Modeling and Synthesis of Transmission Line for Multi-Channel Communications

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Outline

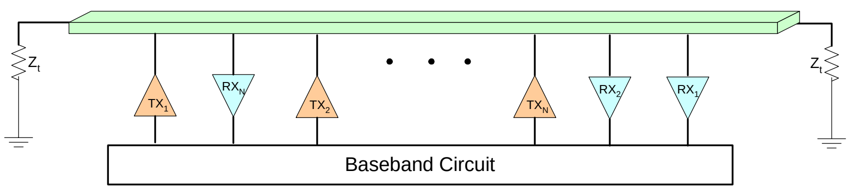
- Introduction
- Frequency domain models for multi-port transmission lines
  - Voltage response
  - SNR model
  - Signal distortion metrics
- Synthesis of RF interconnects
- Conclusion

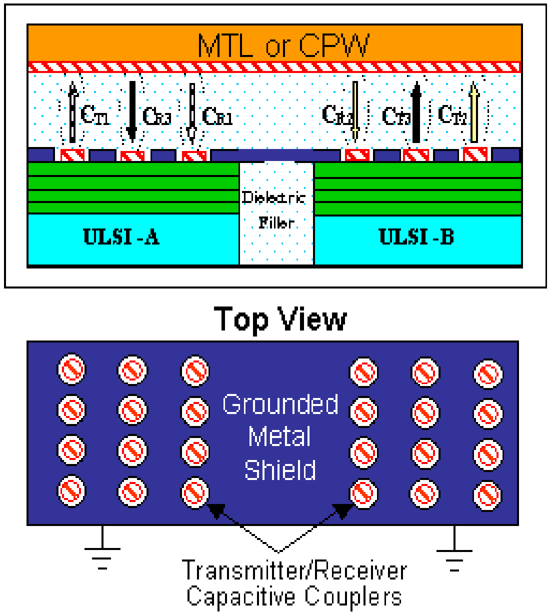
Introduction

- Traditional interconnects
  - Inherent signal distortion
  - Large RC delay
- Digital communication via transmission lines
  - Transmit baseband digital signals
  - Transmit digital signals via high frequency carriers
    - Example: RF interconnects

RF Interconnects

- Transmit signals via high-frequency carrier signals
  - CPW/MTL transmission line
  - Analog modulators and demodulators
  - Capacitive couplers





- Advantages:
  - Multiple accesses: FDMA, CDMA
  - Reconfigurable: CDMA
  - High speed: close to speed of light
  - Lower distortion
  - Immune to digital switching noise

Design of RF Interconnects

- Manual designs
  - RF modulated clock tree on PCB [Ryu et. al. 2002]
  - Single link on-chip RF interconnect [Shin and Chang 2002]

- Limitations in manual design
  - Overdesign leads to Large interconnect area
  - Hard to consider multiple ports and branches
  - Long design cycle

Need automatic synthesis

Our Contributions

- Closed-form SNR models
  - Multiple ports
  - Branches
  - Terminations
- Signal distortion metrics
  - Amplitude
  - Phase delay
- Automatic synthesis of RF interconnects
  - Minimize area under SNR and signal distortion constraints

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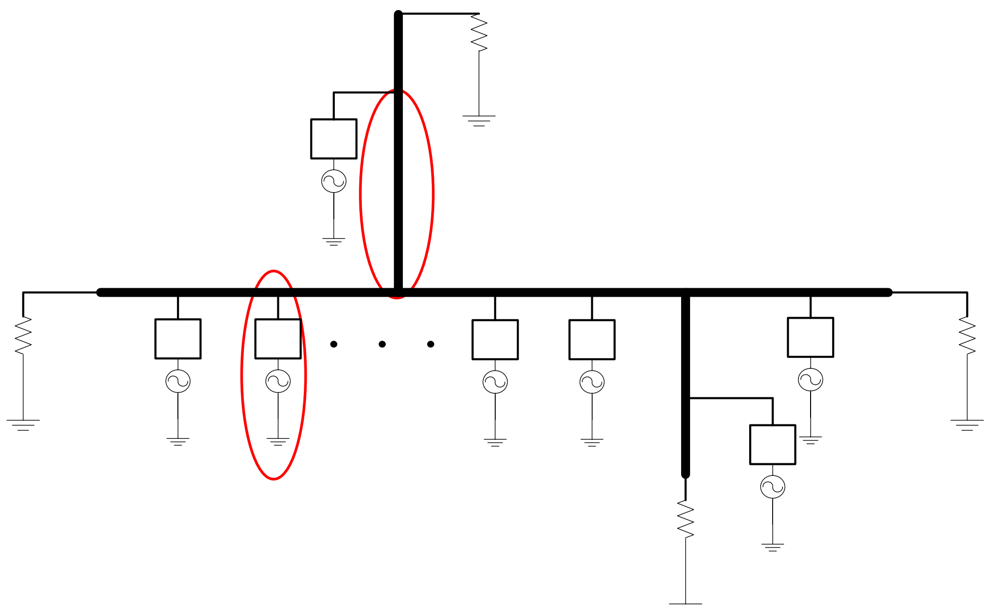
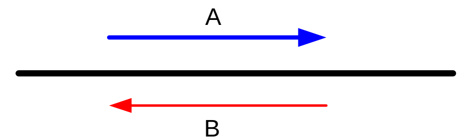
Circuit Model

