DBBT
Digital Broadcasting & Broadband Technologies

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Telekomunikaciona merenja

TM P09 2018

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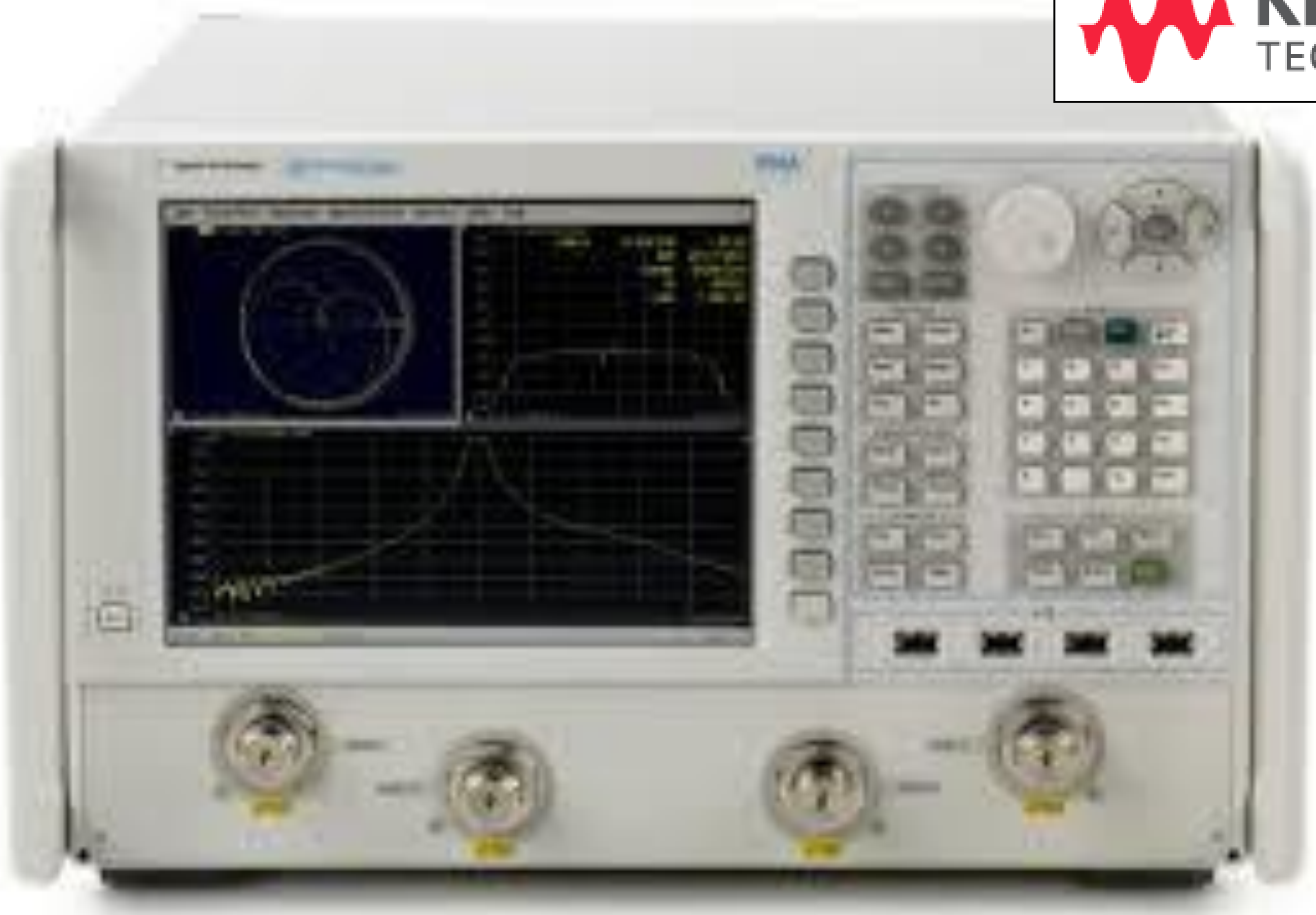
Analizator parametara električne mreže

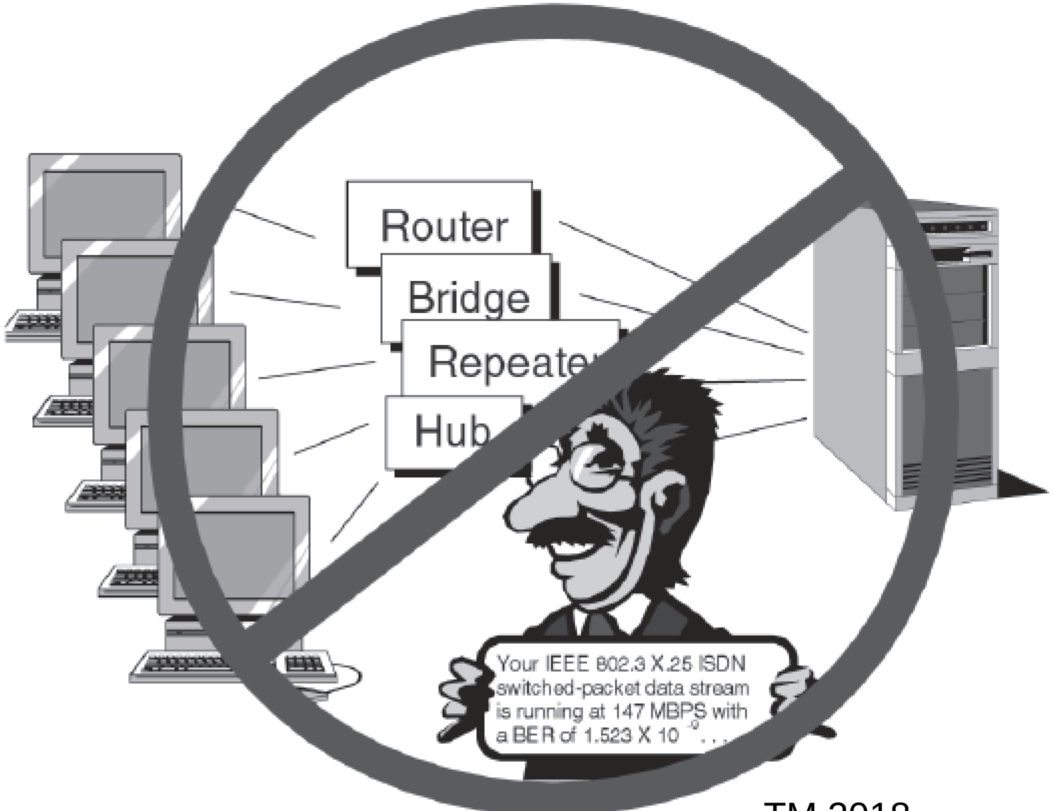


Analizator mreže

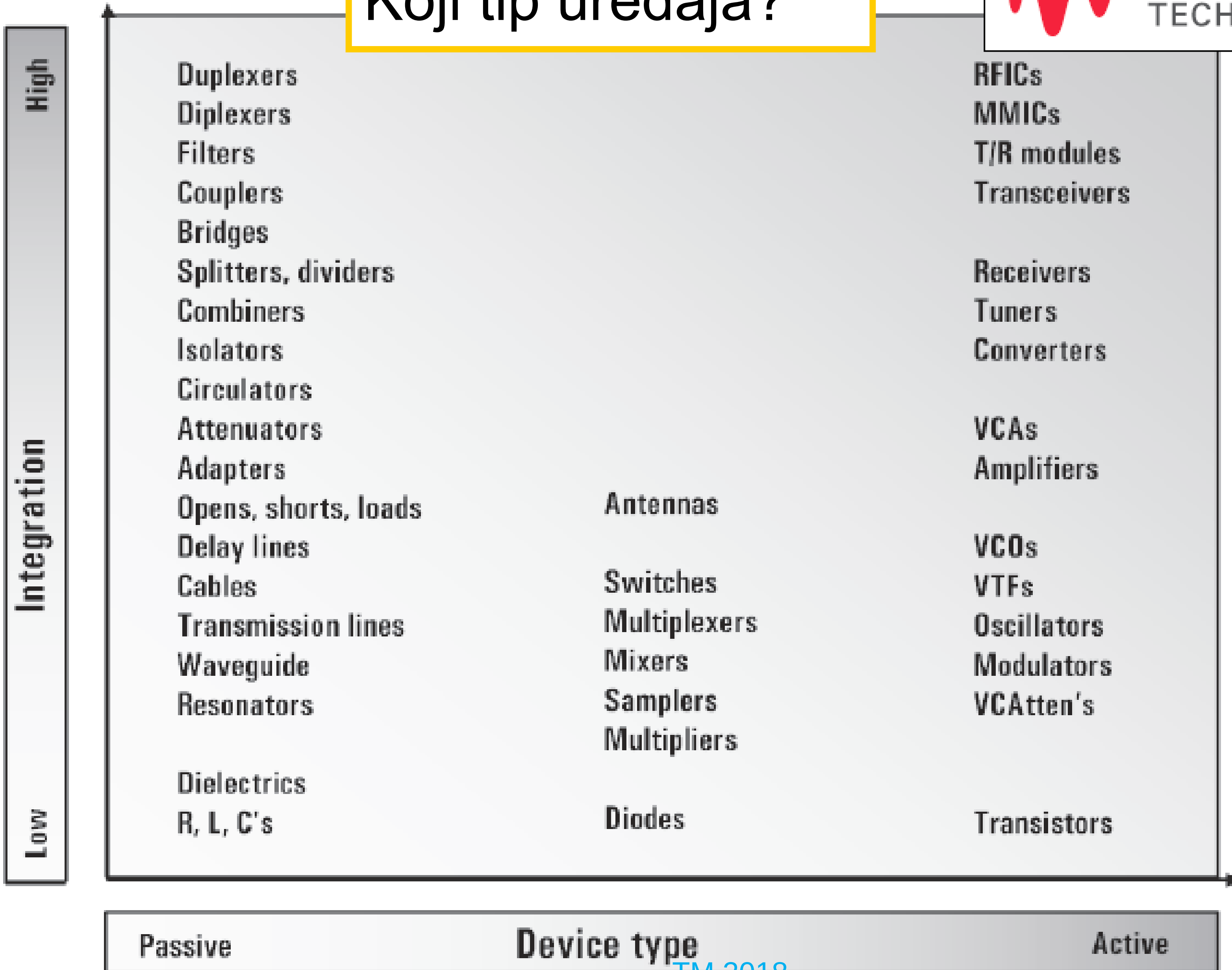
- Merenja u visokofrekvencijskim električnim mrežama analizatorom mreža
- Karakterizacija linearnih i nelinearnih osobina uređaja
- Počinje se od osnova RF (linija prenosa, Smitov dijagram, refleksija, S-parametri
- Modelovanje greške, poboljšanje tačnosti, tehnike kalibracije
- swept-frequency, swept-power merenja
- Filtri i pojačavači

Analizator mreže

- Analizator mreže NIJE analizator računarske mreže; kada su nastali, nisu postojale računarske mreže; to su električne mreže (kola, komponente, uređaji)

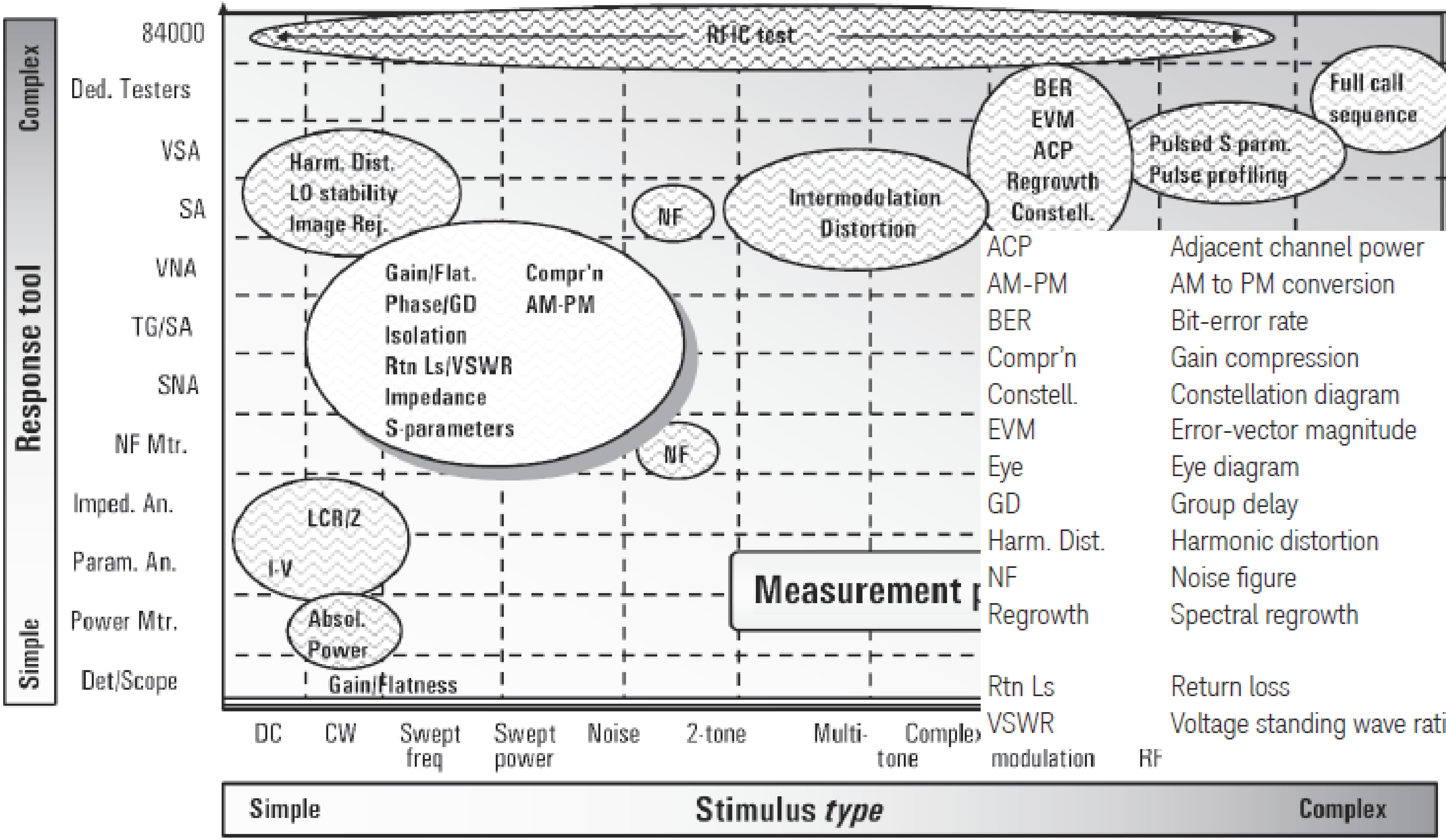


Koji tip uređaja?



KEYSIGHT TECHNOLOGIES

NF Mtr.	Noise-figure meter
Imped. An.	Impedance analyzer (LCR meter)
Power Mtr.	Power meter
Det./Scope	Diode detector/oscilloscope

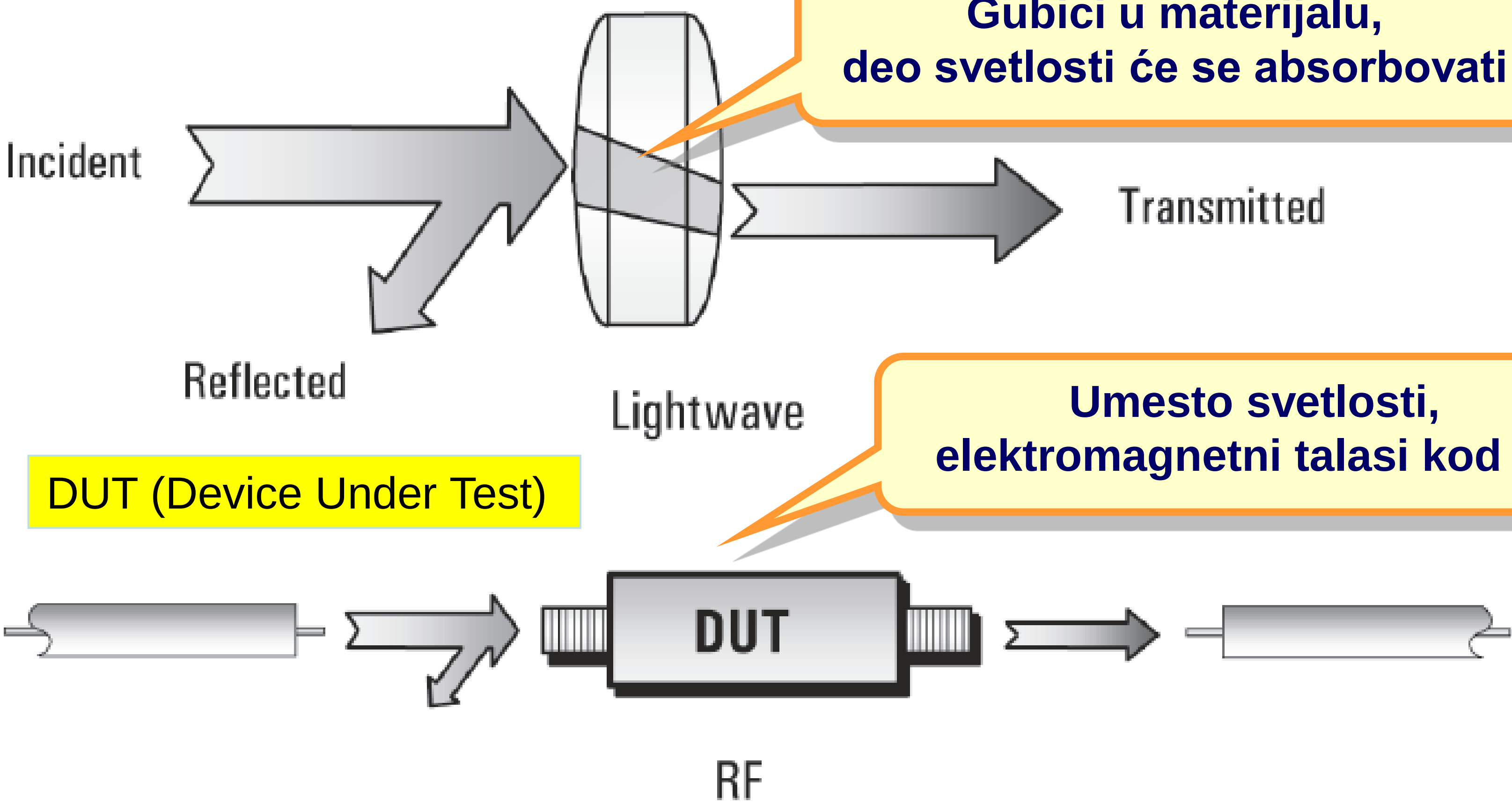


ACP	Adjacent channel power
AM-PM	AM to PM conversion
BER	Bit-error rate
Compr'n	Gain compression
Constell.	Constellation diagram
EVM	Error-vector magnitude
Eye	Eye diagram
GD	Group delay
Harm. Dist.	Harmonic distortion
NF	Noise figure
Regrowth	Spectral regrowth
Rtn Ls	Return loss
VSWR	Voltage standing wave ratio

Optički i RF prenos

- incident, reflected and transmitted waves traveling along transmission lines

Gubici u materijalu,
deo svetlosti će se absorbovati



Umesto svetlosti,
elektromagnetni talasi kod RF

DUT (Device Under Test)

Zašto se rade ova merenja?

Lakše je testirati manje složene sisteme nego ceo sistem!

– Verify specifications of "building blocks" for more complex RF systems
– Ensure distortionless transmission of communications signals

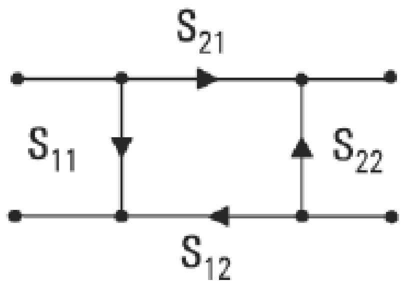
  -- linear: constant amplitude, linear phase / constant group delay
  -- nonlinear: harmonics, intermodulation, compression, AM-to-PM conversion

– Ensure good match when absorbing power (e.g., an antenna)

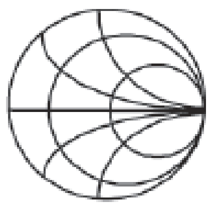
Komponente su sastavni blokovi složenih sistema (mikser, pojačavač, filter). Da odgovara simulaciji!

I amplitudska i fazna karakteristika

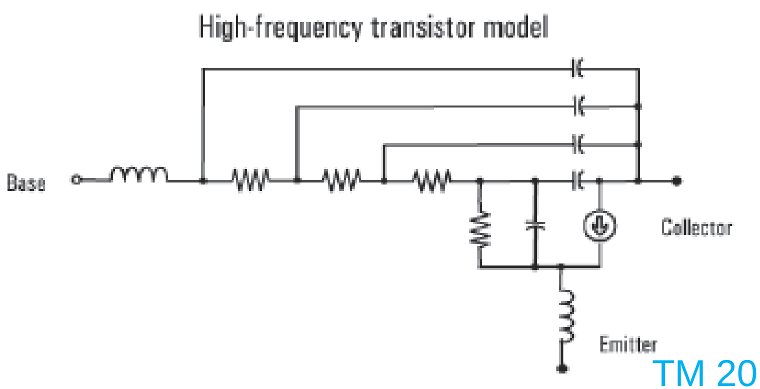
1. Complete characterization of linear networks



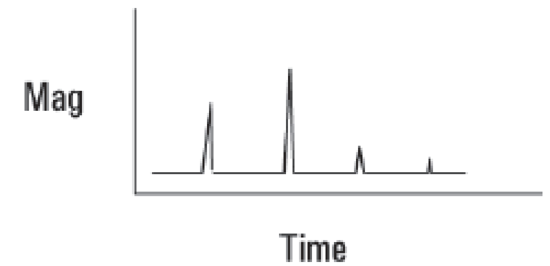
2. Complex impedance needed to design matching circuits



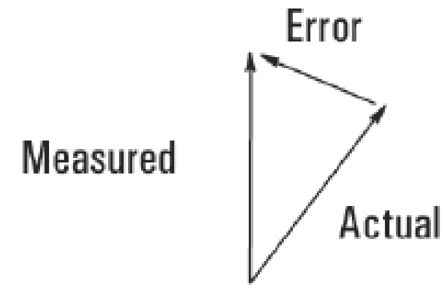
3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction



Merenja refleksije i prenosa

- What measurements do we make?
  - -- Transmission-line basics
  - -- Reflection and transmission parameters
  - -- S-parameter definition
- Network analyzer hardware
  - -- Signal separation devices
  - -- Detection types
  - -- Dynamic range
  - -- T/R versus S-parameter test sets
- Error models and calibration
  - -- Types of measurement error
  - -- One- and two-port models
  - -- Error-correction choices
  - -- Basic uncertainty calculations
- Example measurements
- Appendix

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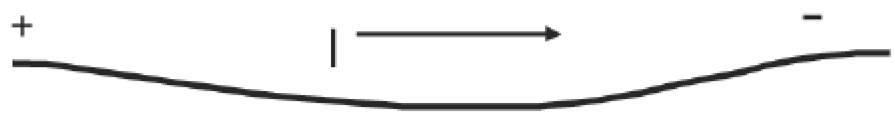
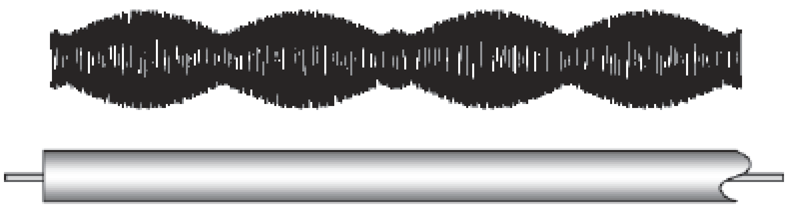
Prenosni medijum



Low frequencies

- wavelengths > > wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

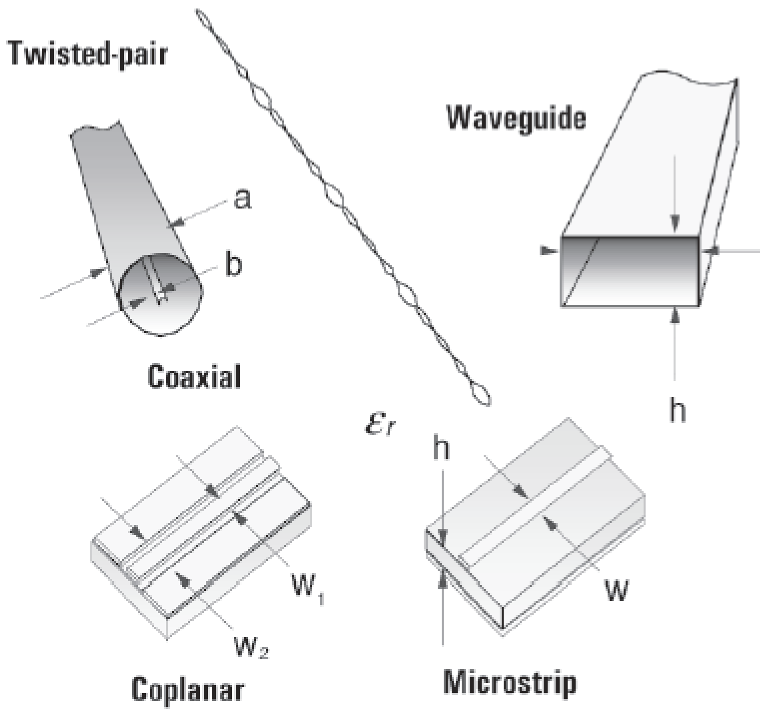


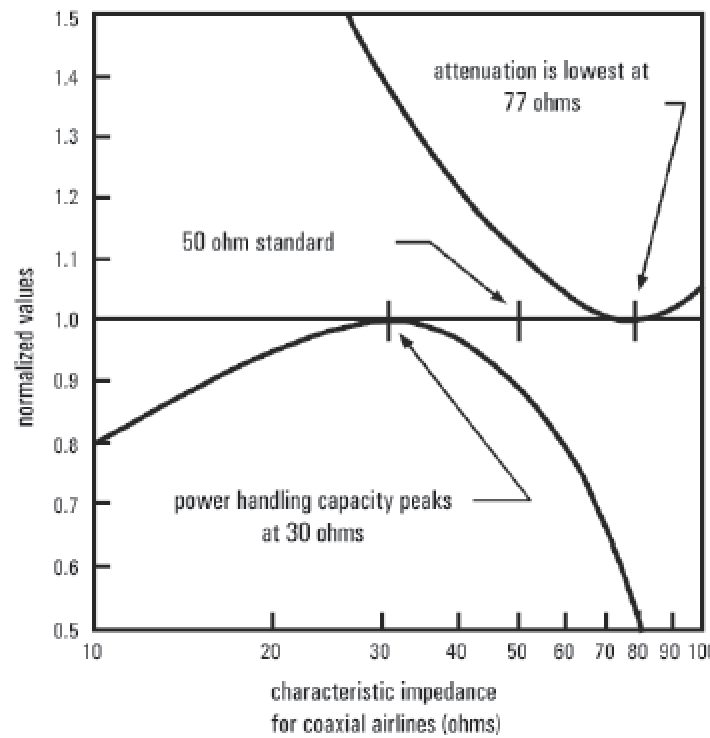
High frequencies

- wavelength ≈ or < < length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Z_0) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

