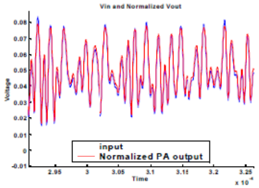
Memory Effect in Power Amplifiers

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

Time Domain Response of Power Amplifiers

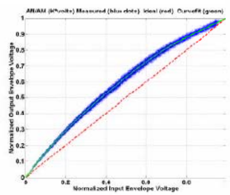
Input and output waveforms vs time (CDMA signal)



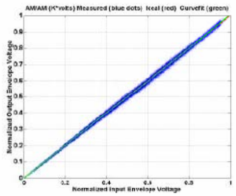
Memory effects:
- **impact channel model**
- **generate inter-chip interference (ICI)**

Vout vs Vin

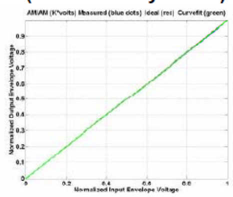
No correction



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

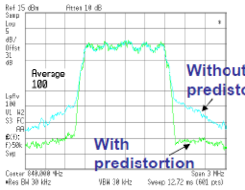
Goal: To obtain a transfer function or an impulse response for the RF envelope.

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**

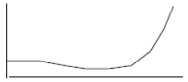
Perturbation techniques:
- **Small signal expansion about large signal state**

"Standard Model" for Characterization of Nonideal Amplifier



AM-AM conversion

AM-PM conversion

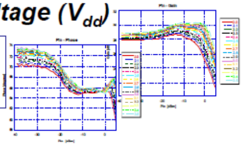


input envelope $x(t)=a(t)\exp(j\phi(t))$ ⇨ AM/AM & AM/PM conversion $G(a(t))$ $\Psi(a(t))$ ⇨ output envelope $y(t)=a(t)G(a(t))^* \exp(j\phi(t)+j\Psi(a(t)))$

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})

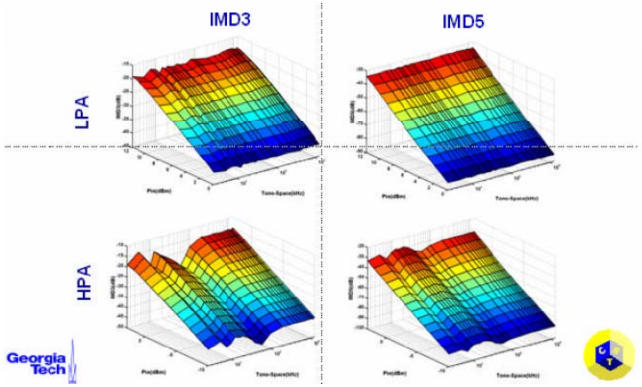


input envelope $x(t)=a(t)\exp(j\phi(t))$ → $Z=f(a(t))$ → AM/AM & AM/PM conversion $G(a(t),Z)$ $\Psi(a(t),Z)$ → output envelope $y(t)=a(t)G(a(t))^* \exp(j\phi(t)+j\Psi(a(t)))$

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

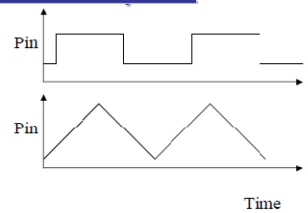


Extraction of Accurate Behavioral Models for Power Amplifiers with Memory Effects using Two Tone Measurements, Hyunchul Ku, Michael D. McKinley and J. Stevenson Kenney, IMS 2002

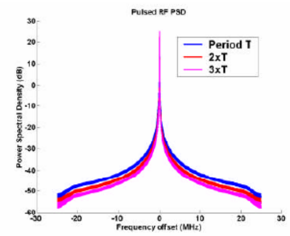
Shaped RF Envelopes

Envelope Domain:

- Square waveforms
- Triangle waveforms



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



Augmented Behavioral Characterization – Blackbox ABC

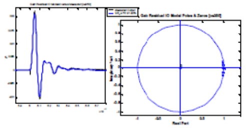
Gain and phase depend on additional parameter, Z
but this parameter may not be accessible

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

input envelope x(t)=a(t) exp(jϕ(t))

AM/AM & AM/PM conversion G(a(t),Z(t)) Ψ(a(t),Z(t))

output envelope y(t)=a(t)G(a(t)* exp(jϕ(t)+jΨ(a(t)))



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

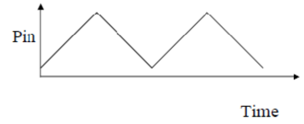
Draxler, et al (2003)

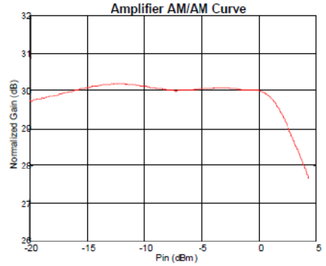
AM/AM & AM/PM Comparison CW and Sawtooth Waveforms

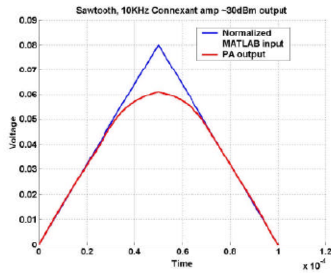
AM/AM and AM/PM becomes:

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

over the range of P_i.

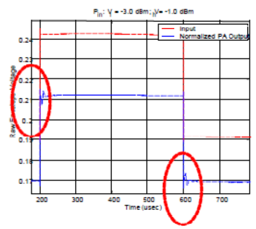


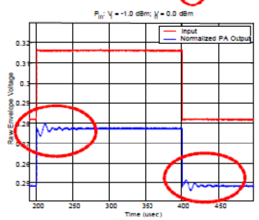




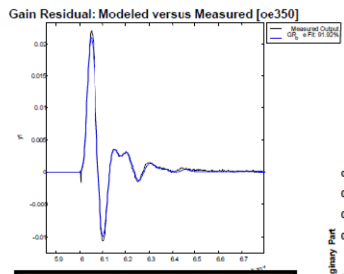
Squarewave Extraction Data

- 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.



