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RF Interconnects

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ABSTRACT : Radio Frequency System In Package (SiP) consists of Integrated Circuits (ICs), surface mount device (SMD) components and embedded passive components. The routing to interconnect these components introduces high order of parasitics at RF. These parasitics affect the overall performance of the system. These interconnects include bond wires, transmission lines and transmission line discontinuities. The embedded components like capacitors and inductors are used to reduce the over all size of the system with optimal performance. This article brings out the hierarchy that connects individual active devices at the lowest level to system level connections at the highest. The article also describes the methodology for analysis and modeling of different types of interconnects.

List of Symbols

SiP	-	System in Package
SoC	-	System on Chip
EDA	-	Electronic Design Automation
c	-	Speed of light in free space = 2.9998E+08 m/s
λ_0	-	Free space wavelength
λ	-	wavelength
Zo	-	Characteristic Impedance
σ	-	Conductivity
p	-	Mathematical constant = 3.14159265
θ	-	Angle specified in degrees
ω	-	Angular frequency
F	-	Frequency
η	-	Intrinsic free space impedance = 377
ρ	-	Resistivity of the material
K	-	Complete elliptical function of first kind
K′	-	Complementary function
L	-	Inductance
C	-	Capacitance
R	-	Resistance
G	-	Conductance
ε_r	-	Dielectric constant
ε_{re}	-	Effective dielectric constant
α_c	-	Conductor loss
α_d	-	Dielectric loss
ν_p	-	Phase velocity
dB	-	Decibels, unit of measurement
mm	-	Microns, unit of measurement
Ω	-	Ohms, unit of measurement of resistance.
H	-	Henries, unit of measurement of inductance.
F	-	Farad, unit of measurement of capacitance.
mil	-	Unit of measurement which is 1/1000th of an inch.
S11	-	Input reflection coefficient or return loss.
S12	-	Reverse gain or insertion loss
S21	-	Forward gain or transmission loss
S22	-	Output reflection coefficient.
MLIN	-	Microstrip line
SLIN	-	Stripline
EC	-	Electric circuit
LE	-	Lumped element

I. INTRODUCTION

Electrical connections are part of a hierarchy that connects individual active devices at the lowest level to system-level connections at the highest. One way of defining the interconnect hierarchy is as follows:

Level 1 Interconnect: Chips

Level 2 Interconnect: Multichip Modules (Package)

Level 3 Interconnect: Printed Circuit Board PCB (Package)

Level 4 Interconnect: Backplane (Package)

The size of interconnects varies with interconnect level with the smallest interconnects, both in cross-section and in length, being at the chip level. Also the way they are designed and modeled depends on the physical size of the connections, whether digital or analogue circuitry is being interconnected, and on the clock or operating frequency.

Interconnects now dominate the performance of many high-speed digital circuits and for RF and microwave circuits they have always been critical circuit components. The lower the level in the interconnect hierarchy generally the shorter the connection and the higher the performance in terms of lower delay to transmit a signal from one point to another. A high performance system realizes a greater proportion of interconnections at the lower levels than does a lower cost system with less critical performance requirements. Not every system has all of the levels listed above and even some interconnect networks, especially at microwave frequencies, need not involve active devices. Today's high performance digital systems have many interconnect issues common with microwave (generally 1 to 30GHz) and millimeter wave (above 30GHz) systems and it is appropriate to consider the interconnect issues as a continuum.

Up to the early 1990's on-chip digital signals had components much below 1GHz; relatively short run lengths (constrained by the dimensions of the chip); and widths of several microns; and height of a micron or more. The first two factors resulted in the electrical lengths of on-chip interconnects being much less than a wavelength of the signals present (i.e. of the highest frequency components present).

An interconnect could be adequately modeled as a shunt lumped capacitance. A series resistance completed the model (a so-called RC model) but this was small because of the relatively large cross-sections of the interconnect. This situation has changed because of three main developments, primarily for digital circuits but affecting analogue circuitry because of the rise of mixed signal systems. The main developments are: -

(*a*) Faster clocks, of a gigahertz and above.

