms need to work alongside Modem Algorithms (e.g., Tx Digital Pre Distortion)**





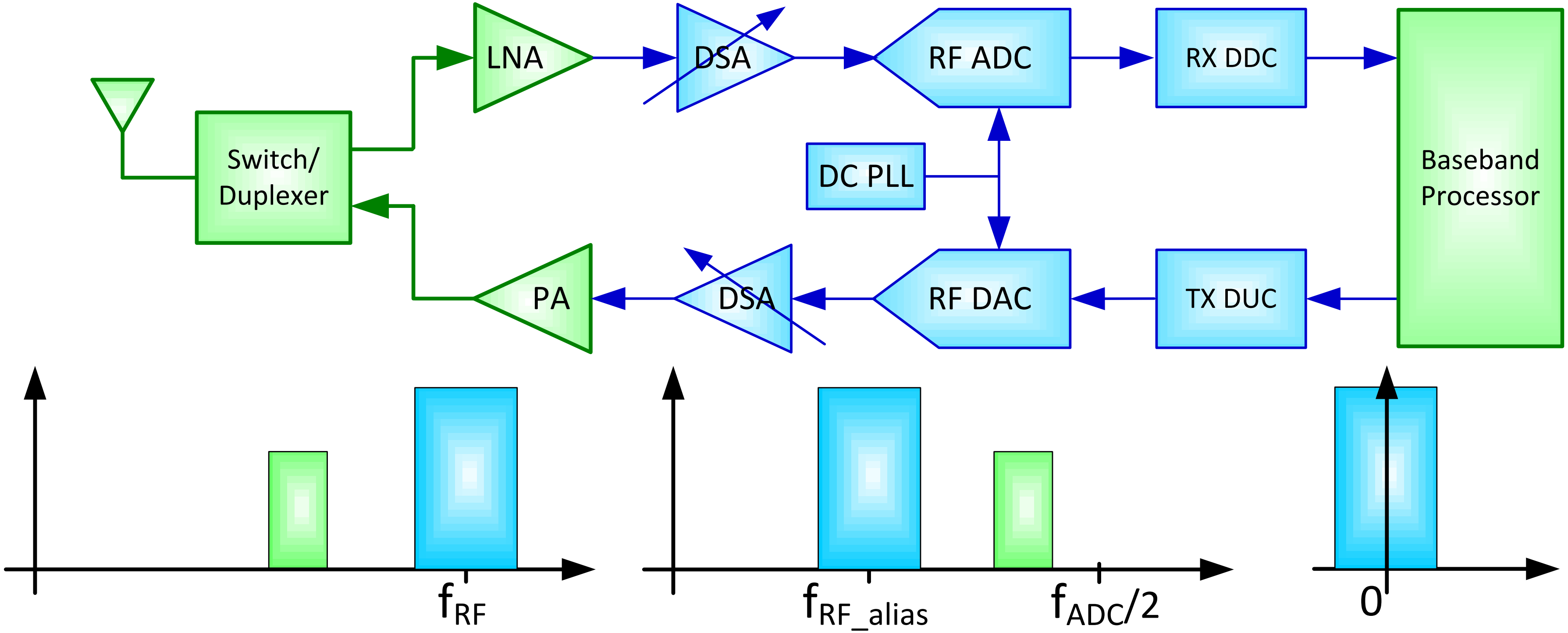
Courtesy: Sarma Gunturi

- **Need signal processing algorithms to estimate/compensate for the I/Q imbalance**
  - **Need to estimate gain and phase to an accuracy of 0.1% & 0.05 degree, respectively**
  - **TX IQ mismatch is estimated by looping back TX RF signal through the FB receiver**
    - **Unknown loop-back channel and FB receivers own IQMM have to be accounted for!**
  - **TX LO leakage should be corrected to be better than -80dB lower than full scale DAC signal**
  - **Should be robust across all real-life dynamic operating scenarios**

