Multi-user Communications

Agenda

- Multiple-Access Technique
- Capacity of Multiple Access
- Random Access Methods

Multiple Access Techniques

1. A common communication channel is shared by many users.
   up-link in a satellite communication, a set of terminals →
   a central computer, a mobile cellular system
2. A broadcast network
   down-links in a satellite system, radio and TV broadcast systems
3. Store-and-forward networks
4. Two-way communication systems

-FDMA (Frequency-division Multiple Access)
-TDMA (Time-division Multiple Access)
-CDMA (Code-division Multiple Access):
for burst and low-duty-cycle information transmission

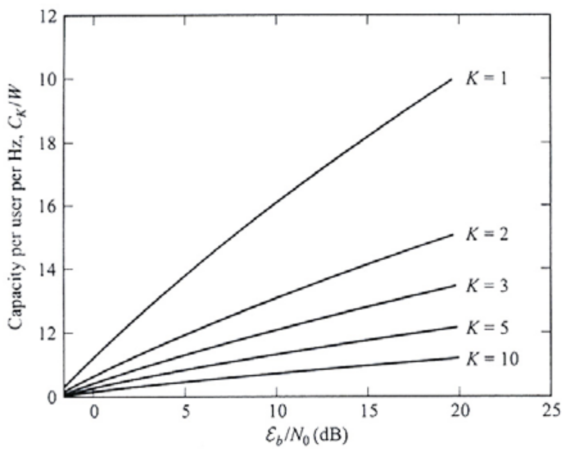
Spread spectrum signals → small cross-correlations
For no spread random access, collision and interference occur.
Retransmission Protocol

Capacity of Multiple Access Methods

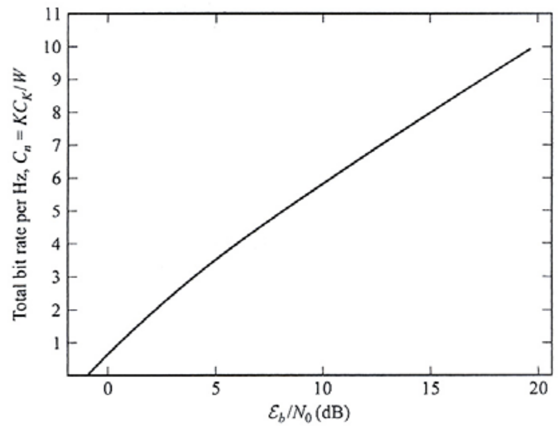
In FDMA, normalized total capacity $C_n = KC_K / W$
(total bit rate for all K users per unit of bandwidth)

$$C_n = \log_2\left(1 + C_n \frac{E_b}{N_0}\right)$$

where W : Bandwidth
E_b : Energy per bit
N_0 : Noise power spectrum desity



Normalized capacity as a function of ε_b / N_0 for FDMA.

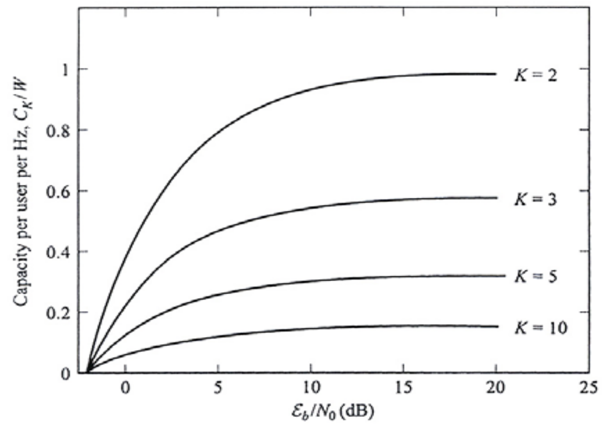


Total capacity per hertz as a function of ε_b / N_0 for FDMA.

In TDMA, there is a practical limit for the transmitter power

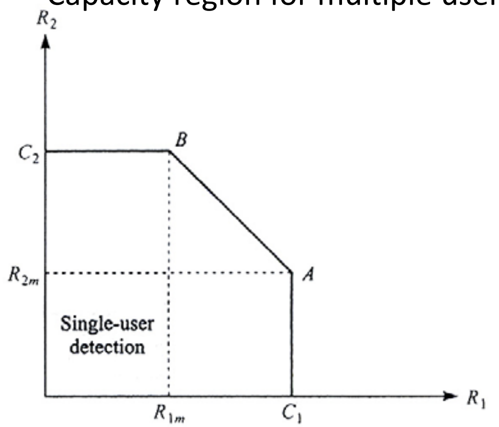
In no cooperative CDMA,

$$C_n \le \log_2 e - \frac{1}{E_b / N_0}$$



Normalized capacity as a function of ε_b / N_0 for noncooperative CDMA.

Capacity region for multiple users



Capacity region of two-user CDMA multiple access Gaussian channel.

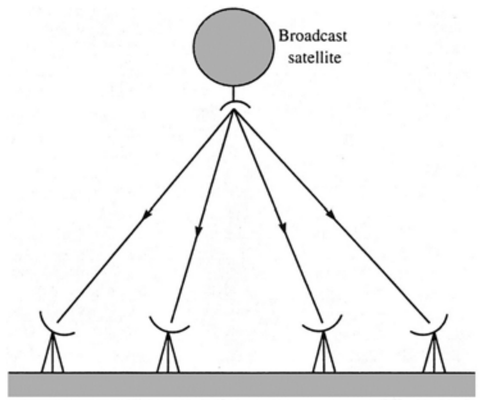
Code-Division Multiple Access

- CDMA Signal and Channel Models
- The Optimum Receiver
  Synchronous Transmission
  Asynchronous Transmission

