

## Multi-user Communications

## Agenda

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

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## 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

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

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

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## 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)

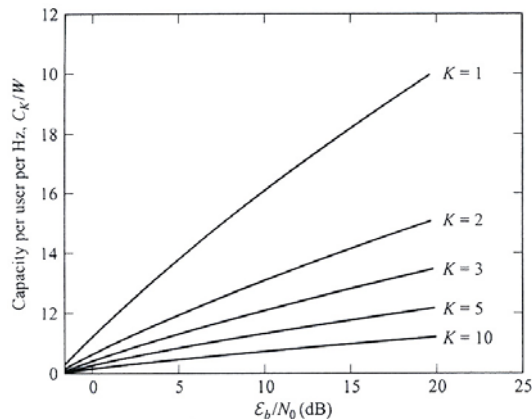
$$C_n = \log_2 \left( 1 + C_n \frac{E_b}{N_0} \right)$$

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

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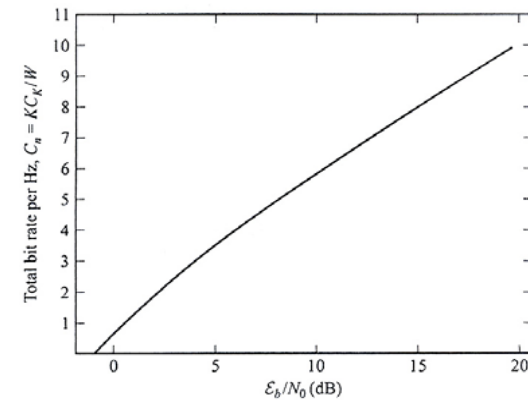


Normalized capacity as a function of  $\epsilon_b / N_0$  for FDMA.

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Total capacity per hertz as a function of  $\epsilon_b / N_0$  for FDMA.

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

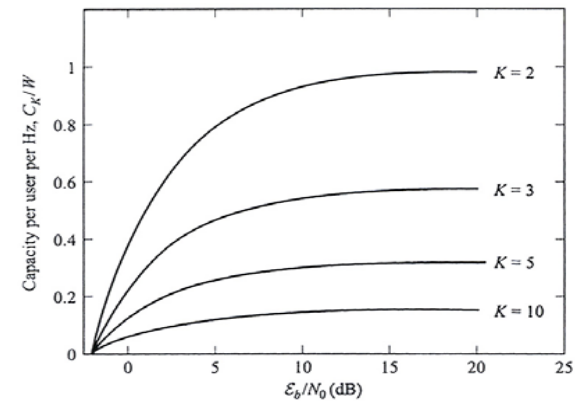
In no cooperative CDMA,

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

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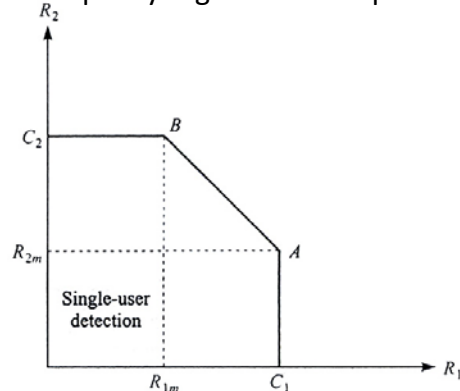
Normalized capacity as a function of  $E_b/N_0$  for noncooperative CDMA.

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Capacity region for multiple users



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

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## Code-Division Multiple Access

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

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- 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

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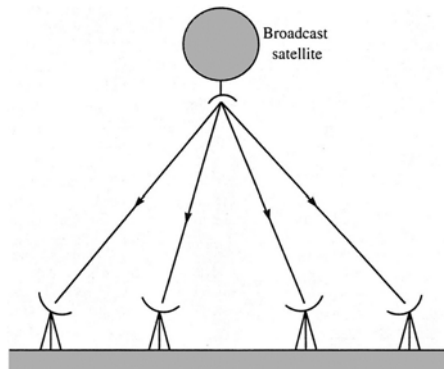
## Random Access Methods

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

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## Packet Transmission

- Poisson Point Process: The start time of packets
- Average rate :  $\lambda$  [packets/s]
- Time duration of a packet :  $T_p$
- Offered channel traffic :  $G = \lambda T_p$

