TEMPEST Low Emission Controlled Design

Volume 3B – Electronic Design

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Based on the Texts:

TEMPEST, A Description and Approach
Hardwire and Cable Design in Secure Communications
TEMPEST Hardware Design
TEMPEST Systems Engineering & Program Management
INFOSEC Engineering

Transformer Isolation

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Transformers Provide Isolation

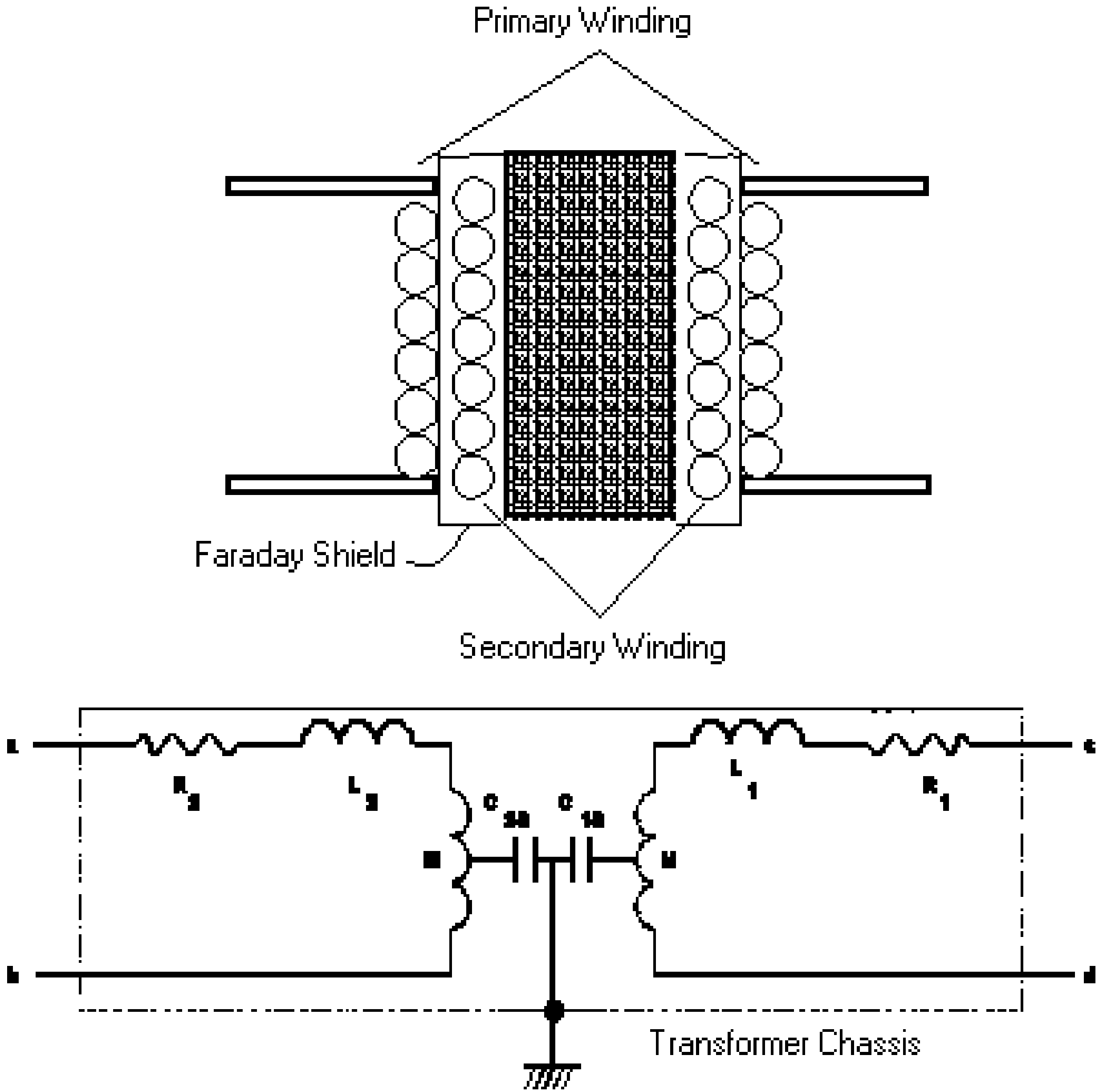
- All transformers provide some level of isolation.
  - The mechanism through which electrical coupling of high frequency noise occurs is the capacitance between the coils of the primary and secondary windings of the transformer.
- Careful transformer application and shielding, including external mu-metal shielding and internal faraday shielding of the windings can greatly reduce both conducted and radiate signal problems.

Regular Transformers

- Constructed with a primary and secondary winding closely wrapped about the same ferrous core.
- Use a single Faraday shield between the primary and secondary windings to divert noise.
- Noise coupling occurs through the capacitance between the coils of the primary and secondary windings.

Regular Transformer Problems

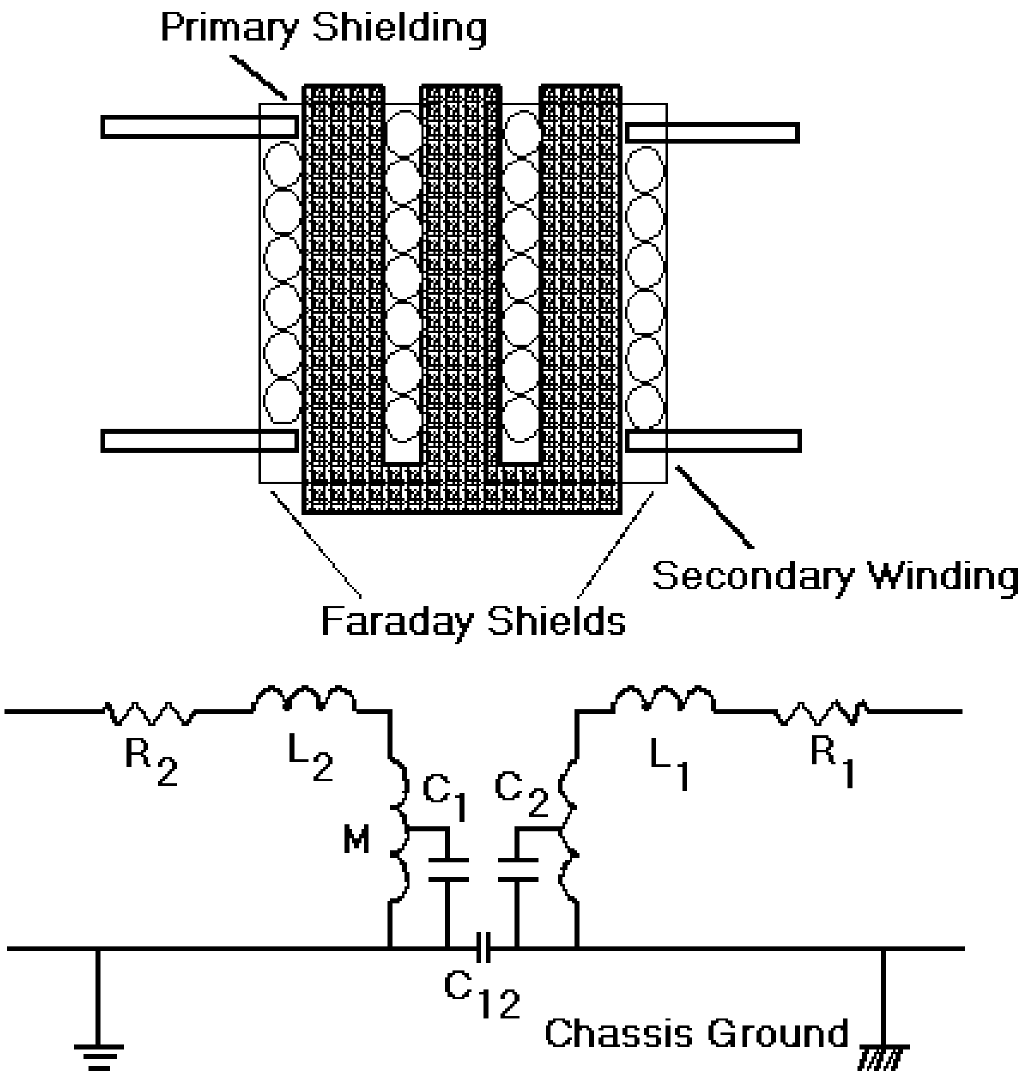
- The problem with a single Faraday shield arises when it is bonded to the ground of either the primary or secondary side of the transformer.
  - While it eliminates inter-capacitance, it also establishes two new capacitances between the shield and both windings.
  - These two capacitances allow high frequency currents to flow in the grounding systems of both the primary and secondary.



Standard Transformer Design

Isolation Transformers

- Constructed with two isolated Faraday shields between the primary and secondary windings.
- The use of two shields diverts noise that would couple across the transformer to the grounds of the circuit in which they occur.
- The coupling capacitance is minimized by increasing the separation between the two Faraday shields.



Isolation Transformer Design

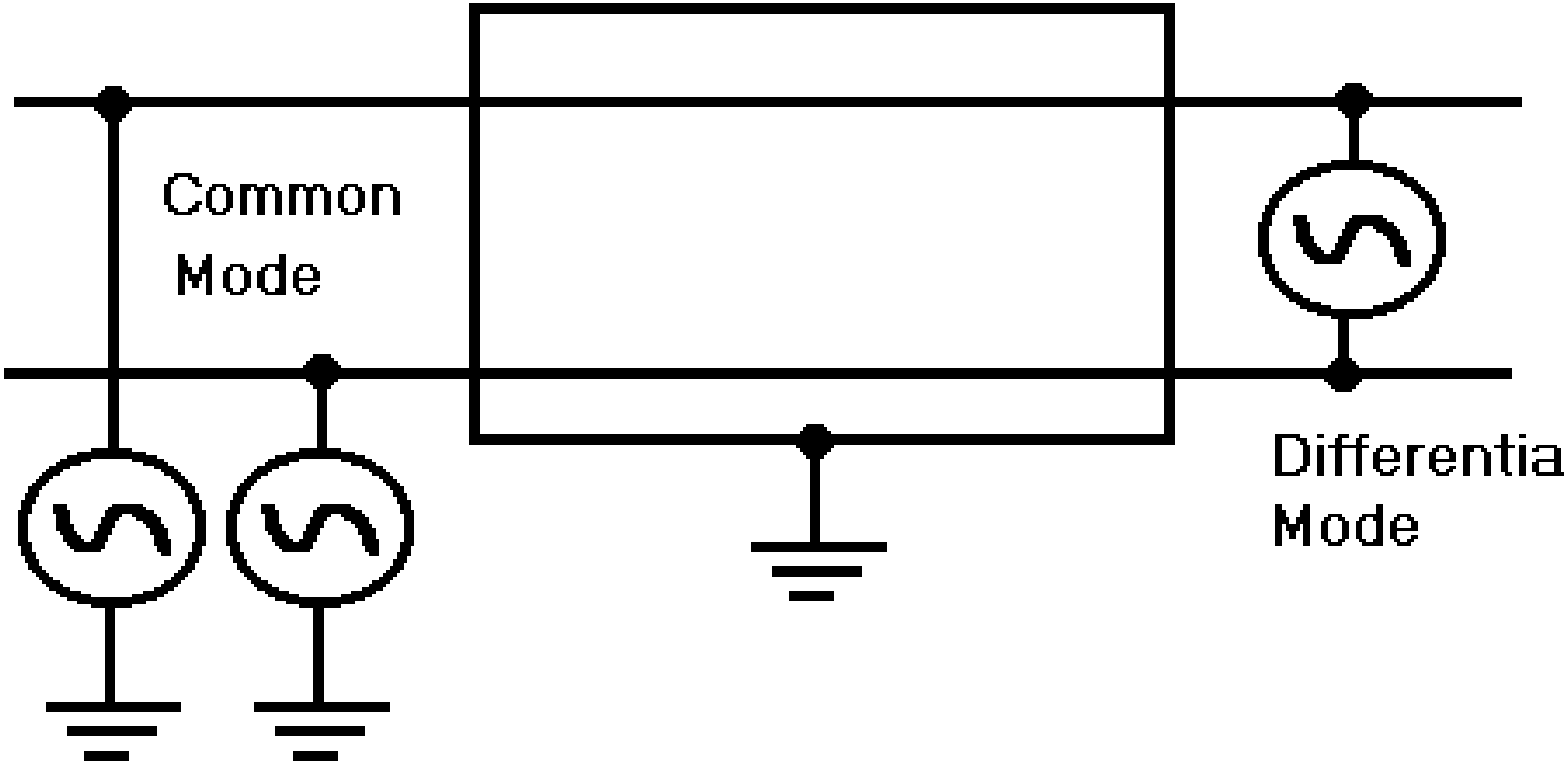
Emission Control

- Emissions appear in three forms in a transformer circuit: common-mode, differential-mode, and electromagnetic.
- Common-mode emissions are referenced to the power system ground.
  - Control these emissions is by grounding the transformer center tap to the system ground via the lowest impedance path possible.
- Key to reducing differential-mode emissions is to differentiate between power generated noise and emissions, and then reduce only the emissions.

Differential-Mode Control

- Emissions and power generated noise are separated by the difference in their frequencies.
- The objective is to transfer the power required by the load at the fundamental power frequency, and to eliminate all higher and lower frequencies.
  - Sub-harmonic frequencies are attenuated by operating the transformer at a relatively high flux density, which is effective in greatly reducing or eliminating these frequencies.
  - Above the fundamental frequency, noise is reduced by introducing as much leakage inductance as possible.

