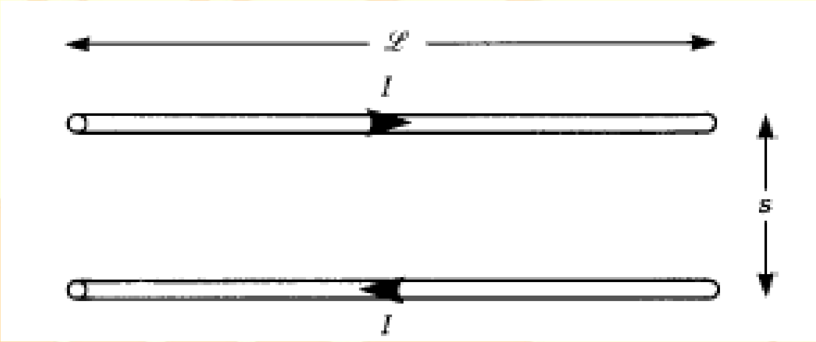
Compatibilità Elettromagnetica

Note sul comportamento non ideale delle interconnessioni

Modello delle interconnessioni



Cosa accade nel range

30 MHZ - 10 GHz?

$$l / \lambda > 0.1$$

no

si

Modello concentrato

(RLC)

Modello distribuito

(TL)

Cavi circolari

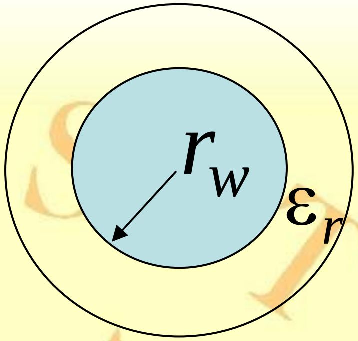


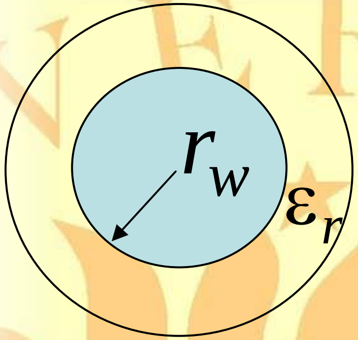
TABLE 5.1 Conductivities (Relative to Copper) and Permeabilities (Relative to Free Space) of Conductors

Conductor	σ_r	μ_r
Silver	1.05	1
Copper—annealed	1.00	1
Gold	0.70	1
Aluminum	0.61	1
Brass	0.26	1
Nickel	0.20	600
Bronze	0.18	1
Tin	0.15	1
Steel (SAE 1045)	0.10	1000
Lead	0.08	1
Monel	0.04	1
Stainless steel (430)	0.02	500
Zinc	0.32	1
Iron	0.17	1000
Beryllium	0.10	1
Mu-metal (at 1 kHz)	0.03	30,000
Permalloy (at 1 kHz)	0.03	80,000

TABLE 5.3 Relative Permittivities of Insulation Dielectrics

Material	ϵ_r
Air	1.0005
Styrofoam	1.03
Polyethylene foam	1.6
Cellular Polyethylene	1.8
Teflon	2.1
Polyethylene	2.3
Polystyrene	2.5
Silicone rubber	3.1
Nylon	3.5
Polyvinyl chloride (PVC)	3.5
Epoxy resin	3.6
Quartz (fused)	3.8
Glass (pyrex)	4.0
Epoxy glass (PCB substrate)	4.7
Bakelite	4.9
Mylar	5.0
Porcelain	6.0
Neoprene	6.7
Polyurethane	7.0
Silicon	12.0

Resistenza ed induttanza interna – skin effect



Resistenza DC $R = \dfrac{\mathscr{L}}{\sigma \pi r_w^2} \quad \Omega$

Spessore di penetrazione $\delta = \dfrac{1}{\sqrt{\pi f \mu_0 \sigma}}$

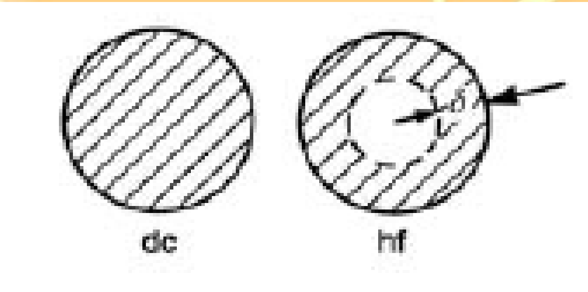


TABLE 5.4 Skin Depth of Copper

f	δ
60 Hz	8.5 mm
1 kHz	2.09 mm
10 KHz	0.66 mm
100 kHz	0.21 mm
1 MHz	2.6 mils
10 MHz	0.82 mils
100 MHz	0.26 mils
1 GHz	0.0823 mils