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## Throughput Performance

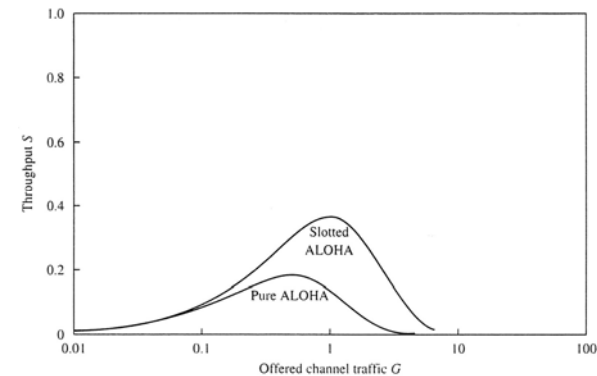
- Unsynchronized random access:  
 $S = G \exp(-2G)$   
 $S_{\max} = 1/(2e) = 0.184 (\text{packets/slot}) @ G = 1/2$
- Slotted ALOHA:  
 $S = G \exp(-G)$  for  $K \rightarrow \infty$   
 $S_{\max} = 1/e = 0.368 (\text{packets/slot}) @ G = 1$

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## Throughput & Delay Performance



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- Carrier Sense Systems and Protocols  
 CSMA / CD  
 (carrier sense multiple access with collision detection)

No persistent CSMA

1-persistent CSMA

$p$ -persistent CSMA

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## 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).

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## 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.

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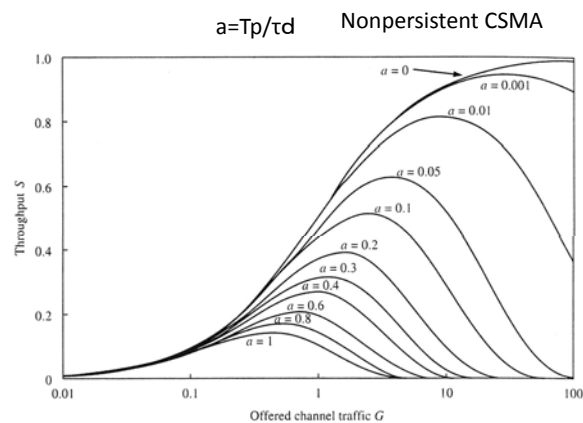
## p-persistent CSMA

- (a) If the channel is idle, the packet is transmitted with probability  $p$ , and with probability  $1-p$  the transmission is delayed by  $\tau$ .
- (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.

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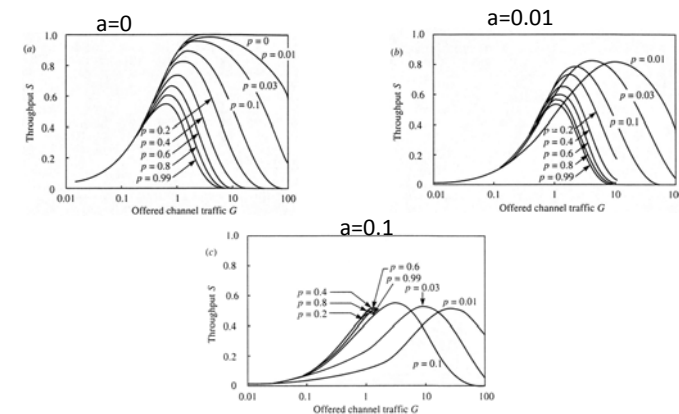
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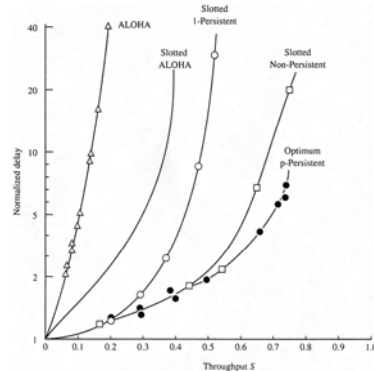
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## Memory Effect in Power Amplifiers

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

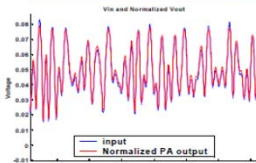
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## Time Domain Response of Power Amplifiers

Input and output waveforms vs time (CDMA signal)

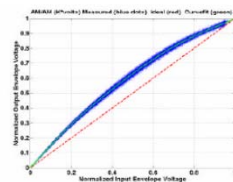


Memory effects:

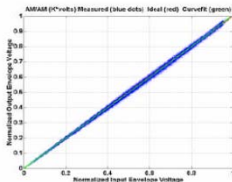
- impact channel model
- generate inter-chip interference (ICI)

$V_{out}$  vs  $V_{in}$

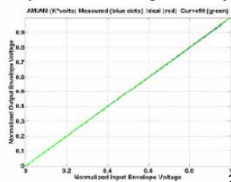
No correction



Memoryless correction



Full correction (with memory effect)



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## Outline

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

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## 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.

