Adaptive Pre-Distorters for Linearization of High Power Amplifiers in OFDM Wireless Communications

(IEEE North Jersey Section CASS/EDS Chapter Distinguished Lecture)

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04/03/2006

Outline

- PART I: Introduction: Our Vision of Technology
- PART II: What is MC/OFDM? - Key Advantages
  - Major Stumbling Block: PAPR
- PART III: Some of the Available Techniques for Mitigation of PAPR in MC/OFDM Transmission – Brief Review
- PART IV: Our Adaptive Pre-Distorters (APD) for Elimination/Mitigation of Nonlinear distortion and hence
- Part V: Other Development: A Tree-PTS Algorithm for Reduction of PAPR
- PART VI: Conclusion: Summary of Presentation and Work in Progress

PART I

INTRODUCTION

Our Vision of Technology

Insertion of Nonlinear/Intelligent Signal Processing
into
Emerging Broadband/Wideband Telecommunications Technologies

What is Broadband Communications?
HIGH DATA TRANSFER RATES
to DEVICES transmitting information

- **2G Wireless Networks**
  - ***voice only***
- **3G Wireless Networks**
  - ***voice and data***
- **4G Wireless Networks**
  - ***Complete merger of computer, telephone, audio, video, motion, and Internet***

What is NONLINEAR SIGNAL PROCESSING?

- **Complete (Linear and Nonlinear) Analytical Processing of Data**

<CHALLENGES AND OPPORTUNITIES>

- **Nonlinear System/Filter MODELING**
- **Nonlinear System/Filter IDENTIFCATION**
- **Nonlinear System/Filter DESIGN**
- **Including: ADAPTATION, LEARNING, EVOLUTION, DISCOVERY, & INVENTION/INNOVATION**

Merger of BROADBAND & NONLINEAR

Will enable:

- Dramatic Increase in Signal Power **Eliminating resulting Nonlinear Distortion And Spectral Leakage**
- Suppression of Non-Gaussian Noise **present in emerging applications**
- Computational Intelligence to play the role of natural intelligence **in human/device and device/device communications**

Merger of BROADBAND & NONLINEAR

Therefore:

FUTURE DIRECTION

- **As humans, electronic sensing and robotic devices, and Internet become *seamlessly integrated*,** NONLINEAR SIGNAL PROCESSING will play an increasingly prominent role in 3G, 4G, 5G, 6G, … Wireless Networks/Internet in the 21st Century

Physical Layer Issues toward future generations Wireless Communications

- MIMO (Multiple Input Multiple Output)
  - Spatial Multiplexing
  - Space Time Coding
- Turbo and LDPC code
- Smart Antenna
- Multi-Carrier (MC) / Orthogonal Frequency Division Multiplexing (OFDM)

PART II

What is MC/OFDM

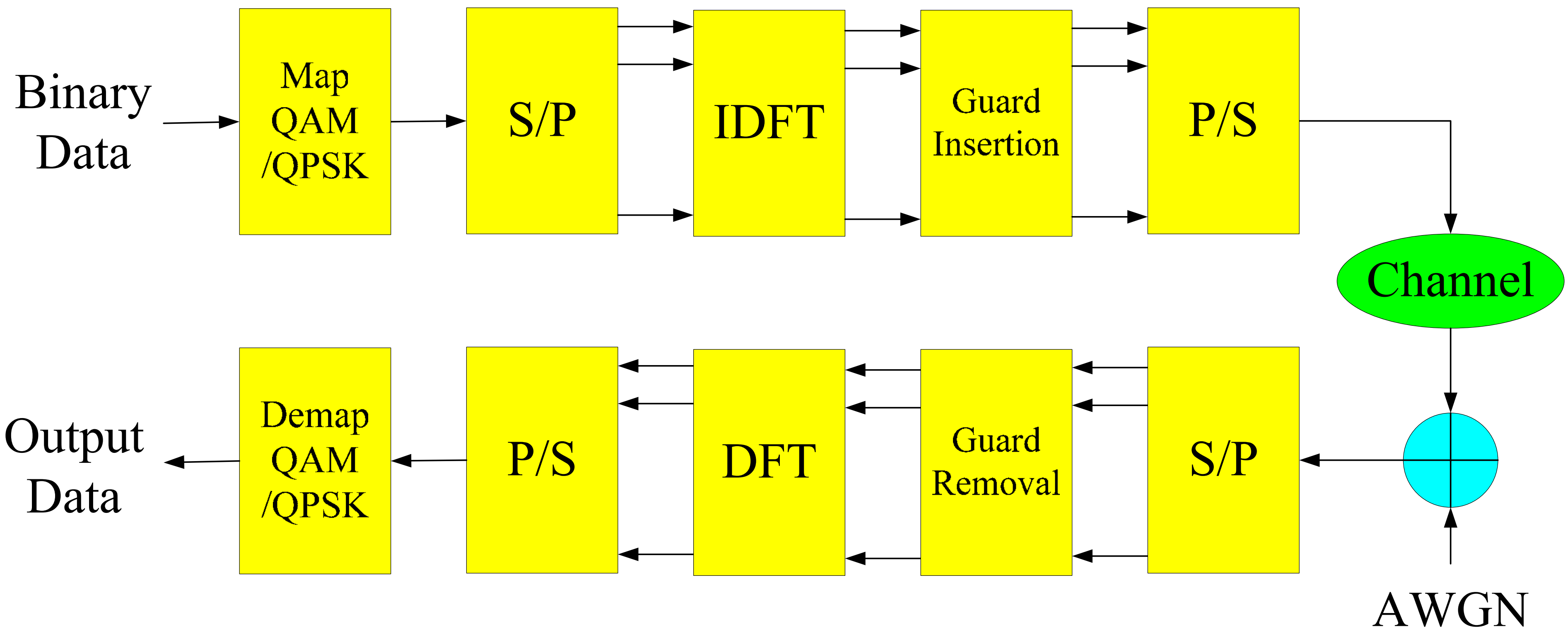
- *Key Advantages*

- Major *Stumbling Block: PAPR*

Orthogonal Frequency Division Multiplexing (OFDM)

- **Multi-carrier modulation/multiplexing technique**
- **Available bandwidth is divided into several sub-channels**
- **Data is serial-to-parallel converted**
- **Symbols are transmitted on different sub-carriers (IDFT is used)**
- **Well-suited for broadband data transmission in wireless channel.**

Block diagram of OFDM system

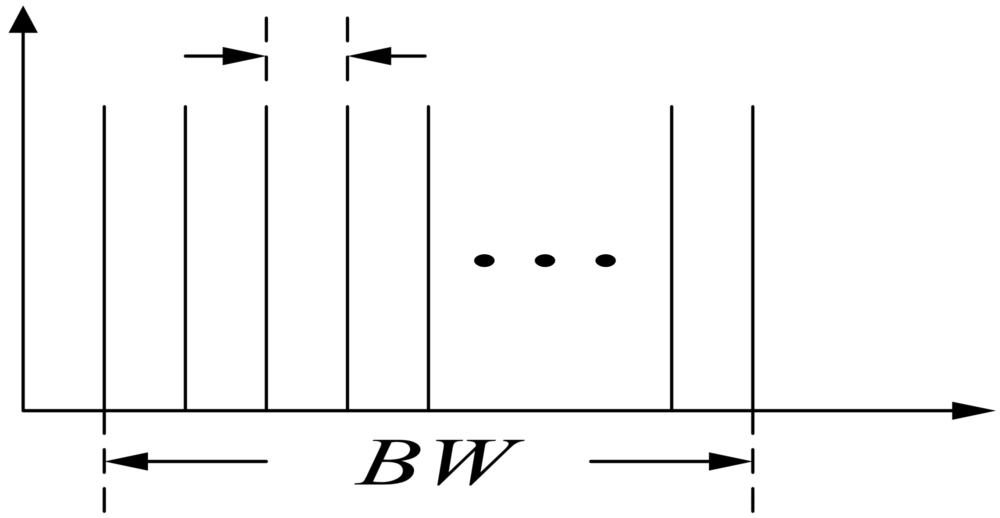


OFDM signal

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j 2\pi f_k t}$$

- where denotes QAM symbol, N is the number of subcarriers, f_k and k^{th} is subcarrier frequency which can be represented as $f_k = k \cdot \frac{1}{N T_s} = k \cdot \frac{1}{T}$

$$\Delta f = BW / N$$



Advantages of OFDM

- **Robustness in multi-path propagation environment**
- **Efficient frequency utilization**
- **High speed transmission systems possible**

OFDM is used in several standards (IEEE 802.11 a/g/n…etc)