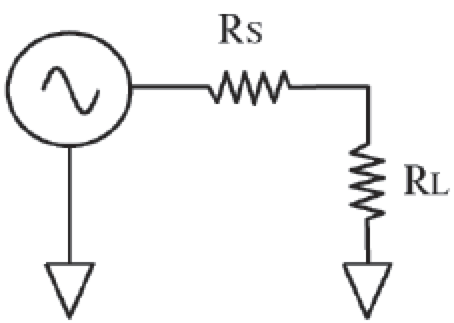
Karakteristična impedansa

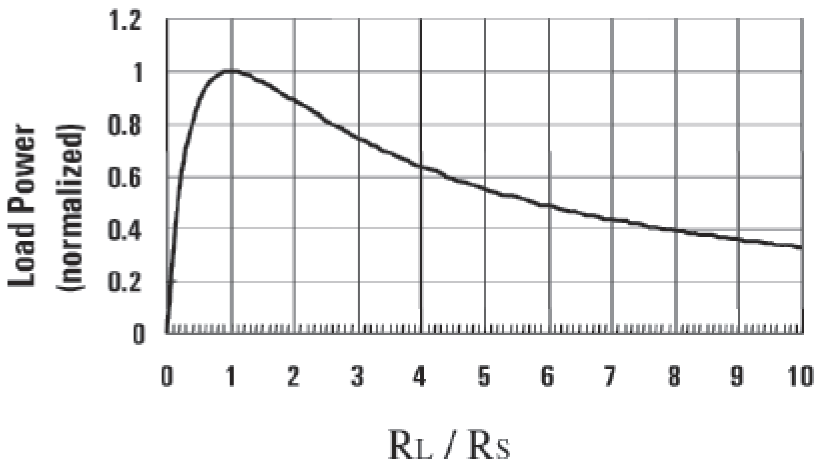
- Z_0 determines relationship between voltage and current waves
- Z_0 is a function of physical dimensions and ε_r
- Z_0 is usually a real impedance (e.g. 50 or 75 ohms)





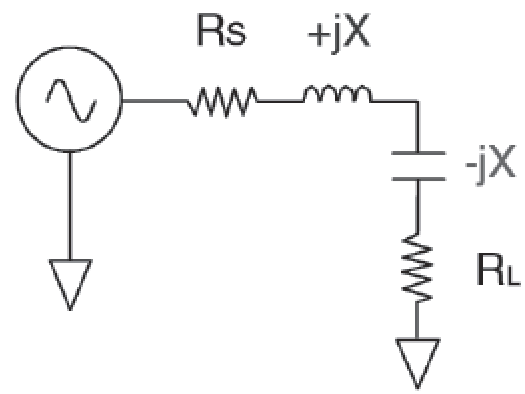
Maksimalni prenos snage



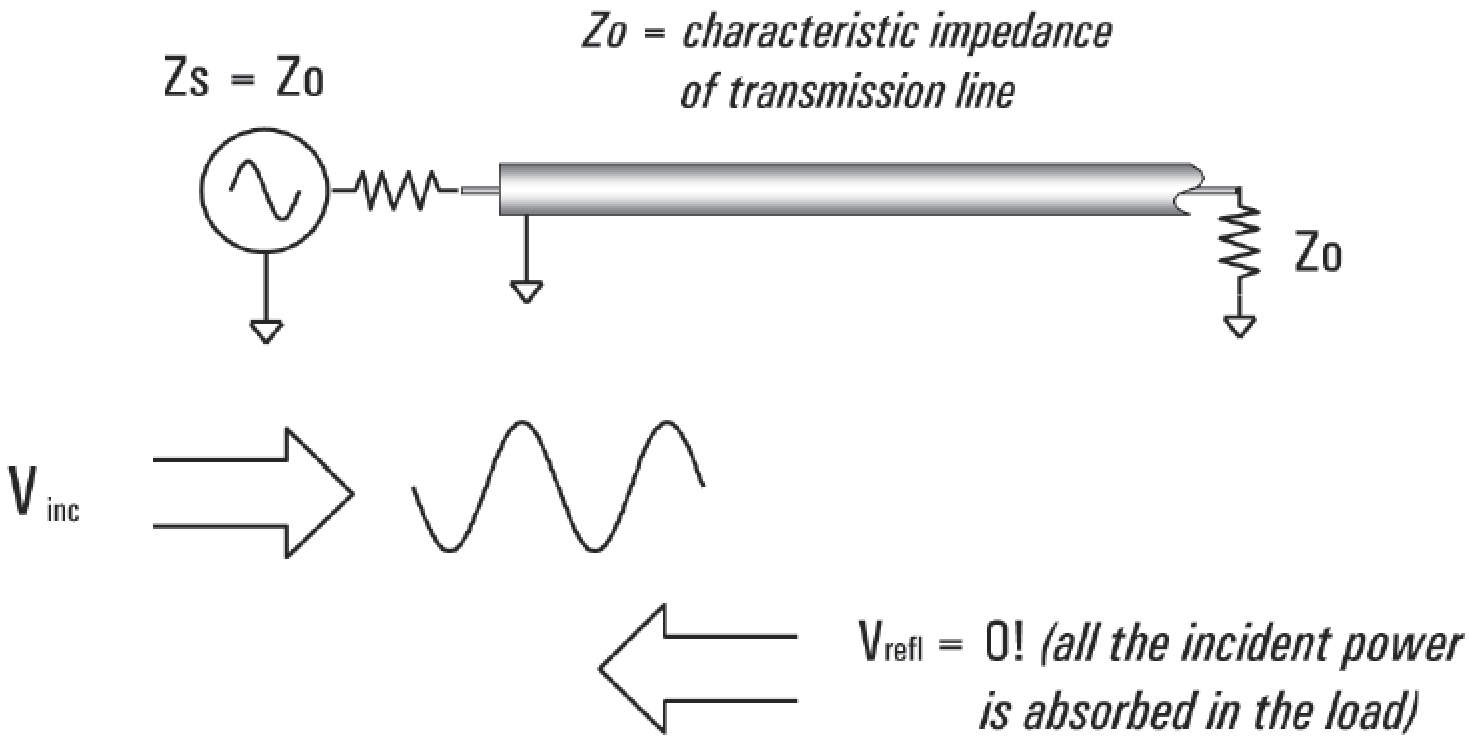


Maximum power is transferred when $R_L = R_S$

For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ **(conjugate match)**

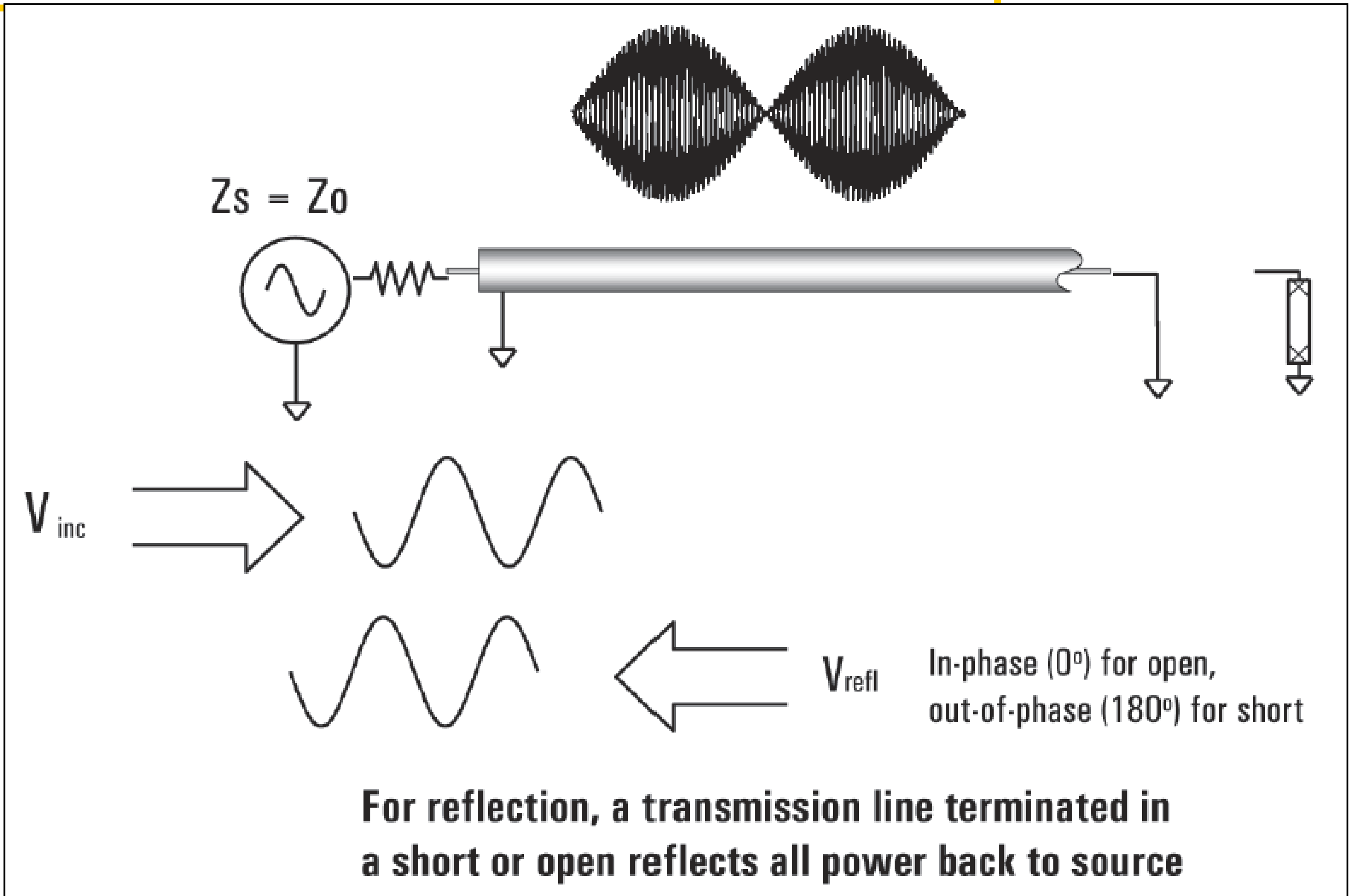


Prenosna linija zatvorena sa Zo

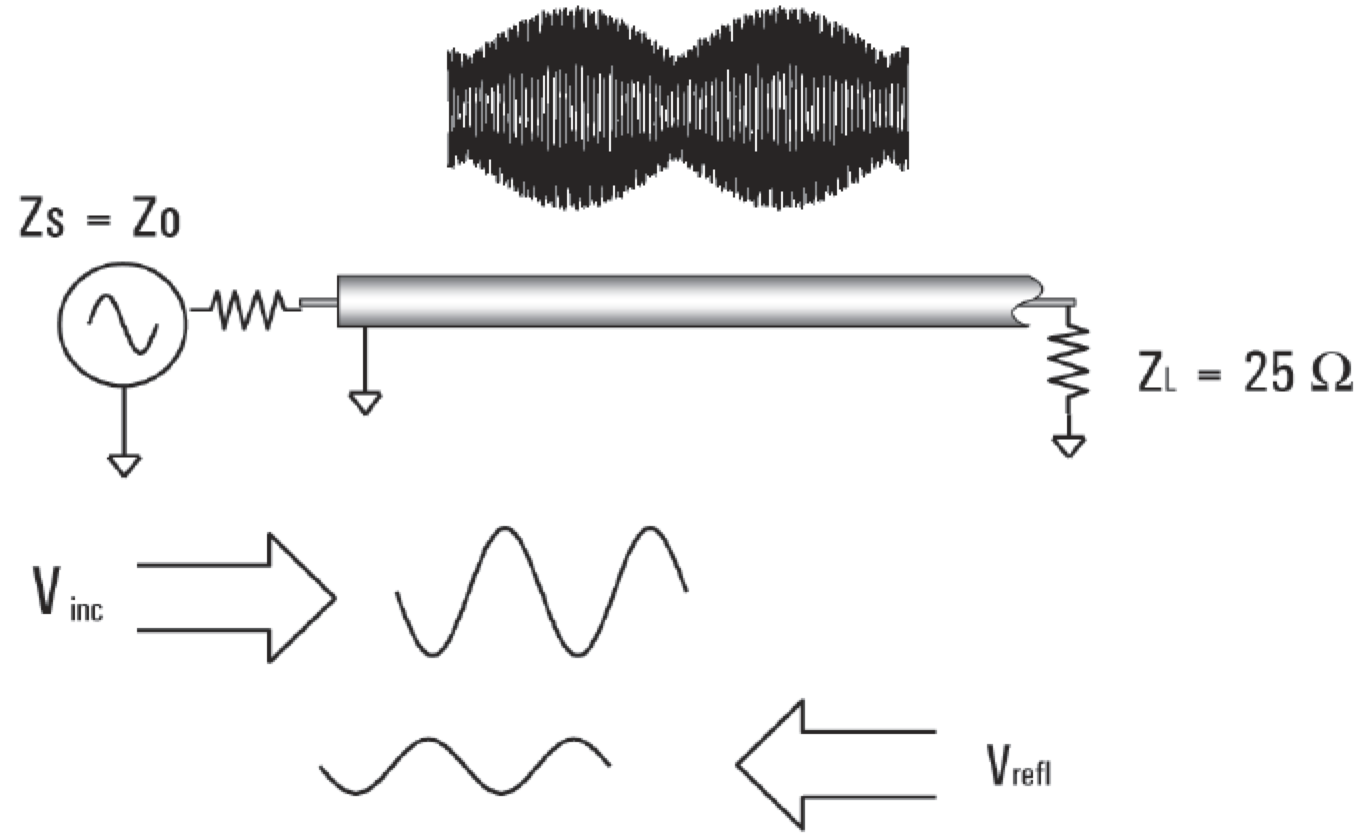


For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

Prenosna linija zatvorena sa kratkim spojem ili otvorenim krajevima

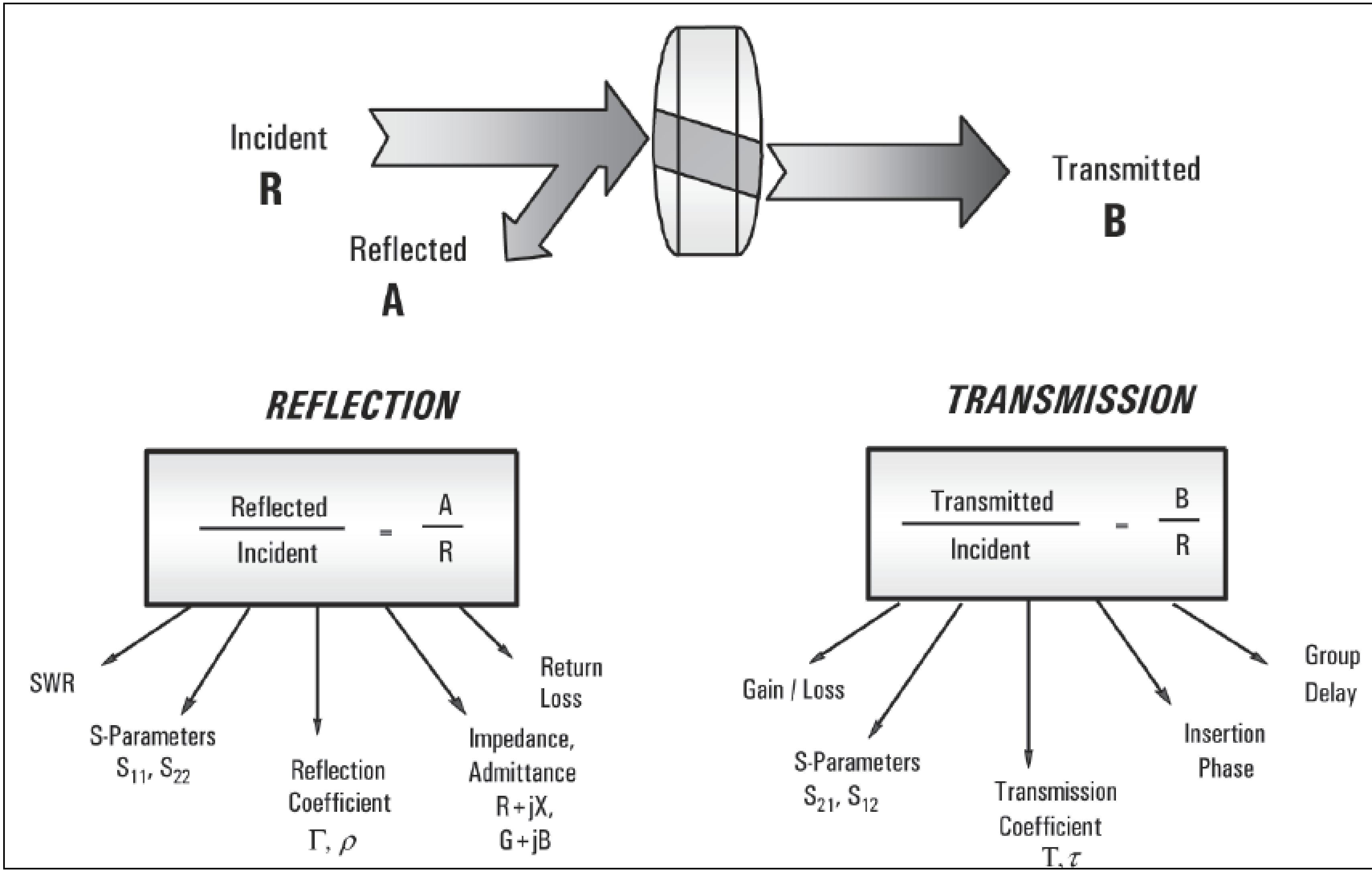


Prenosna linija zatvorena sa 25Ω



Standing wave pattern does not go to zero as with short or open

Karakterizacija



Parametri refleksije

Reflection Coefficient

$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Return loss $= -20 \log(\rho), \quad \rho = |\Gamma|$

Voltage Standing Wave Ratio

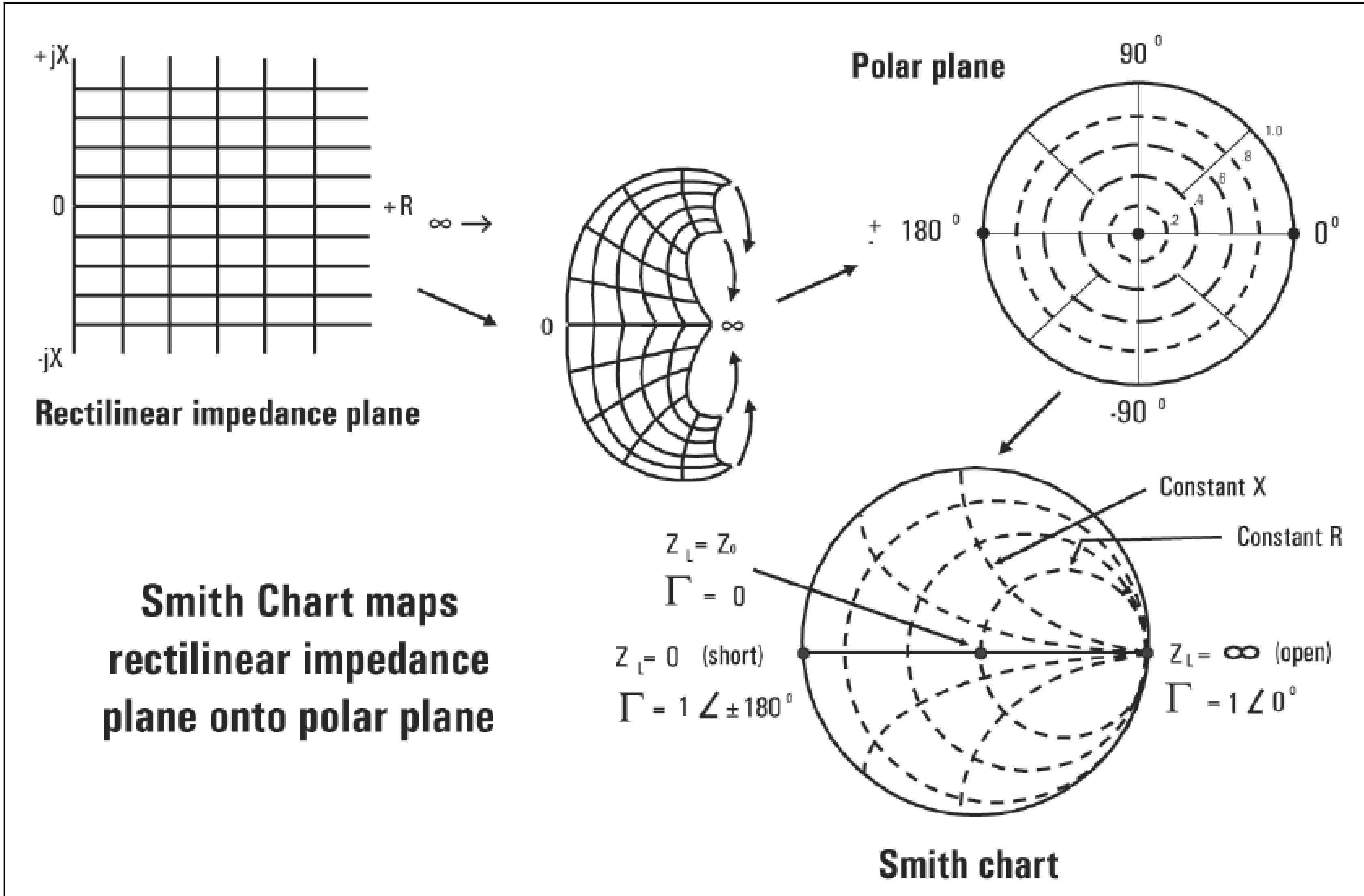
$$\textbf{VSWR} = \frac{E_{max}}{E_{min}} = \frac{1 + \rho}{1 - \rho}$$

No reflection
($Z_L = Z_o$)

Full reflection
(Z_L = open, short)

0	ρ	1
∞ dB	**RL**	0 dB
1	**VSWR**	∞

Smitov dijagram



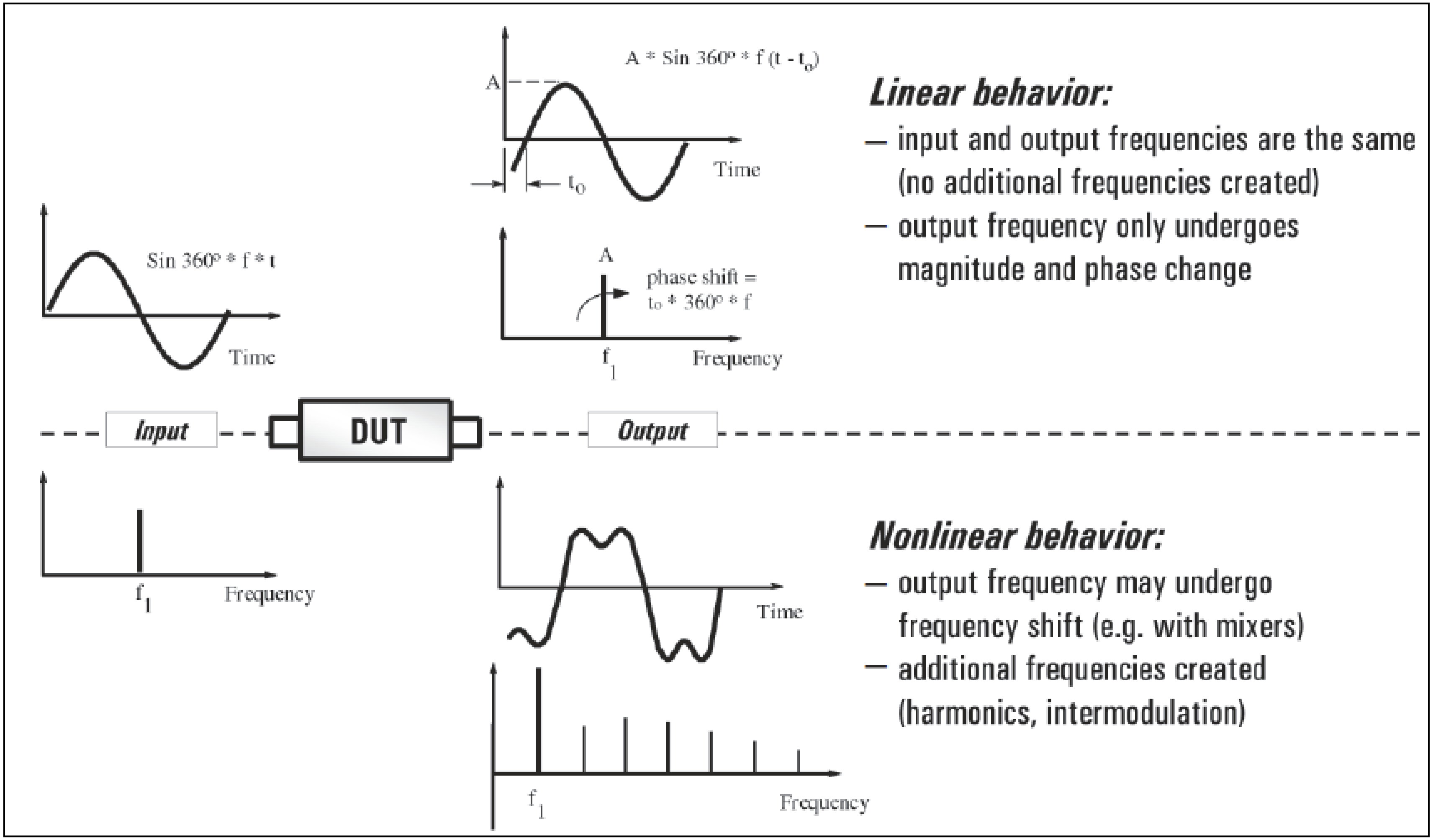
Parametri prenosa

Transmission Coefficient = $T = \dfrac{V_{Transmitted}}{V_{Incident}} = \tau\angle\phi$