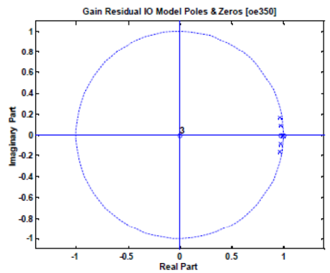


Auto-Regressive Moving Average (ARMA) Model of Gain Residue



Gain Residue

$$k_g \cdot h_z(t) \otimes \Delta x_{in} u_1(t) = \frac{\left| \frac{x_{out}}{x_{in}} \right|}{G_o(x_{in})} - 1$$

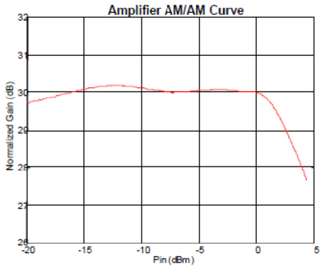


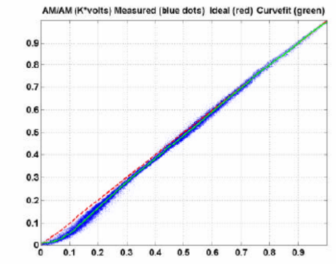
Autoregressive Moving Average Model

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

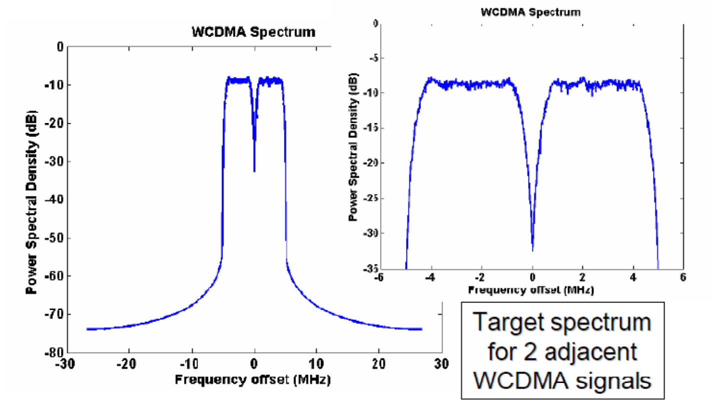
Memoryless Model for Arbitrary Waveform

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





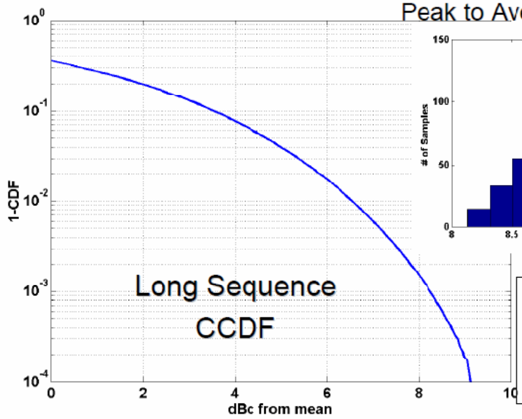
2 Carrier WCDMA Waveform: Power Spectral Density

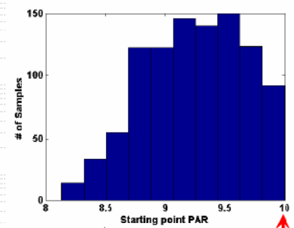


Target spectrum for 2 adjacent WCDMA signals

2x WCDMA Waveform - CCDF

Truncated Sequence Peak to Average Histogram





Peaks reduced by decresting to protect RF power amplifier

Normalized Waveform RMS Error

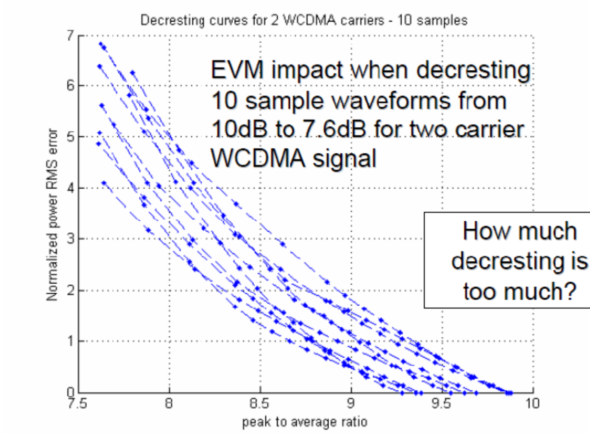
- Over all sample points, n, of a single measurement:
  - Normalize average power of signals to unity: x_α, y_α
- Generate the rms difference between the normalized vectors

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

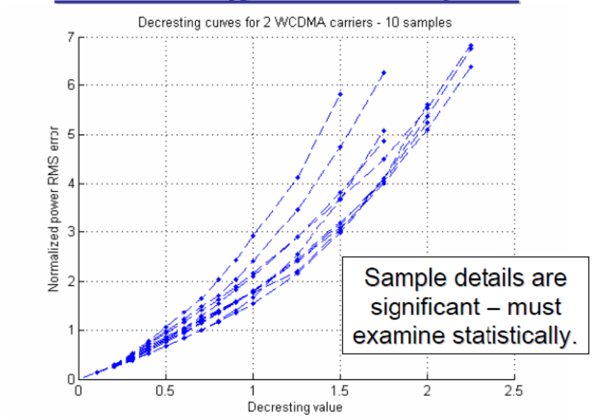
$$\underline{y}_\alpha = \frac{\sqrt{2}\cdot \underline{y}}{\sqrt{\frac{\sum_n (y_0^2)}{n}}}$$