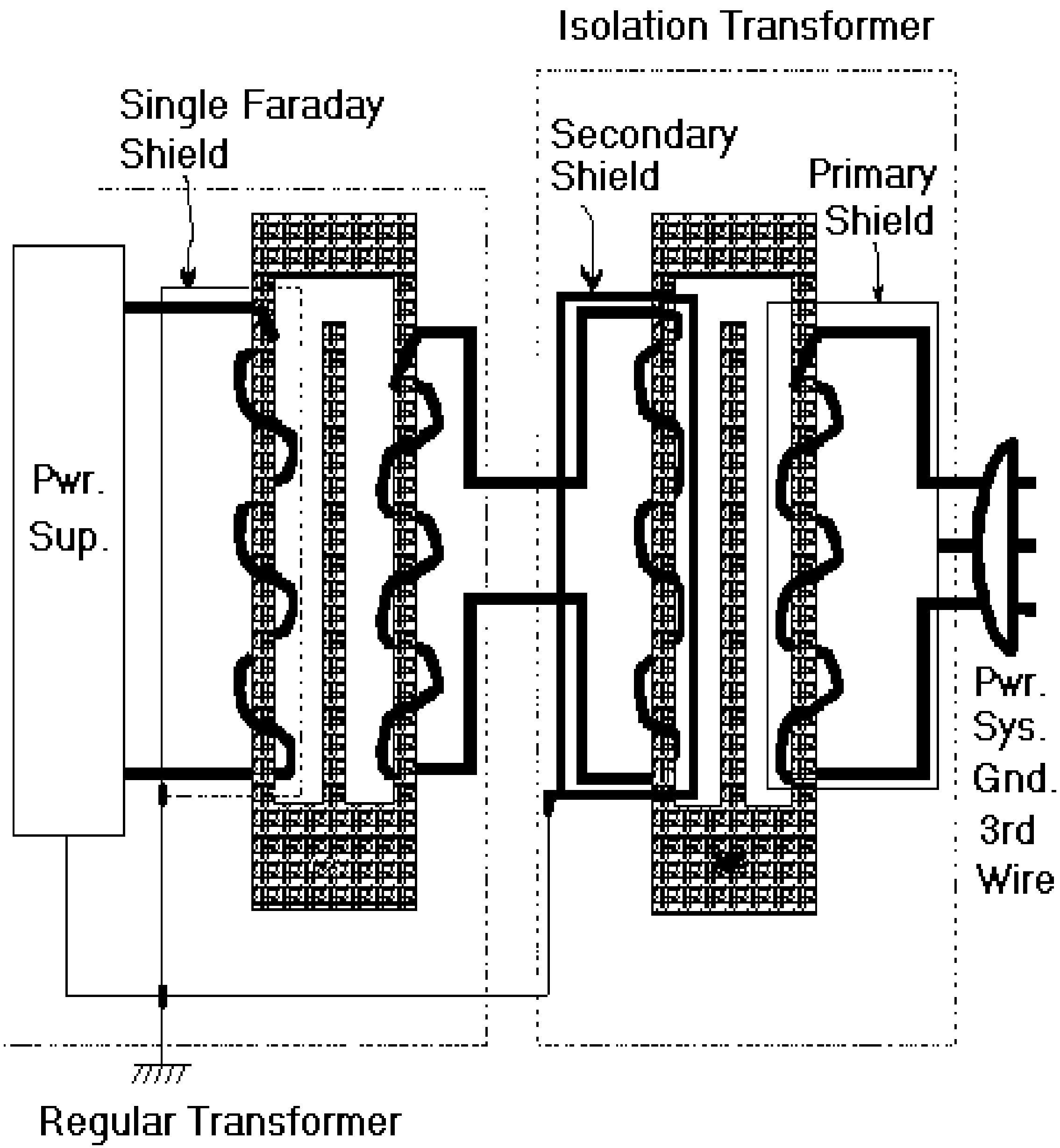
Noise Sources



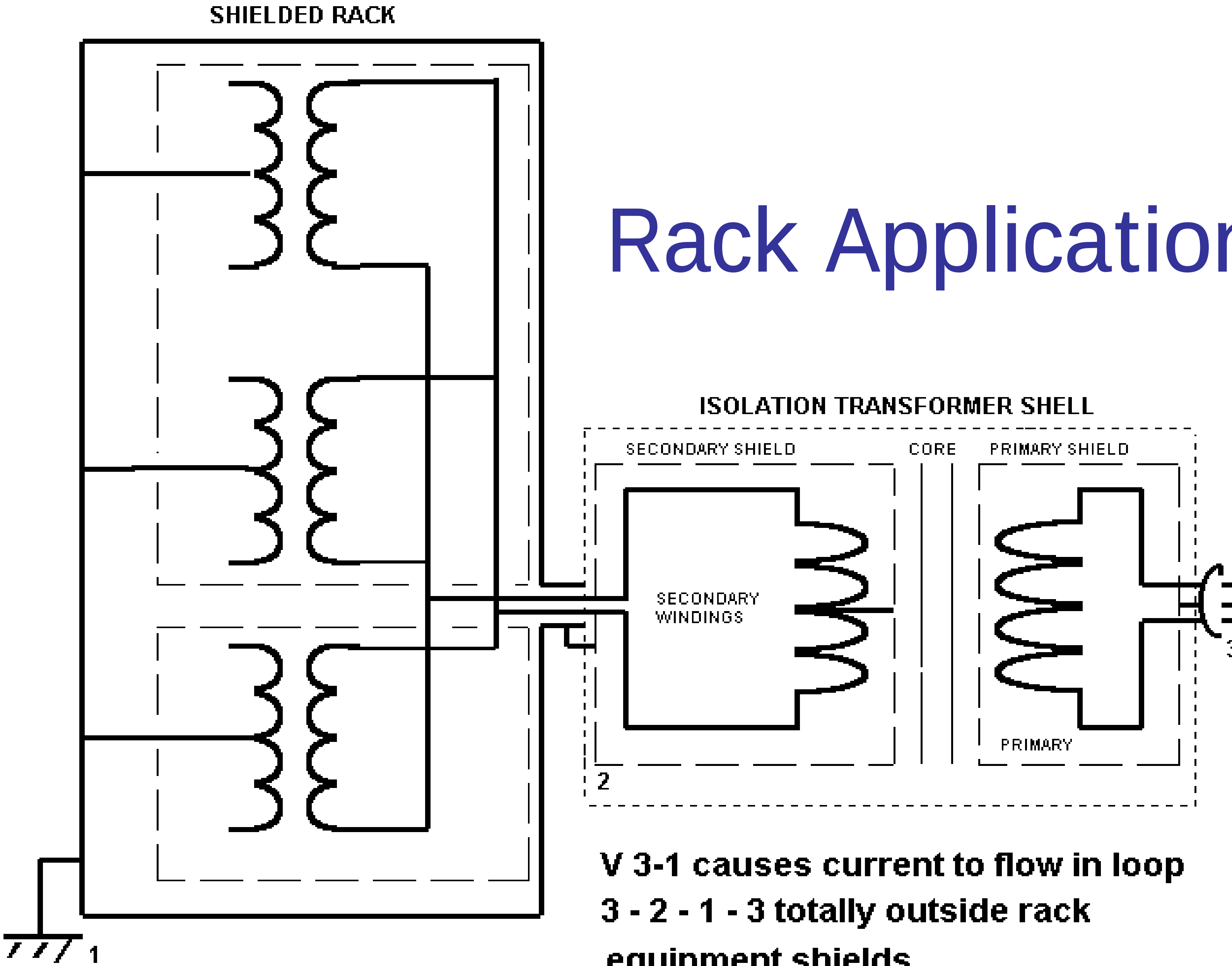
Powerline Control

- Powerline decoupling using transformers extends from the box to the rack to the facility.
- Except for direct line switchers, power sources nearly always rely on some form of line stepdown and rectification for their generation.

Box Level Application

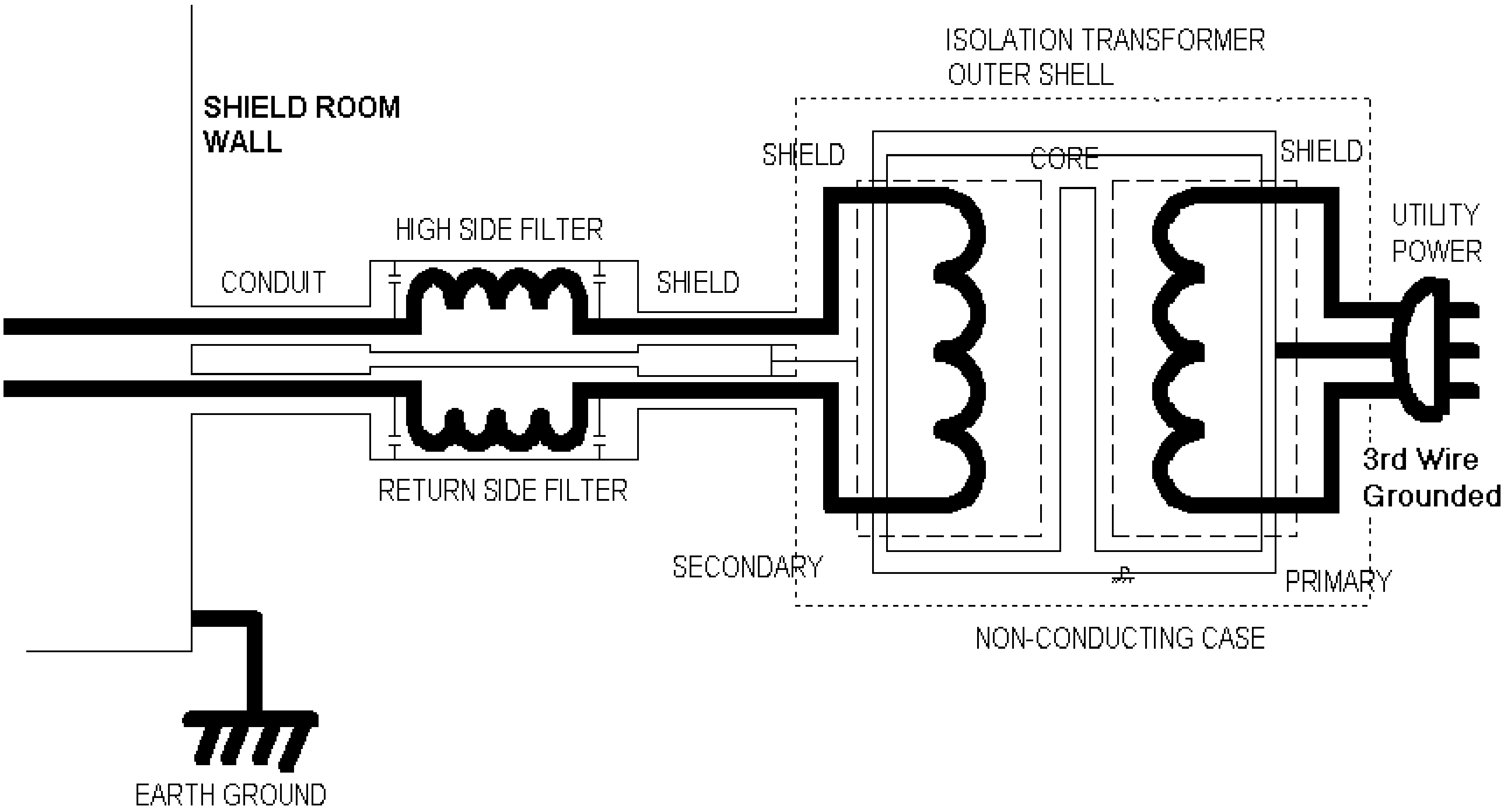


Rack Application



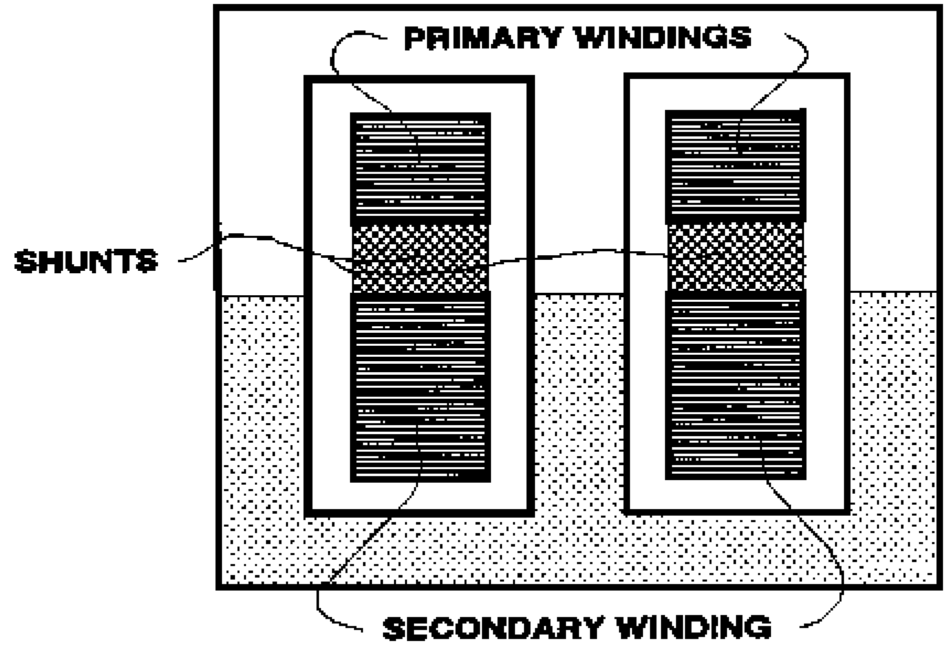
V 3-1 causes current to flow in loop 3 - 2 - 1 - 3 totally outside rack equipment shields