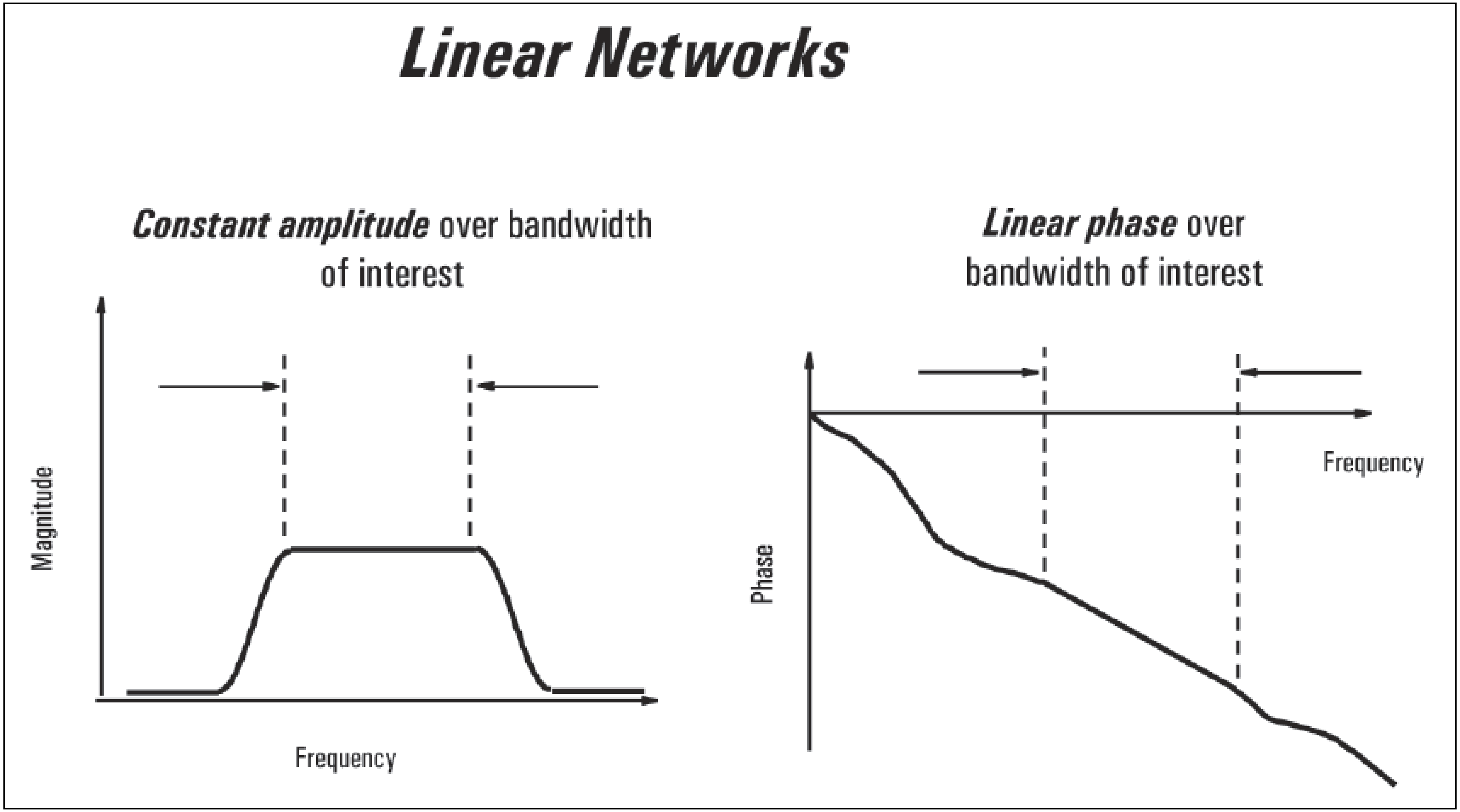
Insertion Loss (dB) = $-20 \text{ Log} \left| \dfrac{V_{Trans}}{V_{Inc}} \right| = -20 \log \tau$

Gain (dB) = $20 \text{ Log} \left| \dfrac{V_{Trans}}{V_{Inc}} \right| = 20 \log \tau$

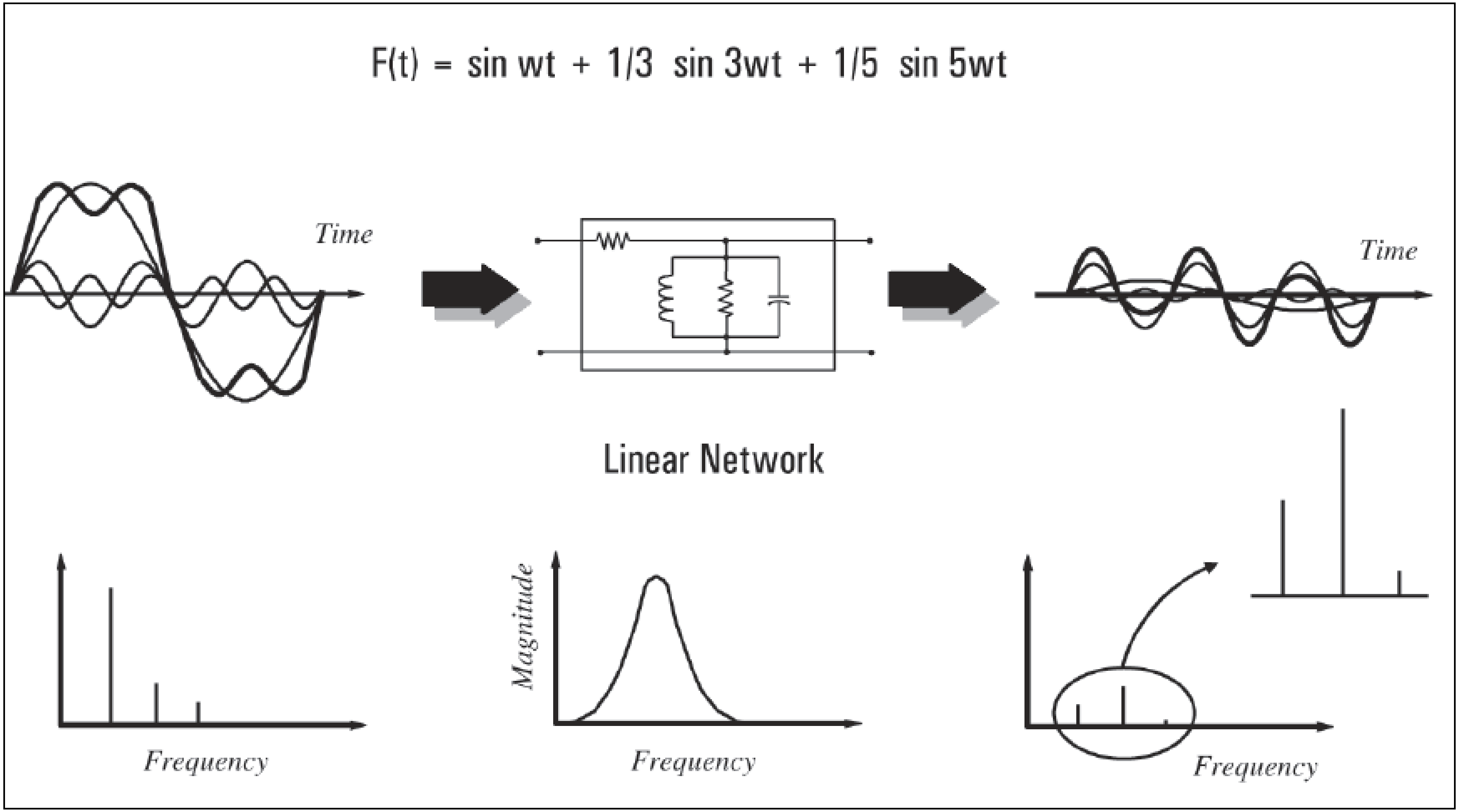
Linearne / nelinearne karakteristike



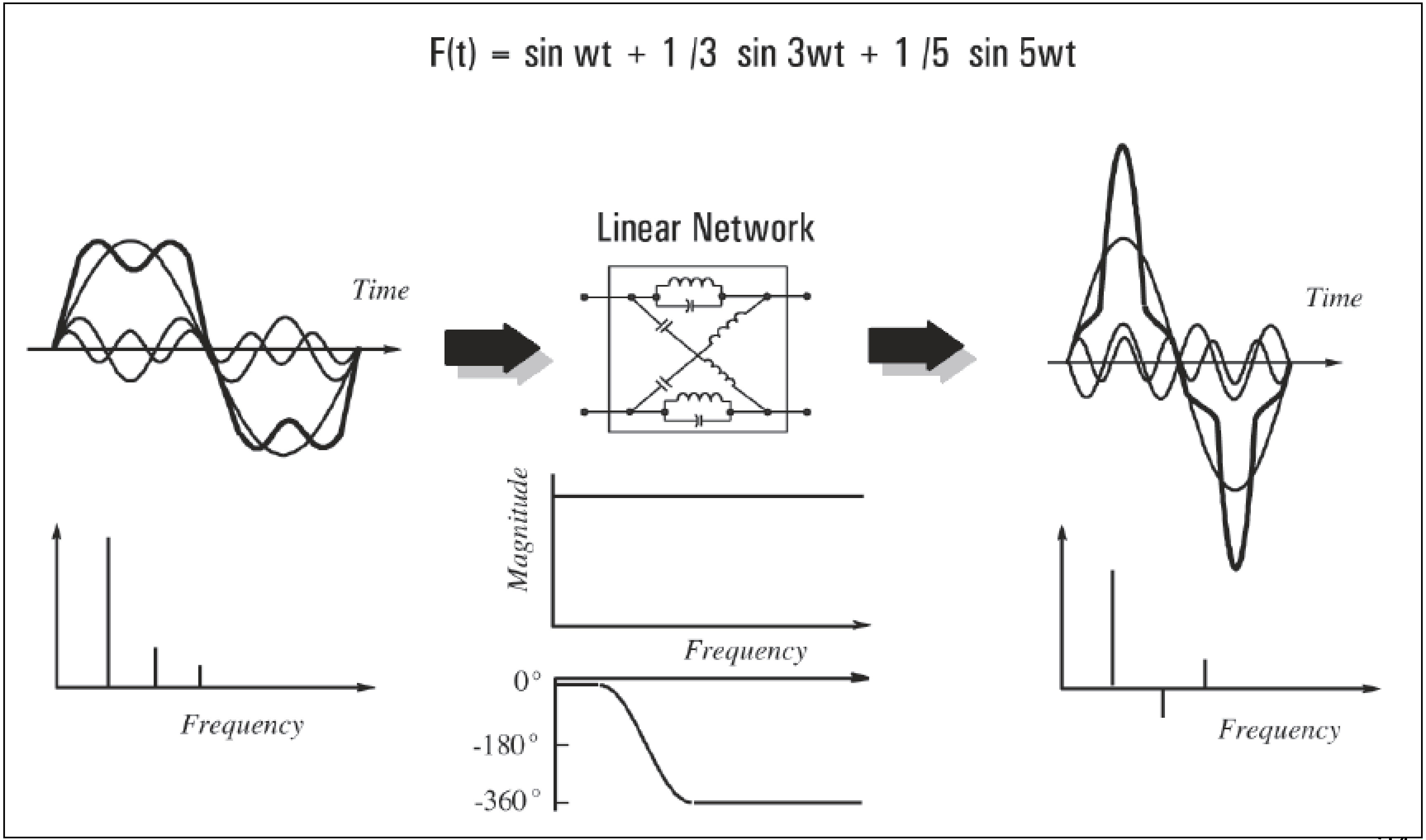
Linearne mreže



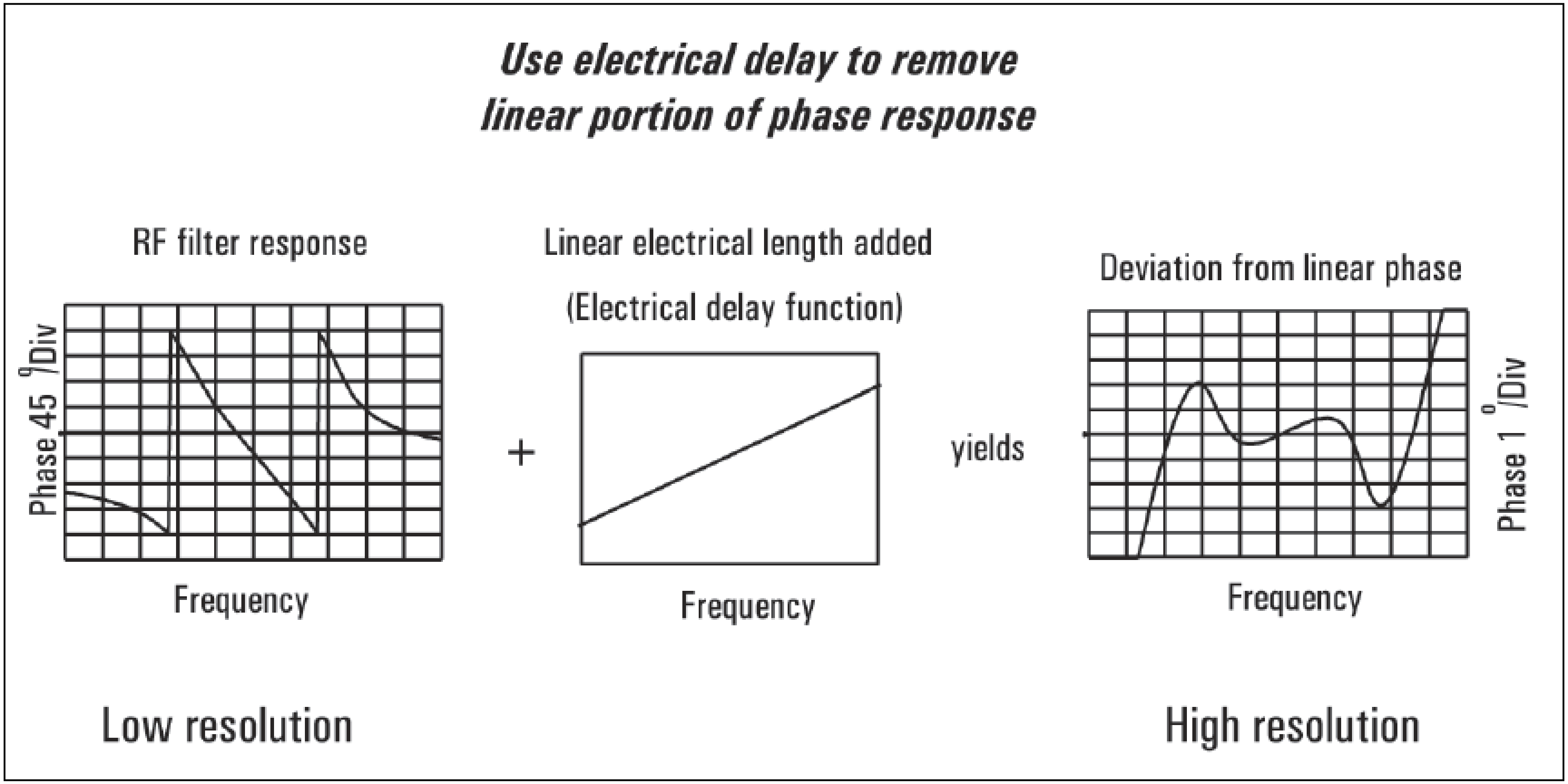
Promena amplitude sa frekvencijom



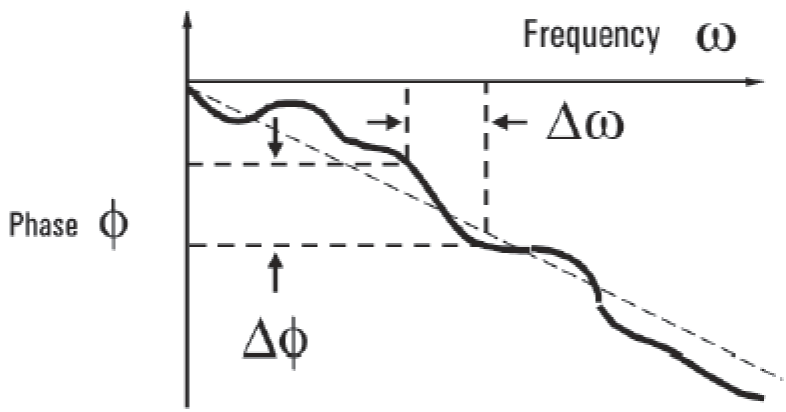
Promena faze sa frekvencijom

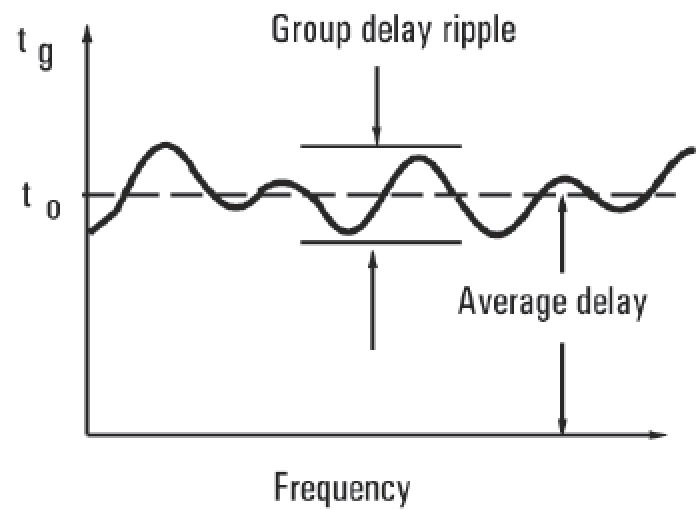


Promena u odnosu na linearnu fazu sa frekvencijom



Promena grupnog kašnjenja sa frekvencijom





Group Delay (t_g) =

$$\frac{-d\phi}{d\omega} = \frac{-1}{360^{o}} * \frac{d\phi}{df}$$

ϕ in radians

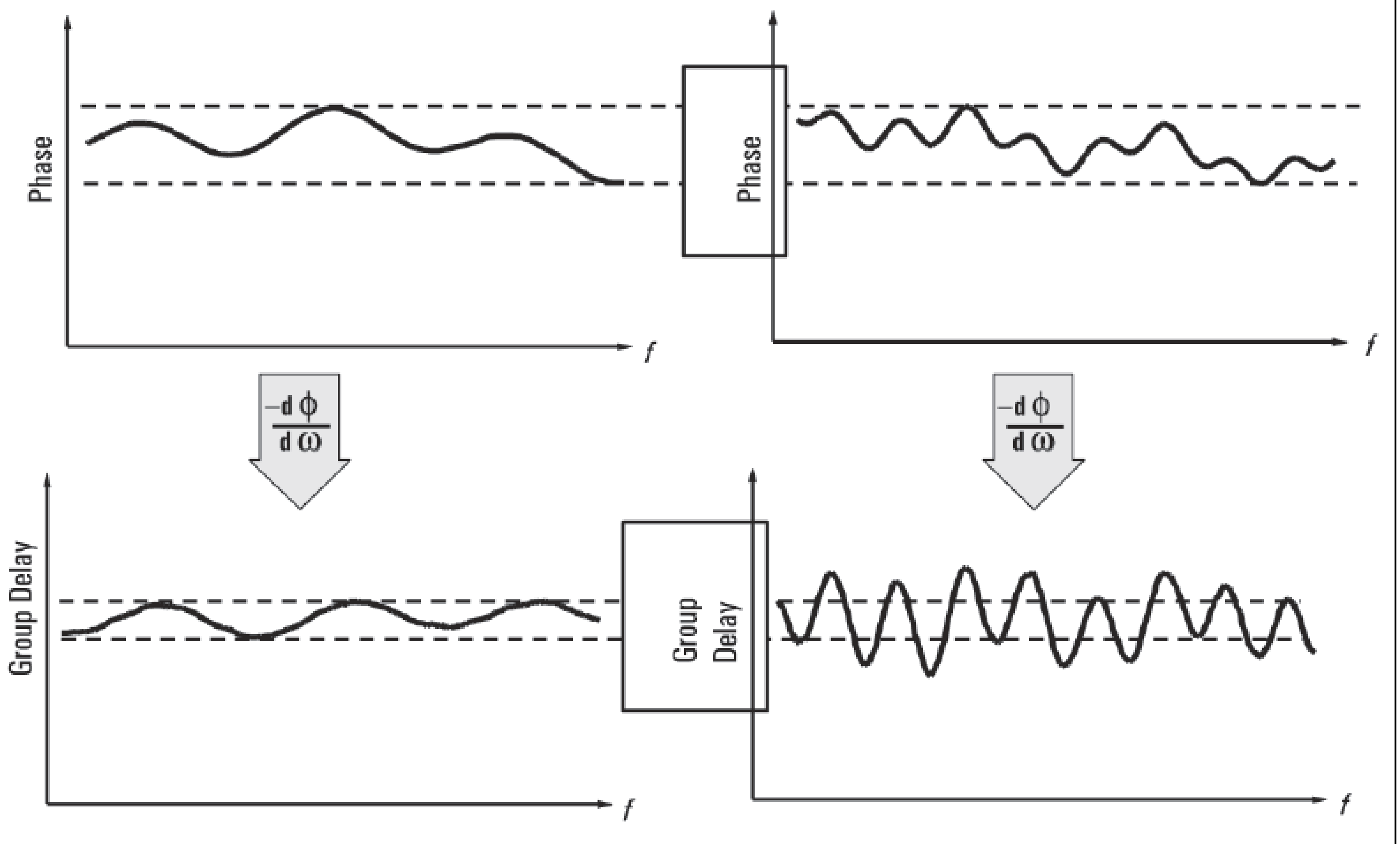
ω in radians/sec

ϕ in degrees

f in Hertz ($\omega = 2\pi f$)

- group-delay ripple indicates phase distortion
- average delay indicates electrical length of DUT
- aperture of measurement is very important

grupno kašnjenje bolje prikazuje devijaciju fazne karakteristike



Same p-p phase ripple can result in different group delay

h, z, y, s parametri

KEYSIGHT TECHNOLOGIES

Using parameters (H, Y, Z, S) to characterize devices:

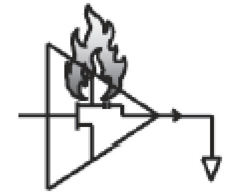
- gives linear behavioral model of our device
- measure parameters (e.g. voltage and current) versus frequency under various source and load conditions (e.g. short and open circuits)
- compute device parameters from measured data
- predict circuit performance under any source and load conditions

H parameters	***Y parameters***	***Z parameters***
$V_1 = h_{11}I_1 + h_{12}V_2$	$I_1 = y_{11}V_1 + y_{12}V_2$	$V_1 = z_{11}I_1 + z_{12}I_2$
$I_2 = h_{21}I_1 + h_{22}V_2$	$I_2 = y_{21}V_1 + y_{22}V_2$	$V_2 = z_{21}I_1 + z_{22}I_2$

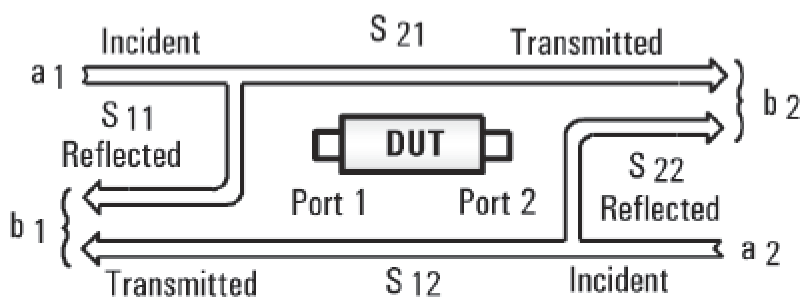
$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit**)*

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$ *(requires **open circuit**)*

s parametri, zato što se ne mogu meriti napon i struja



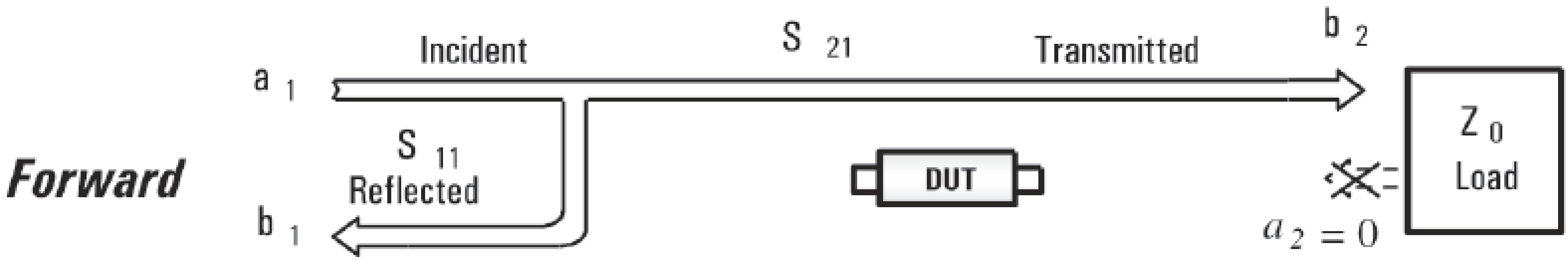
- relatively easy to **obtain** at high frequencies
  - -- measure voltage traveling waves with a vector network analyzer
  - -- don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** S-parameters of multiple devices to predict system performance
- can **compute** H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in our **electronic-simulation** tools



