Receiver-side Compensation of Non-linear Distortion Effects in Multicarrier Systems

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Outline

- Nonlinear PA issues in OFDM/Multicarrier systems
- Known mitigation concepts
- Proposed solution
- Discussion
- Future developments

PHY Layer Research Today

- **Single-link PHY layer research – outdated?**
- **“Standard” impairments in single-link wireless research:**
  - Fading (may be freq. selective, time-varying)
  - AWGN

Reality

- **Impairments present in real systems:**
  - Non-linear behavior of hardware components (PA, DAC/ADC and so on)
  - Complex noise environment (impulsive, non-Gaussian, frequency selective)

OFDM/Multicarrier Systems

- **OFDM**
  - Celebrates its 50th anniversary*
  - De-facto standard for modern high-throughput wireless communication systems
  - Still the major contender for 5G (perhaps with minor modifications or variations)
- **But not without issues:**
  - High peak-to-average power ratio (PAPR) and sensitivity to nonlinear distortions

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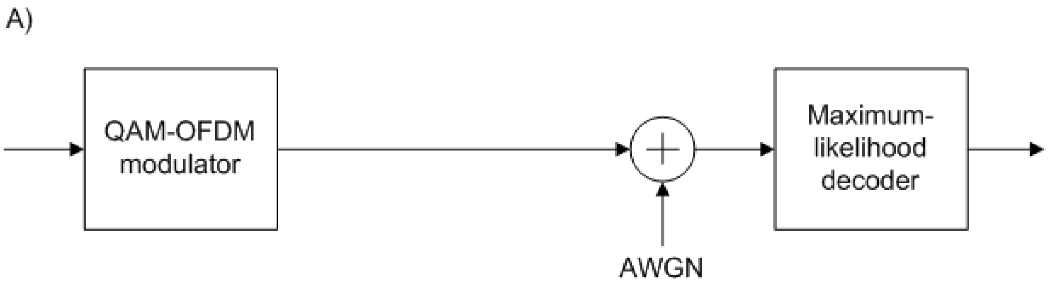
* US 3488445, Orthogonal frequency multiplex data transmission system, filled 14 Nov. 1966

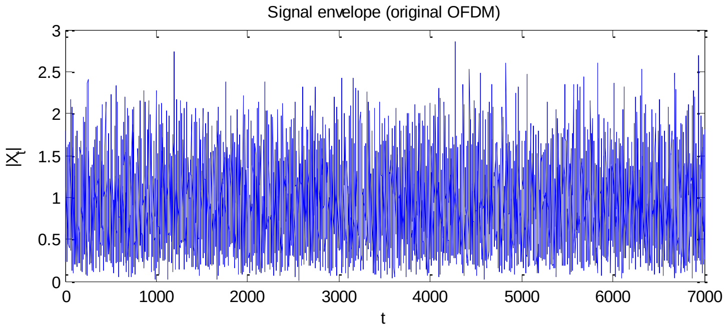
OFDM and PA Nonlinearity

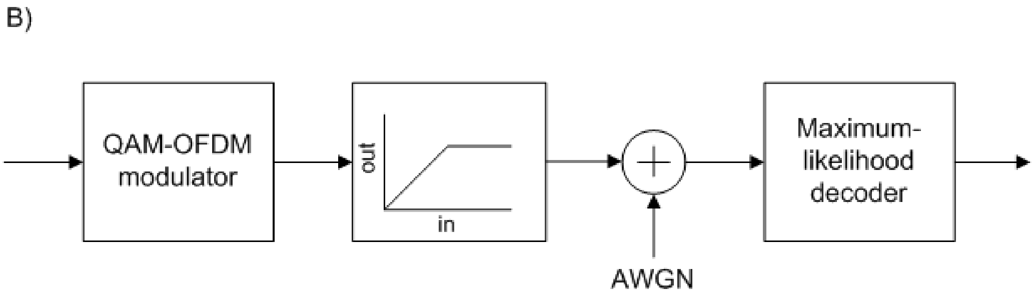
- In-band and out-of-band distortions
- DPD -- working solution, but shifts cost and complexity in TX side
- DPD is not economically feasible and not power-efficient* in some applications: mobile-to-AP uplink, IoT
- Signal integrity requirements of mobile devices are not as stringent as the requirements of base stations and access points
- In 256÷1024- QAM even mild nonlinearity may cause significant EVM/BER degradation, yet acceptable spectral re-growth

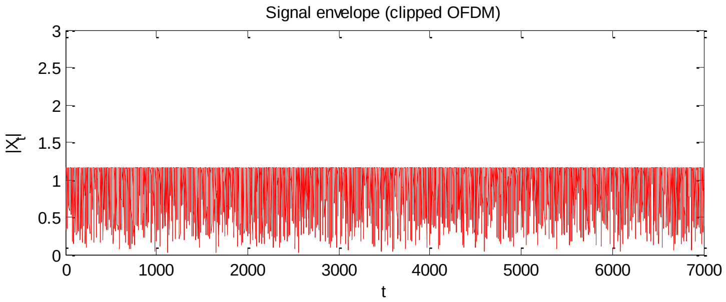
*S. Boumard *et al.*, "Power consumption trade-off between power amplifier OBO, DPD, and clipping and filtering," *26th International Teletraffic Congress (ITC)*, 2014