- Sub-optimum Detectors
  Computational complexity grows linearly with the number of users, *K*.
  Conventional Single-user Detector
  Near-far problem
  Decorrelation Detector
  Minimum Mean-Square-Error Detector
  Other Types of Detectors
- Performance Characteristics of Detectors

Random Access Methods

- ALOHA Systems and Protocols Channel access protocol
  Synchronized (slotted) ALOHA
  Unsynchronized (un-slotted) ALOHA
  Throughput for slotted ALOHA



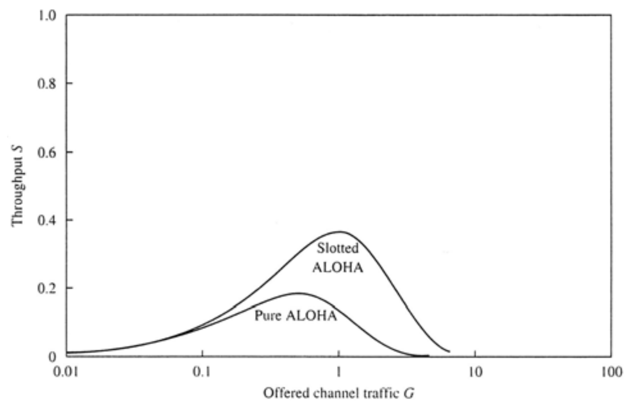
Packet Transmission

- Poisson Point Process: The start time of packets
- Average rate : λ [packets/s]
- Time duration of a packet : Tp
- Offered channel traffic : G=λTp

Throughput Performance

- Unsynchronized random access:
  S=Gexp(-2G)
  Smax=1/(2e)=0.184(packets/slot) @G=1/2
- Slotted ALOHA:
  S=Gexp(-G) for K→∞
  Smax=1/e=0.368(packets/slot) @G=1

Throughput & Delay Performance



- Carrier Sense Systems and Protocols
  CSMA / CD
  (carrier sense multiple access with collision detection)
  No persistent CSMA
  1-persistent CSMA
  p-persistent CSMA

Nonpersistent CSMA

- (a) If the channel is idle, the user transmits a packet.
- (b) If the channel is sensed busy, the user schedules the packet transmission at a later time according to some delay distribution. At the end of the delay interval, repeats steps(a) and (b).

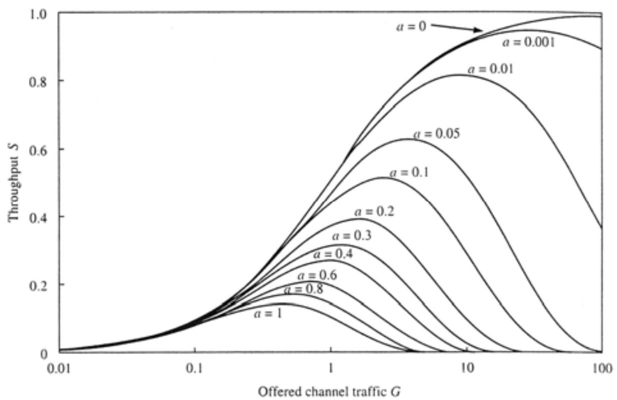
1-persistent CSMA

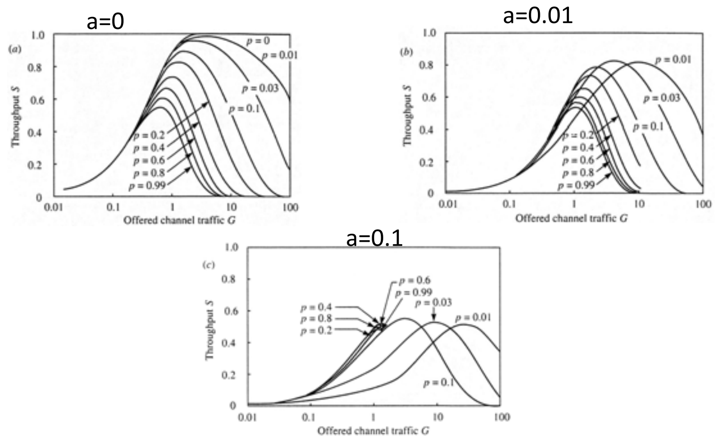
- (a) If the channel is sensed idle, the user transmits the packet with probability 1.
- (b) If the channel is sensed busy, the user waits until the channel becomes idle and transmits a packet with probability one. Note that in this protocol, a collision will always occur when one user has a packet to transmit.

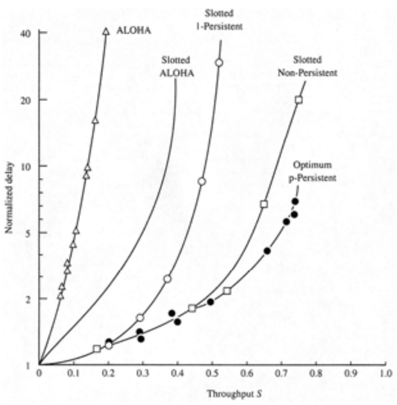
p-persistent CSMA

- (a) If the channel is idle, the packet is transmitted with probability p, and with probability 1-p the transmission is delayed by τ.
- (b) If at $t=\tau$, the channel is still sensed to be idle, step (a) is repeated. If a collision occurs, the user schedules retransmission of the packets according to some preselected transmission delay distribution.
- (c) If at $t=\tau$, the channel is sensed busy, the user waits until it becomes idle, and then operates as in (a) and (b) above.

a=Tp/τd Nonpersistent CSMA





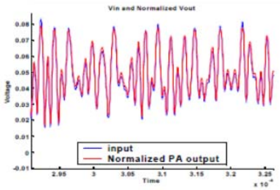


Memory Effect in Power Amplifiers

- Nonlinearity of PA
- Modeling of Nonlinearity
- Intermodulation, EVM, ACPR
- Distortion Compensation
- High Efficient PA