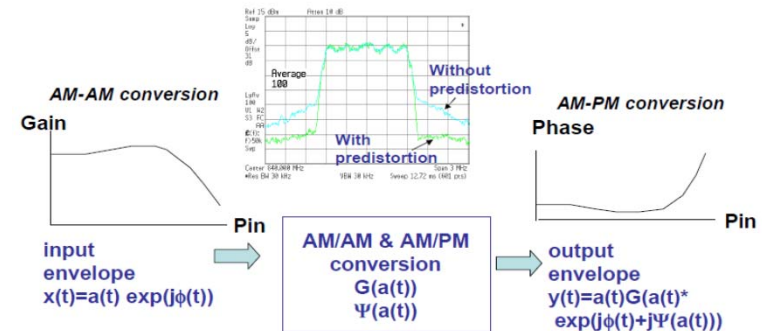
- CW signals
- Parameterized CW
- Two tone
- Shaped RF envelopes
- Multi-sine generated
- Realistic truncated waveforms

Perturbation techniques:

- Small signal expansion about large signal state

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## "Standard Model" for Characterization of Nonideal Amplifier



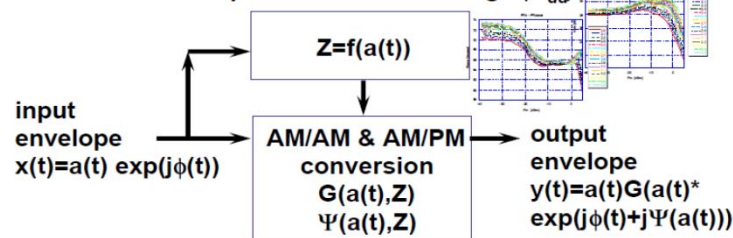
Measure with single RF sinewave input - CW  
(power sweep of S21 with network analyzer)  
Envelope time-scale for simulation  
Spectral shape computed via FFT

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## Augmented Behavioral Characterization – ABC Model

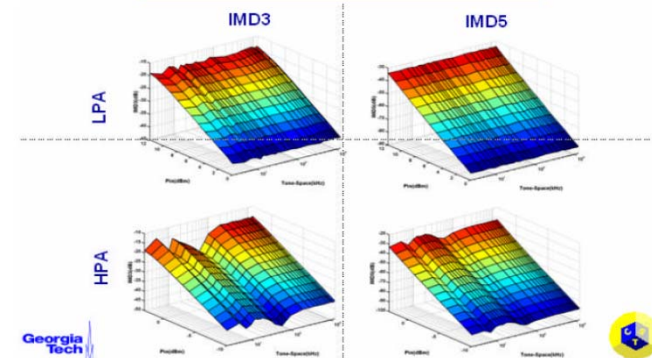
Gain and phase depend on measurable parameter,  $Z$   
such as temperature or bias voltage ( $V_{dd}$ )



Independently measure gain and phase vs  $Z$   
Develop simple model (possibly with memory!)  
of  $Z$  dependence on input amplitude Asbeck, et al (2002)

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## 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

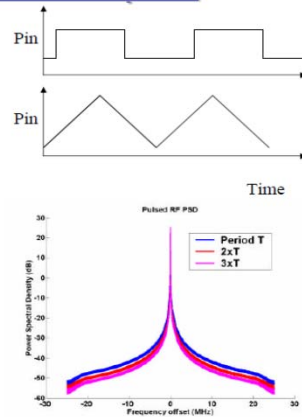
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## Shaped RF Envelopes

Envelope Domain:

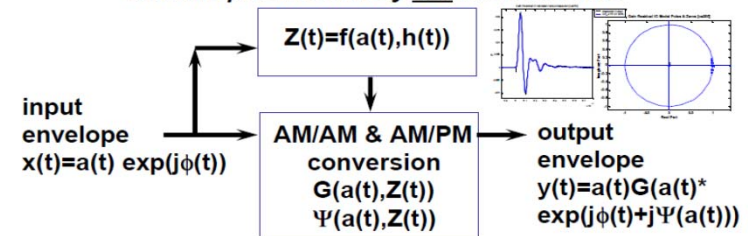
- Square waveforms
- Triangle waveforms
- Greater spectral richness
- Expanded exploration of internal states
  - Bias
  - Thermal
  - Others