(*b*) Longer interconnects as the lateral dimensions of large chips are around 2cm.

(*c*) Fine lithography enabling interconnects to have cross-sectional dimensions of less than a micron.

The consequences of these developments are that RC modeling is not always adequate. However on-chip digital interconnects are highly irregular and densely packed and often do not even approximate interconnections of uniform transmission line segments.

Such an interconnect could be conveniently modeled as a transmission line. With RF and microwave chips there are relatively few active devices and so the provision of interconnects large enough (to effectively minimize interconnect resistance) and of defined ground planes for good current return paths can be accommodated at reasonable cost. The characterization of and modeling required for these interconnects is a major topic.

II. THE PHYSICAL BASIS OF INTERCONNECTS

Electrical interconnections are generally made using metallic conductors, although conductive path can be made using doped semiconductors and superconductors. Metallic conductors, such as copper and aluminium, the most common types used, are crystals with positively charged ions locked into position in a regular lattice. The ion here is made up of the nucleus of an atom which is positively charged and a complement of electrons local to each atom which almost, but not quite, balance the positive charge. In a metallic crystal there are some 'free' electrons shared by several ions with the overall effect that the positive and negative charges are balanced and the free electrons can wander around the lattice. The wandering electrons travel in random directions at a speed which is a substantial portion of c, the ultimate speed of light. This speed can typically be c/3 at room temperature in copper. These electrons are moving randomly with no overall average movement, therefore they do not transmit information. When an electric force field, E, is applied, the electrons begin to accelerate in the opposite direction to E. This gives rise to an average movement of electrons in one direction and this movement of charge carriers, crossing a fixed position per unit of time, constitutes current I. At absolute zero temperature the lattice is motionless and the electrons can, essentially, move through the lattice unimpeded. With an applied E field (the voltage V divided by the distance over which e is applied) the electrons would eventually reach a speed only limited by speed-of-light considerations. As the temperature increase the lattice becomes vibrate to and the electrons start colliding with it. These collisions impede the movement of electrons and this constitutes electrical resistance R. therefore the ultimate speed of electrons is limited, and thus so is current. The higher temperature the higher the electric resistance and the lower the average speed or current. This is the underlying physical basis of O'hms law (V = IR).The movement of charge, and the electric & magnetic fields that establishes, is also the basis for information transfer in interconnects. Note, however, that signals can move much faster than the electrons themselves.

The movement of charge results in a magnetic field, and hence magnetic energy storage. The ability of a structure to store magnetic energy is described as its inductance L. Similarly the rearrangement of charge to produce localized net positive or negative results in electric field, and this electric energy storage with the capacitance C indicating the amount of energy that can be stored. The ratio of the energy stored in magnetic and electric forms $(\propto \sqrt{L/C})$ and the rate at which the energy can be moved $(\propto 1/\sqrt{LC})$ determine the characteristics of an interconnect.

III. WHAT AN INTERCONNECT IS AND HOW INFORMATION IS TRANSMITTED

An interconnect can take various forms, either delivering power to part of an electronic circuits or being the means by which information is transmitted from one point to one or more other points in a circuit. We are concerned with the design of interconnect to ensure reliable undistorted transmission of information. In low frequency analog and digital circuits interconnects can be viewed simply as wires and, provided that the wire has low resistance and current capability, the interconnects can be largely ignored. However, if the transmission must be over a considerably distance then the interconnect must be considered as part of a circuit.

The key determinant of whether an interconnect can be considered as an invisible connection is whether the signal anywhere along the interconnect has the same value at a particular instance. If the value of the signal varies along the line (at an instance), then it may be necessary to consider transmission line effects. A typical criterion used is that if the length of interconnects is less than l/20 of the highest frequency component of a signal, then transmission line effects can be safely ignored and the circuit can be modeled as a single RLC circuit. The ultimate limit is determined by speed of light, but this is reduced by the relative permittivity of the material in which the field exists. The best term describing this physical phenomenon is retardation. In addition to retardation other properties of the interconnects must be considered, including its resistance, current carrying capability, interaction of a signal while those on other interconnects.