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

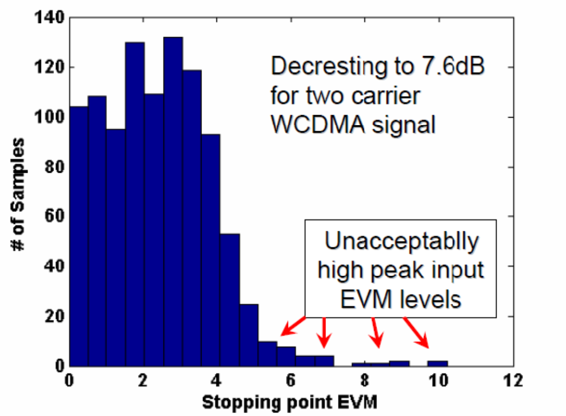
2x WCDMA Waveform – Decresting – EVM impact



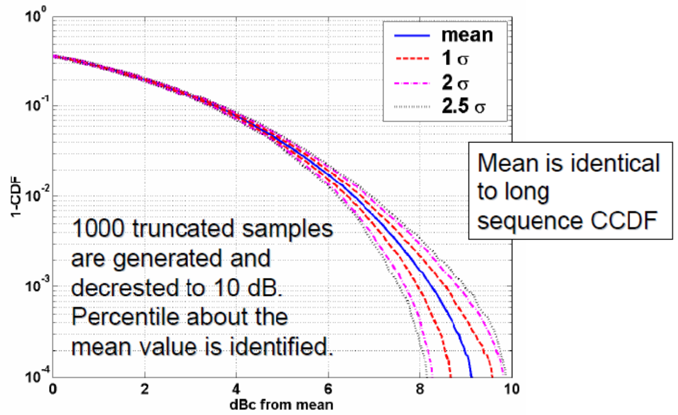
2x WCDMA Waveform – Decresting – EVM impact



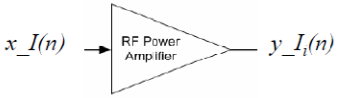
2x WCDMA Waveform – Decresting EVM impact



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: $G(xI_n)$

Memoryless DPD

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

Memory Mitigation DPD

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

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

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

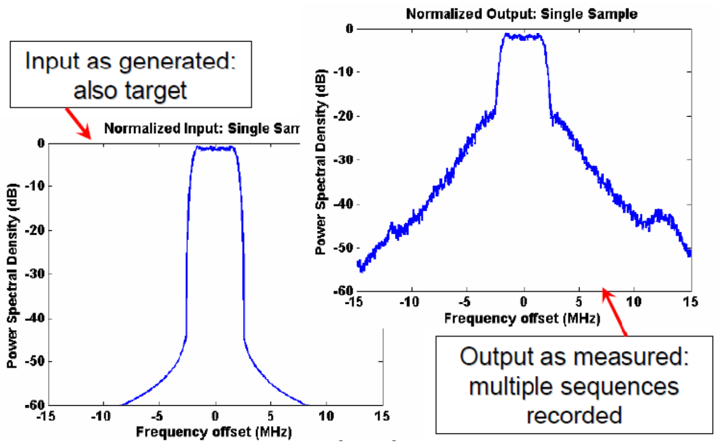
$$yI_n - G(xI_n) \cdot xI_n = Mem + Noise$$

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

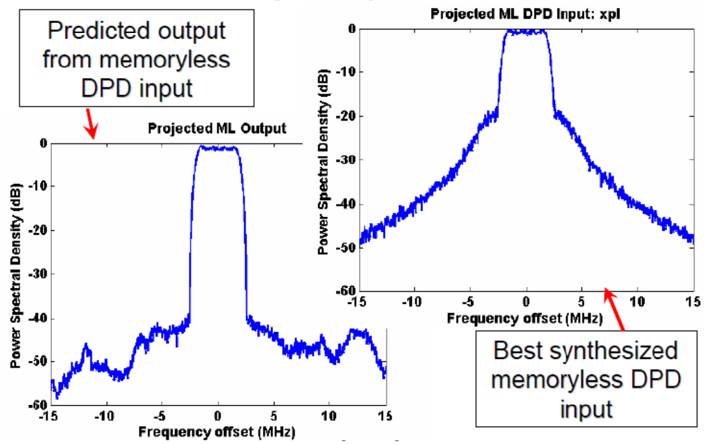
$$ypI_n \approx G_0 \cdot xI_n + Mem + Noise$$

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

DPD Projections
First Measurements

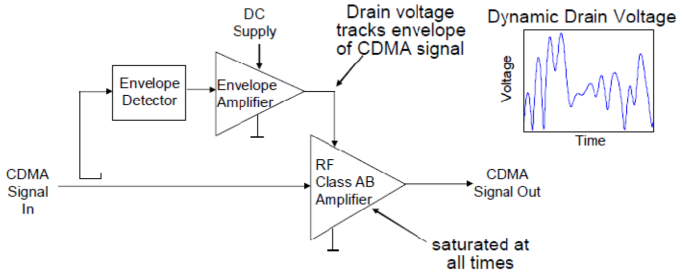


DPD Projections
Memoryless performance



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

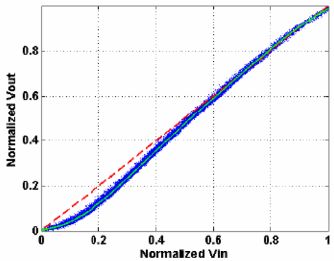
Philips Amplifier Results: LDMOS in ET System

	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

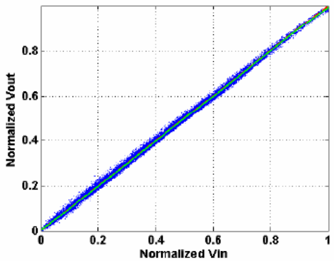
LDMOS Class AB amplifier for WCDMA *without ET* : PAE=___%

Memoryless Digital Predistortion

Original measurement



with memoryless DPD



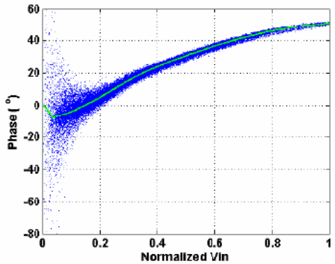
Blue points – instantaneous V_{out} vs. V_{in}

