NONLINEAR BEHAVIORAL-LEVEL SIMULATION FOR RF/MICROWAVE APPLICATIONS

By Sergey L. Loyka

Laboratory of Electromagnetism and Acoustic
Swiss Federal Institute of Technology
LEMA-EPFL-Ecublens
CH-1015 Lausanne
Switzerland
e-mail: sergey.loyka@epfl.ch

Laboratory of Electromagnetic Compatibility
Belorussian State University of
Informatics and Radioelectronics,
P.Brovki St. 6, Minsk 220027
Republic of Belarus
e-mail: sergey.loyka@ieee.org

Presentation Plan

1. Introduction
2. General consideration of behavioral-level simulation techniques
   - 2.1. The quadrature technique
   - 2.2. The discrete technique
   - 2.3. Recent progress - The instantaneous quadrature technique
   - 2.4. Instantaneous transfer characteristic
3. Modeling and characterization issues
   - 3.1. AM-AM & AM-PM measurement versus simulation
   - 3.2. How to represent the characteristic: Splines, Orthogonal series, Non-Orthogonal series, Genetic algorithm, Neural networks, Simple analytical formulas etc.
   - 3.3. Accuracy of approximation and related issues

  - 3.4. Tone-spacing effect

4. Possible applications:
   - 4.1. Power amplifiers,
   - 4.2. RF/microwave subsystems & systems
   - 4.3. Active array antennas
   - 4.4. Bell Labs limit for channel capacity & active array simulation

5. Conclusion

1. INTRODUCTION

- Exponential increase in the number of communication systems $\rightarrow$ digital systems
- Difference from analog ones in nonlinear characterization $\rightarrow$ ACPR, EVM, PSR etc.
- System designers need simulation tools $\rightarrow$ change of simulation approaches
- Widespread use of behavioral-level techniques
- Two most-popular ones – quadrature technique & discrete technique

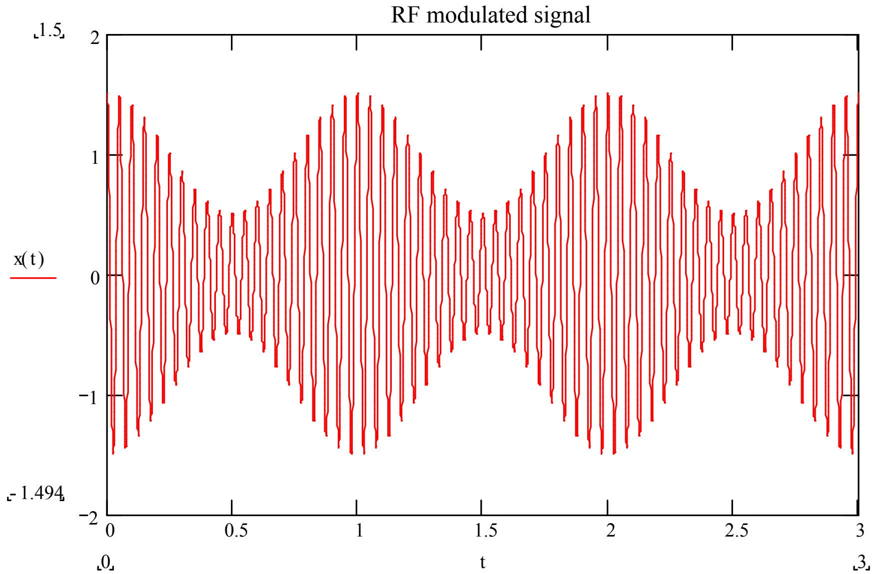
2. GENERAL CONSIDERATION OF BEHAVIORAL-LEVEL SIMULATION TECHNIQUES

- Two well-know techniques: the quadrature modeling technique & the discrete technique.
- Recently proposed one – the “instantaneous” quadrature technique.
- Historical remarks: the quadrature modeling technique is the oldest one – 1972 (TWT power amplifiers modeling, presently - SSPA),
- The discrete technique – 1988 (receiving path modeling under interference conditions),
- The “instantaneous” quadrature technique – 1998 (wide range of applications is expected).
- “Ten years” law – every decade we get a new behavioral-level simulation technique!

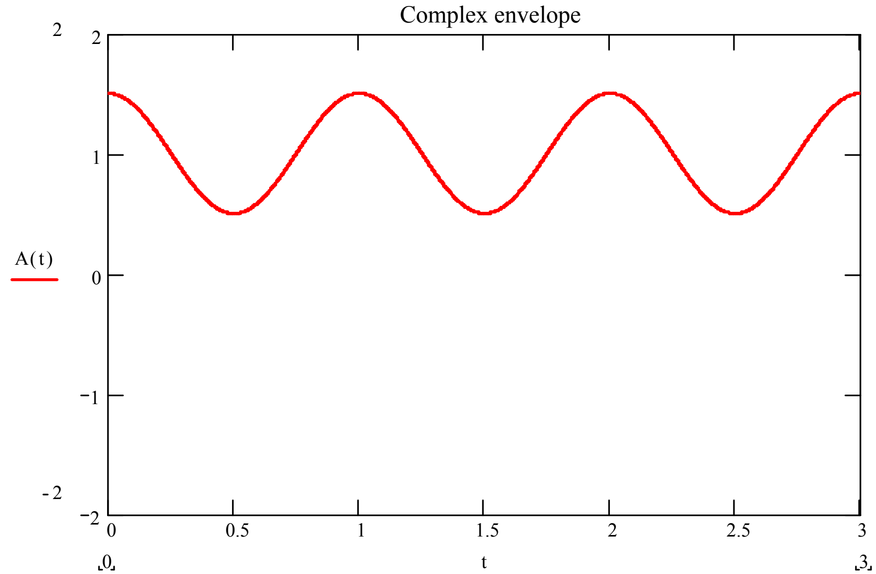
2.1. THE QUADRATURE MODELING TECHNIQUE

- The main idea: use of complex envelope instead of real narrow-band signals. No carrier information.

RF signal



Complex envelope



- The same in mathematical language:

RF modulated signal:

$$x(t) = A(t)\cos\left(w_0 t + j\,(t)\right) = Re\left\{A(t)\cdot\exp\left[j\cdot(w_0 t + j\,(t))\right]\right\}$$

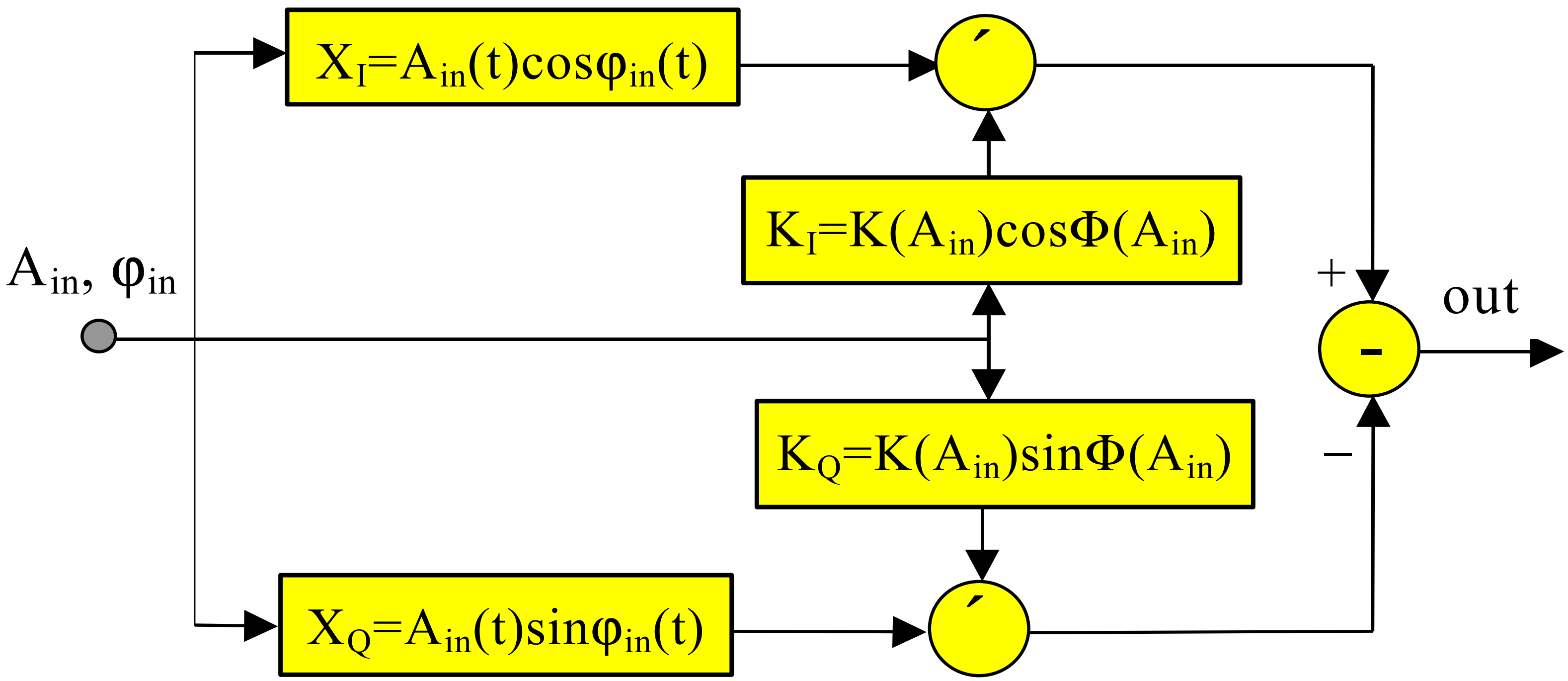
Complex envelope:

$$\overline{A(t)} = A(t)\cdot\exp\left[j j\,(t))\right] = A(t)\cos j\,(t) + jA(t)\sin j\,(t)$$

- A nonlinear stage is characterized by AM-AM and AM-PM transfer characteristics

$$K(A_{in}) = \frac{A_{out}}{A_{in}}, \quad \Phi(A_{in}) = j_{\,out} - j_{\,in}$$

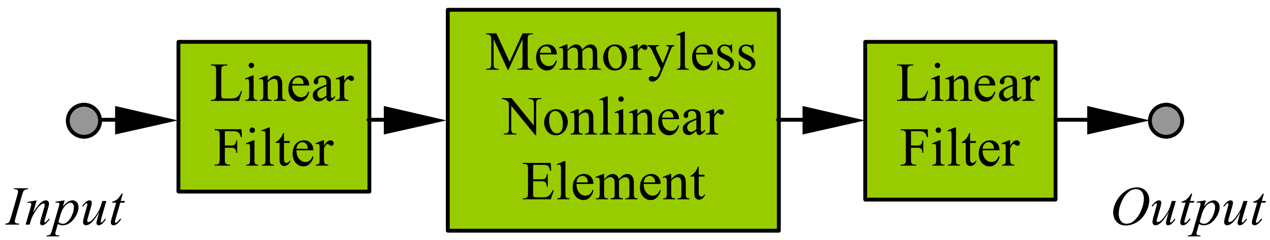
- Both characteristics depend on the input signal amplitude, not on the instant value ! (they are “amplitude” , not “instantaneous” ones)
- Consequences: sampling at the baseband frequency → high computational efficiency.
- Uses two channels – in-phase & quadrature ones – to model AM-PM as well as AM-AM



- Limitations: no frequency response, no harmonics, no multiple carriers, no tone-spacing effect.