$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

s parametri, zato što se ne mogu meriti napon i struja

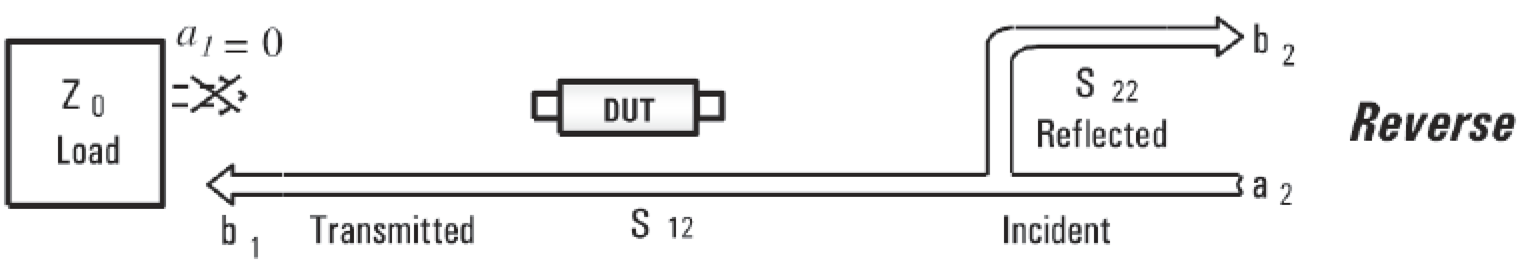


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0}$$

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0}$$



s parametri, log razmera

S11 = forward reflection coefficient ***(input match)***

S22 = reverse reflection coefficient ***(output match)***

S21 = forward transmission coefficient ***(gain or loss)***

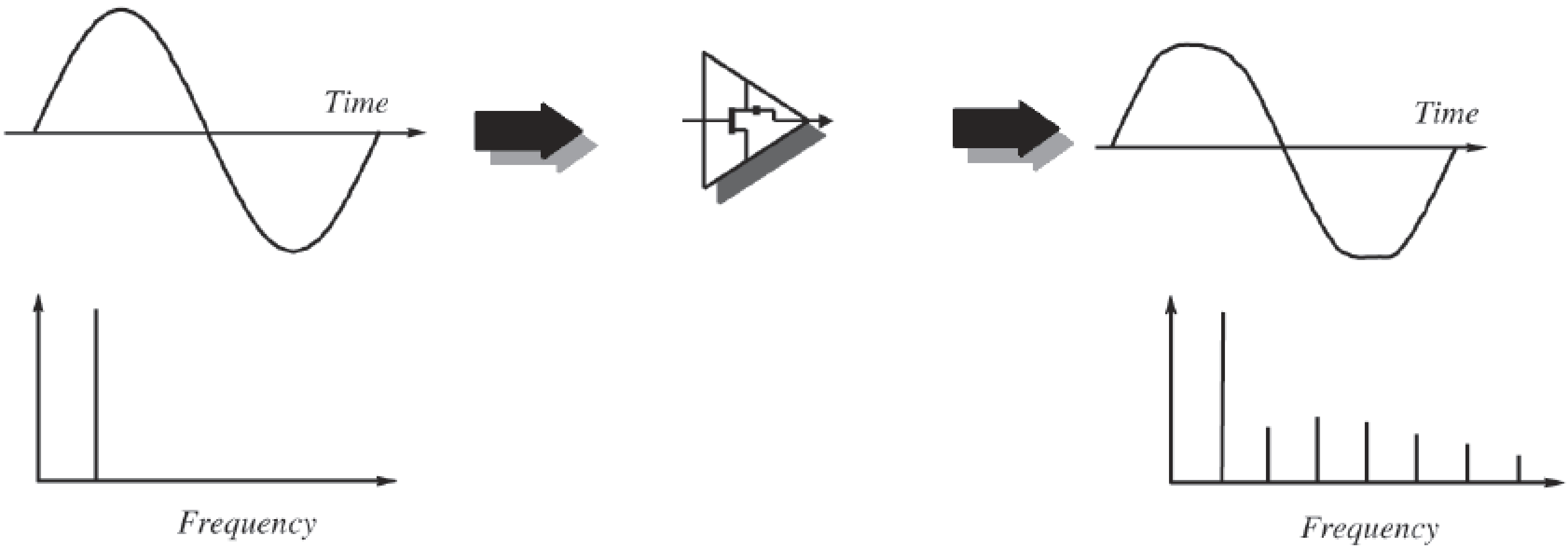
S12 = reverse transmission coefficient ***(isolation)***

Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format

Nelinearne mreže

Nonlinear Networks

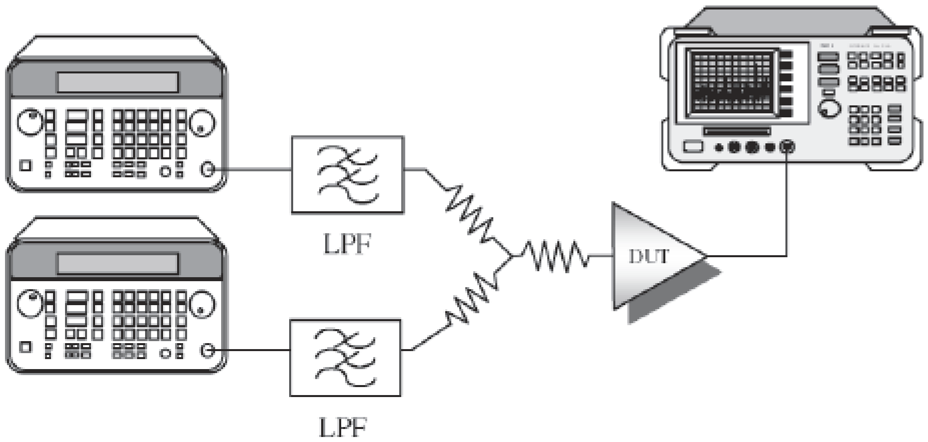
- Saturation, crossover, intermodulation, and other nonlinear effects can cause signal distortion
- Effect on system depends on amount and type of distortion and system architecture

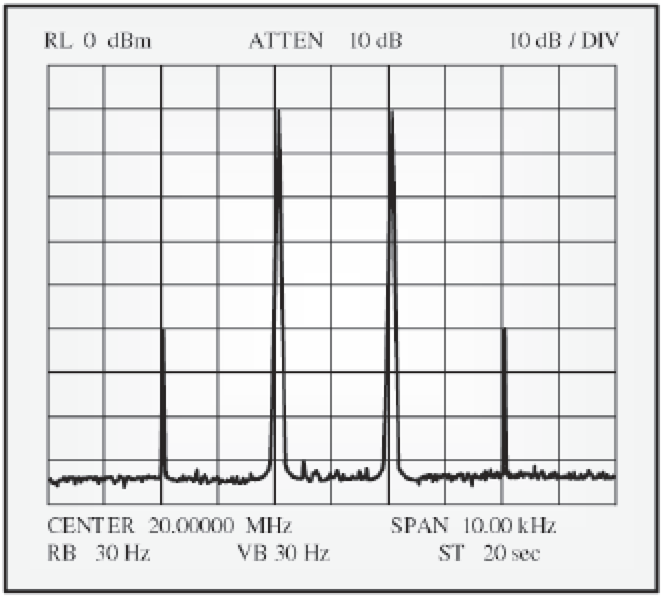


Merenje nelinearnog ponašanja

Most common measurements:

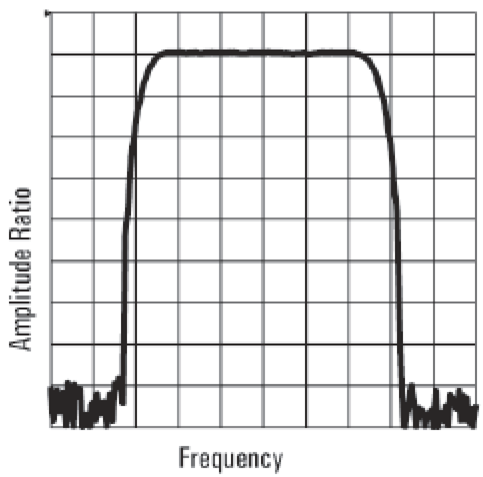
- using a ***network analyzer*** and power sweeps
  - -- gain compression
  - -- AM to PM conversion
- using a ***spectrum analyzer*** + source(s)
  - -- harmonics, particularly second and third
  - -- intermodulation products resulting from two or more RF carriers

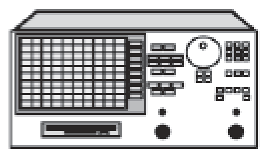




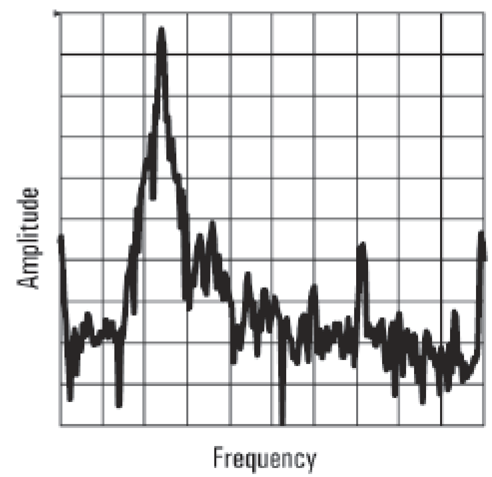
Analizator mreže i spektra

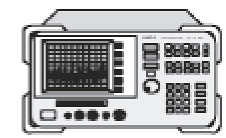
Network and ***Spectrum*** Analyzers?





Measures known signal





Measures unknown signals

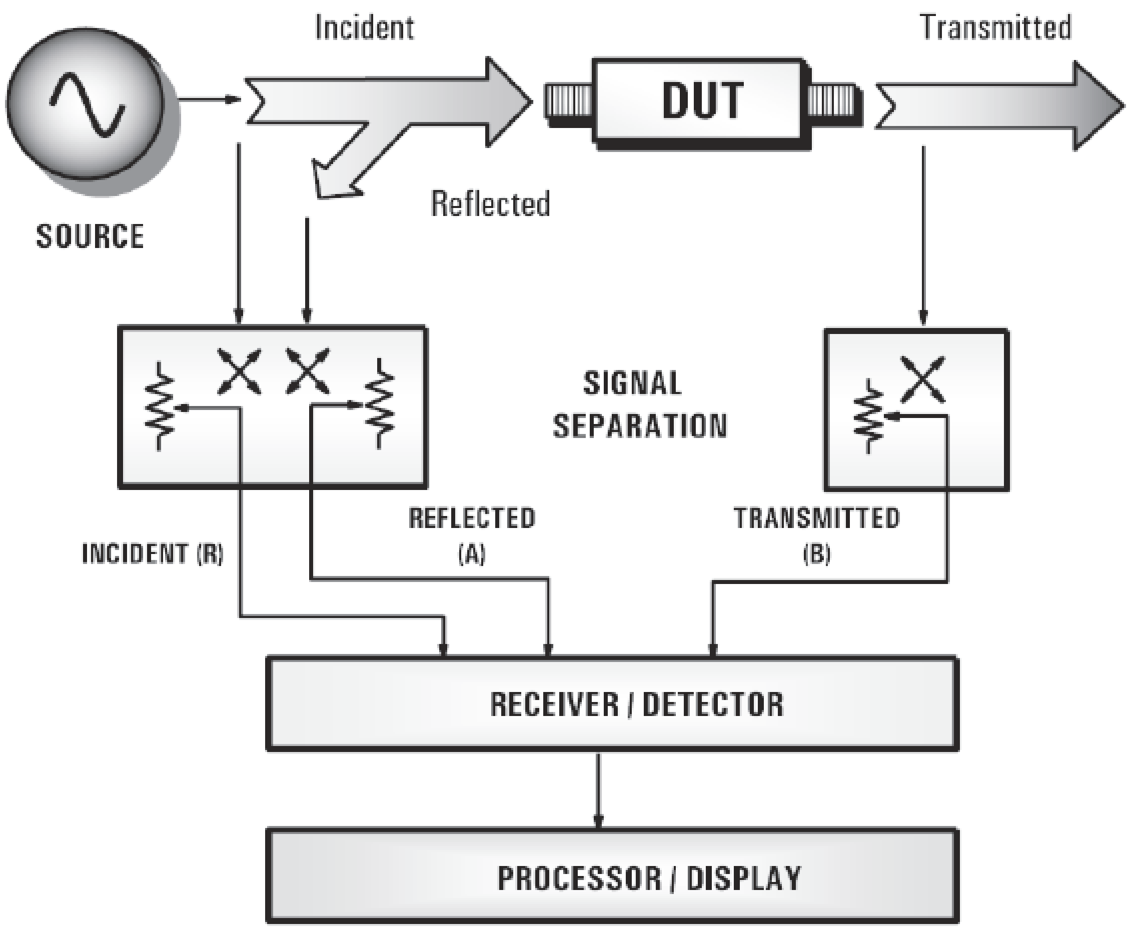
Network analyzers:

- measure components, devices, circuits, sub-assemblies
- contain source and receiver
- display ratioed amplitude and phase (frequency or power sweeps)
- offer advanced error correction

Spectrum analyzers:

- measure signal amplitude characteristics carrier level, sidebands, harmonics...)
- can demodulate (& measure) complex signals
- are receivers only (single channel)
- can be used for scalar component test (*no phase*) with tracking gen. or ext. source(s)

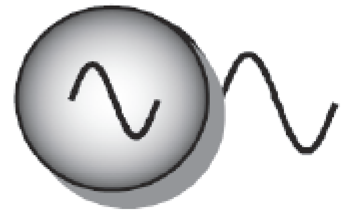
Blok dijagram analizatora mreže

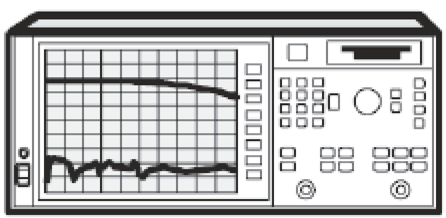


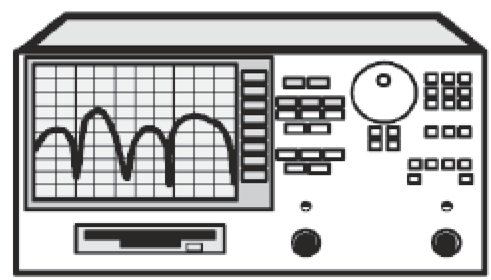
Analizator mreže

Generator signala

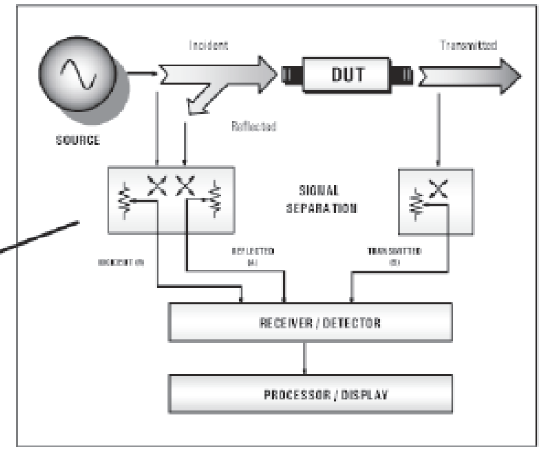
- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
- Most Keysight analyzers sold today have *integrated, synthesized* sources





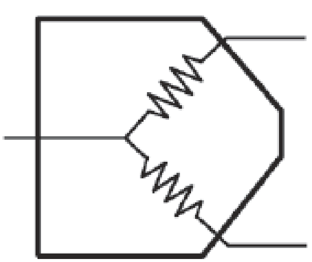


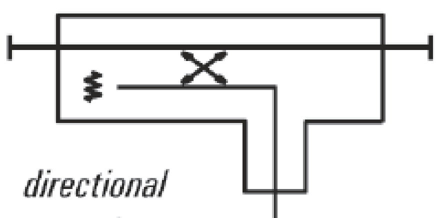
Analizator mreže
Razdvajanje signala



- measure incident signal for reference
- separate incident and reflected signals

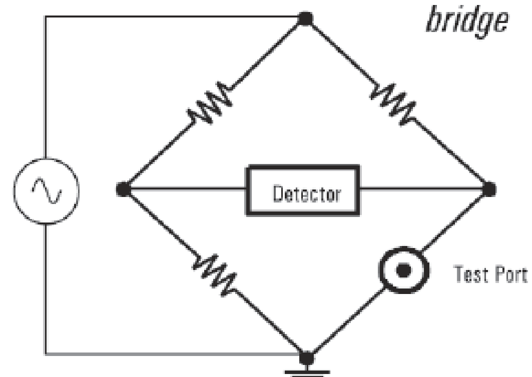
splitter





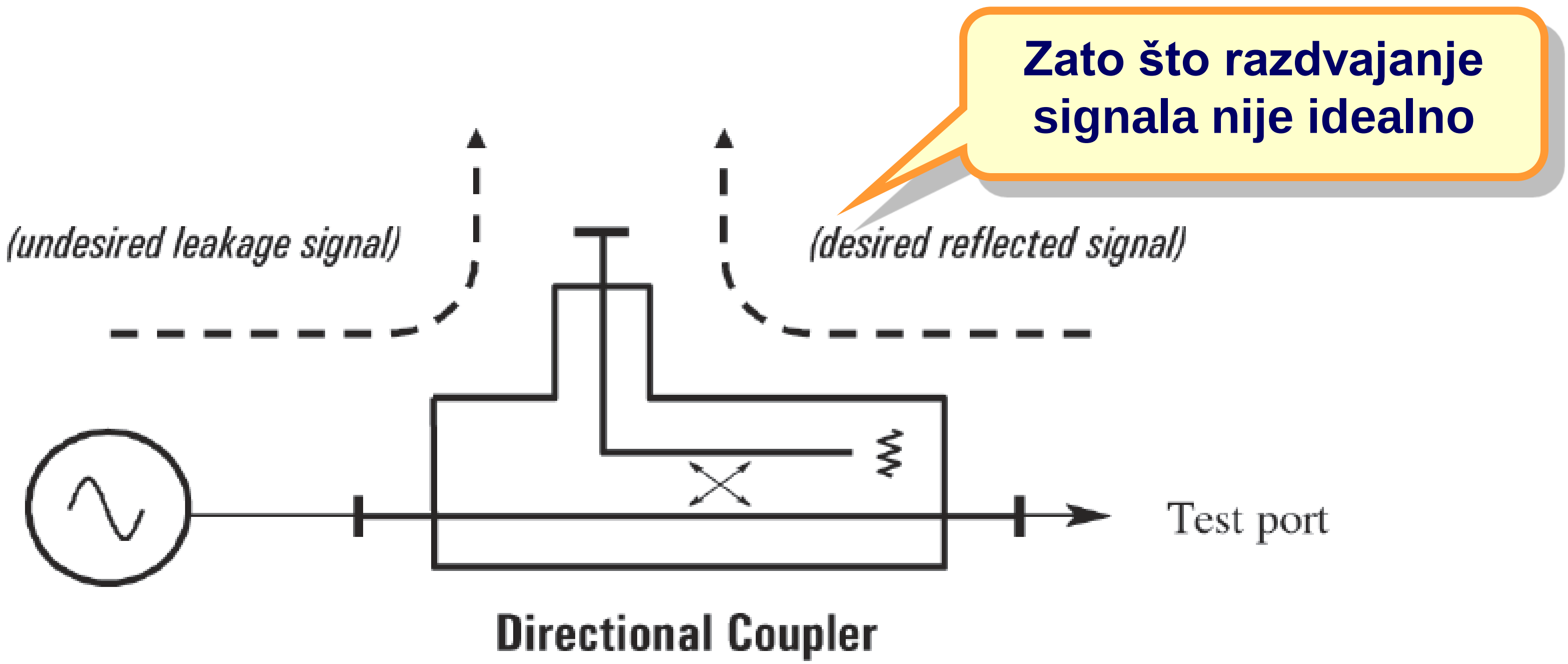
directional coupler

bridge

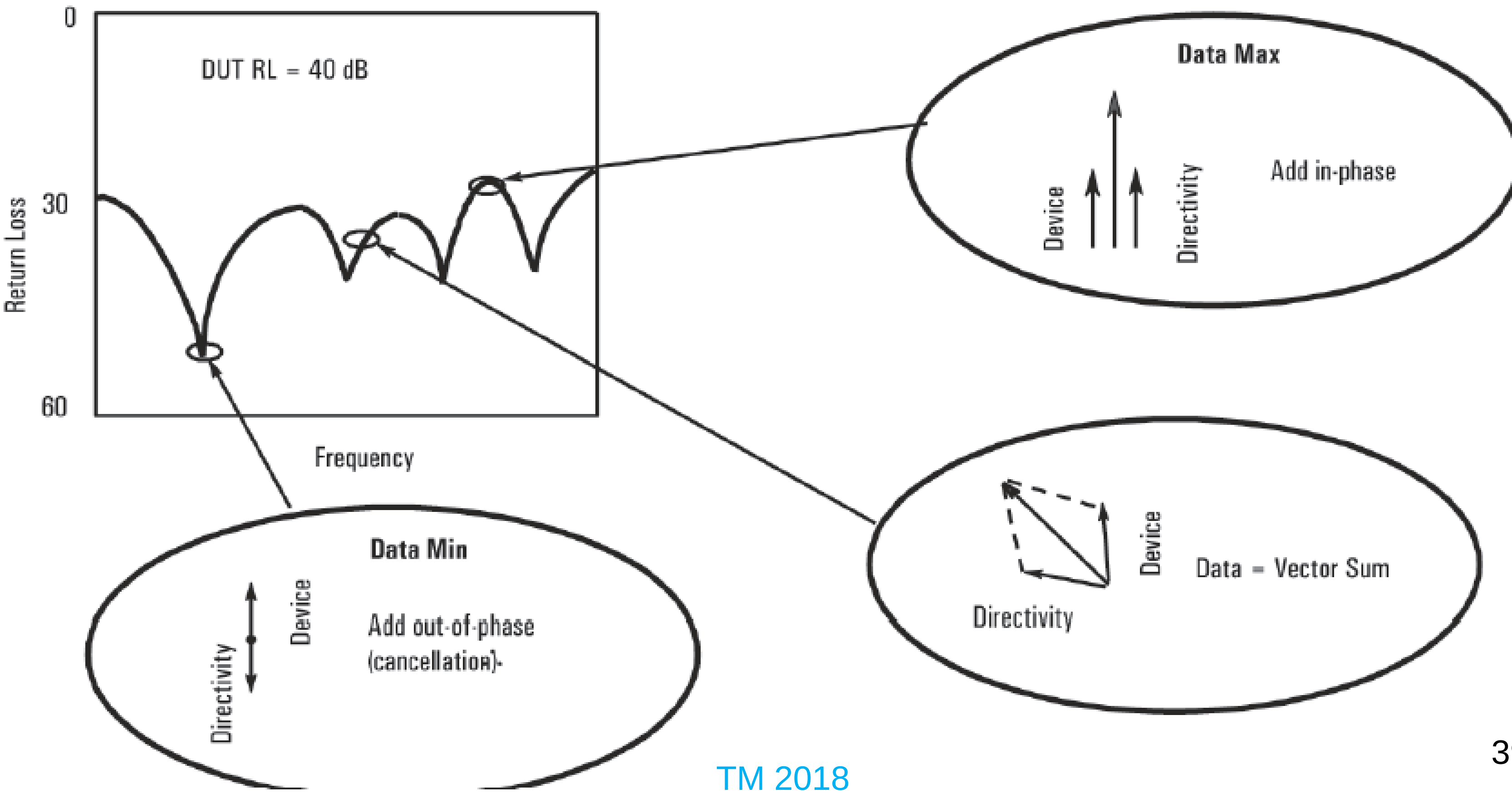


Analizator mreže
Usmeravanje signala

Directivity is a measure of how well a coupler can separate signals moving in opposite directions

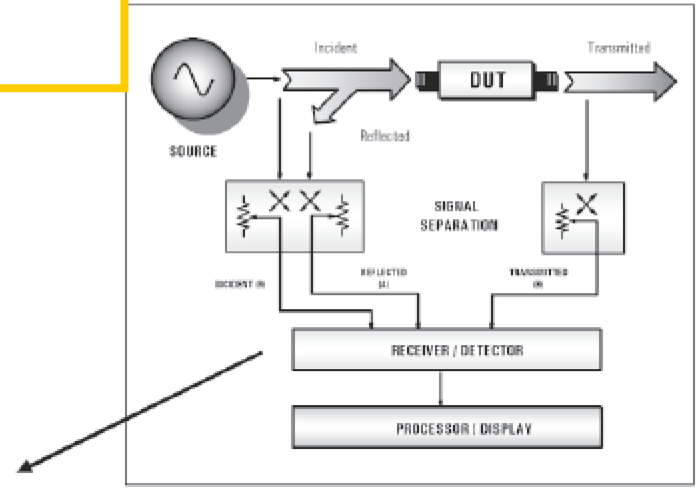


Directivity error is the main reason we see a large ripple pattern in many measurements of return loss. At the peaks of the ripple, directivity is adding in phase with the reflection from the DUT. In some cases, directivity will cancel the DUT's reflection, resulting in a sharp dip in the response.