RF Sampling Architecture

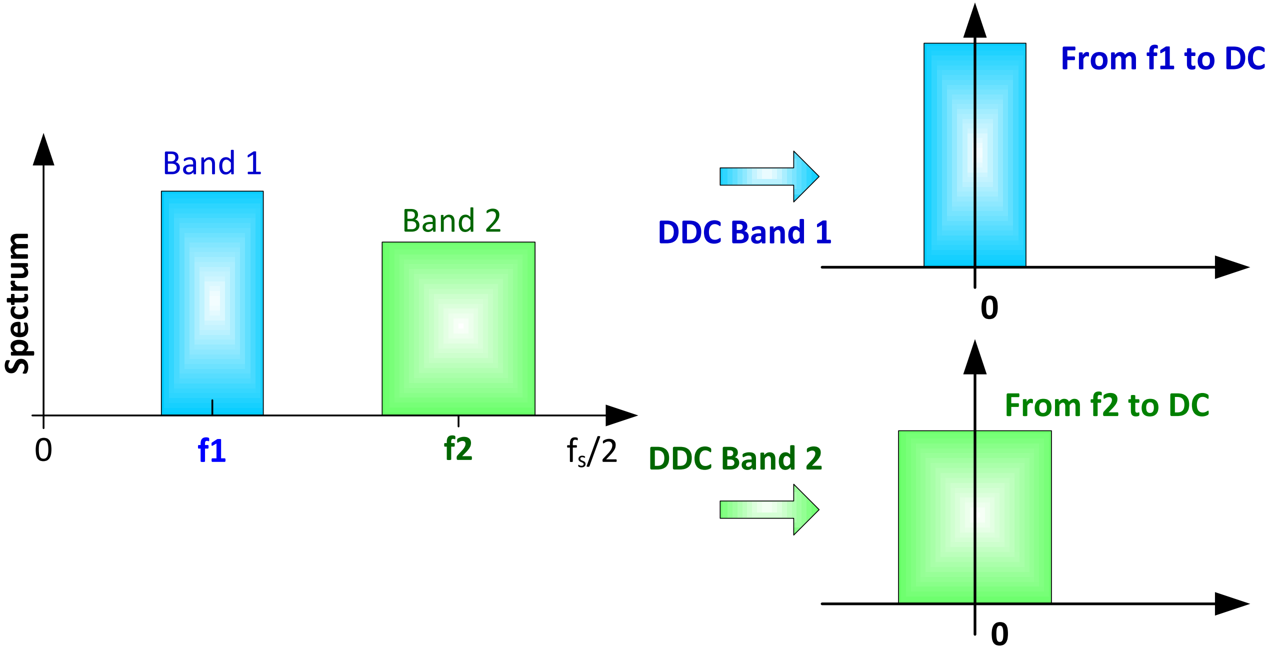
RF Sampling Architecture

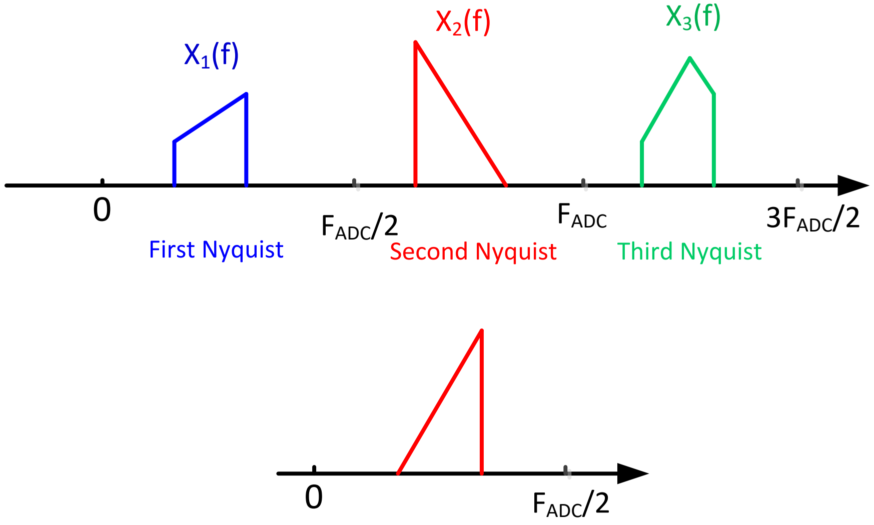
- **The RF signal is directly sampled using Giga-sample ADC/DACs**
- **The frequency up-conversion & frequency down-conversion is implemented in digital using Digital Up Converter (DUC) & Digital Down Converter (DDC).**