ML-decoding Example



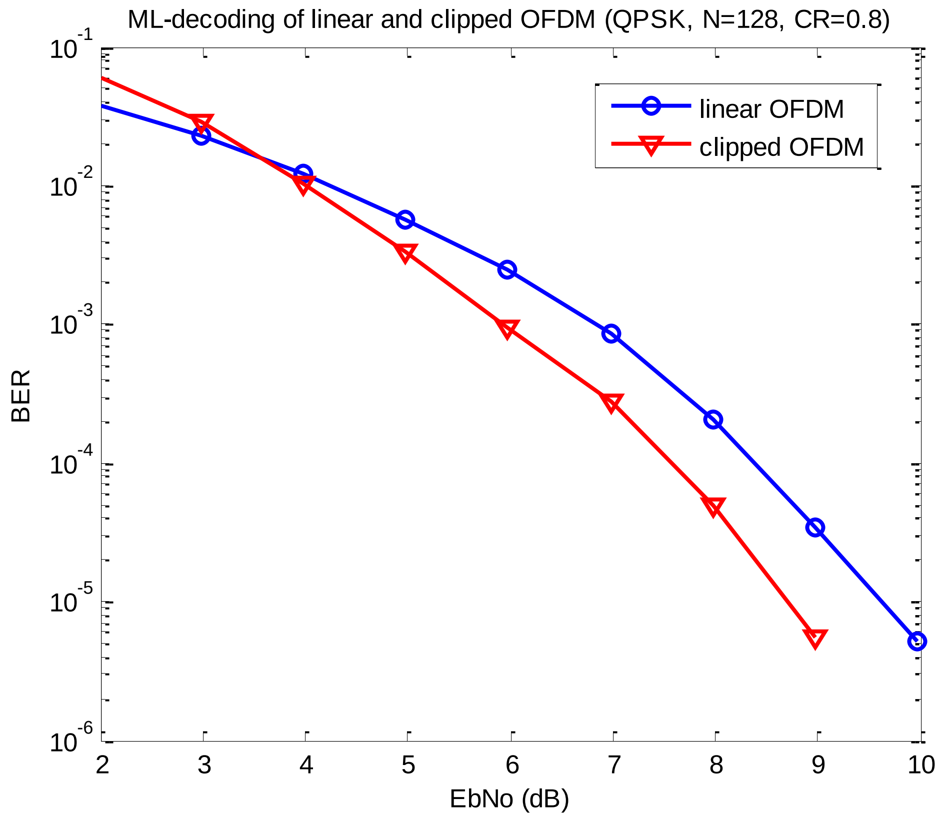






BER vs EbNo?

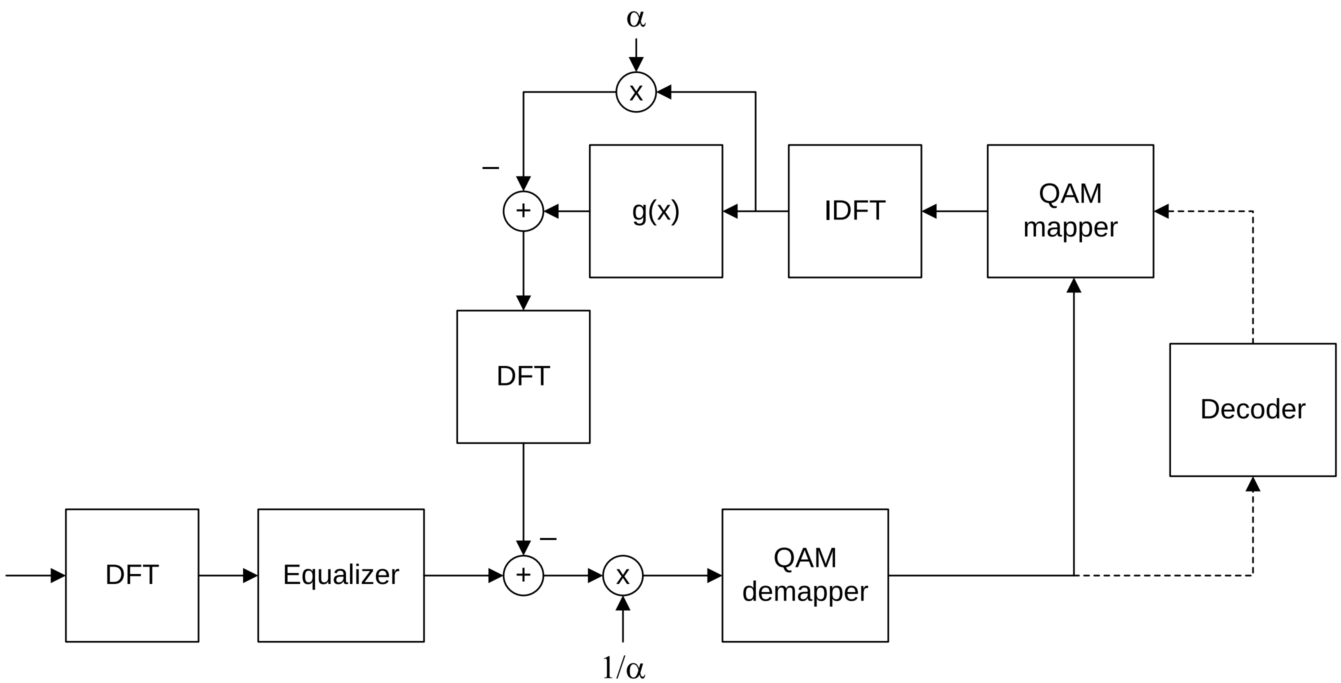
ML-decoding Example



For more discussion see: J. Guerreiro, R. Dinis and P. Montezuma, "On the Optimum Multicarrier Performance With Memoryless Nonlinearities," in IEEE Transactions on Communications, Feb. 2015

Receiver-side Compensation

- ML-decoder is too complex $O(M^N)$
- Decision-feedback compensation concept:



J. Tellado, L. M. C. Hoo and J. M. Cioffi,"Maximum-likelihood detection of nonlinearly distorted multicarrier symbols by iterative decoding", IEEE Trans. Commun., Vol. 51, No. 2, Feb. 2003

L. G. Baltar, et al, "OFDM receivers with iterative nonlinear distortion cancellation,“ IEEE Eleventh International Workshop on Signal Processing Advances in Wireless Communications, 2010

Typical assumptions

- Number of subcarriers is sufficiently large (Bussgang theorem for Gaussian signals)
- Not too many errors after first decision (<10%)
- Receiver knows the PA transfer function g(x)
- Receiver can perfectly estimate channel $\boldsymbol{H}$

Previous "Practical" Attempts

F. H. Gregorio, et al, "Receiver-side nonlinearities mitigation using an extended iterative decision-based technique," Signal Processing, Aug. 2011