2.2. THE DISCRETE TECHNIQUE

- Basis of the discrete technique is a representation of the system block diagram as linear filters and memoryless nonlinear elements.
- Example: a single-stage radio amplifier,



- The process of signal passage through linear filters is simulated in the frequency domain using the complex transfer factor,

$$S_{out}(f_n) = S_{in}(f_n) \cdot K(f_n).$$

- The process of signal passage through a nonlinear memoryless element is simulated in the time domain,

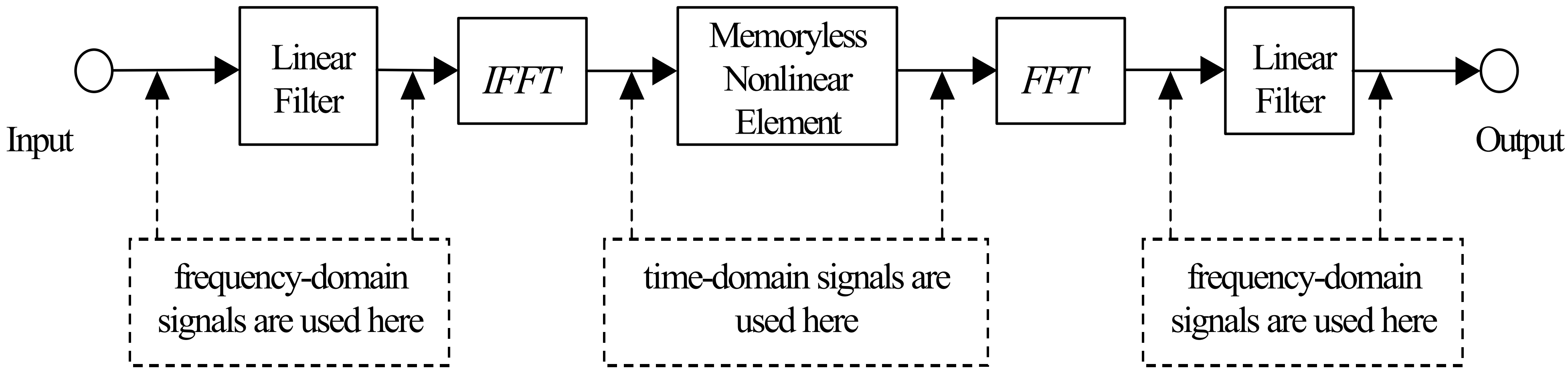
$$u_{out}(t_k) = f\left[u_{in}(t_k)\right]$$

- The transition from the time domain to the frequency domain and vise versa is made with the use of the direct and inverse Fast Fourier Transform (FFT):

$$S_n = \frac{1}{N}\sum_{k=0}^{N-1} u_k \cdot W^{nk}, \quad u_k = \sum_{n=0}^{N-1} S_n \cdot W^{-nk}, \quad W = e^{-j(2p/N)}$$

- Instantaneous values of input and output signals are used in the discrete technique. It allows one to carry out simulation over a wide frequency range (to predict carrier harmonics, to simulate multicarrier systems, to account for the system frequency response etc.)

- An illustration of the simulation process:



- Some issues related to the discrete technique:
  - The maximum frequency F_{max} , frequency sample interval Df , time sample interval Dt and the number of samples N are related:

$$\Delta t = \frac{1}{2 \cdot F_{max}} \quad , \quad N = \frac{T}{\Delta t} = \frac{1}{\Delta t \cdot \Delta f}$$

  - Nonlinear transformation causes input spectrum to expand I (order of nonlinearity) times:

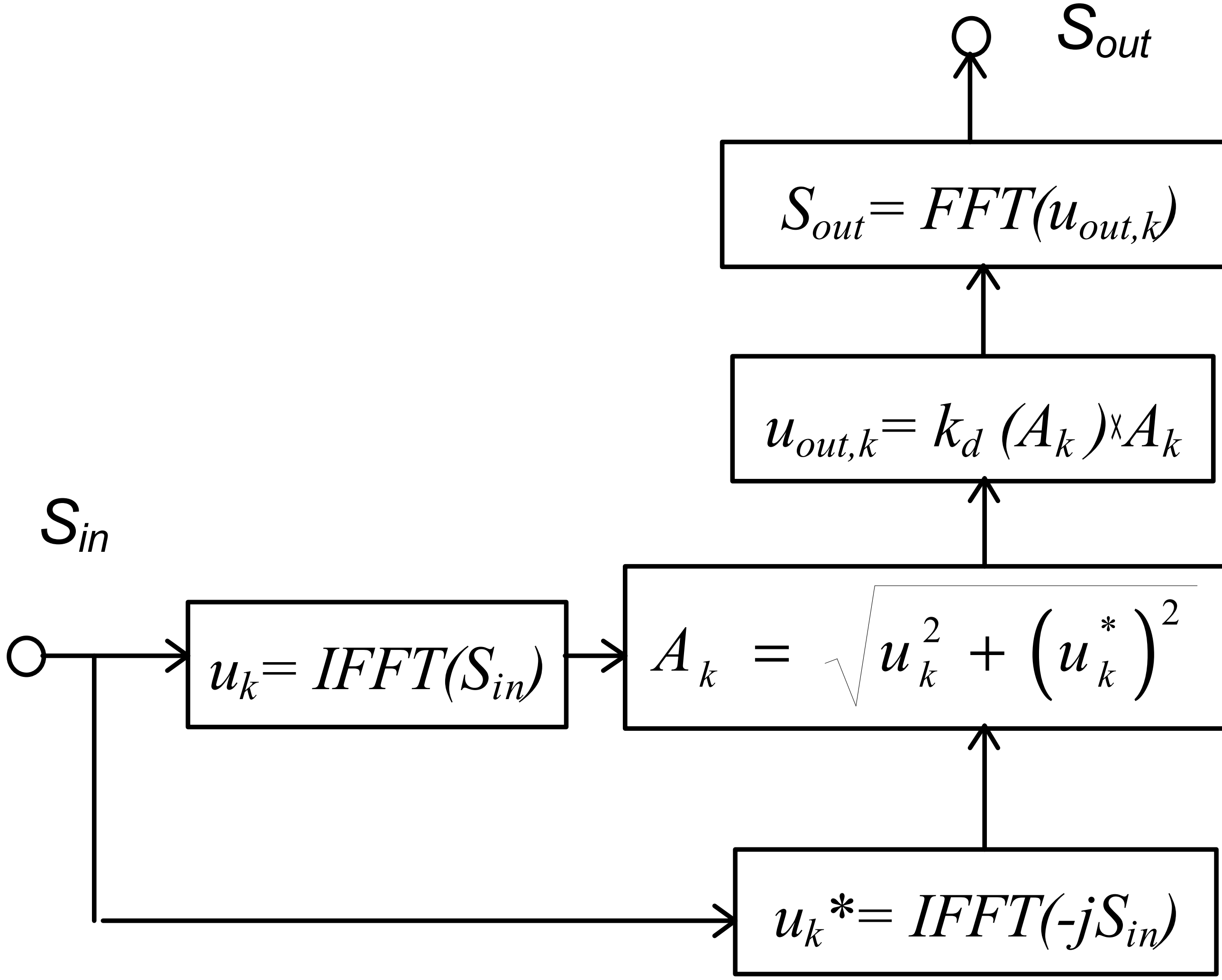
$$F_{in,\max} = \frac{2 \cdot F_{\max}}{I+1} = \frac{1}{(I+1) \cdot \Delta t},$$

  - Polynomial approximation of the nonlinear transfer function can be used to control the spectrum expansion.

- Some issues related to the discrete technique:
  - Non-polynomial models can also be used but special care must be taken in order to avoid the spectrum aliasing. Practical values of the safety factor $I \approx 5 - 50$.
  - The analysis dynamic range is limited by errors in the time domain signal quantization i.e. by the accuracy of computer data presentation (≈300 dB).
  - In order to achieve such a high dynamic range, all input frequencies must be round-off to sample FFT frequencies.
  - When simulating multistage systems, the quantization noise caused by the time-domain quantization is accumulated. This effect can be eliminated by periodic "cleaning out" the spectrum.
  - Utilization of geometrically spaced sample frequencies reduces the number of samples. However, it will slightly decrease the FFT efficiency.

- Some issues related to the discrete technique:
  - Further improvement in computational efficiency → two-stage simulation scheme: (1) first, the radio system simulation correct to carrier frequencies (low frequency resolution) is carried out, (2) all interference signals are sequentially analyzed at high frequency resolution (correct to modulating spectra) and with transformation to low frequencies.
  - Automatic identification of interference sources is also possible (using the dichotomy search procedure).

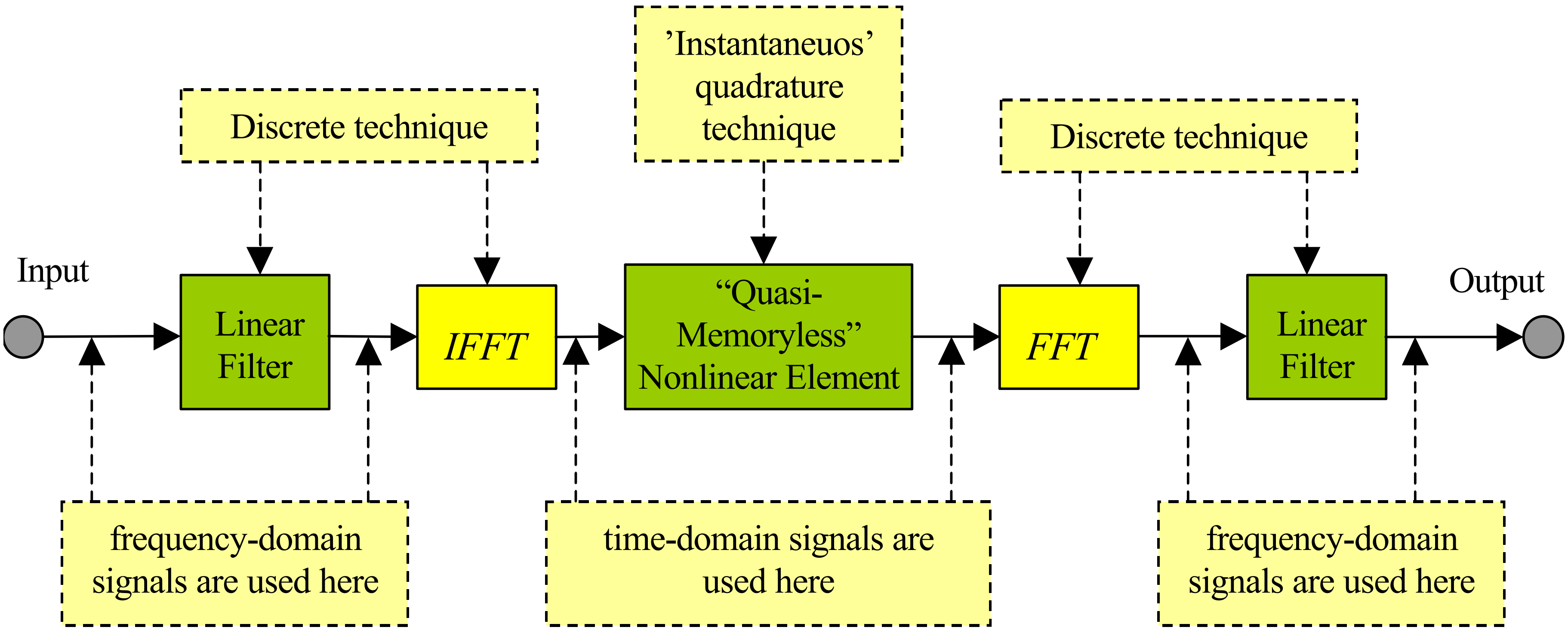
- Detector simulation



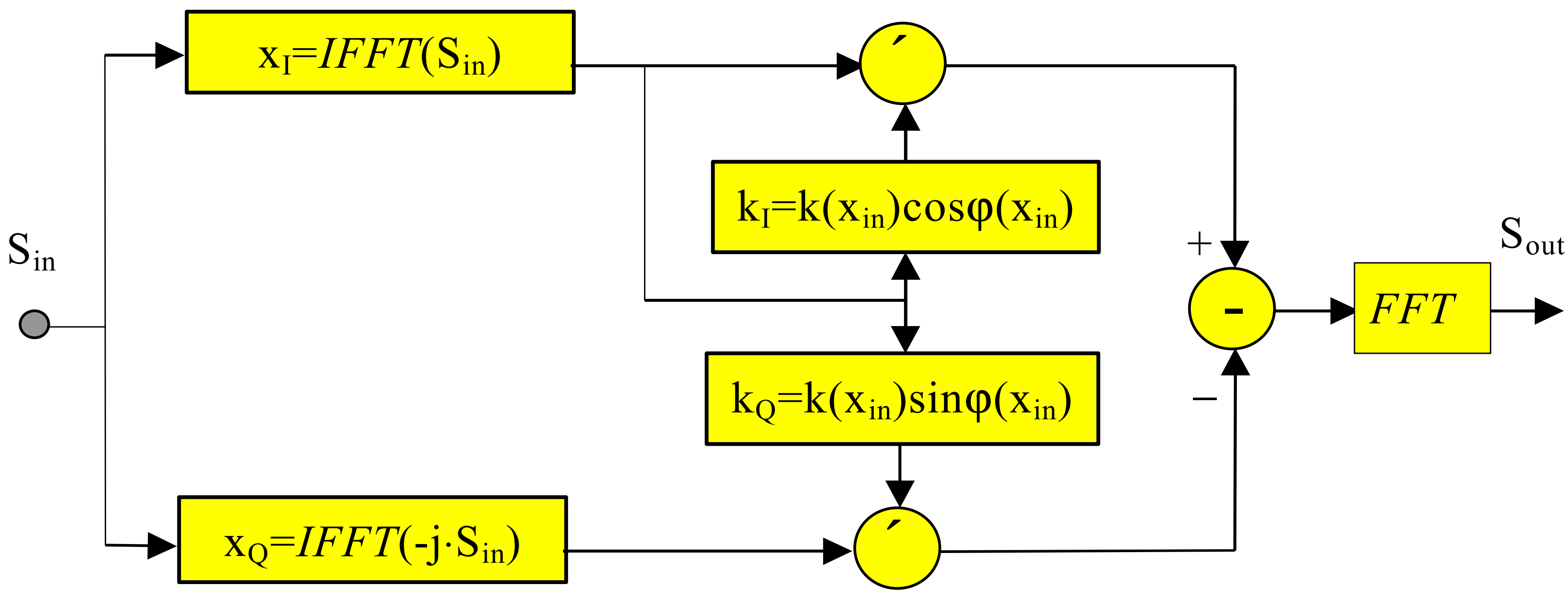
2.3. INSTANTANEOUS QUADRATURE TECHNIQUE

- The main idea of the combined technique is to use advantages of both techniques. In order to model signals and systems over a wide frequency range, the instantaneous values of signals must be used, not the complex envelope. In order to model AM-PM conversion, the quadrature modeling structure should be used.
- Thus, the modeling process consists of the following items.
  1. The modeling of linear filters is carried in the frequency domain.
  2. The modeling of nonlinear elements is carried out in the time domain using the quadrature technique, but the instantaneous signal values are used, not the complex envelope.
  3. Transform from the frequency (time) domain to the time (frequency) domain is made by IFFT (FFT) (very computationally efficient).
  4. Hilbert transform in the frequency domain is used to calculate the signal amplitude and in-phase and quadrature components.