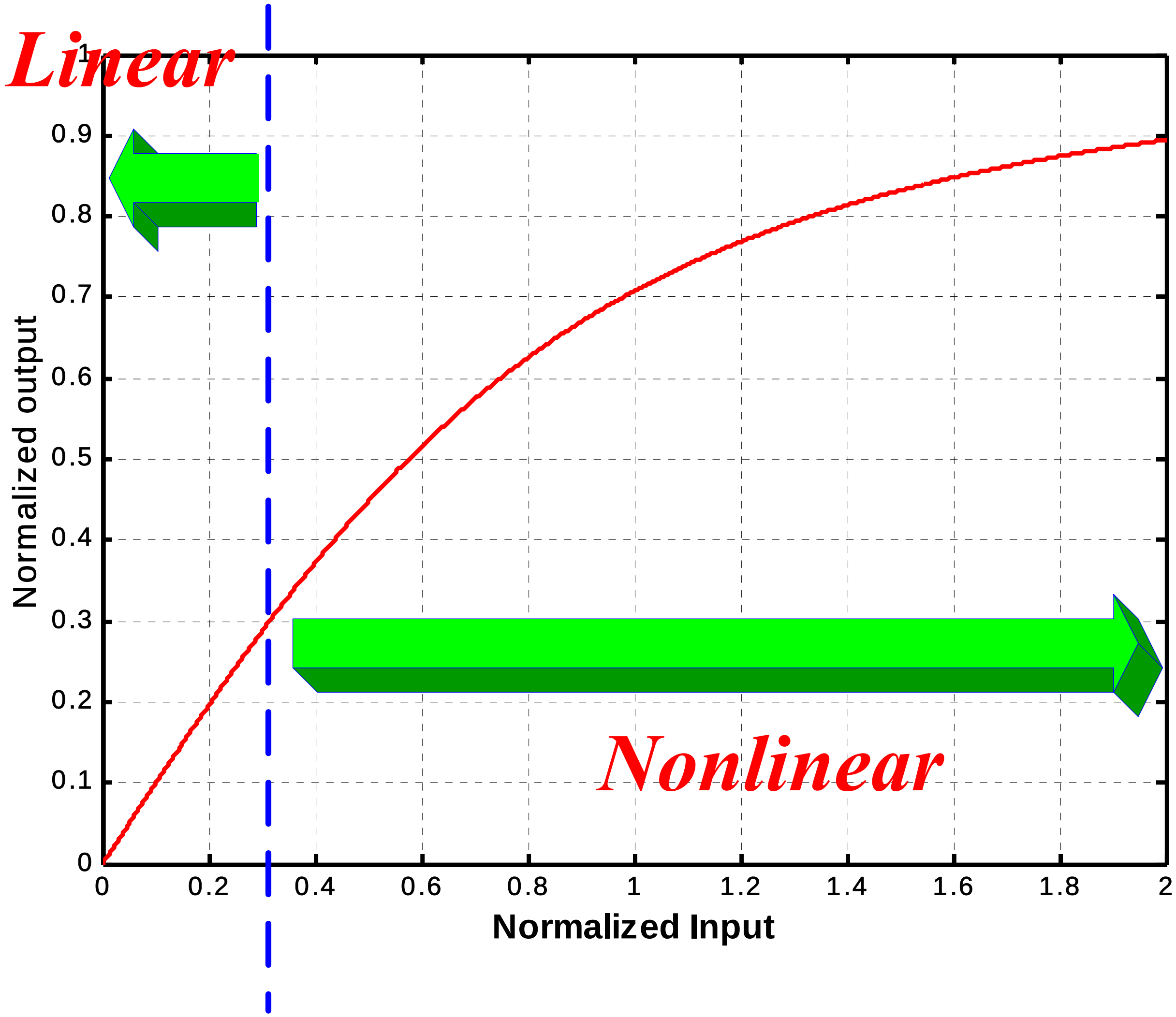
OFDM is a Prime Candidate for Several Next Generation Wireless System

Main Disadvantage of OFDM

- **High Peak-to-Average Power Ratio (PAPR)**
  - Summation in IDFT causes large PAPR and issue of amplifier non-linearity arises

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j\frac{2\pi kn}{N}}$$

The problem of nonlinear HPA



PART III

Some of the Available Techniques for Mitigation of PAPR in MC/OFDM Transmission: *Brief Review*

PAPR reduction techniques

(1) Clipping and Filtering

(2) Coding

(3) Partial Transmit Sequence (PTS)

(4) Selective Mapping (SLM)

(5) Interleaving

(6) Tone Reservation / Injection

(7) Active Constellation Extension (ACE)

(8) Companding

PAPR reduction techniques

- **Clipping and Filtering**

$$\hat{x}(n) = \begin{cases} x(n), & |x(n)| \le A_{\max} \\ A_{\max} e^{j\phi(n)}, & |x(n)| > A_{\max} \end{cases}$$

where $A_{\max}$ is maximum allowable amplitude after clipping and $\phi(n)$ is phase of input signal.

- To reduce Out of Band Radiation (OBR), Filtering is necessary

PAPR reduction techniques

- **Coding**
  - Reduce PAPR by block coding
  - Need a lot of redundancy
  - Usually no error correction capability

PAPR reduction techniques

- **Partial Transmit Sequence (PTS)**
  - Data block is partitioned several disjoint subblocks.
  - Each sub-block is weighted by a phase factor to reduce PAPR.
  - SI (Side Information) is necessary.

PAPR reduction techniques

- **Selective Mapping (SLM)**

  - From one input signal, generate several different OFDM signals

  - Among them, choose the signal which shows minimum PAPR

  - SI (Side Information) is necessary.

PAPR reduction techniques

- **Inter-leaving**
  - Several inter-leavers are used to generate several OFDM signals.
  - The performance is depending on the number of inter-leavers and design of inter-leavers.

PAPR reduction techniques

- **Tone Reservation (TR) / Injection (TI)**
  - Some of sub-carriers are reserved for PAPR reduction of OFDM signal (TR).
  - Increase the constellation size so that each of the points in the original basic constellation can be mapped into several equivalent points in the expanded constellation (TI).

PAPR reduction techniques

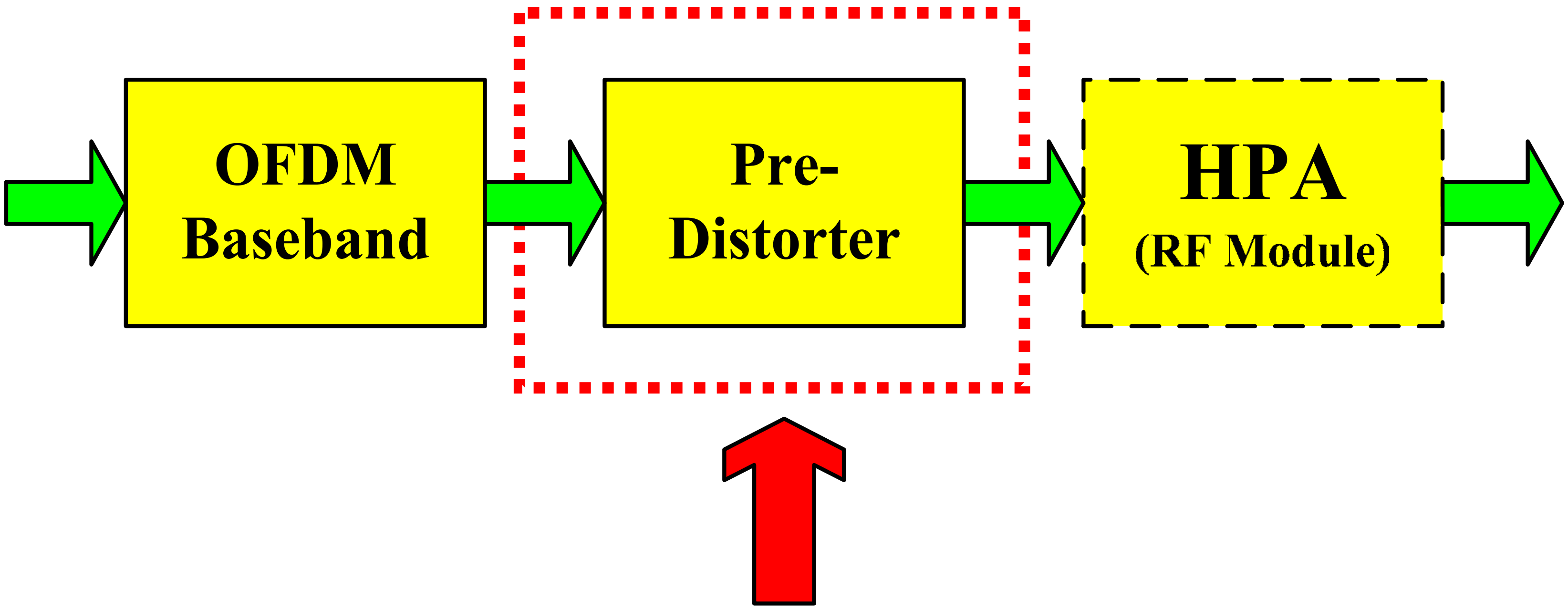
- **Active Constellation Extension (ACE)**
  - Some of the outer signal constellation points in the data block are dynamically extended toward the outside of the original constellation such that the PAPR of the data block is reduced.

