Method for the Determination of the Optimal Noise Parameters from SPICE Simulations

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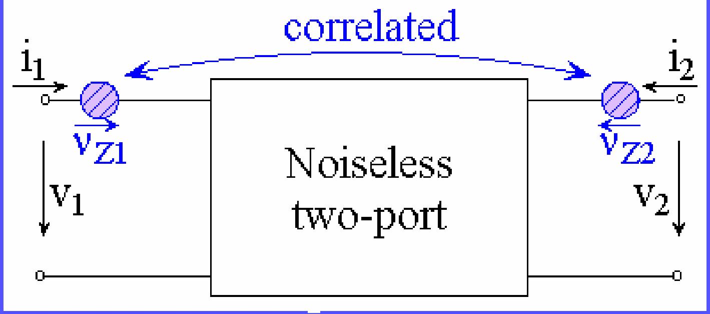
Purpose

- Method for extending circuit simulators' capability to perform direct noise parameter determination
- Integrating the calculus in *CADENCE* environment

Outline

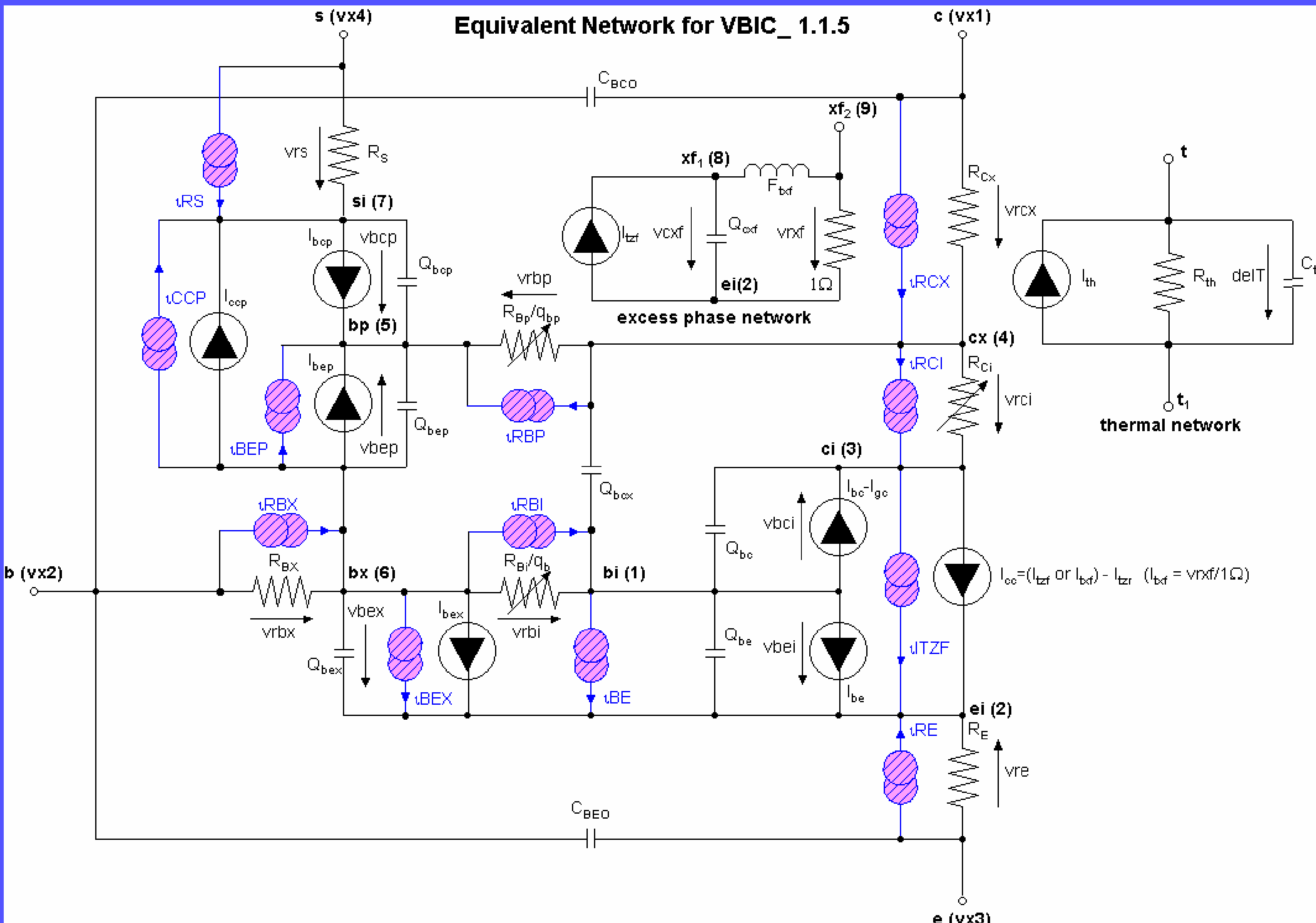
- Noise analysis limitation in recent circuit simulators
- Noise correlation basics
- Determination of the missing cross correlation term