Simulating a single-stage RF amplifier by the 'instantaneous' quadrature technique:



Modeling broadband nonlinear element by the ‘instanteneous’ quadrature technique:



2.4. INSTANTANEOUS TRANSFER CHARACTERISTICS

- Using the instantaneous quadrature technique requires for the instantaneous voltage and phase transfer characteristics of nonlinear elements (not the same as amplitude characteristic !).

$$k(x_{in}) \neq K(A_{in}), \quad \varphi(x_{in}) \neq \Phi(A_{in})$$

- Only the 1st zone (fundamental) envelope (amplitude) characteristics can be determined by measurements or circuit-level simulations: AM-AM & AM-PM.
- Thus, one needs a technique to calculate the instantaneous transfer characteristics from amplitude ones.

- A system of two integral equations gives relations between the envelope and odd instantaneous characteristics:

$$\frac{4}{\pi}\int_0^1 k_I(A_{in}t)\frac{t^2 dt}{\sqrt{1-t^2}} = K(A_{in})\cos\Phi(A_{in})$$

$$\frac{4}{\pi}\int_0^1 k_Q(A_{in}t)\sqrt{1-t^2}\,dt = K(A_{in})\sin\Phi(A_{in})$$

- Two ways to solve the system:
    1. Numerically, using method of moments
    2. Quasi-analytically, using the Bessel (cosine) series expansion method

2.4.1. NUMERICAL CALCULATION OF ODD INSTANTANEOUS TRANSFER CHARACTERISTICS

- Using the method of moments, integral equations are reduced to the systems of linear equations
- For piecewise constant basis functions and point matching technique, the matrixes of these equations are upper triangular ones, so the systems of linear equations can be solved analytically.

$$k_{I,n} = \frac{a_n - \sum_{j=1}^{n-1} k_{I,j} A_{jn}}{A_{nn}}, \quad k_{Q,n} = \frac{b_n - \sum_{j=1}^{n-1} k_{Q,j} B_{jn}}{B_{nn}}$$

$$a_n = K\left(\frac{n}{N}A_{in}\right)\cos\Phi\left(\frac{n}{N}A_{in}\right) \quad ,$$

$$n = \overline{1,N}$$

$$b_n = K\left(\frac{n}{N}A_{in}\right)\sin\Phi\left(\frac{n}{N}A_{in}\right),$$

$$A_{jn} = \frac{2}{\pi}\left\{a_{jn} - a_{j-1,n} + b_{j-1,n} - b_{jn}\right\}, \quad a_{jn} = \sin^{-1}\left(\frac{j}{n}\right)$$

$$B_{jn} = \frac{2}{\pi}\left\{a_{jn} - a_{j-1,n} + b_{jn} - b_{j-1,n}\right\}, \quad b_{jn} = \frac{j}{n}\sqrt{1-\left(\frac{j}{n}\right)^2}$$

2.4.2. QUASI-ANALYTICAL CALCULATION OF ODD INSTANTANEOUS TRANSFER CHARACTERISTICS

- Bessel function series are used to represent the envelope characteristics:

$$A_{out,p}(A_{in}) = \sum_{i=odd} A_{p,i} J1(i\xi A_{in}), \quad A_{out,q}(A_{in}) = \sum_{i=odd} A_{q,i} J1(i\xi A_{in})$$

where $\xi = \pi / (2A_{in,max})$.

- Then the instantaneous transfer factors (gains) are presented as sine and cosine series:

$$k_p(x_{in}) = \sum_{i=odd} \frac{i\xi}{2} A_{p,i} \frac{sin(i\xi x_{in})}{i\xi x_{in}}, \quad k_q(x_{in}) = \sum_{i=odd} \frac{i\xi}{2} A_{q,i} \, cos(i\xi x_{in})$$

- Least-squares curve fitting technique together with the singular value decomposition technique are used to calculate the Bessel series expansion coefficients (non-orthogonal functions!).
- Polynomial series can also be used for quasi-analytical solution of the integral equations, but the Bessel series usually requires fewer terms.
- IE works as a high-pass filter!

2.4.3. CALCULATION OF EVEN INSTANTANEOUS TRANSFER CHARACTERISTICS

- Previous calculations give only the odd part of transfer characteristics. In order to calculate the even part (and even-order nonlinear products!), new system of integral equations must be used:

$$\frac{4}{\pi}\int_0^1 k_I(A_{in}t)\frac{t(2t^2-1)dt}{\sqrt{1-t^2}} = K_2(A_{in})\cos\Phi_2(A_{in})$$

$$\frac{8}{\pi}\int_0^1 k_Q(A_{in}t)\cdot t\sqrt{1-t^2}\,dt = K_2(A_{in})\sin\Phi_2(A_{in})$$

- Using the method of moments, these integral equations are reduced to the systems of linear equations.

- For piecewise constant basis functions and point matching technique, the matrixes of these equations are upper triangular ones, so the systems of linear equations can also be solved analytically (similar to the previous case, for odd part):

$$k_{I,n} = \frac{a_n - \sum_{j=1}^{n-1} k_{I,j} A_{jn}}{A_{nn}}, \quad k_{Q,n} = \frac{b_n - \sum_{j=1}^{n-1} k_{Q,j} B_{jn}}{B_{nn}}$$

$$a_n = K_2\left(\frac{n}{N}A_{in}\right)\cos\Phi_2\left(\frac{n}{N}A_{in}\right), \quad n=\overline{1,N}$$

$$b_n = K_2\left(\frac{n}{N}A_{in}\right)\sin\Phi_2\left(\frac{n}{N}A_{in}\right),$$

$$A_{jn} = \frac{8}{3\pi}\left\{b_{j-1,n}\cdot a_{j-1,n} - b_{j,n}\cdot a_{jn}\right\}, \quad a_{jn} = \frac{1}{2} + \left(\frac{j}{n}\right)^2$$

$$B_{jn} = \frac{8}{3\pi}\left\{b_{j-1,n}^3 - b_{j,n}^3\right\}, \quad b_{jn} = \sqrt{1-\left(\frac{j}{n}\right)^2}$$

- 2^{nd} order AM-AM & AM-PM characteristics must be simulated or measured for these calculations.
- Circuit-level simulation of these characteristics – in general, no problem (pay attention to the simulation accuracy. Usually, error for 2^{nd} order characteristics is higher than for 1^{st} order ones!).
- Measurement of 2^{nd} order AM-AM (using a spectrum analyzer) – in general, no problem (pay attention to the measurement accuracy, especially to avoid the measurement setup nonlinearities!).
- Measurement of 2^{nd} order AM-PM – general-purpose instrument is not suitable. Special techniques must be used.
- In general, calculation errors are substantially higher for 2^{nd} order characteristics – special care must be taken!
- No any analytical or quasi-analytical solution is now available – everybody's contribution is strongly welcome!

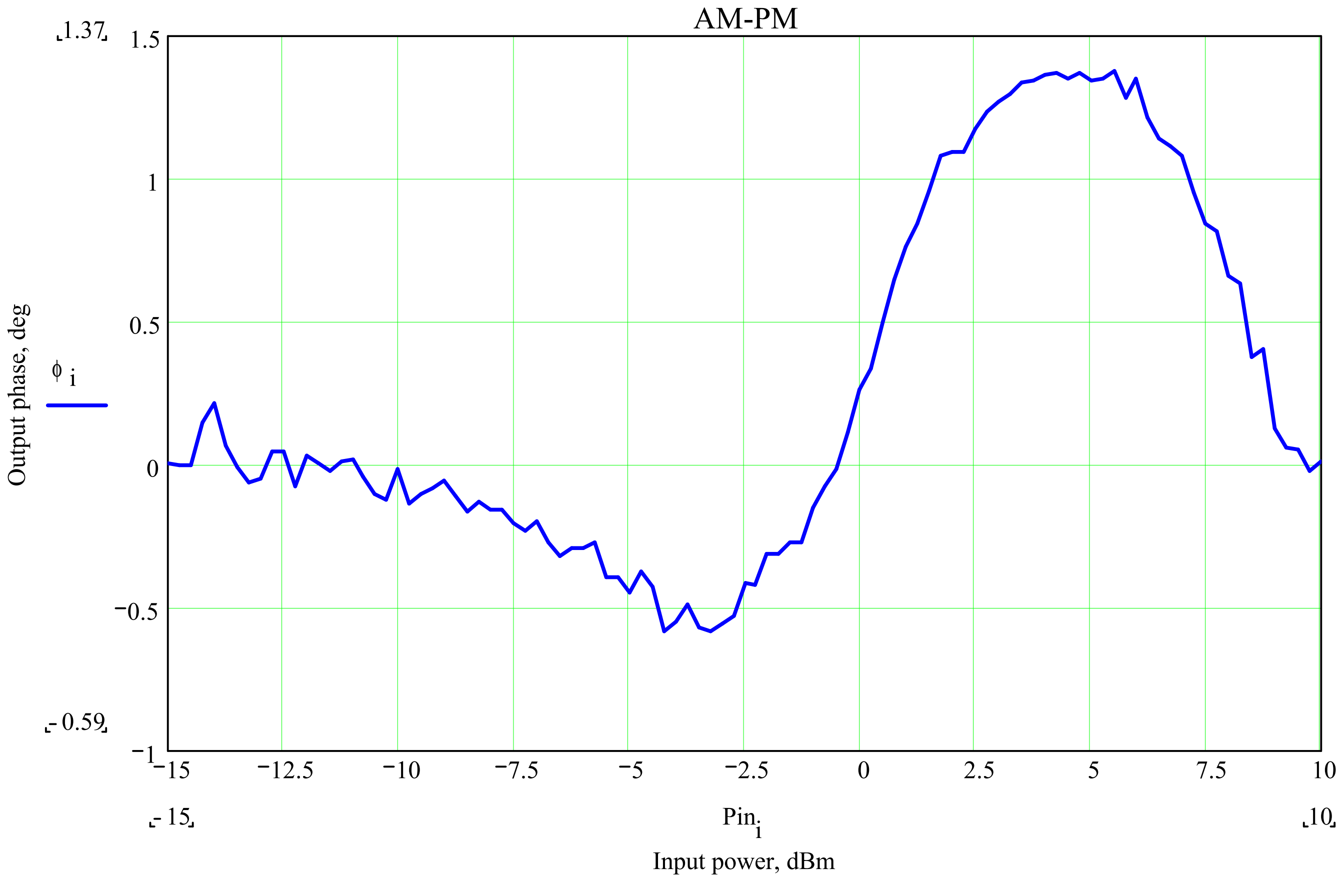
3. Modeling and Characterization Issues

- Some issues relevant to modeling and characterization for behavioral-level simulation:
  - AM-AM & AM-PM measurement versus simulation.
  - How represent (approximate) the characteristics: Splines, Orthogonal series, Non-Orthogonal series, Genetic algorithm, Neural networks, Simple analytical formulas etc.
  - Accuracy of approximation, its influence on the entire simulation accuracy and related issues.