Time Domain Response of Power Amplifiers

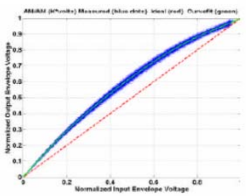
Input and output waveforms vs time (CDMA signal)



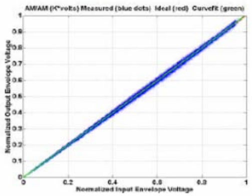
Memory effects:
- **impact channel model**
- **generate inter-chip interference (ICI)**

Vout vs Vin

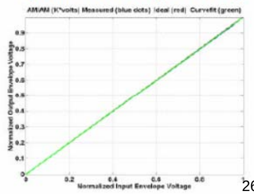
No correction



Memoryless correction



Full correction (with memory effect)



Outline

- Introduction
- Signals, behavioral models, and memory effects
- Impact of decresting and truncating realistic signals
- Measurement based predictions of digital predistortion
  - memoryless compensation
  - deterministic memory effect compensation
- Examples of RF power amplifiers
- Conclusions

Signals and Memory Model Transfer Functions

Goal: To obtain a transfer function or an impulse response for the RF envelope.

Procedure: Use different test signals to extract the circuit performance over the stimulus parameter space.

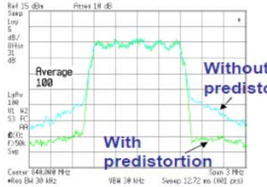
- CW signals
- Parameterized CW
- Two tone
- Shaped RF envelopes
- Multi-sine generated
- Realistic truncated waveforms

Perturbation techniques:

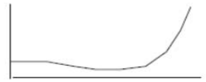
- Small signal expansion about large signal state

"Standard Model" for Characterization of Nonideal Amplifier

AM-AM conversion



AM-PM conversion

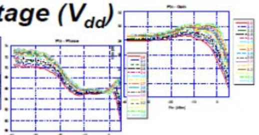


input envelope $x(t)=a(t)\exp(j\phi(t))$ → AM/AM & AM/PM conversion $G(a(t))$ $\Psi(a(t))$ → output envelope $y(t)=a(t)G(a(t))^{*}\exp(j\phi(t)+j\Psi(a(t)))$

Measure with single RF sinewave input - CW
(power sweep of S21 with network analyzer)
Envelope time-scale for simulation
Spectral shape computed via FFT

Augmented Behavioral Characterization – ABC Model

Gain and phase depend on measurable parameter, Z ***such as temperature or bias voltage (V_{dd})***

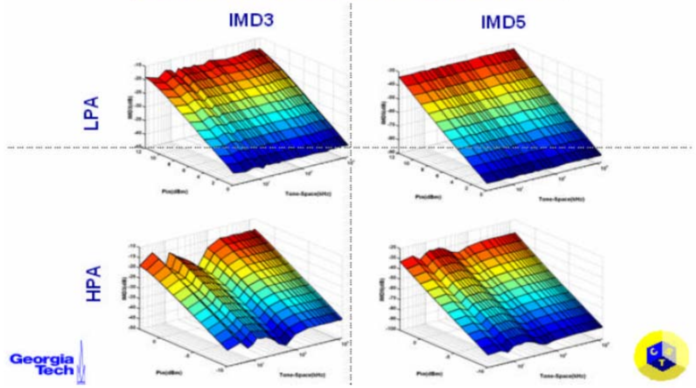


input envelope $x(t)=a(t)\exp(j\phi(t))$ → $Z=f(a(t))$ → AM/AM & AM/PM conversion $G(a(t),Z)$ $\Psi(a(t),Z)$ → output envelope $y(t)=a(t)G(a(t))^{*}\exp(j\phi(t)+j\Psi(a(t)))$

Independently measure gain and phase vs Z
Develop simple model (possibly with memory!) of Z dependence on input amplitude

Asbeck, et al (2002)

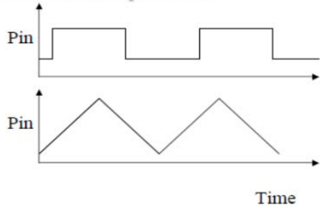
IMD Measurements



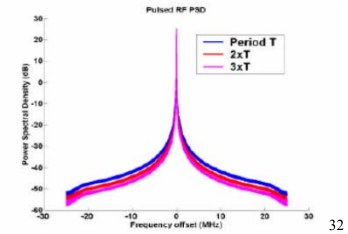
Extraction of Accurate Behavioral Models for Power Amplifiers with Memory Effects using Two Tone Measurements, Hyunchul Ku, Michael D. McKinley and J. Stevenson Kenney, IMS 2002

Shaped RF Envelopes

Envelope Domain:
- Square waveforms
- Triangle waveforms



- Greater spectral richness
- Expanded exploration of internal states
  - Bias
  - Thermal
  - Others



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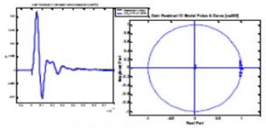
Augmented Behavioral Characterization – Blackbox ABC

Gain and phase depend on additional parameter, Z
but this parameter may <u>not</u> be accessible

input envelope
$x(t)=a(t)\exp(j\phi(t))$

$Z(t)=f(a(t),h(t))$



AM/AM & AM/PM conversion
$G(a(t),Z(t))$
$\Psi(a(t),Z(t))$

output envelope
$y(t)=a(t)G(a(t)^*$
$\exp(j\phi(t)+j\Psi(a(t)))$

Extract gain residue, h, from square wave measurement
Extract pole/zero model for gain residue
and apply as modulation on Z(t).

