Comment #18
T-Coil Model for COM

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IEEE P802.3bs 400GbE Task Force
May 25-27, 2016 IEEE 802.3 interim meeting

Supporters

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Comment #18

Comment Type **TR** *Comment Status* **D**

The device capacitance C_d of 0.28pF causes too much reflection in COM model.

Just a lump capacitor is too simple and does not represent actual device characteristics with T-Coil (Termination Coil) which is commonly used in many actual devices at this high data rate.

SuggestedRemedy

Add T-Coil to the COM model.

A presentation to propose the detail model and parameters of T-Coil for COM will be given at the Task Force meeting in May 2016.

Overview

- T-Coil is not new. There is no secret.
  - US Patent 3,155,927 in 1964 [1]

- This proposal is a simple bridged-T T-Coil model that has been commonly used.

- For *any* given device capacitance C_d, we can always derive *ideal* parameter values that makes Z_{in} (the input impedance of the device) *resistive for all frequencies*.
  - *Perfect matching* with ideal parameter values: Too good for real devices.

- Parameter values are intentionally deviated from ideal values.
  - Make it realistic.

T-Coil has been known in public >50 years

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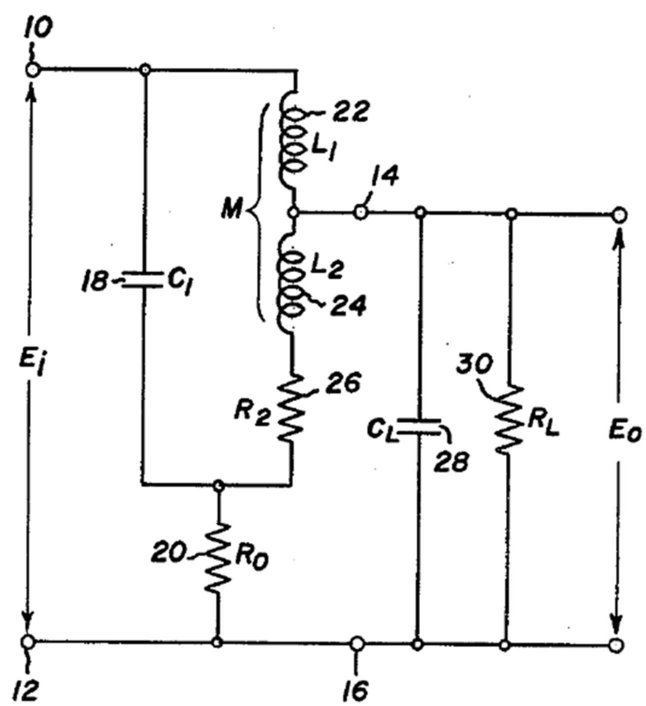
- US Patent 3,155,927 “Bridged-T Termination Network” issued in 1964 [1]

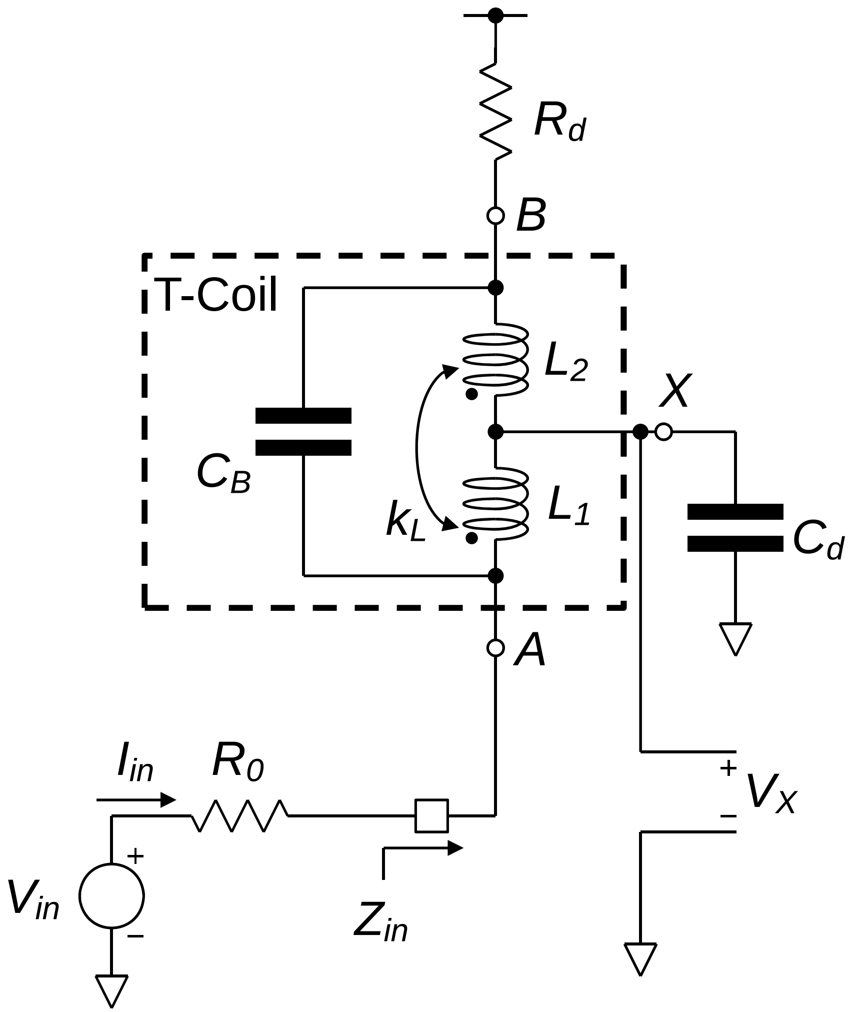
Nov. 3, 1964 T. T. TRUE 3,155,927

BRIDGED-T TERMINATION NETWORK

Filed Sept. 12, 1960



T-Coil Model [1,2]



$$\Gamma_1 = \Gamma_2 = \frac{Z_{in} - R_0}{Z_{in} + R_0}$$

Ideal T-Coil Parameters

$Z_{in} = R_0$ at all frequencies, when

$$k_L = \frac{4\zeta^2 - 1}{4\zeta^2 + 1}$$

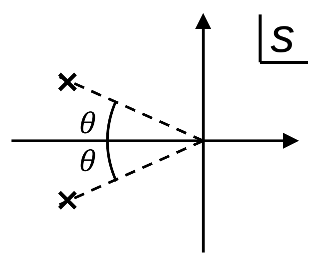
$$C_B = \frac{C_d}{16\zeta^2}$$

$$L_1 = L_2 = \frac{C_d {R_0}^2}{4}\left(1 + \frac{1}{4\zeta^2}\right)$$

$$R_d = R_0$$

ζ: damping ratio of V_X/I_{in}

Locations of complex poles of V_X/I_{in}



$$\zeta = \frac{1}{\sqrt{1 + \tan^2\theta}}$$

Equivalent Circuits [3]