Limitations



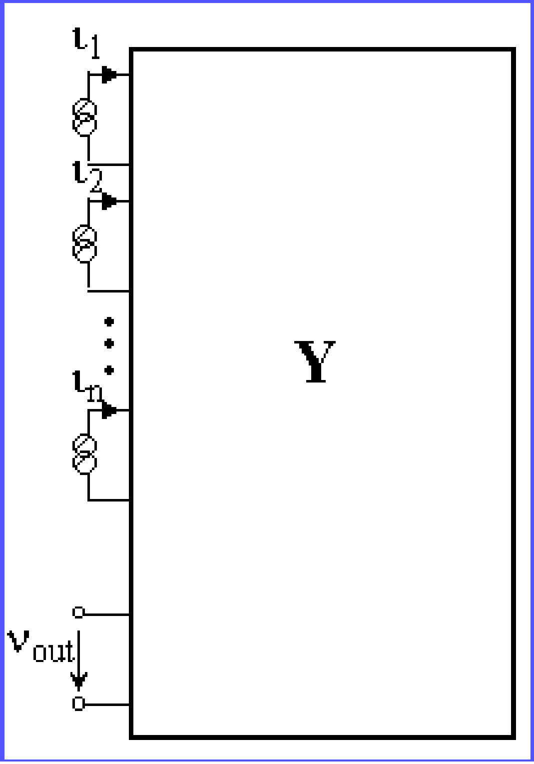
- general noisy two-port has correlated noise sources
- circuit simulators compute an autocorrelation term only
- noise parameters can not be directly obtained in absence of cross-correlation information
- suggested optimization is long and inconvenient to configure
- designers' choice: simplified models for *input* transistor

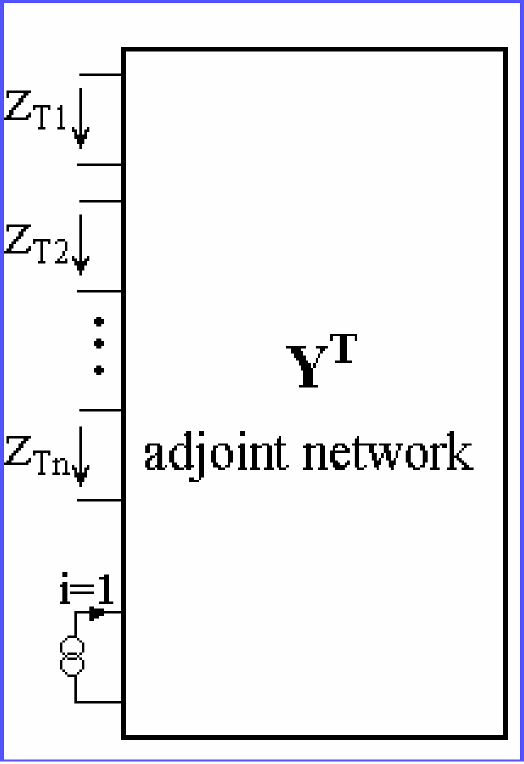
Noise Sources in VBIC

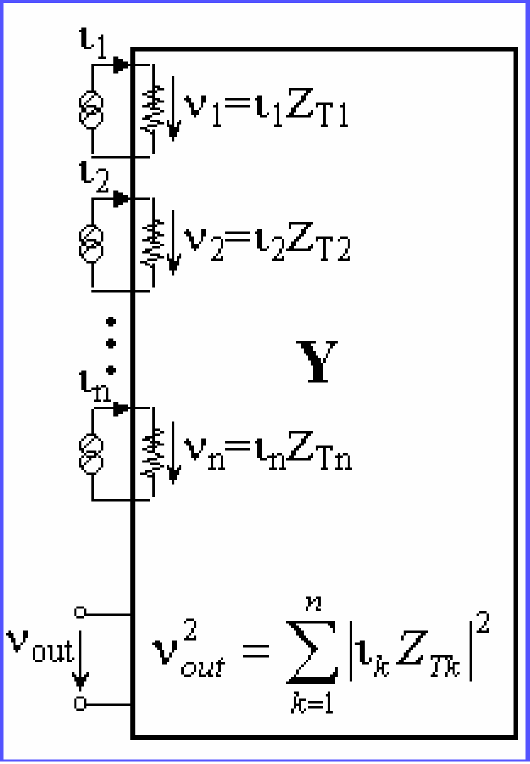


State-of-Art Noise Evaluation

- Nodal admittance matrices of adjoints are transposes (adjoint: controlled source configurations “inverted”)
- Transfer impedance calculated by interreciprocity
- Transferred noise squares are superimposed