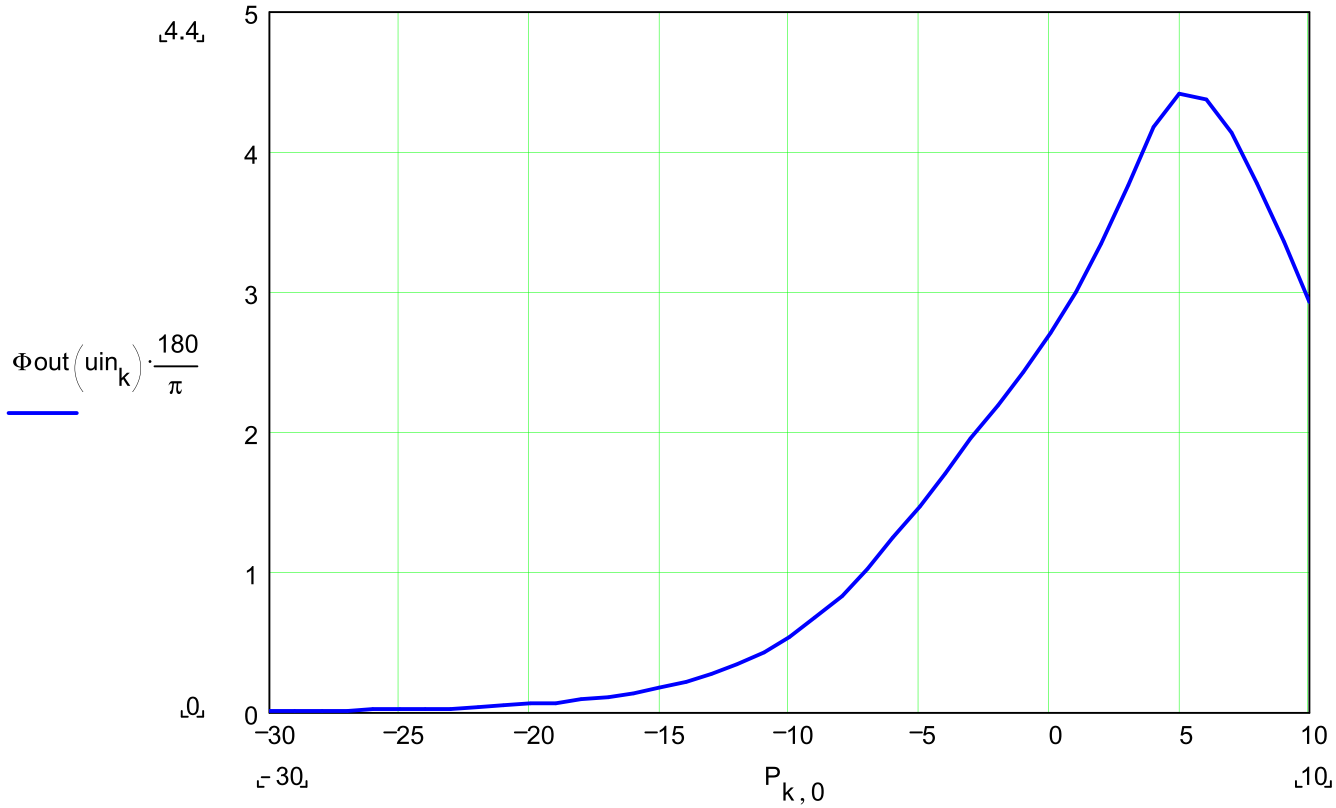
3.1. AM-AM & AM-PM MEASUREMENT VERSUS SIMULATION

- Two approaches are possible for obtaining AM-AM & AM-PM characteristics – measurement and simulation.
- Usually, measured characteristic is more reliable and more close to the reality (but special care must be taken to avoid large measurement errors). It depends on measurement setup in much smaller extent than simulated one on simulation technique.
- But measurements are more time and money consuming. Measurements are not possible on early design phases (no any fabricated circuit). Measurement noise and uncertainty is usually higher.
- Special measures must be taken to filter out the measurement noise.

- Example: measured AM-PM characteristic



- Example: HB-simulated AM-PM characteristic



- Simulation can be made at early design phases. It is not so time and money consuming.
- Simulation noise and uncertainty are usually smaller. There is no need to filter out the simulation noise.
- But simulation results may depend substantially on technique and models used. In general, they are not so reliable as measurements.

3.2. HOW TO REPRESENT THE CHARACTERISTICS

- Measured or simulated AM-AM & AM-PM characteristics are know for a number of specific points. Transformation to instantaneous characteristics usually requires for other points. What to do?
- Several solutions are possible:
  - Simple analytical formulas
  - Splines
  - Orthogonal or non-orthogonal series
  - Genetic algorithm
  - Neural networks

3.2.1. SIMPLE ANALYTICAL FORMULAS

- They were used very extensively in the past (most know – Saleh model of TWT), and sometimes are used at the present
- Analysis process is quite simple
- Analytical calculations are possible- no any need for substantial computational power
- Give insight into the system behavior
- Parameters are determined using a curve fitting technique
- Main drawback – poor accuracy

3.2.2. SPLINES

- Very well-known technique
- 3rd order splines are usually used
- Best accuracy if there is no noise in the data
- Good computational efficiency
- Main drawback – don't allow to filter out the measurement (or simulation) noise → are used only for simulated characteristics

3.2.3. ORTHOGONAL OR NON-ORTHOGONAL SERIES

- Which series are used
  - Polynomials (power series) (Non-orthogonal)
  - Chebyshev series (Orthogonal)
  - Bessel series (Non-orthogonal)
  - Sine/cosine series (Orthogonal)
- Least-squares curve-fitting technique together with SVD technique is usually used for non-orthogonal series. The number of data points must be much larger than the number of coefficients.

Chebyshev Series:

- Orthogonality of Chebyshev series over discrete set of points:

$$A_k = \frac{2}{M} \sum_{j=0}^{M} K_{norm}\left(x_j\right) T_k(x_j), \qquad M > 10N$$

- Direct relation to the Fourier transform:

$$a_k = \frac{2}{\pi} \int_0^{\pi} K_{norm}\left(\cos\theta\right) \cos(k\theta)\, d\theta$$

- Be careful to avoid the aliasing effect!

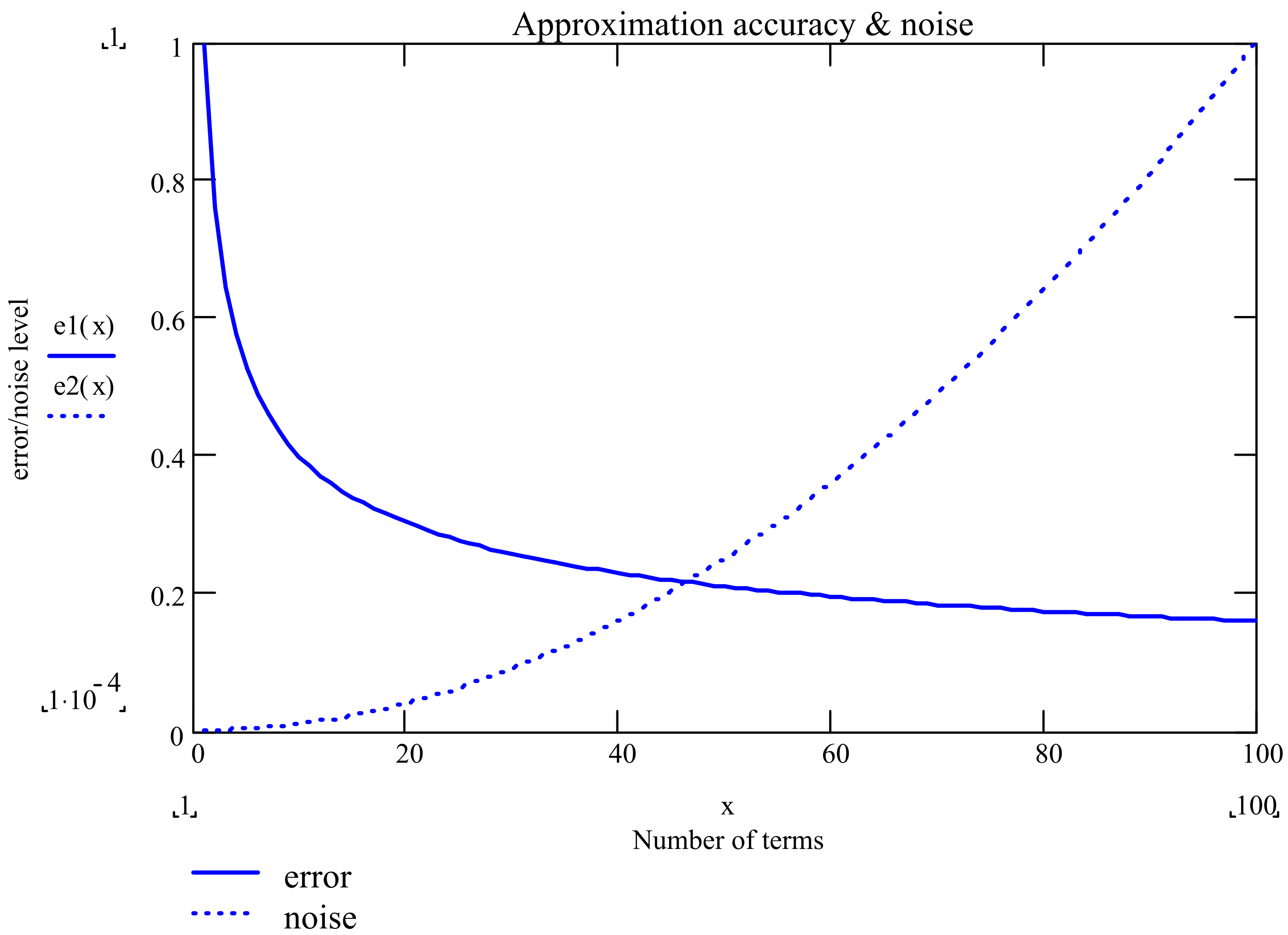
$$A_k = a_k - a_{2M-k} - a_{2M+k} + a_{4M-k} + a_{4M+k} - \ldots, \quad k = \overline{0,N}$$

- Main advantages of Chebyshev series: (1) numerically stable, (2) give finite spectrum expansion, (3) fastest convergence among polynomials
- Bessel series: usually, they converge faster than others (especially, for fast-oscillating characteristics).
- Sine/cosine series – allow to use all the powerful Fourier analysis. Convergence speed/accuracy – medium between Chebyshev and Bessel series.
- In general, series expansions give good possibility to filter out the measurement/simulation noise by the number of terms:

$$y(x) = y_{real}(x) + \varepsilon(x)$$

- No any mathematical technique for optimum number of terms

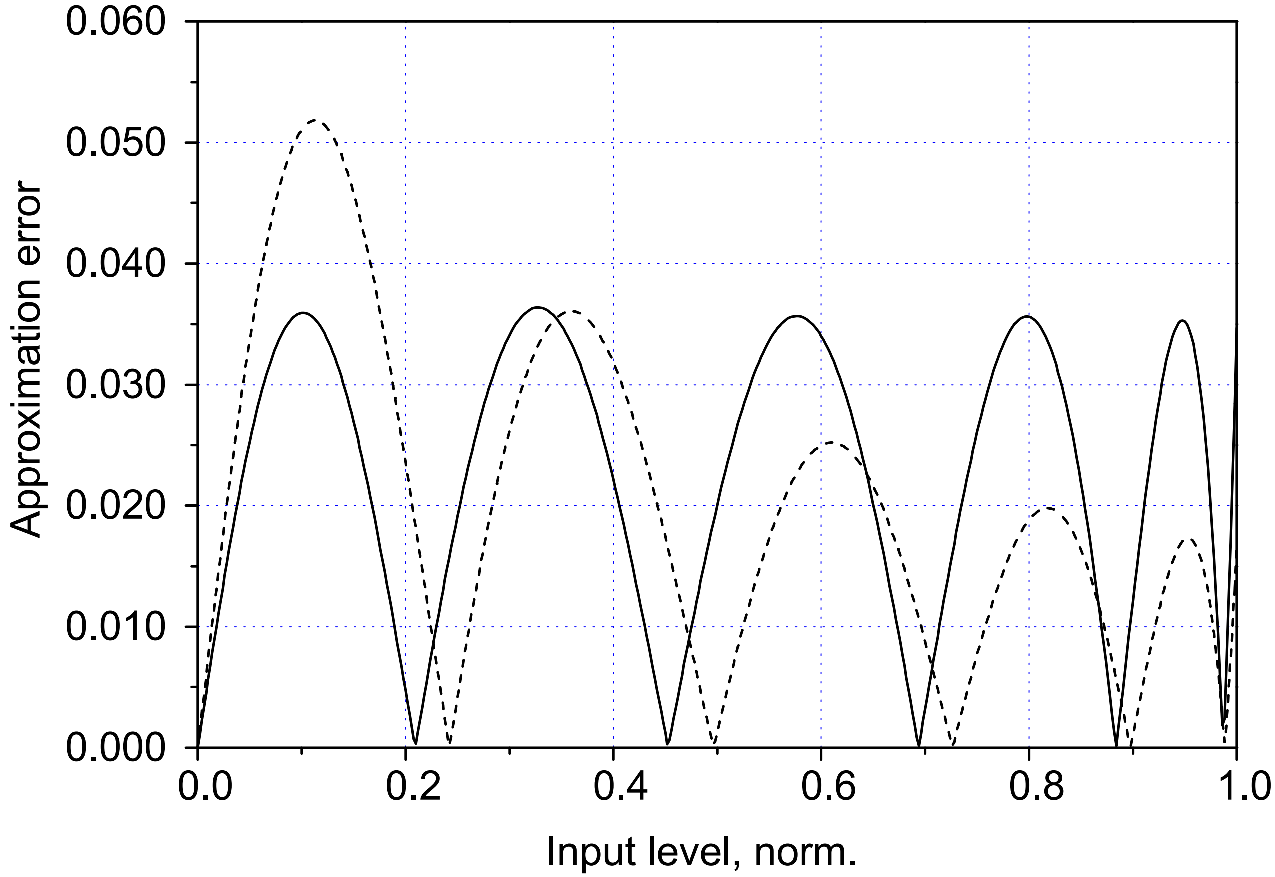
Approximation accuracy & noise versus number of terms



3.2.4. GENETIC ALGORITHM

- No any finite procedure to calculate minimax approximation coefficients
- There are some iterative techniques, but they have a lot of drawbacks – convergence to local minima, slow convergence, numerically unstable etc.
- Genetic algorithm approximation – completely new technique:
  - Search for global optimum
  - Numerically stable
  - Very robust (any criterion can be used, not only minimax one)
  - Gives the best possible approximation
  - Measurement noise filtering out is possible
- Only preliminary work has been done. Much work must be done in future.