- Uniform transmission line model between discontinuities
  - Discontinuities: ports, junctions and terminations
- Linear transceiver model
  - Impedance and voltage source
- Model each frequency channel in frequency domain
  - Multiple frequency channels



Equations for Voltage Response

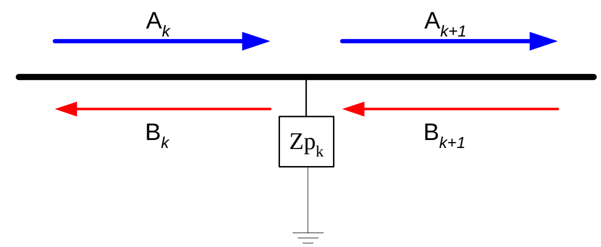
- Each segment between adjacent discontinuities is a transmission line



$$V(x) = A\exp(-\gamma(x - x_k)) + B\exp(\gamma(x - x_k))$$

$$I(x) = A/Z_0 \exp(-\gamma(x - x_k)) - B/Z_0 \exp(\gamma(x - x_k))$$

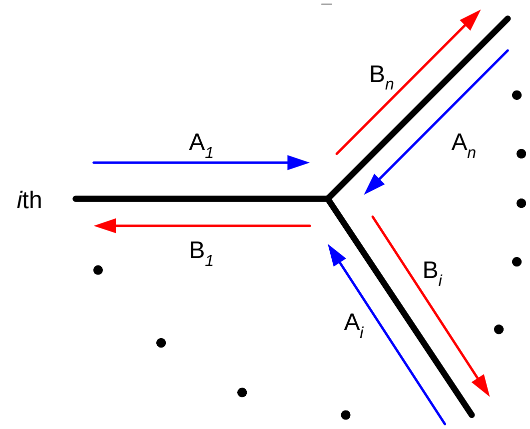
- At each port



$$V_k(x_k) = V_{k+1}(x_k)$$

$$Z_{pk}(I_k(x_k) - I_{k+1}(x_k)) = V_k(x_k) - V_{pk}$$

- At each branching point



$$\sum_{i=1} (A_i / Z_i - B_i / Z_i) = 0$$

$$A_i + B_i = A_j + B_j$$

- At each termination

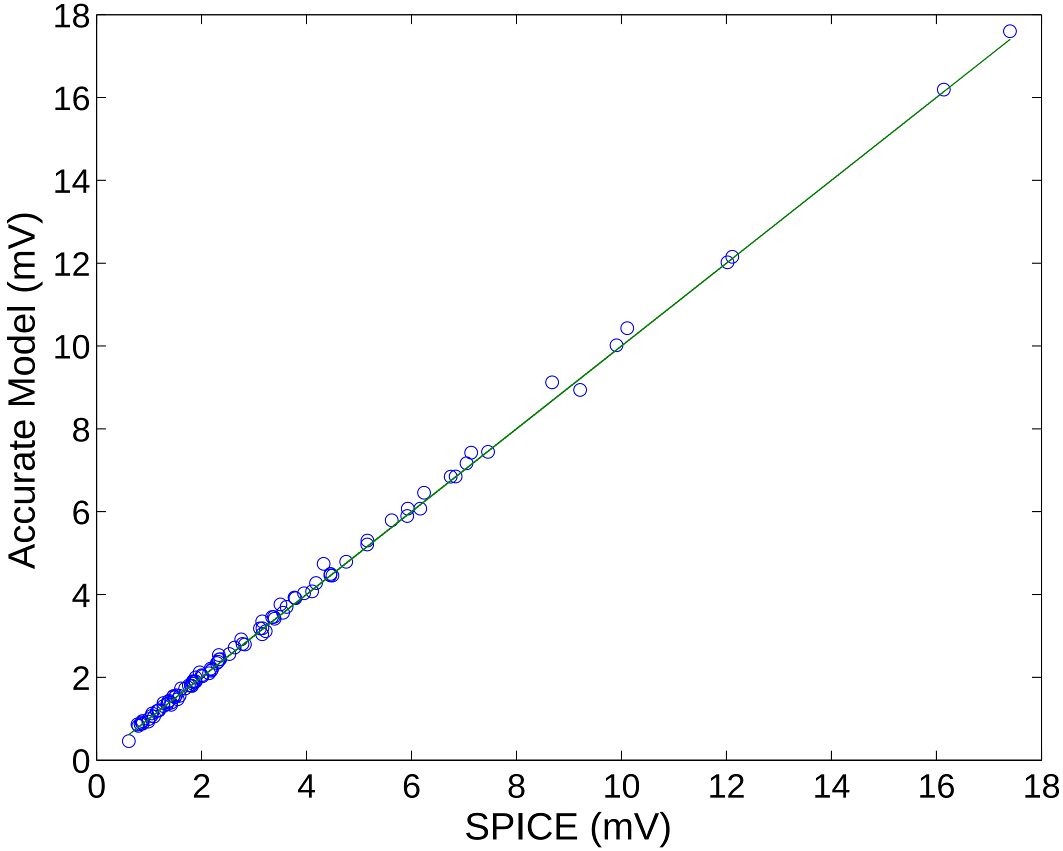
$$\frac{B}{A} = \frac{Z_0 - Z_t}{Z_0 + Z_t}$$