- **Companding**
  - Compress the signal before going through the HPA and de-compress the signal at the receiver

PART IV

New Adaptive Pre-Distorters (APD) for Elimination/Mitigation of Nonlinear distortion

PRE-DISTORTER



New Pre-Distorters

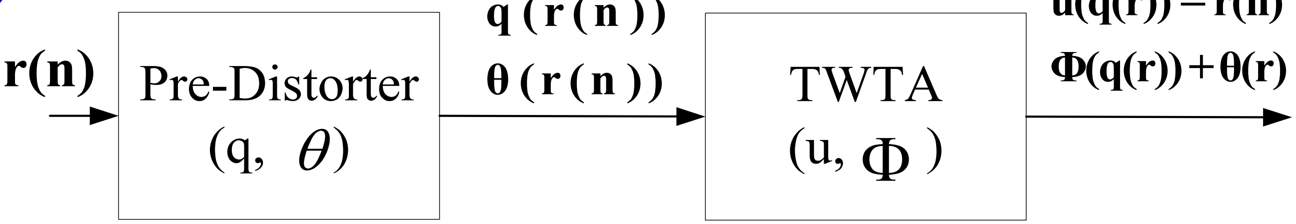
- **New model-based PDs for TWTA and SSPA developed by us will be described**
- **(Re.: Byung Moo Lee and R. J. P. de Figueiredo, "Adaptive Pre-Distorters for Linearization of High Power Amplifiers in OFDM Wireless Communications,"** ***Circuits, Systems & Signal Processing*****, vol.25, no.1, Feb. 2006, pp.59-80)**

- **Rather than general approximation of nonlinear systems, we use exact inverses of Saleh's TWTA model and Rapp's SSPA model (*our approach can be applied to other similar analytic models based on analogous analytic processing of the signal*).**

- **Much lower complexity than other approaches and little time delay**

- **Fast learning capabilities because of few parameters**

Pre-distorter-equipped TWTA system



$u(q(r)) = r(n)$

$\Phi(q(r)) + \theta(r) = 0$

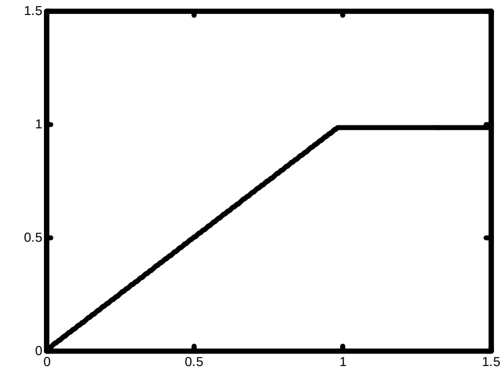
$$q(r) = \frac{\alpha - \sqrt{\alpha^2 - 4r^2\beta}}{2r\beta}$$

$$u[q(r)] = \frac{\alpha q(r)}{1+\beta q(r)^2} = r(n)$$

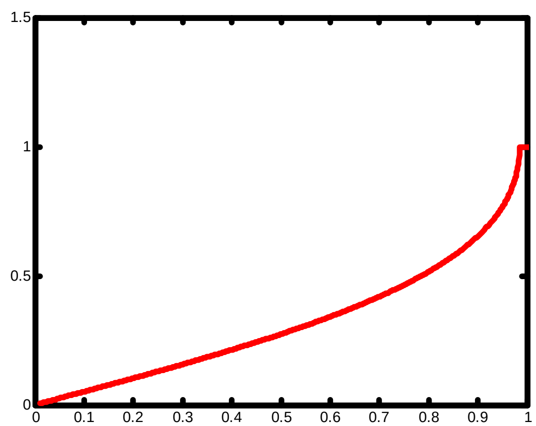
$$\theta(r) = -\Phi(q) = -\frac{\gamma (q(r))^2}{1+\varepsilon (q(r))^2}$$

(Exact Inverse)

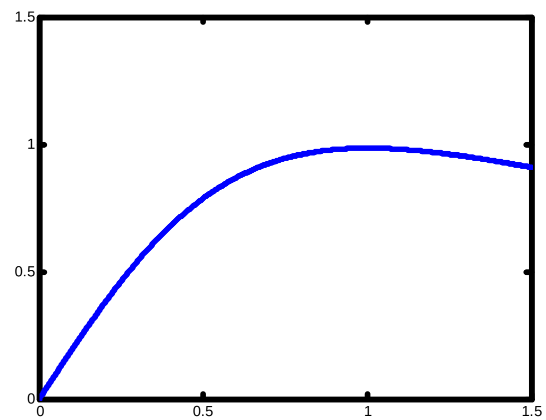
$$\Phi[q(r)] = \frac{\gamma q(r)^2}{1+\varepsilon q(r)^2}$$



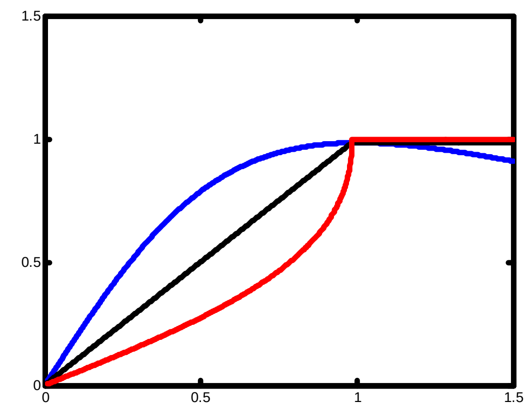
< u(q(r(n))) = r(n) >



< PD, exact inverse>

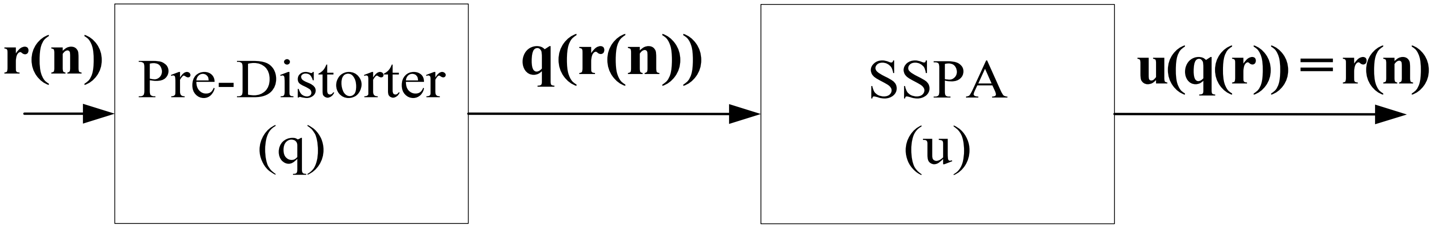


< TWTA model>



< PD+TWTA= compensation>

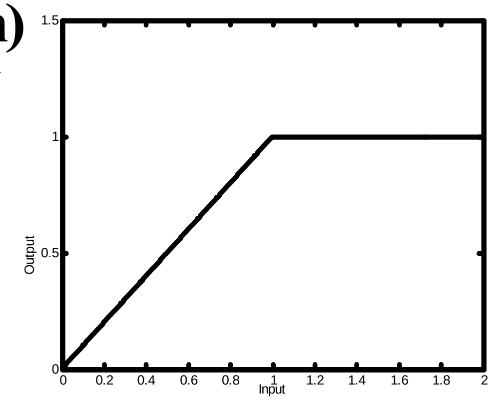
Pre-distorter-equipped SSPA system



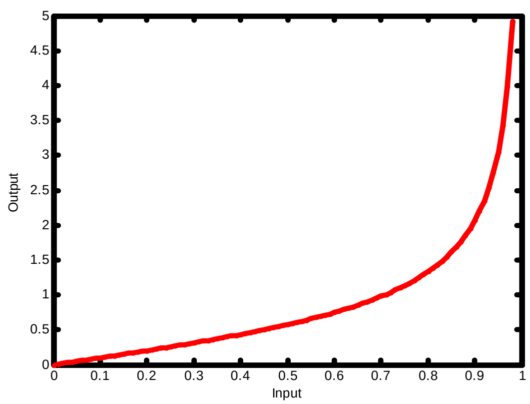
$$q[r(n)] = \frac{r(n)}{\left[1 - \left(\frac{r(n)}{A_o}\right)^{2p}\right]^{\frac{1}{2p}}}$$