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## Augmented Behavioral Characterization – Blackbox ABC

Gain and phase depend on additional parameter,  $Z$  but this parameter may not be accessible



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)

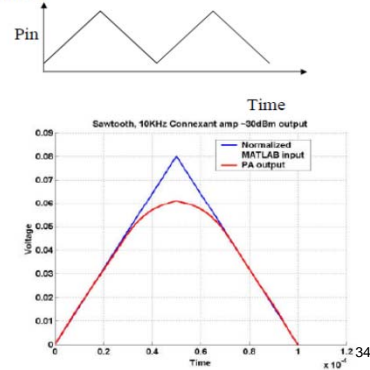
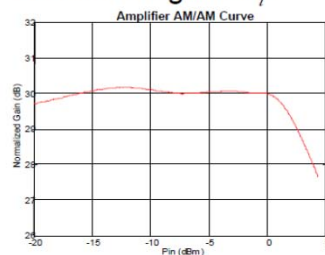
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## AM/AM & AM/PM Comparison CW and Sawtooth Waveforms

AM/AM and AM/PM becomes:

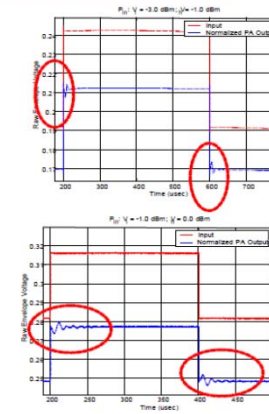
$$G_0 = E \left\{ \frac{P_o(n)}{P_i(n)} \right\}$$

over the range of  $P_i$ .



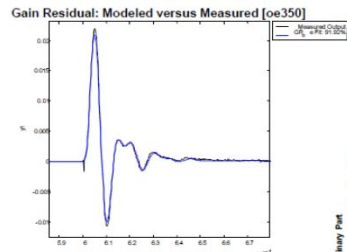
## Squarewave Extraction Data

- 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.



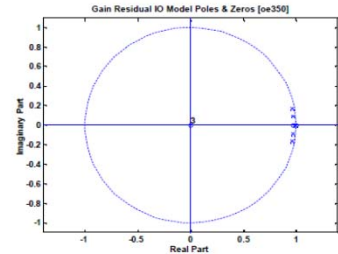
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## Auto-Regressive Moving Average (ARMA) Model of Gain Residue



**Gain Residue**

$$k_g \cdot h_z(t) \otimes \Delta x_m u_{-1}(t) = \frac{x_{out}}{G_o(x_m)} - 1$$



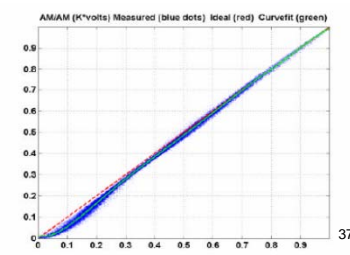
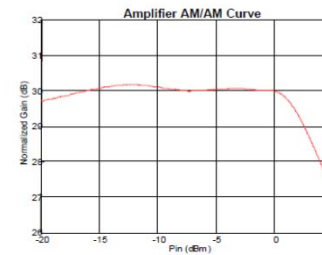
**Autoregressive Moving Average Model**

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

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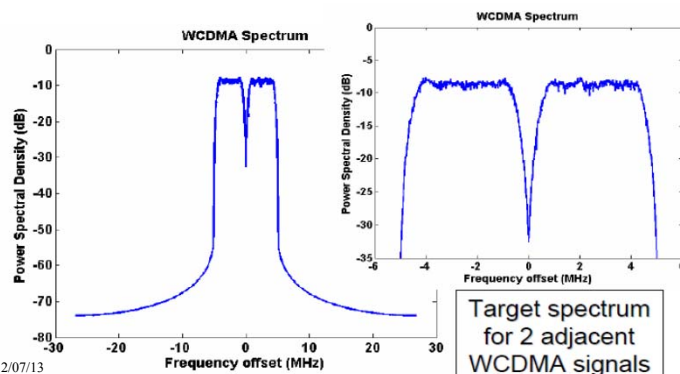
## Memoryless Model for Arbitrary Waveform