Genetic Algorithm Approximation Versus Chebyshev Approximation:



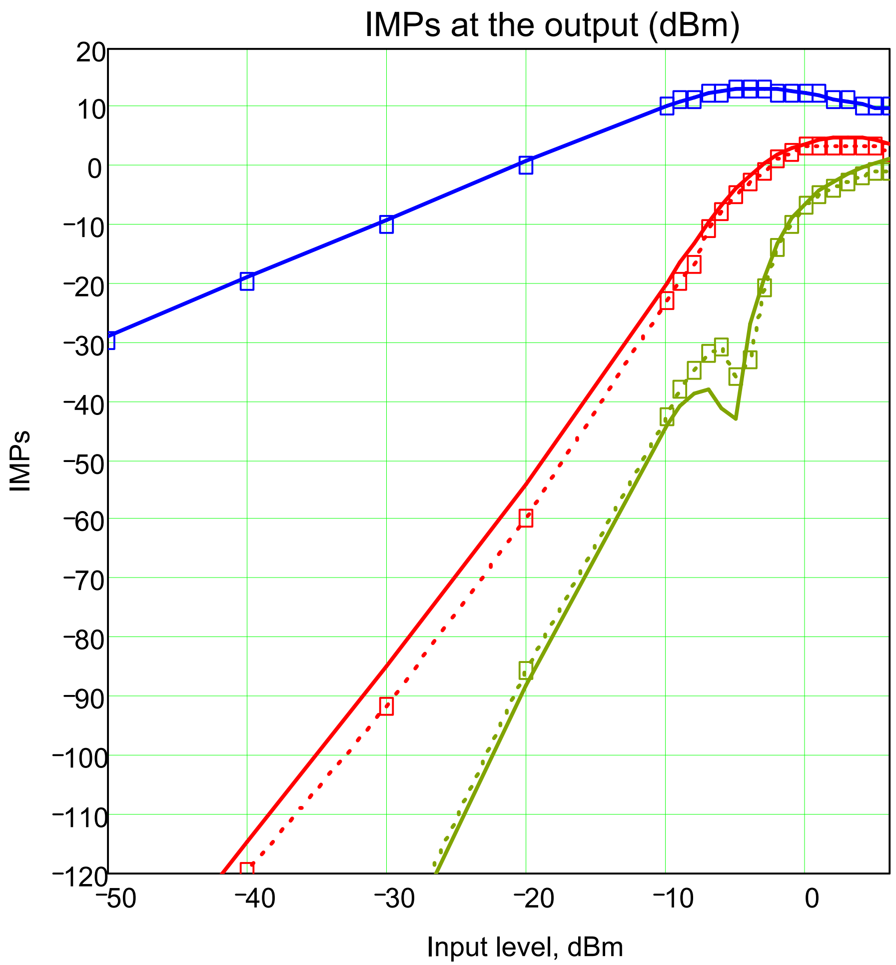
3.2.5. NEURAL NETWORKS

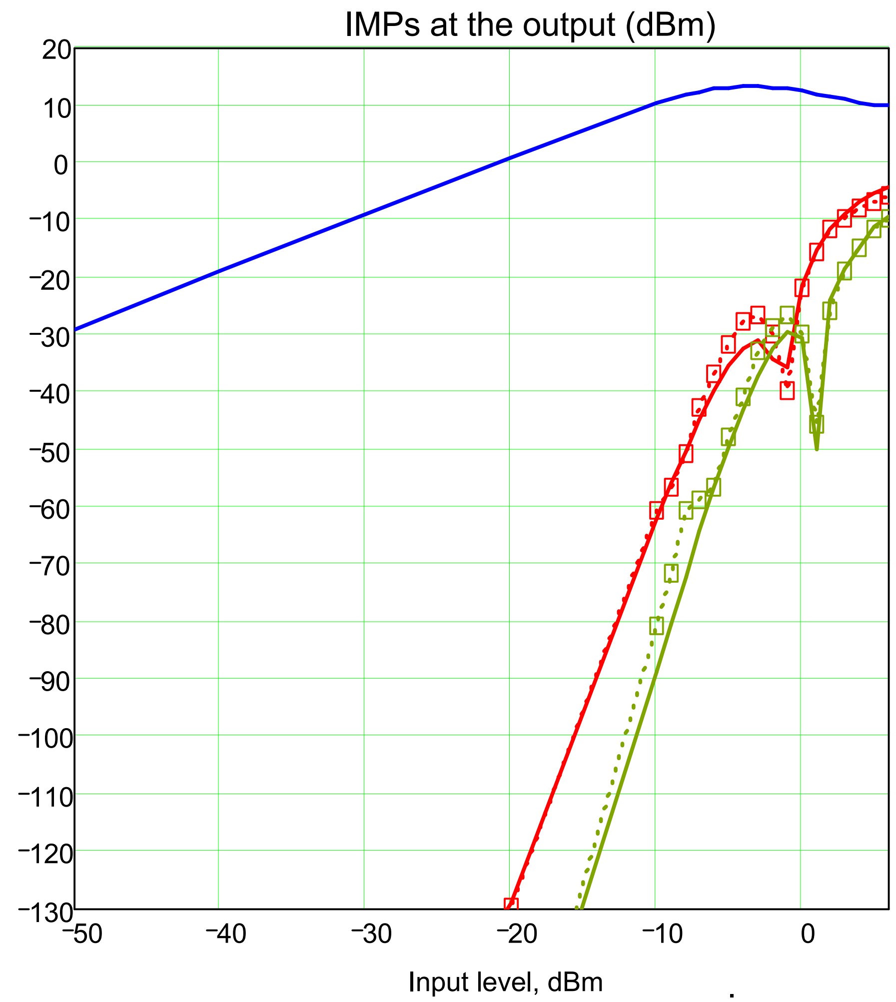
- Neural Networks – another type of novel evolutionary computation techniques.
- They are universal approximators. Successfully used for many approximation and optimization problems.
- Behavioral simulation – comparison with old analytical models (Saleh TWT model) only.
- Possible area of fast progress in future.

3.3. ACCURACY OF APPROXIMATION & RELATED ISSUES

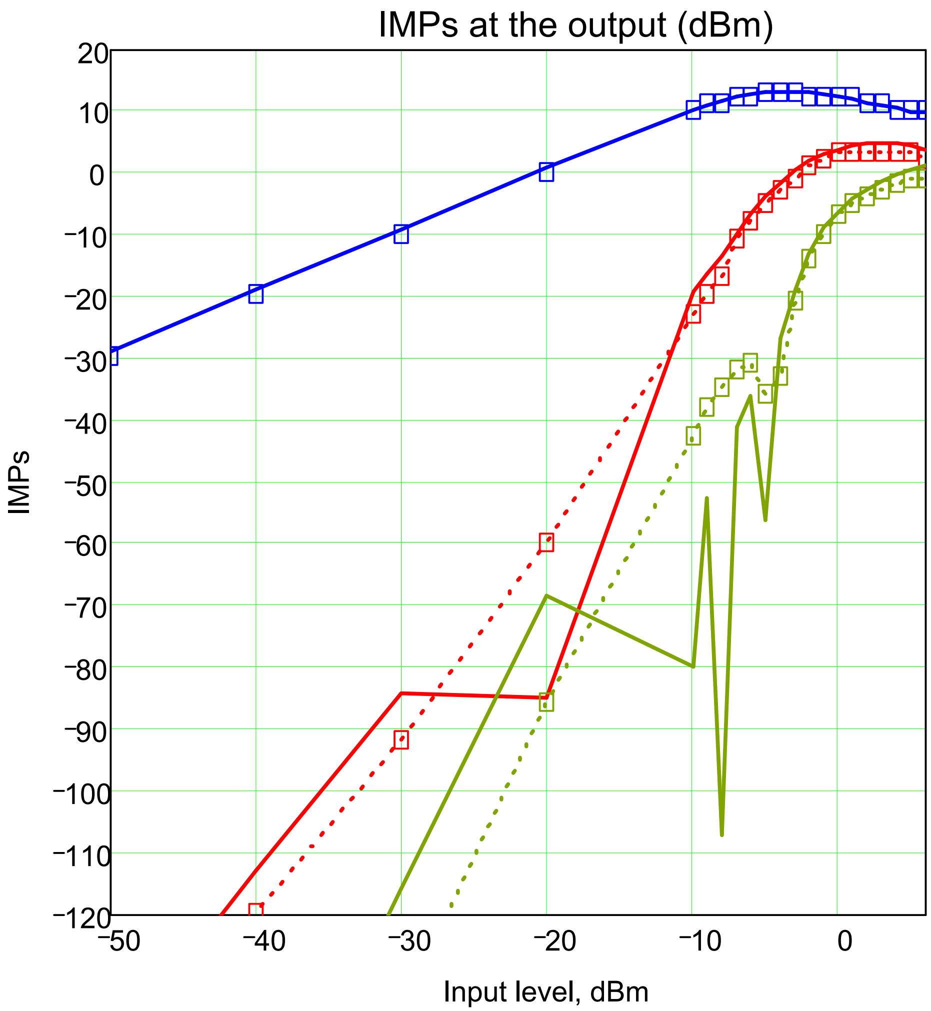
- Accurate approximation of transfer characteristics are extremely important for the entire simulation.
- Small inaccuracy in transfer characteristic may lead to very large inaccuracy in final result – nonlinear problem!
- Two kinds of approximation: (1) approximation of measured/simulated AM-AM & AM-PM, (2) approximation of instantaneous characteristics – to filter out the computational noise.
- Practical approximation orders:
  - Chebyshev polynomials: in-phase channel – 10-30, quadrature channel – 40-100
  - Bessel series: in-phase channel – 5-15, quadrature channel – 10-40
  - Splines – only for 1st kind approximation