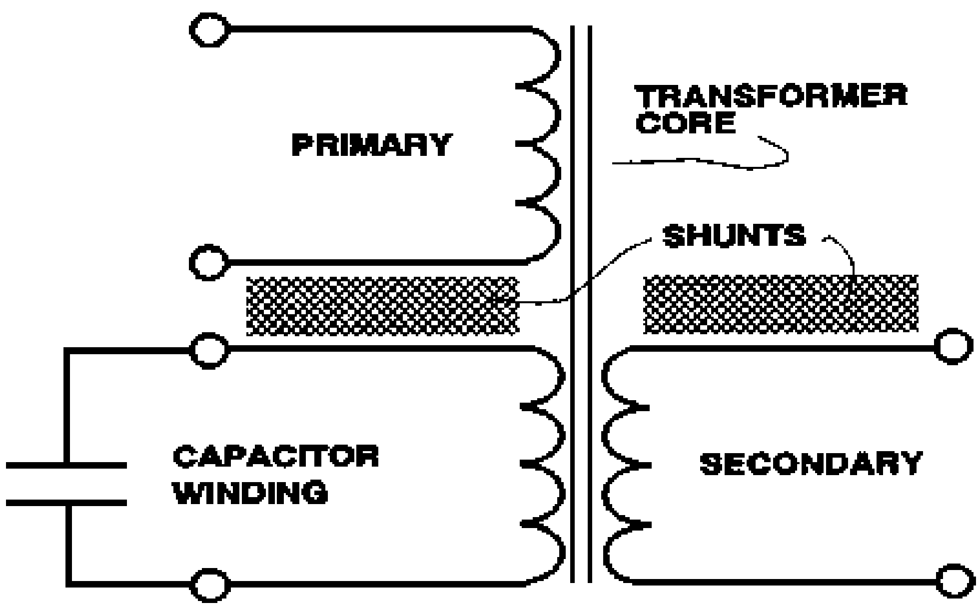
Room Isolated Power & Ground



Ferro-Resonant Tuning

- It is possible to select transformer core material which almost, but not quite, saturates when exposed to a specified power level at 60 Hz ac.
- Tuning the transformer core allows the saturation point to be adjusted based on variable loads.
- Since the core is in saturation, the output voltage remains constant despite line current surges.
- Provides effective isolation without additional filtering.





- Ferro-Resonant Transformer Design
- Narrow 50-66 Hz Input Current Range Allowed

Emission Controlled Power Supply Design

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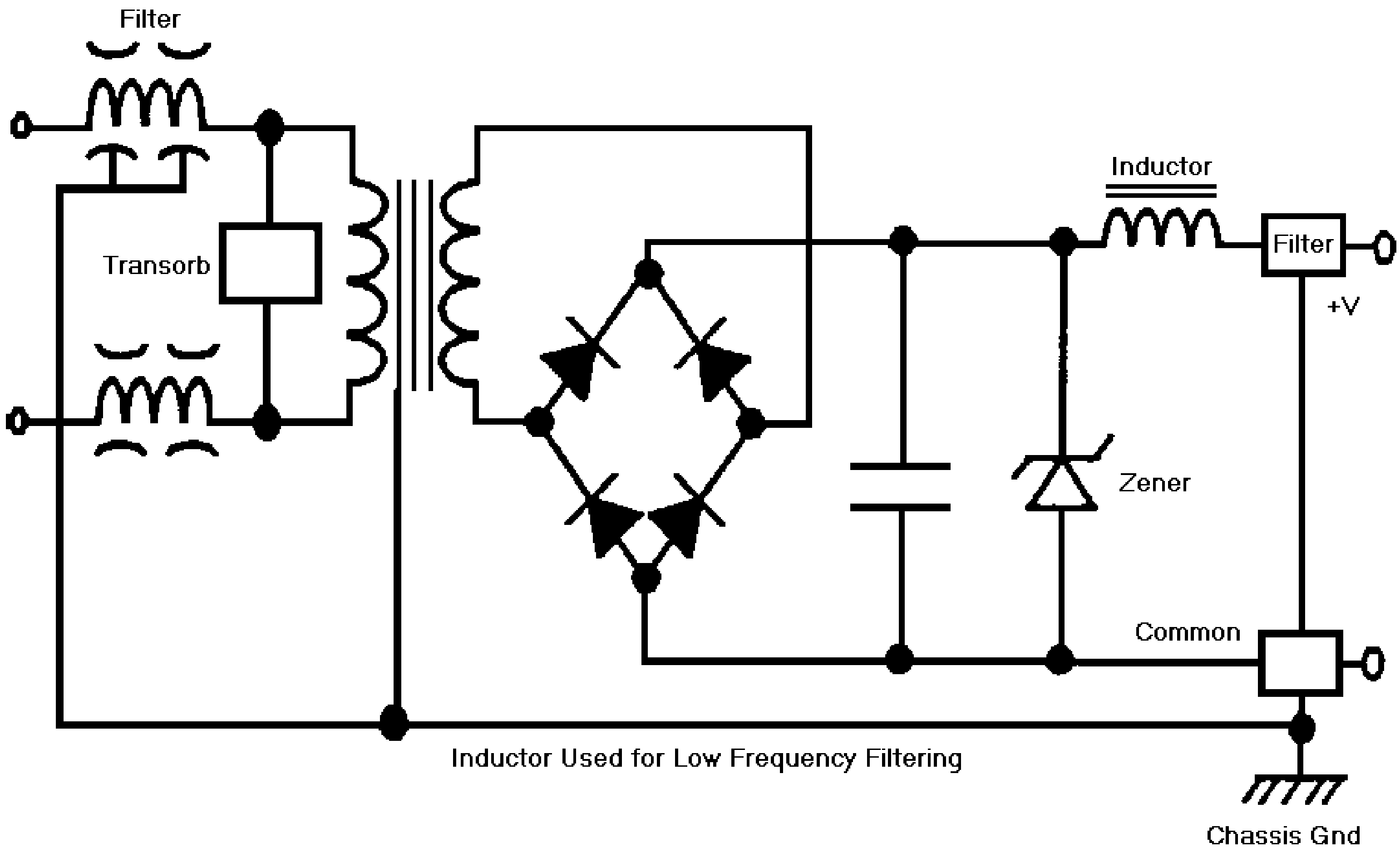
Power Supply Types

- Power supplies are classified by the technique used for voltage regulation.
- Primarily there are linear supplies, switchers, and ferro-regulated supplies (unswitchers).
- Switcher variation types include resonant mode converters or pulse width modulated types.
- Linears are either series, shunt, or a series/shunt combination.

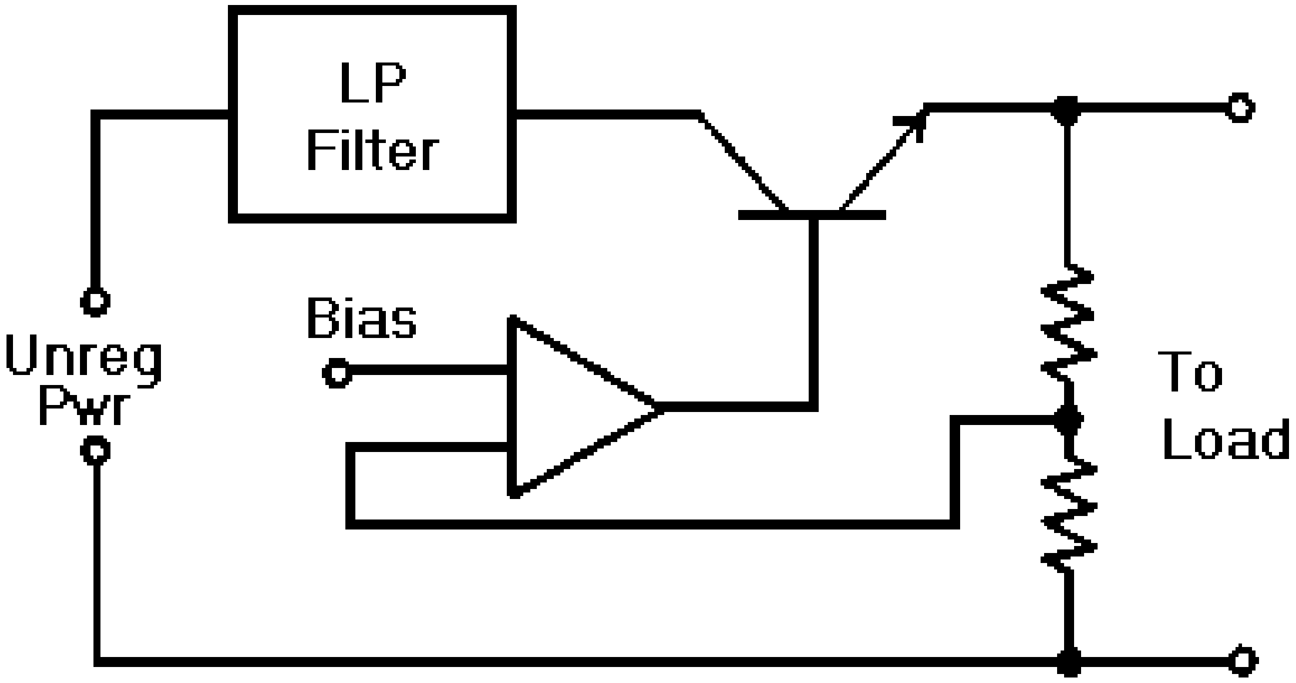
Power Supply Input Controls

- EMI powerline filters with both common-mode and differential-mode filtering are standard.
  - Best approach applies emission controlled filtering at DC output where smaller filters are more effective.
- A common commercial practice is to provide AC directly to the switching device, then use a small high frequency transformer before rectifying, and ripple filtering with a capacitor.
  - Using capacitor regulated rectifier voltage directly provides the least isolation between output and input.

Typical AC/DC Input



Series Regulators



- Provide good forward isolation.
- No reverse isolation.
- Cheap.

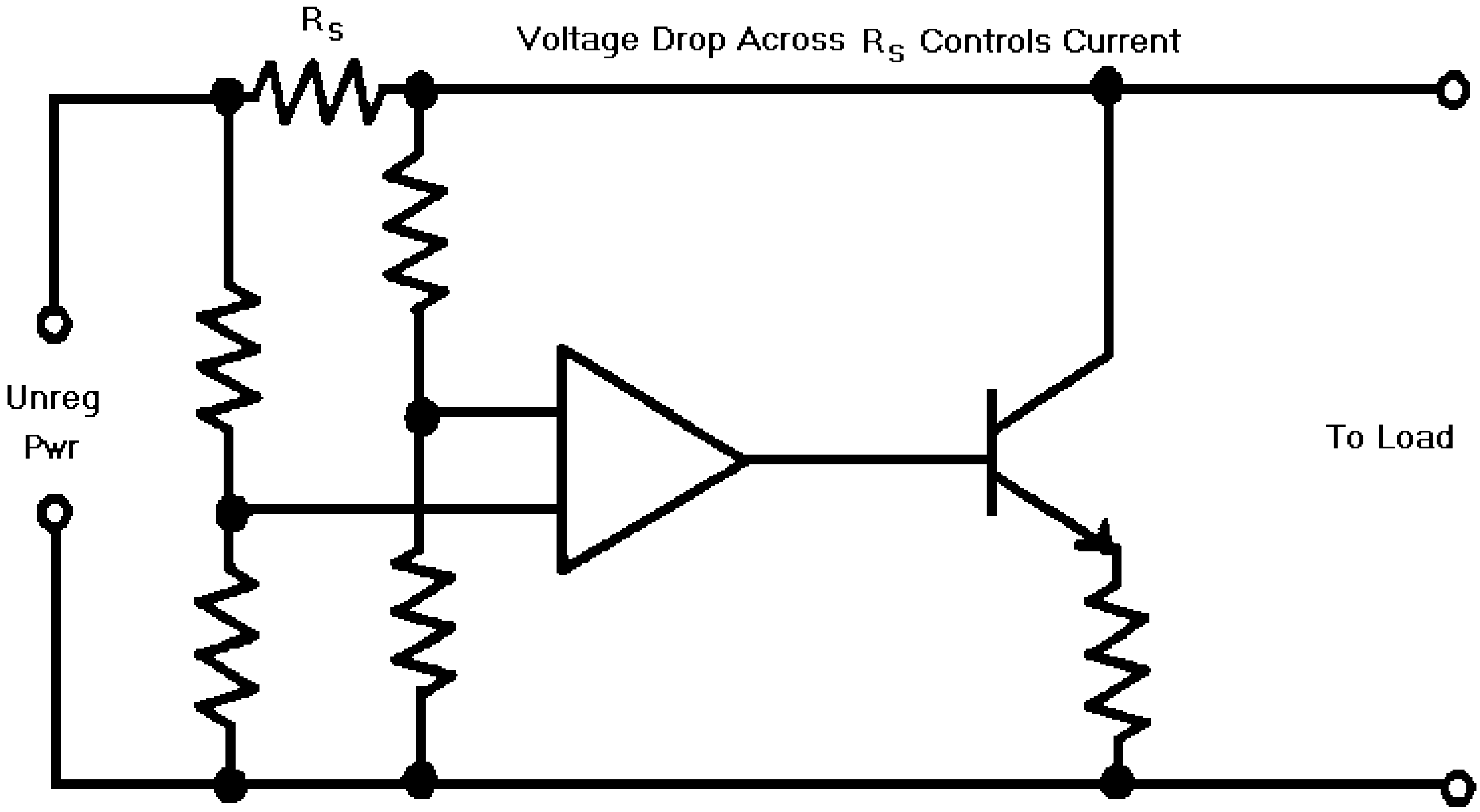
Switchers

- Popular.
- Available COTS.
- High efficiency.
- Easy to filter.
- Low reverse isolation.