RF Sampling Architecture – Multi Band Support

- **Single RF/Analog supports Dual band by duplicating the DUC/DDC**
- **Wideband RF/Analog supports signals in multiple Nyquist frequency range (1st, 2nd, 3rd etc.)**
  - **Signal in even Nyquist will be spectrally flipped.**





RF Sampling Architecture – Advantages & Challenges

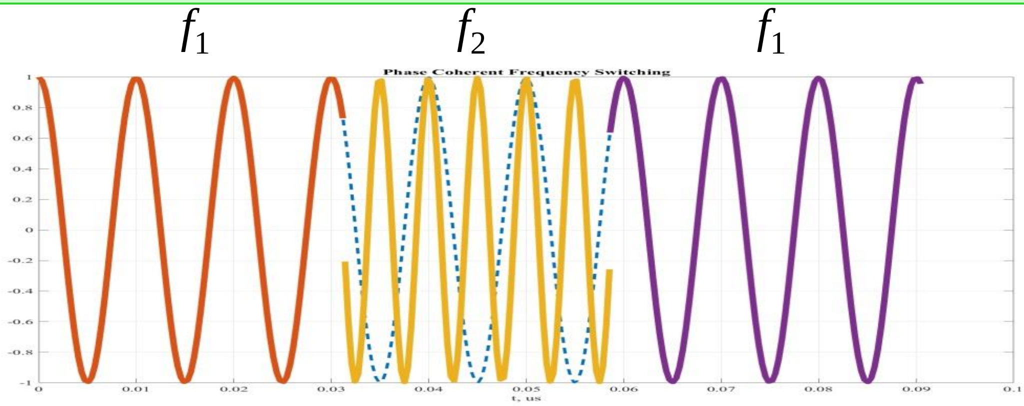
- Eliminates the need for RF Mixers/PLL
  - ⇒ Cost savings in RF
- Eliminates IQ mismatch & TX LO leakage
  - ⇒ Easy to comply with emission mask
  - ⇒ Avoids signal processing calibration algorithms
- Wider signal BW enabled by multi-GSPS DAC/ADCs
  - ⇒ Easy to support 800 MHz BW
- Dual band support with single RF/analog transceiver chain. Only DUC/DDC needs to be duplicated
  - ⇒ Relaxes analog baseband design

- DSA and data-converters need to process the entire RF bandwidth
  - ⇒ How can these be designed to minimize increase in cost & power consumption?
- Digital front-end needs to process multi-GSPS rate signals
  - ⇒ How can this be achieved with controlled increase in digital complexity

TI pioneered RF Sampling architectures for latest generation of wireless base stations

TDD and Phase Coherence

- **Wireless base station transceivers need to support phase coherence in the LOs**
  - ⇒ **Across TDD epochs (for coherent signal processing)**
  - ⇒ **Across frequency switching epochs (if applicable, for calibrations)**
- **Phase-coherence: If an LO / NCO switches from f1 to f2 and then back to f1, the LO waveform phase after switch-back to f1 should be identical to what it would have been without a switch.**

