Power Supply Decoupling (Bypassing)

Decoupling becomes very important in both digital and analog dc circuits. In these dc circuits, any slight variations in voltage within the circuit may cause improper operation. For example, in Fig. 3.69, noise (random fluctuations in supply voltage) present on the V_{CC} line can cause problems by presenting improper voltage levels to an IC's sensitive supply lead. (Some ICs will act erratically if this happens.) However, by placing a bypass capacitor in parallel to the IC's input, the capacitor will bypass the high-frequency noise around the IC to ground, thus maintaining a steady dc voltage. The bypass capacitor acts to decouple the IC from the supply.

It's important to note that variations within the supply voltage line aren't caused just by random low-level fluctuations. They are also caused by sudden fluctua-tions in voltage caused by high- current switching action that draws sudden, large amounts of current from the supply line. The more current these devices draw, the bigger the ripple in the supply line. Relay and motor switching is notorious in this regard. (Usually these devices incorporate a snubber diode or some type of local transient suppressor to limit the magnitude of the transient. However, low- level, high- frequency ringing that occurs after switching will often sneak into the line.) Even TTL and CMOS ICs can generate current spikes in the power lines, due to a

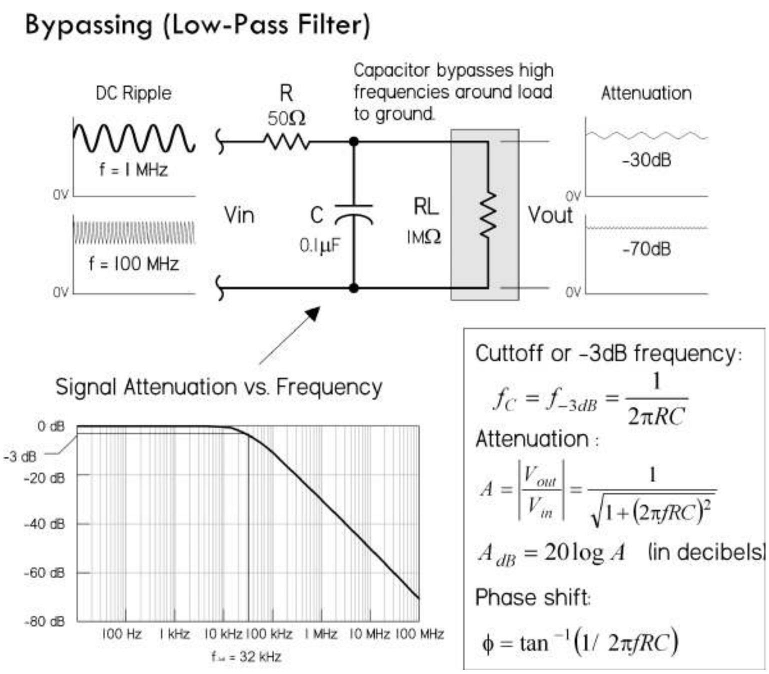


FIGURE 3.68

In this circuit,the RC section acts like a low-pass filter, which attenuates high frequencies from reaching the load or circuit element.

As $X_C < R_L$, signals bypass R_L through C.
As $X_C > R_L$, signals pass through R_L.

where $X_C = 1/(2\pi fC)$, the capacitor's reactance. In other words, at high frequencies, X_C gets small, so signals tend to be diverted around R_L through C.

The graph in the figure shows the attenuation versus frequency response, and the equations tell you how to calculate the cutoff frequency, attenuation, and phase shift.

Note that the R in the circuit in this figure isn't often physically present as a dis-crete component. It may represent, say, the inherent resistance present in the power sup-ply line (which is usually much smaller than what's shown). Though R helps set the fre-quency response, it can reduce the clamping efficiency.