- Special training symbols with very low PAPR to minimize nonlinearity effect on channel estimation
- + 3 training symbols for PA model estimation
- Issues:
  - Overhead for training (4 symbols, at least)
  - Slow convergence of PA-model estimator
  - Not compatible with legacy systems
  - Limited performance improvement

Our Approach

- Parameterized (polynomial) model of arbitrary nonlinear transfer function
- Frequency-domain representation of nonlinear distortion terms
- Joint channel and PA model estimation
- PA-parameter adaptation per OFDM symbol to take into account non-Bussgang properties of OFDM with limited number of subcarriers

Key Equations

- Post-DFT signal representation:

$$\mathbf{R} = \alpha \mathbf{H} \left(\mathbf{S} + \sum_{p=3,5,\ldots}^{P} c_p \left(\mathbf{d}^{(p)} - T^{(p)} \mathbf{S} \right) \right) + \mathbf{w}$$

$\mathbf{R}$	received signal
$\mathbf{S}$	data symbol
$\mathbf{H}$	channel response: $\mathbf{H} = diag\left(\left[H_0, H_1, \ldots, H_{N-1}\right]\right)$
α	scaling factor
$\{c_p\}$	nonlinearity model parameters
$\mathbf{d}^{(p)}$	p-th order distortion components: $\left\{d_k^{(p)}\right\} = \underbrace{\{S_k\} * \{S_k\} * \{S_k\}}_{(P+1)/2} * \ldots * \underbrace{\{S_{N-k}^*\} * \{S_{N-k}^*\}}_{(P-1)/2}$
$T^{(p)}$	modulation-dependent constants
$\mathbf{w}$	additive white Gaussian noise

Joint Channel and PA Estimator

- LS-type solution

$$J = \sum_{m=1}^{M} \left\| \mathbf{R}^{(m)} - \alpha \mathbf{H} \left(\mathbf{S}^{(m)} + \sum_{p=3,5,\ldots}^{P} c_p \left(\mathbf{d}^{(p,m)} - T^{(p)} \mathbf{S}^{(m)} \right) \right) \right\|^2$$

M – number of OFDM symbols used for training

$M \times N$ nonlinear equations for $N+(P-1)/2$ unknown parameters

No closed-form solution, but simple iterative approximation works well:

1. If $\boldsymbol{c}$ is known we can find closed-form solution for $\boldsymbol{H}$
2. If $\boldsymbol{H}$ is know we can find closed-form solution for $\boldsymbol{c}$

Start from $\mathbf{c}=0$, and work iteratively through steps 1) and 2) until convergence

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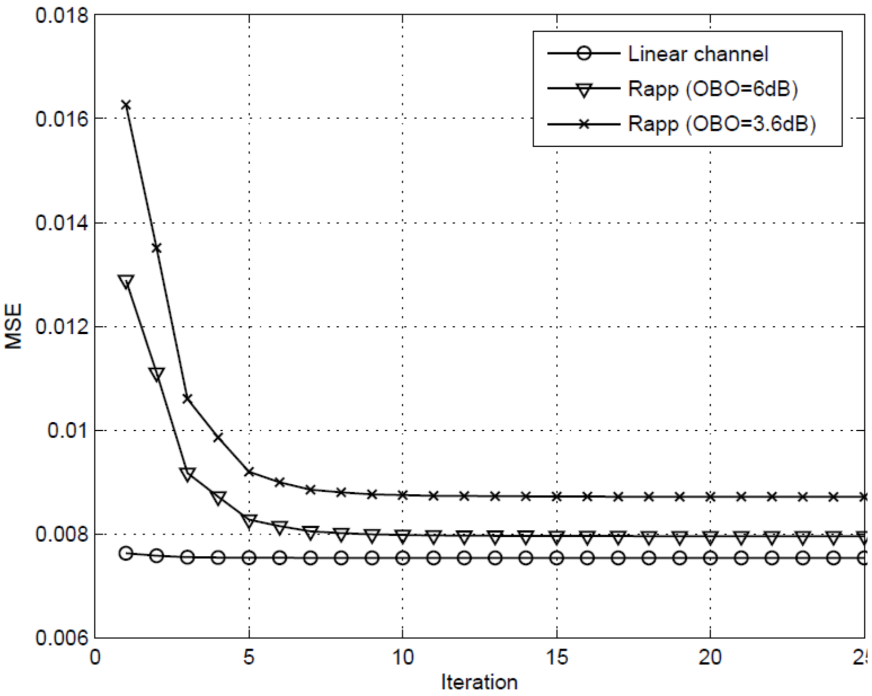
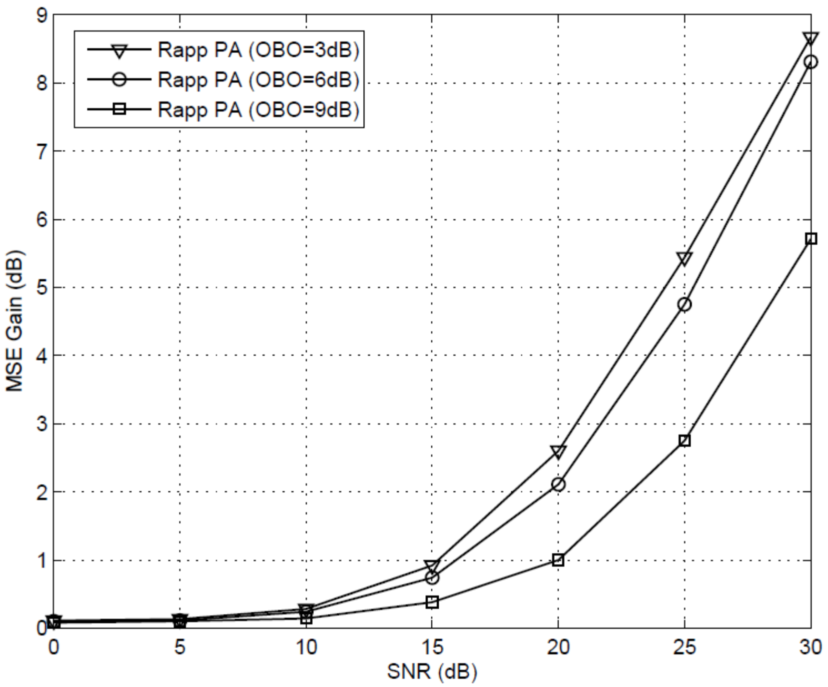
Note: at least two different OFDM symbols are needed for joint channel + PA-model estimation

