# Power Bus Decoupling Algorithm

## Purpose of Algorithm

To estimate the magnitude of the noise voltage on the power bus nets.

## Description of Algorithm

This algorithm is applied only to digital power bus nets. For each digital power bus net, decoupling capacitors are identified then the noise voltage is calculated based on the effective impedance of the decoupling capacitors and the transient current on the net.

This algorithm consists of several functions. the function *LocateDecouplingCapacitor*(net) identifies all the decoupling capacitors on the power bus. *CalculateSeriesInductance*(capacitor) calculates the connection inductance, $L$, of each decoupling capacitor. The total effective capacitance, $C_{eff}$, of a net is calculated using the capacitance of the decoupling capacitors together with connection inductances and the interplane capacitance, $C_o$. the transient current, $I_p$, drawn from the power bus by each net is determined using the function *EstimateTransientCurrent*(net). Finally, the transient peak noise voltage induced on the power bus by each net is calculated using $C_{eff}$ and $I_p$.

The functions mentioned above are described in following sections.

### Identification of decoupling capacitors

**Subroutine**: *LocateDecouplingCapacitor*(net). Returns a flag indicating whether or not decoupling capacitors are provided on the net and stores the names of available decoupling capacitors.

For each digital power net, the subroutine identifies the capacitors connected between the net and ground. Decoupling capacitors with a value larger than 200 nF are ignored, since the parasitic inductance of these capacitors tends to prevent them from being effective at high frequencies. If there is at least one capacitor with a value less than 200 nF available, the names of the available capacitors are stored and a flag is set to 1. Otherwise, the flag is set to 0.

### Calculation of Series Inductance

**Subroutine**: *CalculateSeriesInductance*(net). Calculates and stores the series inductance associated the traces that connect decoupling capacitors.

The connection inductance associated with decoupling capacitors plays an important role at high frequencies. This subroutine calculates the inductance due to traces that connect the capacitor between a power net and ground. Figure 1 illustrates typical layouts for connecting a decoupling capacitor.

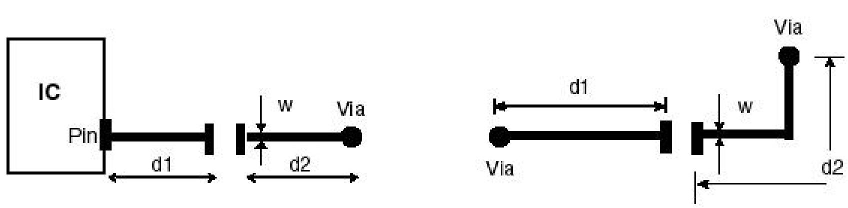


Figure 1. Typical geometry of traces for connecting power bus decoupling capacitors

The series inductance corresponding to the traces is calculated using the following equation.

$$L = 200 \times (d_1 + d_2) \times [2 + \ln(h/w)] + 1 \quad [nH] \tag{1}$$

where, *h* is the height of the traces above the reference plane. The partial inductance associated with the vias, solder pads and ESL of the capacitor is approximated as 1 nH, which is the second term in Equation (1). The subroutine stores the calculated series inductance for each capacitor on the net.

## Calculation of Total Effective Bus Capacitance

**Subroutine**: *CalculateTotalEffectiveBusCapacitor*(net). Return the value of the effective decoupling capacitance at each frequency.

In general, power bus coupling is accomplished by multiple capacitors for a net. Figure 2 shows an equivalent circuit model of a typical power bus.

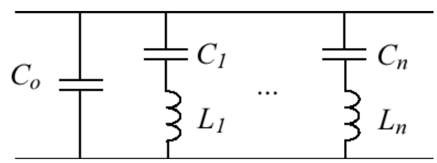


Figure 2. Equivalent circuit model of a power bus

The total capacitance of the circuit shown in Figure 2 is found by the sum of the interplane capacitance, $C_o$, and all the decoupling capacitances, $C_i$, in parallel. The effective capacitance of each decoupling capacitor changes with frequency due to the series inductance and is calculated as [1]

$$C_{eff,i} = \min\left( \left| C_i / (1 - w^2 L_i C_i) \right|,\ 2C_i \right) \qquad (2)$$

If the effective capacitance of a decoupling capacitor is much smaller than the interplane capacitance (ie, $C_{eff,i} < C_o/10$), the capacitor is ignored and stored in a list of ineffective capacitors.

For a given net, this subroutine returns the sum of all the effective capacitances plus the interplane capacitance for all the frequency blocks and narrowband frequencies.