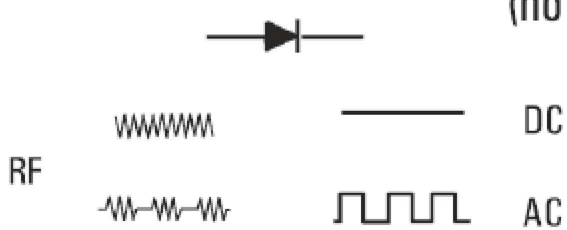


Analizator mreže
Detektori

KEYSIGHT TECHNOLOGIES

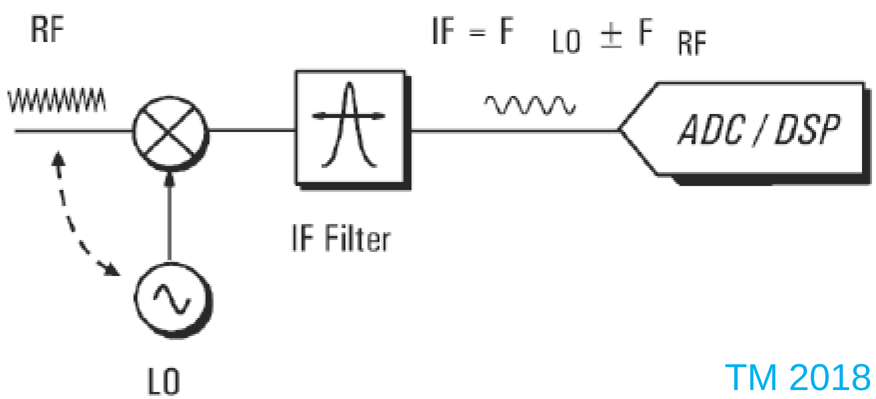


Diode



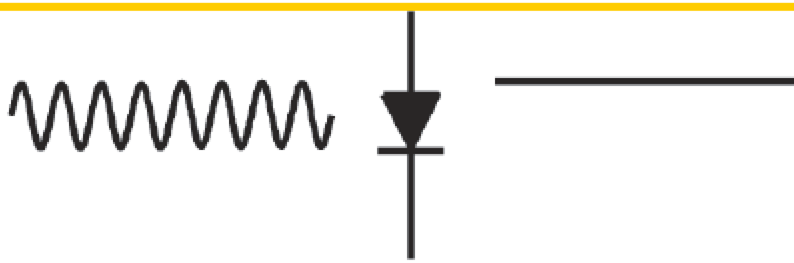
Scalar **broadband**
(no phase information)

Tuned Receiver

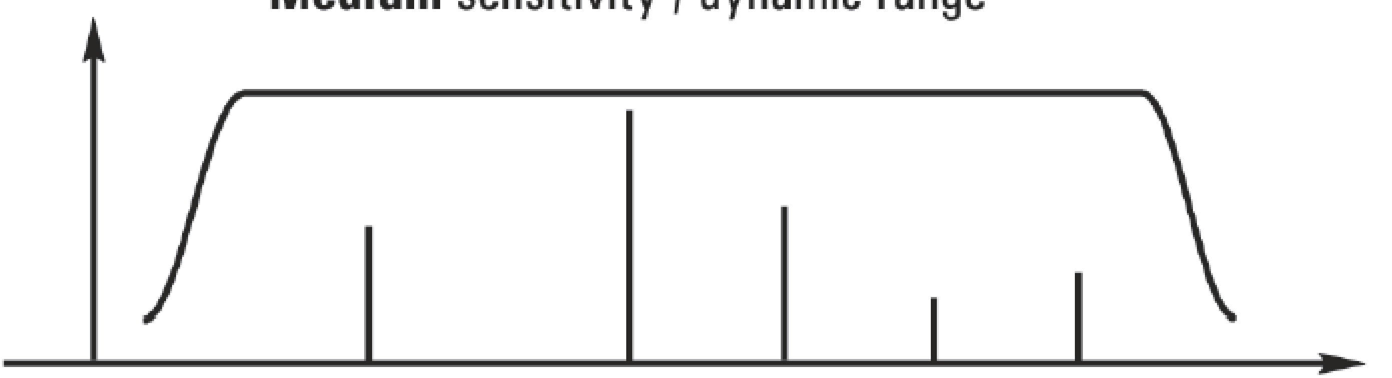


Vector
(magnitude and phase)

Analizator mreže
Širokopojasni diodni detektor

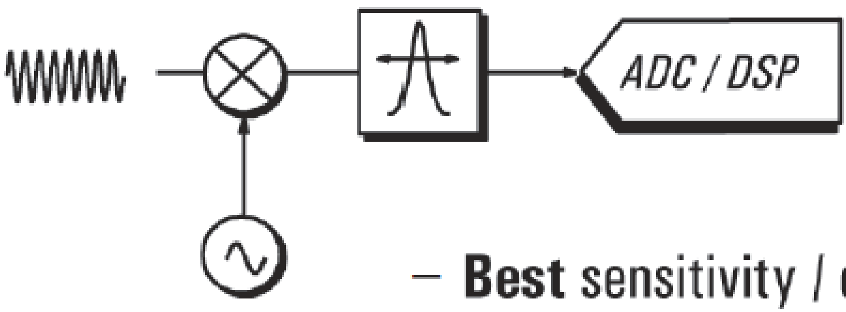


- Easy to make **broadband**
- **Inexpensive** compared to tuned receiver
- Good for measuring frequency-translating devices
- Improve dynamic range by increasing power
- **Medium** sensitivity / dynamic range

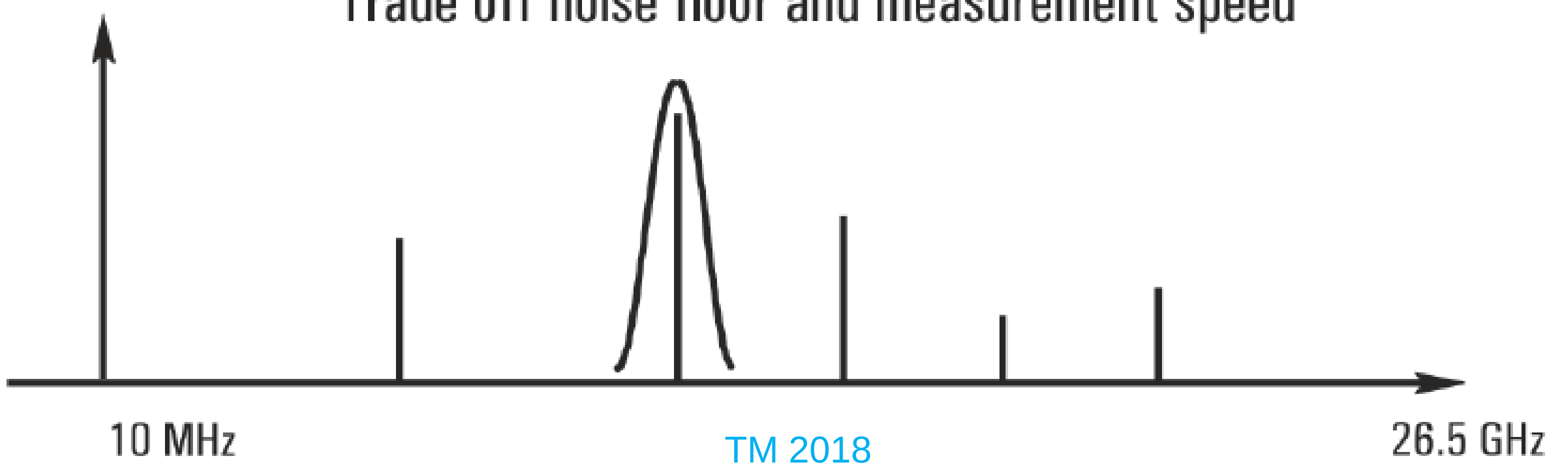


Analizator mreže

Uskopojasni detektor
Tuned Receiver

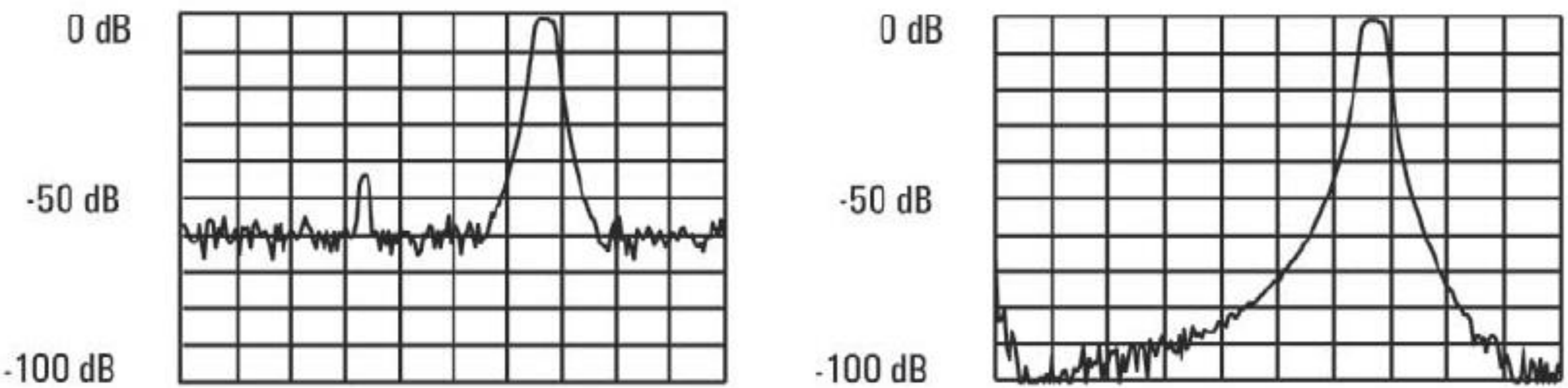


- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal **rejection**
- Improve dynamic range by increasing **power**,
- decreasing IF **bandwidth**, or **averaging**
- Trade off noise floor and measurement speed



Analizator mreže
Upoređivanje tehnika prijemnika

Broadband (diode) detection	***Narrowband (tuned-receiver) detection***

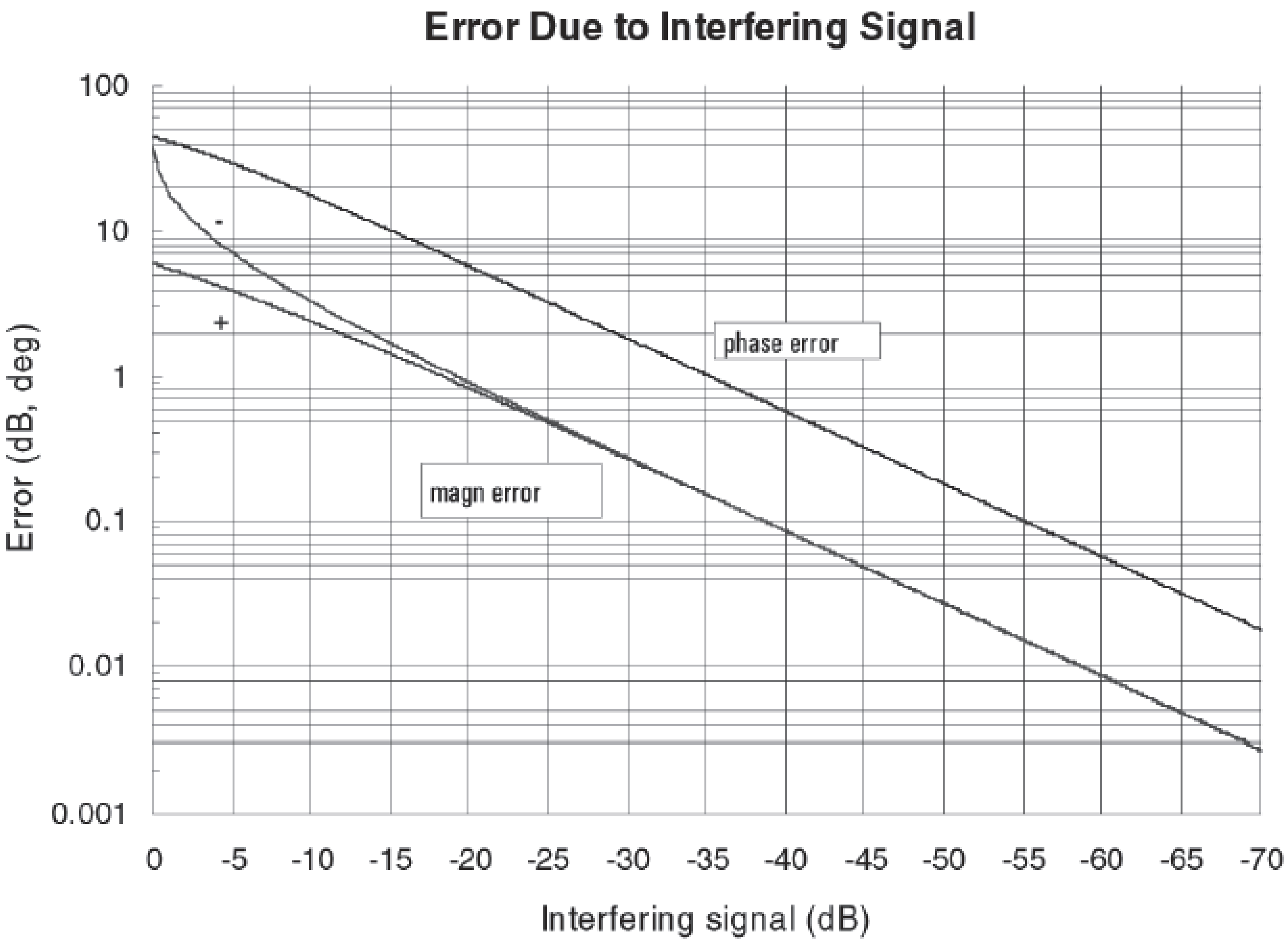


Broadband (diode) detection: -60 dBm Sensitivity
- higher noise floor
- false responses

Narrowband (tuned-receiver) detection: < -100 dBm Sensitivity
- high dynamic range
- harmonic immunity

Dynamic range = maximum receiver power - receiver noise floor

Analizator mreže
Dinamički opseg

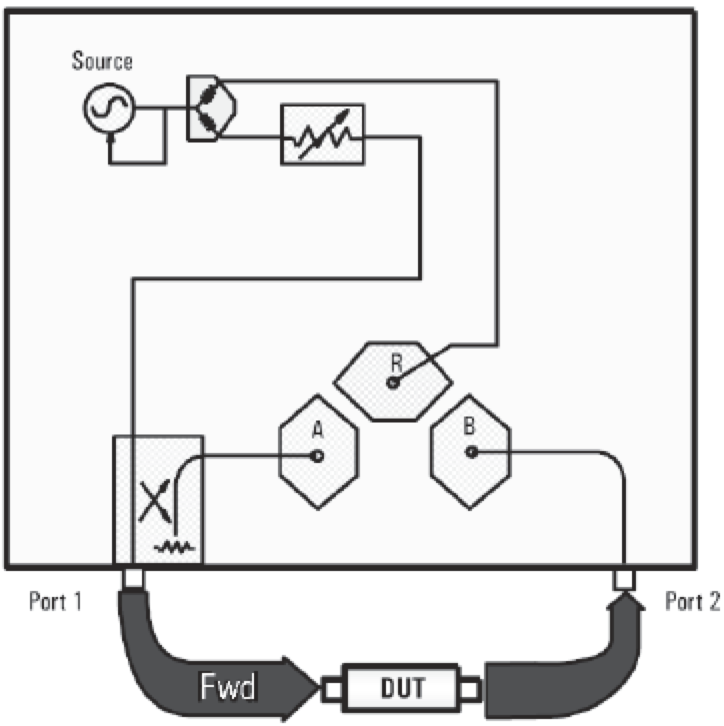


Dynamic range is very important for measurement accuracy!

Analizator mreže

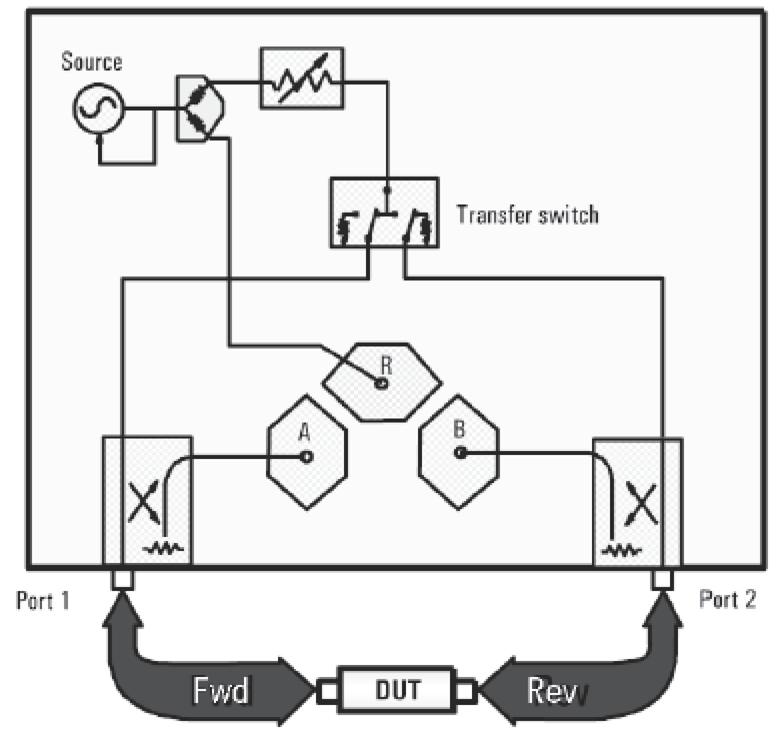
T/R vs S-Parameter Test Sets

Transmission/Reflection Test Set



- RF always comes out port 1
- port 2 is always receiver
- **response, one port** cal available

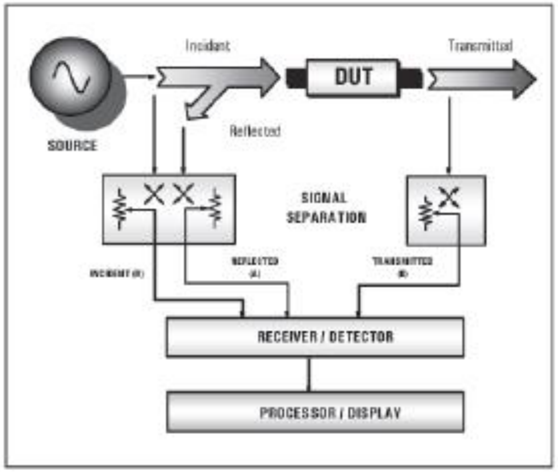
S Parameter Test Set



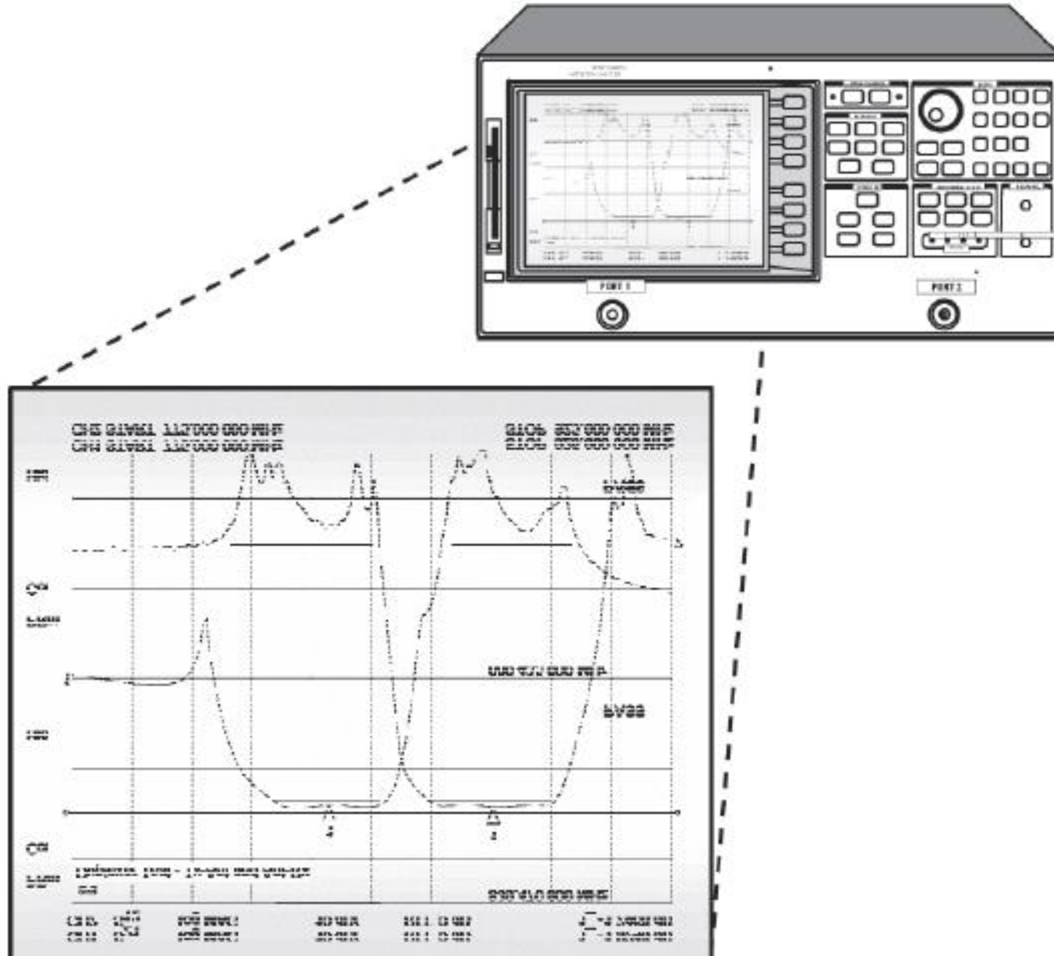
- RF comes out port 1 or port 2
- forward and reverse measurements
- **two port** calibration possible

Analizator mreže
Procesor – displej

KEYSIGHT TECHNOLOGIES



- markers
- limit lines
- pass/fail indicators
- linear/log formats
- grid/polar/Smith charts

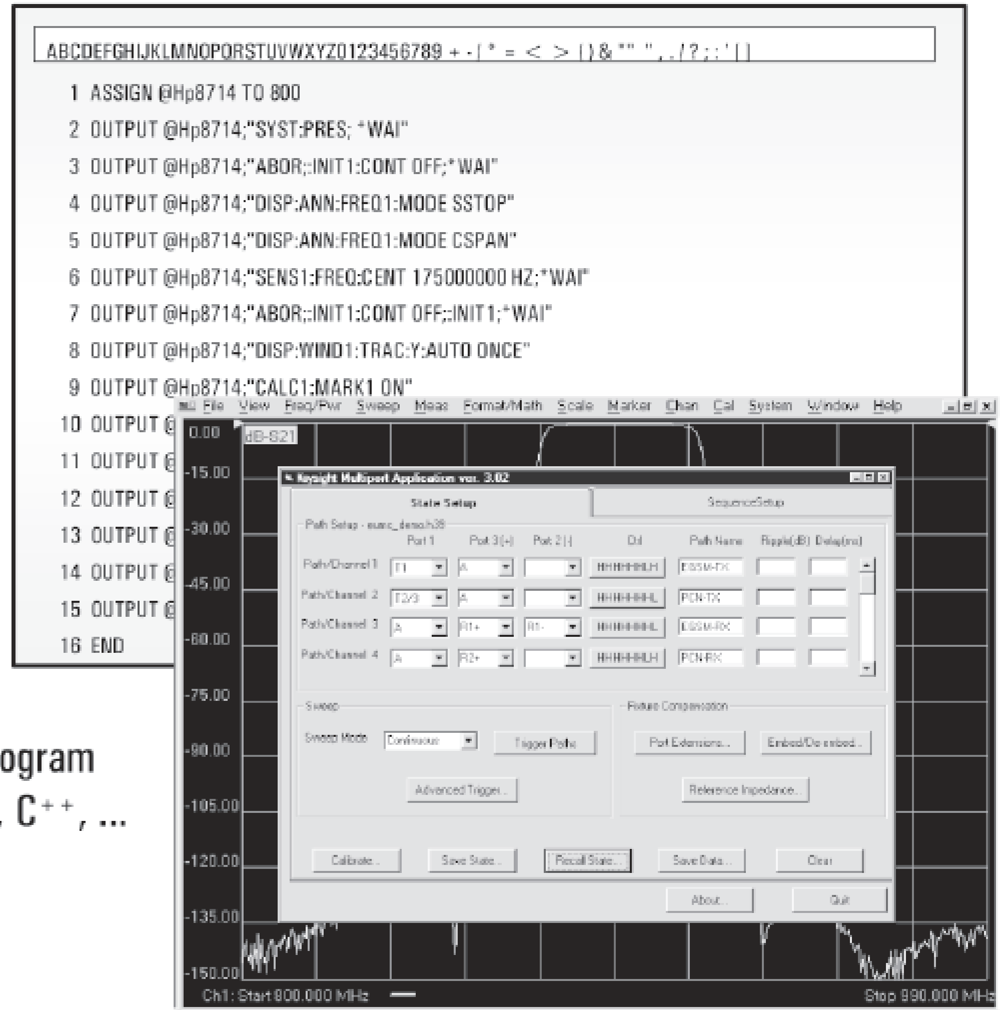


Analizator mreže - automatizacija

Simple: **recall states**

More powerful:

– **Test sequencing**
  - -- available on 8753/ 8720 families
  - -- keystroke recording
  - -- some advanced functions
– **IBASIC**
  - -- available on 8712 family
  - -- sophisticated programs
  - -- custom user interfaces
– **Windows compatible programs**
  - -- PNA Series:
    - -- use <u>any</u> Windows-compatible program
    - -- e.g. Visual Basic, VEE, LabView, C++, ...
  - -- ENA Series: VBA only



RF vektor analizator

KEYSIGHT TECHNOLOGIES

PNA series
- 3, 6, 9 GHz - 2, 3 ports
- highest dynamic range
- advanced LAN connectivity
- internal Windows automation
- program via SCPI or COM/DCOM

8753ET/ES series
- 3, 6 GHz – 50/75 Ω
- rich feature set
- frequency offset and harmonic sweeps

ENA series
- 3, 8.5 GHz
- 2, 3, 4, 7, 9 ports
- excellent RF performance
- balanced measurements
- internal VBA automation

8712ET/ES series
- 1.3, 3 GHz - 50/75 Ω
- lowest cost
- narrowband and broadband detection
- IBASIC / LAN

4395A series NA/SA combination
- 500 MHz, 1.8 GHz
- impedance-measuring option
- fast, FFT-based spectrum analysis
- IBASIC

E5100A/B
- 180, 300 MHz
- fast, small, economical
- for crystals, resonators, filters

Mikrotalasni vektor analizator

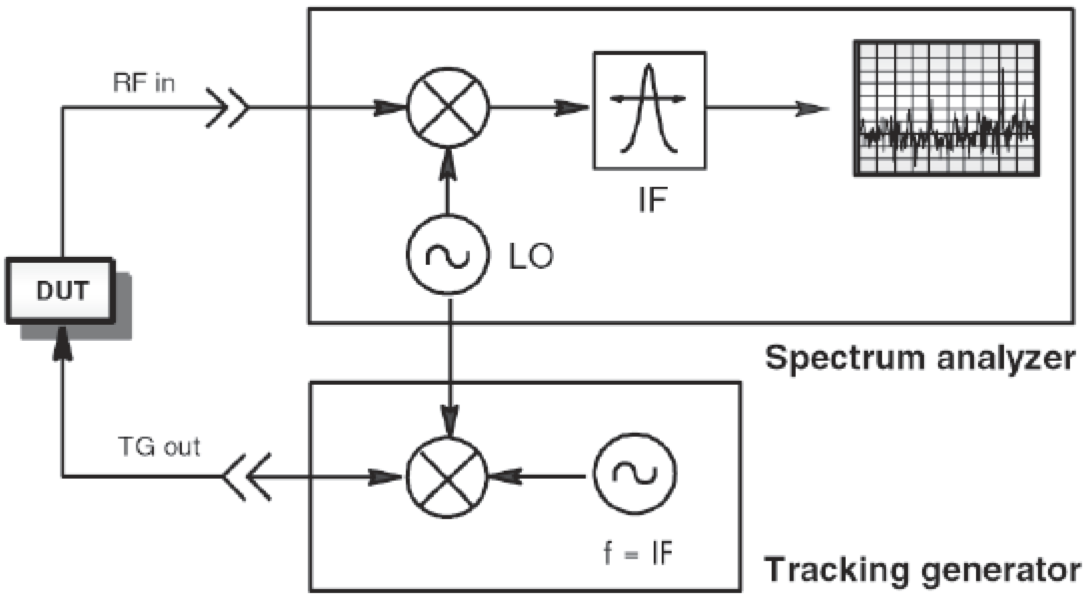
KEYSIGHT TECHNOLOGIES

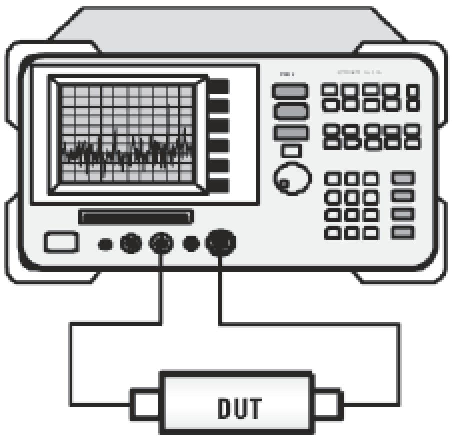
8720ET/ES series
- 13.5, 20, 40 GHz
- economical
- fast, small, integrated
- test mixers, high-power amps

8510C series
- 110 GHz *in coax*
- modular, flexible
- pulse systems
- Tx/Rx module test

PNA series
- 20, 40, 50 GHz
- highest dynamic range and speed
- very low trace noise
- advanced LAN connectivity
- internal Windows automation
- program via SCPI or COM/DCOM

Spektrum analizator, praćenje





Key differences from network analyzer:

- **one channel** -- no ratioed or phase measurements
- More **expensive** than scalar NA (but better dynamic range)
- Only error correction available is **normalization** (and possibly open-short averaging)
- Poorer **accuracy**
- Small **incremental cost** if SA is required for other measurements

Kalibracija

- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
  - measurement errors
  - what is vector error correction?
  - calibration types
  - accuracy examples
  - calibration considerations
- Example measurements
- Appendix