Shunt Regulators

- Seldom commercially manufactured.
- Extremely poor efficiency.
- Generate heat.
- Fair forward/high reverse isolation.
- Best design for TEMPEST emission control.

Shunt Regulator



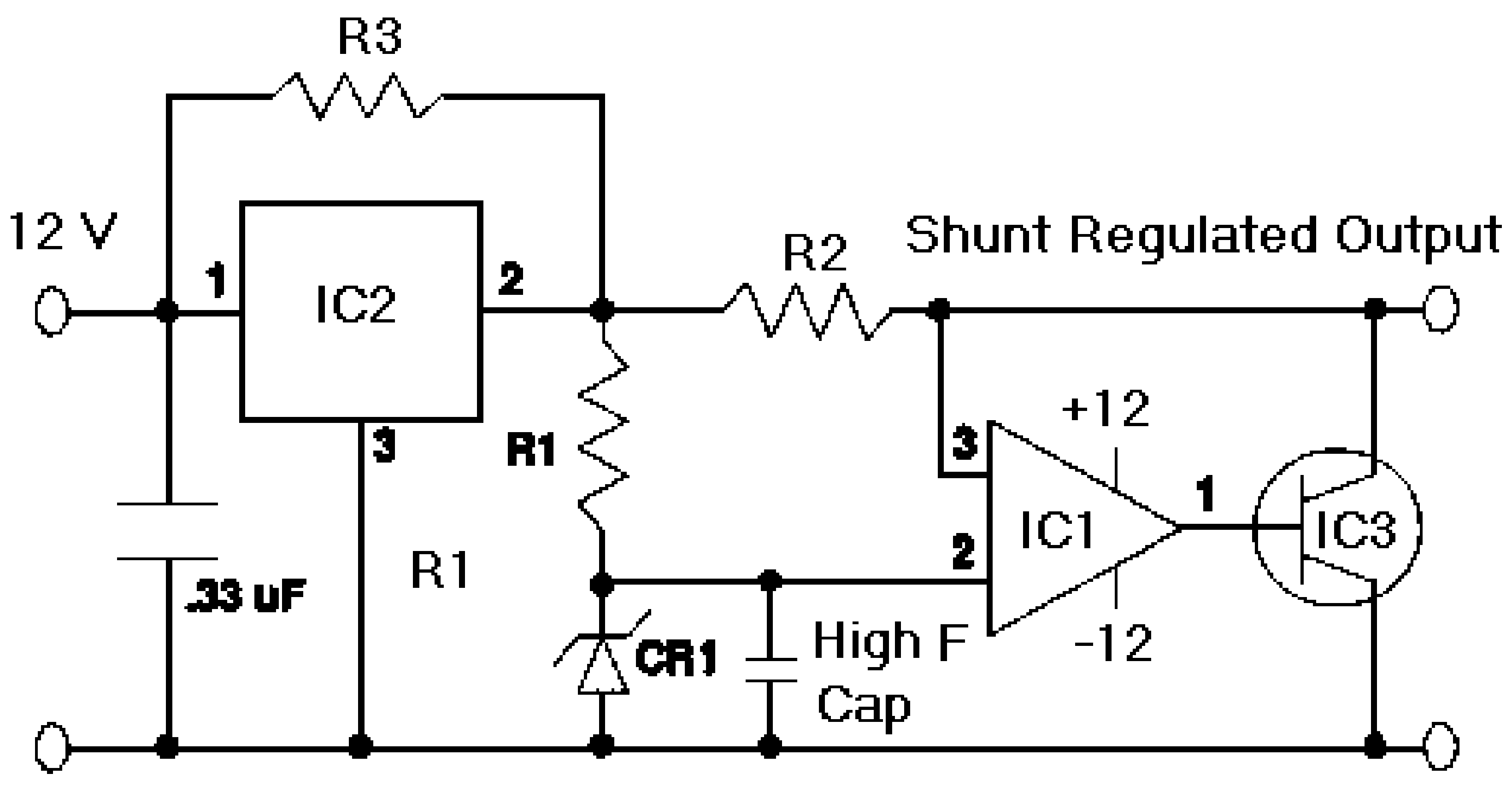
Series-Shunt Approach

- Shunt regulation involves sinking or using current at a constant level despite 1oad requirements.
- Since voltage levels from a current source will vary without some type of voltage regulation incorporated, shunt regulation for greatly varying loads also requires some form of series regulation.

Series-Shunt Design Rules

- When laying out the board, insure that IC2 and the ICl/IC3 set are physically isolated.
- For a two-sided board, do not run traces in parallel on directly opposite sides.
- Make sure that the 12 volt input and the regulated output are physically separated.
- Cover all unused board space with a ground shield.
- Use a split ground plane for the input and the output.

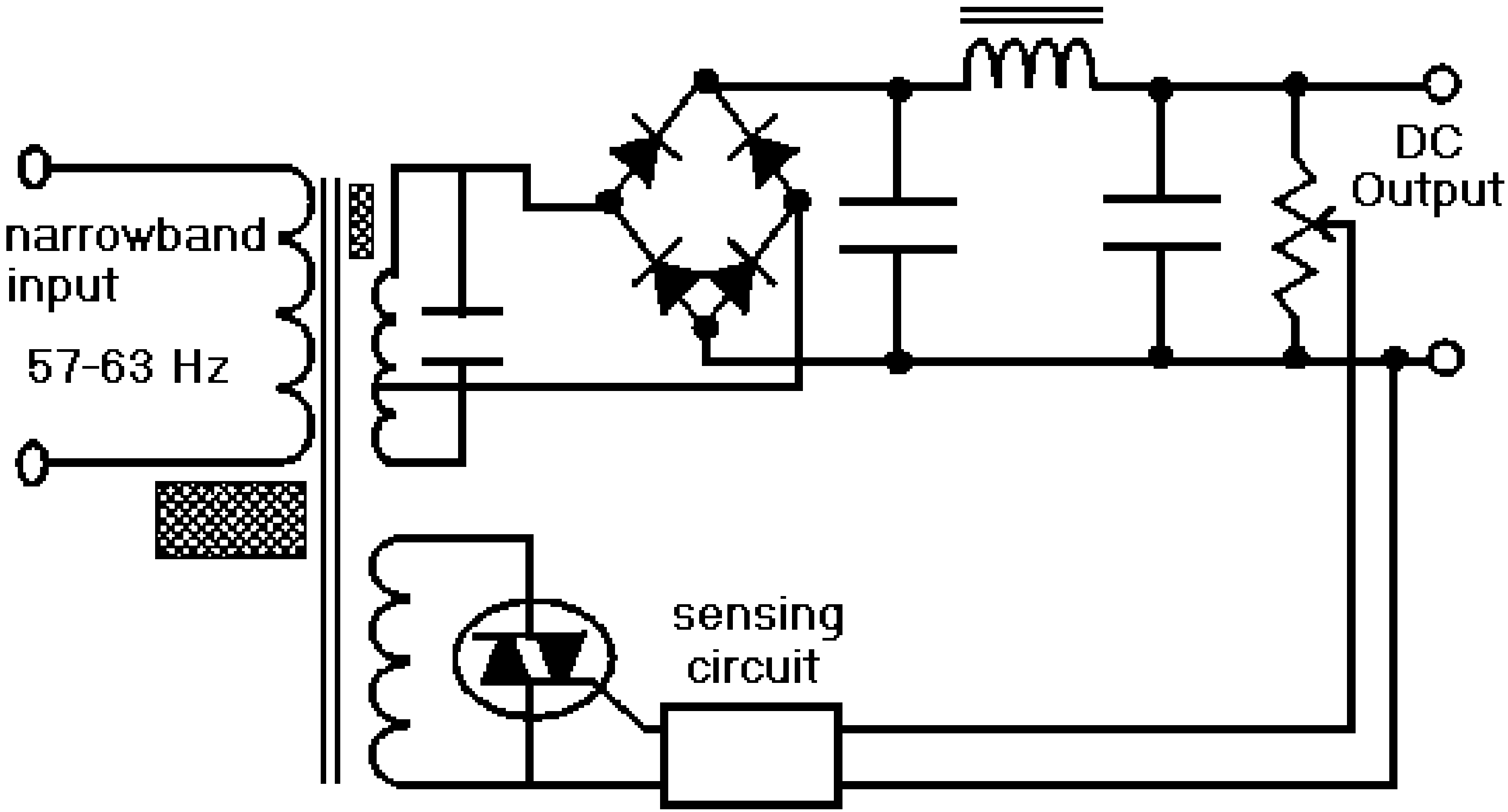
Typical Series-Shunt



Ferro-Resonant (Regulated) Power Supplies

- Ferro-resonant supplies use a technique similar to saturated magnetic regulators, but without attendant core losses.
  - Ferro-resonance here refers to the hysteresis or elastic after effects resulting from the interaction of magnetic fields with iron based transformer material.
- Regulation is achieved using a specially designed transformer with two secondary windings, one shunted by a capacitor that essentially tunes the transformer core in a way so as to prevent large core saturation losses.

Ferro-Resonant Power Supply



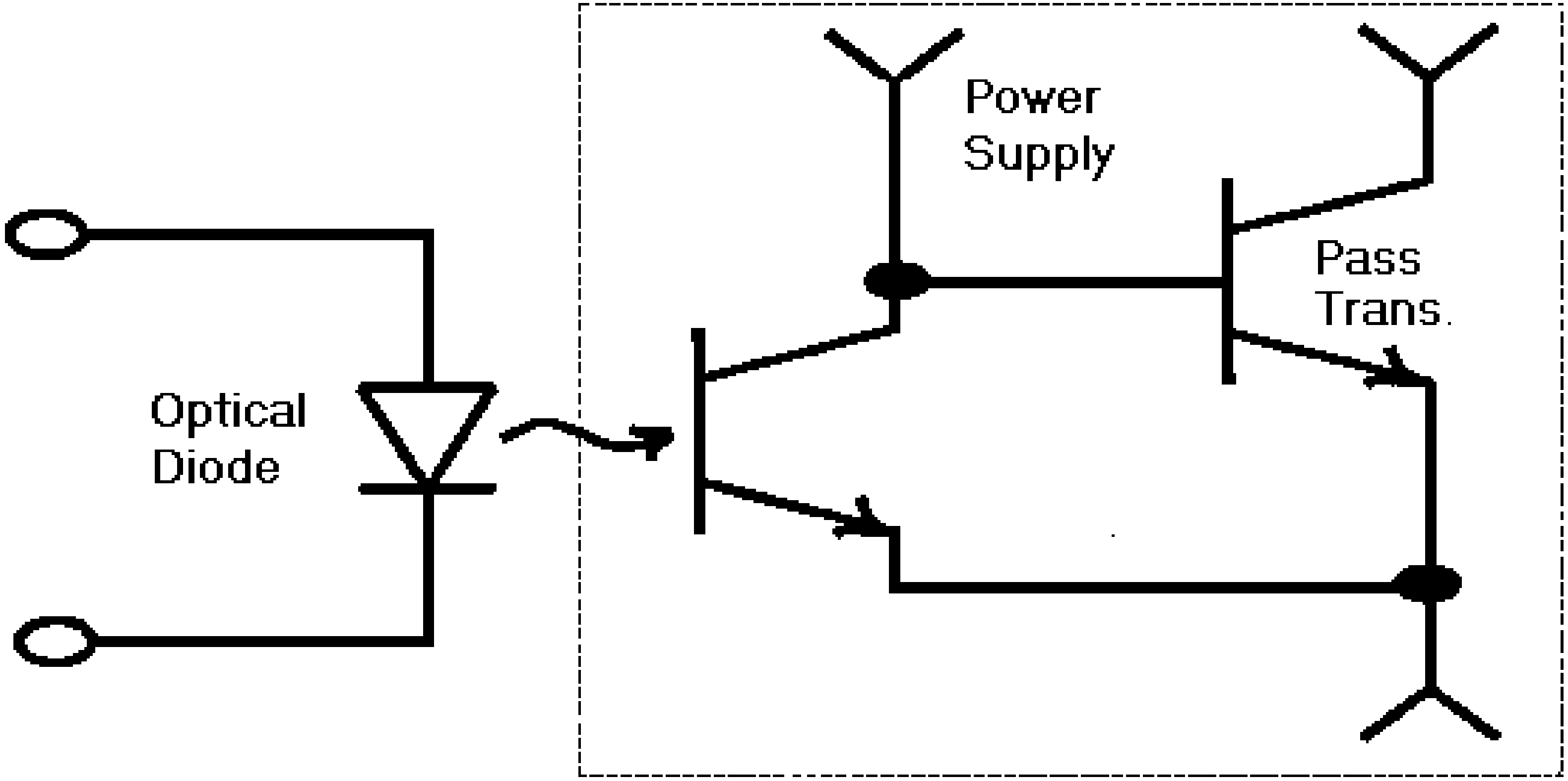
Optical Feedback Control

- Optical feedback control on a regulator requires that enough collector current be supplied to insure complete series regulator cutoff.
  - There is a possibility that a significant noise source may be located within the isolated power system.
  - Buffer amps are used to increase source current without loosing isolation characteristics.
- Have a frequency response to 500 kHz.
- Provide 80-90 db reverse isolation.
- Low coupling capacitance for better common mode rejection.