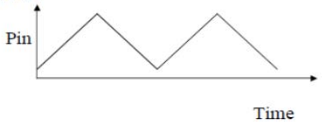
Draxler, et al (2003)

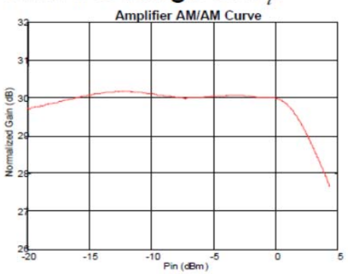
AM/AM & AM/PM Comparison CW and Sawtooth Waveforms

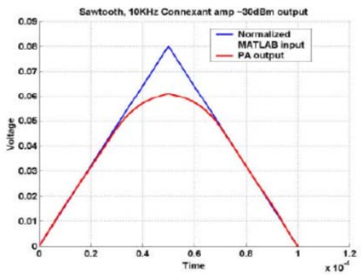
AM/AM and AM/PM becomes:

$$G_0 = E\left\{ \frac{P_o(n)}{P_i(n)} \middle| P_i \right\}$$

over the range of P_i.

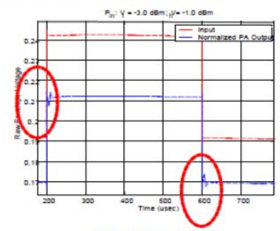


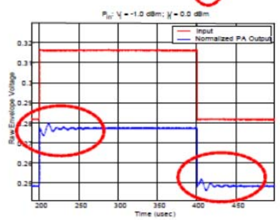




Squarewave Extraction Data

- •Obtain data at multiple power levels for the square wave over a wide operating region.
- •Select a number of samples over a the region with consistent characteristics.
- •Remove the steady state gain characteristics.
- •Identify the time sequence to be used for extraction of the gain residue.
- •Over a large range the gain residue is amplitude independent; however, it does change as the amplifier goes into compression.





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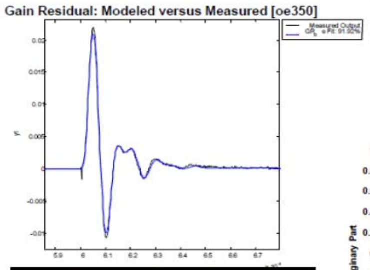
Auto-Regressive Moving Average (ARMA) Model of Gain Residue

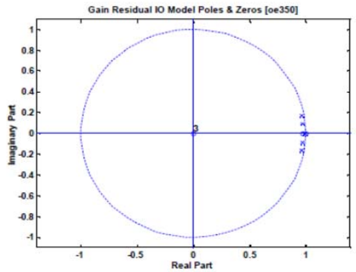


Gain Residue

$$k_g \cdot h_z(t) \otimes \Delta x_{in} u_{-1}(t) \,| = \frac{\left|\frac{x_{out}}{x_{in}}\right|}{G_o(x_{in})} - 1$$

Autoregressive Moving Average Model

$$h_z(q) = \frac{B(q)}{F(q)} u(t - nk) + e(t)$$



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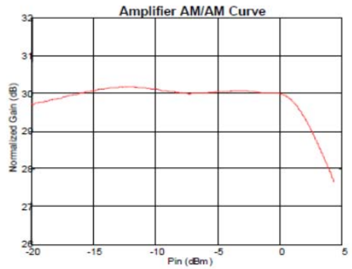
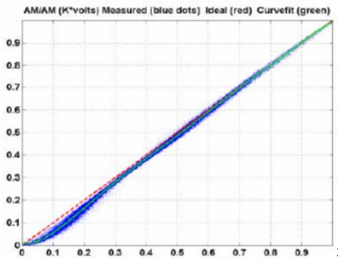
Memoryless Model for Arbitrary Waveform

- AM/AM and AM/PM compression characteristics
- Instantaneous gain expected values
- Deviations highlight shifts: thermal equilibrium, bias network state changes…





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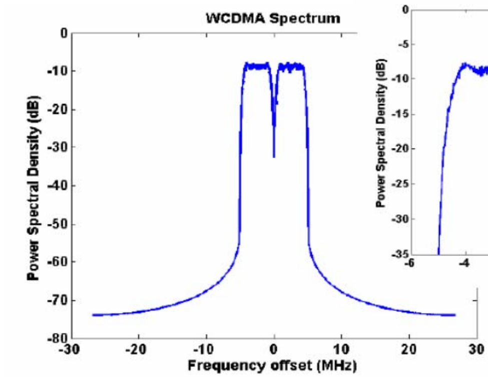
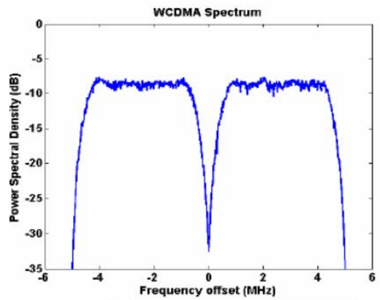
2 Carrier WCDMA Waveform: Power Spectral Density





Target spectrum for 2 adjacent WCDMA signals

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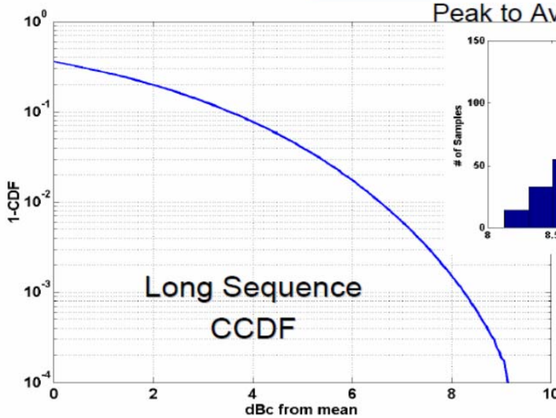
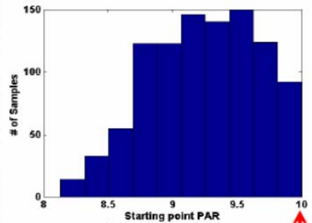
2x WCDMA Waveform - CCDF