Purple line – gain target

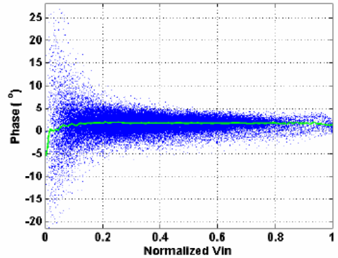
Green line – expected value of gain

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

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

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

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

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

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

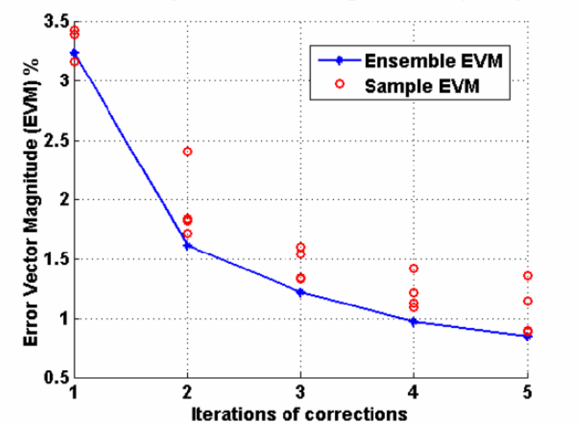
Noise: random

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

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

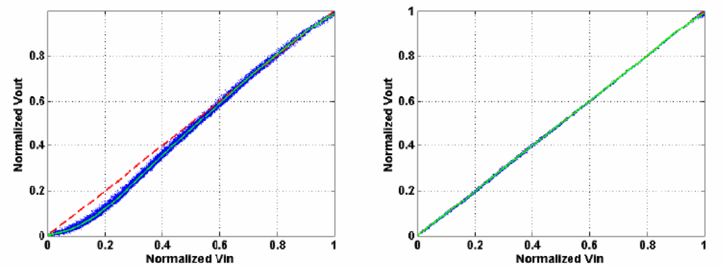
Note: *similarities to LMS algorithm*

RF Power Amplifier with Envelope Tracking Bias (ET)



Predistortion with Memory Model

Original measurement DPD including memory



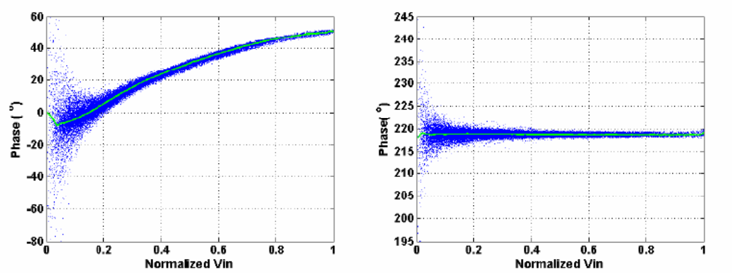
Blue points – instantaneous V_{out} vs. V_{in}

Purple line – gain target

Green line – expected value of gain

Predistortion with Memory Model (Phase)

Original measurement DPD including memory



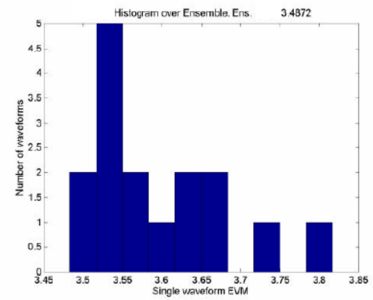
Blue points – instantaneous V_{out} vs. V_{in}

Purple line – phase target

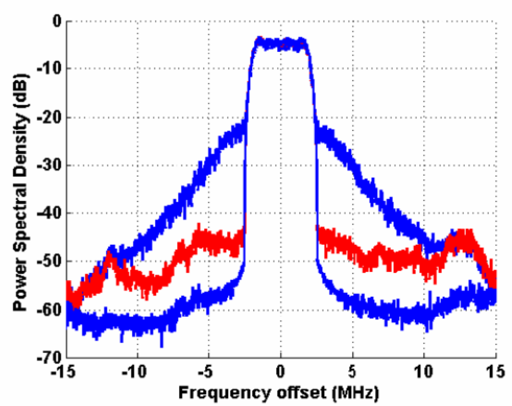
Green line – expected value of phase

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)

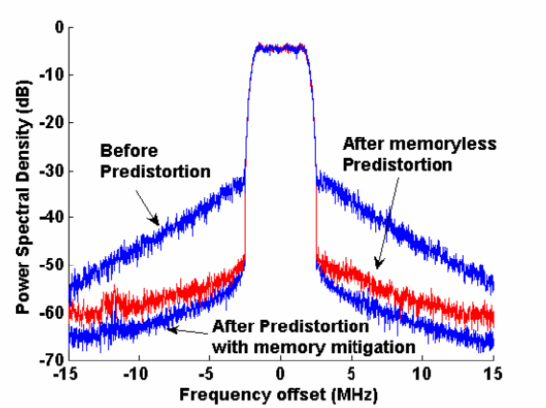


Nitronex Amplifier Results: GaN HFETs in ET System

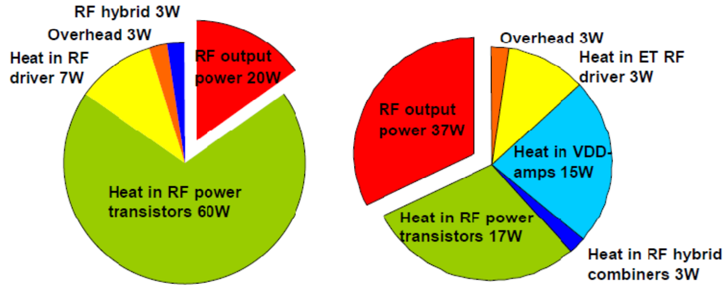
	Gain (dB)	Po (W)	DE (%)	PAE (%)	EVM (%)	ACLR1 (dBc)	ACLR2 (dBc)
Spec.		20 min			7	45	50
Before	10.3	36.5	51.7	49.3	12.1	-32	-41
After ML DPD	10	37.2	53.4	50.7	1.74	-48	-53
After Memory DPD	-	-	-	-	0.7	-52	-58