Evens and Odds

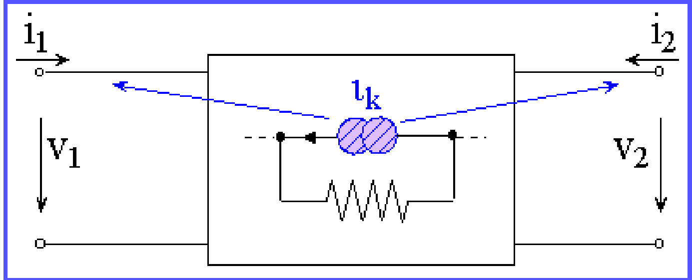
Efficiencies

- Inverse matrix of transpose is the transpose of the inverse: only one matrix inversion is necessary
- Determination of all transfer impedance is performed in one step
- Noise calculation is reduced to a set of multiplication followed by superposition at the output

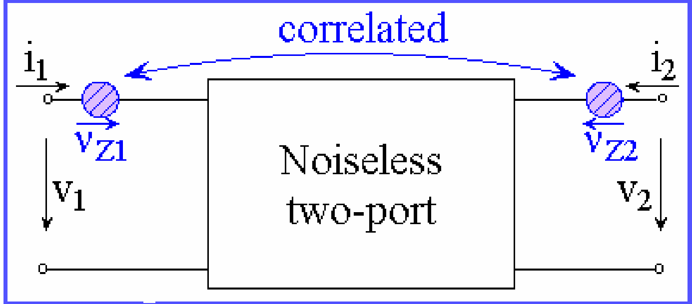
Deficiencies

- Correlation of noise sources (e.g. Ib-Ic) can not be handled
- *Optimization* is to be used for noise parameter determination

Two-Port Noise



Noise is propagating to terminals through internal network elements



Internal noise represented by two *correlated* terminal noise sources

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \mathbf{Z} \cdot \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} v_{Z1} \\ v_{Z2} \end{bmatrix}$$

Small signal parameter (SSP) description is necessary but insufficient

Noise Correlation Matrix (NCM)

$$\mathbf{C}_Z = \frac{1}{2\Delta f}\left\langle \begin{bmatrix} v_{Z1} \\ v_{Z2} \end{bmatrix} \cdot \begin{bmatrix} v_{Z1} \\ v_{Z2} \end{bmatrix}^H \right\rangle = \frac{1}{2\Delta f}\left\langle \begin{bmatrix} v_{Z1} \\ v_{Z2} \end{bmatrix} \cdot \begin{bmatrix} v_{Z1}^* & v_{Z2}^* \end{bmatrix} \right\rangle = \frac{1}{2\Delta f}\begin{bmatrix} \langle v_{?1} v_{Z1}^* \rangle & \langle v_{?1} v_{Z2}^* \rangle \\ \langle v_{?2} v_{Z1}^* \rangle & \langle v_{?2} v_{Z2}^* \rangle \end{bmatrix}$$

$\langle v_{Z1} v_{Z1}^* \rangle, \langle v_{Z2} v_{Z2}^* \rangle$ diagonal elements: autocorrelation of equivalent noise sources (real powers)