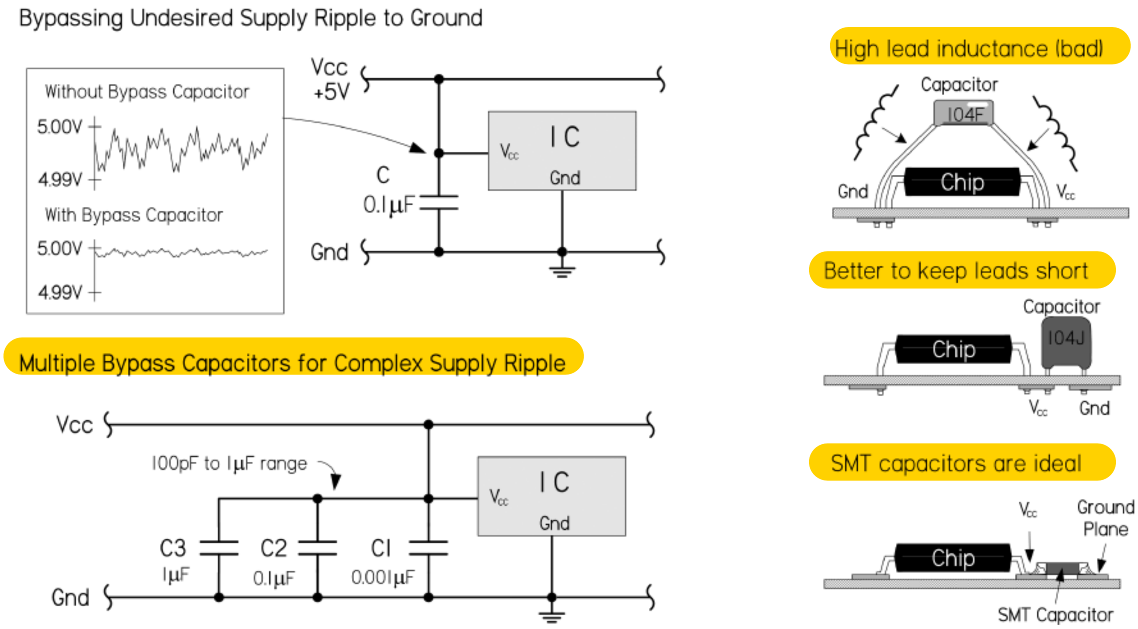


FIGURE 3.69 **The top circuit uses a 0.1-μF decoupling capacitor to keep the dc supply line free of high-frequency transients. The lower circuit uses three capacitors of different capacitance levels to handle a wide range of transient frequencies.**

transient state in which both output transistors are simultaneously on. The resis-tance between the 5-V supply terminals limits the supply current, and as speed increases this resistance gets smaller, and the transient currents increase to as high as 100 mA. These transient currents usually contain high frequencies due to the fast switching of the logic device. When the current spikes propagate down a power distribution system, they can develop 10- to 100-mV voltage spikes. Even worse, if an entire bus changes states, the effects are additive, resulting in transients as high as 500 mV propagating down the power lines. Such large transients wreak havoc within logic circuits.

It's important to regard the power supply and the distribution systems (wires, PCB bus, etc.) as nonideal. The power supply contains internal resistance, and the sup-ply distribution system (wires, PCB traces, etc.) contains small amounts of resistance, inductance, and capacitance. Any sudden demands in current from a device attached to the distribution system will thus result in a voltage dip in the supply—use Ohm's law.

SELECTING AND PLACING DECOUPLING CAPACITORS

What Needs Bypassing: High clock- rate logic circuits and other sensitive analog cir-cuits all require decoupling of the power supplies. As a general rule of thumb, use one 0.1-μF ceramic per digital chip, two 0.1-μF ceramics per analog chip, (one on each supply where positive and negative supplies are used) and one 1-μF tantalum per every eight ICs or per IC row, though you can often do with less. Also, a good place for bypass capacitors is on power connectors. Anytime power lines are leading off to another board or long wire, it's a good idea to throw in a bypass capacitor; long wires act like inductive antennas, picking up electrical noise from any magnetic field. A capacitor at both ends of the wire is a good idea—a 0.01-μF or 0.001-μF capacitor connected across the line will often do the trick.

Placement: Capacitor placement is crucial for good high-frequency decoupling. Place capacitors as close as possible to the IC, between power pin and ground pin, and ensure that leads consist of wide PC tracks. Run traces from device to capacitor, then to power planes. Capacitor lead lengths must be kept short (less than 1.5 mm); even a small amount of wire has considerable inductance, which can resonate with the capacitor. Surface-mount capacitors are excellent in this regard, since you can place them almost on top of the power leads, thus eliminating lead inductance.