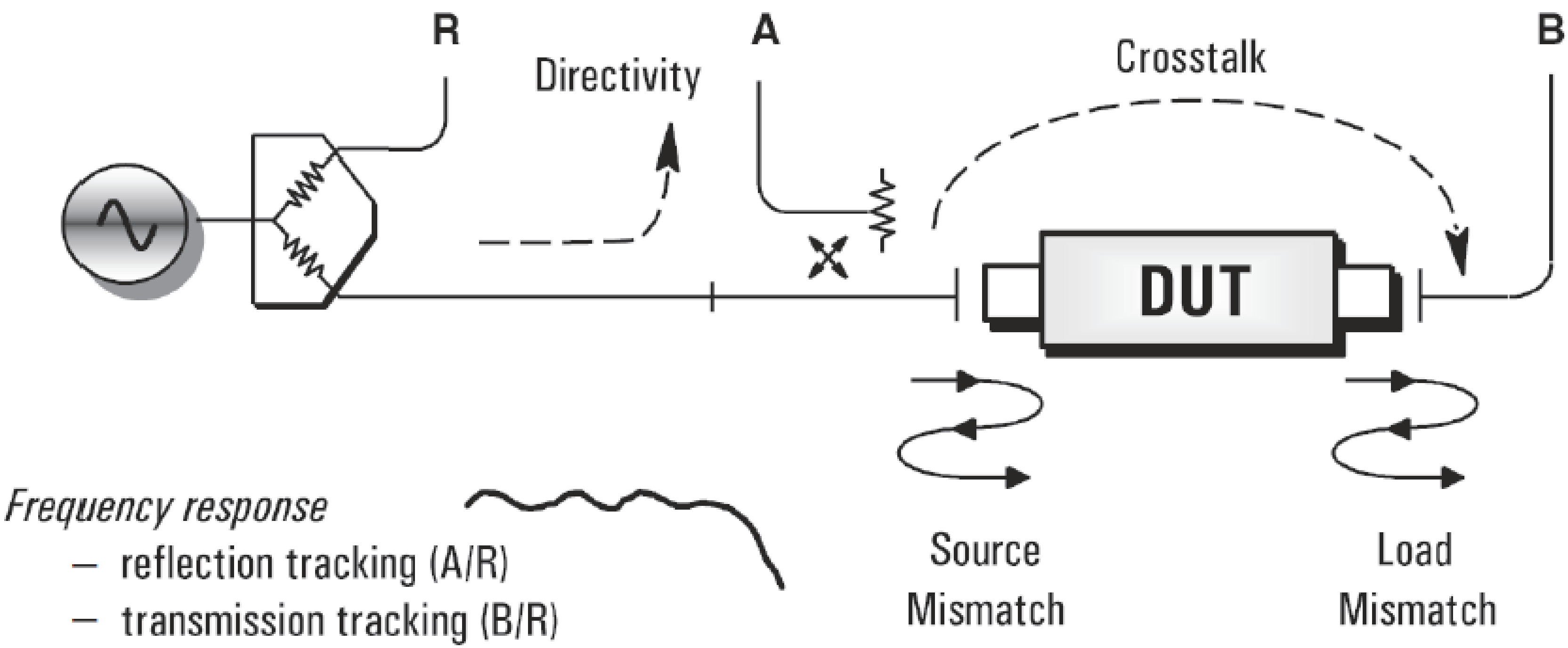
Systematic errors
- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

Random errors
- **vary** with time in random fashion (unpredictable)
- main contributors: instrument **noise,** switch and connector **repeatability**

Drift errors
- due to system performance changing ***after*** a calibration has been done
- primarily caused by **temperature variation**

KEYSIGHT TECHNOLOGIES

Sistematske merne greške

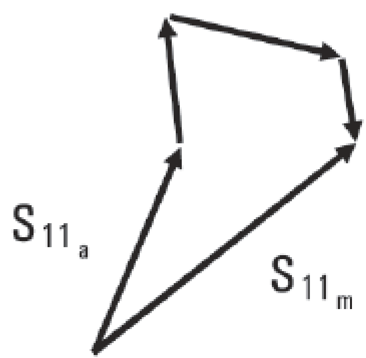


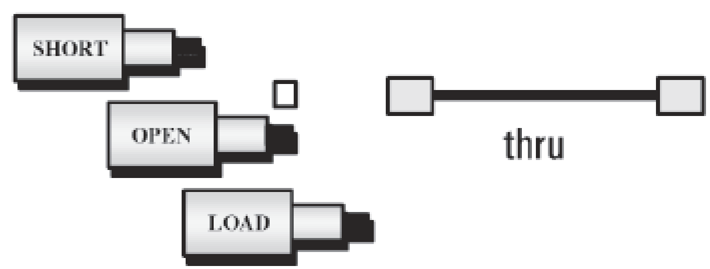
Six forward and six reverse error terms yields 12 error terms for two-port devices

Tipovi korekcije greške

– **response (normalization)**
  - -- simple to perform
  - -- only corrects for tracking errors
  - -- stores reference trace in memory, then does data divided by memory

– **vector**
  - -- requires more standards
  - -- requires an analyzer that can measure phase
  - -- accounts for all major sources of systematic error

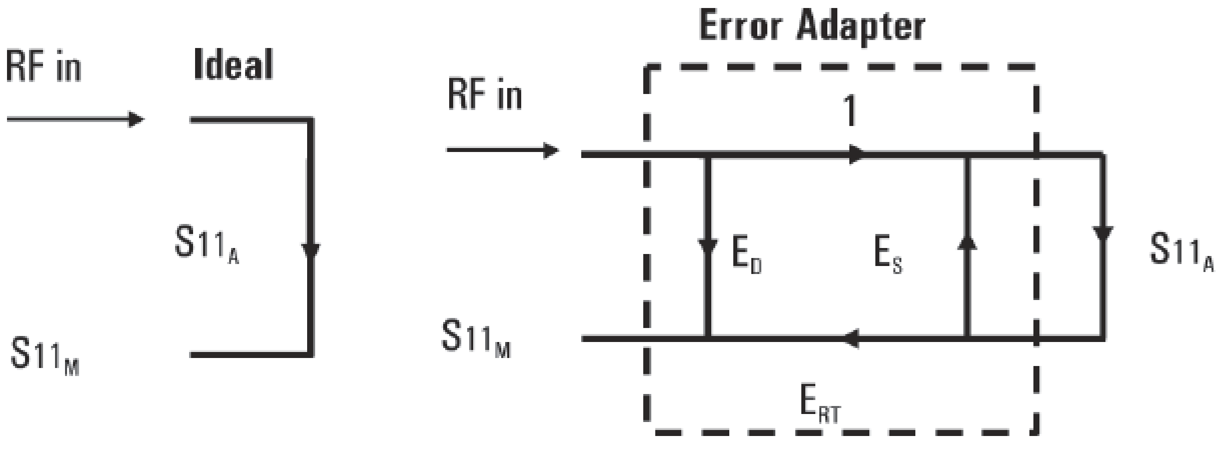




Korekcija greške vektora

- Process of characterizing systematic error terms
  - -- measure **known standards**
  - -- remove effects from subsequent measurements
- **1-port calibration** *(reflection measurements)*
  - -- only 3 systematic error terms measured
  - -- directivity, source match, and reflection tracking
- **Full 2-port calibration** *(reflection and transmission measurements)*
  - -- 12 systematic error terms measured
  - -- usually requires 12 measurements on four known standards (SOLT)
- Standards defined in **cal kit definition** file
  - -- network analyzer contains standard cal kit definitions
  - -- **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - -- User-built standards must be characterized and entered into user cal-kit

Model sa jednim portom



E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

$S11_A$ = Actual

To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

$$S11_M = E_D + E_{RT}\left[\frac{S11_A}{1 - E_S\, S11_A}\right]$$

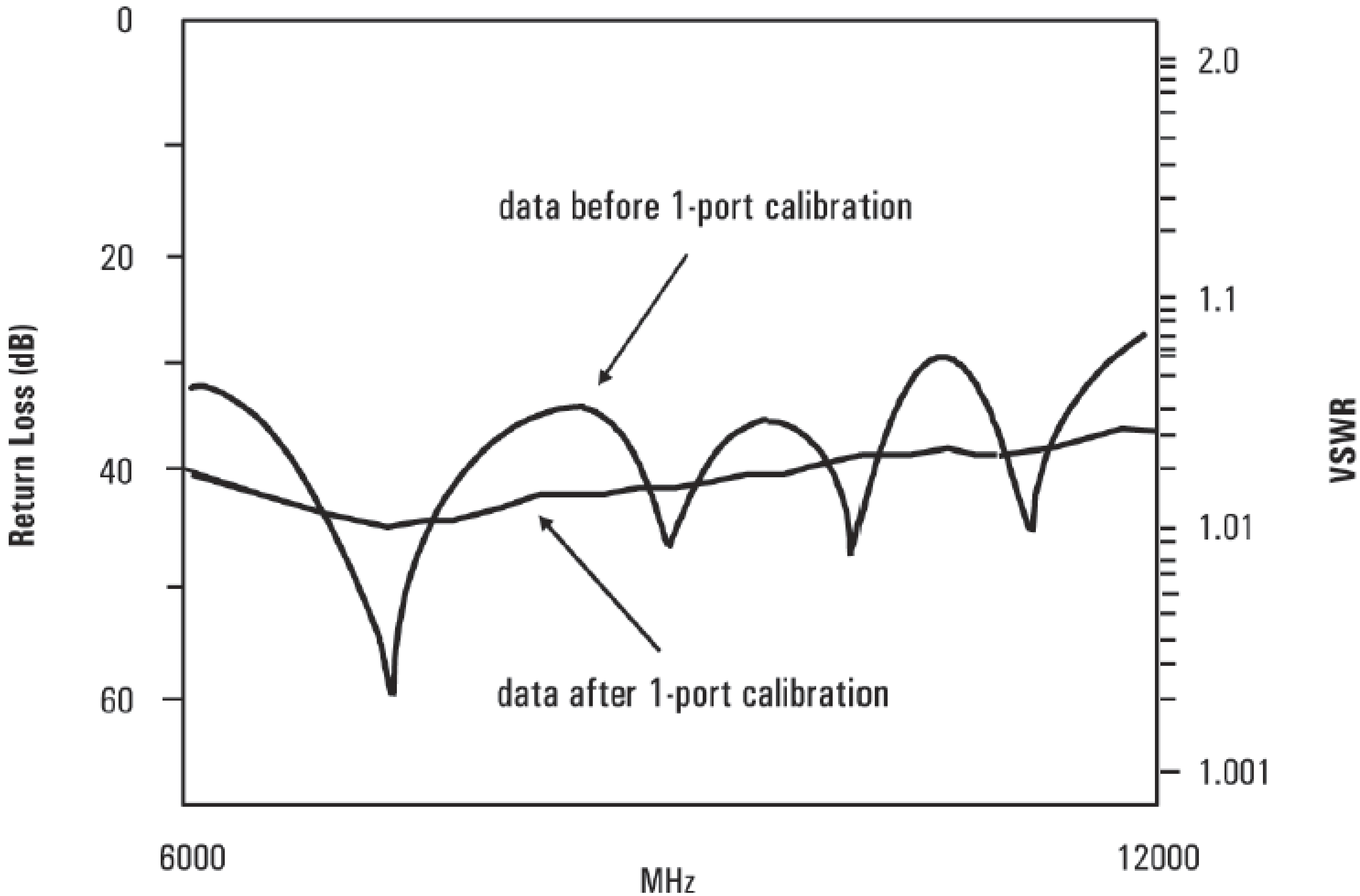
– Assumes good termination at port two if testing two-port devices

– If using port 2 of NA *and* DUT reverse isolation is low (e.g., filter passband):

-- assumption of good termination is not valid

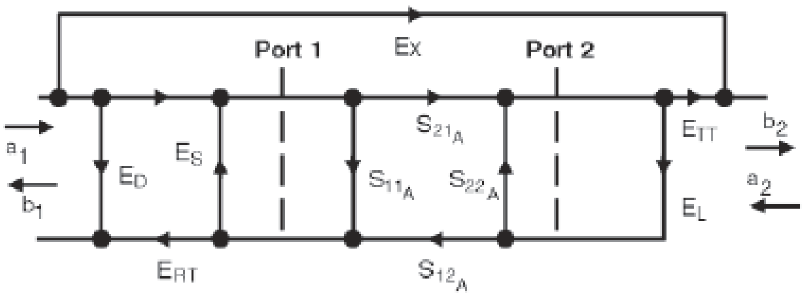
-- two-port error correction yields better results

Jedno-portni – pre i posle kalibracije

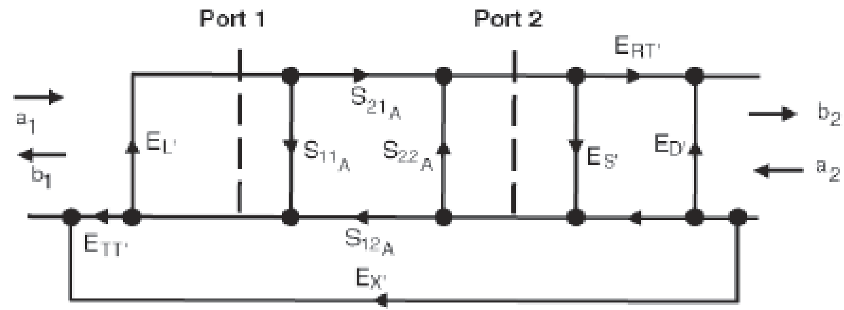


Sa dva porta

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** network analyzers!!!

$$S_{11a} = \frac{(\frac{S_{11m}-E_D}{E_{RT}})(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}{(1+\frac{S_{11m}-E_{D'}}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

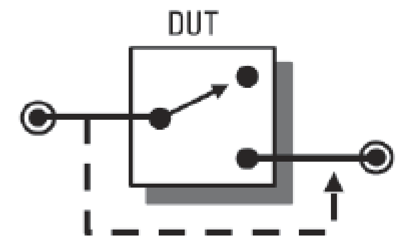
$$S_{21a} = \frac{(\frac{S_{21m}-E_X}{E_{TT}})(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L))}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{12a} = \frac{(\frac{S_{12m}-E_X'}{E_{TT}'})(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L'))}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

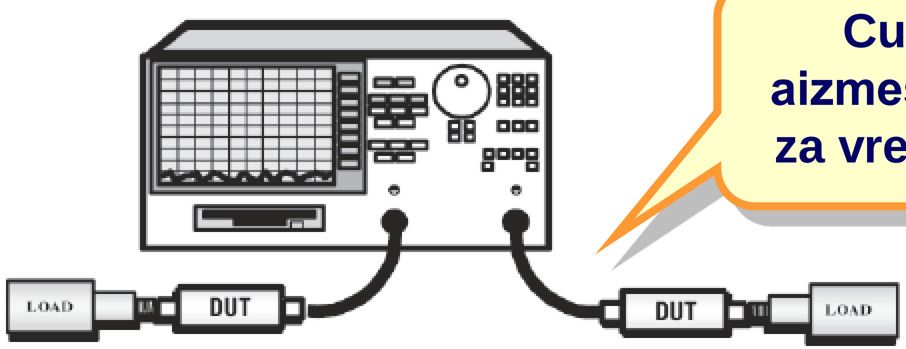
$$S_{22a} = \frac{(\frac{S_{22m}-E_D'}{E_{R.}})(1+\frac{S_{11m}-E_D}{E_{RT}}E_S) - E_L'(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

Preslušavanje

– Can be a problem with:
  - -- high isolation devices (e.g., switch in open position)
  - -- high dynamic range devices (some filter stopbands)

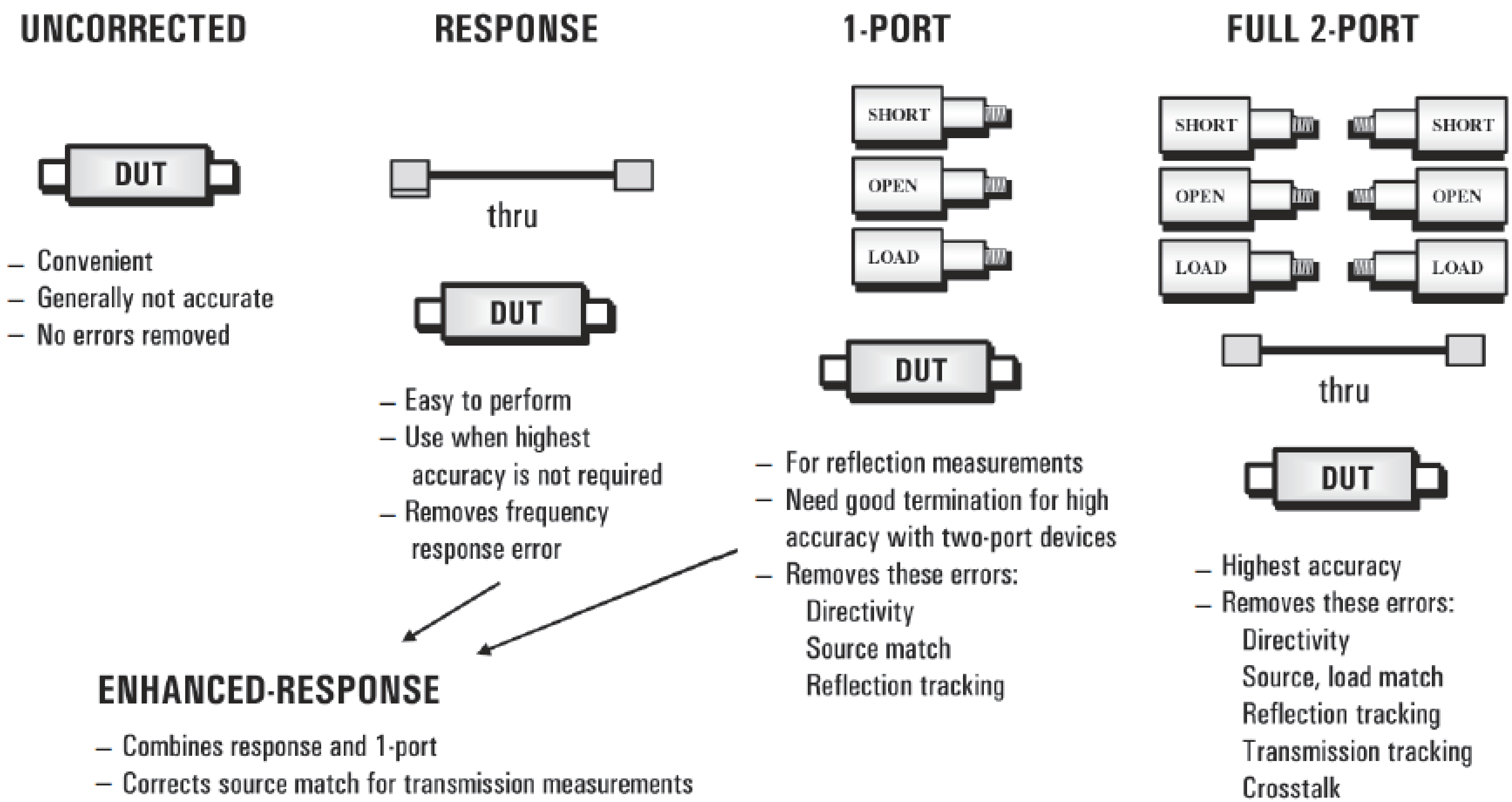


– Isolation calibration
  - -- adds noise to error model (measuring near noise floor of system)
  - -- only perform if really needed (use averaging if necessary)
  - -- if crosstalk is **independent** of DUT match, use two terminations
  - -- if **dependent** on DUT match, use DUT with termination on output

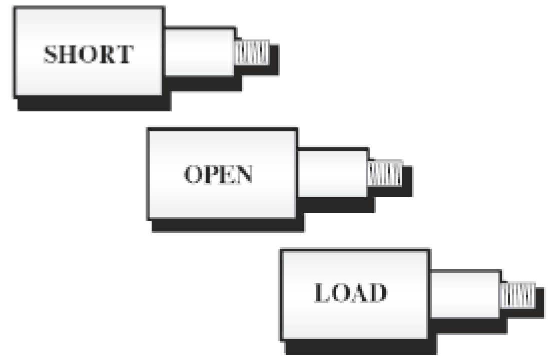


Curenje signal aizmešu test portova za vreme emitovanja

Kalibracioni standardi



Kalibracija - zaključak



Reflection	Test Set (cal type): T/R (one-port)	S-parameter (two-port)
– Reflection tracking	✓	✓
– Directivity	✓	✓
– Source match	✓	
– Load match	✗	

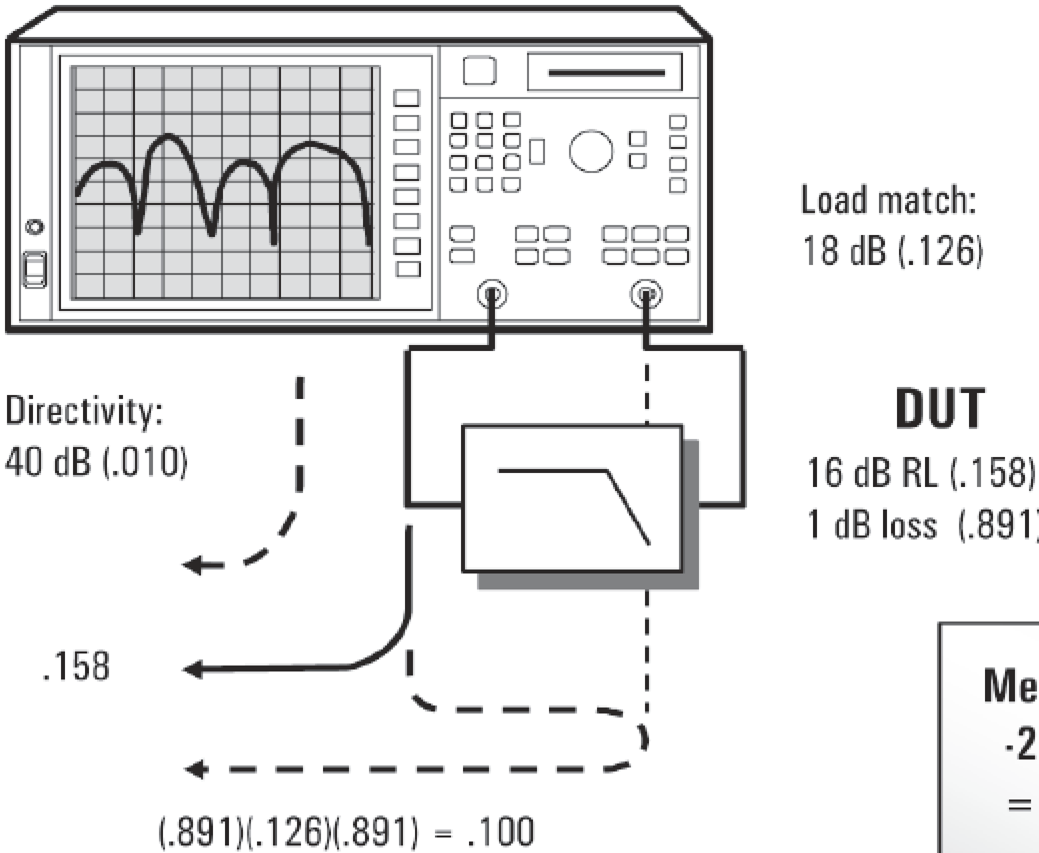
Transmission	Test Set (cal type): T/R (response, isolation)	S-parameter (two-port)
– Transmission Tracking	✓	✓
– Crosstalk	✓	✓
– Source match	(✓*) ✗	✓
– Load match	✗	✓

✓ *error can be corrected*

✗ *error cannot be corrected*

✓ * *enhanced response cal* corrects for source match during transmission measurements

Primer refleksije kod jedno-pornih



Remember: convert all dB values to linear for uncertainty calculations!