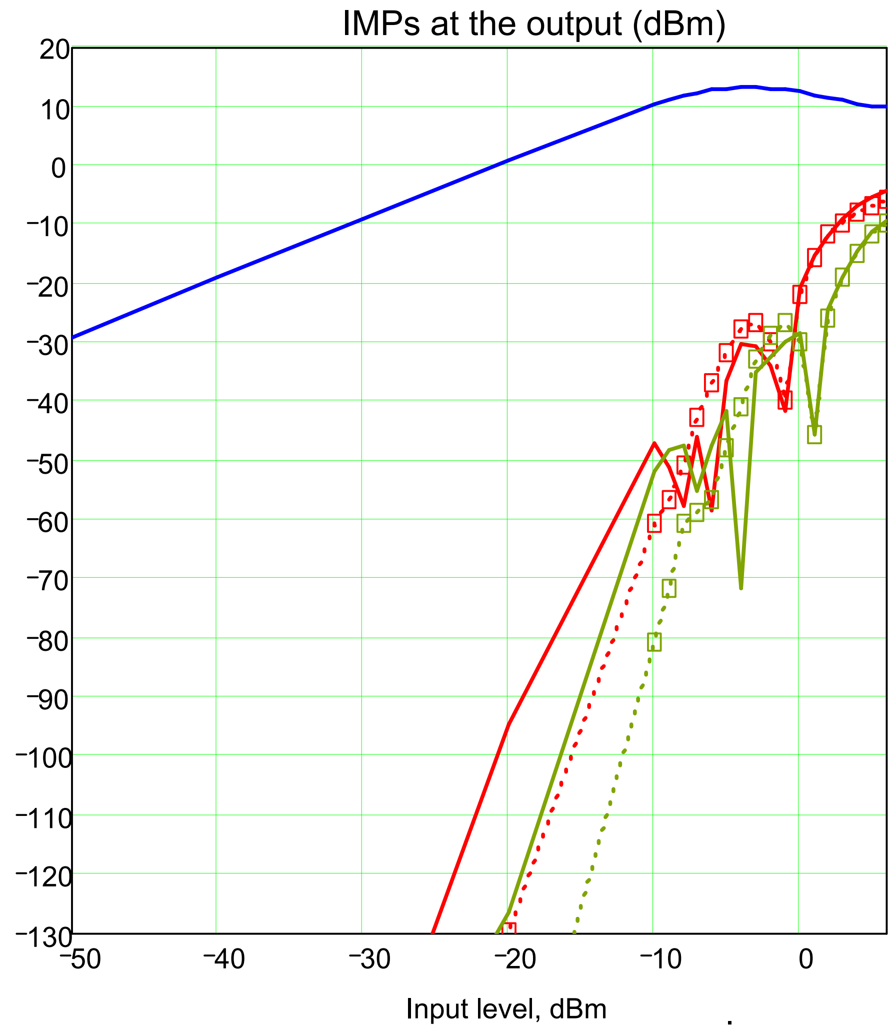
IMPs measurements versus behavioral-level simulation (N=24)



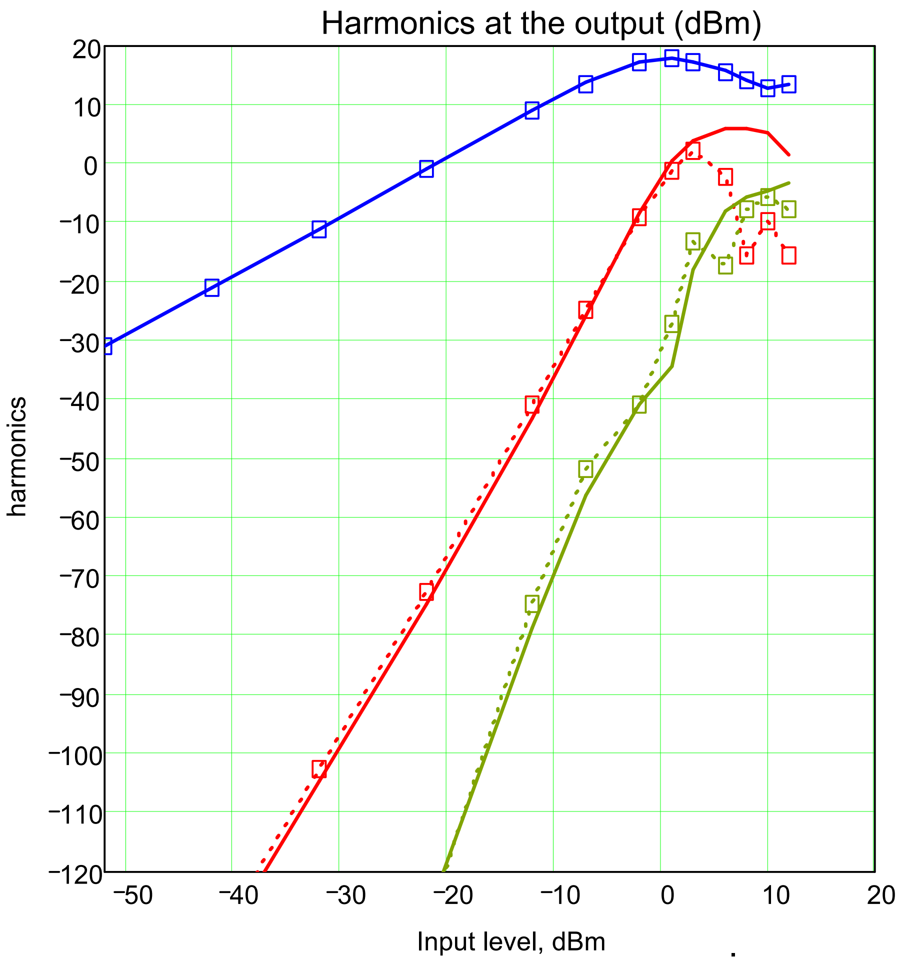


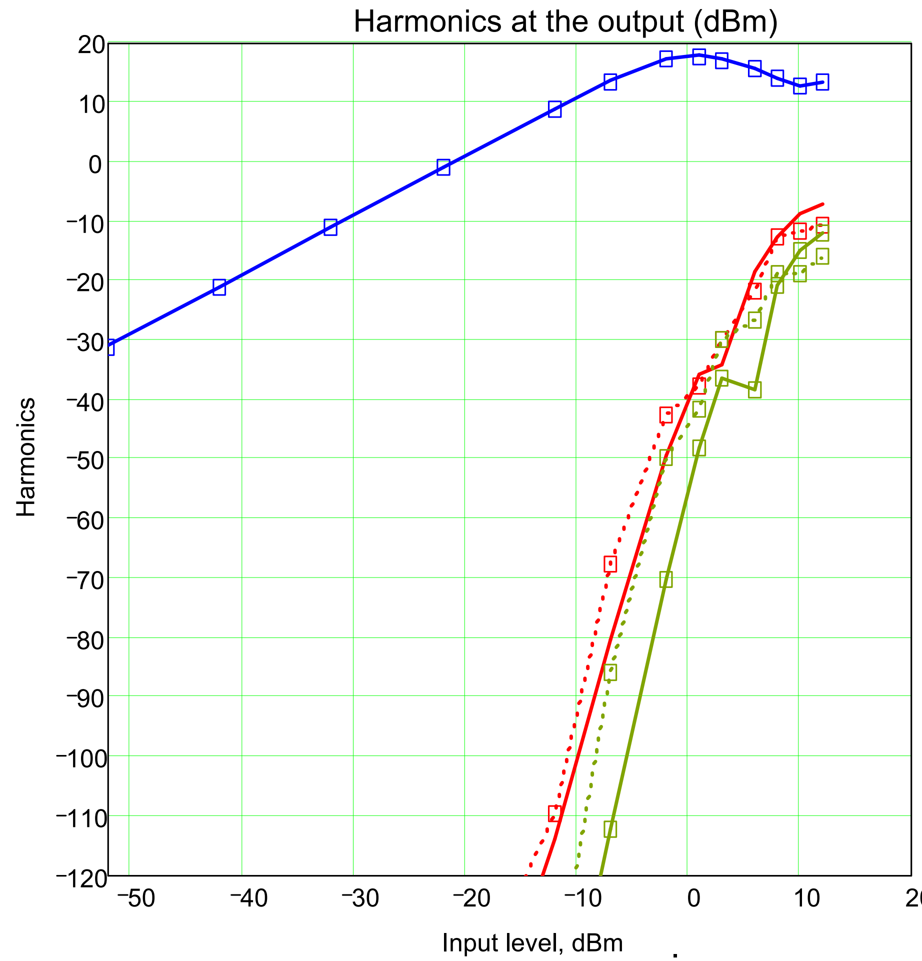
IMPs measurements versus behavioral-level simulation (N=64)



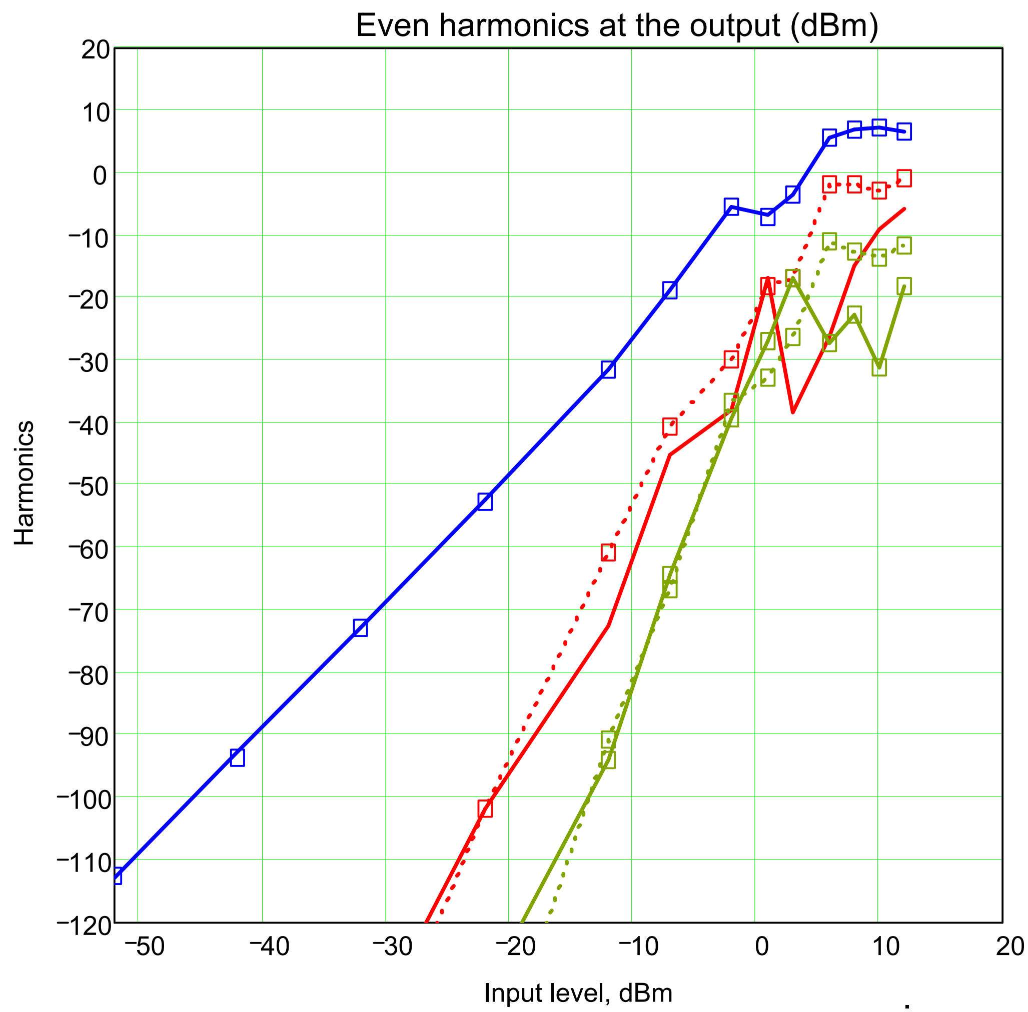


Harmonics measurements versus behavioral-level simulation (N=24)





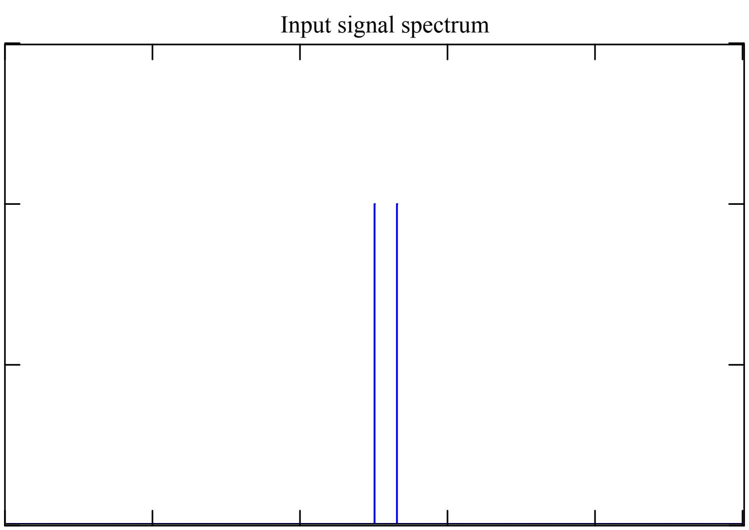
Even harmonics measurements versus behavioral-level simulation (N=24)



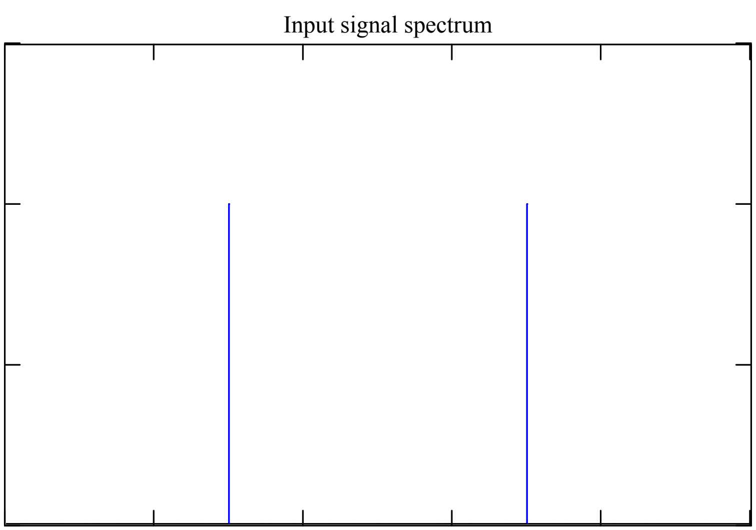
3.4. TONE-SPACING EFFECT

- Principal limitation to behavioral-level simulation accuracy – tone-spacing effect (also known as bias decoupling network effect)
- What's this ? When 2 input tones are located close enough (<1MHz) – good accuracy. When they are separated wider – poor accuracy.