Truncated Sequence Peak to Average Histogram





Peaks reduced by decresting to protect RF power amplifier

2013/07/19

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Normalized Waveform RMS Error

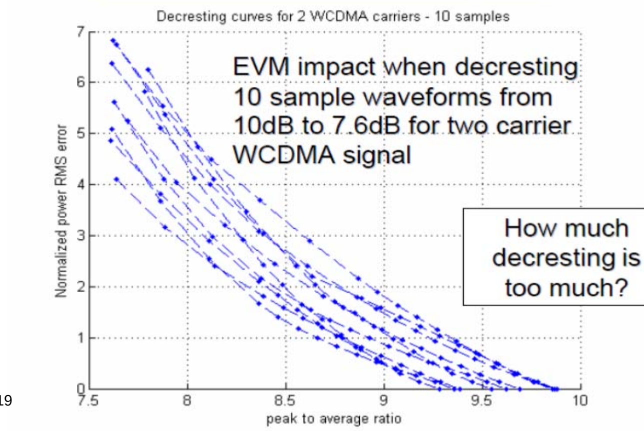
- Over all sample points, n, of a single measurement:
  - Normalize average power of signals to unity: x_a, y_a
- Generate the rms difference between the normalized vectors

$$\underline{x}_\alpha = \frac{\sqrt{2}\cdot \underline{x}}{\sqrt{\frac{\sum_n (x_0^2)}{n}}}$$

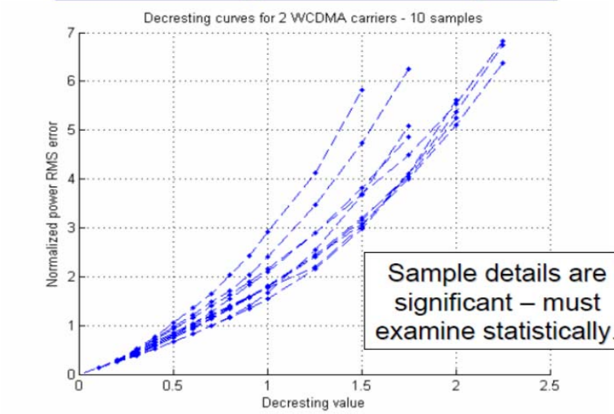
$$\underline{y}_\alpha = \frac{\sqrt{2}\cdot \underline{y}}{\sqrt{\frac{\sum_n (y_0^2)}{n}}}$$

$$EVM_{rms} = \sqrt{\frac{\sum_n (|y_\alpha - x_\alpha|^2)}{n}}$$

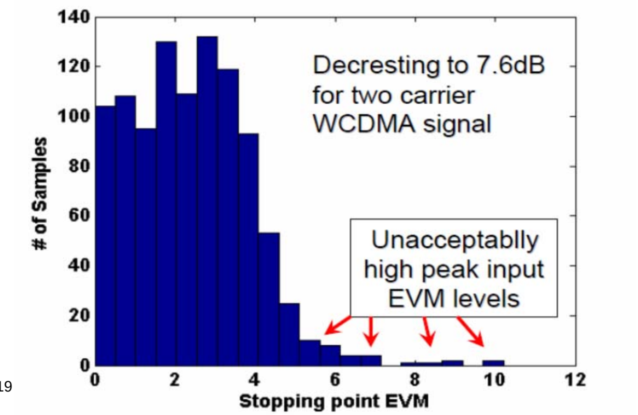
2x WCDMA Waveform – Decresting – EVM impact



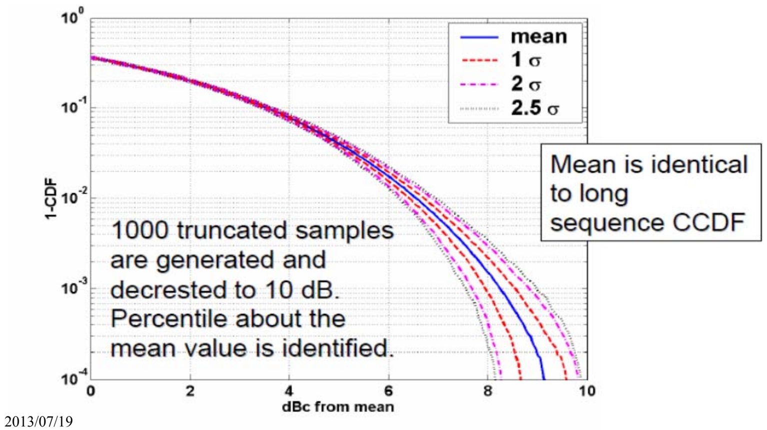
2x WCDMA Waveform – Decresting – EVM impact



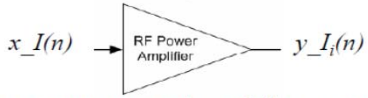
2x WCDMA Waveform – Decresting EVM impact



2x WCDMA Waveform – Ensemble CCDF Variation Plot



DPD Projections



Take two measurements of the same, production qualified, exploration waveform:

- First measurement sets the expected gain characteristics (memoryless impact)
- Second measurement is used to roughly estimate the non-deterministic memory effect (more than 2 improves accuracy).