(Exact Inverse)

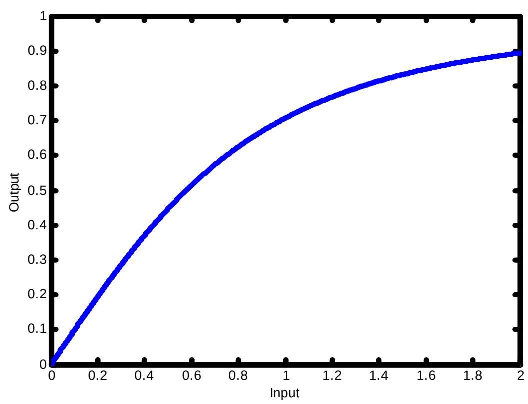
$$u[q(r)] = \frac{q(r)}{\left[1 + \left(\frac{q(r)}{A_o}\right)^{2p}\right]^{\frac{1}{2p}}} = r(n)$$



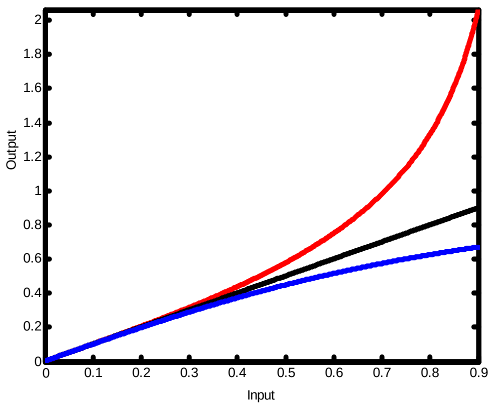
$< u(q(r(n))) = r(n) >$



< PD, exact inverse>

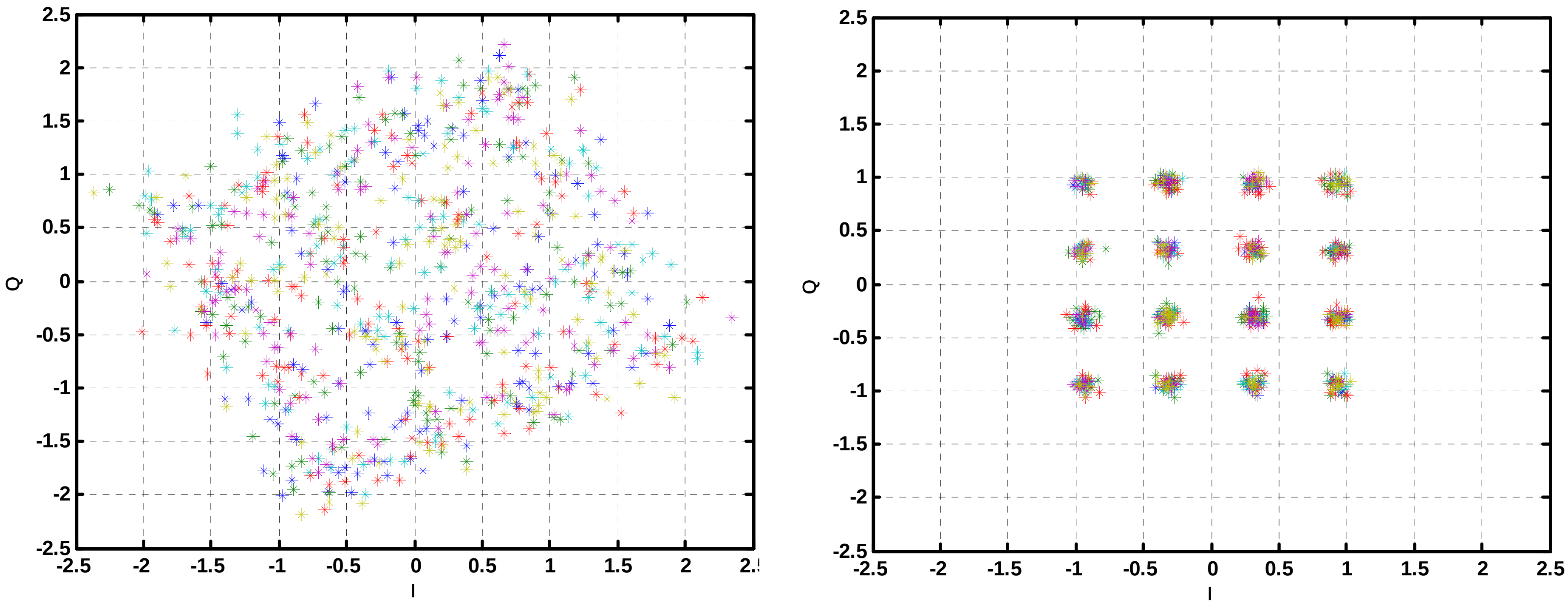