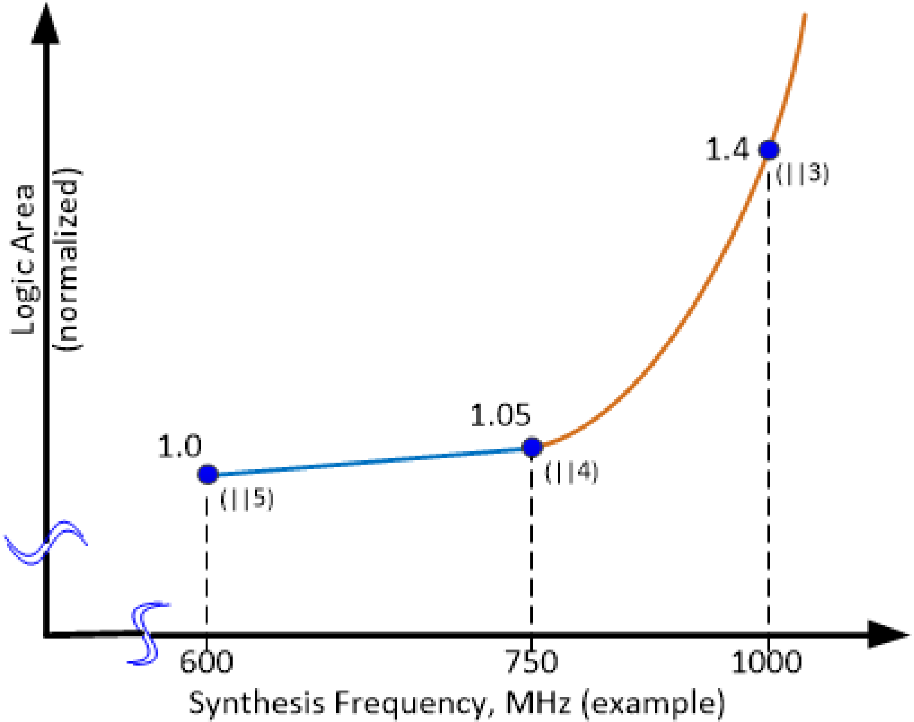


- **Phase coherence is easy to ensure in digital mixers using NCOs (How?)**
  - ⇒ **Possible not just for TDD coherence, but also across actual frequency switches (How?)**
- **What about ZIF?**

RF Sampling Architecture – Challenges

- **High speed digital signal processing at multi-GSPS rates is needed**
- **Typically requires parallelized implementation. Multiple trade-offs exist.**
- **If we need to run some logic at 3 GSPS, we could consider many synthesis frequency and parallelization options:**
  - **⇒ ||5 @ 600 MHz**
  - **⇒ ||4 @ 750 MHz**
  - **⇒ ||3 @ 1000 MHz**
- **What are the trade-offs and what is the sweet spot?**

- **In a given technology node, the area of a typical digital block/module shows the following trend with synth frequency.**