DPD Projections

- Original input: $xI(n)$
- Original output: $yI_1(n)$
- Second output: $yI_2(n)$
- Amplifier gain: $G_n(\underline{xI}_n)$
- Expected gain: $G(xI_n)$

$$yI_1(n) = G_n(\underline{xI}_n) \cdot xI(n)$$

$$G(xI_n) = E(G_n(\underline{xI}_n) | xI_n)$$

Memoryless DPD

- DPD input: $xpI(n)$
- Projected output: $ypIe(n)$

$$yI_n - G(xI_n) \cdot xI_n = Mem + Noise$$

$$Noise \approx \frac{|yI_1(n) - yI_2(n)|}{2}$$

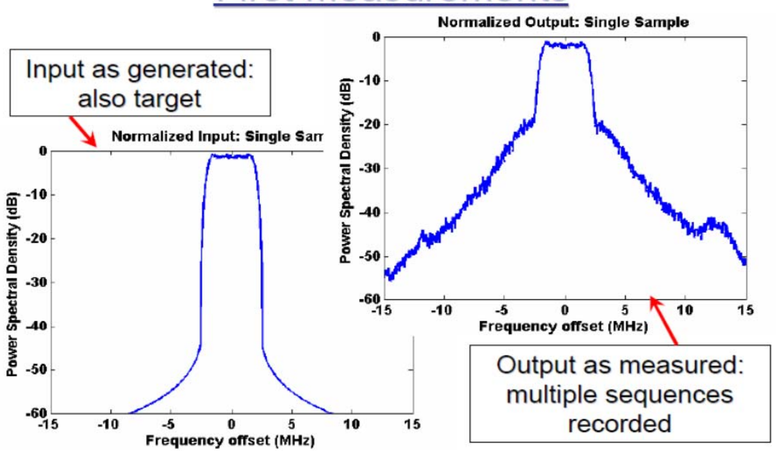
Memory Mitigation DPD

- DPD input: $xppI(n)$
- Projected output: $yppIe(n)$

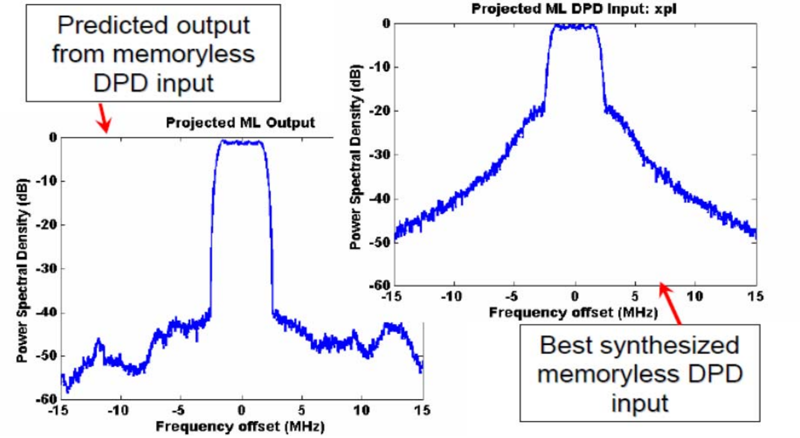
$$ypI_n \approx G_0 \cdot xI_n + Mem + Noise$$

$$yppI_n \approx G_0 \cdot xI_n + Noise$$

DPD Projections First Measurements

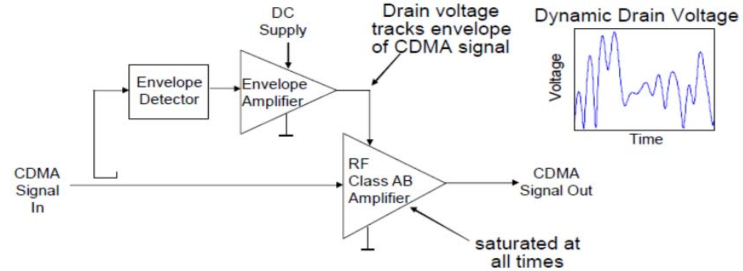


DPD Projections
Memoryless performance



Envelope Tracking Technique

- Maximizes PA efficiency by keeping RF transistor saturated for all envelope amplitudes
- Envelope Amplifier provides dynamic drain voltage



Ref: Don Kimball, et al

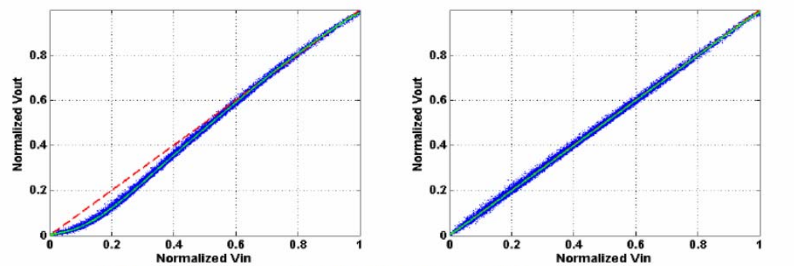
Philips Amplifier Results: LDMOS in ET System

	Gain (dB)	Po (W)	DE (%)	PAE (%)	EVM (%)	ACLR1 (dBc)	ACLR2 (dBc)
Spec.		20 min			7	45	50
Before	14.6	20.85	35.7	35.3	45	-23	-40
After ML DPD	14.6	23.4	37.0	36.6	3.5	-42	-47
After Memory DPD	-	-	-	-	<1.4	-53	-57

LDMOS Class AB amplifier for WCDMA *without ET*: PAE=___%

Memoryless Digital Predistortion

Original measurement with memoryless DPD



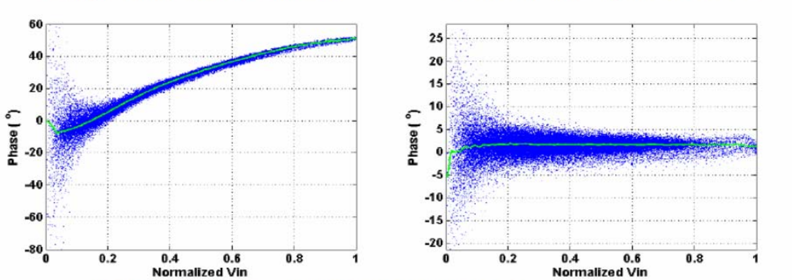
Blue points – instantaneous V_{out} vs. V_{in}