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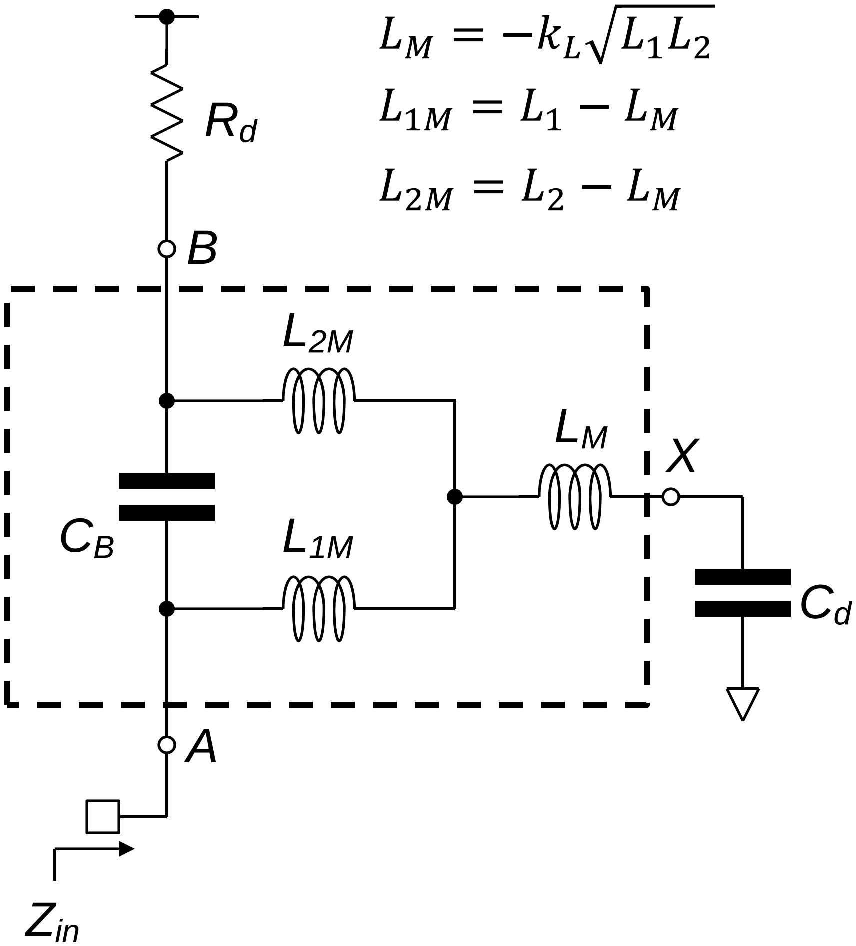
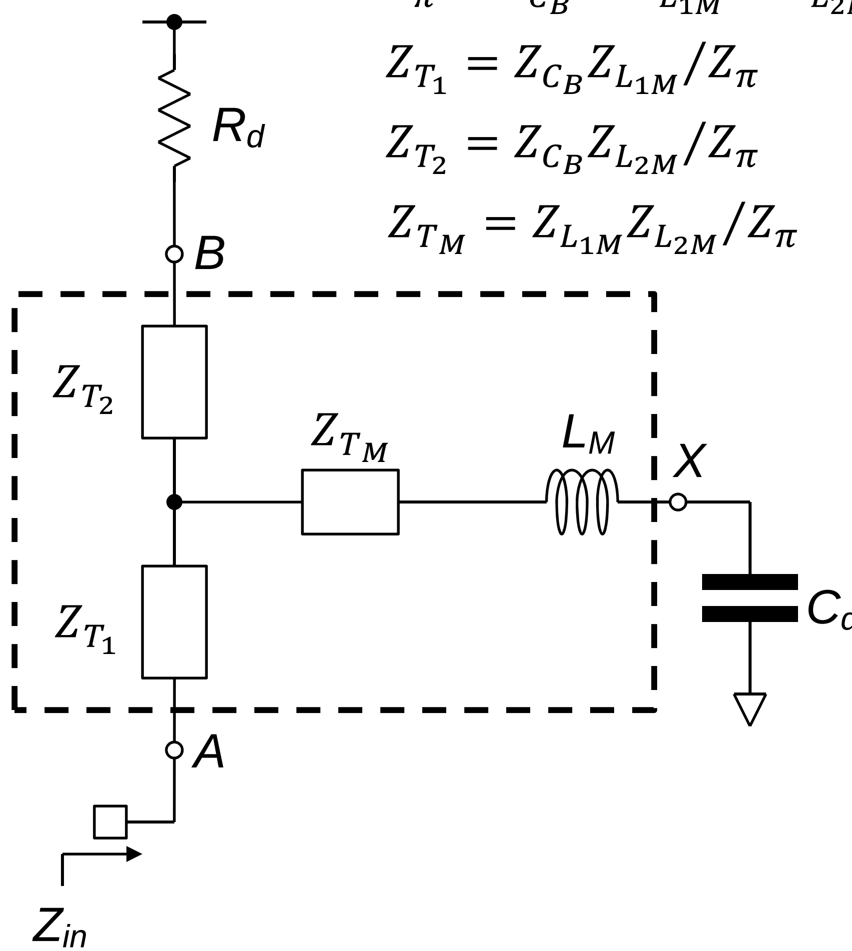
De-couple L_1 and L_2

$$L_M = -k_L\sqrt{L_1 L_2}$$
$$L_{1M} = L_1 - L_M$$
$$L_{2M} = L_2 - L_M$$



From π model to T model

$$Z_\pi = Z_{C_B} + Z_{L_{1M}} + Z_{L_{2M}}$$
$$Z_{T_1} = Z_{C_B} Z_{L_{1M}} / Z_\pi$$
$$Z_{T_2} = Z_{C_B} Z_{L_{2M}} / Z_\pi$$
$$Z_{T_M} = Z_{L_{1M}} Z_{L_{2M}} / Z_\pi$$



Equations of Impedance Calculations

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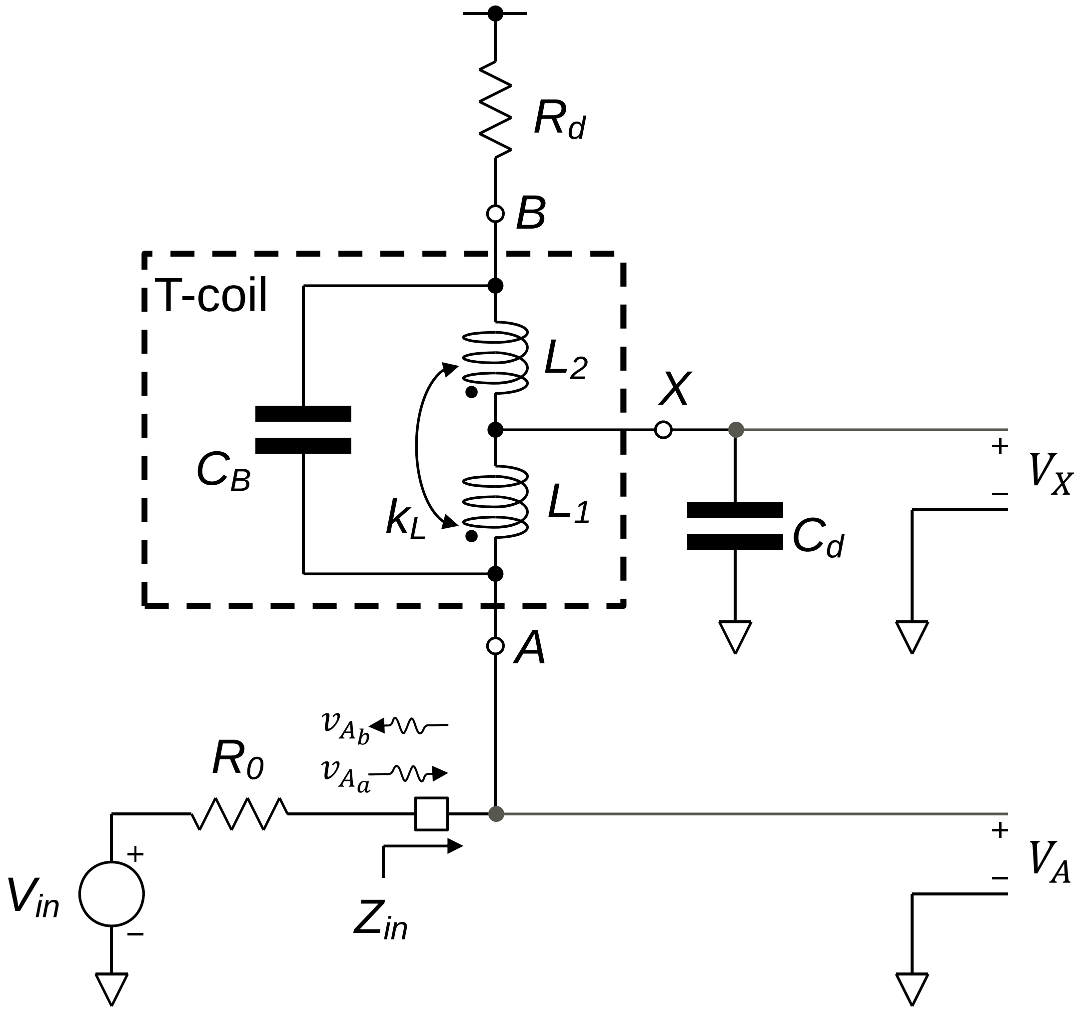
$$L_M = -k_L\sqrt{L_1L_2}$$
$$L_{1M} = L_1 - L_M$$
$$L_{2M} = L_2 - L_M$$
$$Z_{C_B} = 1/j\omega C_B$$
$$Z_{C_d} = 1/j\omega C_d$$
$$Z_{L_{1M}} = j\omega L_{1M}$$
$$Z_{L_{2M}} = j\omega L_{2M}$$
$$Z_{L_M} = j\omega L_M$$
$$Z_\pi = Z_{C_B} + Z_{L_{1M}} + Z_{L_{2M}}$$
$$Z_{T_1} = Z_{C_B}Z_{L_{1M}}/Z_\pi$$
$$Z_{T_2} = Z_{C_B}Z_{L_{2M}}/Z_\pi$$
$$Z_{T_M} = Z_{L_{1M}}Z_{L_{2M}}/Z_\pi$$