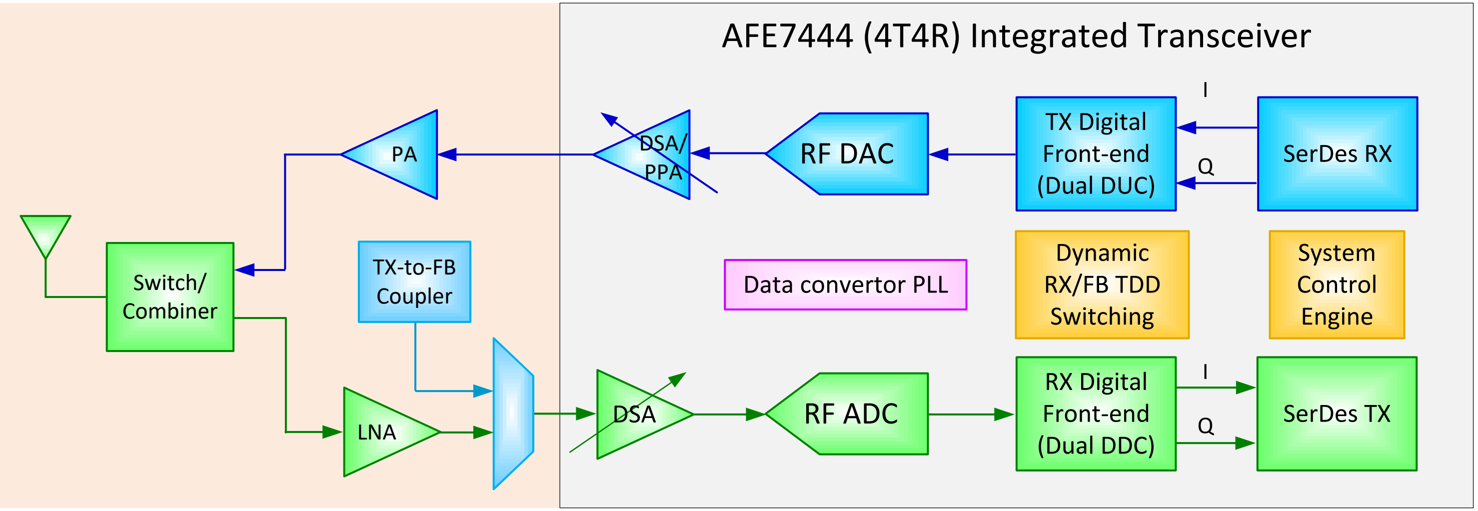


RF Sampling Architecture – Challenges

Synthesis Frequency (MHz)	Area per instance (norm. units)	Parallelization	Net Area (norm. units)	Power (norm. units)
600	1	5	5	3
750	1.05	4	4.2	3.15
1000	1.4	3	4.2	4.2

- **The "knee" of the area vs. frequency curve usually turns out have the best balance between area and power**
- **Even with a given parallelization, many architecture and/or micro-architecture options are possible to "push out the knee" .**
- **Lots of scope for research and innovations in this area.**

AFE7444 (4T4R) – RF Sampling Integrated 4G/5G Transceiver



AFE74xx is industry's first RF Sampling Transceiver targeted for wireless base-stations

- **RF Sampling architecture with 4 TX & 4 RX Channels**
  - **RF sampling with 3 GSPS 14-bit ADC & 9 GSPS 14-bit DAC**
  - **Supports >4 GHz RF frequency range**
  - **Very wide Signal Bandwidth Support of >1 GHz**
  - **Integrated wide-band RF digital step attenuator (DSA)**
  - **Dual-band Digital Up-Converters (DUC) & Down-Converters (DDC)**
  - **Internal AGC to optimally control integrated DSA**
  - **In-built PA Protection feature for the Transmit Channels**

- **Re-use of receiver chain between RX & Feedback channels through phase-coherent dynamic switching**
  - **Optimizes system cost by ~15% for TDD base stations**
- **Fast phase-coherent digital frequency hopping**
- **Industry's highest performance with the lowest power consumption (~50% lower for dual band)**
  - **RX SNR of >60 dBFS over 1.5 GHz bandwidth**
  - **TX output power of >4 dBm**

AFE7444 RF Sampling Transceiver – Product Summary

This product has been commercially deployed by all tier-1 wireless base station vendors in multiple 4G dual-band macro, massive MIMO 5G and mm-wave 5G base stations, around the world

http://www.ti.com/product/AFE7444

Product Comparison	**TI AFE76xx / AFE74xx**	**Legacy Products**
Architecture	RF Sampling	Zero-IF
No. of Channels	4T4R	2T2R1F
No. of Bands	Dual	Single
Supported TX/FB Bandwidth	~1 GHz	~400 MHz
Supported RX Bandwidth	~1 GHz	~200 MHz
Dynamic RX/FB Switching	Yes	No

With AFE74xx, TI has driven customer adoption of the RF sampling technology for Wireless Base Stations
⇒ Enables wide-band support, smaller form factor, enhanced performance and low power consumption