Size of Capacitor: The frequency of the ripple has a role in choosing the capacitor value. A rule of thumb: the higher the frequency ripple, the smaller the bypass capacitor. In Fig. 3.69, a 0.01- to 0.1-μF capacitor with a self- resonant frequency from around 10 to 100 MHz is used to handle high-frequency transients. If you have very high-frequency components in your circuit, it might be worth using a pair of capacitors in parallel—one large value (say, 0.01 μF) and one small value (say, 100 pF). If there is a complex ripple, several bypass capacitors in parallel may be used, each one targeting a slightly different frequency. For example, in the lower circuit in Fig. 3.69, C_1 (1 μF) catches the lower voltage dips that are rela-tively low in frequency (associated with bus transients), C_2 (0.1 μF) the midrange frequencies, and C_3 (0.001 μF) the higher frequencies. In general, local decoupling values range from 100 pF to 1 μF. It's generally not a good idea to place a large 1-μF capacitor on each individual IC, except in critical cases; if there is less than 10 cm of reasonably wide PC track between each IC and the capacitor, it's possible to share it among several ICs.

Type of Capacitor: The type of capacitor used in decoupling is very important. Avoid capacitors with low ESR, high inductance, and high dissipation factor. For example, aluminum electrolytic capacitors are not a good choice for high-frequency decoupling. However, a 1-μF tantalum electrolytic, as mentioned before, is useful when decoupling at lower frequencies. Monolithic ceramic capacitors, especially surface- mount types, are an excellent choice for high- frequency decoupling due to their low ESL and good frequency response. Polyester and polypropylene capaci-tors are also good choices, provided you keep lead lengths short. The capacitor you eventually choose will depend on the frequency range you're trying to eliminate. See Table 3.7 for suggested decoupling capacitors.