$$Z_X = Z_{T_M} + Z_{L_M} + Z_{C_d}$$
$$Z_{in} = Z_{T_1} + \frac{\left(R_d + Z_{T_2}\right)Z_X}{R_d + Z_{T_2} + Z_X}$$
$$Z_{out} = Z_{T_2} + \frac{\left(R_0 + Z_{T_1}\right)Z_X}{R_0 + Z_{T_1} + Z_X}$$

Voltage Transfer Function at Rx Input [1,2]

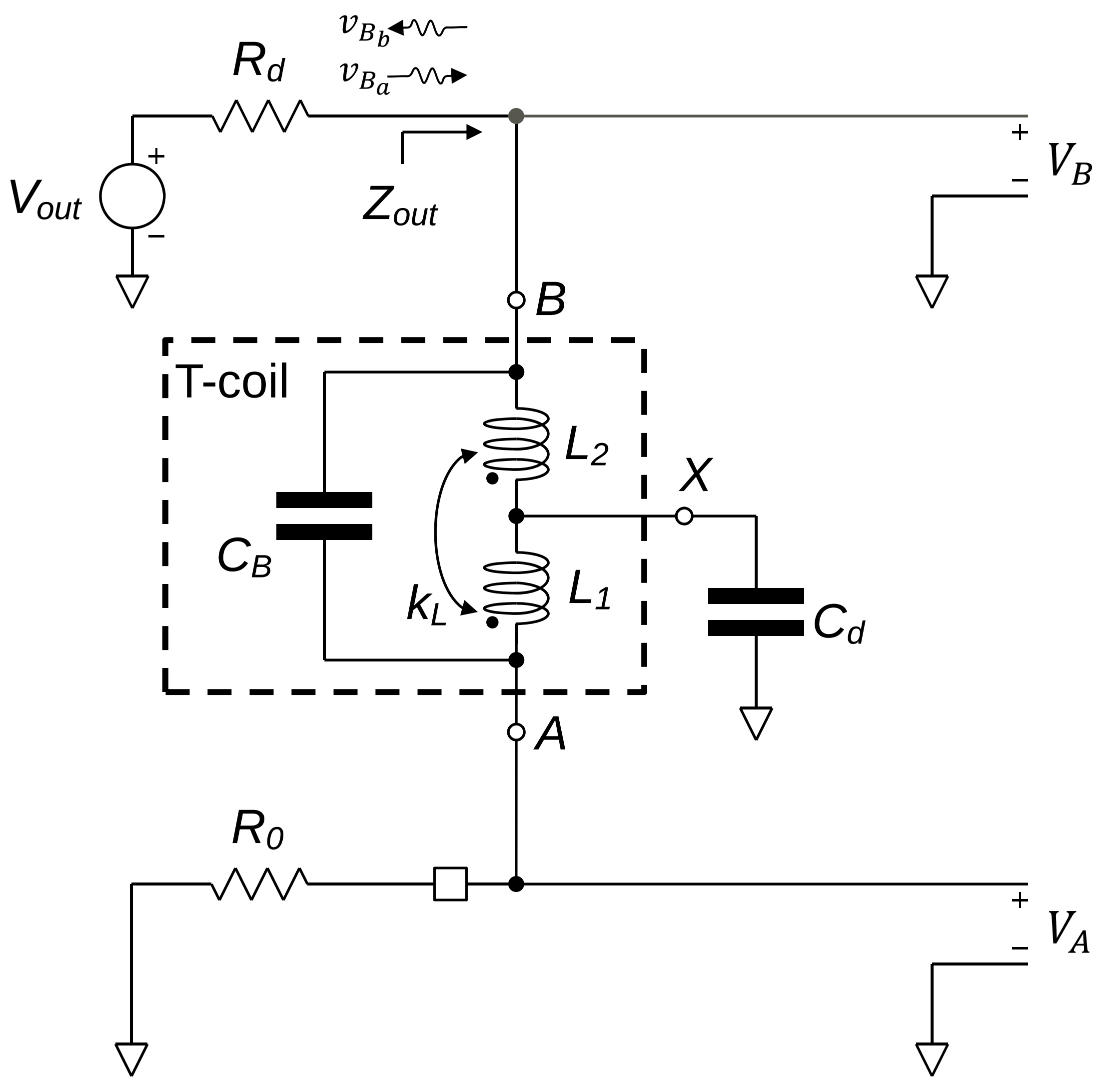


$$\frac{v_{A_b}}{v_{A_a}} = \frac{Z_{in} - R_0}{Z_{in} + R_0}$$

$$V_A = v_{A_a} + v_{A_b}$$
$$= \frac{2Z_{in}}{Z_{in} + R_0} v_{A_a}$$

$$H_{21}^{(RX)} = \frac{V_X}{v_{A_a}}$$
$$= \frac{2Z_{C_d}\left(R_d + Z_{T_2}\right)}{(Z_{in} + R_0)\left(R_d + Z_{T_2} + Z_X\right)}$$

Voltage Transfer Function at Tx Output [4]



$$\frac{v_{B_b}}{v_{B_a}} = \frac{Z_{out} - R_d}{Z_{out} + R_d}$$

$$V_B = v_{B_a} + v_{B_b}$$

$$= \frac{2Z_{out}}{Z_{out} + R_d} v_{B_a}$$

$$H_{21}^{(TX)} = \frac{V_A}{v_{B_a}}$$

$$= \frac{2R_0 Z_X}{(Z_{out} + R_d)\left(R_0 + Z_{T_1} + Z_X\right)}$$

Parameters of T-Coil Model for COM

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Parameter	Symbol	Current	Ideal	Proposed Values		Units
				Test 1	Test 2	
Package transmission line length	z_p			12	30	mm
Single-ended reference resistance	R_0	50	50	50		ohms
Single-ended termination resistance	R_d	55	50	50 * 1.10	50 * 0.90	ohms
Single-ended device capacitance	C_d	2.8×10^{-4}	6×10^{-4}	6×10^{-4} * 0.85		nF
T-coil bridge capacitance	C_B	N/A	5×10^{-5}	5×10^{-5} * 1.15		nF
T-coil inductance on pad side	L_1	0	500	500		pH
T-coil inductance on terminator side	L_2	0	500	500		pH
T-coil coupling coefficient	k_L	N/A	0.50	0.50		–