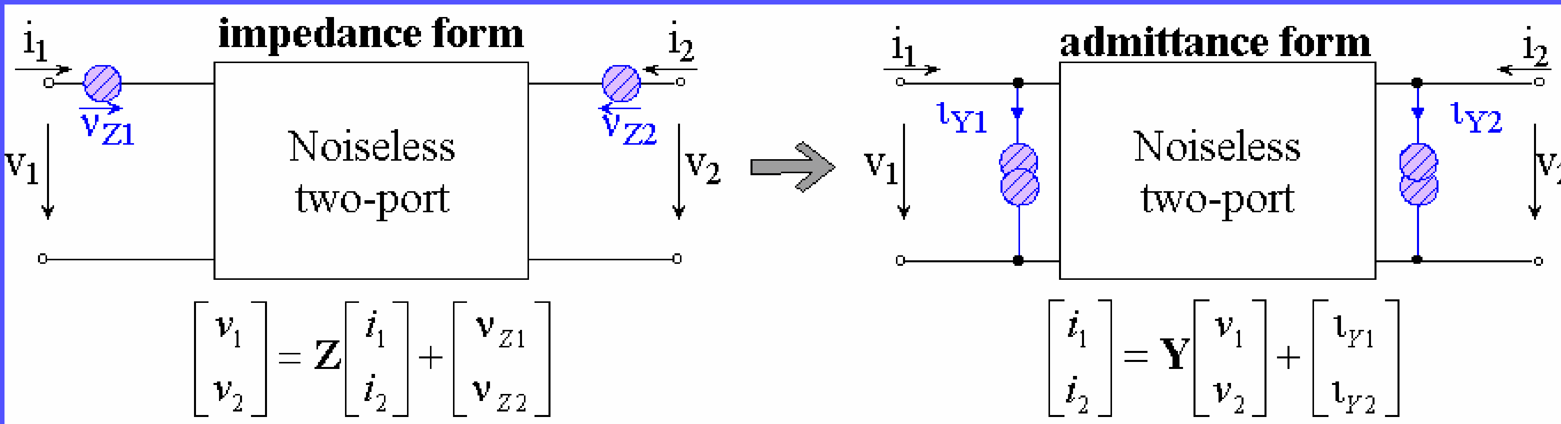
$\langle v_{Z1} v_{Z2}^* \rangle, \langle v_{Z2} v_{Z1}^* \rangle$ off-diagonals: cross-correlation of eq. noise sources (complex powers)

noiseless two-ports: *one single SSP matrix*

noisy two-ports: *a pair of NCM and SSP matrices*

Elements of C_Z: power spectral densities (PSD, S_x) [V^2/Hz], [A^2/Hz] or [VA/Hz]

Noise Correlation Matrix: Conversion



set $i_1=i_2=0$ in Z and substitute the voltage vector in Y

$$\begin{bmatrix} \iota_{Y1} \\ \iota_{Y2} \end{bmatrix} = -\mathbf{Y} \begin{bmatrix} v_{Z1} \\ v_{Z2} \end{bmatrix}$$

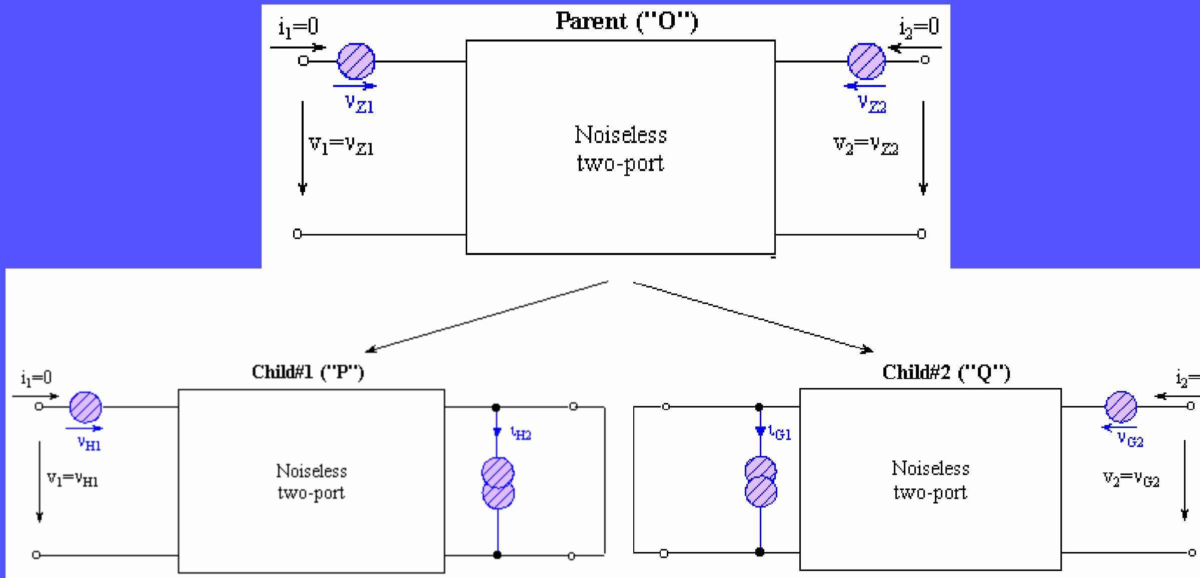
$$\mathbf{C}_Y = \left\langle \begin{bmatrix} \iota_{Y1} \\ \iota_{Y2} \end{bmatrix} \cdot \begin{bmatrix} \iota_{Y1} \\ \iota_{Y2} \end{bmatrix}^H \right\rangle = \mathbf{Y}\mathbf{C}_Z\mathbf{Y}^H$$