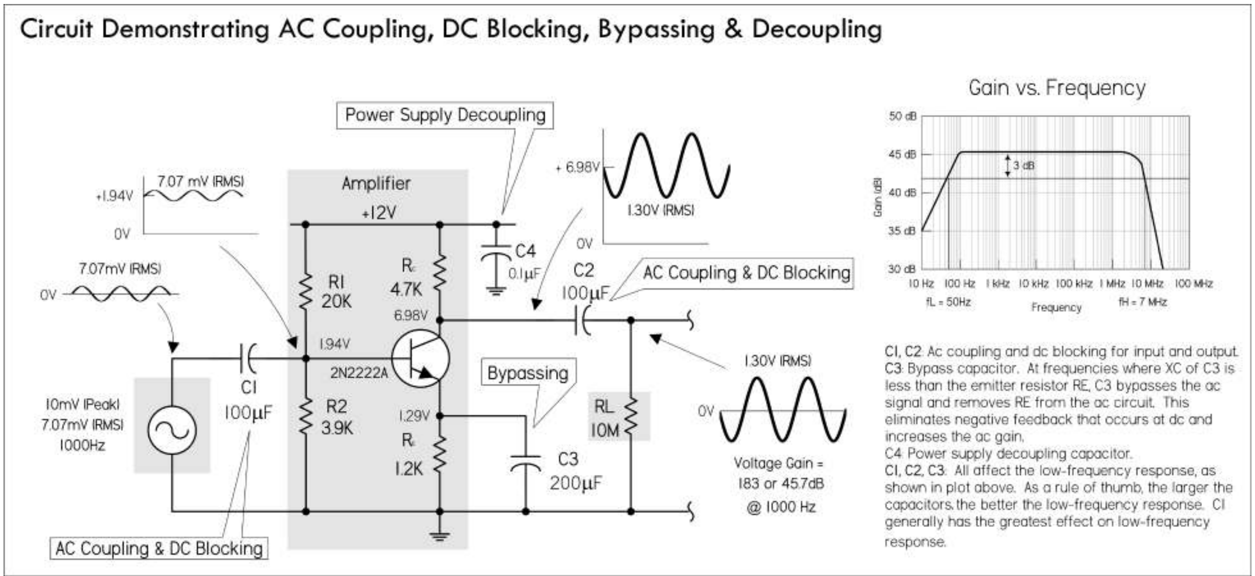


FIGURE 3.70

TABLE 3.7 Capacitor Comparison

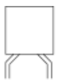
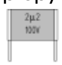
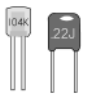
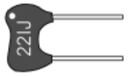
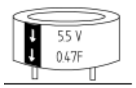
TYPE		1. WVDC 2. CAPACITANCE 3. DIELECTRIC ABSORPTION 4. STANDARD TOLERANCE	IR 1. $<1\mu F$ 2. $>1\mu F$ ($M\Omega$-μF)	FREQUENCY RESPONSE 1. (1= POOR, 10 = BEST) 2. MAX. FREQUENCY	TEMPERATURE RANGE	DF @ 1 KHZ, % (MAX.)	STABILITY 1000 HOURS %ΔC	ADVANTAGES/DISADVANTAGES	APPLICATIONS
Multilayer Ceramics	NPO	25–200 V 1pF–0.01 µF 0.6% ±1 (F), ±2% (G), ±5% (J), ±10% (K)	10^5 NA	9 100 MHz	–55°C, +125°C	0.1%	0.1%	Good stability, low inductance, low DA, good frequency response. Very low temperature drift, very low aging, voltage coefficient, frequency coefficient, leakage, and dissipation factor. More expensive than the other types of ceramics.	Excellent in HF decoupling (into the GHz range) due to low series inductance. High-frequency switch-mode power supplies. Used in many analog applications, such as HF switch-mode power supplies, but avoided in sample-hold and integrators, where DA may be a problem.
 	Stable	25–200 V 220 pF–0.47 µF 2.5% ±5% (J), ±10% (K), ±20% (M)	10^5 2500	8 10 MHz	–55°C, +125°C	2.5%	10%	Low inductance, wide range of values, small, higher density than dipped ceramic. Poor stability, poor DA, high voltage coefficient, and significant aging rate. Sensitive to vibration—some types may be resonant with comparatively high Q.	Best suited for coupling/dc blocking and power supply bypassing. They should be used only in linear applications where performance and stability are of no great concern.
	(High-K) HiK	25–100 V 0.25 pF–22 µF NA ±20% (M), ±80%–20% (Z)	10^4 10^3	8 10 MHz	+10°C, +85°C and –55°C, +85°C	4.0%	20%	Very poor stability, especially with temperature variations. Poor DA and high voltage coefficient. Not suited for high-temperature environment. Short longevity.	Limited mainly to dc blocking and power supply bypassing. Even then, change in capacitance due to aging, temperature, and voltage coefficients must be taken into consideration. Use lowest-K material you can get.
Ceramic Disc (NPO, Stable, HiK) 		50–10,000 V 1pF–0.1 µF Same as multilayers	Same as multilayers	8 Same as multilayers	–55°C, +85°C	0.1% – 4.0%	Same as multilayers	Inexpensive, wide range of values, and popular. Same features as multilayers.	Used in coupling and bypassing, but can be quite inductive if leads are long. Internal structure not coiled, so can be used in high-frequency applications. See applications of multilayers.
Polystyrene 		30–600 V 100 pF–0.027 µF 0.05% ±65%	10^6 NA	6 NA	–55°C, +70°C	0.1%	2%	Inexpensive, low DA available, wide range of values, good stability. High isolation resistance. Damaged by temperatures >+70°C. Large case size, high inductance.	Not used in high-frequency applications—inside acts like an inductor coil. Works well in filter circuits or timing circuits that run at several hundred kHz or less. Good choice for coupling and/or storage applications due to high isolation resistance.