System Matrix

- Sparse band matrix
  - 2n+2b variables with n ports and b branches
  - Complexity of O(n+b)
- Two-port line

$$
\begin{bmatrix}
1-\gamma_1\frac{Z_s}{Z_0} & 1+\gamma_1\frac{Z_s}{Z_0}e^{-\ell_1} & 0 & 0 & 0 & 0 \\
e^{-\gamma\ell_1} & 1 & -1 & -e^{-\gamma\ell_2} & 0 & 0 \\
-\gamma\frac{Z_{p1}}{Z_0}e^{-\gamma\ell_1} & \gamma\frac{Z_{p1}}{Z_0} & 1+\gamma\frac{Z_{p1}}{Z_0} & (1-\gamma\frac{Z_{p1}}{Z_0})e^{-\gamma\ell_2} & 0 & 0 \\
0 & 0 & e^{-\gamma\ell_2} & 1 & -1 & -e^{-\gamma\ell_3} \\
0 & 0 & -\gamma\frac{Z_{p2}}{Z_0}e^{-\gamma\ell_2} & \gamma\frac{Z_{p2}}{Z_0} & 1+\gamma\frac{Z_{p2}}{Z_0} & (1-\gamma\frac{Z_{p1}}{Z_0})e^{-\gamma\ell_3} \\
0 & 0 & 0 & 0 & (1-\gamma\frac{Z_{p3}}{Z_0})e^{-\gamma\ell_3} & 1+\gamma\frac{Z_{p3}}{Z_0}
\end{bmatrix}
\begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \end{bmatrix}
=
\begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
$$

Experiment Verification



- Highly accurate compared to SPICE simulations

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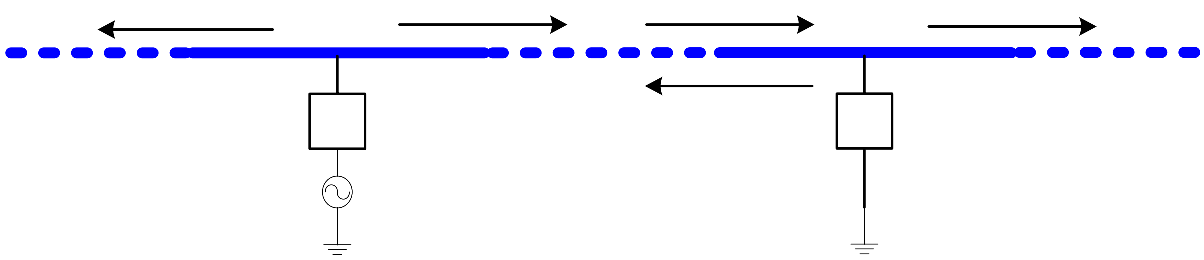
Model of One Segment

- First order approximation
- Ignoring reflections from other discontinuities

$$A_2 = \frac{Z_0/2}{Z_0/2 + Z_s} V_s \qquad A_3 = \frac{2A_2}{2 + Z_0/Z_r} \exp(-\gamma\ell) \qquad B_3 = -\frac{A_2}{1 + 2Z_r/Z_0} \exp(-\gamma\ell)$$