General transformation P® Q

$$\mathbf{C}_Q = \mathbf{T}_{P2Q}\mathbf{C}_P\mathbf{T}_{P2Q}^H$$

Concept

compute the two autocorrelation terms of Parent



compute one autocorrelation term of Child#1

compute one autocorrelation term of Child#2

connect values by NCM transformation formulae

Details

NCM transformation O to P $\mathbf{C}_P = \mathbf{T}_{O2P}\mathbf{C}_O\mathbf{T}_{O2P}^H$ $\mathbf{T}_{O2P} = \begin{bmatrix} t_{p11} & t_{p12} \\ t_{p21} & t_{p22} \end{bmatrix}$

Parent: $2\Delta f\mathbf{C}_O = \begin{bmatrix} d_{o11} & d_{o12} \\ d_{o21} & d_{o22} \end{bmatrix}$ SPICE returns d_{o11} , d_{o22}

d_{p11} can be obtained from Child#1 by SPICE.

Alternatively, by NCM transformation from Parent:

$$d_{p11} = d_{o11}\left|t_{p11}\right|^2 + 2\Re(d_{o12}t_{p11}t_{p12}^*) + d_{o22}\left|t_{p12}\right|^2$$

d_{q22} can be obtained from Child#2 by SPICE.

Alternatively, by NCM transformation from Parent:

$$d_{q22} = d_{o11}\left|t_{q21}\right|^2 + 2\Re(d_{o12}t_{q21}t_{q22}^*) + d_{o22}\left|t_{q22}\right|^2$$

Details (*cont.*)

$$d_{p11} = d_{o11}\left|t_{p11}\right|^2 + 2\Re(d_{o12}t_{p11}t^*_{p12}) + d_{o22}\left|t_{p12}\right|^2 \quad m_1 = \frac{1}{2}\left(d_{p11} - d_{o11}\left|t_{p11}\right|^2 - d_{o22}\left|t_{p12}\right|^2\right)$$

$$d_{q22} = d_{o11}\left|t_{q21}\right|^2 + 2\Re(d_{o12}t_{q21}t^*_{q22}) + d_{o22}\left|t_{q22}\right|^2 \quad m_2 = \frac{1}{2}\left(d_{q22} - d_{o11}\left|t_{q21}\right|^2 - d_{o22}\left|t_{q22}\right|^2\right)$$

Unknown off-diagonal element d_{o12} of Parent results as

$$d_{o12} = j\,\frac{m_2 t^*_{p11} t_{p12} - m_1 t_{q22} t^*_{q21}}{\Im(t_{p11} t^*_{p12} t_{q22} t^*_{q21})}$$