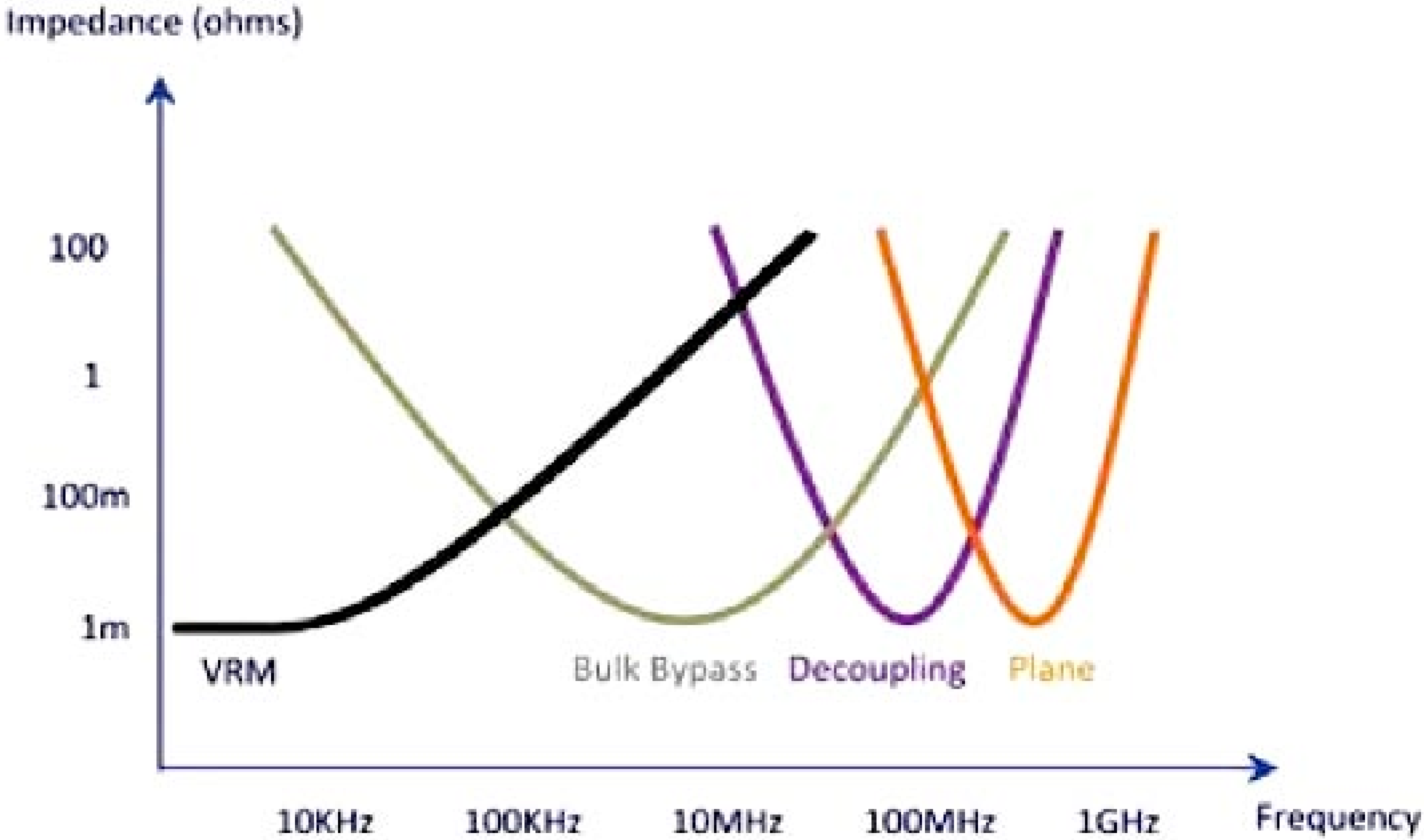
TABLE 3.7 Capacitor Comparison (*Continued*)

TYPE	1. WVDC 2. CAPACITANCE 3. DIELECTRIC ABSORPTION 4. STANDARD TOLERANCE	IR 1. <1μF 2. >1μF (MΩ-μF)	FREQUENCY RESPONSE 1. (1= POOR, 10 = BEST) 2. MAX. FREQUENCY	TEMPERATURE RANGE	DF @ 1 KHZ, % (MAX.)	STABILITY 1000 HOURS %Δ*C*	ADVANTAGES/DISADVANTAGES	APPLICATIONS
Polypropylene Film 	100–600 V 0.001 μF to 0.47 μF 0.05% ±5%	10^5 NA	6 NA	–55°C, +85°C	0.35%	3%	Inexpensive, low DA available, wide range of values, high isolation resistance, damaged by temperatures >105°C, large case size.	Good choice for coupling and/or storage applications due to high isolation resistance. Most stable capacitance for frequencies below 100 kHz, but often used at higher frequencies. Used for noise suppression, blocking, bypassing, coupling, filtering, snubbing, and timing. Good general-purpose capacitor.
Metallized Polypropylene 	100–1250 V 47 pF–10 μF 0.05% [±20% (M), ±10%(K), ±5% (J)]	10^5 NA	6 NA	–55°C, +105°C	0.05%	2%	More compact than film/foil types, but higher DF, lower IR, lower maximum current, lower ac-unique self-healing feature, unlike film/foil, voltage-frequency capability.	Used in moderately high-frequency, high-voltage circuits, and for noise suppression, timing, and snubbing. Used in switching power supplies, audio equipment (provide musically clean dynamic), and many other general-purpose applications.
Polyester Film (Mylar) 	50–600 V 0.001 μF–10 μF 0.5% ±10	10^4 10^3	6 NA	–55°C, +125°C	2%	10%	Moderate stability, inexpensive, low DA available, wide range of values, high isolation resistance, large case size.	Good choice for coupling and/or storage applications due to high isolation resistance. Moderately high-frequency circuits, audio sound quality, oscillator circuits.
Metallized Polyester 	63–1250 V 470 pF–22 μF 0.5% [±20% (M), ±10%(K), ±5% (J)]	10^4 10^3	6 NA	–55°C +125°C	0.8%	NA	More compact than film/foil types, but higher DF, lower IR, lower maximum current, lower ac-voltage-frequency capability. Does have a unique self-healing feature, unlike film/foil, which prevents dielectric breakdown from resulting in catastrophic permanent failure.	General-purpose applications, audio equipment, moderately high-frequency, high-voltage applications. Switching power supplies, blocking, bypassing, filtering, timing, coupling, decoupling, and interference suppression.