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

RF Power Amplifier with Envelope Tracking Bias (ET)



Heat Distribution Comparison



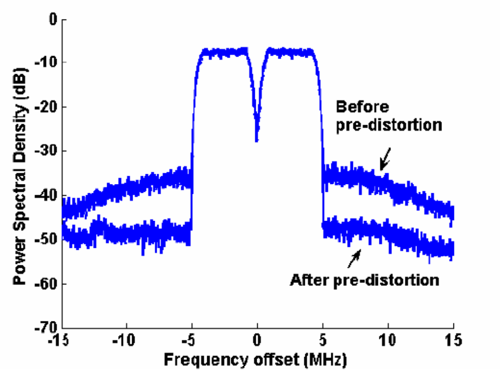
No ET, Predistortion only GaN HPA
Total Heat: 73 W

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.

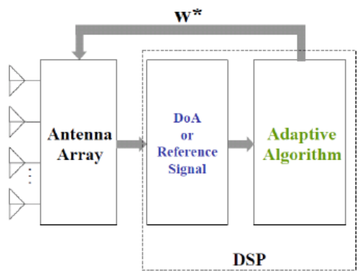
Smart Antenna and Signal Processing

Agenda

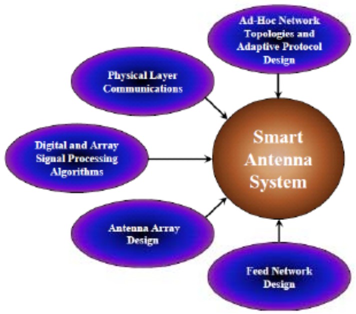
- What is Smart Antenna
- Why are Smart Antenna Systems important
- Impact of Antenna Array Characteristics on :
  1. Mobile Ad-hoc Networks Throughput
  2. Communication Channel BER
- Summary

What is a Smart Antenna ?

Typical Smart Antenna System



Areas of SAS



Why are Smart Antenna Systems important ?

Why are Smart Antenna Systems important ?

- SA integrate radio intelligence (DSP) with array antenna technology to :

  Enhance communication system performance, including :

  - Capacity (in urban area)
  - Range (in rural areas)

  Improve link quality for transmission and reception, by :

  - Multi-path management
  - Mitigation of fading

The previous are accomplished by:

- *Beam steering:*

  Placing beam maxima toward Signals Of Interest (SOI).

2. *Null steering:*

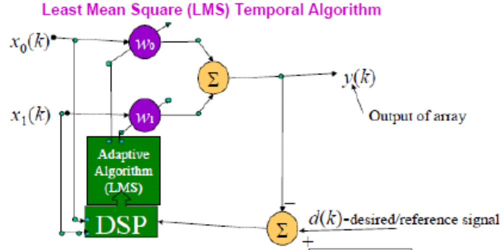
   Placing beam minima, ideally nulls, toward interfering signals;
   Signal Not Of Interest (SNOI).

3. *Spatially separate signals:*

   Allowing different users to share the same spectral and infrastructure resources (SDMA)

Beam-forming Linear Array

Least Mean Square (LMS) Temporal Algorithm

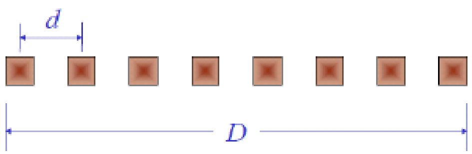


Based on the Weiner's solution: $\mathbf{w}^{opt} = \mathbf{R}^{-1}\mathbf{P}$

$$\mathbf{w}_{k+1} = \mathbf{w}_k + 2\mu\mathbf{x}_k\left(d_k - \mathbf{x}_k^T\mathbf{w}_k\right) \quad \text{where} \quad 0 < \mu < \frac{1}{\lambda_{max}}$$

- R ⇒ auto-correlation matrix of input signal $\mathbf{x}_k$
- P ⇒ cross-correlation matrix between input signal $\mathbf{x}_k$ and desired signal d_k
- λ_{max} ⇒ largest eigenvalue of the auto-correlation matrix **R**
- μ ⇒ convergence factor/step-size parameter; determines convergence rate

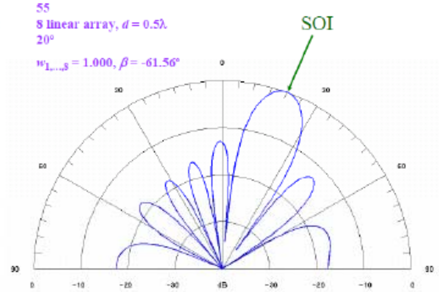
Linear Array Configuration



Beam-forming Linear Array Example

Type: *Array Factor*
Algorithm: LMS
Iterations: 55
Geometry: 8 linear array, $d = 0.5\lambda$
SOI 20°

Results: $w_{1,\ldots,8} = 1.000$, $\beta = -61.56°$



Weights and Phases Comparison

	Uniform (classical)		LMS (i = 55)	
Element	w	β (deg)	w	β (deg)
1	1.0000	0.00	1.0000	0.00
2	1.0000	-61.56	1.0000	-61.56
3	1.0000	-123.12	1.0000	-123.13
4	1.0000	-184.69	1.0000	-184.69
5	1.0000	-246.25	1.0000	-246.25
6	1.0000	-307.82	1.0000	-307.82
7	1.0000	-369.38	1.0000	-369.38
8	1.0000	-430.95	1.0000	-430.95