Small spacing

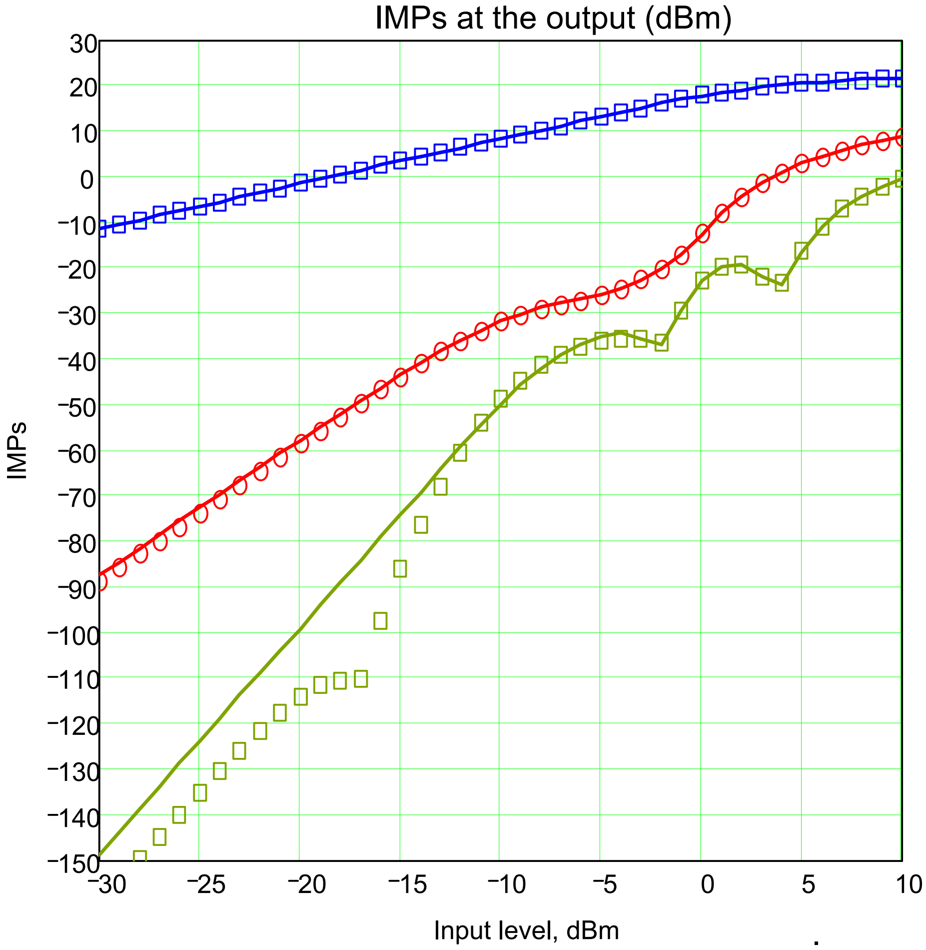


Large spacing

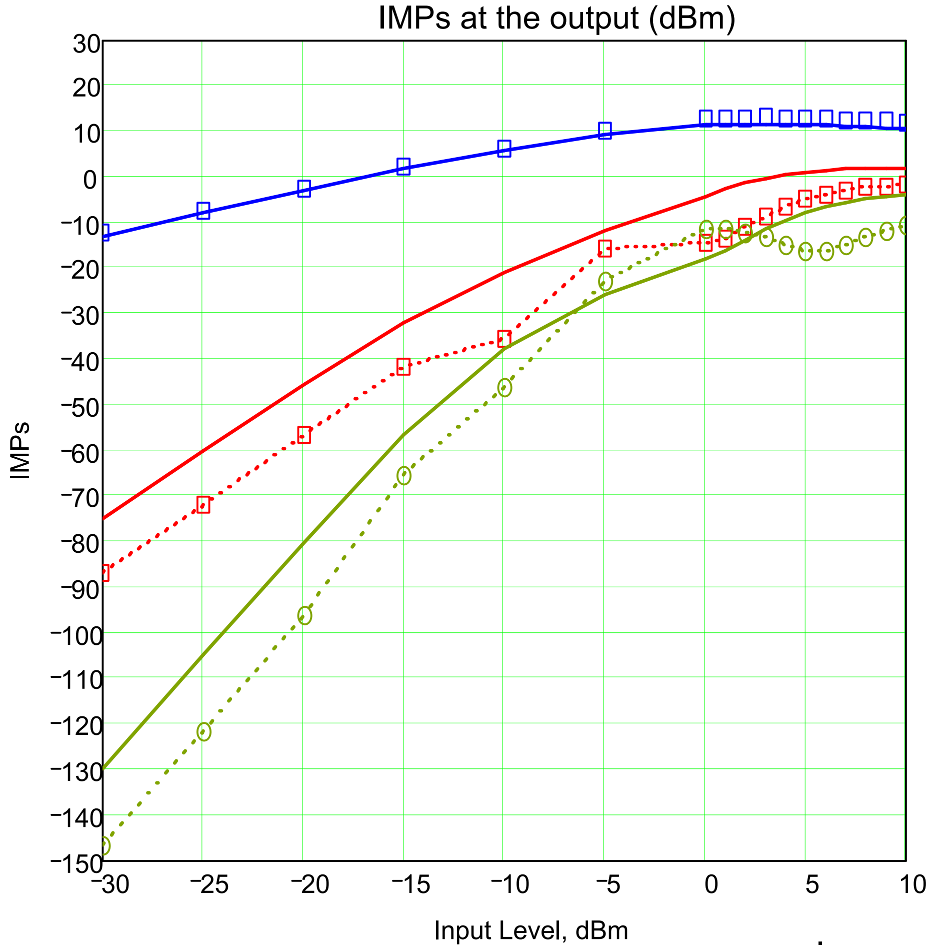


- Reason: 2nd order IMP changes bias conditions at the input & output.
- *"Narrow-band spectra requires only odd characteristics and narrow-band modeling"* – NOT TRUE !
- Accurate simulation of narrow-band spectra requires broad-band modeling!
- No any narrow-band technique can handle this problem.
- Instantaneous quadrature technique is a wide-band one and it can handle this problem.

No tone-spacing effect



Tone-spacing effect



4. POSSIBLE APPLICATIONS

- Several types of possible applications are feasible:
  - Power amplifiers
  - RF/microwave subsystems & systems
  - Active array antennas
  - Bell Labs limit for channel capacity & active array simulation

4.1. POWER AMPLIFIERS

- Simulation of power amplifiers for digital wireless communications:
  - Spectral regrowth
  - Adjacent channel power
  - Error vector magnitude
  - Harmonics
  - Spurious signals

4.2. RF/MICROWAVE SUBSYSTEMS & SYSTEMS

- Simulation of RF/Microwave subsystems & systems (primarily, wireless communications):
  - Mixers, local oscillators, LNA, IFA, AGC (nonlinear performance, nonlinear interference & distortions)
  - Transmitting and receiving paths (nonlinear performance, nonlinear interference & distortions)
  - Entire communication system (nonlinear performance, nonlinear interference & distortions)

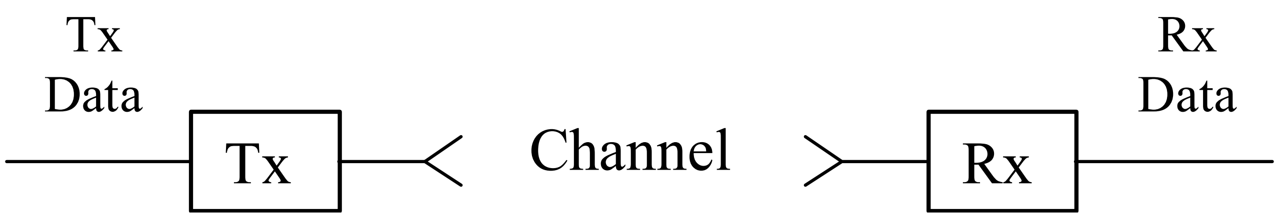
4.3. ACTIVE ARRAY ANTENNAS

- New area of applications: modeling & simulation of active array antennas (nonlinear performance & distortions).
- High complexity of active arrays requires for efficient simulation techniques → behavioral-level simulation.
- Widespread use of active arrays (UMTS, radars etc.) and “overcrowded” spectrum → high demand for simulation

4.4. BELL LABS LIMIT FOR CHANNEL CAPACITY AND ACTIVE ARRAY SIMULATION

- Classical Shannon's limit for channel capacity:

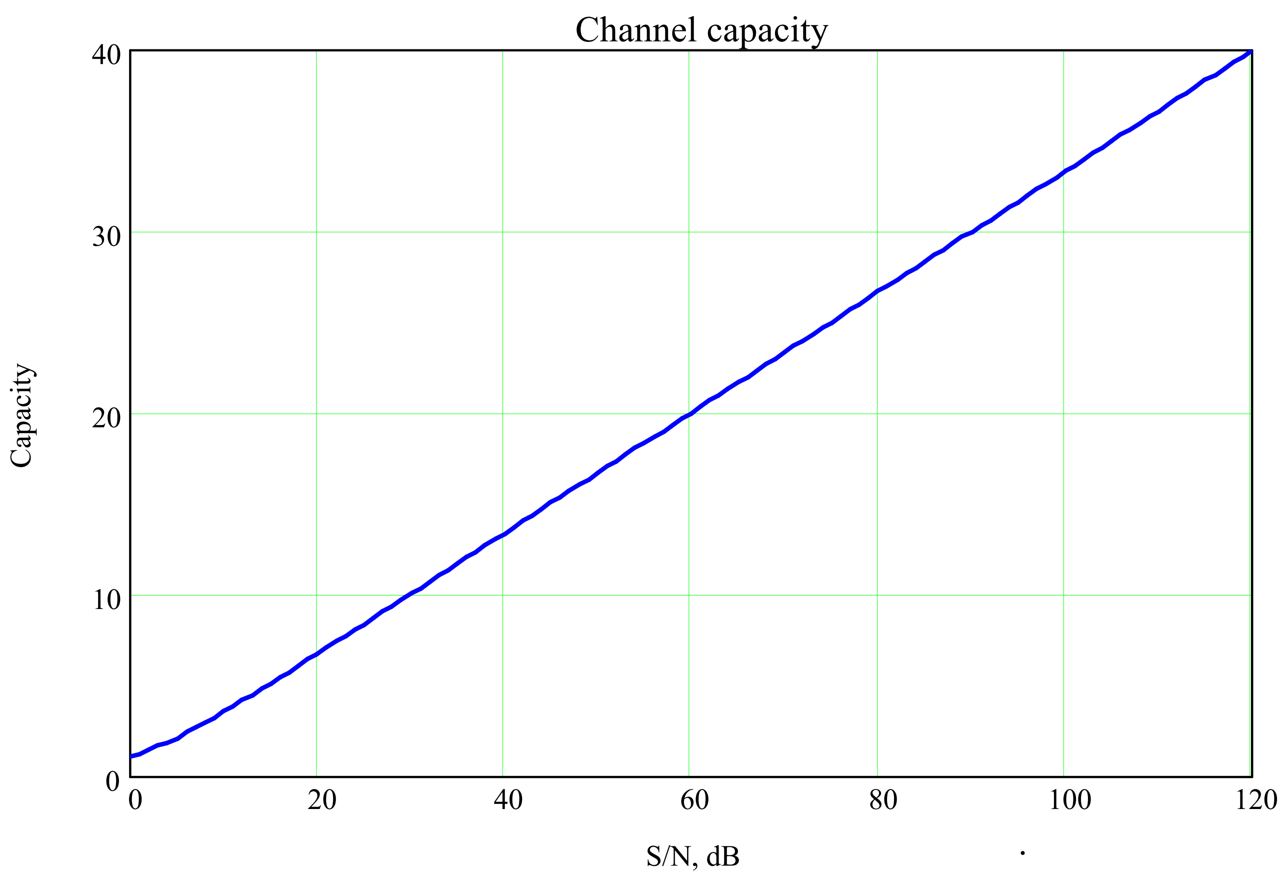
$$C = log_2\left(1 + \frac{S}{N}\right) \quad [bits / Hz / s]$$



- Increases as the log of S/N → very slowly!