Mica 	50–500 V 1 pF–0.09 μF 0.3%–0.7% ±1% ±5%	10^2 NA	7 100	−55°C, +125°C	0.1%	0.1%	Low loss at HF, low inductance, very stable, available in 1% values or better Large, low values (<10 nF), expensive.	Excellent capacitor, good at RF. Used in resonance circuits and high-frequency filters, due to good stability with temperature. Also used in high-voltage circuits due to their good insulation.
Multilayer Glass	50–2000 V 0.5 pF–0.01 μF 0.05% ±1%, ±5%	10^5 NA	9	−75°C, +200°C	0.2%	0.5%	Extremely low stable Q factor at high frequencies, low dielectric absorption, large RF current capability, high operating temperature range, high shock/vibration capability. Excellent stability and long-term stability.	Use in military applications and high-performance commercial sectors. Wide applications: high-temperature circuitry, modulators, RF amplifier output filters, variable-frequency oscillators, amplifier coupling, sample-hold, transistor biasing, ramp integrators, voltage snubbers, etc.
Aluminum Electrolytic 	4 V–450 V 0.1 μF–1 F High +100%, −10%	NA 100	2 NA	−40°C, +85°C	8% at 120 Hz	10%	High currents, high voltages, small size. Very poor stability, poor accuracy, inductive. Usually polar, meaning they can be damaged if placed in reverse polarity.	Not suited for storage or HF coupling applications due to poor isolation resistance and internal inductance. Usually used as a ripple filter in power supplies or as a filter to bypass low-frequency signals. Used in audio bypassing and power supply filtering—at higher frequencies there is too much loss.
Tantalum Electrolytic 	6.3–50 V 0.01–1000 μF High ±20%	10^2 10	5 0.002 MHz	−55°C, +125°C	8%– 24%	10%	Small size, large values, medium inductance. Better capacitance stability than aluminum with temperature. Quite high leakage, usually polarized, expensive, poor stability, poor accuracy.	Not suited for storage or HF coupling applications due to poor isolation resistance and internal inductance. Acts more like an inductor than a capacitor above a few MHz. Used in dc blocking, bypassing, decoupling, filtering, and timing. Usually used as a ripple filter in power supplies or as a filter to bypass low-frequency signals.
Double-Layer Supercapacitor Ultracapacitor 	2.3 V, 5.5 V, 11 V, etc. 0.022–50 F High	NA	NA	−40°C, +70°C	NA	NA	Huge capacitance values, high power output. Exhibit relatively high ESR, and therefore are not recommended for ripple absorption in dc power supply applications. Low leakage, but poor temperature stability.	Actuator applications (relay-solenoid starters), primary power supply for LED displays, electric buzzers, etc. Power backup for CMOS microcomputers. Also used in many interesting low-powered circuits, such as solar- powered robots, where they store energy and act as the primary power source. Many other creative uses.

Radio Frequency Spectrum: Ranges

Designation	Abbreviation	Frequencies	Wavelengths
Very Low Frequency	VLF	3 kHz - 30 kHz	100 km - 10 km
Low Frequency	LF	30 kHz - 300 kHz	10 km - 1 km
Medium Frequency	MF	300 kHz - 3 MHz	1 km - 100 m
High Frequency	HF	3 MHz - 30 MHz	100 m - 10 m
Very High Frequency	VHF	30 MHz - 300 MHz	10 m - 1 m
Ultra High Frequency	UHF	300 MHz - 3 GHz	1 m - 100 mm
Super High Frequency	SHF	3 GHz - 30 GHz	100 mm - 10 mm
Extremely High Frequency	EHF	30 GHz - 300 GHz	10 mm - 1 mm


Impedance (ohms)
100
1
100m
1m
VRM
Bulk Bypass
Decoupling
Plane
10KHz
100KHz
10MHz
100MHz
1GHz
Frequency