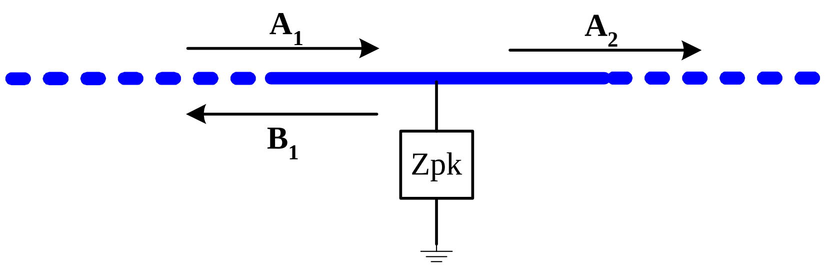
- Signal received by receiver

$$V_r = \frac{R_r Z_0/2}{(Z_0/2 + R_r + \frac{1}{j\omega C_r})(Z_0/2 + R_s + \frac{1}{j\omega C_s})} \exp(-\gamma\ell) V_s$$



Ports and Terminations

- Transmission rate of port k



$$\xi_k = \frac{2}{Z_0 / Z_{pk} + 2}$$

  - Z_{pk}: Impedance of port k
  - Z_0: Characteristic impedance of transmission line

- Reflection rate of port k

$$\rho_k = \frac{1}{1 + 2Z_{pk} / Z_0}$$

- Termination reflection rate:

$$\rho_t = \frac{Z_0 - Z_t}{Z_0 + Z_t}$$

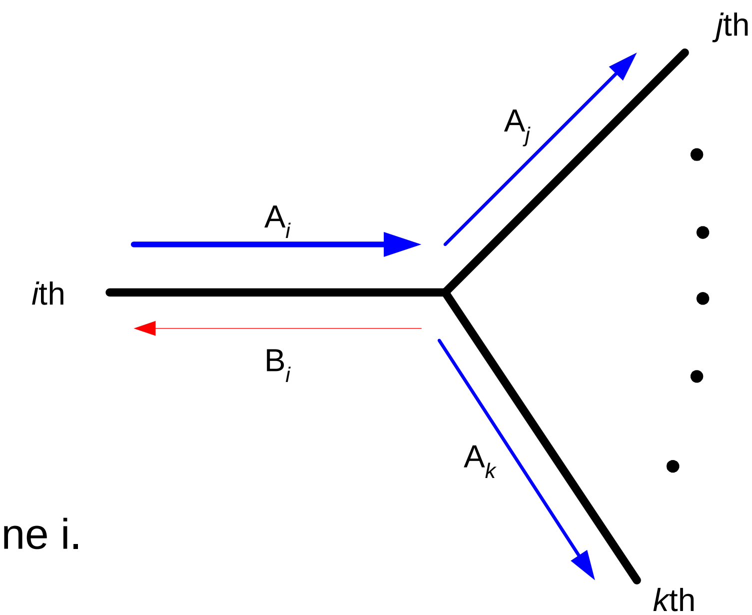
  - Z_t: Impedance of the termination

Branch Junction

- Reflection rate of branch i

$$\rho_i = \frac{Z_{ti} - Z_{0i}}{Z_{ti} + Z_{0i}}$$

  - Z_{ti}: $$Z_{ti} = \frac{1}{\sum_{j \neq i} 1/Z_{0j}}$$
  - Z_{0i}: Characteristic impedance of line i.



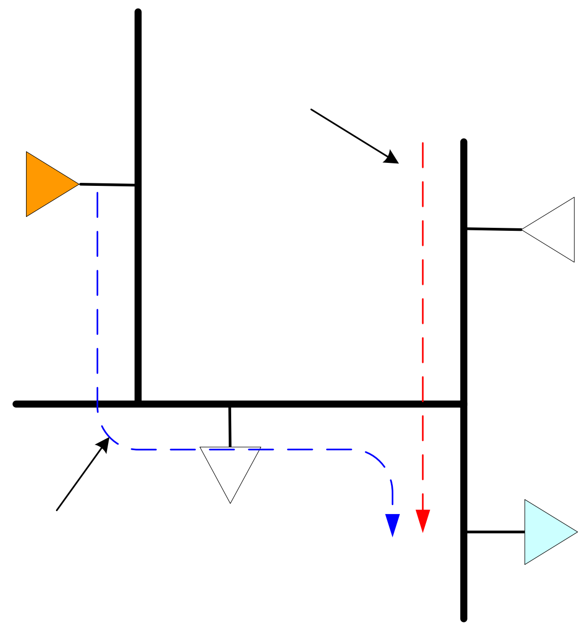
- Transmission rate to other branches:

$$\xi_i = \frac{2}{Z_{0i}/Z_{ti} + 2}$$

Signal-to-noise Ratio (SNR)

- Signal
  - Interconnect attenuation
  - Discontinuity reflection

$$V_s = k_{s,r} \prod_{i \in s \to r, i \neq s} \exp(-l_{i-1,i}\gamma_{i-1,i})\xi_i$$