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



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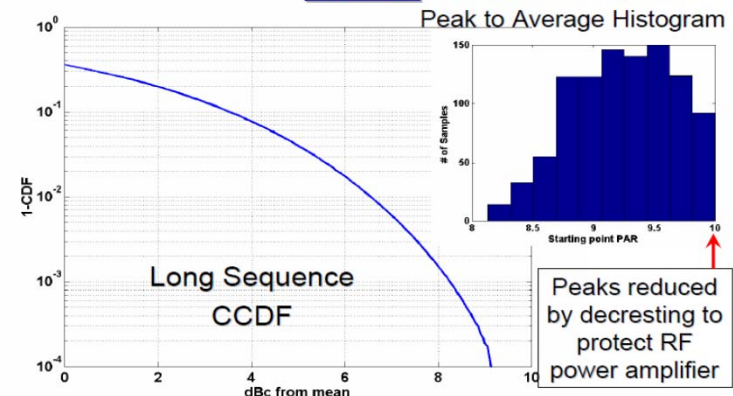
## 2 Carrier WCDMA Waveform: Power Spectral Density



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## 2x WCDMA Waveform - CCDF



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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

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

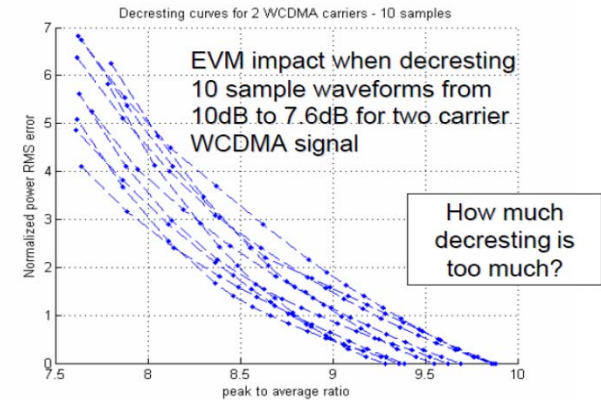
$$\underline{y}_a = \frac{\sqrt{2} \cdot \underline{y}}{\sqrt{\sum_n (y_0^2)}}$$

$$EVM_{rms} = \sqrt{\frac{\sum_n (|y_a - x_a|^2)}{n}}$$

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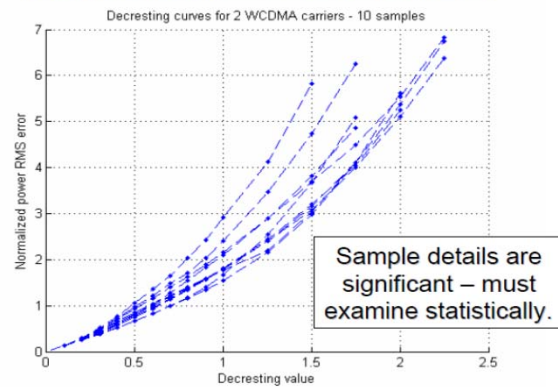
## 2x WCDMA Waveform – Decresting – EVM impact



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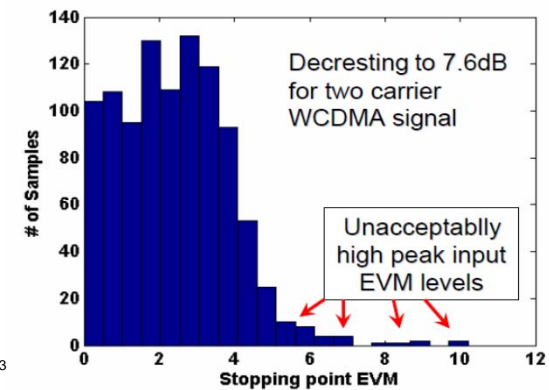
## 2x WCDMA Waveform – Decresting – EVM impact



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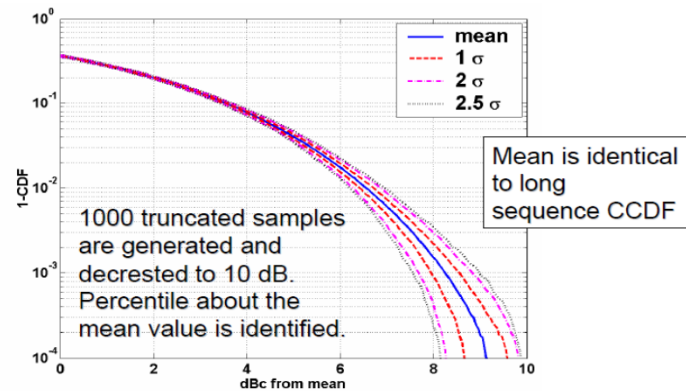
## 2x WCDMA Waveform – Decresting EVM impact



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## 2x WCDMA Waveform – Ensemble CCDF Variation Plot



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## 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).