Linear Array

$N = 8$

$d = 0.5\lambda$

SOI = 20°

Antenna Geometries for Simulations

Weights and Phases Comparison

	LMS (i = 81)	
Element	w	β (deg)
1	1.0000	-11.62
2	0.8982	-57.05
3	1.1384	-109.98
4	1.3760	-178.77
5	1.3760	-252.21
6	1.1384	-321.01
7	0.8982	-373.94
8	1.0000	-419.37

Linear Array

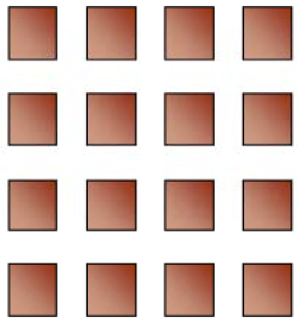
$N = 8$

$d = 0.5\lambda$

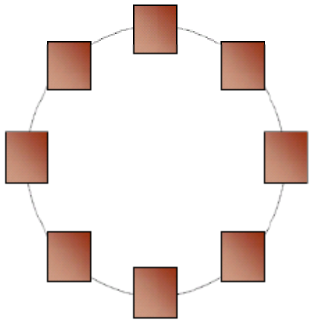
SOI = 20°

SNOI = 45°

Planar Array



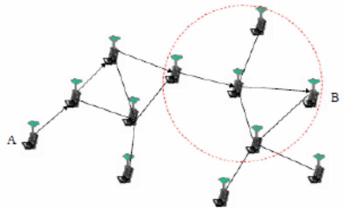
Circular Array



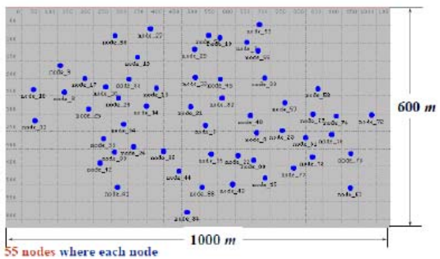
Mobile Ad-hoc Networks

Mobile Ad-hoc Networks (MANETs)

- Nodes move randomly, no fixed network infrastructure
  - Future wireless networks may not be planned and may evolve in an *ad-hoc* fashion
- Data packets are transferred in single hops



Network Model



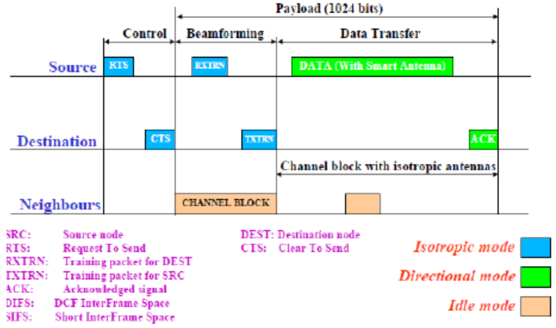
- 55 nodes where each node
  - models traffic as a Poisson distribution
  - mobility is modeled by changing position at random every two packets
- OPNET Modeler/Radio Tool is used to simulate the network

Channel Access in MANETs

Network traffic and access is controlled by adopting a protocol. The protocol chosen for the simulations is the:

Medium Access Control (MAC)

The MAC Protocol
(Based on IEEE 802.11 Standard for WLANs)



Simulation Parameters for MAC

Packet lengths used:

DIFS	0.023 L	Control Packets
SIFS	0.004 L	
RTS	0.011 L	
CTS	0.011 L	
ACK	0.011 L	
TXTRN	Variable	Beamforming Packets
RXTRN	Variable	
DATA	L	Payload (Data)

Network Through-put Simulations

Network Though-put Simulations

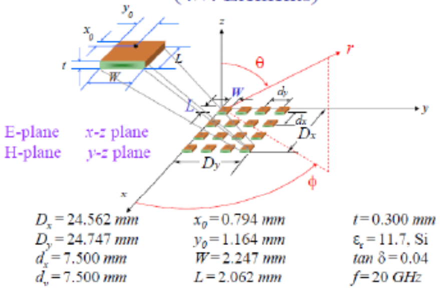
- Array Size (4×4 vs. 8×8)
- Array Distribution (Uniform vs. Tschebyscheff)
- Adaptive vs. Nonadaptive Array
- Beamforming Training Time

Network Through-put Simulations

- Array Size (4×4 vs. 8×8)
- Array Distribution (Uniform vs. Tschebyscheff)

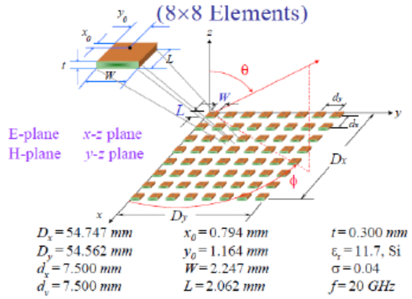
Planar Array Configuration

(4×4 Elements)

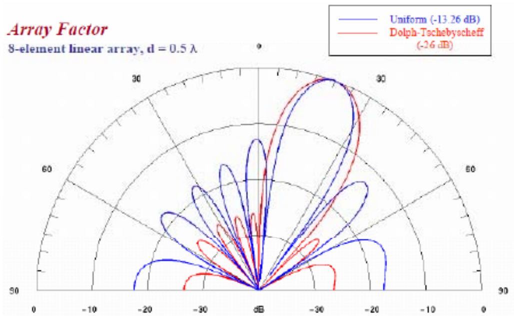


Planar Array Configuration

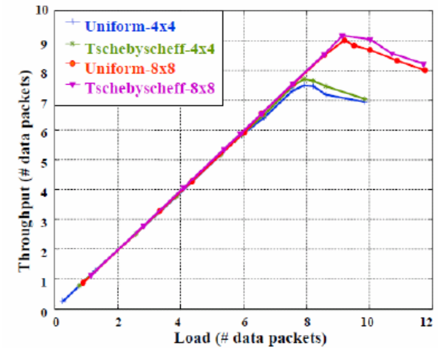
(8×8 Elements)