PA and Channel Estimation Results

MSE of joint channel estimator vs conventional channel estimator





Decision-aided Distortion Compensation

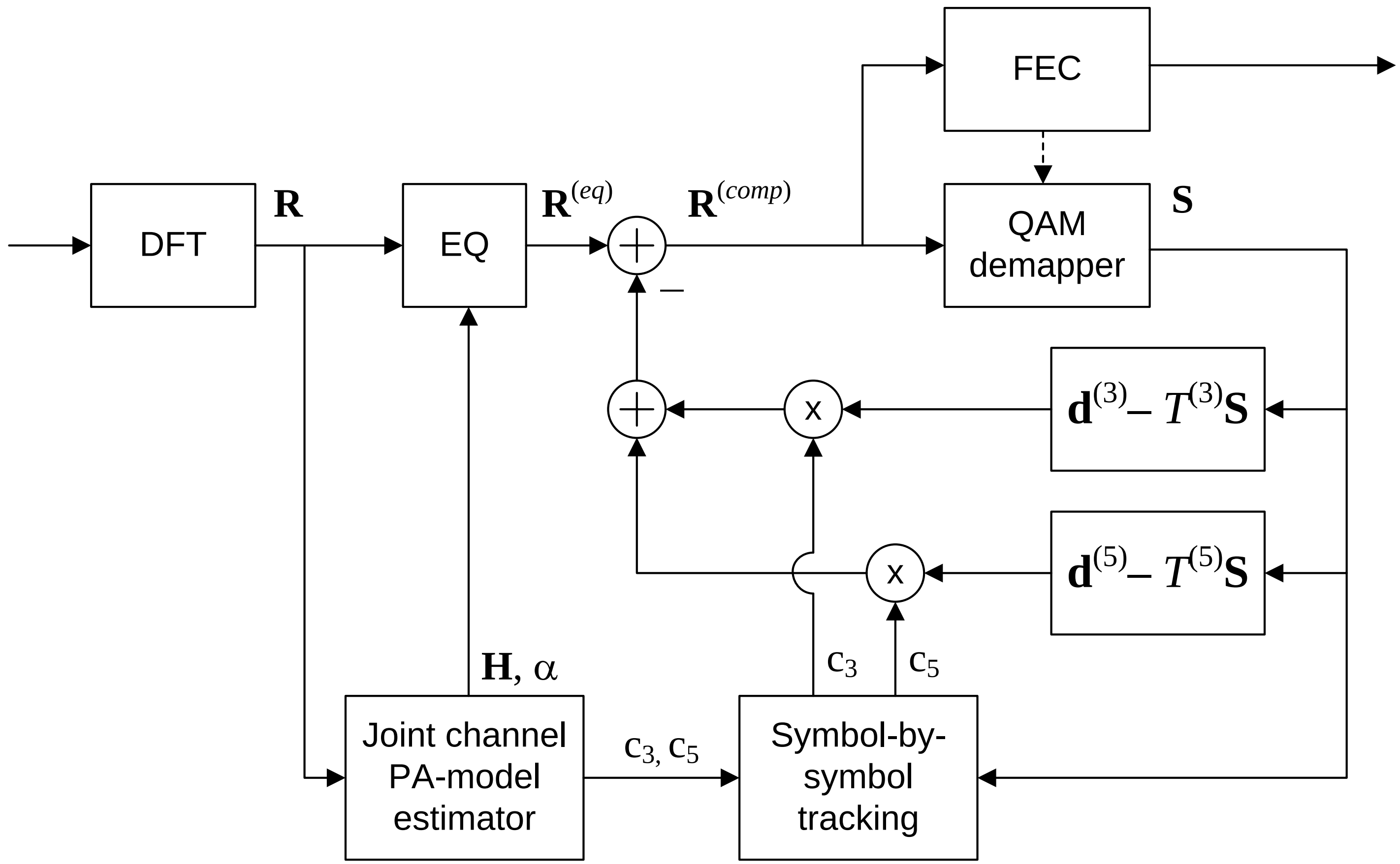
- **Distortion compensation step is similar to a classical concept:**

1. Use equalized signal $\mathbf{R}^{(eq)}$ to obtain tentative decisions
2. Calculate distortion terms $\{d_k^{(p)}\}$, p=3,5,...
3. Compensate the nonlinear distortion products:

$$\mathbf{R}^{(comp)} = \mathbf{R}^{(eq)} - \sum_{p=3,5,...}^{P} c_p \left(\hat{\mathbf{d}}^{(p)} - T^{(p)} \hat{\mathbf{S}} \right)$$

4. Use compensated signal $\mathbf{R}^{(comp)}$ to obtain updated decisions $\mathbf{S}$
5. Repeat steps 2)-4) I times

Complete Block Diagram (*P*=5)