$(\sigma = 5.8 \times 10^7 \text{ S/m}, \ \epsilon_r = 1, \ \mu_r = 1)$

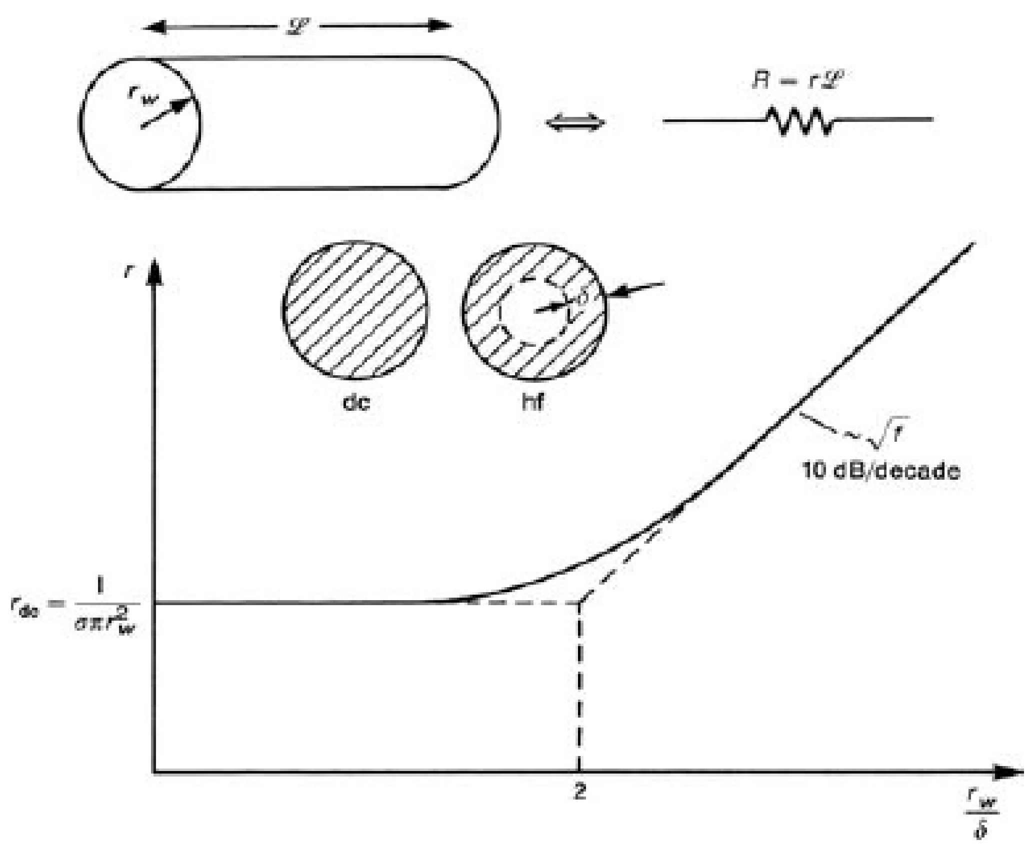
Resistenza interna – skin effect

$$R = \frac{\mathscr{L}}{\sigma \pi r_w^2} \quad \Omega$$

$$r_{\mathrm{lf}} = r_{\mathrm{dc}} \quad \text{for } r_w \ll \delta$$

$$r_{\mathrm{hf}} = \frac{r_w}{2\delta} r_{\mathrm{dc}} \quad \text{for } r_w \gg \delta$$