Array Design



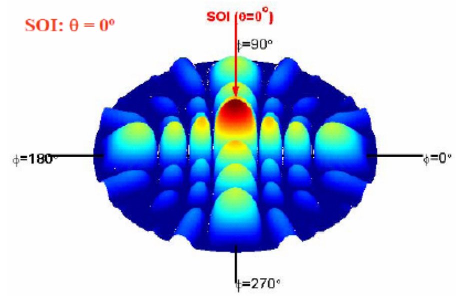
Through-put for Different Antenna Patterns



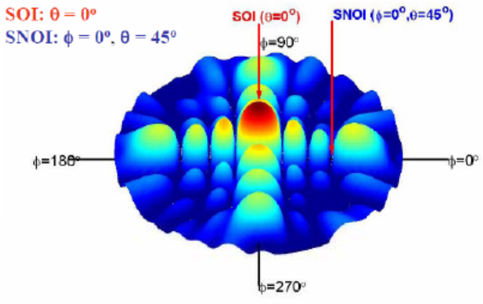
Network Through-put Simulations

- Adaptive vs. Non-adaptive Array

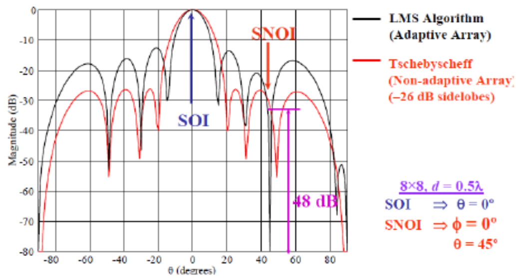
Non-adaptive Pattern



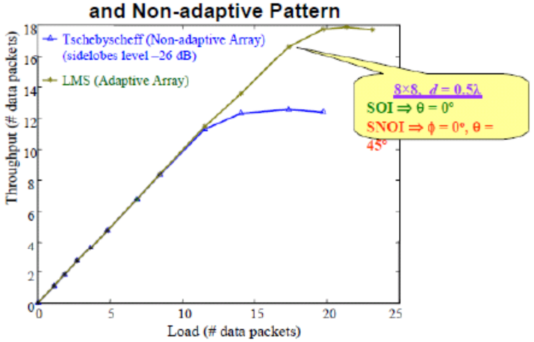
Adaptive Pattern



LMS Algorithm (Adaptive Pattern) vs. Tschebyscheff (Non-adaptive Pattern)



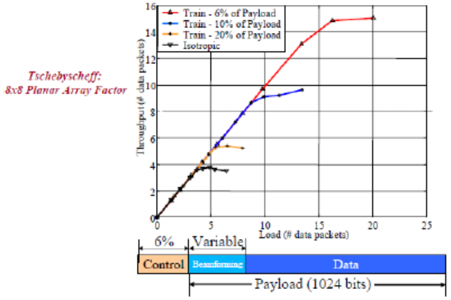
Through-put for adaptive Pattern and Non-adaptive Pattern



Network Throughput Simulations

Beam-forming Training Time

Through-put for Different Training/Beam-forming Periods



Summary

Based on the Network Simulations, MANETs employing smart antennas can achieve higher capacity, as measured by *throughput*, by the using the following antenna array designs guidelines:

- Larger planar arrays (in this project: 8 x 8 vs. 4 x 4)
- Lower sidelobes (in this project: -26 dB vs. -13.26 dB)
- Fully adaptive array with deep nulls/minima towards the SNOIs
- Short beamforming training times

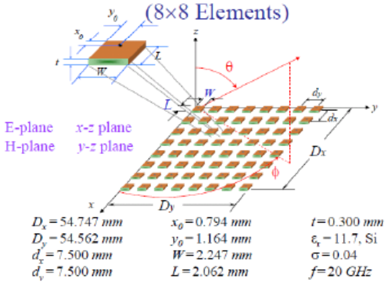
Communication System BER

Binary Phase Shift Keying (BPSK)
vs.
Trellis Coded Modulation (TCM)
vs.
Multipath/Fading

Signals Corrupted with
Additive White Gaussian Noise Channel (AWGN)

Binary Phase Shift Keying (BPSK) over AWGN

Planar Array Configuration

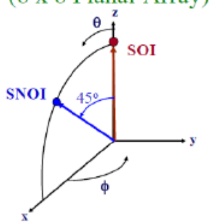


Signal used for Antenna Pattern Adaptation

	SOI		SNOI	
	ϕ_o	θ_o	ϕ_o	θ_o
Case 1*	0^o	0^o	0^o	45^o
Case 2	45^o	30^o	45^o	60^o

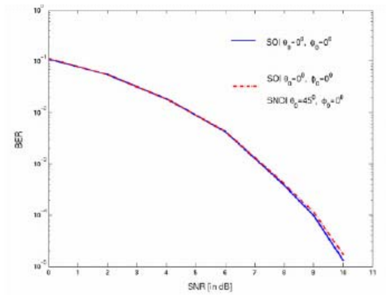
Case I
SOI: $\phi = 0^o$, $\theta = 0^o$
SNOI: $\phi = 0^o$, $\theta = 45^o$

(8 x 8 Planar Array)



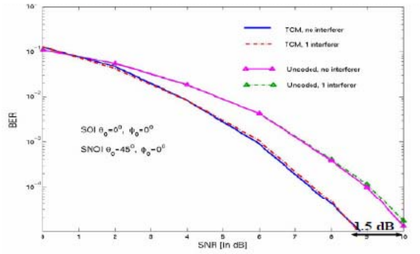
Workshop: Reconfigurable and Smart Antennas IMS 2007:

BER over Binary/Uncoded AWGN Channel
(using 60 symbols for training sequence)



Trellis Code QPSK Modulation over AWGN Channel

BER over AWGN Channel (Uncoded/Binary vs. Trellis Code Mod.)