< SSPA model>

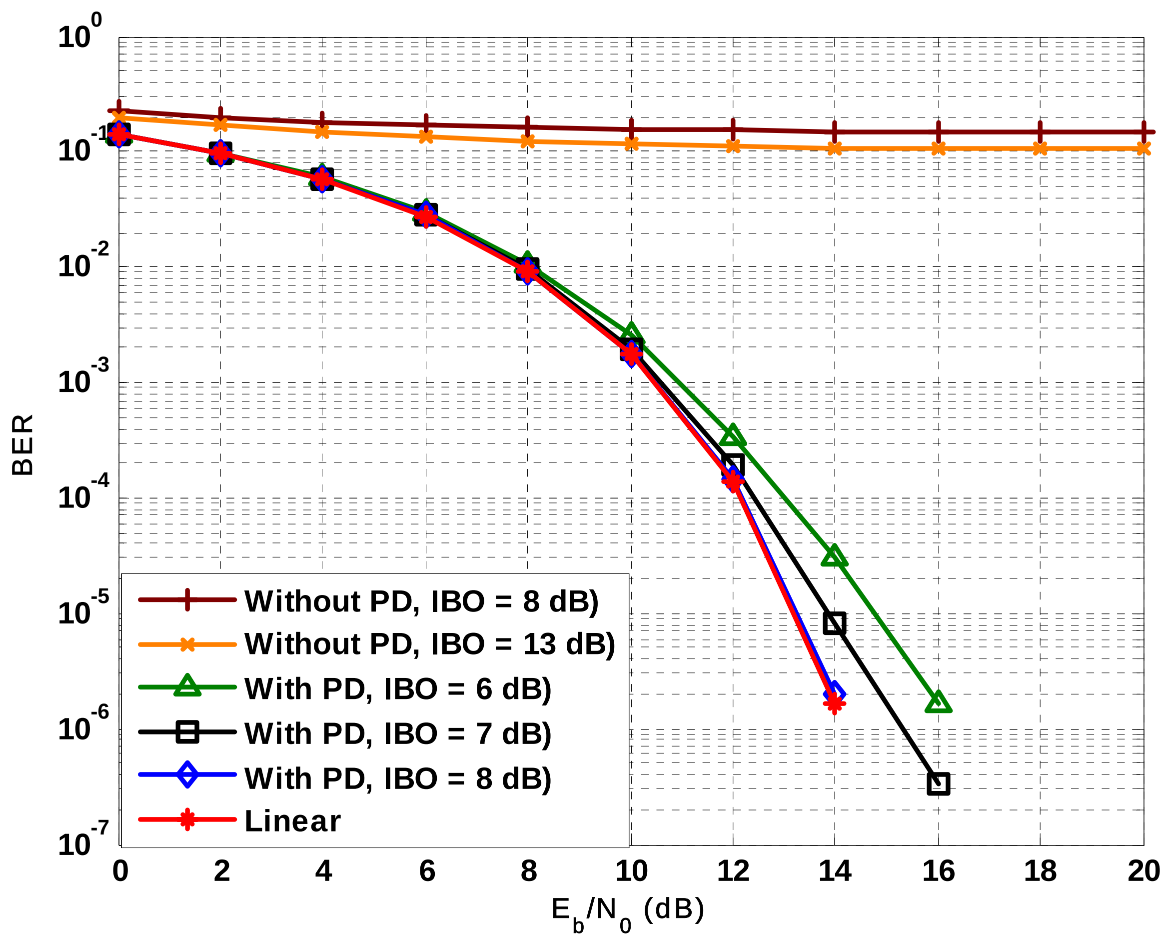


<PD+SSPA= compensation>

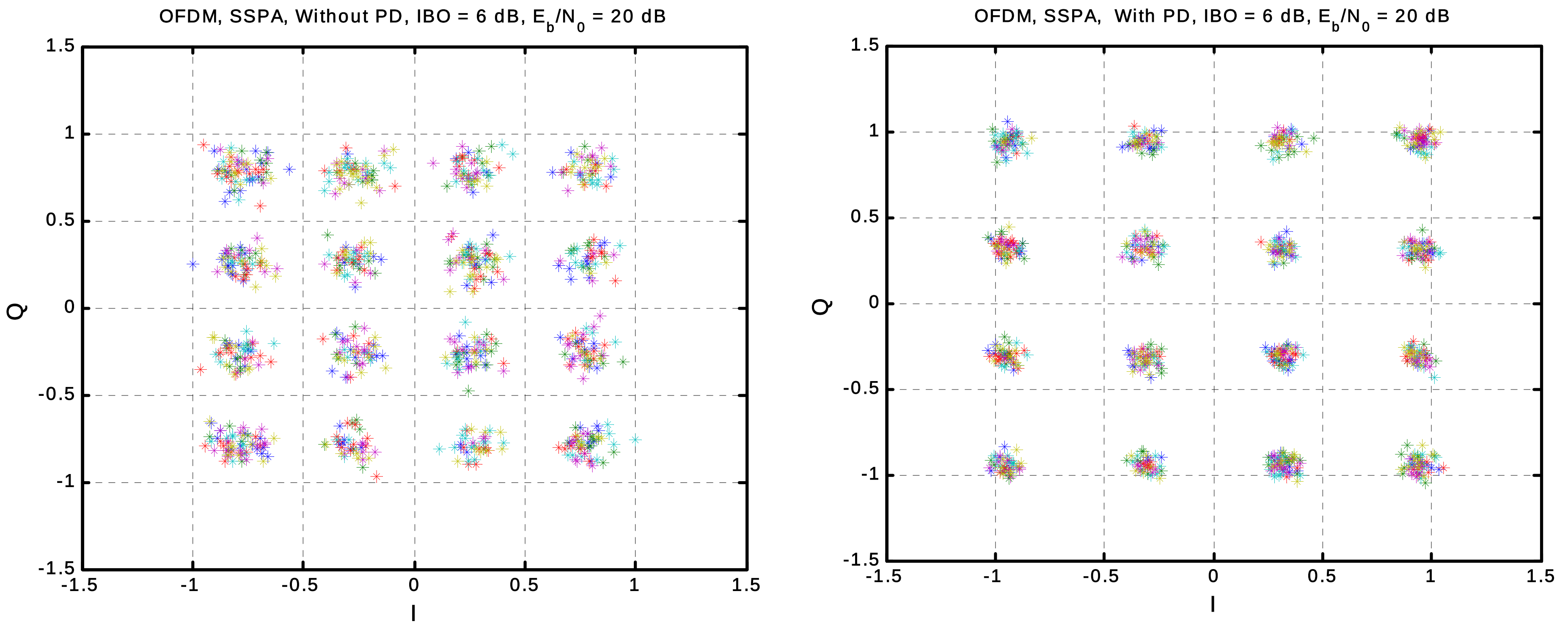
Simulation Result of TWTA With and Without PD, IBO=6dB, SNR= 20dB



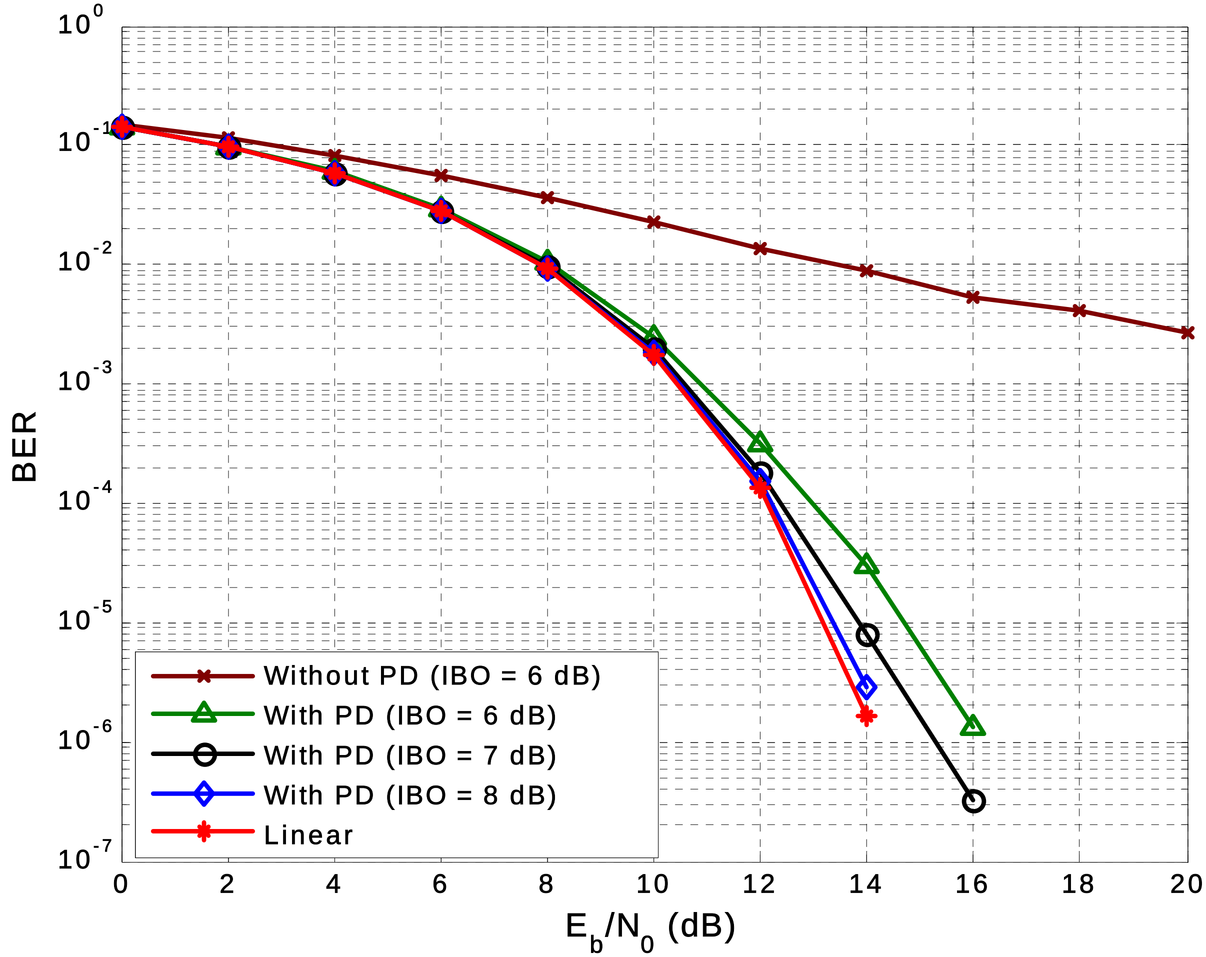
Simulation Result of TWTA With and Without PD