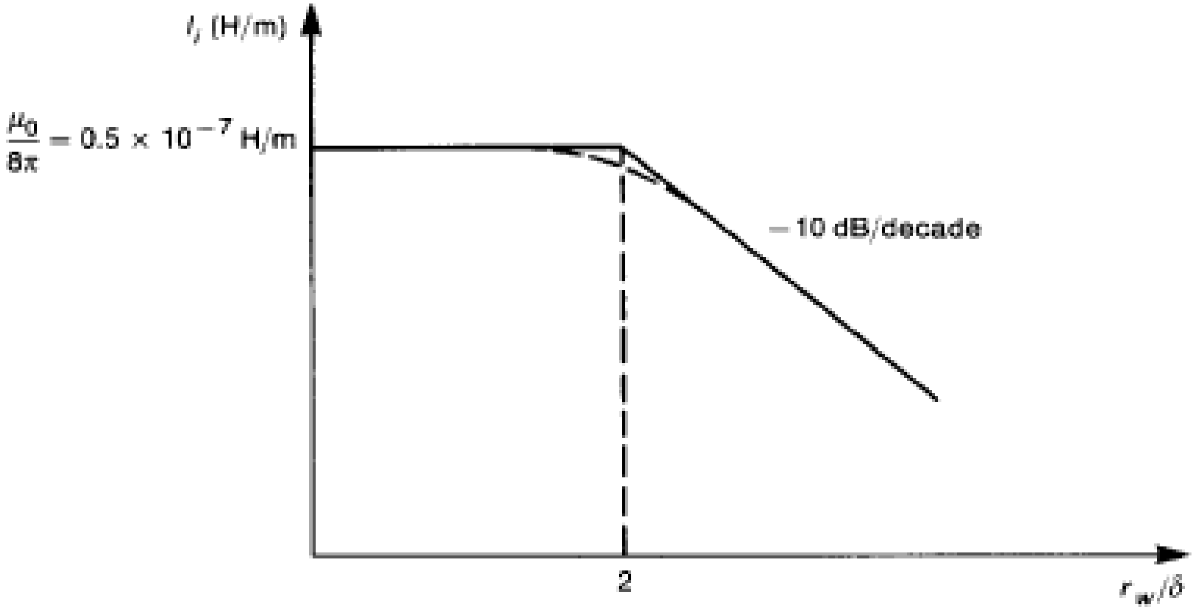
$$= \frac{1}{2 r_w} \sqrt{\frac{\mu_0}{\pi \sigma}} \sqrt{f}$$



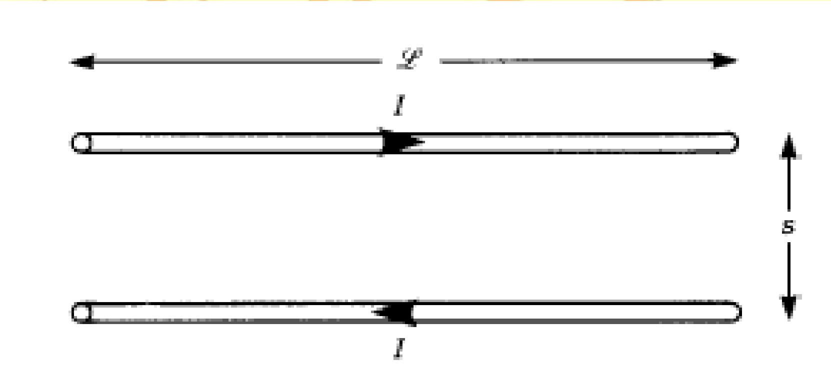
Induttanza interna – skin effect

$$l_{i,\,\mathrm{dc}} = \frac{\mu_0}{8\pi} \quad \text{for } r_w \ll \delta$$

$$l_{i,\,\mathrm{hf}} = \frac{2\delta}{r_w} l_{i,\,\mathrm{dc}} \quad \text{for } r_w \gg \delta$$
$$= \frac{1}{4\pi r_w}\sqrt{\frac{\mu_0}{\pi\sigma}}\frac{1}{\sqrt{f}}$$



Induttanza esterna: è associata ad un loop di corrente



$$L_{loop} = 2l_i\mathscr{L} + l_e\mathscr{L}.$$

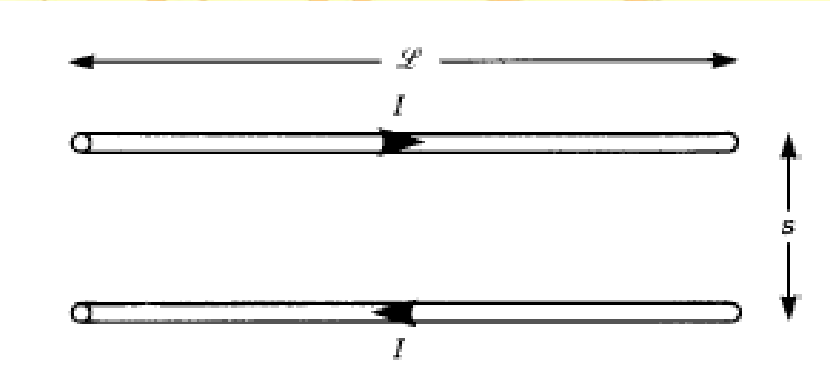
Modo differenziale

Wide separation

$(s/r_w > 5)$

$$l_e = \frac{\psi_m/\mathscr{L}}{I} = \frac{\mu_0}{\pi}\ln\left(\frac{s}{r_w}\right) \quad \text{(in H/m)}$$