Optical Feedback Applications

- Digital interface between peripherals to eliminate:
  - Ground loops
  - Noise spikes
  - Common-mode impedance problem areas.
- DC overcurrent control for power supplies.

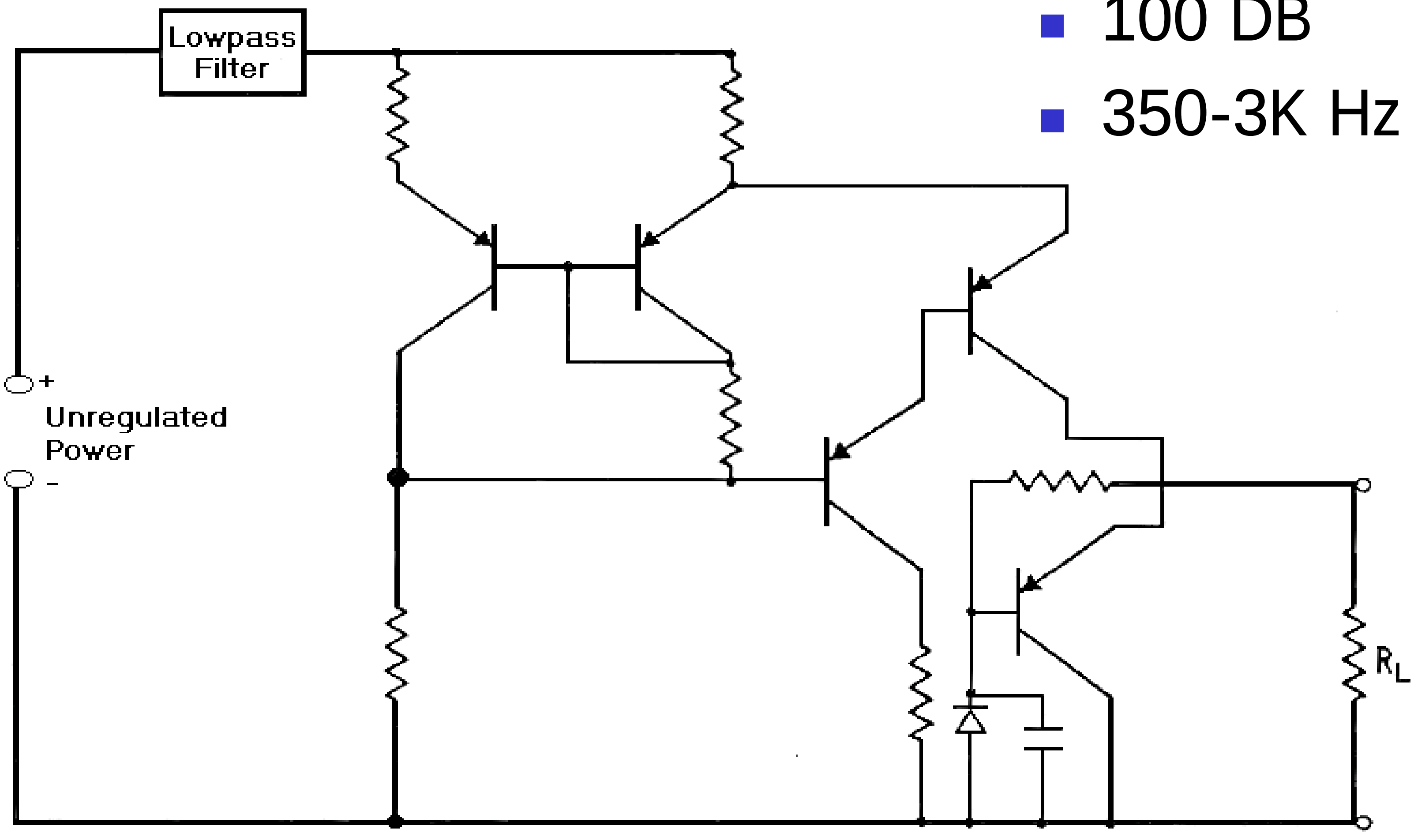
Series Regulator With Optical Feedback



Emission Suppression Steps

- Less efficiency provides more isolation.
- Shunt or series shunt regulation is usually necessary for voice frequency applications.
- The secondary of switching supplies should be referenced to the center point ground for box applications, or referenced as system needs dictate when multiple power supplies are involved.
- Fiber-optic feedback to control the primary offers the most isolation when feedback is required.

Analog Series-Shunt Isolation

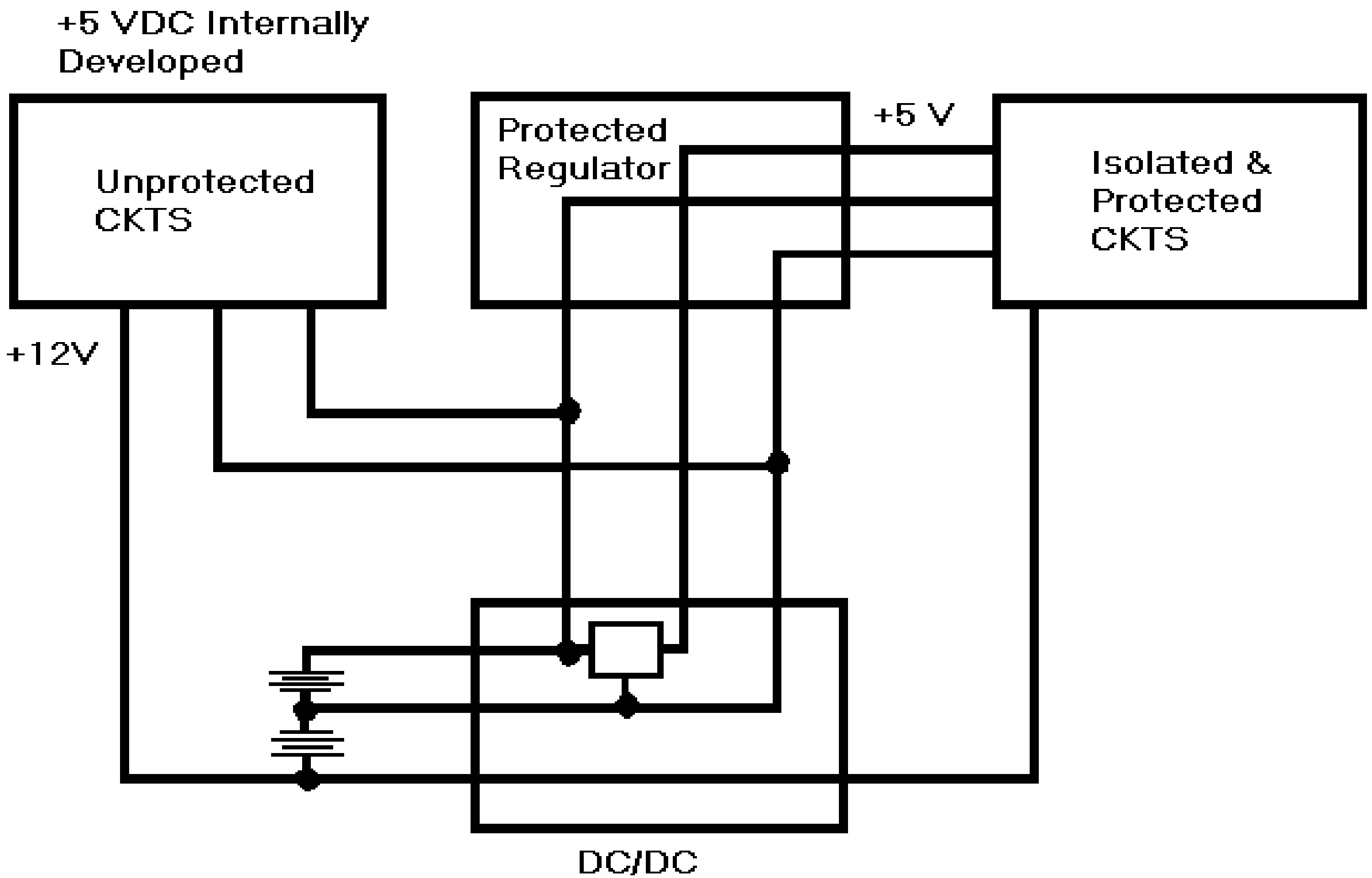


- 100 DB
- 350-3K Hz

Emission Suppression Steps

- Always apply emission controlled filters at the DC output.
- Isolated re-regulation is required from BLACK to RED. However, only standard forward regulation is required from RED to BLACK.
- Use torroid wound inductors only when additional isolation is provided at the emission controlled envelope interface.

Re-regulated Power System



Emission Suppression Steps

- Always design for the lowest noise possible in order to eliminate noise sources that could be modulated and re-radiated or conducted.
- The easiest method of lowering the possibility of a high frequency PWM switcher indicating data transfers is to reduce the switchers efficiency.
- Power supply circuits should be multipoint grounded to minimize the generation of ground noise and carriers.

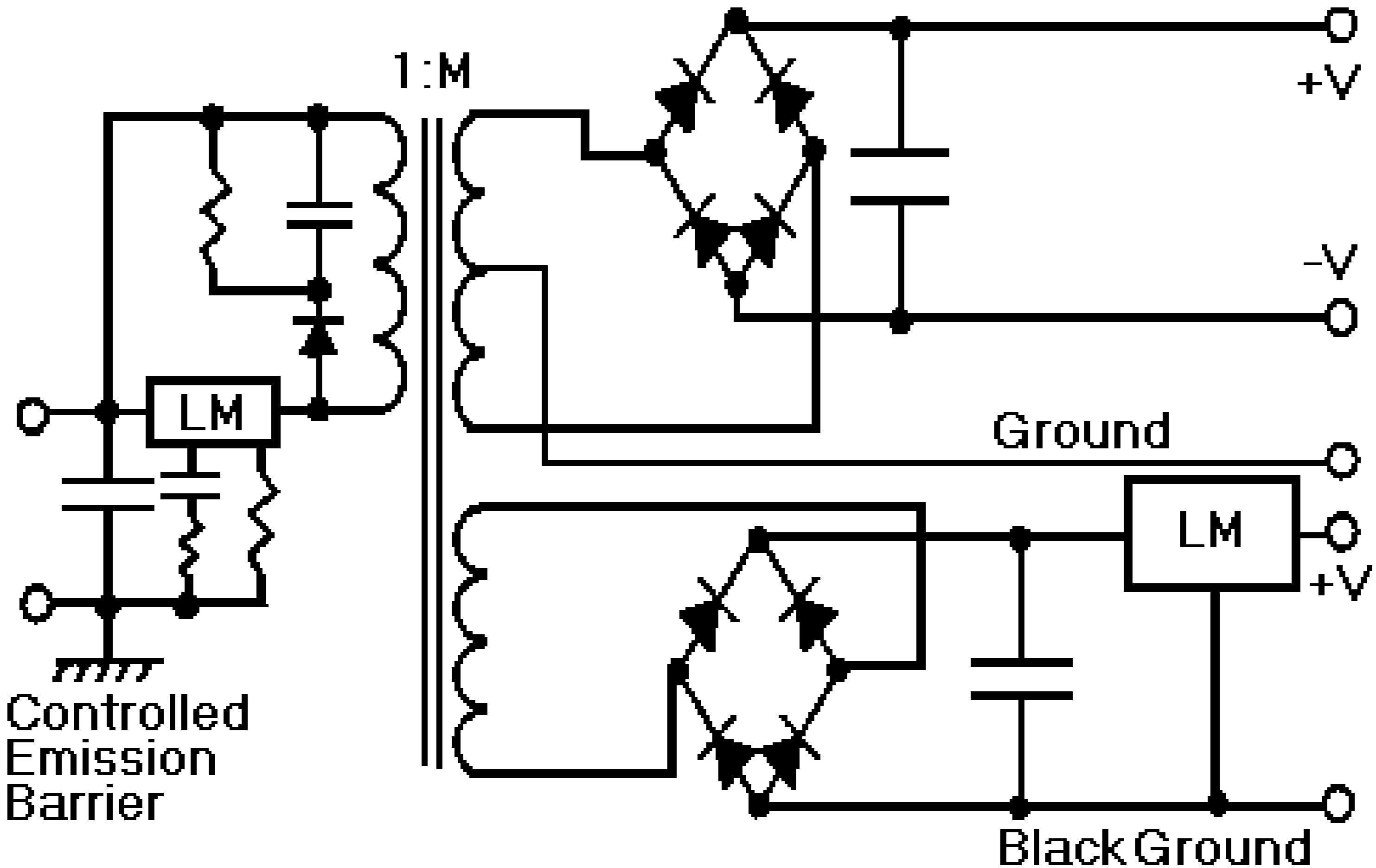
Emission Suppression Steps

- Shunt regulation is preferred over series regulation since series regulation only isolates in one direction.
  - Use a shunt or series shunt when lower frequency emission controlled signals are present.
- Concentrate on applying filtering on the DC output lines, not the AC input lines, and use Baluns if available.
- Isolated battery power is preferred, but if DC power is supplied, it must be DC to DC converted.