## Estimation of Transient Current

**Subroutine**: *EstimateTransientCurrent*(net). Estimates the transient current drawn from the power bus by each IC and the transition times at rising and falling edges.

Figure 1 illustrates a typical configuration of an IC and the corresponding transient power-bus current and output signal voltage waveforms. The transient current is determined by the logic family of the device.

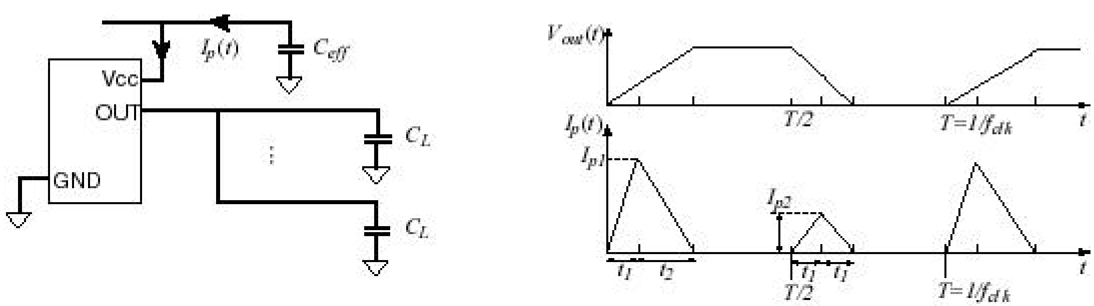


Figure 3. Typical transient power-bus current and output voltage waveforms

If the device is TTL, the following set of equations is used.

$$I_{p1} = N \cdot \frac{(V_{cc} - \Delta V)}{R} \tag{3}$$

$$I_{p2} = 0 \tag{4}$$

$$t_1 = \Delta t / 2 \tag{5}$$

$$t_2 = 2RC_L = 2R(10\ pF) \tag{6}$$

where, $N$ is the number of outputs and $Dt$ is the transition time. $C_L$ is set to its typical value, 10 pF, for convenience. Other parameters are determined by the type of the device and shown in Table 1.

Table 1. Default critical parameters for transient current calculation

| TTL family | | CMOS family | |
|---|---|---|---|
| LS | R = 110 Ω, ΔV = 0.6 V, Δt = 6 ns | MG | Ignore (too slow) |
| ALS | R = 40 Ω, ΔV = 1.0 V, Δt = 3 ns | HC | $C_{PD}$ = 50 pF<br>Switching time Δt = 4 ns |
| ABT | R = 40 Ω, ΔV = 1.0 V, Δt = 3 ns | FACT | $I_{CCD}$ = 0.31 mA/MHz<br>Switching time Δt = 2 ns |
| FAST | R = 35 Ω, ΔV = 0.6 V, Δt = 2 ns | LVC and LCX | $C_{PD}$ = 50 pF<br>Switching time Δt = 3 ns |

If the device is CMOS, the transient current drawn by the power bus is the sum of the quiescent current, the current associated with inputs, through current (the current drawn when both transistors in the output stages are switching) and the output current. The magnitude of the current associated with quiescent and input ports are much smaller than those of through current and output currents. Therefore only through current and output current are considered in this algorithm. The magnitude of through current can be calculated using an equivalent "power dissipation capacitance $C_{PD}$ [pF] " or "dynamic power supply current $I_{CCD}$ [$m$A/MHz] ". Considering the effects of both currents, the total transient current drawn from the power bus and other parameters are calculated using following equations.

$$I_{p1} = \begin{cases} \dfrac{(C_{PD} + N\,C_L)\,V_{CC}}{\Delta t} & \text{when } C_{PD} \text{ is available} \\[2ex] \dfrac{N\,C_L\,V_{CC} + I_{CCD}}{\Delta t} & \text{when } I_{CCD} \text{ is available} \end{cases} \tag{7}$$

$$I_{p2} = \begin{cases} \dfrac{C_{PD}\,V_{CC}}{\Delta t} & \text{when } C_{PD} \text{ is available} \\[2ex] \dfrac{I_{CCD}}{\Delta t} & \text{when } I_{CCD} \text{ is available} \end{cases} \tag{8}$$

$$t_1 = \Delta t / 2 \tag{9}$$

$$t_2 = \begin{cases} \dfrac{N\,C_L}{C_{PD}} \cdot t_1 & \text{when } C_{PD} \text{ is available} \\ \dfrac{N\,C_L\,V_{CC}}{I_{CCD}} \cdot t_1 & \text{when } I_{CCD} \text{ is available} \end{cases} \qquad (10)$$

The parameters are determined by default values given in Table 1 unless otherwise specified in the personality file.