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## DPD Projections

- Original input:  $xI(n)$
  - Original output:  $yI_1(n)$
  - Second output:  $yI_2(n)$
  - Amplifier gain:  $G_n(xI_n)$
  - Expected gain:  $G(xI_n)$
- $$yI_1(n) = G_n(xI_n) \cdot xI(n)$$
- $$G(xI_n) = E(G_n(xI_n) | xI_n)$$
- $$yI_n - G(xI_n) \cdot xI_n = Mem + Noise$$

### Memoryless DPD

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

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

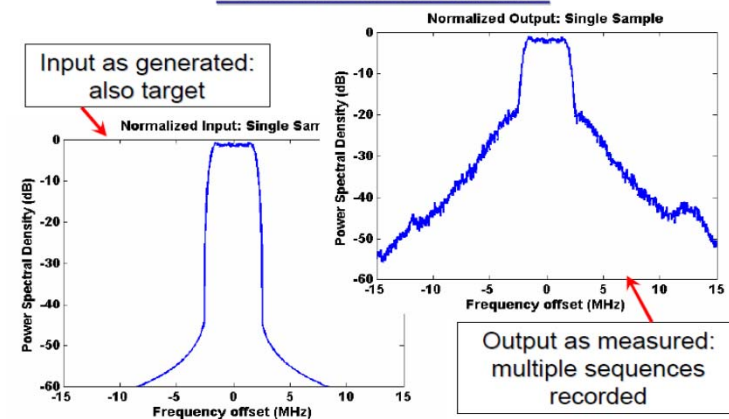
### Memory Mitigation DPD

- DPD input:  $xppI(n)$
  - Projected output:  $yppIe(n)$
- $$ypI_n \approx G_0 \cdot xI_n + Mem + Noise$$
- $$yppI_n \approx G_0 \cdot xI_n + Noise$$

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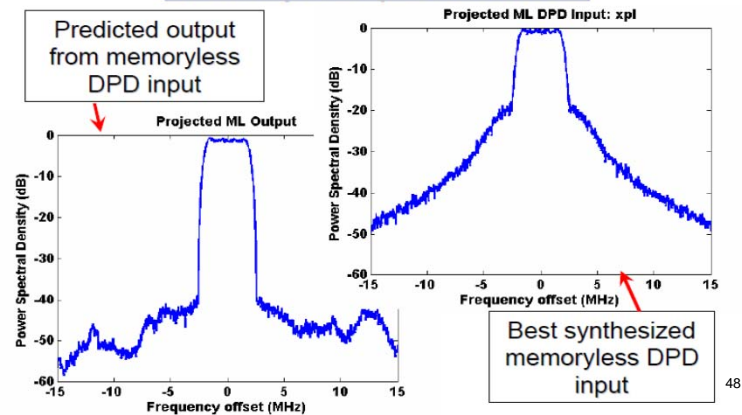
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## DPD Projections First Measurements



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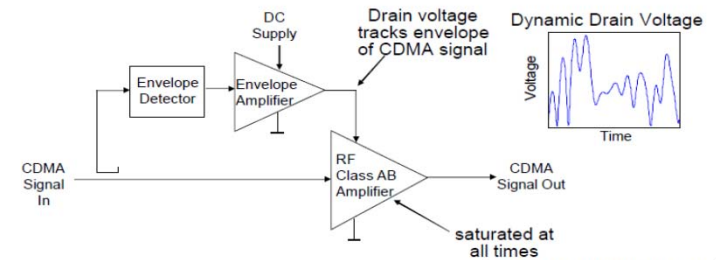
## DPD Projections Memoryless performance



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## Envelope Tracking Technique

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



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Ref: Don Kimball, et al

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## 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