Emission Suppression Steps

- Transformer coupling provides DC isolation between input and output power, but only isolation transformers can isolate high frequency common mode coupling.
- Separate transformer secondary power and power supplied to sensitive circuitry.
- Higher frequency switchers are easier to filter or otherwise noise suppress and are preferred over low frequency switchers.

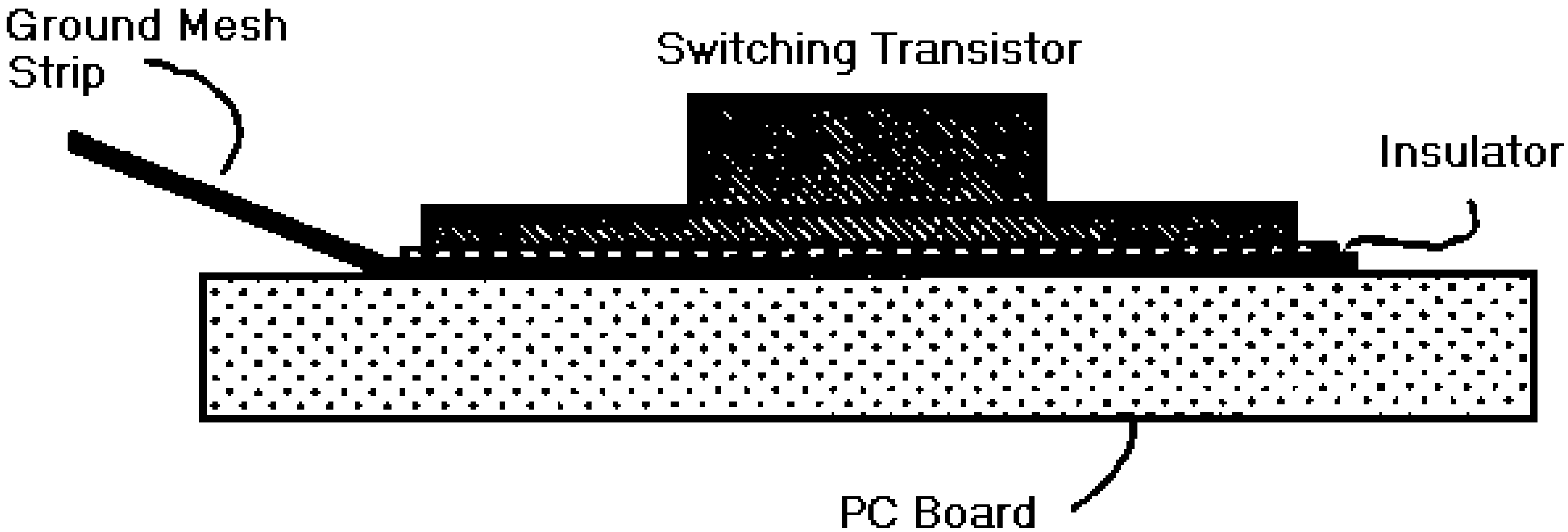
Emission Isolated Flyback Regulator



Emission Suppression Steps

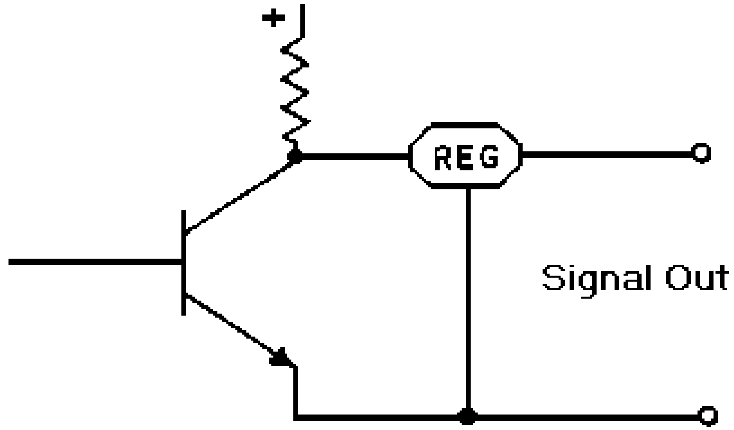
- Insure harmonics of the switcher, and their cross modulation products, do not fall within the protected RF circuit bandwidths.
- Reduce switching transistor noise problems by:
  - Reduce collector to heat sink capacitance.
  - Slow down turn on to reduce higher frequency oscillations.
  - Reduce transformer saturation by adding delay capacitance to the switching transistors base.

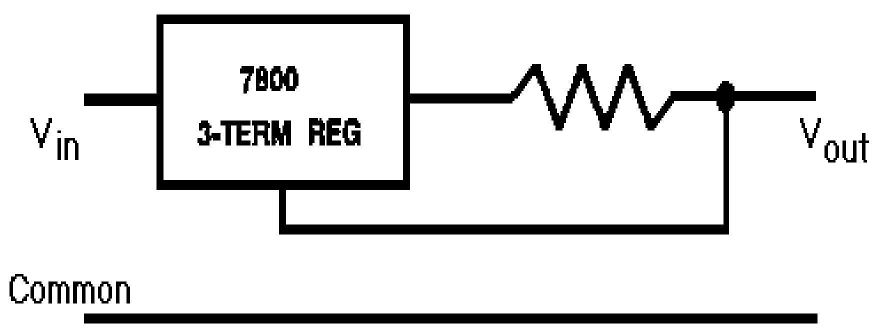
Switching Transistor Noise Suppression



Composite of Characteristics		
Series regulator	80 db forward rejection no reverse isolation	Most efficient
Series-Shunt regulator	80 to 100 db forward and reverse isolation	Less efficient
Shunt regulator	100 db plus forward and reverse isolation	Least efficient
Linear supplies	Isolation similar to type of regulator used	Additional loss in core windings and EMI filter efficiency 60% to 80%
Switching supplies	Less isolation - dependent on the level of regulation efficiency and the elasticity of the PWM circuit.	Higher efficiency Common mode coupling must be controlled Opto-isolation is effective
Ferro-regulation	Large signal attenuation and isolation	Efficiencies of 70%-80z. non-portable
Three terminal series regulator	No reverse isolation	Useful in dc/dc regulator applications where filtering provided prior to regulator Very good when used as a wave shaper on controlled output lines