- Justification for proposed values
  - C_d is approximately doubled to take account of parasitic cap of T-Coil
  - Tolerance is chosen by common sense in electrical engineering
    - Inductance is easy to control
      - It depends on permeability and large loop area which are both not sensitive to variation
    - Capacitance is difficult to control
      - It depends on permittivity and small electrode gap which are both sensitive to variation
  - Sign of deviation is chosen to be the worst case (slide 14-15)

Rx/Tx Reflection Characteristics with T-Coil

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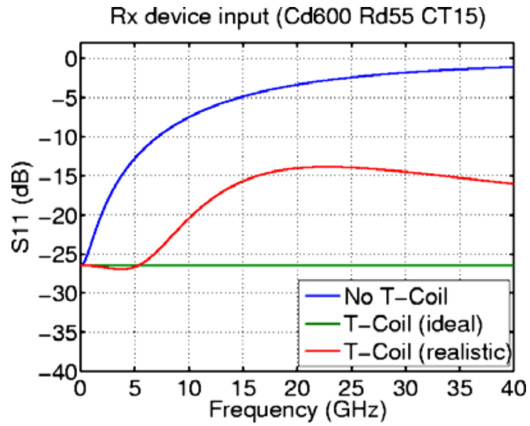
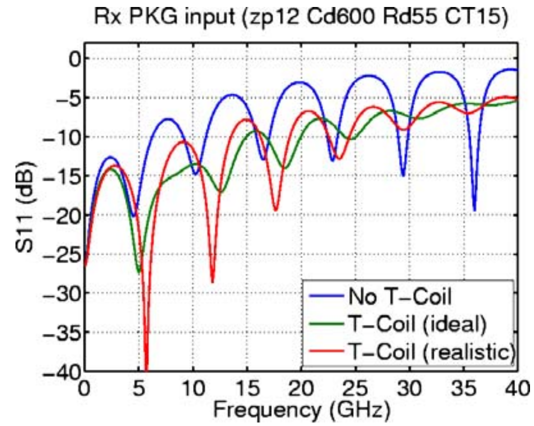
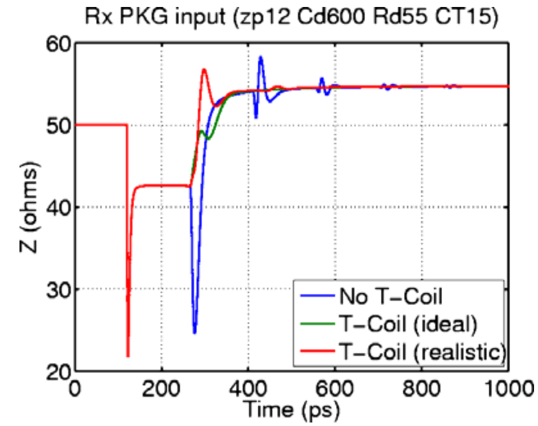
S11/S22 at Device input | S11/S22 at Package input | TDR at PKG input

Test 1

zp=12mm

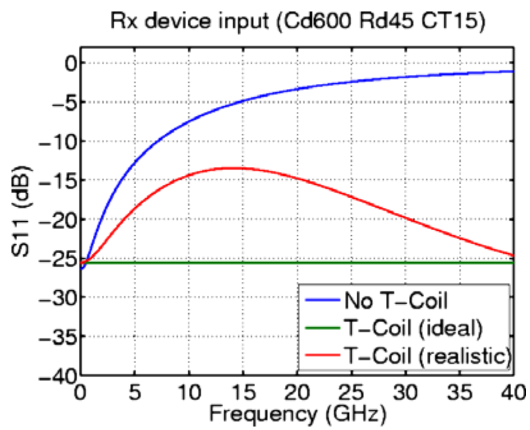


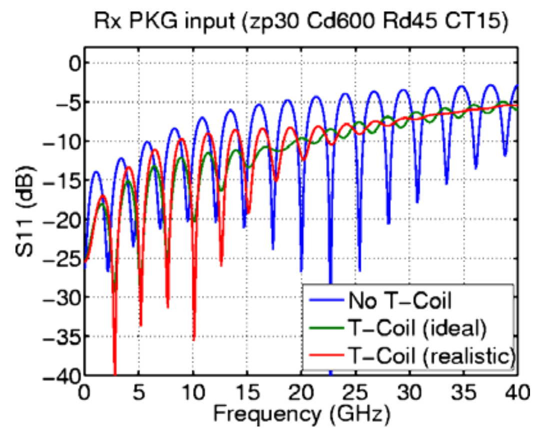


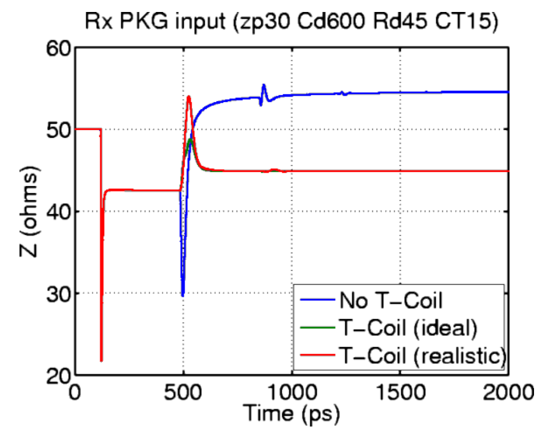


Test 2

zp=30mm







Model	R_d	Other parameters
No T-Coil	55 ohms	C_d=280fF
T-Coil (ideal)	55 ohms (Test 1) 45 ohms (Test 2)	C_d=600fF, no deviation
T-Coil (realistic)		Proposed values

TDR was observed with 10mm PCB trace.

Step rise time is 0.5ps at the input of 10mm PCB trace. PCB trace uses equations (93A-13) and (93A-14) with parameters in Table 92-12 excepting Z_c = 100 ohms.