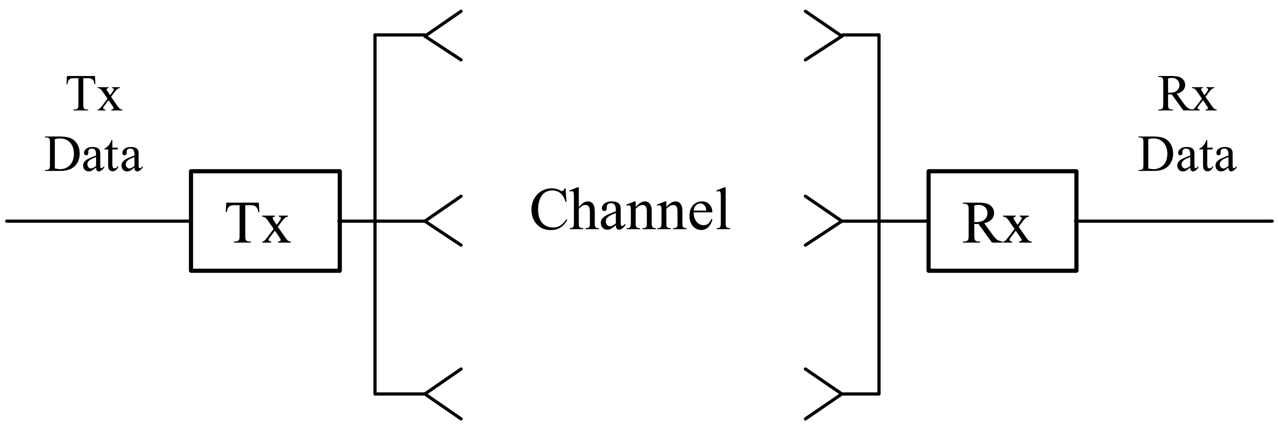
- Realistic values: few bits/Hz/s :

Shannon's channel capacity limit



- Try to use directional antennas to increase C ?

$$C = log_2\left(1 + \frac{S}{N} \cdot M\right) \quad [bits / Hz / s]$$

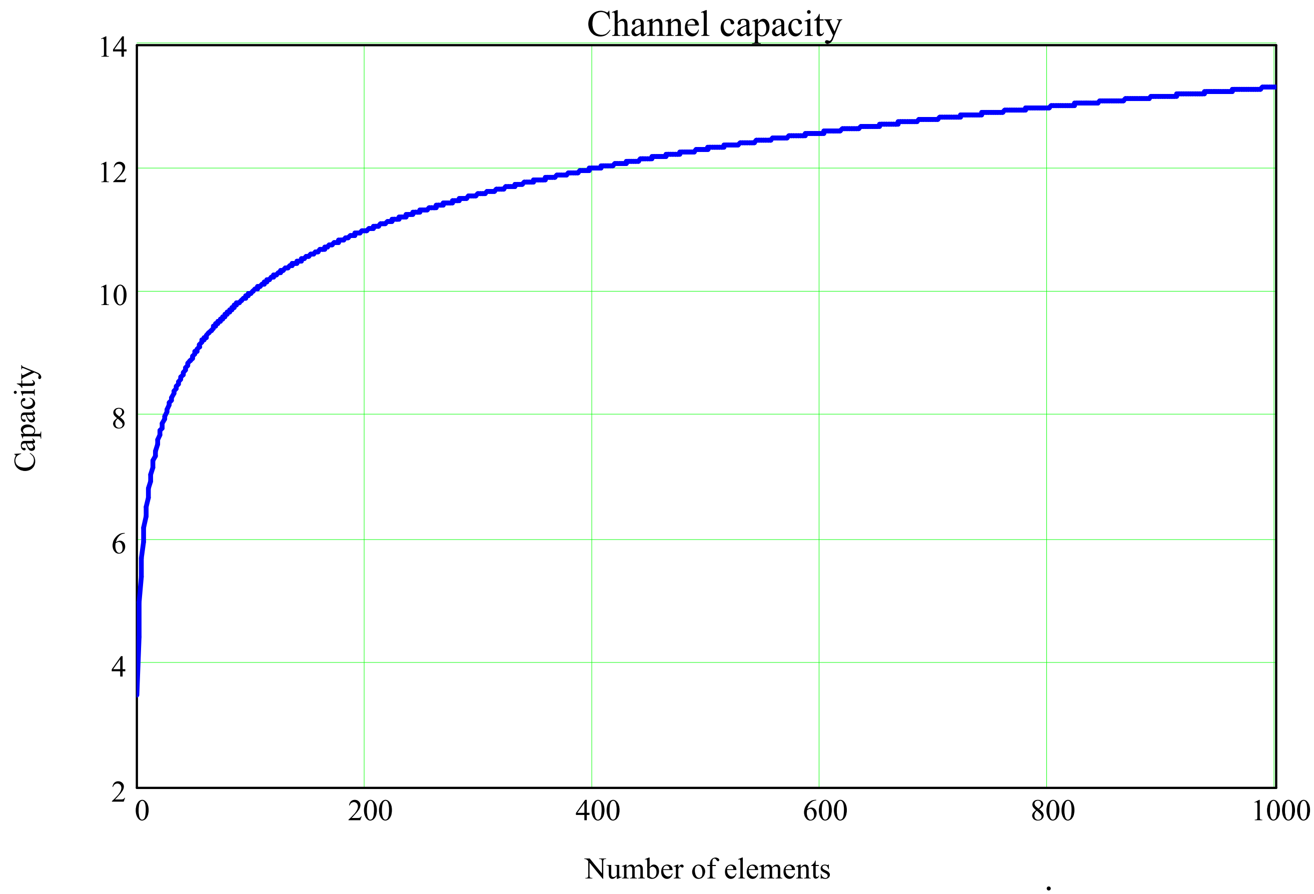


M – number of array elements

- Increases as the log of M → very slowly!

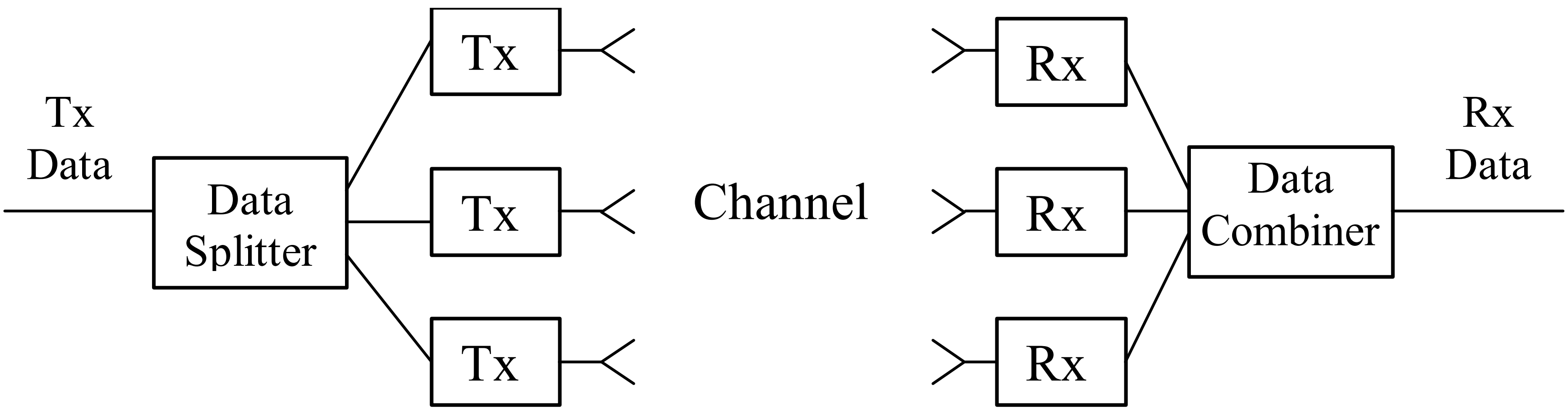
- Realistic values: few bits/Hz/s :

Channel capacity versus number of array elements (S/N=10dB)



- Split not only the carrier, but also the information!

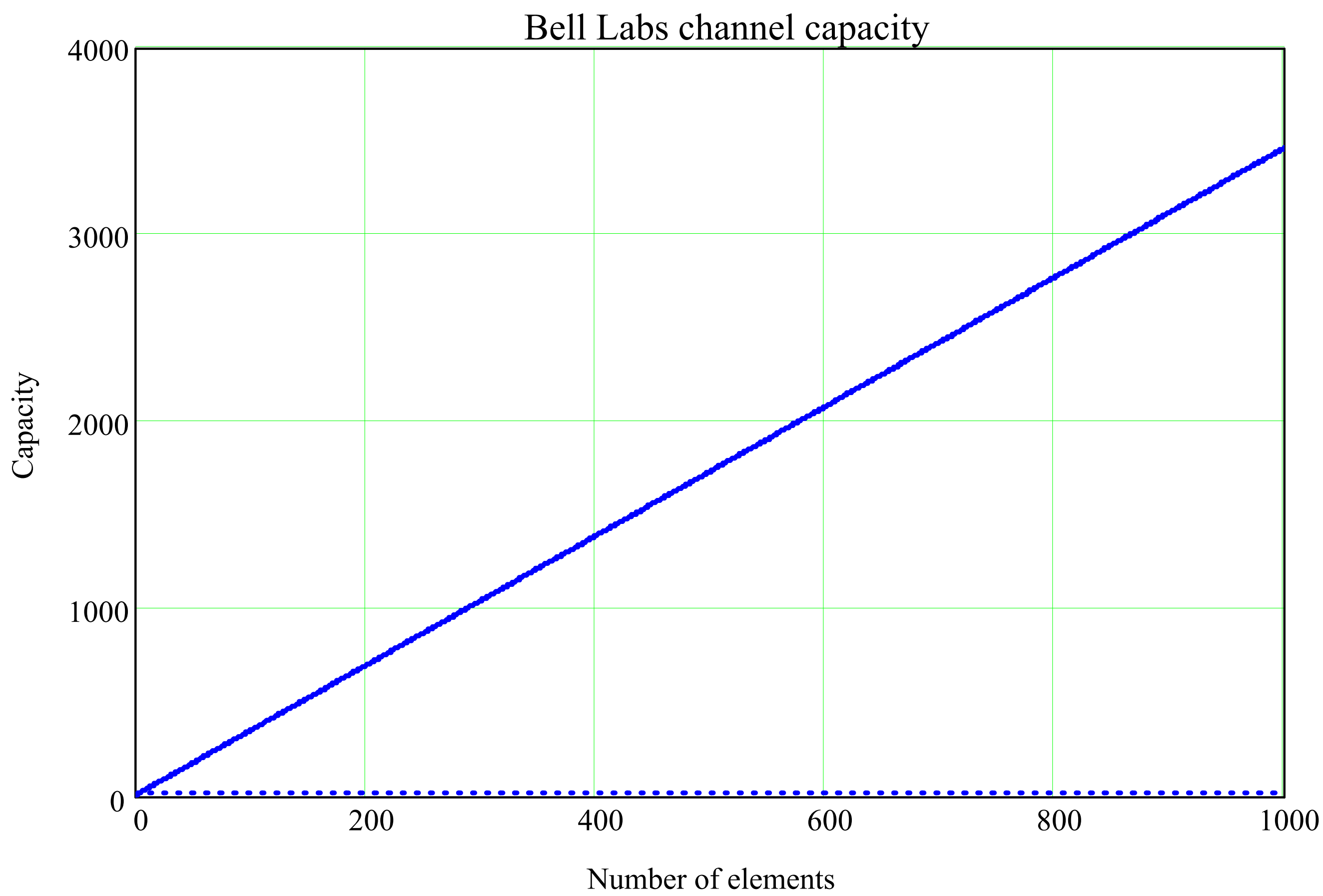
$$C = M \cdot log_2\left(1+\frac{S}{N}\right) \quad [bits / Hz / s]$$



- Increases as M $\rightarrow$ enormous channel capacity!

- Realistic values: 100s bits/Hz/s !

Bell Labs channel capacity



- First breakthrough in communication theory for the last 50 years!
- Relies substantially on active array technology
- Works substantially in multipath & multisignal environment → potential for nonlinear interference and distortions is "tremendous" !
- Extremely high demand for nonlinear analysis & simulation of active arrays is expected.

5. CONCLUSION

- ???