At high clocking speeds, and at RF and Microwave frequencies, retardation can be significant and an interconnects can be considered to be an instantaneous connection. The interconnects can have an appreciable impact on the operation of the circuit. As a result it can be used as a circuit element in Microwave and millimeter wave circuits and even in quite sophisticated circuits.

IV. WHEN AN INTERCONNECT SHOULD BE TREATED AS TRANSMISSION LINE

If the level of signal is reasonably constant along entire length of an interconnect, then it can safely be treated as a lumped element and need not be treated as a transmission line. If the signal is sinusoid then it is generally agreed that the signal does not change much in time over an interval equal to one twentieth of the period T of the signal. Consider a sinusoidally varying signal $x(t) = A \sin (wt)$, where $w = 2\pi f$ is the radian frequency of signal and $f = 1/T$ is its frequency so that $x(t) = A \sin(2\pi/T)$. The maximum change occurs when the signal goes from time $t = -\alpha t/2 = +\alpha T/2$, where a is the fraction of period. So in one twentieth of period ($\alpha = 0.005$) the signal can change by 16% of its maximum possible change in value. So when interconnect line is less than 1/20th of wavelength, λ, of the signal, it is regarded as safe to use a circuit model of resistors and capacitors of the interconnects. Specifying length in terms of a fraction of a wavelength is same as using the signal duration in time as a fraction of the period. (In 1/20th of a period it can change by 31% and in 1/5th of the period it can change by 59%). With digital signal time of flight delay Tf is compared to the rise time Tr is defined as the time required for the signal to change from 10% to 90% of its final value.

The time of flight delay $Tf = l/v$ ... (1)

Where l is the interconnect length and v is the propagation speed. The general guideline is that transmission modeling is necessary when

$$Tr < 2.5 \ Tf \quad \text{... (2)}$$

As then the signal has changed by more than 40% of its value. It is generally regarded that the line can be modeled by capacitors and resistors when

$$Tr > 5 \ Tf \quad \text{... (3)}$$

When a transmission model is necessary, either a spice-compatible distributed RLC model is used or else a full transmission model is needed. Which is chosen depends on the accuracy needed and also the capability of an available circuit simulation program. Note that the RLC model can not fully capture the retardation phenomenon completely.

Table 1: Modeling Criteria for sinusoidal and digital signals.

Signal type	*Model required*	
	Transmission line, or RLC	***Lumped R, C***
Sinusoid	$1 > \lambda/10$	$\lambda < 1/20$
Digital pulse	$Tr < 2.5 \ Tf$	$Tr > 5 \ Tf$

For both the sinusoidal and pulse signal there is a grey area in which it is not clear which type of model should be used.

V. MODELING OF INTERCONNECTS

A range of Models are used for interconnects depending on:

- The accuracy required.
- The amenability of the net to modeling.
- The frequency of operation.

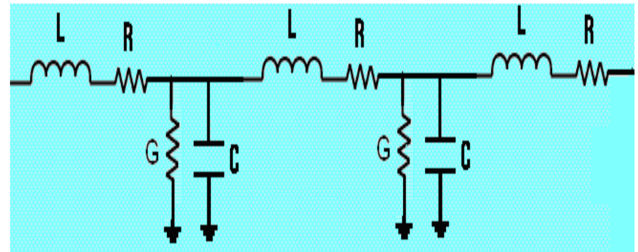

Figure 1: RLC model of an interconnect

Interconnects are commonly modeled as RLC networks where the inductors and capacitors networks are arrived at separately using static calculations of the effect of very small segments of interconnects on other small segments.