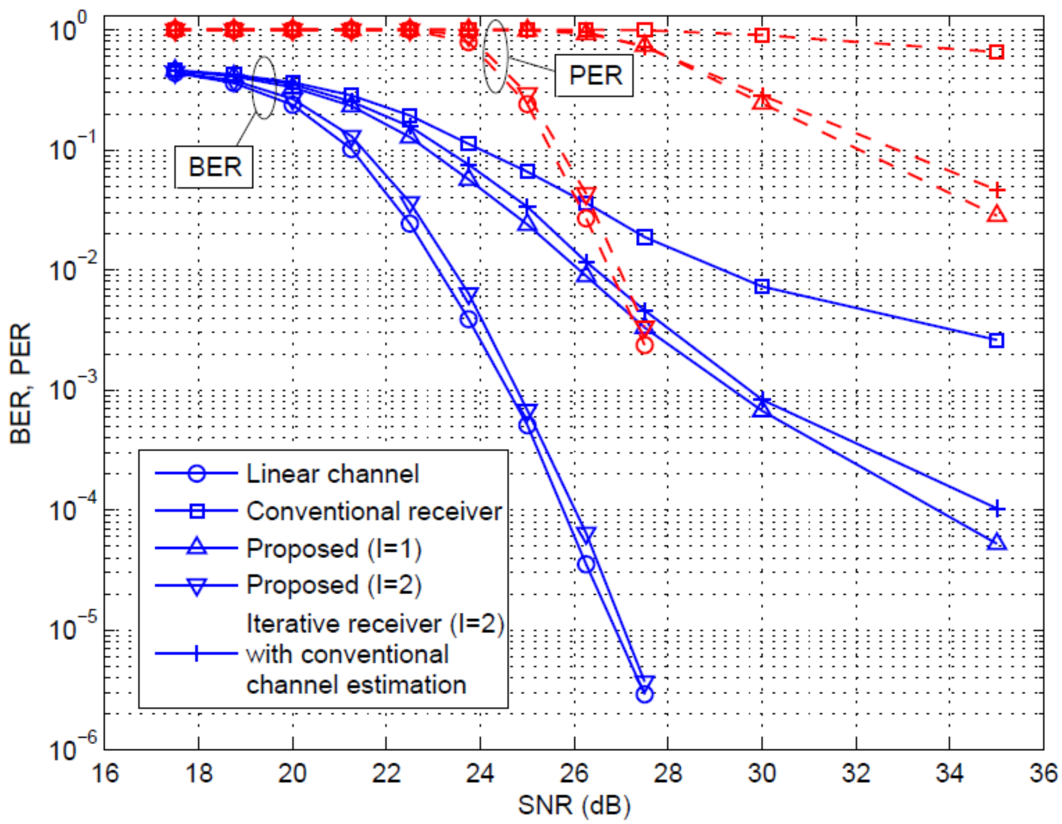


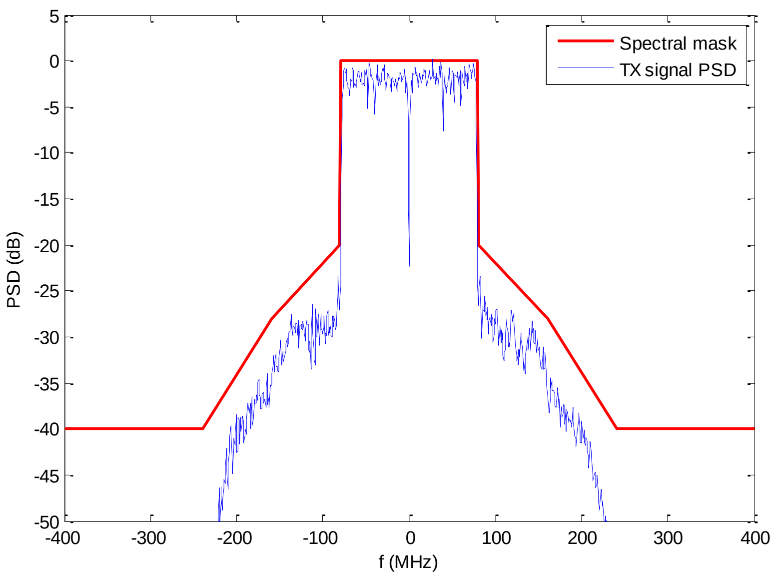
Application Example

- IEEE 802.11ac (legacy and VHT modes)
- Single TX -> Single or Multiple RX
- L-LTF/VHT-LTF **and** L-SIG/SIG-B for training
- Rapp PA model ($v=2\div4$) and soft-limiter
- OBO is set to meet spectral mask requirements
- Block fading multipath channels