Purple line – gain target

Green line – expected value of gain

Memoryless Digital Predistortion (Phase)

Original measurement with memoryless DPD



Blue points – instantaneous V_{out} vs. V_{in}

Purple line – phase target

Green line – expected value of phase

Ensemble Input/Output RMS Error

- Perform an ensemble average over many measurements: $E\{.\}$
- Over all sample points: n
  - Normalize average power of both signals to unity: x_a, y_a
- Generate the rms difference between the normalized vectors

$$\underline{x}_0 = E\{\underline{x}\},\ \underline{y}_0 = E\{\underline{y}\}$$

$$\underline{x}_\alpha = \frac{\sqrt{2}\cdot \underline{x}_0}{\sqrt{\frac{\sum_n (x_0^2)}{n}}}$$

$$\underline{y}_\alpha = \frac{\sqrt{2}\cdot \underline{y}_0}{\sqrt{\frac{\sum_n (y_0^2)}{n}}}$$

$$EVM_{rms} = \sqrt{\frac{\sum_n (|y_\alpha - x_\alpha|^2)}{n}}$$

Contraction approximation

$y'_n = G_n(\underline{xp}_n)xp_n$ Input /Output Equation

$G(xp_n) = E(G_n(\underline{xp}_n))$ Memoryless gain:

expected gain for a given x_n

$y'_n = G(xp_n)x_n + Mem + Noise$ Partitions of IO Equation

Mem: repeatable

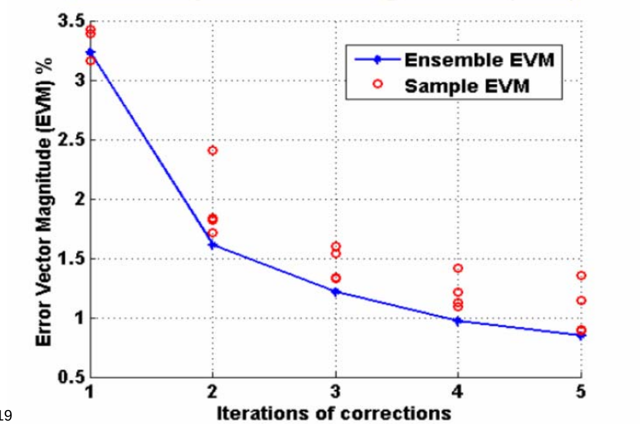
Noise: random

$xp_n^i = xp_n^{(i-1)} - \Delta x_n^{(i-1)}$ $\underline{xp}_n{}^i$ correction equation

$\Delta x_n^{(i-1)} = \frac{\alpha \cdot e_c^{(i-1)}}{G_n(\underline{xp}_n^{(i-1)})}$? x adjustment equation

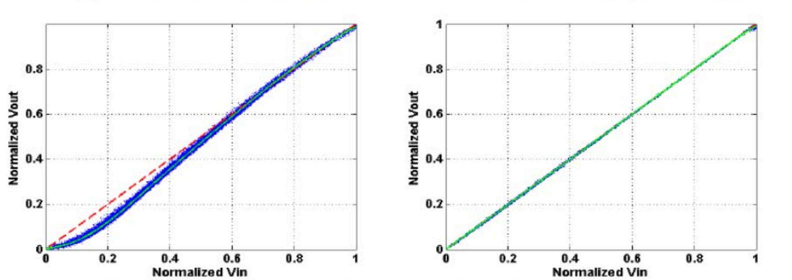
Note: *similarities to LMS algorithm*

RF Power Amplifier with Envelope Tracking Bias (ET)



Predistortion with Memory Model

Original measurement DPD including memory



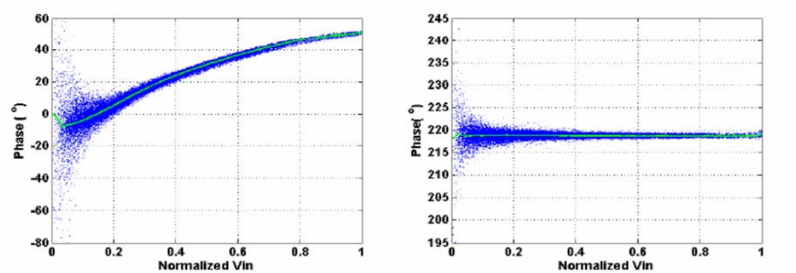
Blue points – instantaneous V_{out} vs. V_{in}

Purple line – gain target

Green line – expected value of gain

Predistortion with Memory Model (Phase)

Original measurement DPD including memory



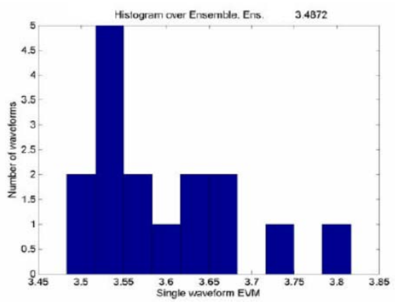
Blue points – instantaneous V_{out} vs. V_{in}

Purple line – phase target

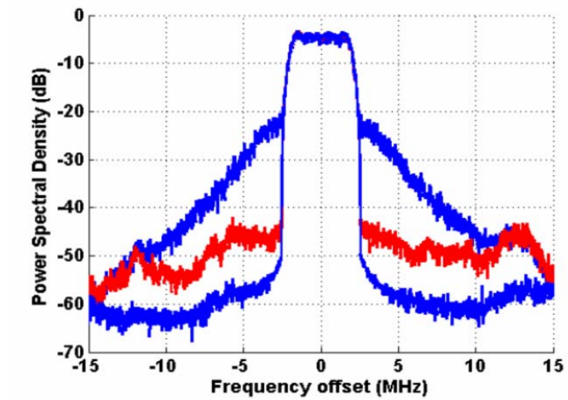
Green line – expected value of phase

Typical RMS error histogram with Ensemble RMS error (N=16)

- Capture 16 samples
- Ensemble RMS error is typically at lower range.
- As $E\{e_c^i\}$ becomes small, more ensemble members are needed to have confidence in the ensemble means and variances.