Rx Transfer Characteristics with T-Coil

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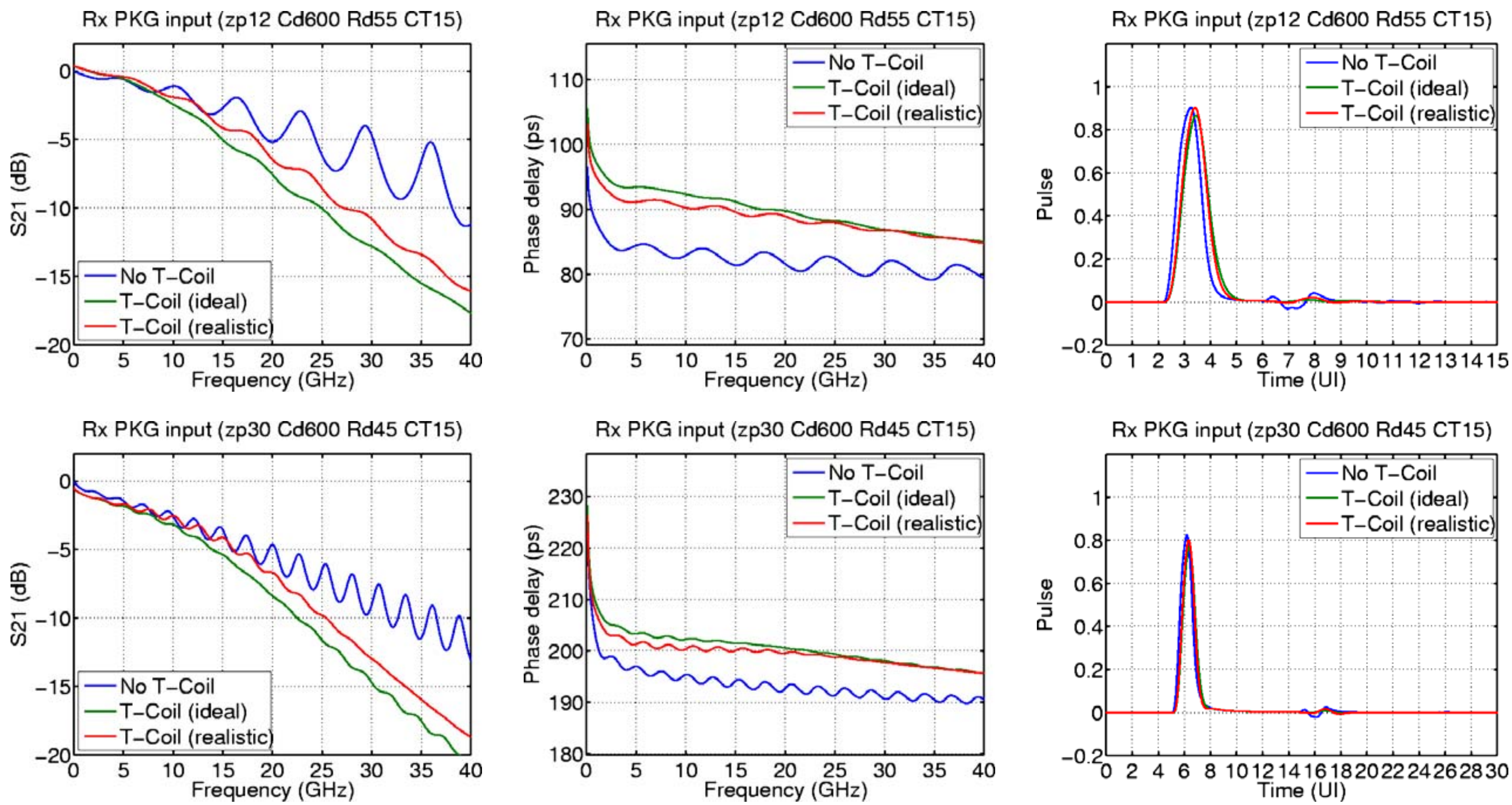
S21 (dB) | S21 (phase delay) | SBPR

Test 1

zp=12mm

Test 2

zp=30mm



Model	R_d	Other parameters
No T-Coil	55 ohms	C_d=280fF
T-Coil (ideal)	55 ohms (Test 1) 45 ohms (Test 2)	C_d=600fF, no deviation
T-Coil (realistic)		Proposed values

SBPR (Single-Bit Pulse Response)

1 UI = 1 / 26.5625Gbaud

Rise & fall time of input pulse = 0.5UI

Tx Transfer Characteristics with T-Coil

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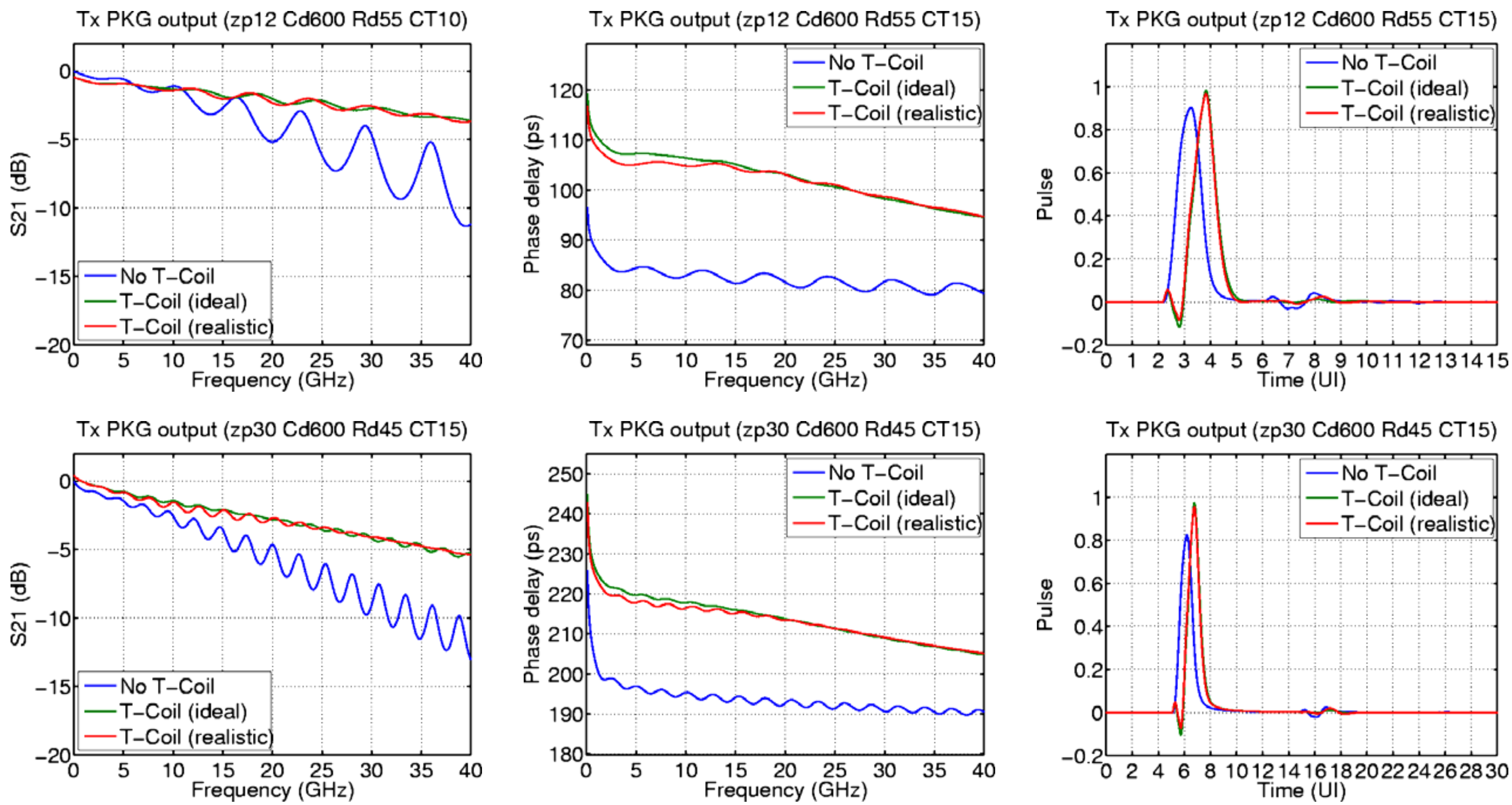
S21 (dB) | S21 (phase delay) | SBPR

Test 1

zp=12mm

Test 2

zp=30mm



Model	R_d	Other parameters
No T-Coil	55 ohms	C_d=280fF
T-Coil (ideal)	55 ohms (Test 1) 45 ohms (Test 2)	C_d=600fF, no deviation
T-Coil (realistic)		Proposed values

SBPR (Single-Bit Pulse Response)