Noise parameters can now be calculated from known NCM of Parent

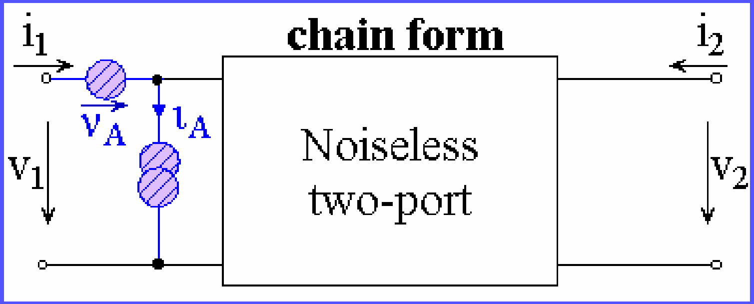
Allowed Configurations *(1…4)*

Parent	Child#1	Child#2
Z $d_{Z11} = \langle \nu_{Z1}\nu^*_{Z1}\rangle; \quad d_{Z22} = \langle \nu_{Z}$ $\mathbf{T}_{Z2A} = \begin{bmatrix} 1 & -a_{12} \\ 0 & -a_{22} \end{bmatrix}$	**Y** $d_{Y11} = \langle \iota_{Y1}\iota^*_{Y1}\rangle; \quad d_{Y22} = \langle \iota_{Y2}\iota^*_{Y2}\rangle$ $\mathbf{T}_{Z2Y} = -\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$	
Z $d_{Z11} = \langle \nu_{Z1}\nu^*_{Z1}\rangle; \quad d_{Z22} = \langle \nu_{Z}$ $\mathbf{T}_{Z2A} = \begin{bmatrix} 1 & -a_{12} \\ 0 & -a_{22} \end{bmatrix}$	**H** $d_{H11} = \langle \nu_{H1}\nu^*_{H1}\rangle$ $\mathbf{T}_{Z2H} = \begin{bmatrix} 1 & -h_{12} \\ 0 & -h_{22} \end{bmatrix}$	**G** $d_{G22} = \langle \nu_{G2}\nu^*_{G2}\rangle$ $\mathbf{T}_{Z2G} = \begin{bmatrix} -g_{11} & 0 \\ -g_{21} & 1 \end{bmatrix}$
Y $d_{Y11} = \langle \iota_{Y1}\iota^*_{Y1}\rangle; \quad d_{Y22} = \langle \iota_{Y2}$ $\mathbf{T}_{Y2A} = \begin{bmatrix} 0 & a_{12} \\ 1 & a_{22} \end{bmatrix}$	**Z** $d_{Z11} = \langle \nu_{Z1}\nu^*_{Z1}\rangle; \quad d_{Z22} = \langle \nu_{Z2}\nu^*_{Z2}\rangle$ $\mathbf{T}_{Y2Z} = -\begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix}$	
Y $d_{Y11} = \langle \iota_{Y1}\iota^*_{Y1}\rangle; \quad d_{Y22} = \langle \iota_{Y2}$ $\mathbf{T}_{Y2A} = \begin{bmatrix} 0 & a_{12} \\ 1 & a_{22} \end{bmatrix}$	**G** $d_{G11} = \langle \iota_{G1}\iota^*_{G1}\rangle$ $\mathbf{T}_{Y2G} = \begin{bmatrix} 1 & -g_{12} \\ 0 & -g_{22} \end{bmatrix}$	**H** $d_{H22} = \langle \iota_{H2}\iota^*_{H2}\rangle$ $\mathbf{T}_{Y2H} = \begin{bmatrix} -h_{11} & 0 \\ -h_{21} & 1 \end{bmatrix}$

Allowed Configurations *(5…8)*

Parent	Child#1	Child#2
H $d_{H11} = \left\langle \nu_{H1}\nu^{*}_{H1} \right\rangle; \quad d_{H22} = \left\langle \iota_{H}\right.$ $\mathbf{T}_{H2A} = \begin{bmatrix} 1 & a_{12} \\ 0 & a_{22} \end{bmatrix}$	**G** $d_{G11} = \left\langle \iota_{G1}\iota^{*}_{G1} \right\rangle; \quad d_{G22} = \left\langle \nu_{G2}\nu^{*}_{G2} \right\rangle$ $\mathbf{T}_{H2G} = -\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}$	
H $d_{H11} = \left\langle \nu_{H1}\nu^{*}_{H1} \right\rangle; \quad d_{H22} = \left\langle \iota_{H}\right.$ $\mathbf{T}_{H2A} = \begin{bmatrix} 1 & a_{12} \\ 0 & a_{22} \end{bmatrix}$	**Z** $d_{Z11} = \left\langle \nu_{Z1}\nu^{*}_{Z1} \right\rangle$ $\mathbf{T}_{H2Z} = \begin{bmatrix} 1 & -z_{12} \\ 0 & -z_{22} \end{bmatrix}$	**Y** $d_{Y22} = \left\langle \iota_{Y2}\iota^{*}_{Y2} \right\rangle$ $\mathbf{T}_{H2Y} = \begin{bmatrix} y_{11} & 0 \\ y_{21} & 1 \end{bmatrix}$
G $d_{G11} = \left\langle \iota_{G1}\iota^{*}_{G1} \right\rangle; \quad d_{G22} = \left\langle \nu_{G}\right.$ $\mathbf{T}_{G2A} = \begin{bmatrix} 0 & -a_{11} \\ 1 & -a_{21} \end{bmatrix}$	**H** $d_{H11} = \left\langle \nu_{H1}\nu^{*}_{H1} \right\rangle; \quad d_{H22} = \left\langle \iota_{H2}\iota^{*}_{H2} \right\rangle$ $\mathbf{T}_{G2H} = -\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$	
G $d_{G11} = \left\langle \iota_{G1}\iota^{*}_{G1} \right\rangle; \quad d_{G22} = \left\langle \nu_{G}\right.$ $\mathbf{T}_{G2A} = \begin{bmatrix} 0 & -a_{11} \\ 1 & -a_{21} \end{bmatrix}$	**Y** $d_{Y11} = \left\langle \iota_{Y1}\iota^{*}_{Y1} \right\rangle$ $\mathbf{T}_{G2Y} = \begin{bmatrix} 1 & -y_{12} \\ 0 & -y_{22} \end{bmatrix}$	**Z** $d_{Z22} = \left\langle \nu_{Z2}\nu^{*}_{Z2} \right\rangle$ $\mathbf{T}_{G2Z} = \begin{bmatrix} -z_{11} & 0 \\ -z_{21} & 1 \end{bmatrix}$