RF Power Amplifier with Envelope Tracking Bias (ET)

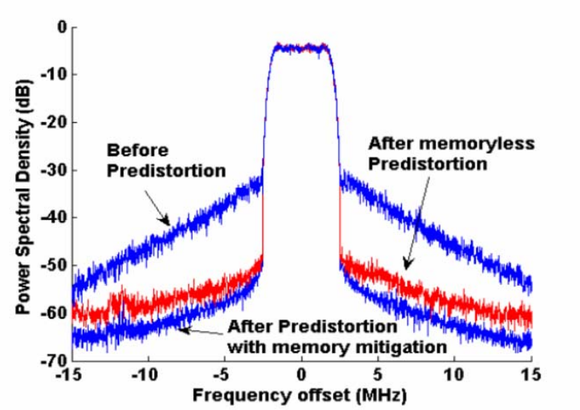


Nitronex Amplifier Results: GaN HFETs in ET System

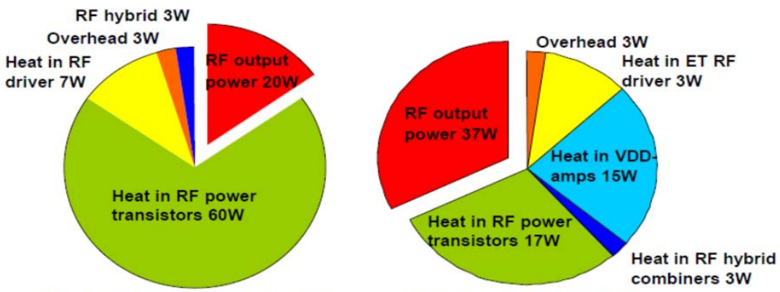
	Gain (dB)	Po (W)	DE (%)	PAE (%)	EVM (%)	ACLR1 (dBc)	ACLR2 (dBc)
Spec.		20 min			7	45	50
Before	10.3	36.5	51.7	49.3	12.1	-32	-41
After ML DPD	10	37.2	53.4	50.7	1.74	-48	-53
After Memory DPD	-	-	-	-	0.7	-52	-58

GaN Class AB amplifier for WCDMA *without ET*: PAE=25%

RF Power Amplifier with Envelope Tracking Bias (ET)



Heat Distribution Comparison



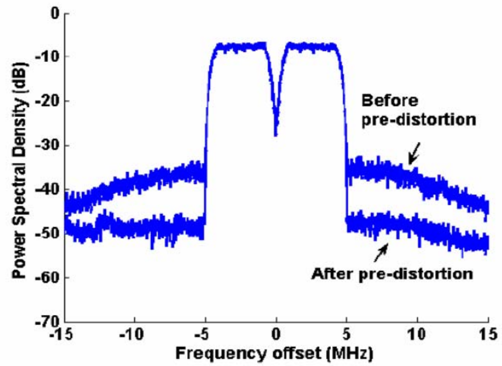
No ET, Predistortion only GaN HPA
Total Heat: 73 W

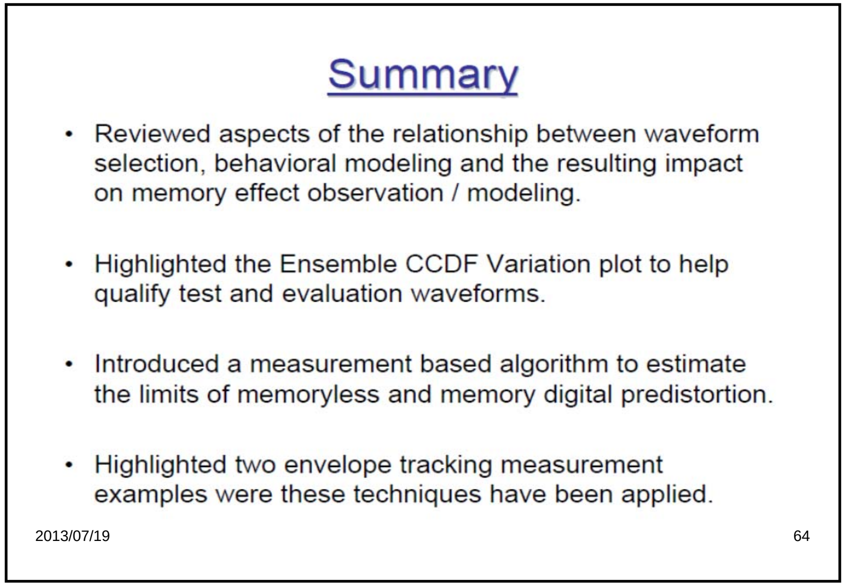
PD + ET GaN HPA
Total Heat: 41 W

Junction temperatures for RF devices dramatically reduced due to both lower total heat and heat density

NTX GaN: 2x WCDMA

Preliminary Results




Summary
• Reviewed aspects of the relationship between waveform selection, behavioral modeling and the resulting impact on memory effect observation / modeling.
• Highlighted the Ensemble CCDF Variation plot to help qualify test and evaluation waveforms.
• Introduced a measurement based algorithm to estimate the limits of memoryless and memory digital predistortion.
• Highlighted two envelope tracking measurement examples were these techniques have been applied.
2013/07/19
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