1 UI = 1 / 26.5625Gbaud

Rise & fall time of input pulse = 0.5UI

Study for Sign of Deviations

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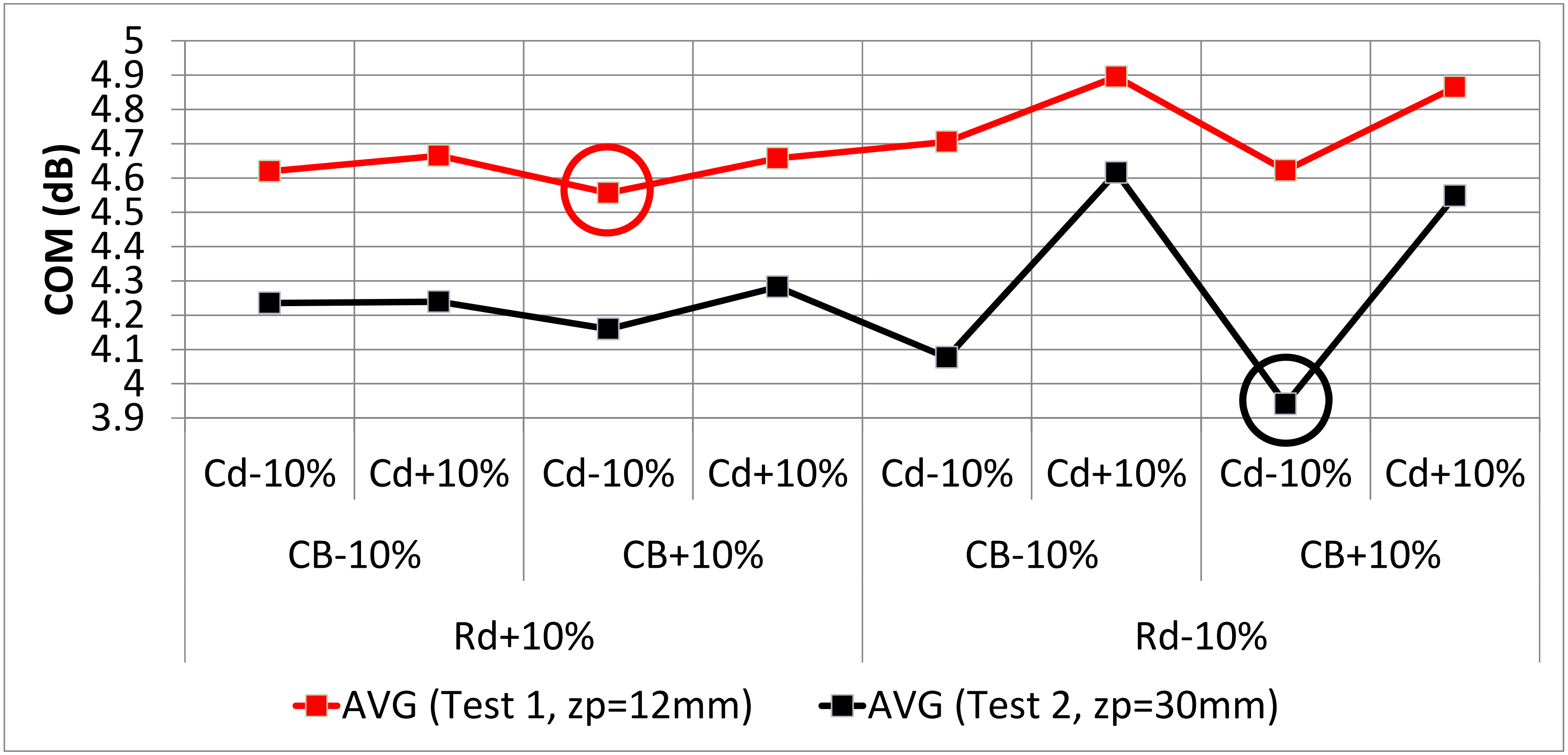
- Simulation Conditions (Difference from Draft D1.3 Annex120D)

Parameter	Symbol	Units	Optimal	Simulation Conditions
Single-ended reference resistance	R_0	ohms	50	50
Single-ended termination resistance	R_d	ohms	50	50 * (0.90 or 1.10)
Single-ended device capacitance	C_d	fF	600	600 * (0.90 or 1.10)
T-coil bridge capacitance	C_B	fF	50	50 * (0.90 or 1.10)
T-coil inductance on pad side	L_1	pH	500	500
T-coil inductance on terminator side	L_2	pH	500	500
T-coil coupling coefficient	k_L	–	0.50	0.50

- 10 Tested Channels
  - CH1 through CH7 are from mellitz_3bs_01_0714.pdf
  - CH8 is from shanbhag_02_0914.pdf
  - CH9 and CH10 are from mellitz_3bs_01_0315.pdf
- 2 Test Cases
  - Package Trace Length: z_p = 12mm or 30mm

Results of Study for Sign of Deviations

- Worst case for Test 1 (zp=12mm)
  - Rd +10%, Cd -10%, CB +10%
- Worst case for Test 2 (zp=30mm)
  - Rd -10%, Cd -10%, CB +10%



Study for Capacitor Tolerance

- Simulation Conditions (Difference from Draft D1.3 Annex 120D)

Condition		With T-coil					No T-coil	Units
Capacitor tolerance		0%	5%	10%	15%	20%		
Symbol	R_0	50					50	ohms
	R_d	55 for Test 1 (z_p=12mm), 45 for Test 2 (z_p=30mm)					55	ohms
	C_d	600	570	540	510	480	280	fF
	C_B	50.0	52.5	55.0	57.5	60.0	0	fF
	L_1	500					0	pH
	L_2	500					0	pH
	k_L	0.50					0	–

- 10 Tested Channels
  - CH1 through CH7 are from mellitz_3bs_01_0714.pdf
  - CH8 is from shanbhag_02_0914.pdf
  - CH9 and CH10 are from mellitz_3bs_01_0315.pdf
- 2 Test Cases
  - Package Trace Length: z_p = 12mm or 30mm

Results of Study for Capacitor Tolerance

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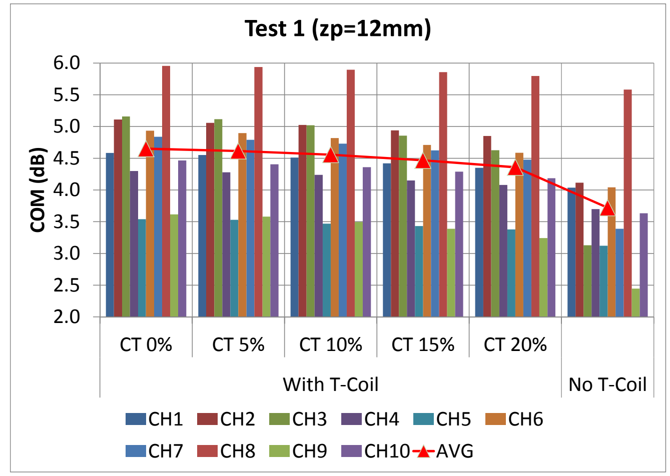
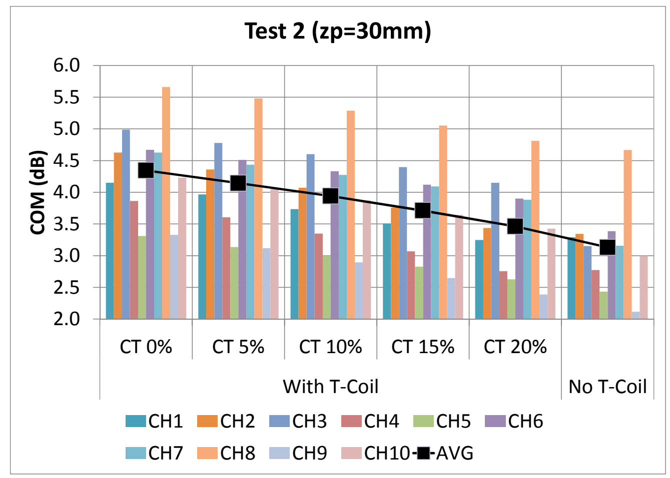
Condition	Capacitor tolerance	Test 1 (zp=12mm)										
		CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	AVG
With T-coil	0%	4.58	5.11	5.16	4.30	3.54	4.93	4.84	5.95	3.62	4.46	4.65
	5%	4.55	5.06	5.12	4.28	3.53	4.90	4.79	5.94	3.58	4.41	4.61
	10%	4.51	5.03	5.02	4.24	3.47	4.82	4.73	5.89	3.50	4.36	4.56
	15%	4.42	4.94	4.86	4.15	3.43	4.71	4.62	5.86	3.39	4.29	4.47
	20%	4.35	4.85	4.63	4.08	3.38	4.59	4.48	5.80	3.24	4.18	4.36
No T-coil		4.04	4.12	3.13	3.70	3.12	4.04	3.39	5.58	2.45	3.63	3.72
Improvement(CT15%)		0.38	0.82	1.73	0.45	0.31	0.67	1.23	0.27	0.94	0.65	0.75