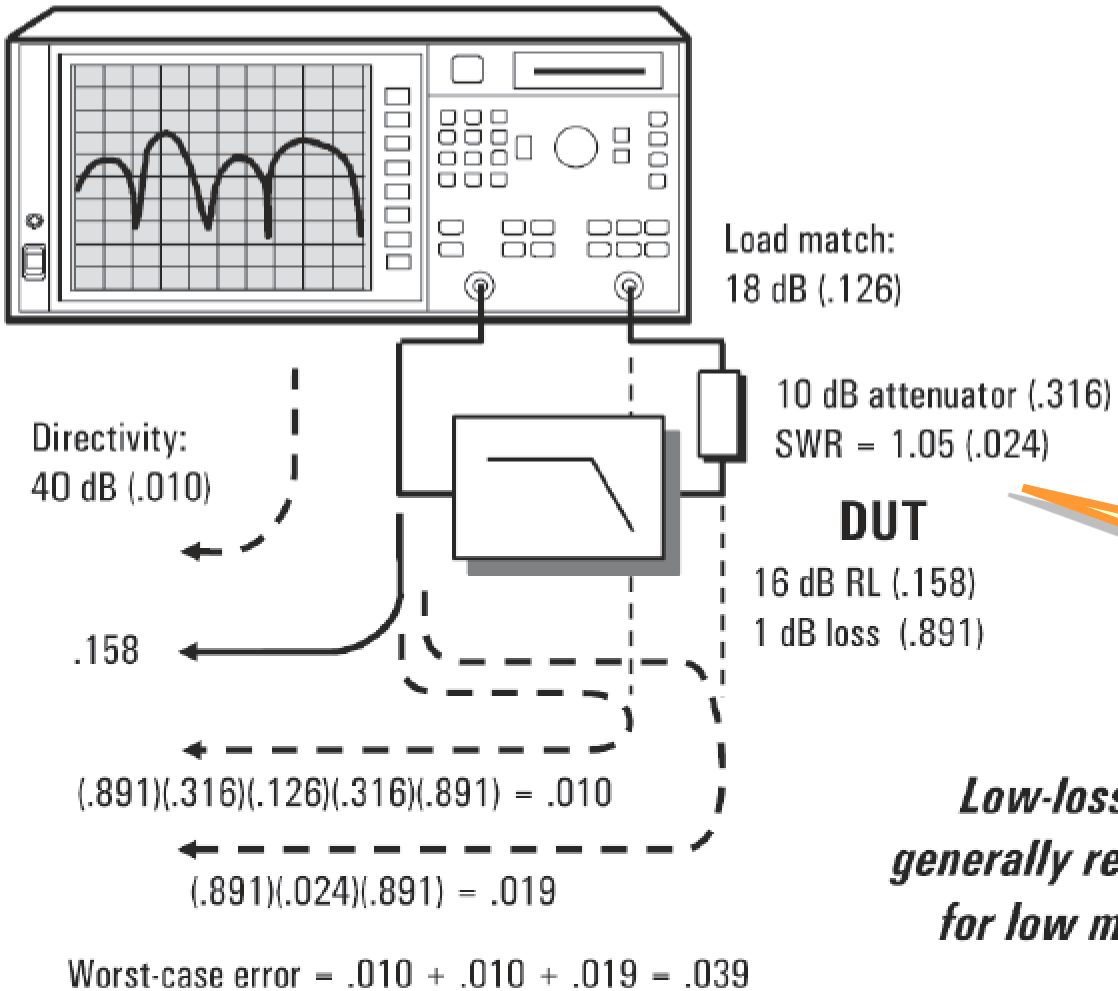
$$\rho \text{ or } loss_{(linear)} = 10^{\left(\frac{-dB}{20}\right)}$$

Measurement uncertainty:

-20 * log (.158 + .100 + .010)
= 11.4 dB (-4.6dB)

-20 * log (.158 - .100 - .010)
= 26.4 dB (+10.4 dB)

Primer refleksije kod jedno-pornih + oslabljivač



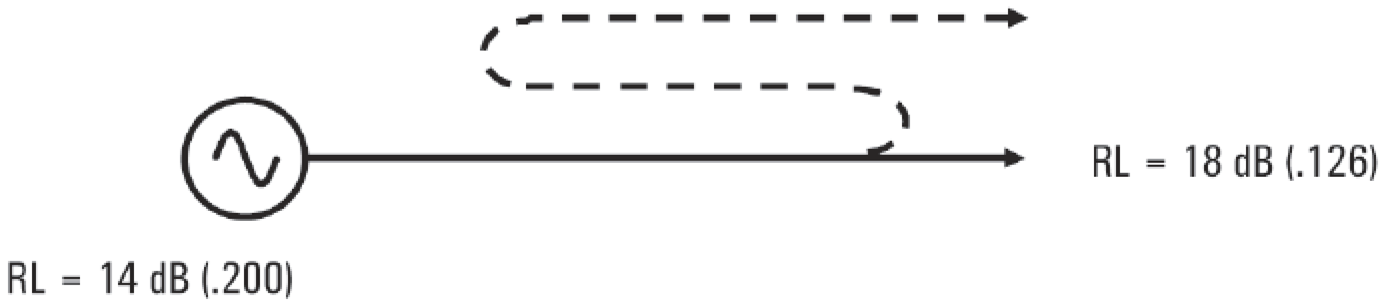
Measurement uncertainty:

-20 * log (.158 + .039)
= 14.1 dB (-1.9 dB)

-20 * log (.158 - .039)
= 18.5 dB (+2.5 dB)

Low-loss bi-directional devices generally require two-port calibration for low measurement uncertainty

Transmission Example
Using Response Calibration



Thru calibration (normalization) builds error into measurement due to source and load match interaction

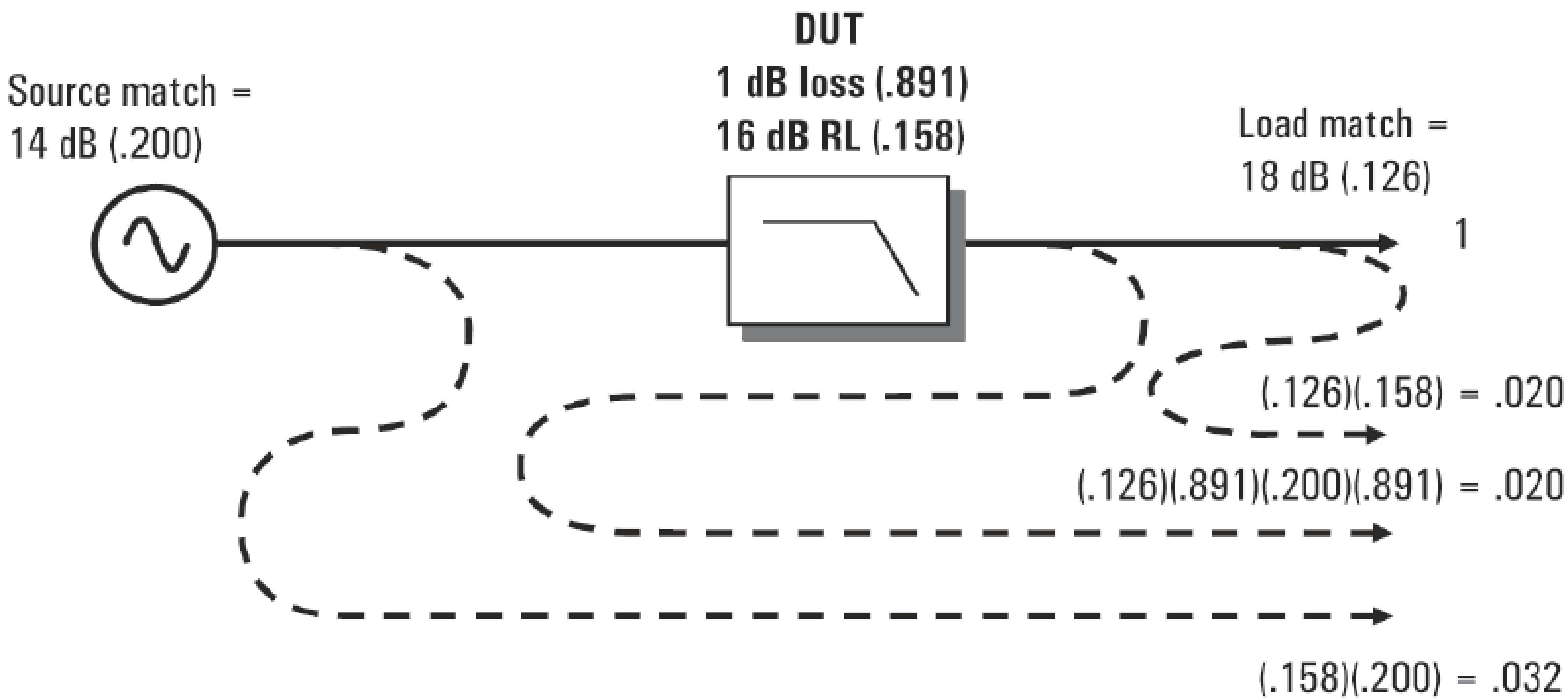
Calibration Uncertainty

$$= (1 \pm \rho_S \rho_L)$$

$$= (1 \pm (.200)(.126))$$

$$= \pm 0.22 \text{ dB}$$

Filter Measurement with Response Calibration

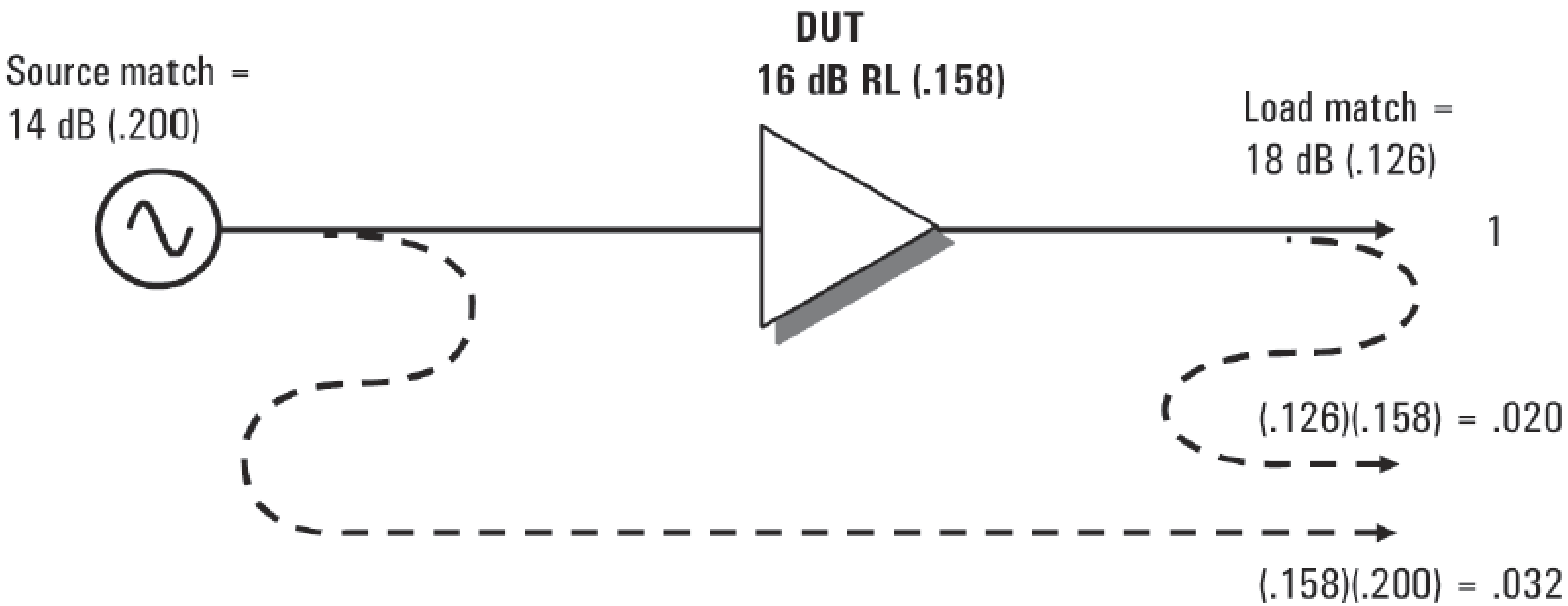


Total measurement uncertainty:
+0.60 + 0.22 = + 0.82 dB
· 065 · 0.22 = · 0.87 dB

Measurement uncertainty
= 1 ± (.020+.020+.032)
= 1 ± .072
= + 0.60 dB
· 0.65 dB

TM 2018

Measuring Amplifiers with a Response Calibration



Total measurement uncertainty:

+0.44 + 0.22 = + 0.66 dB

- 046 - 0.22 = - 0.68 dB

Measurement uncertainty

= 1 ± (.020+.032)

= 1 ± .052

= + 0.44 dB

- 0.46 dB

Filter Measurements Using the Enhanced Response Calibration

KEYSIGHT TECHNOLOGIES

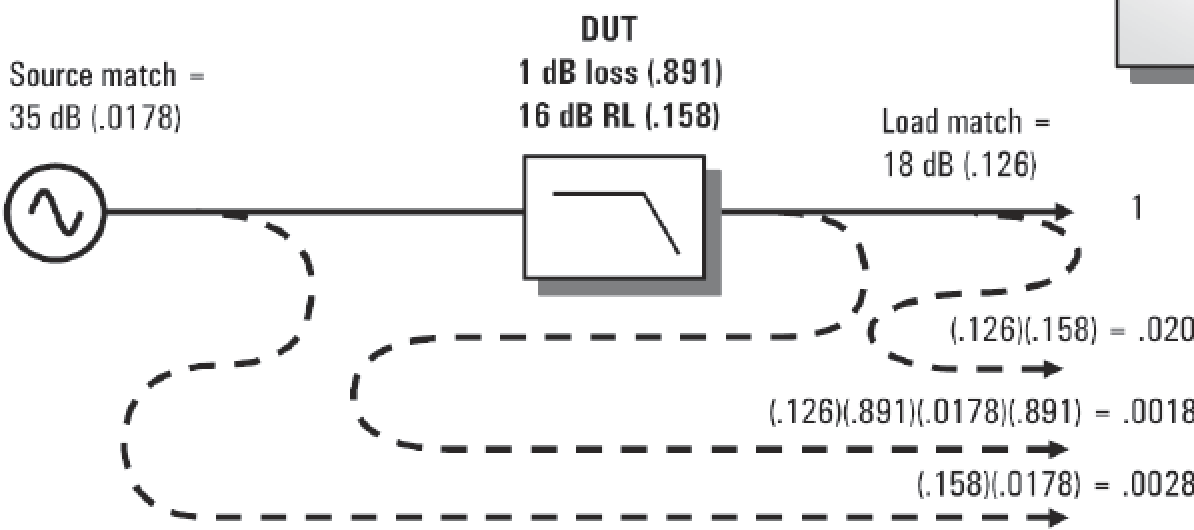
Effective source match = 35 dB!

Calibration Uncertainty

$= (1 \pm \rho_S \, \rho_L)$

$= (1 \pm (.0178)(.126)$

$= \pm .02$ dB



Measurement uncertainty

$= 1 \pm (.020 + .0018 + .0028)$

$= 1 \pm .0246$

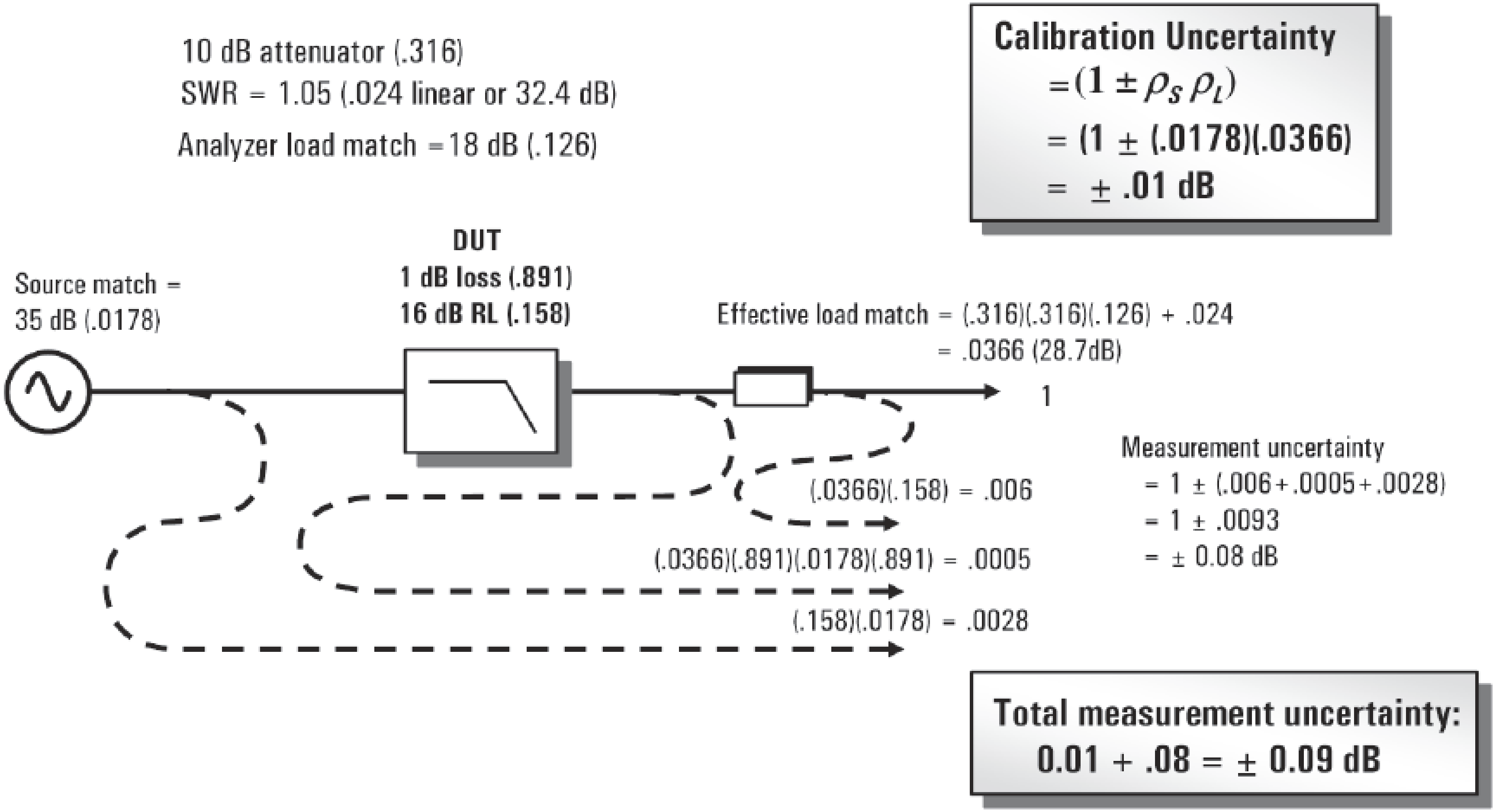
$= + 0.211$ dB

$- 0.216$ dB

Total measurement uncertainty:

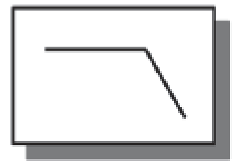
$0.22 + .02 = \pm 0.24$ dB

Using the Enhanced Response Calibration Plus an Attenuator



Calibrating Measurement Uncertainty After a 2-Port Calibration

KEYSIGHT TECHNOLOGIES



DUT
1 dB loss (0.891)
16 dB RL (0.158)

Corrected error terms:
(8753ES 1.3-3 GHz Type-N)

Directivity	=	47 dB
Source match	=	36 dB
Load match	=	47 dB
Refl. tracking	=	.019 dB
Trans. tracking	=	.026 dB
Isolation	=	100 dB

Reflection uncertainty

$$S_{11m} = S_{11a} \pm (E_D + S_{11a}{}^2 E_S + S_{21a} S_{12a} E_L + S_{11a}(1 - E_{RT}))$$

$$= 0.158 \pm (.0045 + 0.158^2 * .0158 + 0.891^2 * .0045 + 0.158 * .0022)$$

$$= 0.158 \pm .0088 = 16 \text{ dB } \mathbf{+0.53 \text{ dB}, -0.44 \text{ dB (worst-case)}}$$

Transmission uncertainty

$$S_{21m} = S_{21a} \pm S_{21a}(E_I / S_{21a} + S_{11a} E_S + S_{21a} S_{12a} E_S E_L + S_{22a} E_L + (1 - E_{TT}))$$

$$= 0.891 \pm 0.891(10^{-6} / 0.891 + 0.158 * .0158 + 0.891^2 * .0158 * .0045 + 0.158 * .0045 + .003)$$

$$= 0.891 \pm .0056 = 1 \text{ dB } \mathbf{\pm 0.05 \text{ dB (worst-case)}}$$

Comparison of Measurement Examples

Reflection

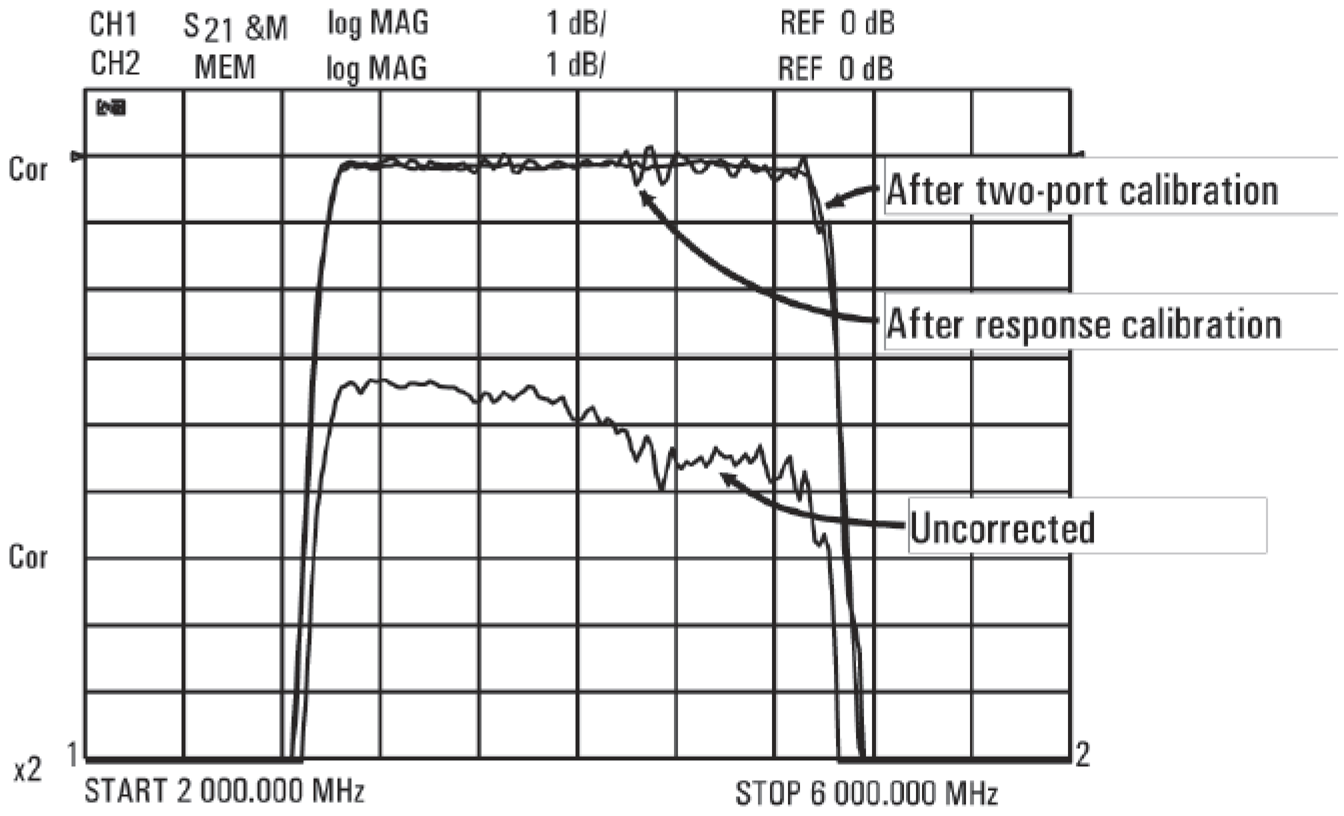
Calibration type	Measurement uncertainty
One-port	-4.6/ 10.4 dB
One-port + attenuator	-1.9/ 2.5 dB
Two-port	-0.44/ 0.53 dB

Transmission

Calibration type	Calibration uncertainty	Measurement uncertainty	Total uncertainty
Response	±0.22 dB	0.60/ -0.65 dB	0.82/ -0.87 dB
Enhanced response	±0.02 dB	±0.22 dB	±0.24 dB
Enh. response + attenuator	±0.01 dB	±0.08 dB	±0.09 dB
Two port	-----		±0.05 dB

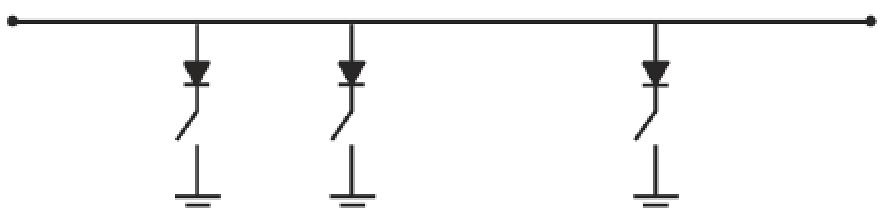
Response Versus 2-Port Calibration

Measuring filter insertion loss



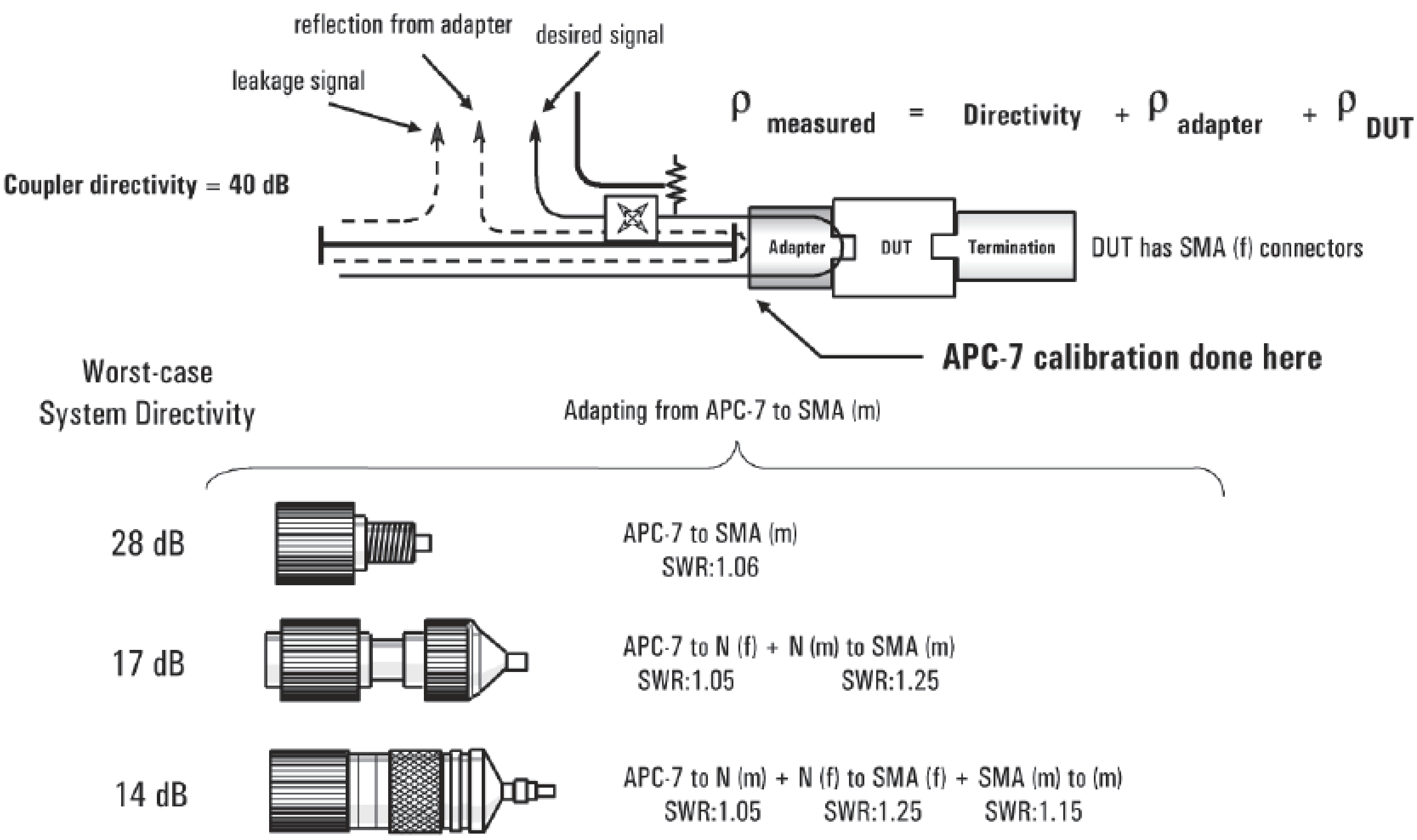
ECal: Electronic Calibration

– Variety of modules cover 300 kHz to 26.5 GHz
– 2 and 4-port versions available
– Choose from six connector types (50 Ω and 75 Ω)
– Mix and match connectors (3.5mm, Type-N, 7/16)
– Single-connection
  -- reduces calibration time
  -- makes calibrations easy to perform
  -- minimizes wear on cables and standards
  -- eliminates operator errors
– Highly repeatable temperature-compensated terminations provide excellent accuracy



Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

Adapteri

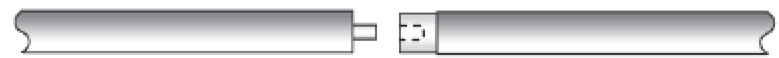


reflection from adapter
desired signal
leakage signal
ρ measured = Directivity + ρ adapter + ρ DUT
Coupler directivity = 40 dB
Adapter
DUT
Termination
DUT has SMA (f) connectors
APC-7 calibration done here
Worst-case
System Directivity
Adapting from APC-7 to SMA (m)
28 dB
APC-7 to SMA (m)
SWR:1.06
17 dB
APC-7 to N (f) + N (m) to SMA (m)
SWR:1.05
SWR:1.25
14 dB
APC-7 to N (m) + N (f) to SMA (f) + SMA (m) to (m)
SWR:1.05
SWR:1.25
SWR:1.15

Calibrating Non-Insertable Devices

When doing a through cal, normally test ports mate directly

- cables can be connected directly without an adapter
- result is a zero length through



What is an insertable device?