- Reflection noise from discontinuities
  - Ports
  - Branches
  - Terminations

$$V_n = k_{s,r} \sum_{p \notin s \to r} \Big(\prod_{i \in s \to p, i \neq s} \exp(-l_{i-1,i}\gamma_{i-1,i})\xi_i \cdot \rho_p \cdot \prod_{j \in p \to r, j \neq p} \exp(-l_{j-1,j}\gamma_{j-1,j})\xi_j \Big)$$

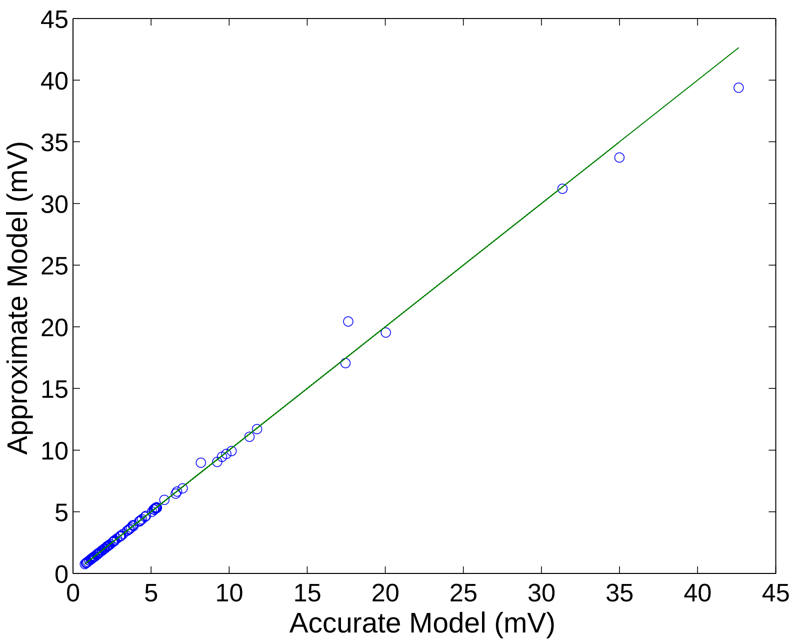
- SNR

$$SNR = 10\log\frac{V_s^2/2R_r}{V_n^2/2R_r + P_n}$$

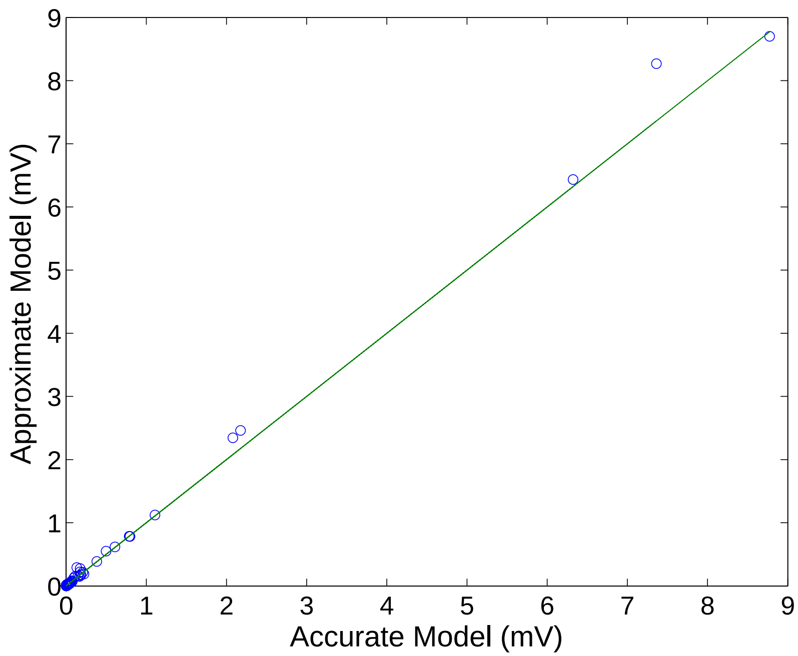
  - P_n: Intrinsic noise of transceivers