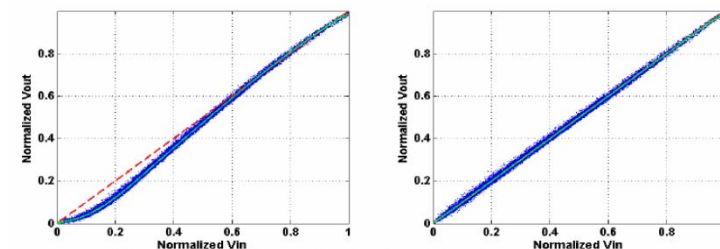
2012/07/13 LDMOS Class AB amplifier for WCDMA without ET: PAE=\_\_\_%

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## 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

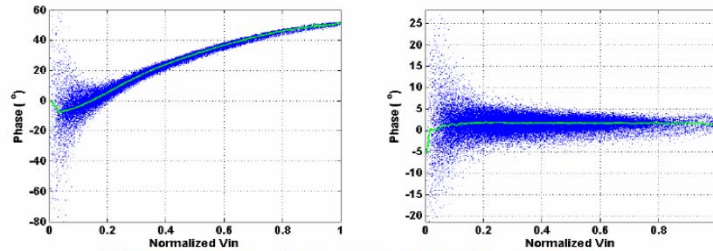
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## Memoryless Digital Predistortion (Phase)

Original measurement

with memoryless DPD



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

Purple line – phase target

Green line – expected value of phase

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## Ensemble Input/Output RMS Error

- Perform an ensemble average over many measurements:  
 $E\{\cdot\}$

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

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

- Over all sample points:  $n$ 
  - Normalize average power of both signals to unity:  $x_\alpha, y_\alpha$

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

- Generate the rms difference between the normalized vectors

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

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## Contraction approximation

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

$$G(xp_n) = E(G_n(xp_n)) \quad \text{Memoryless gain:}$$

expected gain for a given  $x_n$

$$y'_n = G(xp_n)x_n + \text{Mem} + \text{Noise}$$

Partitions of IO Equation

Mem: repeatable

Noise: random

$$xp_n^i = xp_n^{(i-1)} - \Delta x_n^{(i-1)} \quad xp_n^i \text{ correction equation}$$

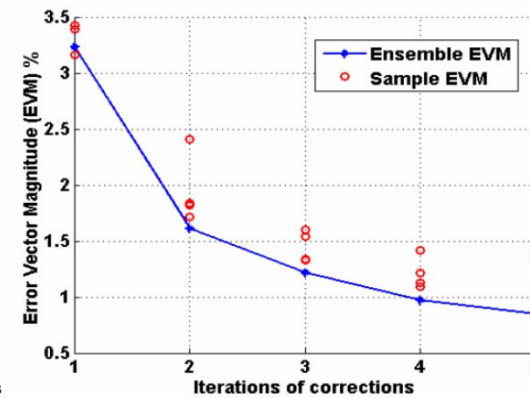
$$\Delta x_n^{(i-1)} = \frac{\alpha \cdot e_c^{(i-1)}}{G_n(xp_n^{(i-1)})} \quad ? x \text{ adjustment equation}$$

Note: similarities to LMS algorithm

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## RF Power Amplifier with Envelope Tracking Bias (ET)

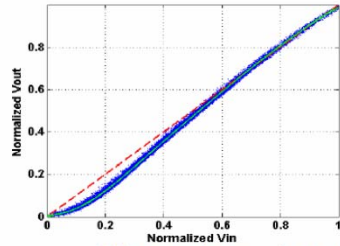


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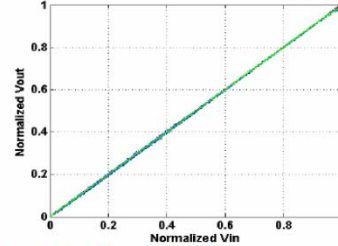
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### Predistortion with Memory Model

Original measurement



DPD including memory



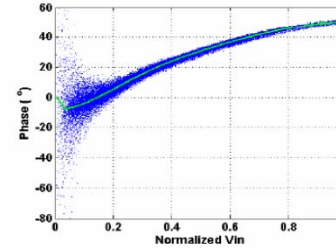
Blue points – instantaneous  $V_{out}$  vs.  $V_{in}$   
 Purple line – gain target  
 Green line – expected value of gain