Simulation Results

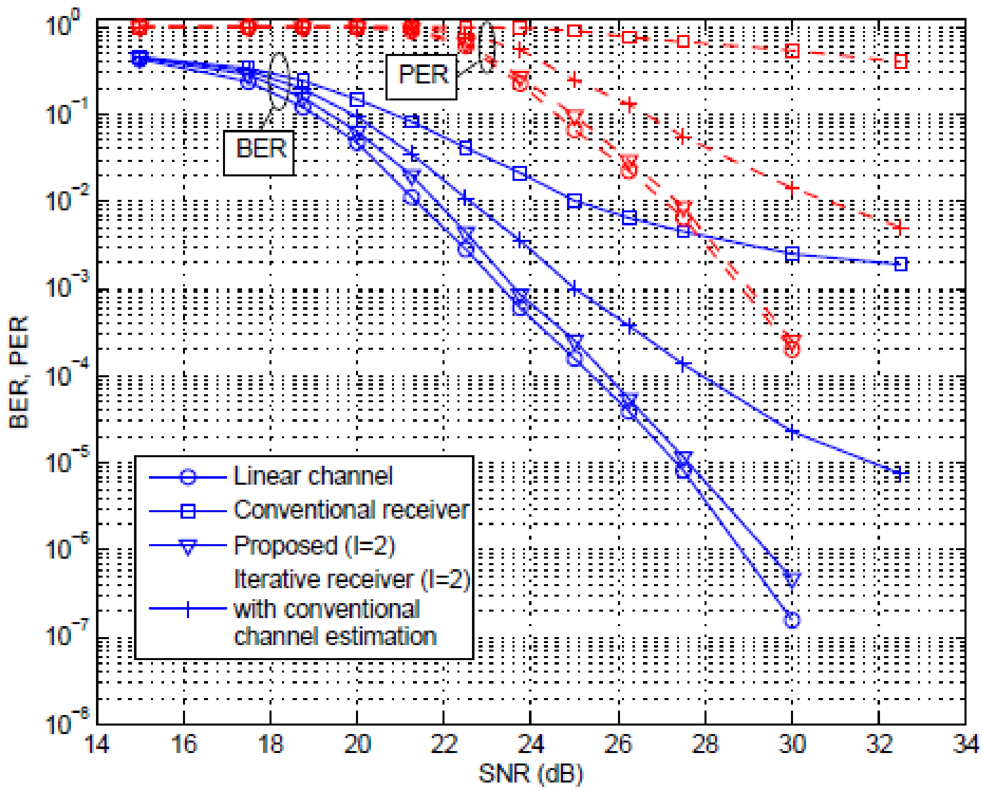
- AWGN, N=484, 256-QAM, ¾ Code Rate

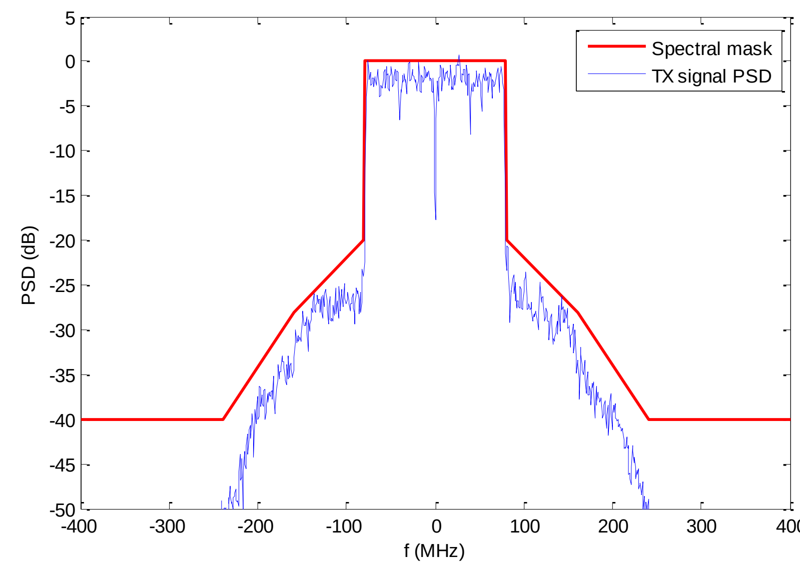




Simulation Results (cont.)

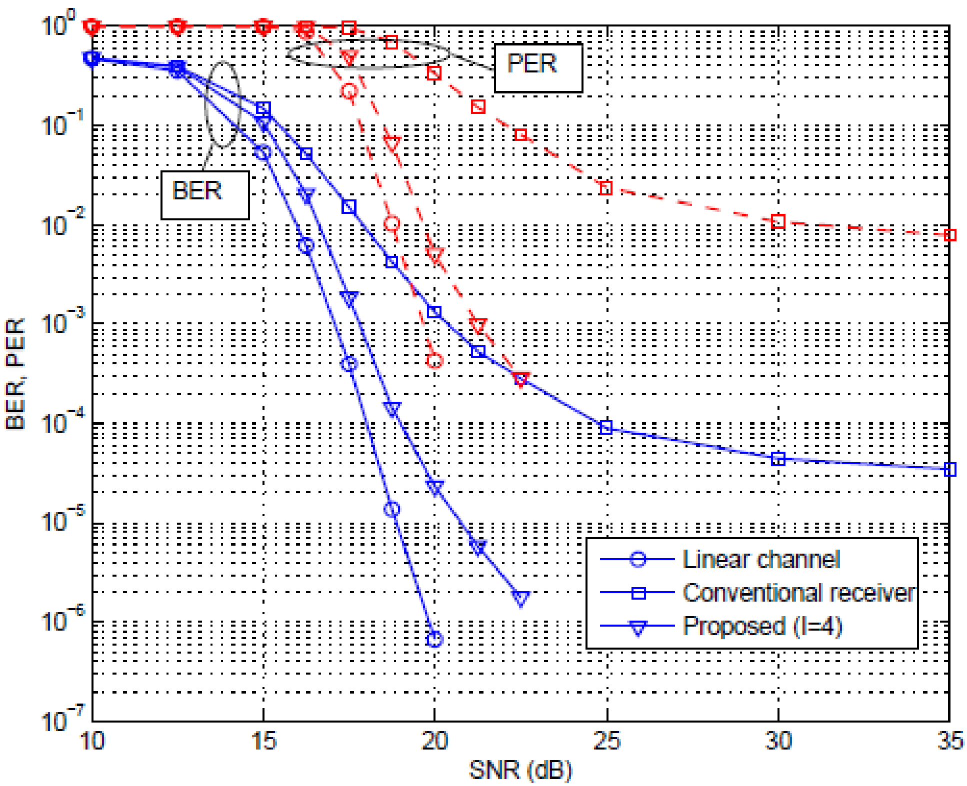
- Channel B, N=484, 256-QAM, ¾ Code rate

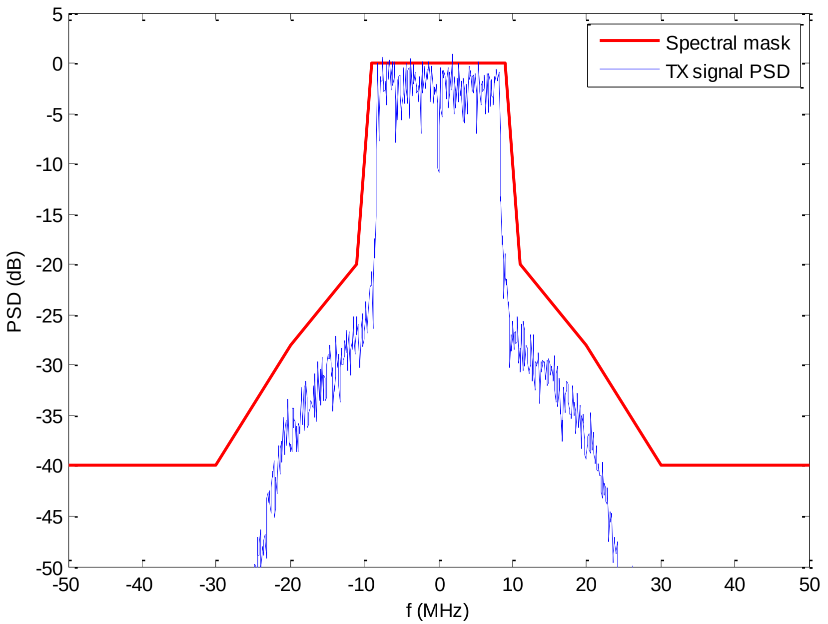




Simulation Results (cont.)