Noise Factor



$$\mathbf{C}_A = \begin{bmatrix} \langle \nu_A \nu_A^* \rangle & \langle \nu_A \iota_A^* \rangle \\ \langle \iota_A \nu_A^* \rangle & \langle \iota_A \iota_A^* \rangle \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{12}^* & c_{22} \end{bmatrix}$$

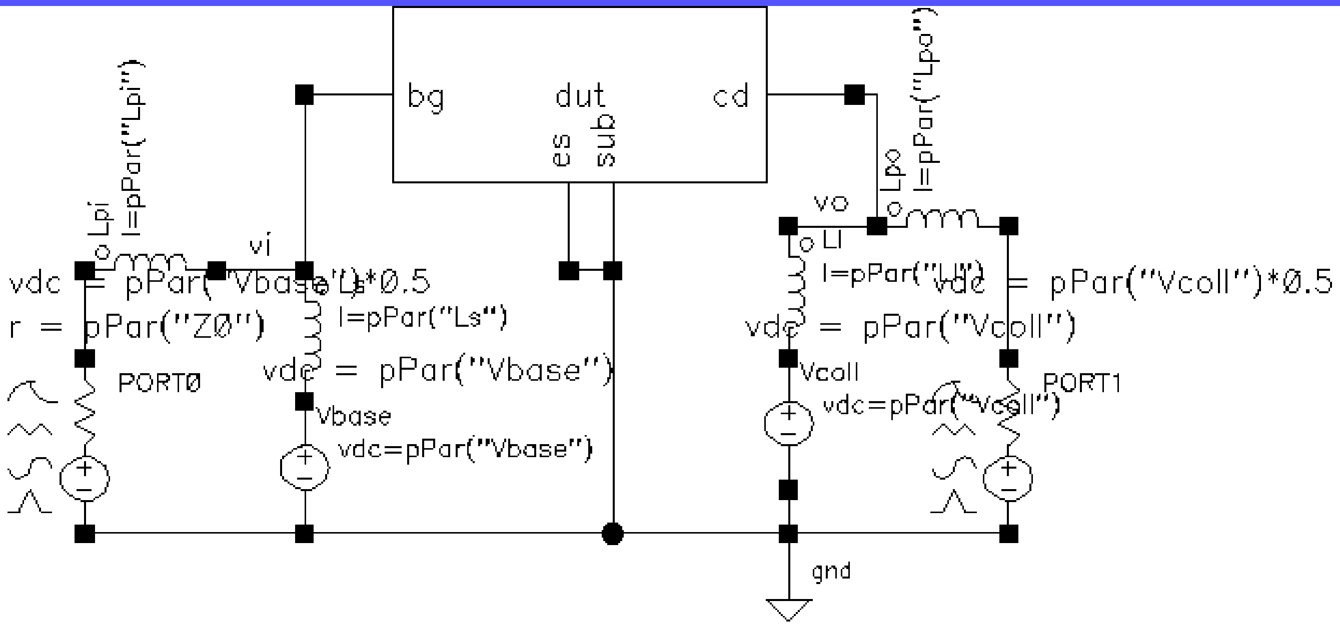
Noise parameters from chain noise correlation matrix

$$B_{Sopt} = \Im\left(\frac{c_{12}}{c_{11}}\right); \quad G_{Sopt} = \sqrt{\frac{c_{22}}{c_{11}} - B_{Sopt}^2}; \quad R_n = \frac{c_{11}}{2kT}; \quad F_{\min} = 1 + \frac{1}{kT}\left[\Re(c_{12}) + c_{11} G_{Sopt}\right]$$