Condition	Capacitor tolerance	Test 2 (zp=30mm)										
		CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	AVG
With T-coil	0%	4.15	4.63	4.99	3.86	3.31	4.67	4.63	5.66	3.33	4.23	4.34
	5%	3.97	4.36	4.78	3.61	3.14	4.51	4.44	5.48	3.12	4.05	4.14
	10%	3.73	4.07	4.60	3.35	3.00	4.33	4.27	5.29	2.89	3.87	3.94
	15%	3.51	3.76	4.40	3.07	2.83	4.12	4.09	5.05	2.65	3.64	3.71
	20%	3.25	3.44	4.15	2.76	2.63	3.90	3.88	4.81	2.39	3.43	3.46
No T-coil		3.29	3.34	3.15	2.77	2.43	3.38	3.16	4.67	2.12	3.00	3.13
Improvement(CT15%)		0.21	0.42	1.25	0.29	0.39	0.73	0.94	0.39	0.53	0.65	0.58



Study for Device Capacitance

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- Simulation Conditions (Difference from Draft D1.3 Annex 120D)

Condition		With T-coil								No T-coil		Units
Device Capacitance		1pF	900fF	800fF	700fF	600fF	500fF	400fF	300fF			
Symbol	R_0	50								50		ohms
	R_d	55 for Test 1 (z_p=12mm), 45 for Test 2 (z_p=30mm)								55		ohms
	C_d	850	765	680	595	510	425	340	255	280	100	fF
	C_B	95.8	86.3	76.7	67.1	57.5	47.9	38.3	28.8	0		fF
	L_1	833	750	667	583	500	417	300	250	0		pH
	L_2	833	750	667	583	500	417	300	250	0		pH
	k_L	0.50								0		–

- 10 Tested Channels
  - CH1 through CH7 are from mellitz_3bs_01_0714.pdf
  - CH8 is from shanbhag_02_0914.pdf
  - CH9 and CH10 are from mellitz_3bs_01_0315.pdf
- 2 Test Cases
  - Package Trace Length: z_p = 12mm or 30mm

Results of Study for Device Capacitance

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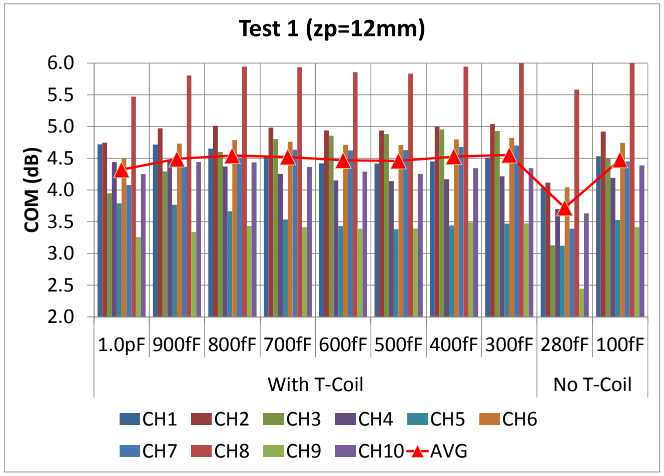
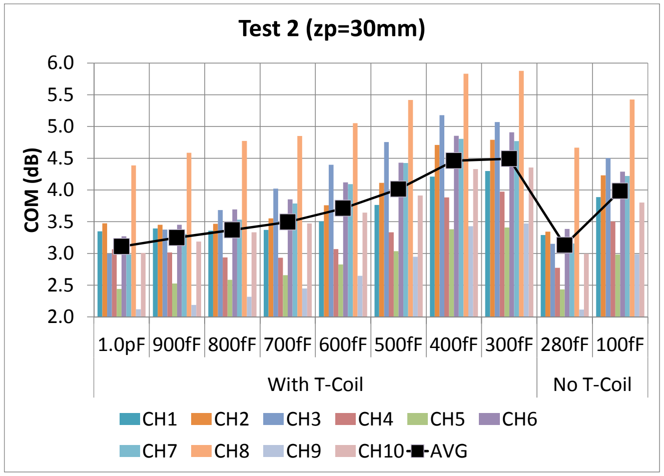
Condition	Device capacitance	Test 1 (zp=12mm)										
		CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	AVG
With T-coil	1.0pF	4.72	4.74	3.95	4.44	3.79	4.49	4.08	5.47	3.26	4.25	4.32
	900fF	4.71	4.97	4.29	4.46	3.77	4.73	4.36	5.80	3.34	4.44	4.49
	800fF	4.65	5.01	4.60	4.37	3.66	4.79	4.51	5.95	3.43	4.43	4.54
	700fF	4.52	4.98	4.80	4.25	3.53	4.76	4.63	5.93	3.42	4.36	4.52
	600fF	4.42	4.94	4.86	4.15	3.43	4.71	4.62	5.86	3.39	4.29	4.47
	500fF	4.42	4.94	4.88	4.14	3.38	4.71	4.63	5.83	3.39	4.25	4.46
	400fF	4.45	5.00	4.95	4.17	3.44	4.80	4.68	5.94	3.49	4.34	4.53
	300fF	4.51	5.04	4.93	4.22	3.47	4.82	4.70	6.02	3.47	4.34	4.55
No T-coil	280fF	4.04	4.12	3.13	3.70	3.12	4.04	3.39	5.58	2.45	3.63	3.72
	100fF	4.53	4.92	4.50	4.19	3.53	4.74	4.45	6.11	3.42	4.39	4.48



Condition	Device capacitance	Test 2 (zp=30mm)										
		CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	AVG
With T-coil	1.0pF	3.35	3.47	3.00	3.07	2.44	3.27	2.99	4.39	2.12	3.01	3.11
	900fF	3.39	3.45	3.38	3.02	2.53	3.45	3.31	4.59	2.19	3.19	3.25
	800fF	3.36	3.47	3.68	2.94	2.59	3.69	3.53	4.77	2.32	3.33	3.37
	700fF	3.37	3.55	4.02	2.93	2.66	3.85	3.79	4.85	2.45	3.47	3.49
	600fF	3.51	3.76	4.40	3.07	2.83	4.12	4.09	5.05	2.65	3.64	3.71
	500fF	3.76	4.11	4.75	3.33	3.04	4.43	4.42	5.42	2.95	3.91	4.01
	400fF	4.21	4.71	5.18	3.88	3.38	4.85	4.81	5.83	3.43	4.33	4.46
	300fF	4.30	4.79	5.07	3.97	3.41	4.91	4.77	5.88	3.47	4.35	4.49
No T-coil	280fF	3.29	3.34	3.15	2.77	2.43	3.38	3.16	4.67	2.12	3.00	3.13
	100fF	3.89	4.23	4.50	3.50	2.98	4.29	4.22	5.43	2.99	3.80	3.98



Proposed Text Changes

- Define equations in slide 7 and parameters in slide 10
- Replace (93A-17) with the following equation

$$\Gamma_1 = \Gamma_2 = \frac{Z_{in} - R_0}{Z_{in} + R_0}$$

- Replace (93A-18) with the following equations

$$H_{21}(f) = H_{21}^{(TX)} \frac{s_{21}(f)(1-\Gamma_1)(1+\Gamma_2)}{1 - s_{11}(f)\Gamma_1 - s_{22}(f)\Gamma_2 + \Gamma_1\Gamma_2\Delta S(f)} H_{21}^{(RX)}$$

$$H_{21}^{(TX)} = \frac{2R_0 Z_X}{(Z_{out} + R_d)\left(R_0 + Z_{T_1} + Z_X\right)}$$

$$H_{21}^{(RX)} = \frac{2Z_{C_d}\left(R_d + Z_{T_2}\right)}{(Z_{in} + R_0)\left(R_d + Z_{T_2} + Z_X\right)}$$

- In Figure 93A-1, replace R_d at Tx with $H_{21}^{(TX)}$ and Γ_1 , and replace R_d at Rx with $H_{21}^{(RX)}$ and Γ_2

Proposed Text Changes

93A.1.2.2 Two-port network for a shunt capacitance

- Remove the description for $S^{(d)}$ in the last paragraph, because it is not referenced from anywhere. The last sentence in 93A.1.2.2 will be as follows:
  - The scattering parameters for the board capacitance C_p are denoted as $S^{(p)} = S(C_p)$.