Simulation Result for SSPA
With and Without PD, IBO =6dB, SNR=20dB



Simulation Result of SSPA with and without PD



$$A_0 = 1 \qquad p = 1$$

PART V

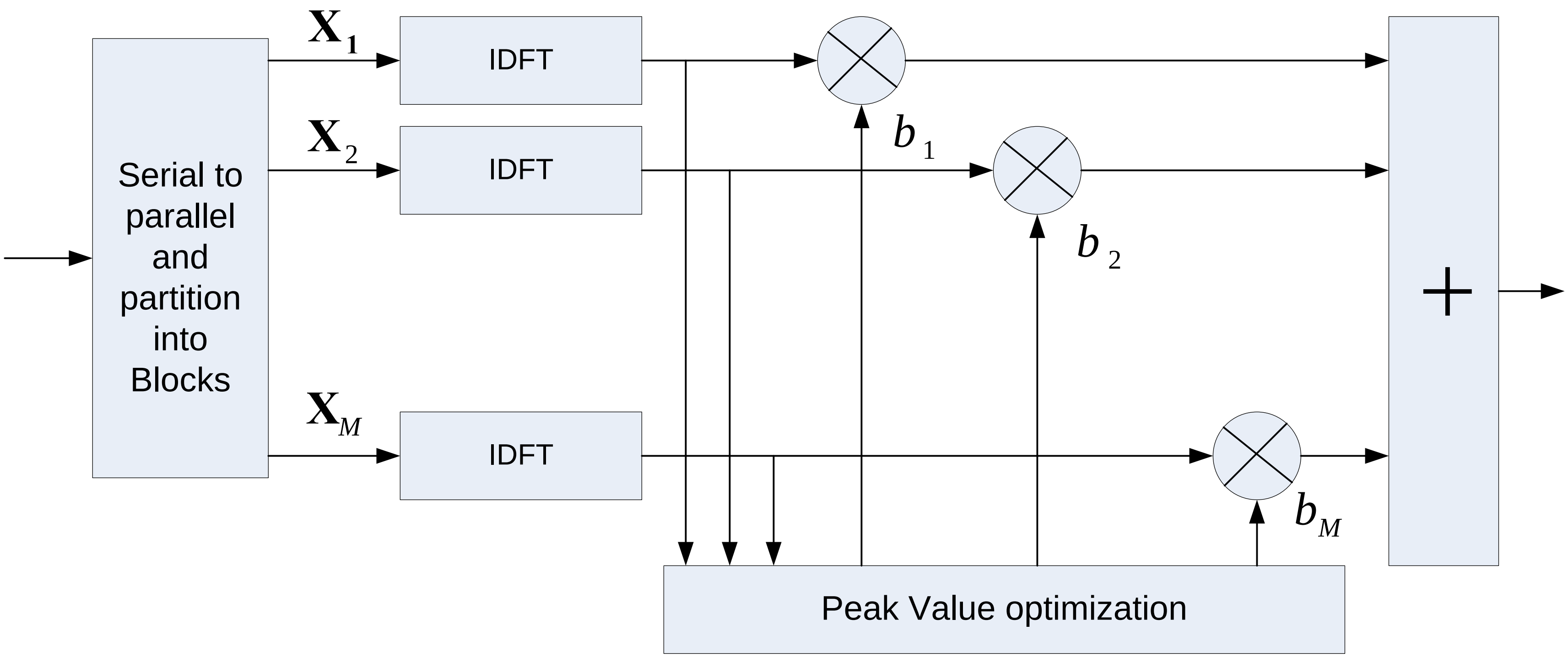
Emerging Development: *Intelligent/Nonlinear Approach*

Combination of our ADP with a Tree-PTS Algorithm

for mitigation of PAPR in MC/OFDM

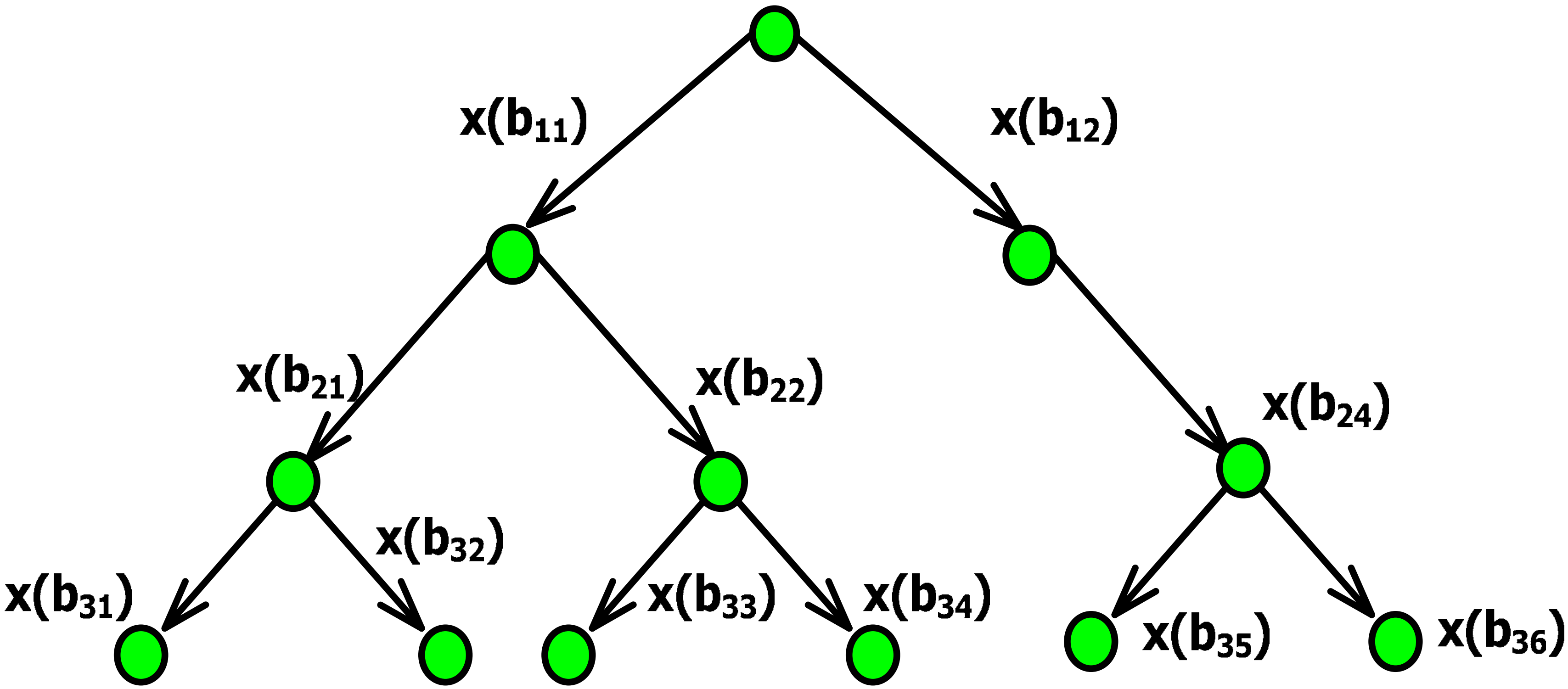
(to appear in *Proc. of ICASSP 2006*)

RECALL: Partial Transmit Sequence (PTS) PAPR reduction technique



$$\mathbf{x}'(\mathbf{b}) = \sum_{m=1}^{M} b_m \cdot \mathbf{x_m}$$

Tree Algorithm



The T-PTS is generalization of PTS technique

- By adjusting two adjustable parameters in T-PTS technique, we can get almost any level of intermediate complexity and performance

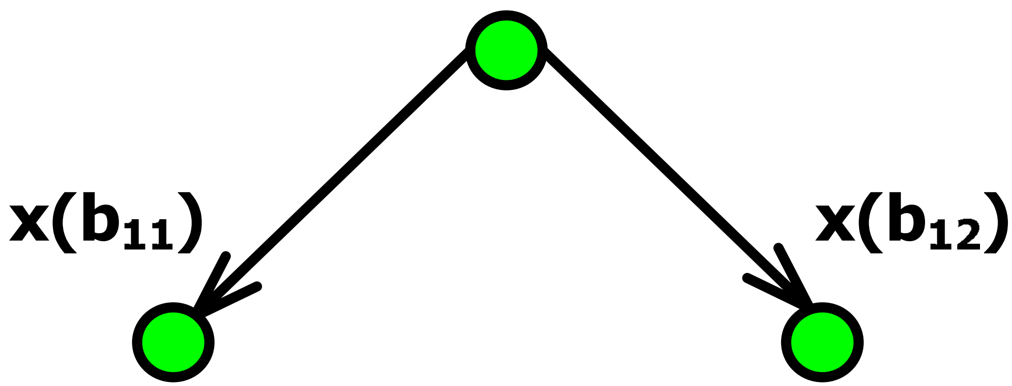
Two Core Steps

- Instead of keeping all of PAPRs and phase information, we keep S of PAPRs and phase information in each subblock where $1 \leq S \leq W$.

- Instead of keeping information until the end of subblock, we keep until T *th* subblocks and continue iteratively where $1 \leq T \leq M$.