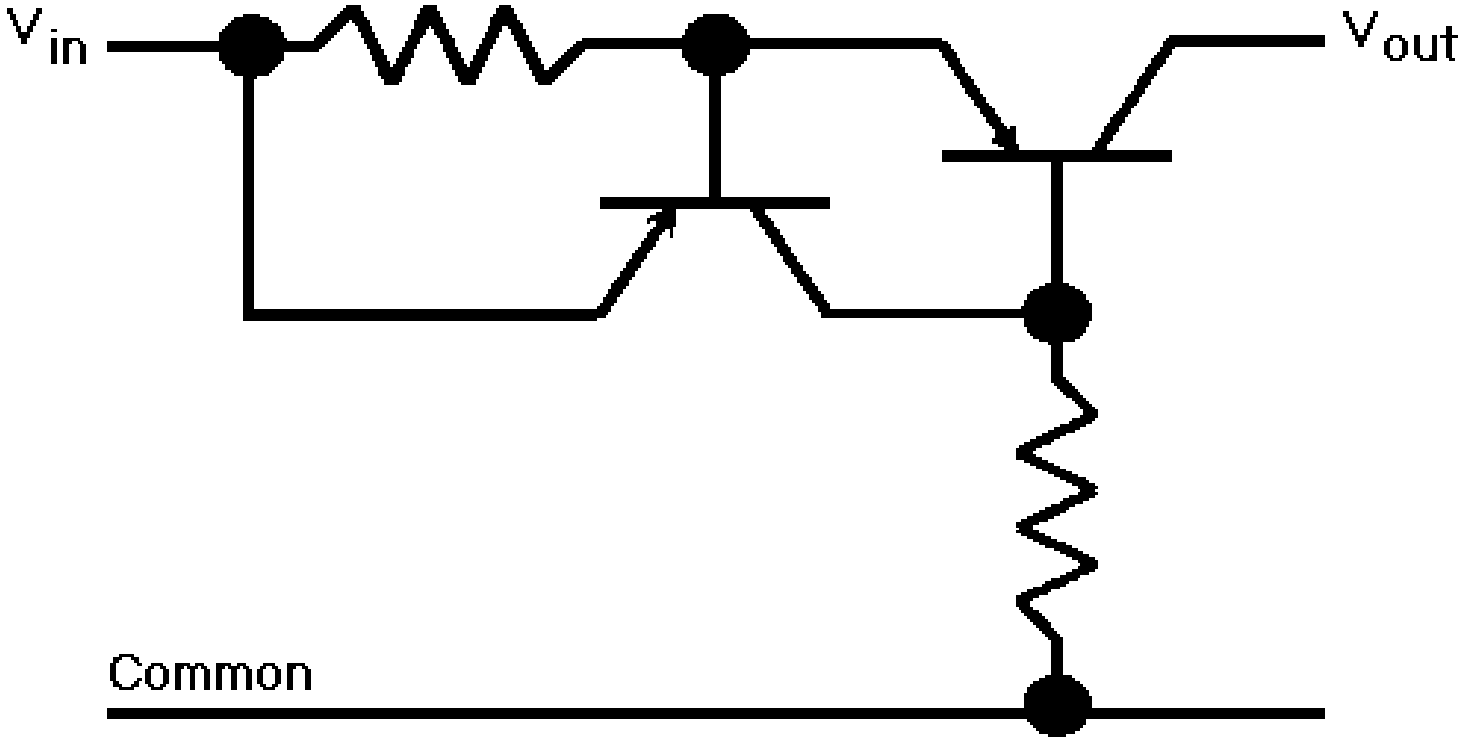
3-Terminal Regulator Uses

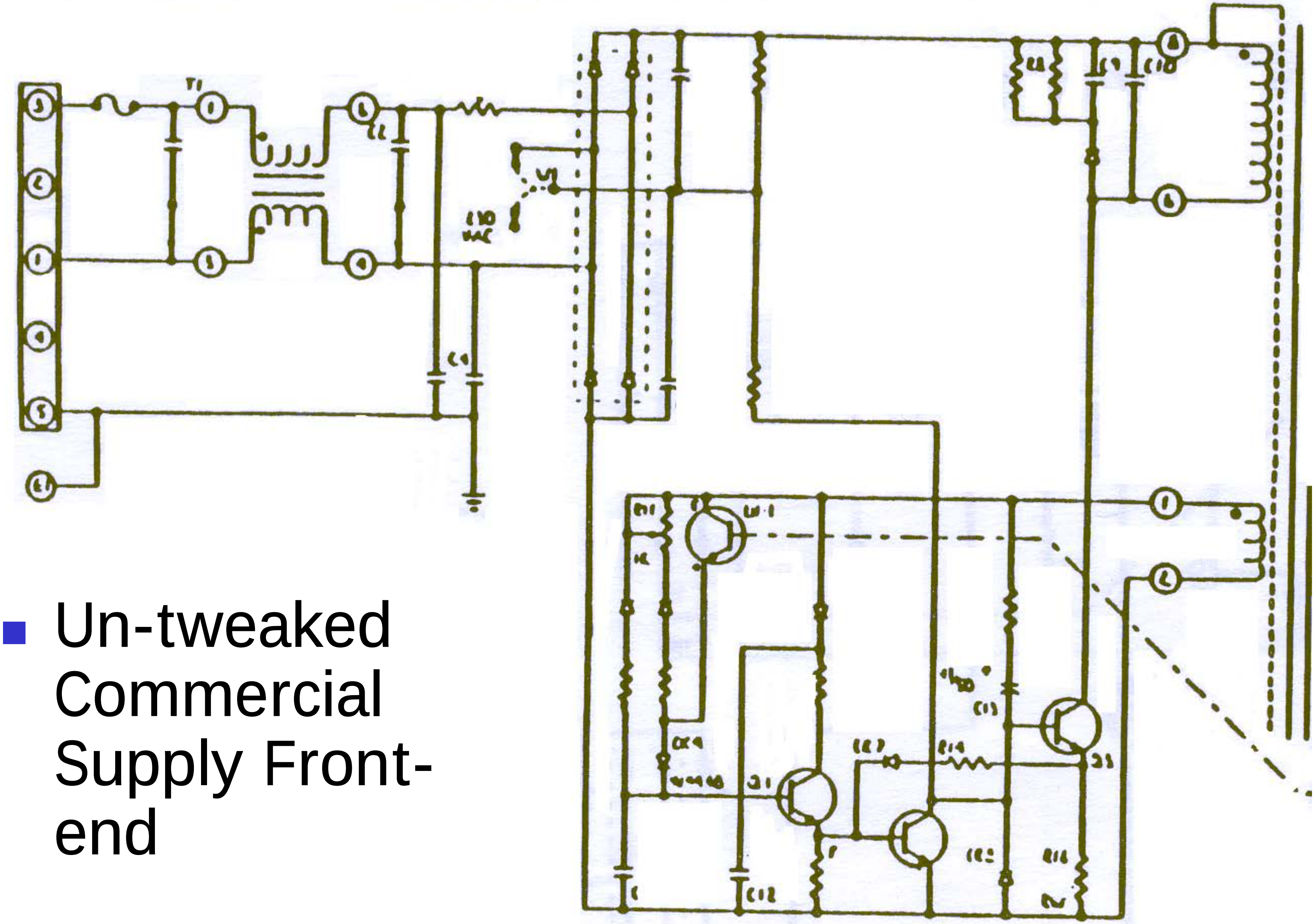




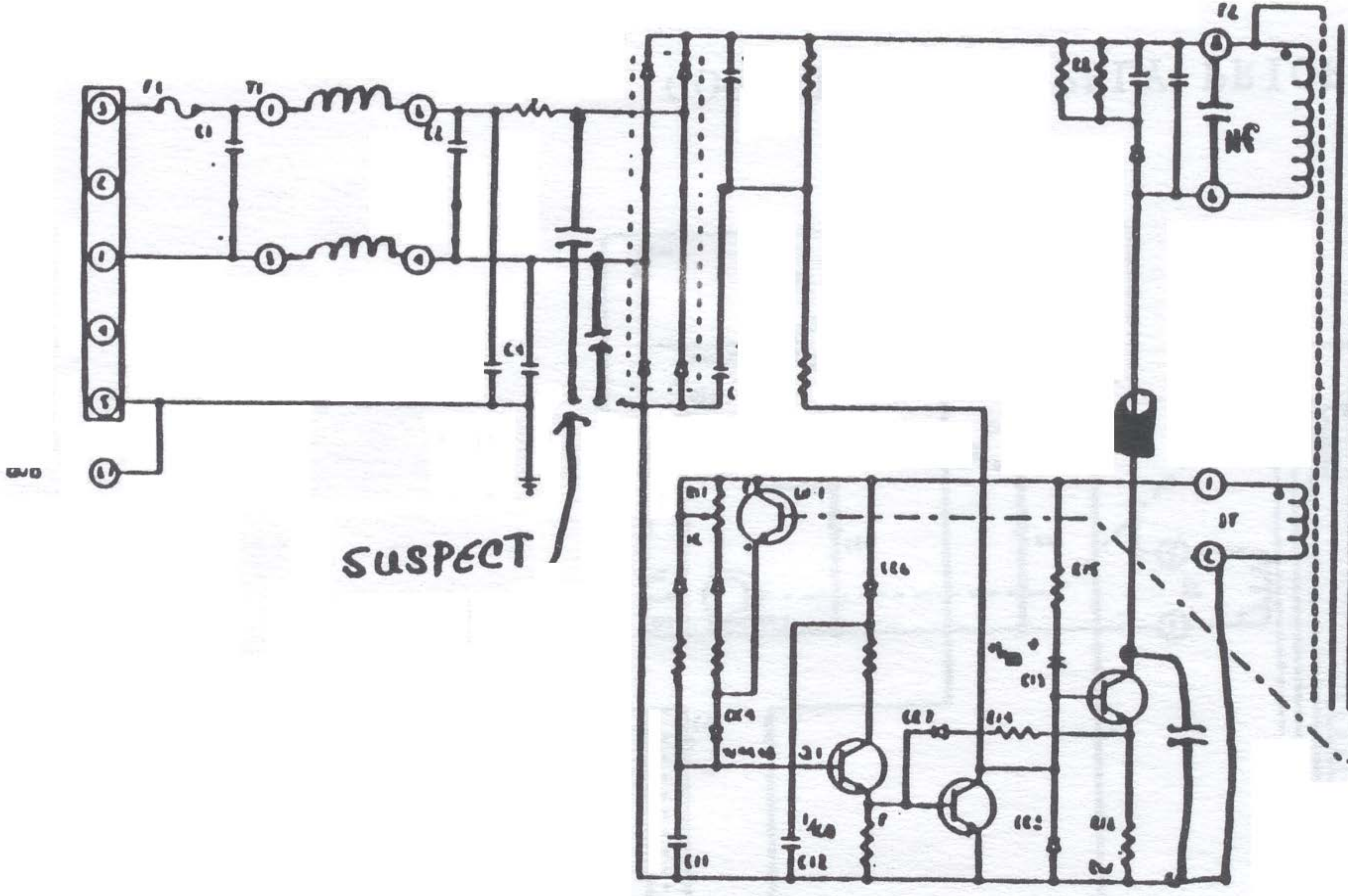
- Waveshapping
- Current Source

Current Source

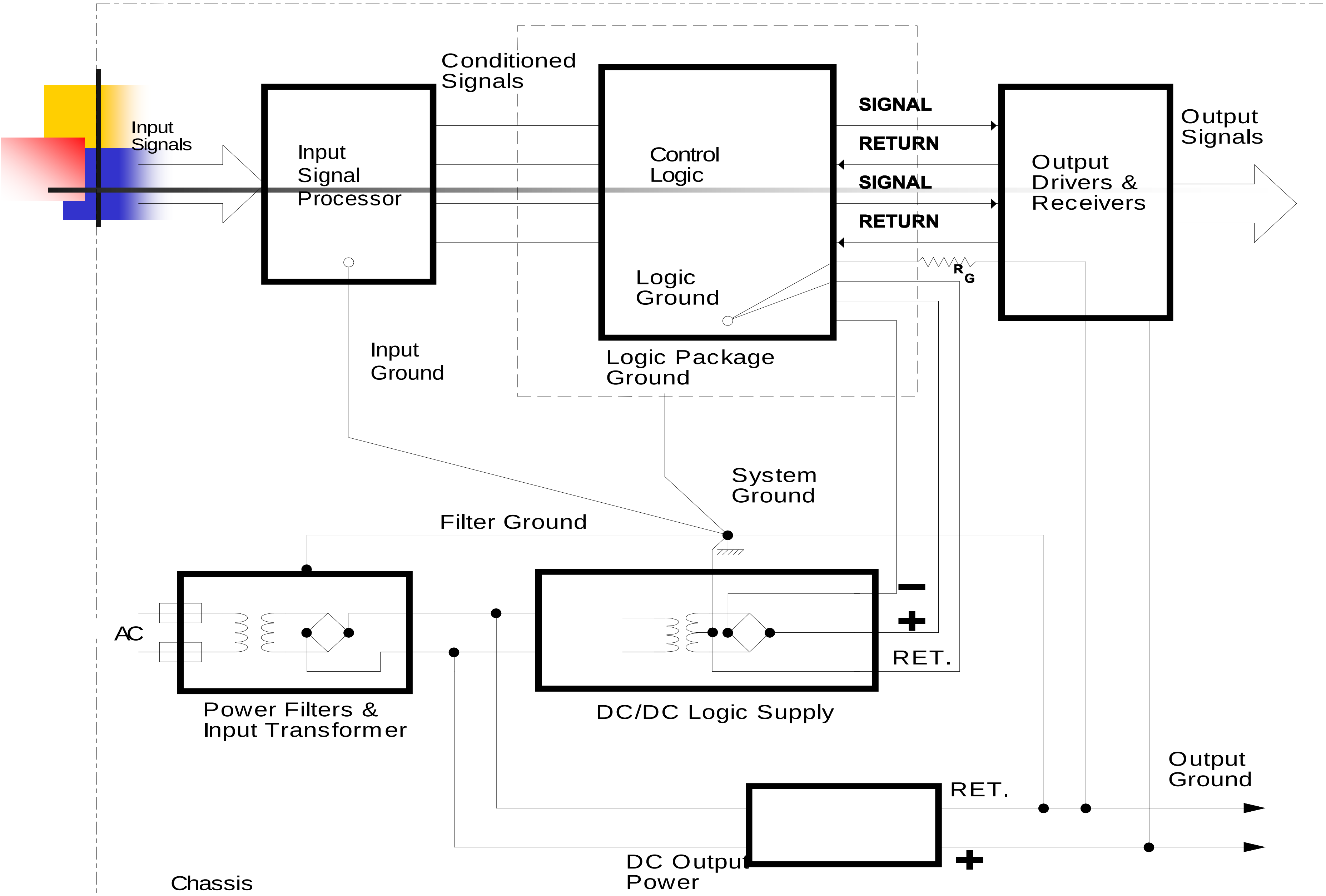




- Un-tweaked Commercial Supply Front-end



GND
SUSPECT


Input
Signals
Input
Signal
Processor
Conditioned
Signals
Control
Logic
Logic
Ground
Logic Package
Ground
SIGNAL
RETURN
SIGNAL
RETURN
RG
Output
Drivers &
Receivers
Output
Signals
Input
Ground
System
Ground
Filter Ground
AC
Power Filters &
Input Transformer
DC/DC Logic Supply
RET.
RET.
Output
Ground
DC Output
Power
Chassis

Summary

- Use dc to dc converters, each with isolated outputs, all referenced to the central power supply system.
- AC power is routed on separate lines to the transceiver and each protected or non-protected area, with isolation transformers and powerline filters installed between the main power feed and each section of the system.
  - The center point ground for the unprotected power system and the transceiver is located close to the main power feed.

Filters and Filter Theory

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Applicability

- Passive filters are more applicable to low emission controlled designs because of stability and sensitivity to noise.
- Passive problems include variable insertion losses, capacitors that turn inductive at high frequencies, and harmonics created by inductor nonlinearity.

Active Filters in Emission Control

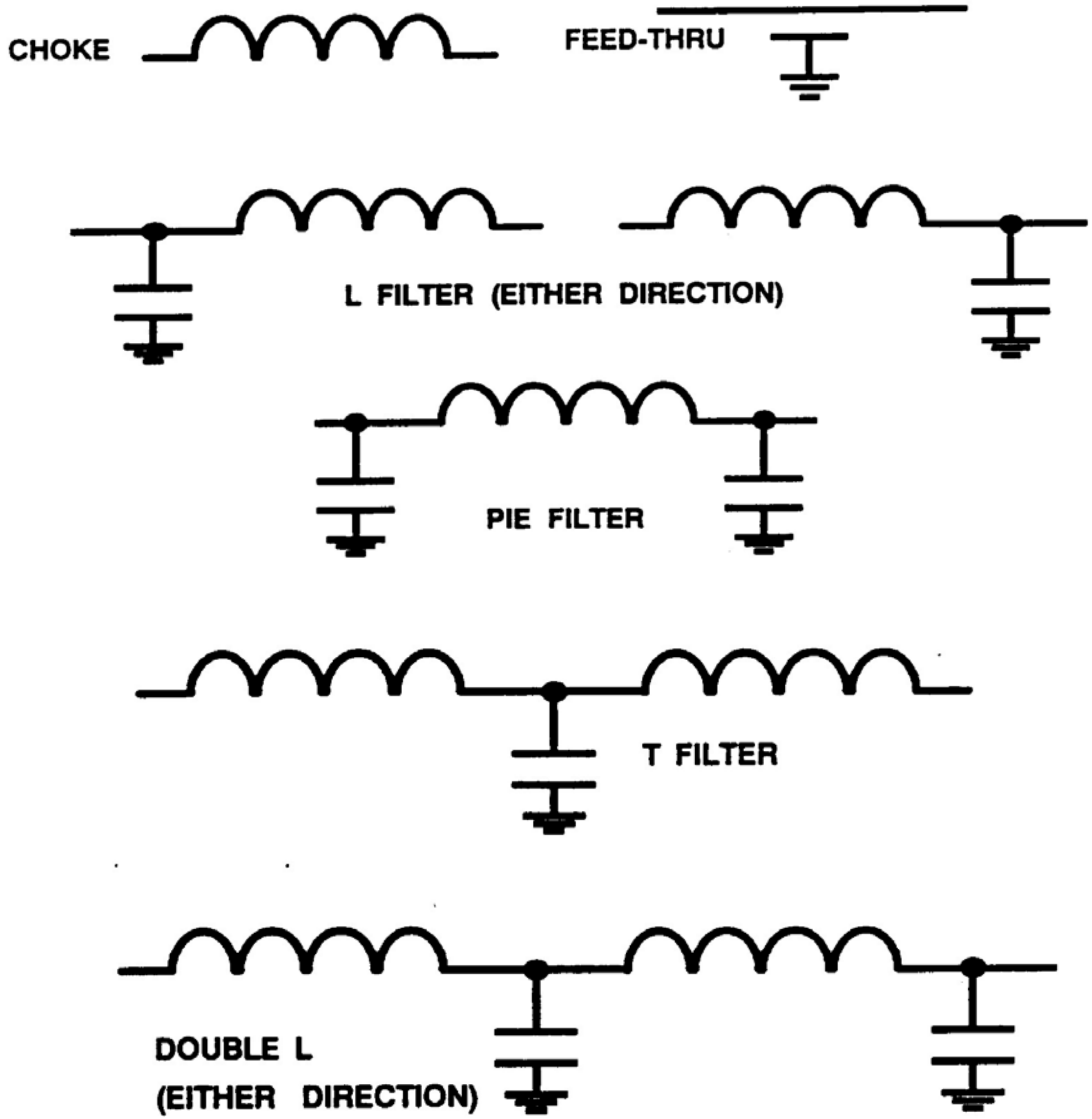
- Big advantage is the ability to increase line impedance using RC rather then LC components for buffering and impedance matching.
- Insufficient emission isolation for applications above 100 MHz.