93A.1.2.4 Assembly of Tx and Rx device package models

- Change the text as follows:

The scattering parameters for the transmitter device package model $S^{(tp)}$ are the result of the cascaded connection of the package transmission line and board capacitance as defined by Equation (93A-15):

$$S^{(tp)} = cascade\left(S^{(l)}, S^{(p)}\right) \quad \text{(93A-15)}$$

Similarly, the scattering parameters for the receiver device package model $S^{(rp)}$ are the result of the cascaded connection of the board capacitance and package transmission line as defined by Equation (93A-16):

$$S^{(tp)} = cascade\left(S^{(p)}, S^{(l)}\right) \quad \text{(93A-16)}$$

Prior Clauses using COM

- Do we get the same results when we bypass T-Coil model?

- Actually, they are not exactly same as before.

- However, the difference is quite small and negligible.

Bypassed T-Coil Model

$$L_M = L_{1M} = L_{2M} = 0$$
$$Z_{L_{1M}} = Z_{L_{2M}} = Z_{L_M} = 0$$
$$Z_\pi = Z_{C_B}$$
$$Z_{T_1} = Z_{T_2} = Z_{T_M} = 0$$
$$Z_X = Z_{C_d}$$
$$Z_{in} = \frac{R_d Z_{C_d}}{R_d + Z_{C_d}}$$
$$Z_{out} = \frac{R_0 Z_{C_d}}{R_0 + Z_{C_d}}$$

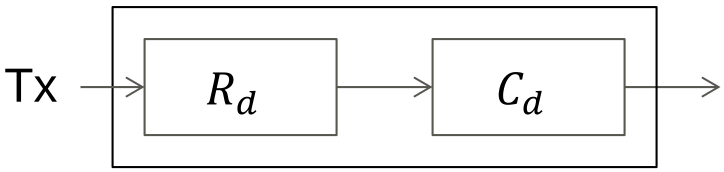
Symbol	Value	Units
C_B	any	nF
L_1	0	pH
L_2	0	pH
k_L	any	–

$$H_{21}^{(TX)} = \frac{2Z_{C_d}R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$
$$H_{21}^{(RX)} = \frac{2Z_{C_d}R_d}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

$$\Gamma_1 = \Gamma_2 = \frac{Z_{in} - R_0}{Z_{in} + R_0} = \frac{Z_{C_d}(R_d - R_0) - R_d R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

Old COM vs Bypassed T-Coil Model

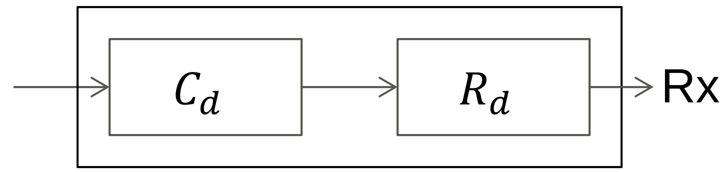
Tx (Old COM)



$$S_{22} = \frac{Z_{C_d}(R_d - R_0) - R_d R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

$$S_{21} = \frac{Z_{C_d}(R_d + R_0)}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

Rx (Old COM)



$$S_{11} = \frac{Z_{C_d}(R_d - R_0) - R_d R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

$$S_{21} = \frac{Z_{C_d}(R_d + R_0)}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

Tx (Bypassed T-Coil)

$$\Gamma_1 = \frac{Z_{C_d}(R_d - R_0) - R_d R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

$$H_{21}^{(TX)} = \frac{2Z_{C_d}R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

Rx (Bypassed T-Coil)

$$\Gamma_2 = \frac{Z_{C_d}(R_d - R_0) - R_d R_0}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

$$H_{21}^{(RX)} = \frac{2Z_{C_d}R_d}{Z_{C_d}(R_d + R_0) + R_d R_0}$$

With bypassed T-Coil, gain is slightly reduced.

Impact on COM by Bypassed T-Coil Model

Test Case	COM definition	CH1	CH2	CH3	CH4	CH5
Test 1 z_p=12mm	Old (No T-Coil model)	4.03813	4.11665	3.12861	3.70049	3.12241
	New (Bypassed T-Coil)	4.03674	4.11506	3.12845	3.70000	3.12171
Test 2 z_p=30mm	Old (No T-Coil model)	3.29391	3.34486	3.15213	2.77763	2.43508
	New (Bypassed T-Coil)	3.29229	3.34358	3.15156	2.77459	2.43403

Test Case	COM definition	CH6	CH7	CH8	CH9	CH10
Test 1 z_p=12mm	Old (No T-Coil model)	4.04191	3.38960	5.58406	2.44744	3.63506
	New (Bypassed T-Coil)	4.04127	3.38940	5.58292	2.44629	3.63455
Test 2 z_p=30mm	Old (No T-Coil model)	3.38557	3.15567	4.66904	2.11688	2.99678
	New (Bypassed T-Coil)	3.38497	3.15547	4.66607	2.11536	2.99598

- CH1 through CH7 are from mellitz_3bs_01_0714.pdf
- CH8 is from shanbhag_02_0914.pdf
- CH9 and CH10 are from mellitz_3bs_01_0315.pdf

- COM is slightly (< 0.003dB) reduced due to reduction of gain.
  - The impact on existing clause is negligible small.

Summary

- I have presented a new T-Coil model for COM.
  - All the detail formula are given for ease of review and implementation.
  - Device capacitance C_d is doubled to account for parasitic cap of T-Coil.
  - Parameter values are deviated from the ideal values based on common sense in electrical engineering.

- A comparison with real T-Coil characteristics is not available for review due to confidentiality.
  - If you can access real T-Coil characteristics, please do your own comparison.
  - If there is S-parameter data of real T-Coil characteristics that is public or OK to release results to public, I can show a comparison.

- For prior clauses using COM, the impact of bypassing the T-Coil model is negligible.

Options to improve the package model of COM

- Option A
  - Use the new T-Coil model in this presentation.
    - Parameters are chosen based on common sense in electrical engineering.
      - We can revise parameters, if comparison with real T-Coil becomes available.

- Option B
  - Reduce the device capacitance C_d to an equivalent lower value.
    - Contribution of comparison with real T-Coil may be desired for justification.

- Option C
  - No change.

References

- [1] Thomas T. True, “Bridged-T Termination Network,” U.S. Patent 3155927, Nov. 1964.
- [2] Sherif Galal, Behzad Razavi, “Broadband ESD Protection Circuits in CMOS Technology,” IEEE J. of Solid-State Circuits, Vol. 38, No. 12, Dec. 2003, pp. 2334-2340.
- [3] S. C. Dutta Roy, “Comments on “Analysis of the Bridged T-coil Circuit Using the Extra-Element Theorem”,” IEEE Trans. on Circuits and Systems – II: Express Briefs, Vol. 54, No. 8, Aug. 2007, pp. 673-674.
- [4] Marcel Kossel, et. al., “A T-Coil-Enhanced 8.5 Gb/s High-Swing SST Transmitter in 65 nm Bulk CMOS With < –16 dB Return Loss over 10 GHz Bandwidth,” IEEE J. of Solid-State Circuits, Vol. 43, No. 12, Dec. 2008, pp. 2905-2920.

Thank you