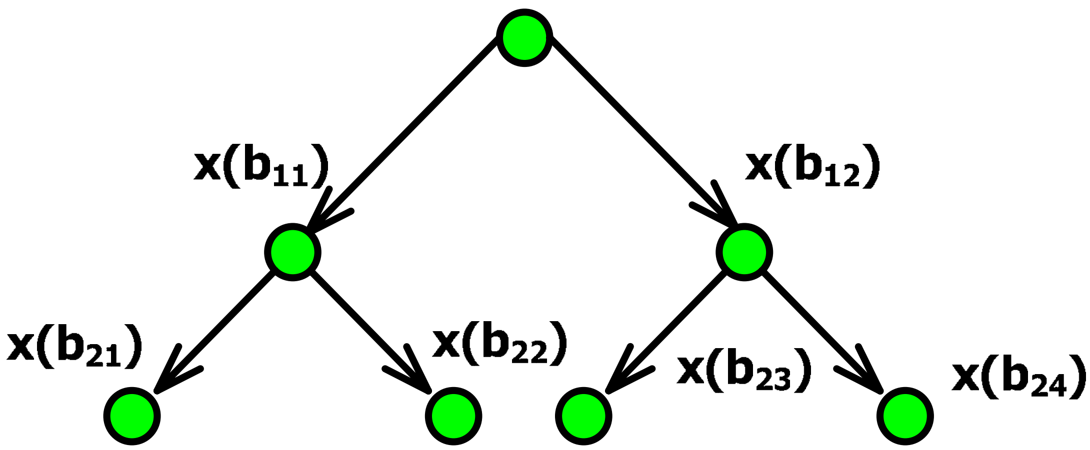
Example of T-PST algorithm (1)

- Let us assume S=2, T=2.
- In the first subblock, calculate PAPRs of the OFDM signals after rotate phases of subblocks using *W* phases factors
- Keep only *S* = 2 phase factors which show minimum PAPRs among *W* phase factors

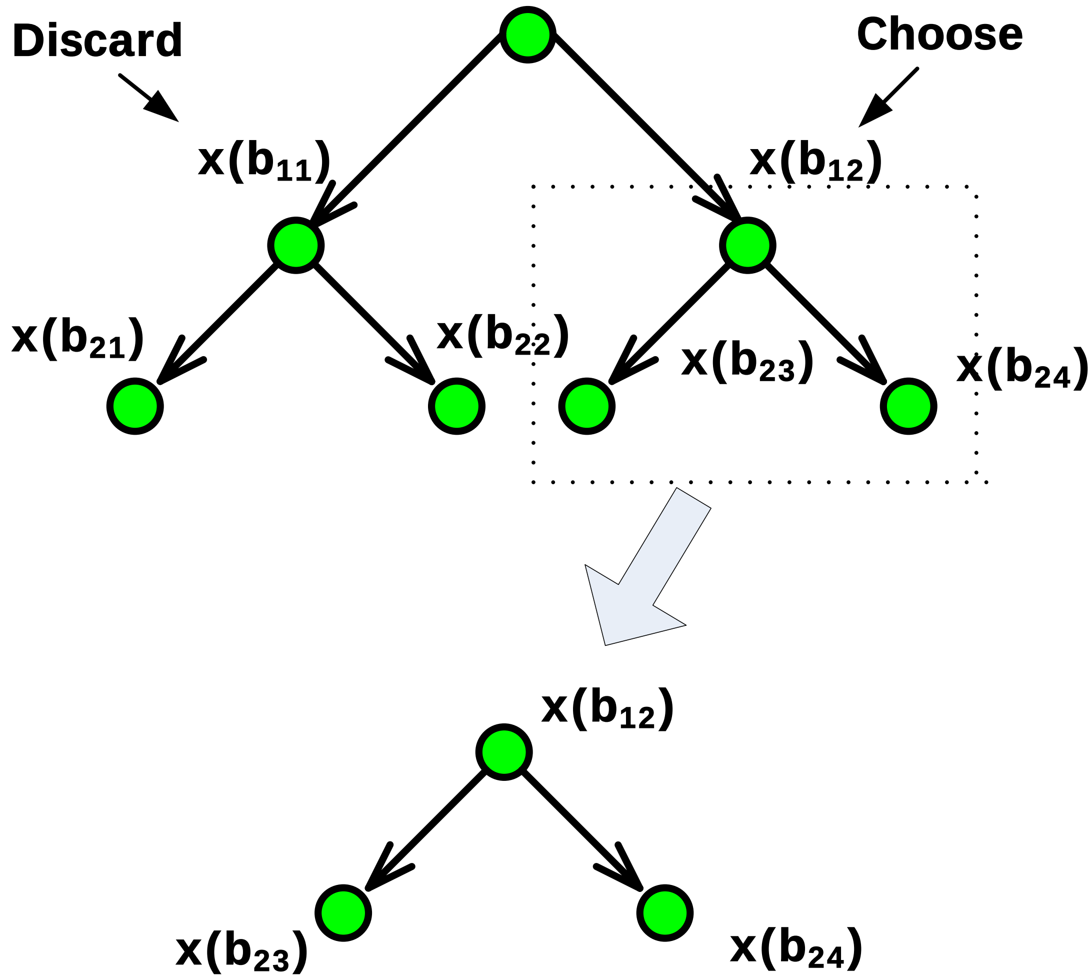


Example of T-PST algorithm (2)

- From each node (in this case from $\mathbf{x}(\mathbf{b}_{11})$ and $\mathbf{x}(\mathbf{b}_{12})$, calculate PAPRs of the OFDM signals after rotate using *W* phase factors at the second subblock.
- Find the minimum *S* PAPRs in the second subblock at each node, in this case $S = 2$.
- The $(T-1)th = 1th$ parent node of minimum PAPR node is a final decision for the first subblock.

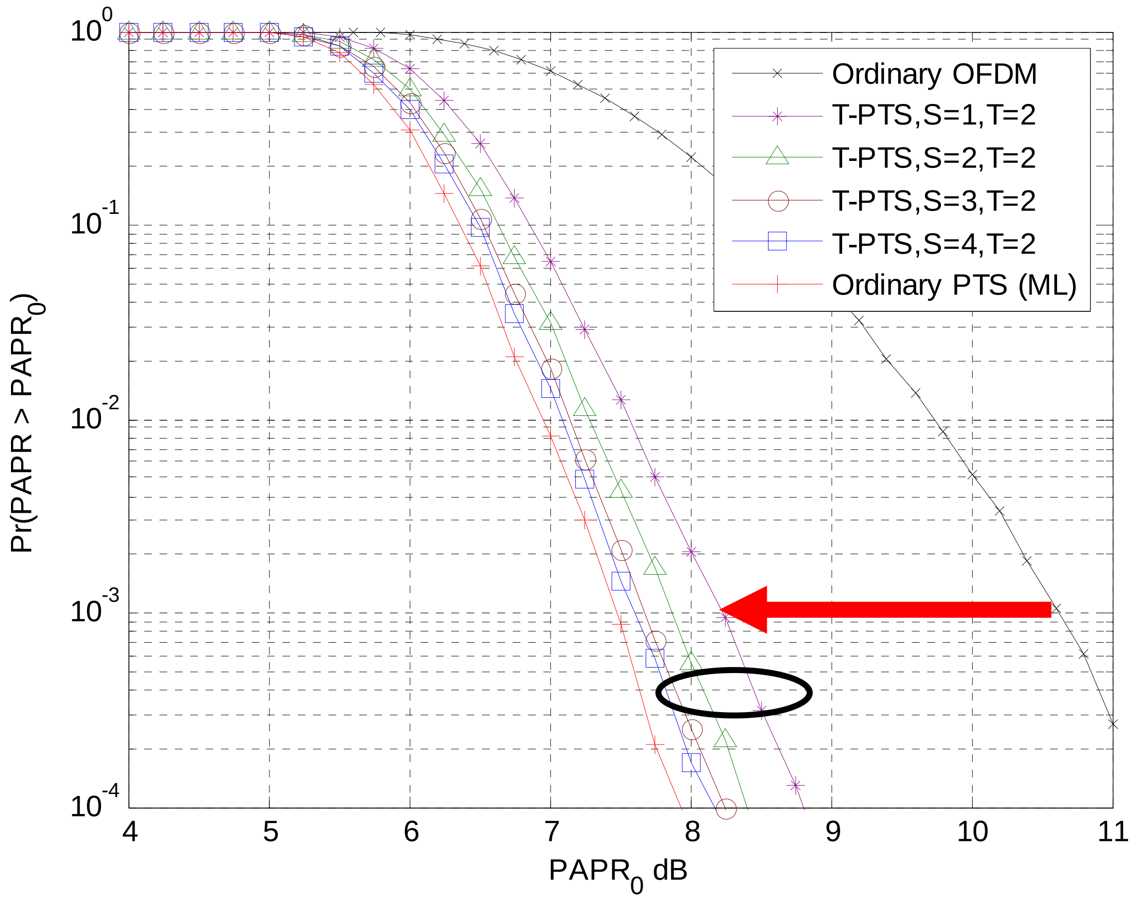


Example of T-PST algorithm (3)