- has same type of connector, but different sex on each port
- has same type of sexless connector on each port (e.g. APC 7)

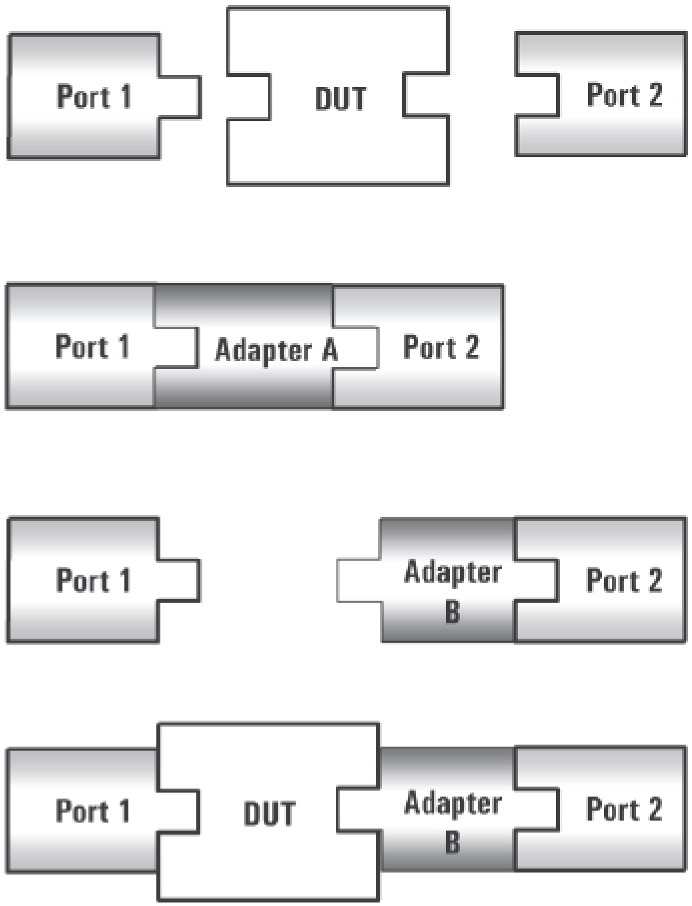
What is a non insertable device?

- one that cannot be inserted in place of a zero length through
- has same connectors on each port (type and sex)
- has different type of connector on each port
  (e.g., waveguide on one port, coaxial on the other)

What calibration choices do I have for non insertable devices?

- use an *uncharacterized* through adapter
- use a *characterized* through adapter (modify cal kit definition)
- swap equal adapters
- adapter removal

Swap Equal Adapters Method

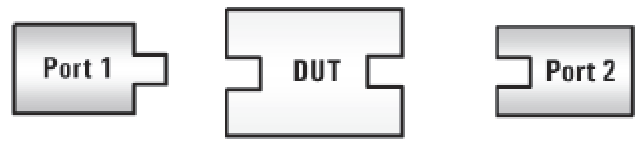


Accuracy depends on how well the adapters are matched - loss, electrical length, match and impedance should all be equal

1. Transmission cal using adapter A.
2. Reflection cal using adapter B.
3. Measure DUT using adapter B.

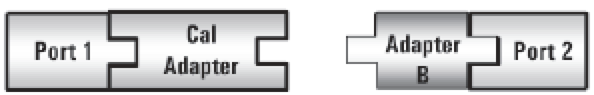
Adapter Removal Calibration

- Calibration is very accurate and traceable
- In firmware of 8753, 8720 and 8510 series
- Also accomplished with ECal modules (85060/90)
- Uses adapter with same connectors as DUT
- Must specify electrical length of adapter to within 1/4 wavelength of highest frequency (to avoid phase ambiguity)



Cal Set 1

1. Perform 2-port cal with adapter on port 2. Save in cal set 1.

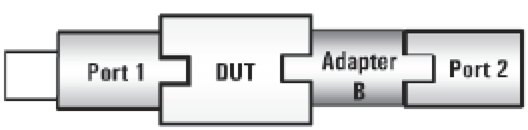


Cal Set 2

2. Perform 2-port cal with adapter on port 1. Save in cal set 2.

[CAL] [MORE] [MODIFY CAL SET]
[ADAPTER REMOVAL]

3. Use ADAPTER REMOVAL to generate new cal set.



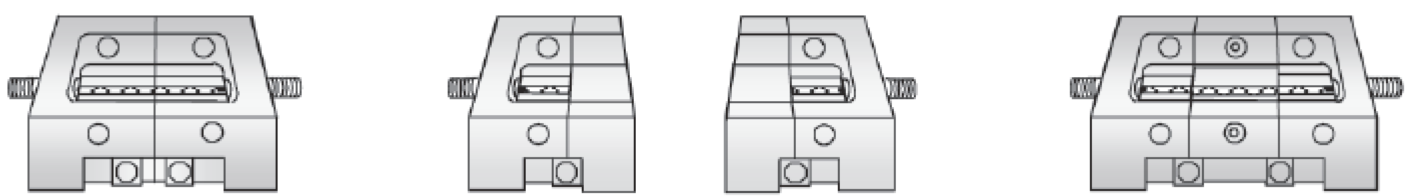
4. Measure DUT without cal adapter.

Thru-Reflect-Line (TRL) Calibration

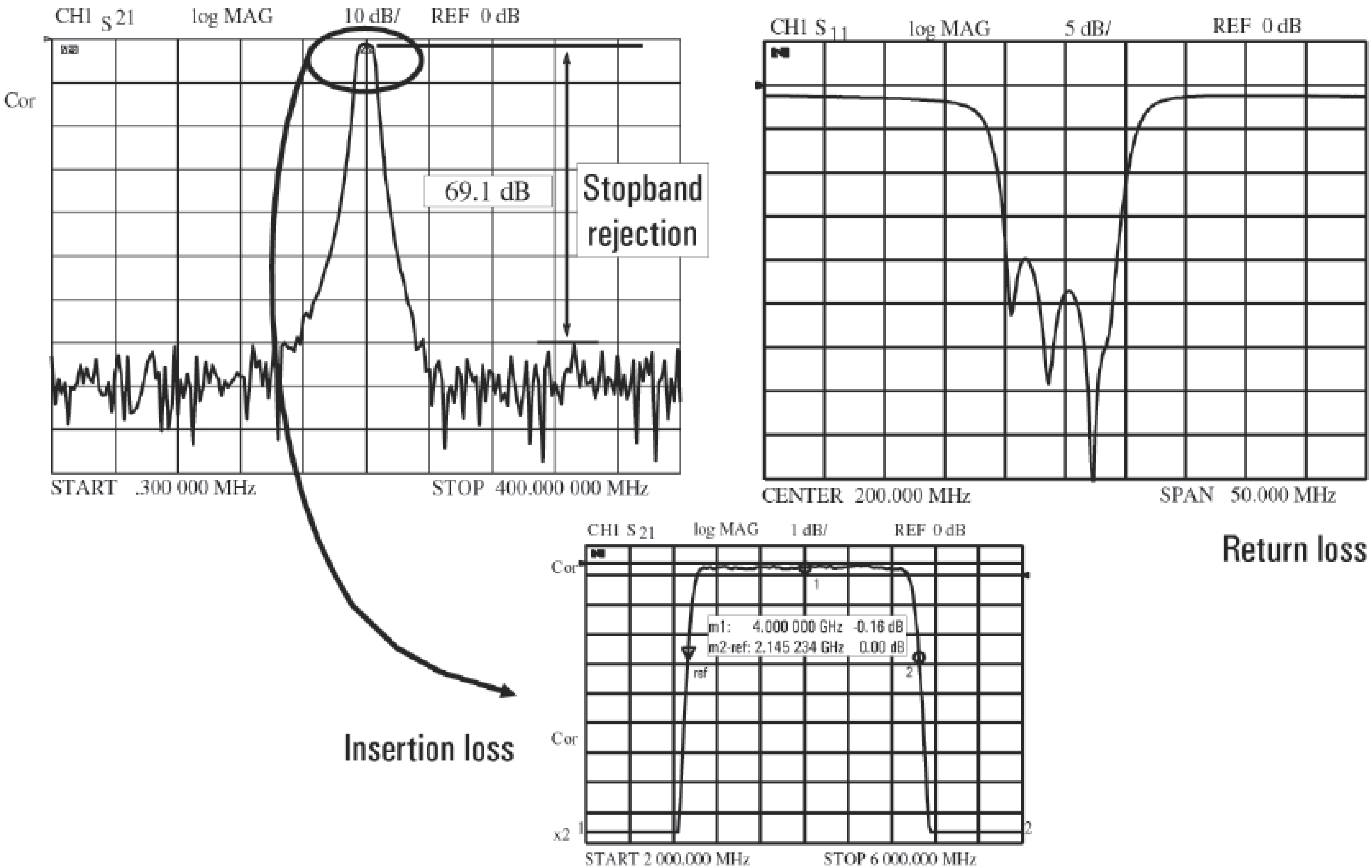
We know about Short-Open-Load-Thru (SOLT) calibration...
What is TRL?

- A two-port calibration technique
- Good for noncoaxial environments (waveguide, fixtures, wafer probing)
- Uses the same 12-term error model as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Two variations: TRL (requires 4 receivers) and TRL* (only three receivers needed)
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

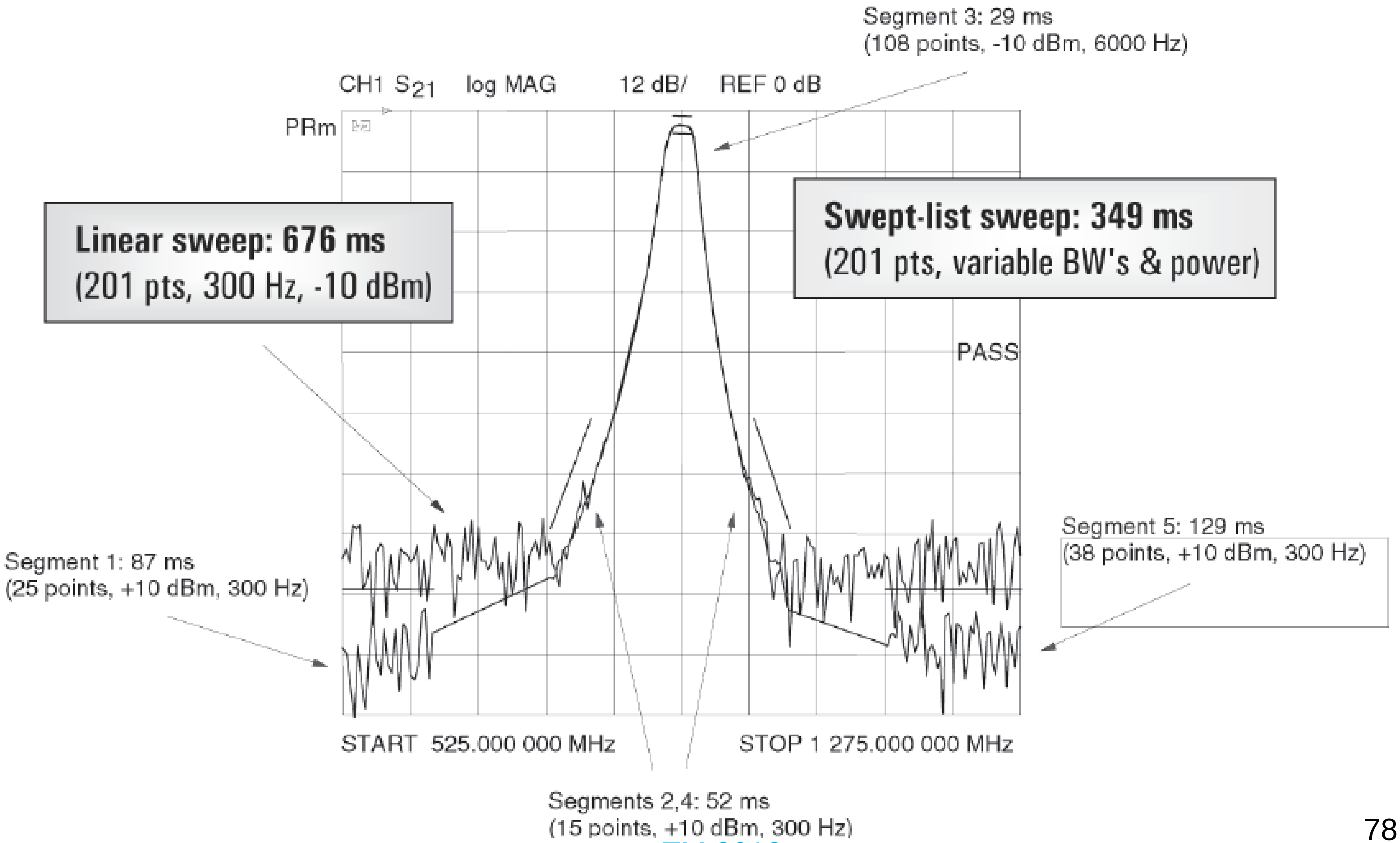
*TRL was developed for **non-coaxial microwave** measurements*



Frequency Sweep – Filter Test

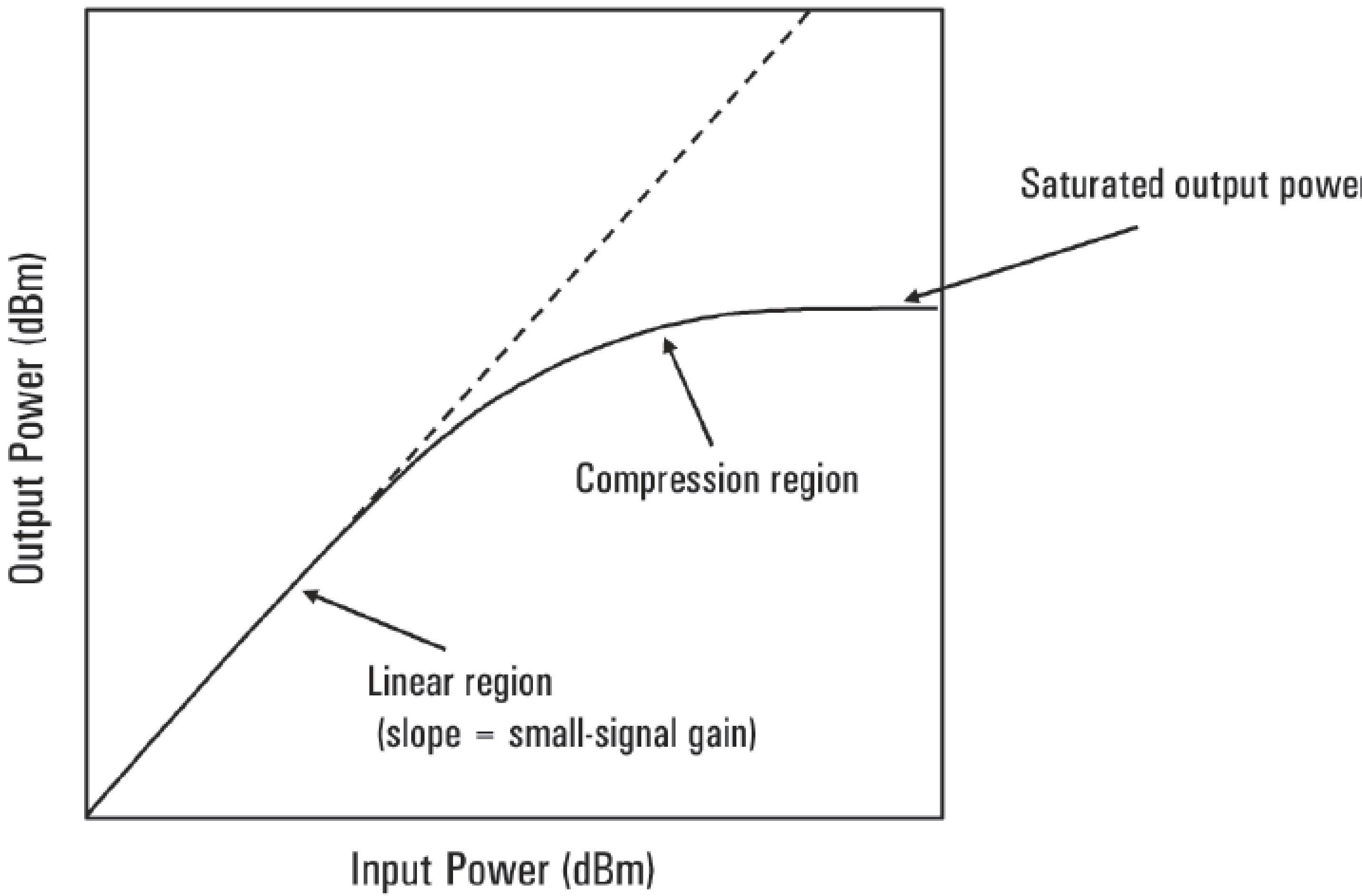


Optimize Filter Measurements With Swept-List Mode

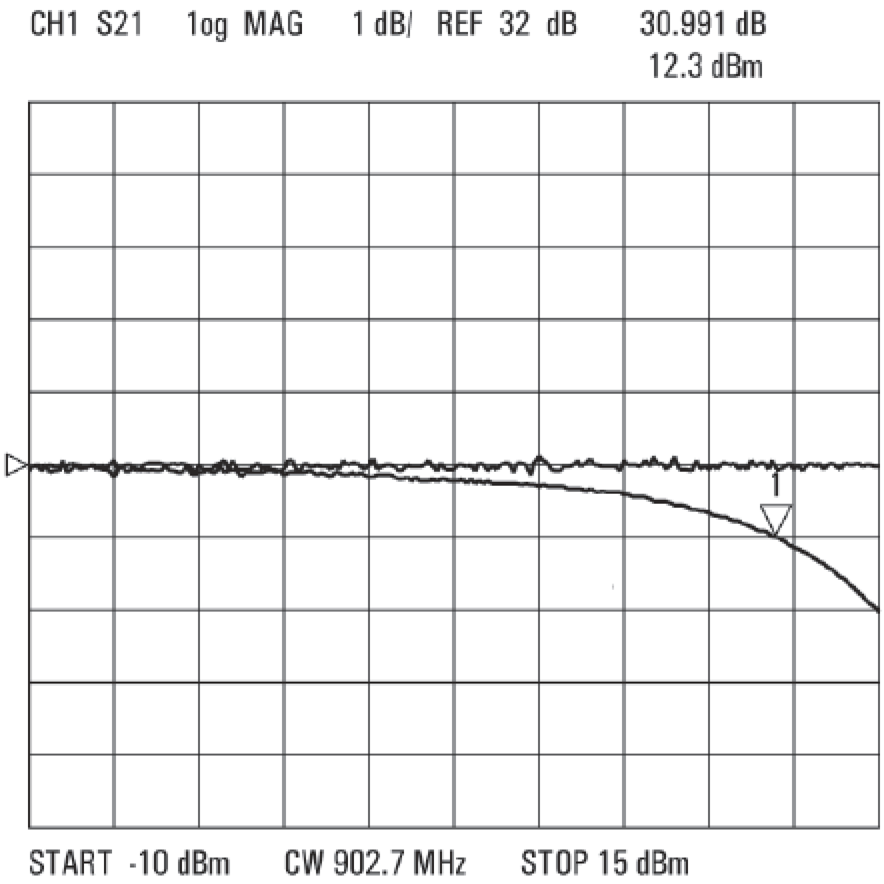


TM 2018

Power Sweeps – Compression



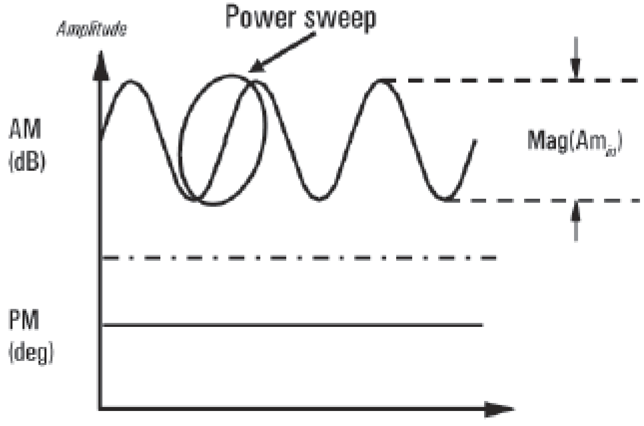
Power Sweep – Gain Compression



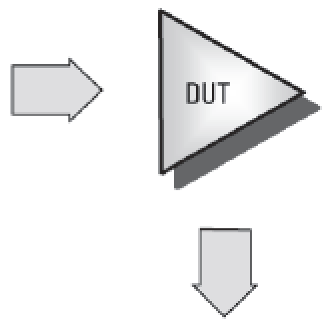
1 dB compression: input power resulting in 1 dB *drop* in gain

AM to PM Conversion

Measure of phase deviation caused by amplitude variations

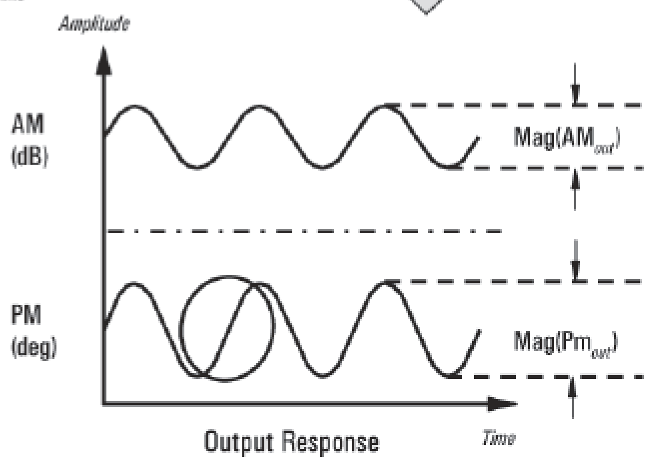


Test Stimulus

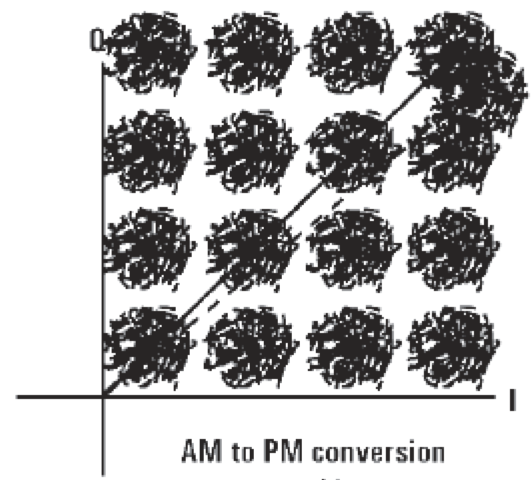


- AM can be undesired: supply ripple, fading, thermal
- AM can be desired: modulation (e.g. QAM)

$$\text{AM - PM Conversion} = \frac{\text{Mag}(Pm_{out})}{\text{Mag}(Am_{in})} \ (\text{deg/dB})$$

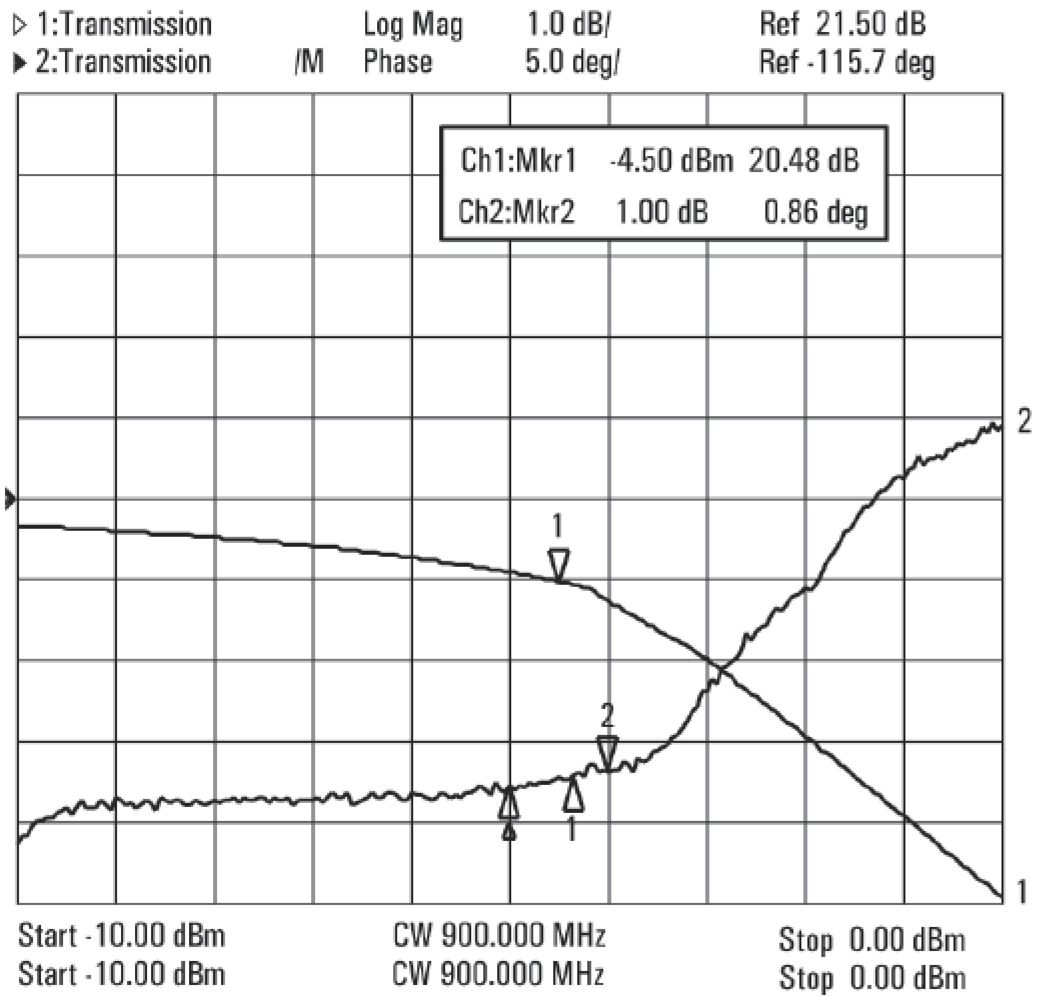


Output Response



AM to PM conversion can cause bit errors

Measuring AM to PM Conversion



- Use transmission setup with a power sweep
- Display phase of S21
- AM - PM = 0.86 deg/dB

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