First order approximation

Model Verification



Received signal



Reflection noise

- Accurate compared to numerical model

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Distortion Metrics

- Distortionless signal requires uniform phase delay and attenuation in frequency channel
  - Phase delay metric

$$\frac{\left|P(\omega_0-\omega_b)-P(\omega_0)\right|}{T(\omega_b)}<0.01$$

    - P(ω): phase delay

$$P(\omega)=\frac{\Delta\phi(\omega)}{\omega}$$

  - Attenuation metric

$$\frac{\left|M(\omega_0-\omega_b)-M(\omega_0)\right|}{M(\omega_0)}<0.01$$

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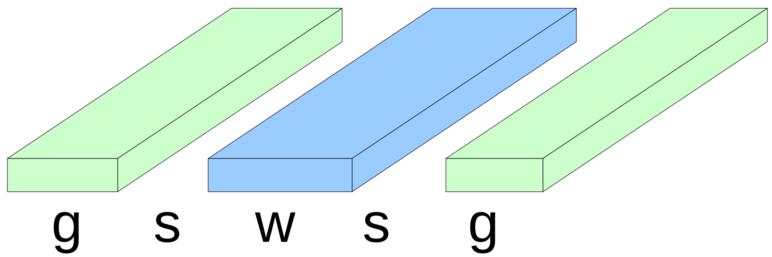
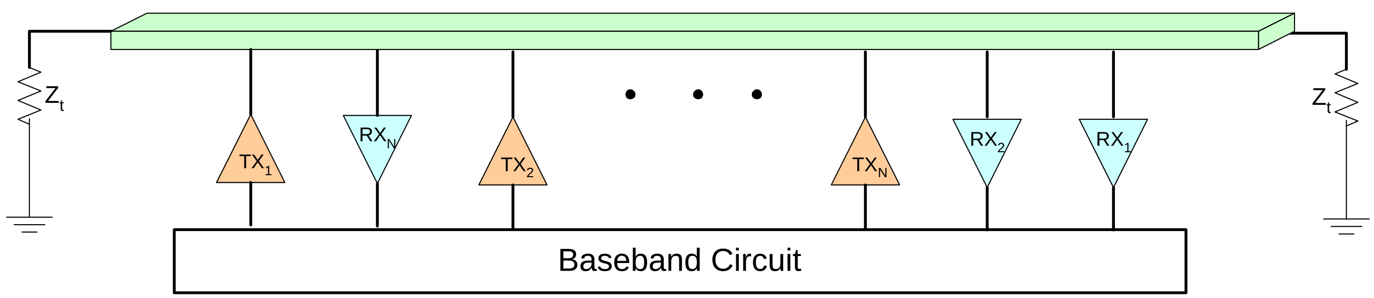
RF Interconnect

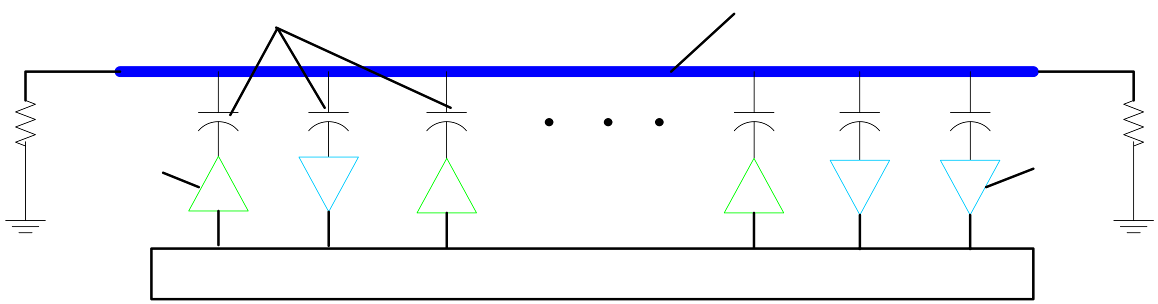
- Using coplanar waveguide (CPW)
  - Design freedoms: w, s, g, size of capacitive couplers
  - Design constraints: SNR and distortion





Problem Formulation

- Given
  - Interconnect topology, transceiver sizes, locations and intrinsic noise.
- Decide
  - CPW interconnect geometries and coupler sizes
- Minimize
  - Total area of the interconnect and couplers
- Such that at each receiver
  - Signal-to-noise ratio is larger than a given bound
  - Distortion is less than a given bound



Synthesis Algorithm

- Simulated annealing algorithm
- Objective function

$$F(w,s,g,C_i) = K_a A + \sum_i (K_s FS_i + K_{pd} FP_i + K_{ad} FA_i)$$

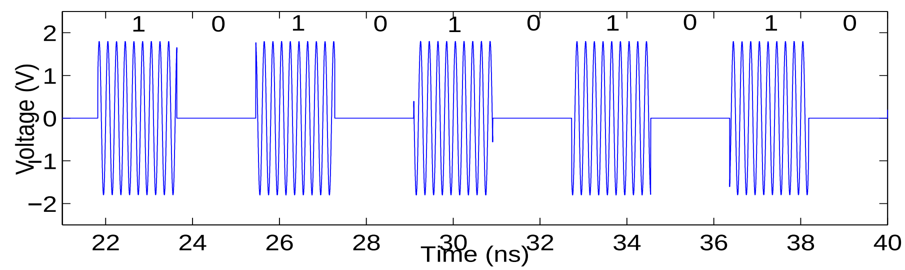
  - A: area
  - FS_i, FP_i and FA_i: penalty function of violation of SNR, phase delay variation and amplitude variation
  - K_a, K_s, K_{pd} and K_{ad}: weight factors
- Assuming uniform transceiver but non-uniform coupler