- AWGN, N=52, 64-QAM, ¾ code rate





PA with Memory Effects

- Algorithm derivations based on memoryless PA model
- Low power PAs used in mobile terminals typically exhibit very weak memory effects
- Hammerstein-type memory model is of no concern, because it will be corrected by channel equalizer
- Wiener-type memory model often shows worse modeling performance*

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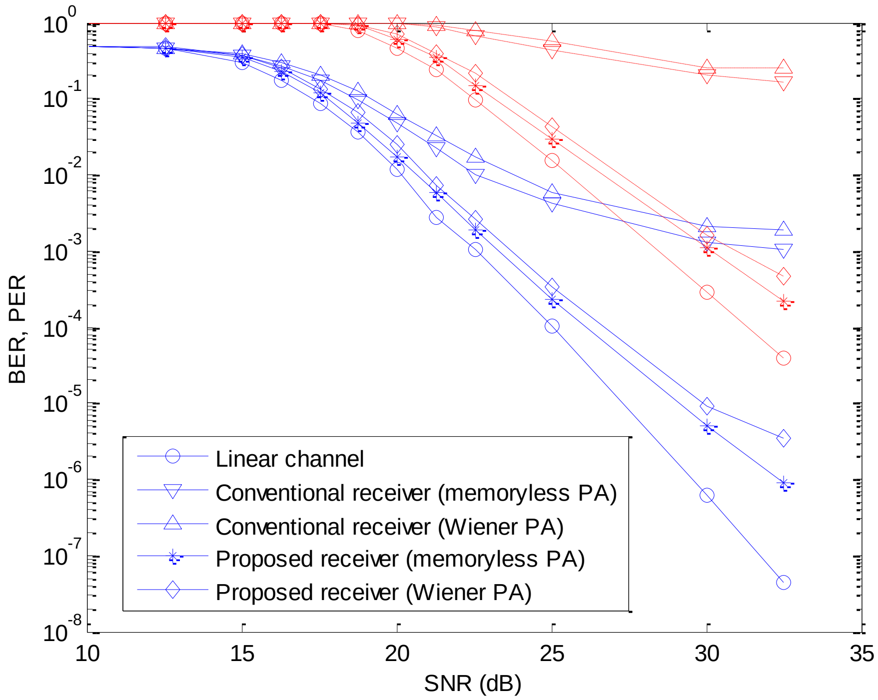
* P. Gilabert, G. Montoro and E. Bertran, "On the Wiener and Hammerstein models for power amplifier predistortion," Asia-Pacific Microwave Conference Proceedings, 2005

PA with Memory Effects (cont.)

- Proposed scheme demonstrates good results for a typical Wiener-type HPA model* (N=52, 64-QAM, CR=3/4, Channel B)

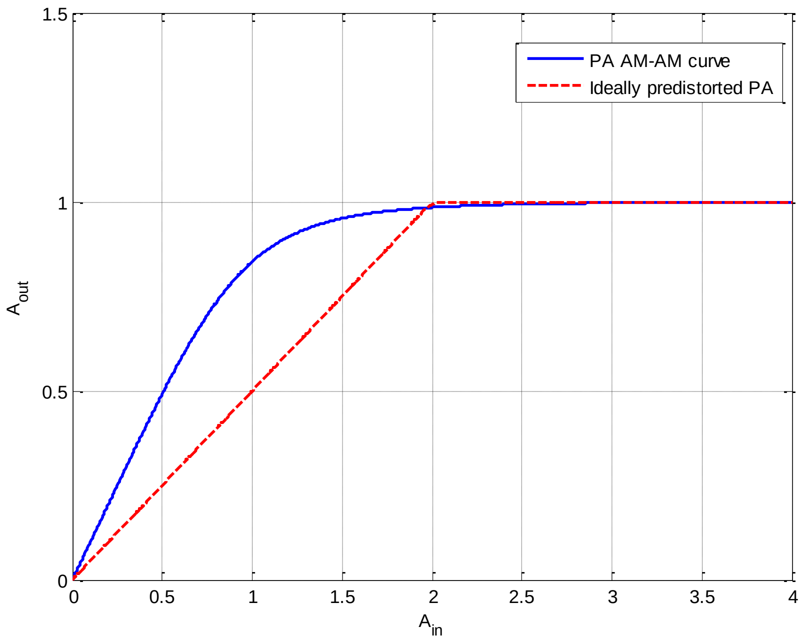


LTI part of Wiener model is given by: $A(z) = (1+0.1z^{-2})/(1-0.1z^{-1})$

* R.Raich,et al, Orthogonal polynomials for power amplifier modeling and predistorter design, IEEE Trans. Veh. Technol., 2004