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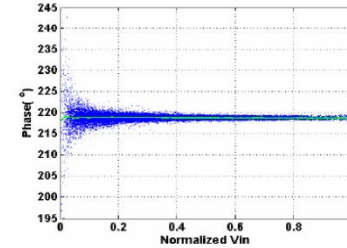
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### Predistortion with Memory Model (Phase)

Original measurement



DPD including memory



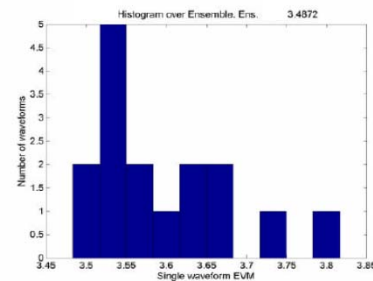
Blue points – instantaneous  $V_{out}$  vs.  $V_{in}$   
 Purple line – phase target  
 Green line – expected value of phase

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

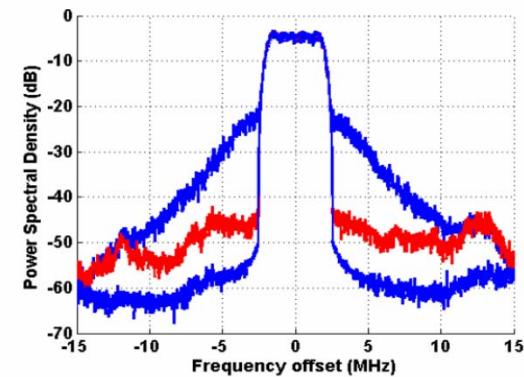
- Capture 16 samples
- Ensemble RMS error is typically at lower range.
- As  $E\{e_c^i\}$  becomes small, more ensemble members are needed to have confidence in the ensemble means and variances.



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### RF Power Amplifier with Envelope Tracking Bias (ET)



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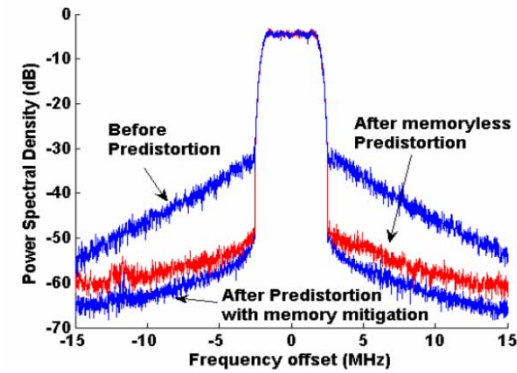
### Nitronex Amplifier Results: GaN HFETs in ET System

	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

2012/07/13 GaN Class AB amplifier for WCDMA without ET : PAE=25%

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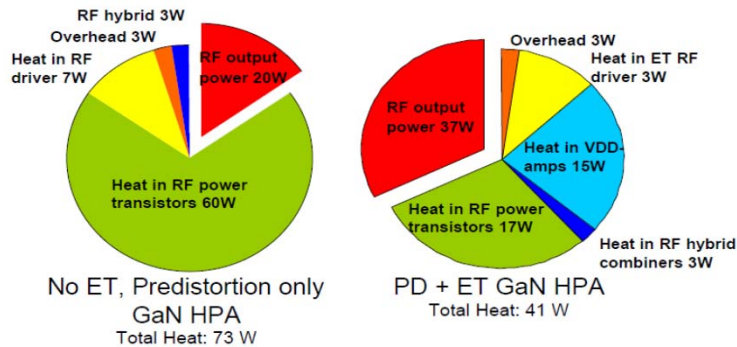
### RF Power Amplifier with Envelope Tracking Bias (ET)



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### Heat Distribution Comparison



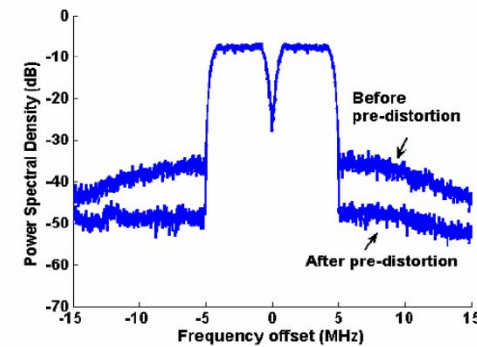
Junction temperatures for RF devices dramatically reduced  
due to both lower total heat and heat density

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### NTX GaN: 2x WCDMA

#### Preliminary Results



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## 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 where these techniques have been applied.

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