## Calculation of Peak Voltage Change in Power Bus

**Subroutine**: *CalculateTransientPeakVoltage*(net). Calculates the magnitude of voltage change in power bus due to transient current drawn by ICs from decoupling capacitors.

The current drawn by an IC creates a voltage change in the power bus net to which the IC is connected. The maximum voltage change is determined by the IC that has the largest value of $I_{p1}$.

The rate of change of voltage across a capacitor is determined not only by capacitance value but also by the value of the connection inductance. This effect can be taken into account by defining an effective capacitance that is time dependent.

$$\Delta V = \frac{I_{p1} \times t_1}{2\,C(t_1)} + \frac{I_{p1} \times t_2}{2\,C(t_2)} \qquad (11)$$

where,

$$C(t_1) = C_o + \sum_{i=1}^{m} \left( \frac{C_i}{1 + 2L_i C_i / t_1^2} \right)$$

$$C(t_2) = C_o + \sum_{i=1}^{m} \left( \frac{C_i}{1 + 2L_i C_i / t_2^2} \right)$$

where, $m$ is the number of decoupling capacitors on the power bus net, $C_o$ is interplane capacitance, and $C_i$ and $L_i$ are the decoupling capacitance and the series inductance of i-th decoupling capacitor, respectively. Refer to Appendix 1 for more details about the time-dependent power bus capacitance.

## Spectrum of Narrowband Power Bus Voltage Noise

**Subroutine**: *NarrowbandVoltageComponent*(net). Calculates the amplitude of harmonics of the power bus voltage noise due to transient current drawn from ICs.

The spectrum of the power bus noise voltage can be obtained from the Fourier series expansion of the current waveform shown in Figure 3(b) together with total effective bus capacitance, $C_{eff}$, which is determined by the subroutine *CalculateTotalEffectiveBusCapacitance*(net).

$$V(f_n) = \frac{I(f_n)}{2p\ f_n C_{eff}(f_n)} \qquad (12)$$

where, $f_n = nf_o$ and I(fn) is $n$-th harmonic of transient current drawn from the power bus. Refer Appendix 2 for detailed expressions for $I(f_n)$.

## Assumptions

- Only digital components are considered.
- Board resonances are not accounted for.
- Capacitors with values larger than 200 nF are neglected.
- At power and ground nets are assumed to be planes.
- Only surface mounted capacitors are considered.

## References

[1] S. Radu, R. E. DuBroff, T. Hubing and T. Van Doren, , “Designing Power Bus Decoupling for CMOS Devices,” *Proceedings of the 1998 IEEE International Symposium on Electromagnetic Compatibility*, Denver, CO, August, 1998, pp. 375-380.

## Appendix 1. Time-Dependent Power Bus Capacitance

Consider a L-C series circuit as shown in Figure a.1, where the current drawn from the capacitor increases linearly with time. The capacitor is charged to $V_o$ at time 0.

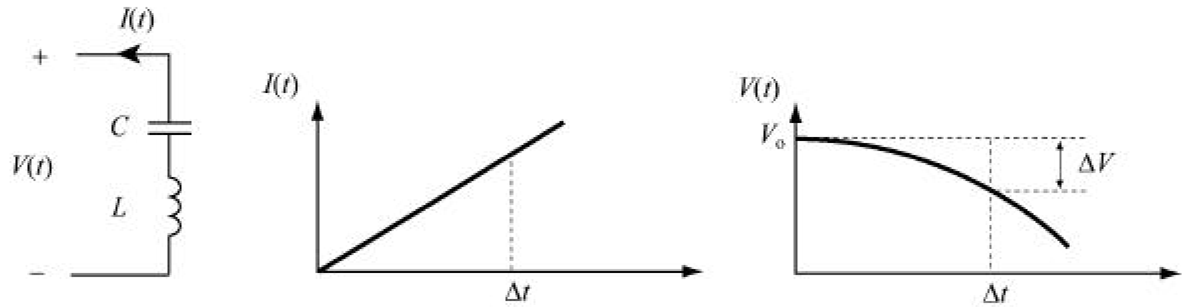


Figure a.1. Voltage variation of L-C series circuit

The differential equation that governs the circuit is

$$V(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int_0^t i(t)\,dt = V_o \qquad \text{(a.1)}$$

Let's consider the voltage variation for a short time period $\Delta t$ ($<< 2p\sqrt{LC}$). Then, equation (a.1) can be approximated as follow.