Uniforms interconnects (with regular cross-section) can be modeled by determining the characteristics of the transmission line, *e.g.* Zo (characteristic impedance) and γ (reflection coefficient) versus frequency, or arriving at a distributed lumped element circuit as shown in Fig. 1.

Entire microwave and millimeter-wave structure can be modeled using electromagnetic modeling software. Many analytic formulas have also been derived for the characteristic of uniform interconnects. These formulas are important in arriving at synthesis formulas that can in design, *i.e.* arriving at the physical dimension of an interconnect structure from its required electrical specifications.

VI. RF INTERCONNECTS ANALYSIS METHODS

- Full wave Analysis
- Static Method
- Closed Form Dispersion Models

A. Full Wave Analysis

The Hybrid mode supported by the microstrip can not be fully described in terms of static capacitances and inductances only. Therefore, one has to be consider time varying electric and magnetic fields and solve the wave equation subject to appropriate boundary conditions. Field analysis of microstrip or any other structure without invoking any quasi-static approximations is known as full wave analysis. Full wave analysis is carried out to determine the propagation constant instead of capacitance evaluated in quasi-static analysis.

Features:

- Exact Formulation
- Frequency Dependent Parameters

- Mode Dependent Parameters
- Applicable to multilayer
- EM Simulators
- Useful for Scientific investigations
- Suitable for data Generation

Limitations:

- Analytically Difficult for Design Engineers
- Programming difficult
- Computationally Slow
- Not suitable for direct CAD application (not useful for synthesis of components and Circuits, and also not useful for Circuits Simulators)

B. Static Method

In a quasi-static analysis, the mode of wave propagation in a microstrip is assumped to be pure TEM. Transmission characteristics are the calculated from the values of two capacitances, one (Ca) for unit length of the microstrip configuration with the dielectric substrate replaced by air and the other (C) for a unit length of the microstrip with the dielectric substrate present. Values of characteristic impedance Zom and the phase constant β can be written in terms of these capacitances as

$$Zom = Zaom\ (Ca/C)^{1/2} \quad \ldots (4)$$

$$\text{And } \beta = \beta_0\ (C/Ca)^{1/2} \quad \ldots (5)$$

where,

$$Zaom = 1/(c\text{Ca}) \text{ and } \beta = \omega\ (C/Ca)^{1/2}$$

Where, *c* is the velocity of electromagnetic wave in free space. There are the various method for calculating the electrostatic capacitances Ca and C.

Various Types of Static Methods:

- Conformal Mapping
- Variational method in space domain
- Variational method in Fourier domain
- Finite Difference Method

Features:

- Frequency Dependent Parameters neglected
- Higher Order Mode neglected
- Applicable to Multilayer Line
- Assumption TEM Mode

Limitations:

- Analytically not very difficult still may not be suitable for R & D Engineers
- Computationally Fast
- Accuracy depends upon algorithms
- Not adopted in Circuits Simulators

C. Closed Form Dispersion Models

The quasi-static methods of microstrip analysis do not take into account the non TEM nature of microstrip mode. The non-TEM behavior causes the effective dielectric constant (ε_{re}) and impedance Zom of the microstrip to be functions of frequency. Of these two, the variation of the effective dielectric constant is more significant. An exact evaluation of these variations involves a full wave analysis of microstrip configuration. However, there are semi-empirical techniques available that lead to a closed-form solution for the dependence ε_r and Zom on frequency. These dispersion may be listed as follows: -

- Model based on coupling between TEM and TMo surface wave modes
- An empirical relation for frequency –dependent phase velocity
- Model based on LSE mode using a dielectric loaded ridged waveguide and its modifications
- Model based on coupling between a TEM mode and a TE mode transmission line
- Model based on coupling between the LSE mode and a surface-wave mode
- Empirical formulae based on full wave numerical data
- Planar waveguide model

Features:

- Model is Computationally Fast
- Adopted to Software
- Accuracy varies from model to model
- Both Static and Dynamic Forms Available

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