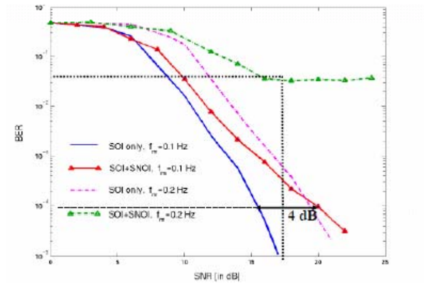


Rayleigh Fading Channel

- *BER* over Rayleigh fading channel with Doppler spreads of $f_m = 0.1$ Hz ($f_m T = 0.001$) and $f_m = 0.2$ Hz ($f_m T = 0.002$)
- The length of the training symbol is 60 symbols and is transmitted periodically every data sequence of length 940 symbols.

(Symbol duration: $T = 10$ ms)

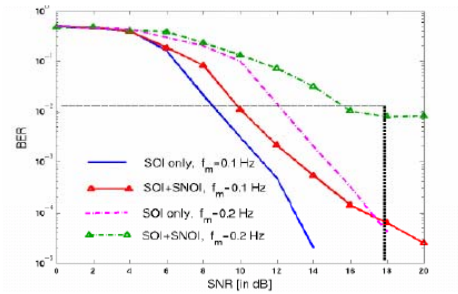
Rayleigh Fading-Binary/Uncoded Channel



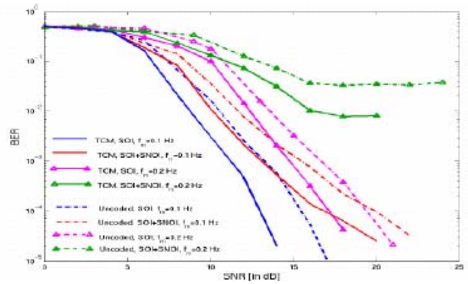
- BER for trellis coded QPSK modulation over Rayleigh fading channel with Doppler spreads of $f_m = 0.1$ Hz ($f_m T$=0.001) and $f_m = 0.2$ Hz ($f_m T = 0.002$) for both cases.
- The length of the training symbol is 60 symbols and is transmitted periodically every data sequence of length 940 symbols.

(Symbol duration: $T = 10$ ms)

Rayleigh Fading Coded Channel (TCM)

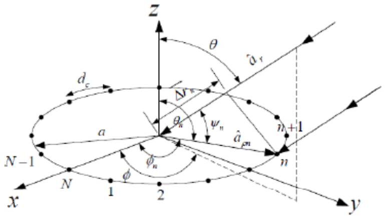


BER over Rayleigh Fading Channel (Binary/Uncoded vs. TCM)



Uniform Circular Arrays (UCAs)

Uniform Circular Array



Communication System BER

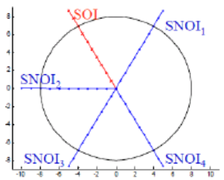
Binary Phase Shift Keying (BPSK)
vs.
Trellis Coded Modulation (TCM)

Signals Corrupted with
Additive White Gaussian Noise Channel (AWGN)

Simulation Environment of UCA

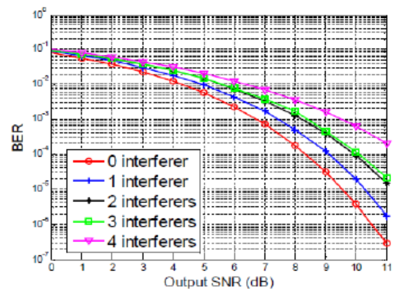
Equal power signals in the same azimuth plane with AWGN

$N = 8,\ d_c = \lambda/2,\ a = 2\lambda/\pi$

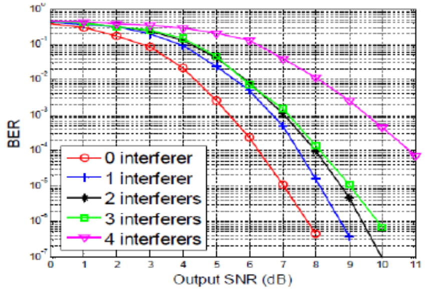


SOI	θ=90°	ϕ=120°
$SNOI_1$	θ=90°	ϕ=60°
$SNOI_2$	θ=90°	ϕ=180°
$SNOI_3$	θ=90°	ϕ=240°
$SNOI_4$	θ=90°	ϕ=300°

Binary Phase Shift Keying



Trellis Code Modulation



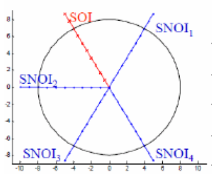
Trellis Code Modulation (TCM)

Well Separated SNOIs
vs.
Random SNOIs

Simulation Environment of UCA

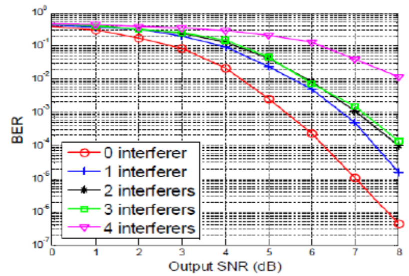
Equal power signals in the same azimuth plane with AWGN

$N = 8,\ d_c = \lambda/2,\ a = 2\lambda\pi$

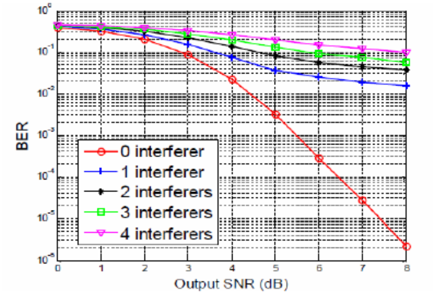


SOI	θ=90°	φ=120°
$SNOI_1$	θ=90°	φ=60°
$SNOI_2$	θ=90°	φ=180°
$SNOI_3$	θ=90°	φ=240°
$SNOI_4$	θ=90°	φ=300°

Well-separated Signals



Random SNOIs (5000 simulations)



Conclusion

By incorporating appropriate adaptive antenna array designs, and digital signal processing and communication algorithms,

Smart Antenna Systems (SAS) can:

- Increase network capacity/*throughput*
- Decrease Communication channel *Bit-Error-Rate* (*BER*)