Synthesis Result: Two Ports and Two Channels

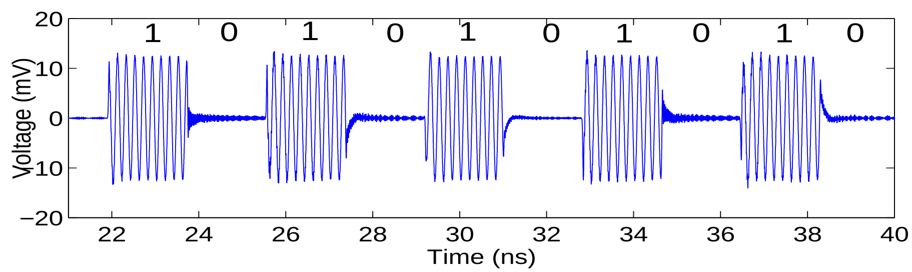
Design	w (um)	s (um)	g (um)	Total width (um)	C_s(fF)	C_r(fF)
manual	-	-	-	100	100	100
Synthesis	2.2	6.0	1.1	16.8	51	49

- Save 80% interconnect area compared to manual design [Chang et. al. 2001].

Input



Output



More Synthesis Results

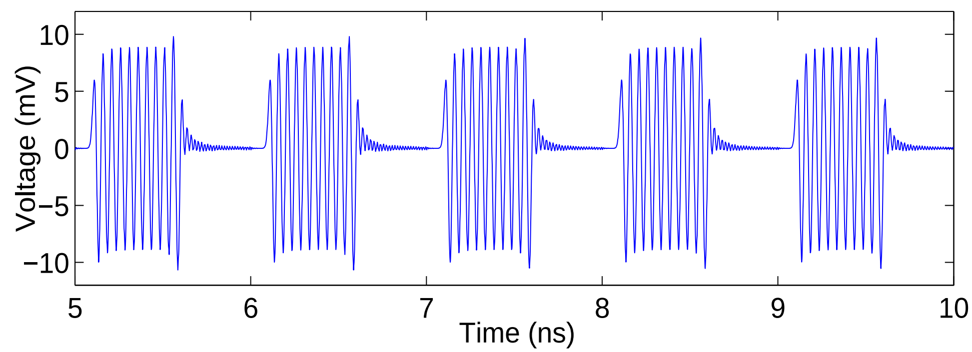
Ports	Channels	Rp(Ω)	l(cm)	Area(μm^2)	C_s(fF)	C_r(fF)
2	1	500	1	51069	24	21
2	1	1000	3	131100	35	30
40	5	500	1	65620	27	10
40	5	1500	1	145455	21	7

- Total area depends on specific design and can be up to 3x different.
- Coupler size varies greatly even in the same design and can be up to 20x different.
- When there are multiple ports, couplers for receivers are much smaller than those for transmitters.

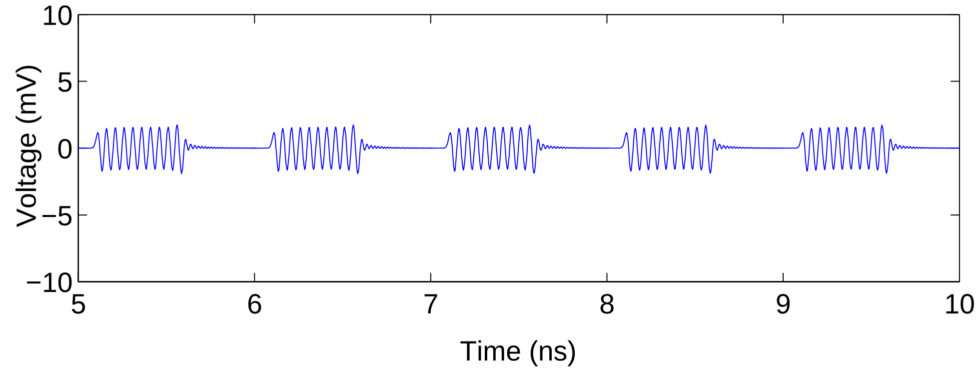
Mismatched Interconnects

- Mismatched interconnect leads to violation of constraints.