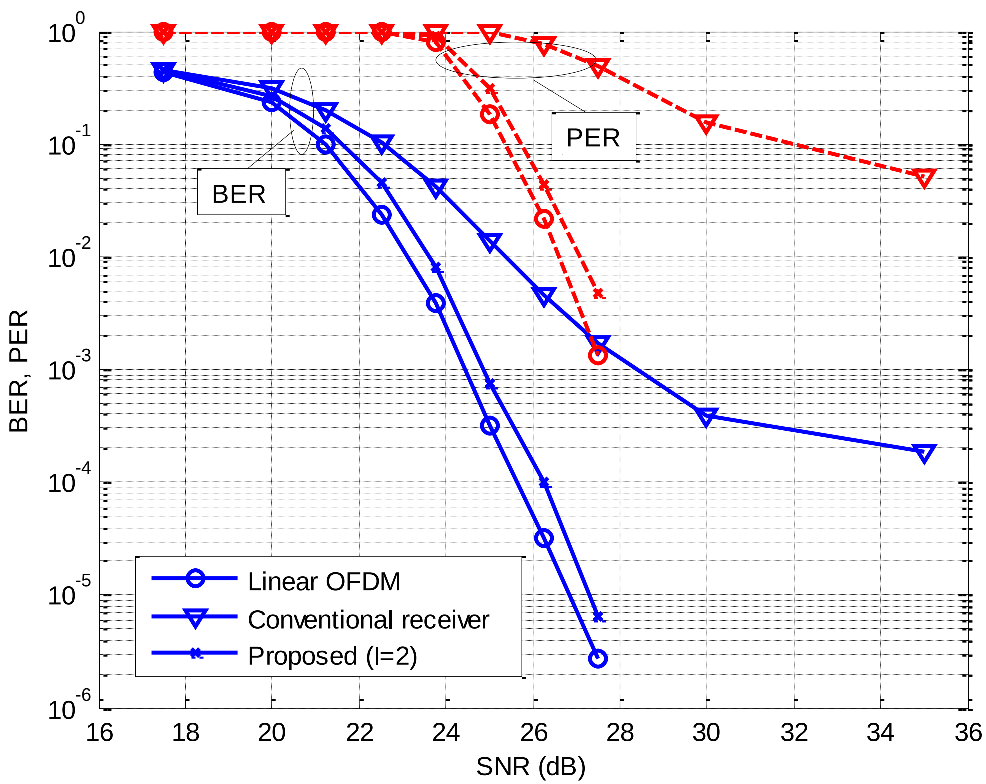
RX Compensation + DPD

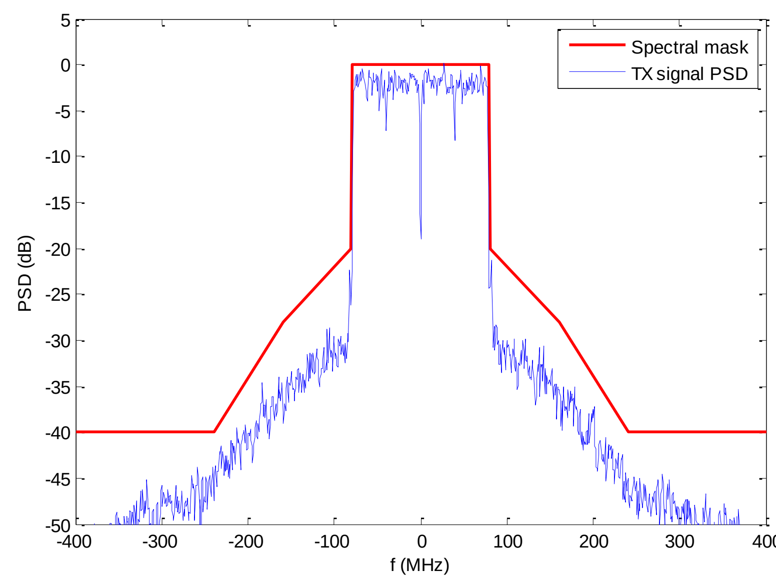
- PA with ideal DPD acts as a "soft-limiter"
- Back-off is still needed to avoid clipping
- No "inversion" technique (RX or TX) can compensate for saturation
- But decision-directed scheme in RX can!



RX Compensation + DPD (cont.)

- AWGN, Soft-limiter, N=484, 256-QAM, Code rate ¾





Note: one would need to back-off by about 2 dB to get the same BER/PER performance with DPD, but without RX compensation

FEC Decision Feedback

- Intuitively, should provide some benefits over slicer decisions
- In case of IEEE802.11ac no improvements due to error-propagation effect
- Soft-mapper approach also does not help
- Yet, in other systems, FEC feedback may provide some benefits

SIMO/MISO/MIMO Channels

- The approach is directly applicable to single TX / multiple RX scenario
- May be used in TX-diversity and MIMO configurations with some modifications

Conclusions

- Receiver-side compensation of nonlinear distortions in OFDM is practically feasible
- Approach is well suited for uplink processing
- Proposed solution takes into account real challenges: estimation of channel response and unknown PA model
- Can be applied to legacy systems (e.g. IEEE802.11ac)
- Implications for future system designs

Insights

- Performance is better when N is large (>100-200)
- No visible improvement for $P>5$ even for soft limiter
- Bussgang theorem does not hold! (legacy mode $N=52$)
  - Complex gain varies from OFDM symbol to OFDM symbol and even from subcarrier to subcarrier
  - Optimal coefficients $\{c_p\}$ depend on PARP of OFDM symbol
  - Solution: re-estimate $\{c_p\}$ at every OFDM symbol in decision-directed mode
  - Trade-off estimation noise vs non-Bussgang behavior with low N

More Insights

- Conventional logic suggests that we use low-PAPR training symbols to minimize PA nonlinearity effect on channel estimation

- In our approach, low-PARP training symbols are no longer necessary for channel estimation

- Moreover, low-PARP training symbols are not recommended for joint channel & PA-model estimation, because they do not provide sufficient dynamic range in training phase

Future Developments

- Improved joint channel & PA model estimation taking into account finite length of channel impulse response
- Application to other types of multicarrier waveforms (ZP-OFDM, UF-OFDM, GFDM)
- TX-diversity and MIMO configurations
- Complexity reduction
- Optimal ML-decoding is still an open issue

Future Developments (cont.)

- No one knows how many mobile transmitters may be affected by nonlinearity
- Our ongoing effort is aimed at investigation of this issue in real-life
- Idea is to collect a lot of data from thousands of different devices
- Use low-cost SDR tools for such massive data collection

More Info

- More technical info:
  - S.V. Zhidkov, "Joint Channel Estimation and Nonlinear Distortion Compensation in OFDM Receivers," pre-print and source code available at http://www.cifrasoft.com/people/szhidkov/ofdm_nonlinear_rx.html

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