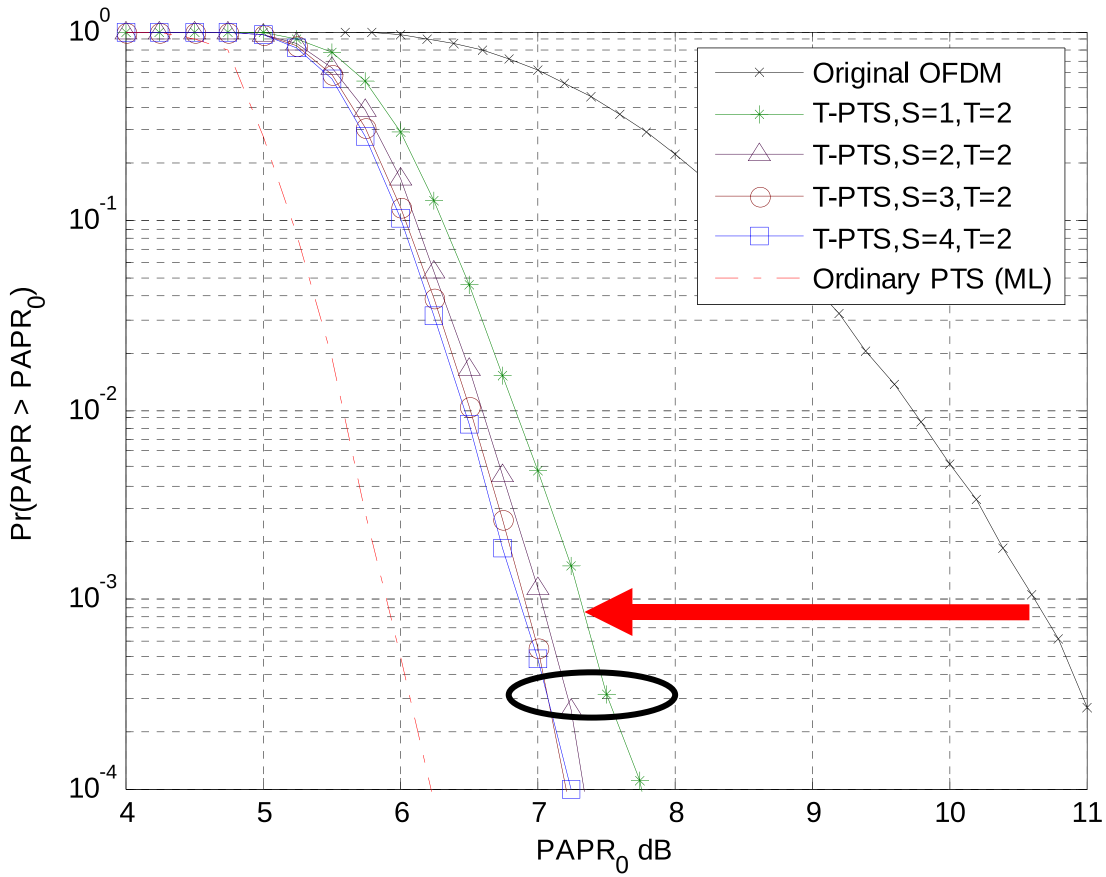
Simulation Results, N=64, L=4, M=4

- **Compared to ordinary PTS(ML), the new T-PTS algorithm reduces complexity by 62.5% by degradation of only about 0.2 dB w. r. t. PAPR**



Simulation Results, N=64, L=4 M=8

- **Compared to ordinary PTS(ML), T-PTS achieves 0.54% reduction in computational complexity with only 1 dB degradation w.r.t. PAPR**



Complexity, M=4
(Expressed in terms of no. of iterations)

- S=1, 2, 3, 4, T=2
- Around 20% ~ 60% computational complexity

	Number of iterations
T-PTS, $S = 1$, $T = 2$	13
T-PTS, $S = 2$, $T = 2$	22
T-PTS, $S = 3$, $T = 2$	31
T-PTS, $S = 4$, $T = 2$	40
Ordinary PTS	64

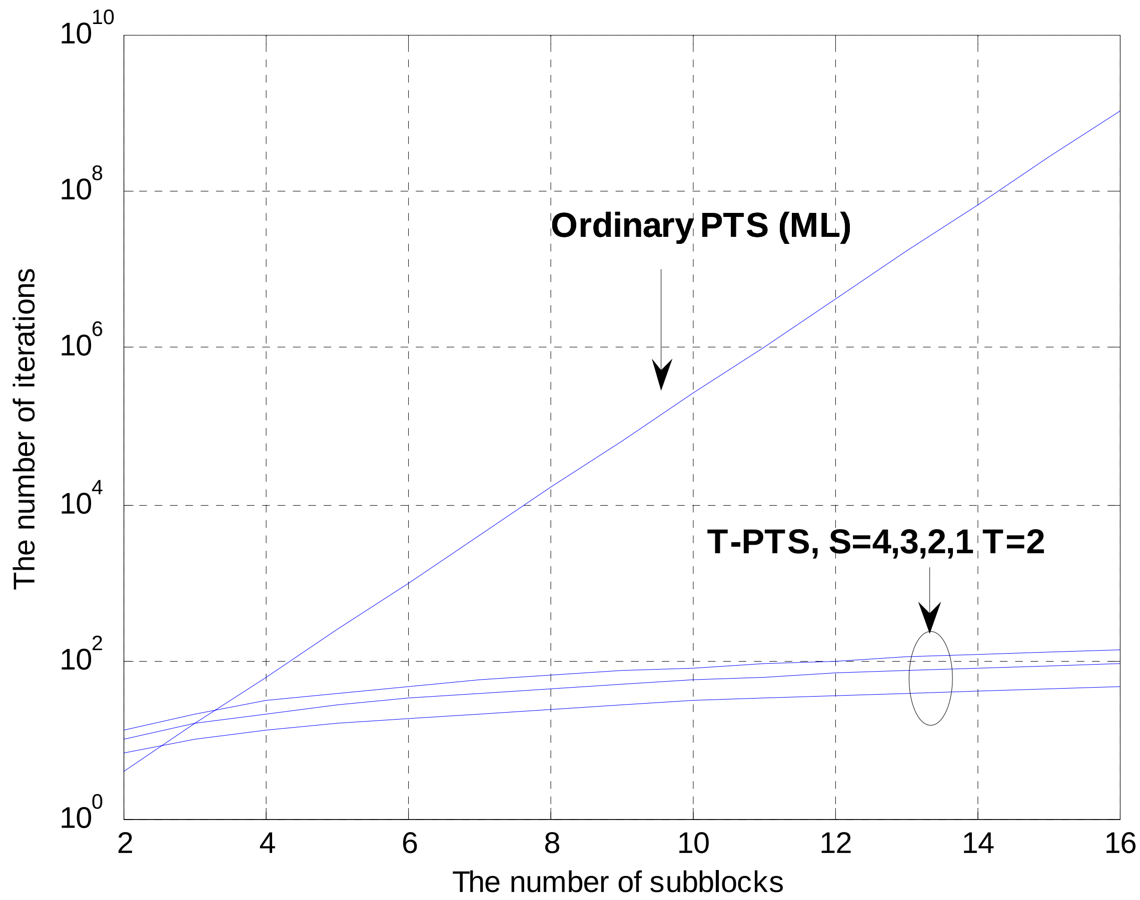
Complexity, M=8 (Expressed in terms of no. of iterations)

- S=1, 2, 3, 4, T=2
- Around 0.15% ~ 0.54% computational complexity

	Number of iterations
T-PTS, $S = 1$, $T = 2$	25
T-PTS, $S = 2$, $T = 2$	46
T-PTS, $S = 3$, $T = 2$	67
T-PTS, $S = 4$, $T = 2$	88
Ordinary PTS	16384

Complexity

- **(Depicted graphically)**



PART VI
Conclusion

An adaptive nonlinear pre-distortion technique that increases the linear range of the High Power Amplifier (HPA) and hence mitigates the effects of high PAPR in MC/OFDM systems has been presented

Other techniques for PAPR reduction have been briefly reviewed and, amongst these, a new technique called PTS-Tree algorithm has been described

Other work in progress is outlined in the following slide

Conclusion (cont)

WORK IS BEING FINALIZED ON THE FOLLOWING PROJECTS *(to be presented at forthcoming conferences*)

- **A New *Tree-PTS Algorithm* for intelligent compromise between performance and complexity *(presented in this lecture)***
- **An *adaptive power management* technique for PAPR reduction**
- ***Combination* of two or more PAPR reduction techniques**
  - Better performance is expected by combination of two or more PAPR reduction techniques
- **A new technique for *efficient power control in Multi-Carrier DS/CDMA via Pricing Strategy***
- **Application of these techniques to *MIMO-MC/OFDM* systems**

Thank you!