Capacità esterna: è associata alla carica per unità di lunghezza

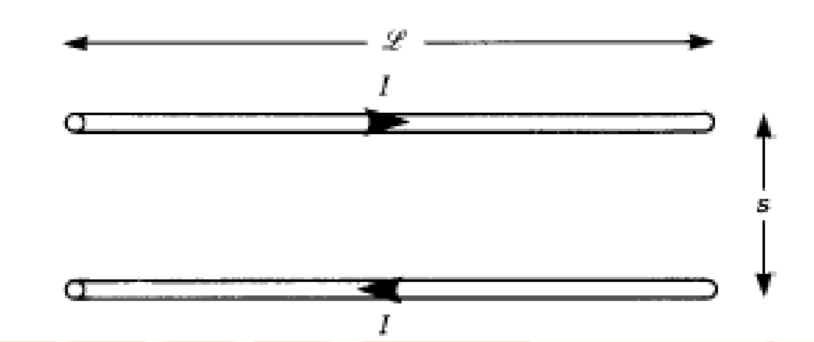


Capacità p.u.l. in assenza di dielettrico

$$c = \frac{Q/\mathscr{L}}{V} = \frac{\pi \epsilon_0}{\ln(s/r_w)} \quad \text{(in F/m)}$$

In presenza di dielettrico si usa una ε_{eff} (ad esempio il valore medio delle ε_r)

Modello di un coppia di conduttori circolari



$$l / \lambda > 0.1$$

no

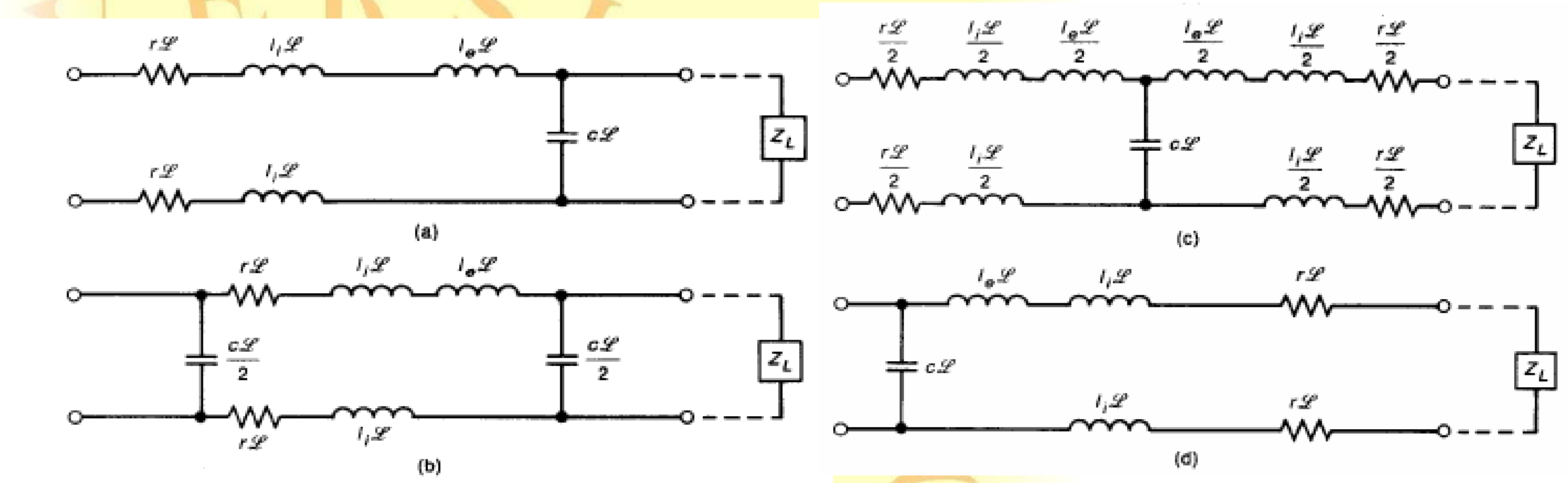
si

Modello concentrato

(RLC)

Modello distribuito (TL) con i parametri p.u.l. (r, l, c) valutati come in precedenza

Modelli concentrati



(a) Lumped backward Γ (b) lumped PI (c) lumped T (d) lumped Γ