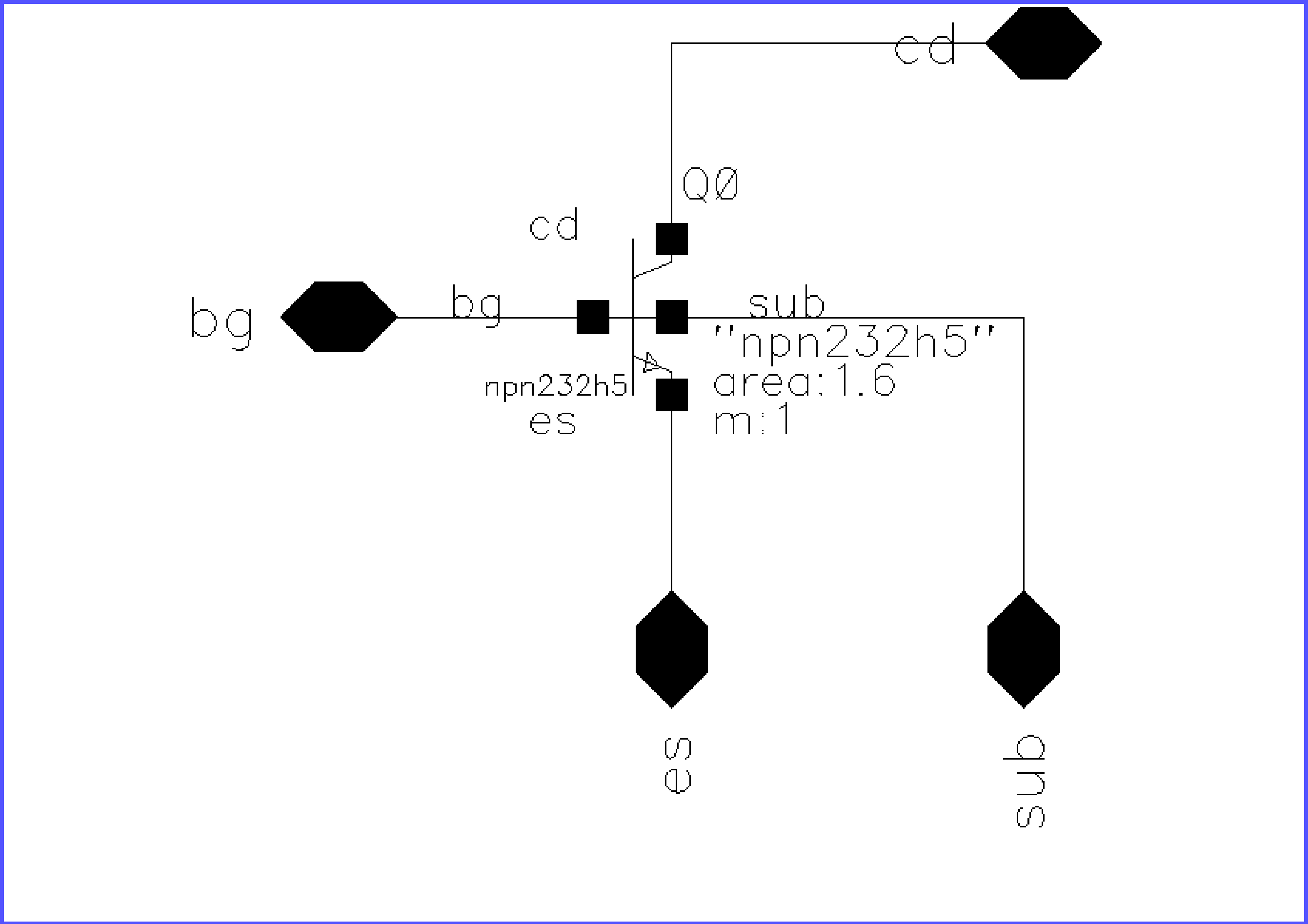
PROCEDURE CODED IN *OCEAN-SCRIPT*

(CADENCE)

Simulation Schematic



Subcircuit for the DUT



Spot Noise Report

```
=================================================================
                        npn232_1.6HV
=================================================================
                GLOBAL NOISE MINIMUM CONDITIONS
======================= fixed parameters =======================
Vce=           2              V
frequency=     2e9            Hz
tamb=          27             C
=================== minimum noise parameters ===================
NFmin=         438.7e-3       dB
Rsopt=         5.83e3         ohms
Xsopt=         354.6e-9       H
Rn=            290.2          ohms
G_att=         19.12          dB
Vbe=           833.3e-3       V
Ib=            224.3e-9       A
Ic=            77.11e-6       A
mZ0=           116.6          (# of instances for Z0 match)
IcZ0=          8.991e-3       A
XsoptZ0=       3.041e-9       H
=================================================================
NFmin_bcksim=  453.3e-3       dB
============ ohmic source minimum noise parameters =============
NFminR=        595.3e-3       dB
RsoptR=        2.472e3        ohms
GattR=         19.78          dB
Vbe=           862.1e-3       V
Ib=            545.3e-9       A
Ic=            194.2e-6       A
mZ0R=          49.43          (# of instances for Z0 match)
IcZ0R=         9.599e-3       A
=================================================================
NFmin_bcksimR= 614.8e-3       dB
=================================================================
```

Min. Noise Figure and Associated Gain

Summary

- Noise parameter computation SPICE simulators
- Cross-correlation term by the involvement of SSPs
- Full noise correlation matrix recovery
- 8 allowed combinations to select from
- Method is applicable to all circuit blocks