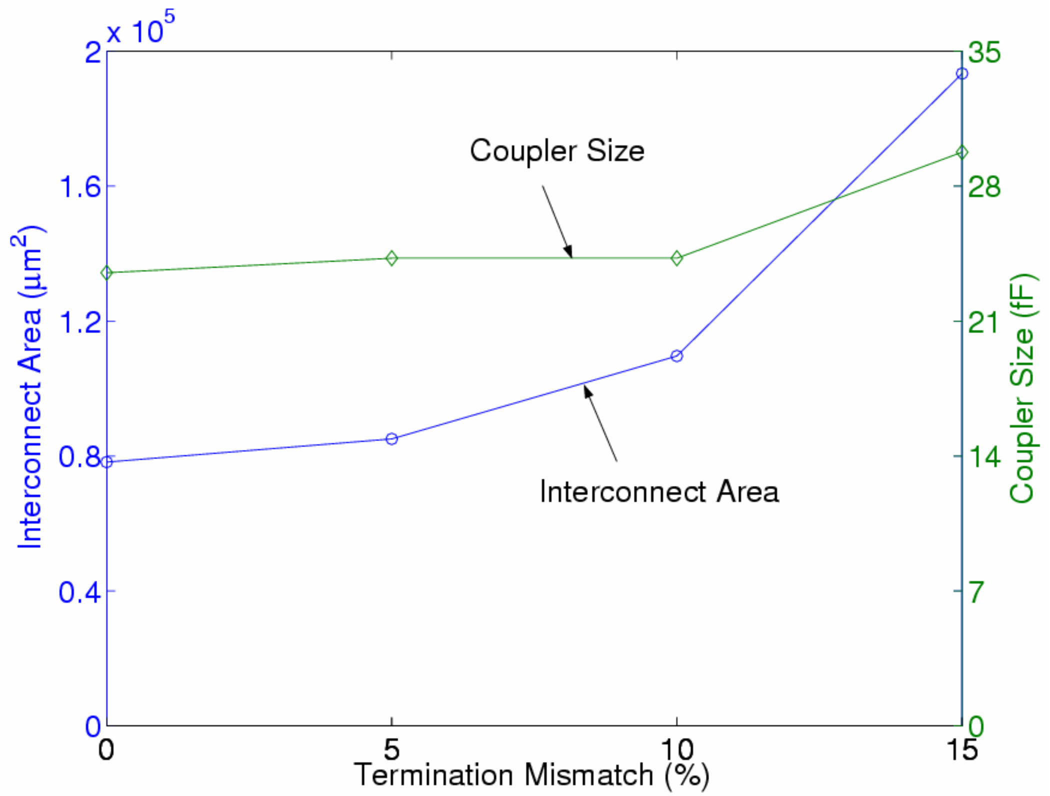
With matched interconnect



With mismatched interconnect



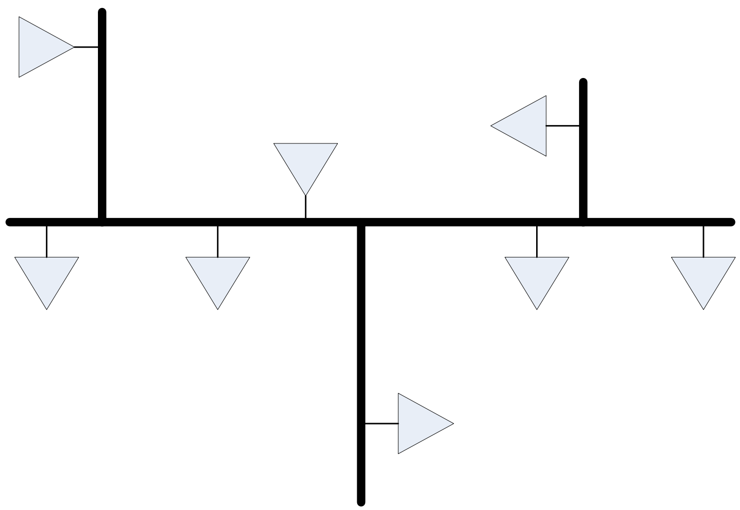
Imperfect Terminations



- Coupler size and interconnect area increase with the termination mismatch

Branched Coplanar Waveguide

Design	length (um)	w (um)	s (um)	g (um)	Total width (um)
AC	1000	0.5	5.1	0.1	5.6
BC	5000	2.7	6.1	1.5	9.3
CD	5000	5.8	2.3	2.3	10.4
DE	6000	1.8	6.1	0.9	8.8
DF	4000	6.4	3.4	2.2	12.0
FG	3000	0.8	8.0	0.3	9.1
FH	2000	2.3	10	1.1	13.4



Conclusion

- RF interconnect is a promising technique with multi-access capability
- We developed an accurate multi-port transmission line model for RF interconnects.
- We derived an efficient and accurate SNR model.
- We synthesized RF interconnects to minimize the total area under the constraints of SNR and distortion.

Thank you!