$$V(\Delta t) + L\frac{i(\Delta t)}{\Delta t} + \frac{1}{C}i(t)\Delta t \cong V_o \qquad \text{(a.2)}$$

By rearranging the equation (a.2) and introducing the effective capacitance $C_{eff}$, the voltage variation during $\Delta t$ is written as follow.

$$\Delta V = V_0 - V(\Delta t) \cong \left[\frac{L}{\Delta t} + \frac{\Delta t}{C}\right]\cdot i(\Delta t) \equiv \frac{Q(\Delta t)}{C_{eff}} = \frac{i(\Delta t)\cdot\Delta t}{2C_{eff}} \qquad \text{(a.3)}$$

Further rearranging yields time dependent effective capacitance.

$$C_{eff} = \frac{C}{1 + \left(2LC / \Delta t^2\right)} \qquad \text{(a.4)}$$

The equation (a.3) and (a.4) provides the easy way to estimate voltage variation due to triangular transient current. Consider the triangular current pulse shown in Figure a2. The voltage change due to the current can be easily calculated as

$$\Delta V = \Delta V(\Delta t_1) + \Delta V(\Delta t_2) = \frac{i_p\cdot\Delta t_1}{2C_{eff}(\Delta t_1)} + \frac{i_p\cdot\Delta t_2}{2C_{eff}(\Delta t_2)} \qquad \text{(a.5)}$$

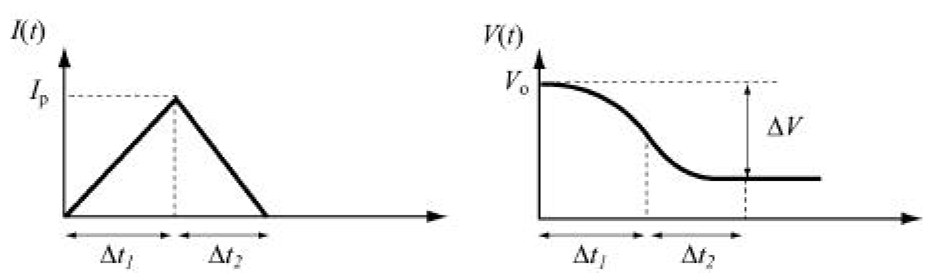


Figure a.2. Triangular current pulse and corresponding voltage variation

## Appendix 2. Time Harmonics of the Transient Current

The spectrum of the transient current can be obtained from the Fourier series expansion of the current waveform shown in Figure 3(b). The amplitudes are given as

$$I(f_n) = \sqrt{a_n^2 + b_n^2} \qquad \text{(a.6)}$$

where,

$$a_n = -\frac{I_{p1}T}{n^2 p^2} \cdot \left[ \frac{\sin^2(p\ f_n t_1)}{t_1} + \frac{\sin(b_{n1})\sin(w_n t_1 + b_{n1})}{t_{F1}} \right]$$

$$- (-1)^n \cdot \frac{I_{p2}T}{n^2 p^2} \cdot \left[ \frac{\sin^2(p\ f_n t_1)}{t_1} + \frac{\sin(b_{n2})\sin(w_n t_1 + b_{n2})}{t_1} \right]$$

$$b_n = \frac{I_{p1}T}{n^2 p^2} \cdot \left[ \frac{\sin(p\ f_n t_1)\cos(p\ f_n t_1)}{t_1} - \frac{\sin(b_{n1})\cos(w_n t_1 + b_{n1})}{t_2} \right]$$

$$+ (-1)^n \cdot \frac{I_{p2}T}{n^2 p^2} \cdot \left[ \frac{\sin(p\ f_n t_1)\cos(p\ f_n t_1)}{t_1} - \frac{\sin(b_{n2})\sin(w_n t_1 + b_{n2})}{t_{F2}} \right]$$

$$t_{F1} = t_2 / e$$

$$t_{F2} = t_1 / e$$

$$b_{n1} = \arctan(p\ f_n t_{F1})$$

$$b_{n2} = \arctan(p\ f_n t_{F2})$$

$$\sin(b_{n1}) = \frac{p\ f_n\ t_{F1}}{\sqrt{1 + (p\ f_n\ t_{F1})^2}}$$

$$\sin(b_{n2}) = \frac{p\ f_n\ t_{F2}}{\sqrt{1 + (p\ f_n\ t_{F2})^2}}$$

$$\cos(b_{n1}) = \frac{1}{\sqrt{1 + (p\ f_n\ t_{F1})^2}}$$

$$\cos(b_{n2}) = \frac{1}{\sqrt{1 + (p\ f_n\ t_{F2})^2}}$$