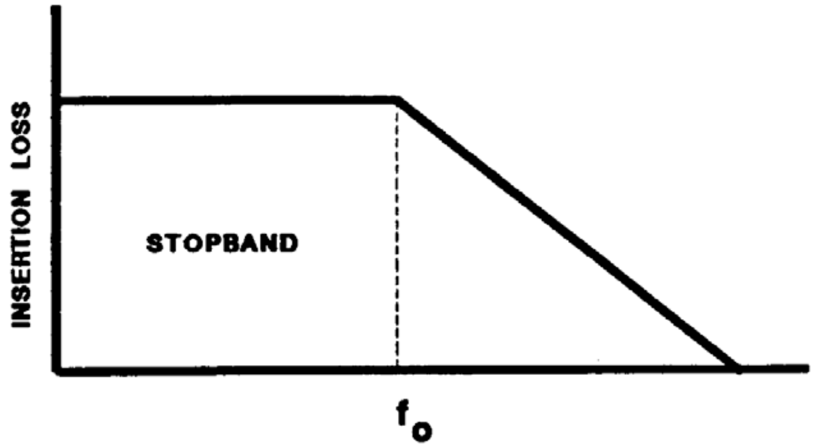
Voice Filtering

- Used in applications to control 300 to 4000 Hz signals for speakers, telephones and modems.
- Low frequency signals are difficult to passively filter so active filters are often used.

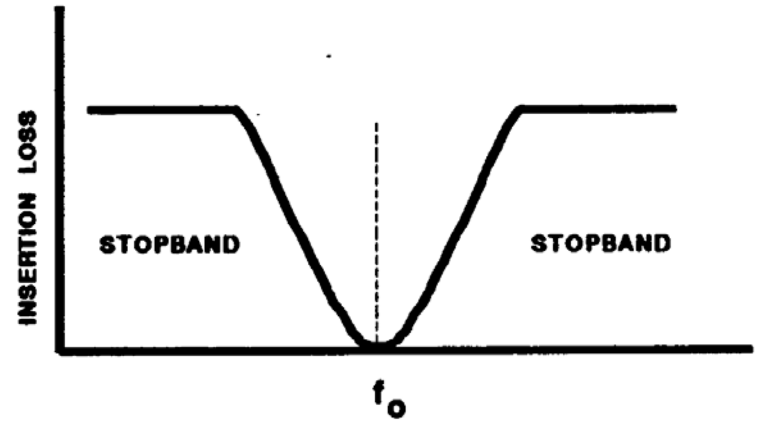
Basic Filter Theory

- Filters can be absorptive or reflective
- Common passive configurations are Pi, L, and T
- Filters are classified in terms of response characteristics as high pass, low pass, band pass, or band reject

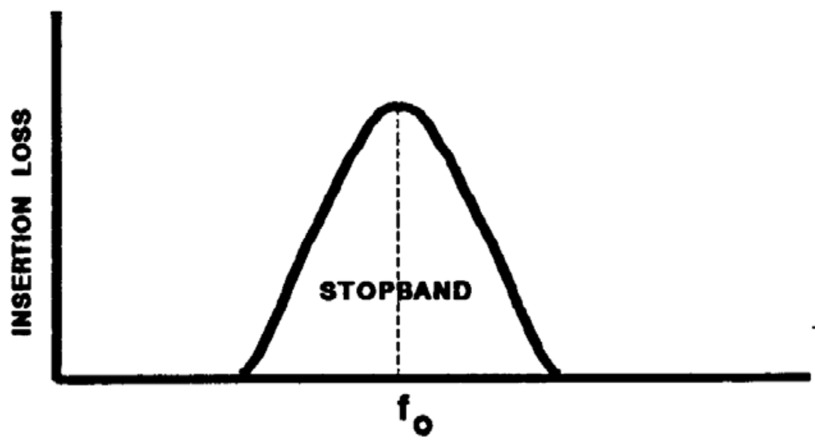

CHOKE
FEED-THRU
L FILTER (EITHER DIRECTION)
PIE FILTER
T FILTER
DOUBLE L
(EITHER DIRECTION)



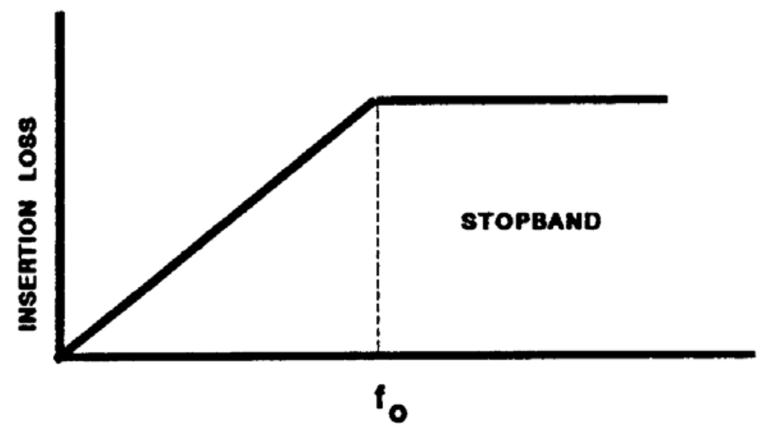
HIGH PASS



BAND PASS



BAND REJECT



LOW PASS

Filter Impedance Effects

- Filters are specified in a 50 ohm system
  - The actual insertion loss provided by the filter is related to the source and load impedance of the line being filtered
- C feedthrough filters are best used when source and load impedance are high

Filter Impedance Effects (Pi & L)

- Pi filters are also best used when both source and load impedance are high, but are also the most generically useable for all applications
- L section filters are used on high impedance noise sources and low impedance lines.
  - This filter type resonates when shocked with transient noise at selected frequencies.
  - The dip in the response curve makes them seldom useable in TEMPEST applications

Filter Impedance Effects (T)

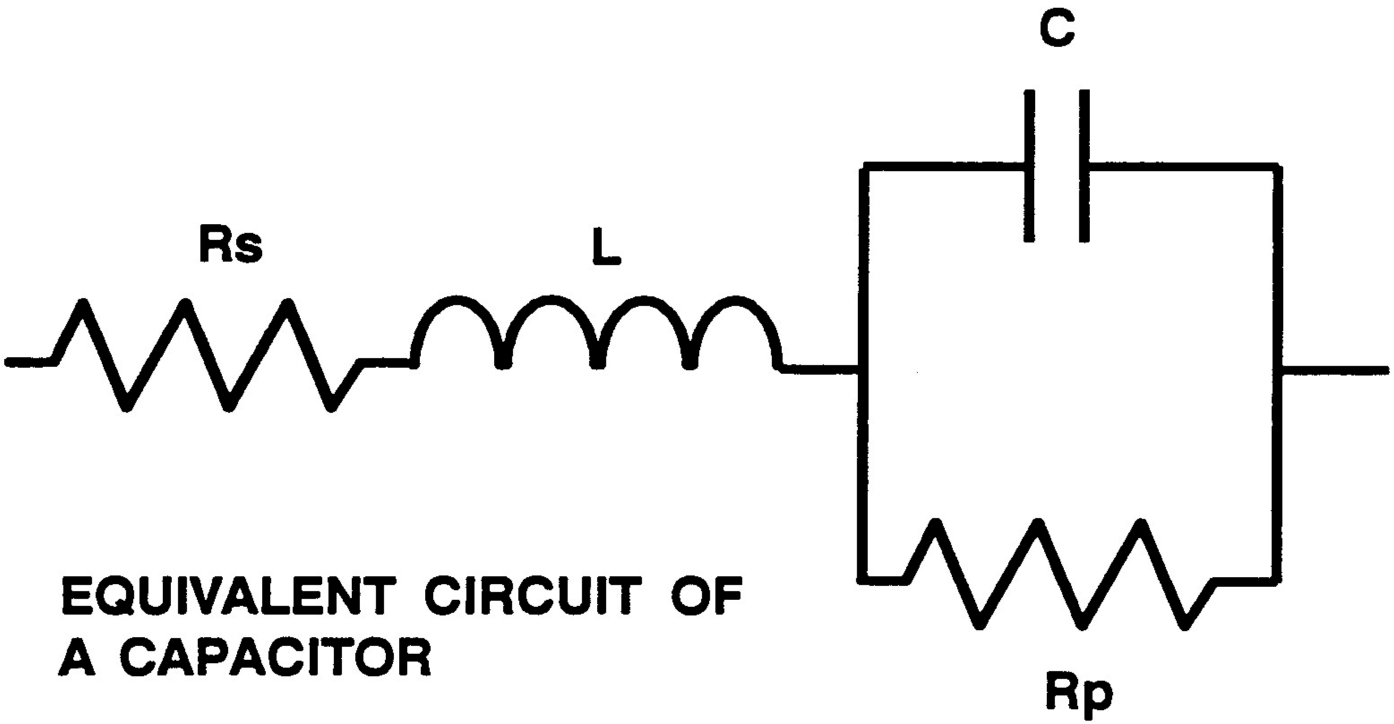
- T section filters are used when both source and load impedances are low.
- This filter is often used in controlled emission breakout box test fixtures

Filter Selection Summary

Required I/O Impedance Matches	
High Input/High Output Impedance	Feed Through Pie Double Pie
High Input/Low Output Impedance	L (C first) Double L (C first)
Low Input/High Output Impedance	L (L first) Double L (L first)
Low Input/Low Output Impedance	Choke T Double T

Capacitive Filters

- Frequency response can change with temperature
- Since capacitors turn inductive at higher frequencies, a resonant impedance will effect their ability to filter at some point
- For very fast (such as f series) logic, capacitive loading drives noise into the ground plane

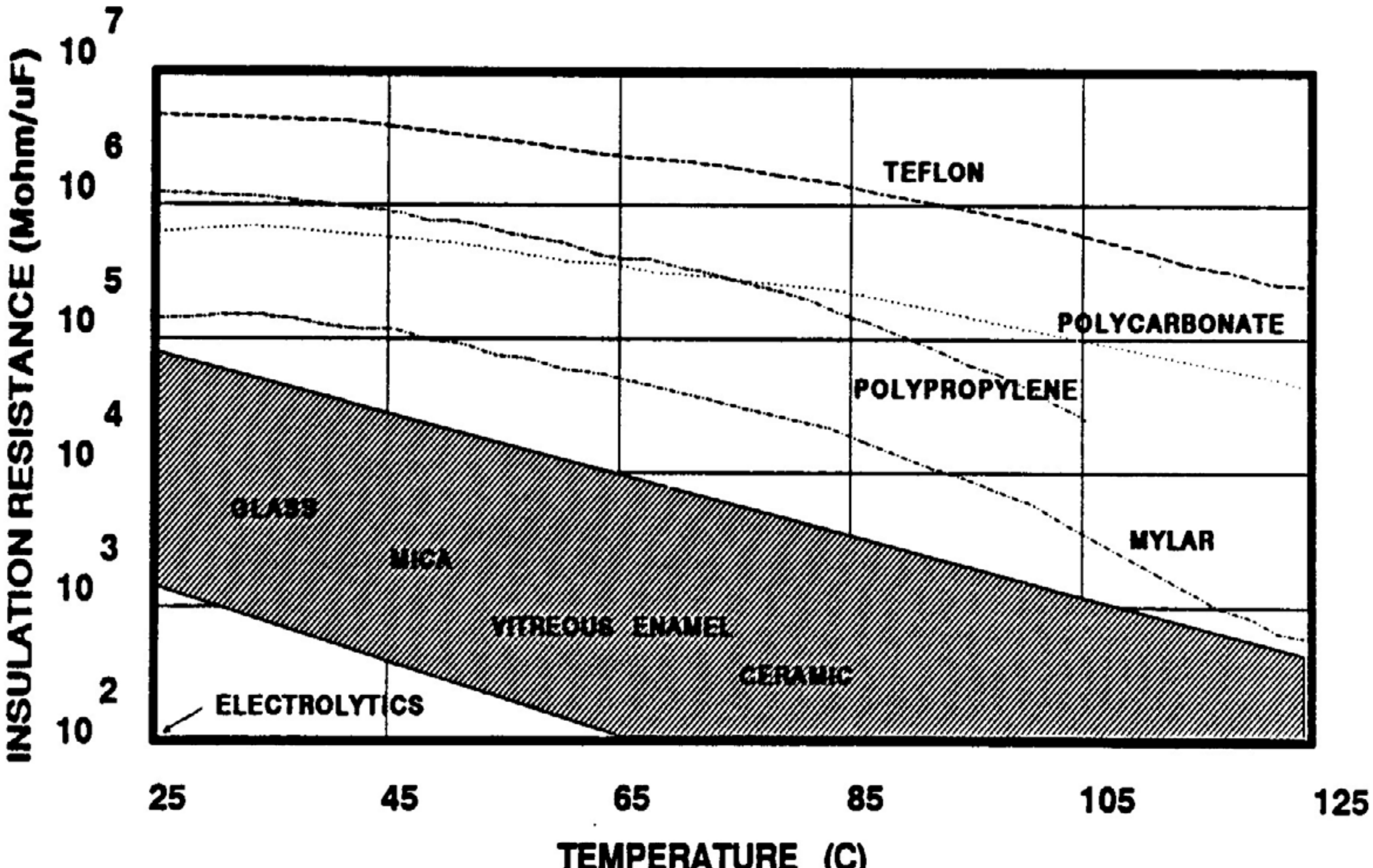


EQUIVALENT CIRCUIT OF A CAPACITOR

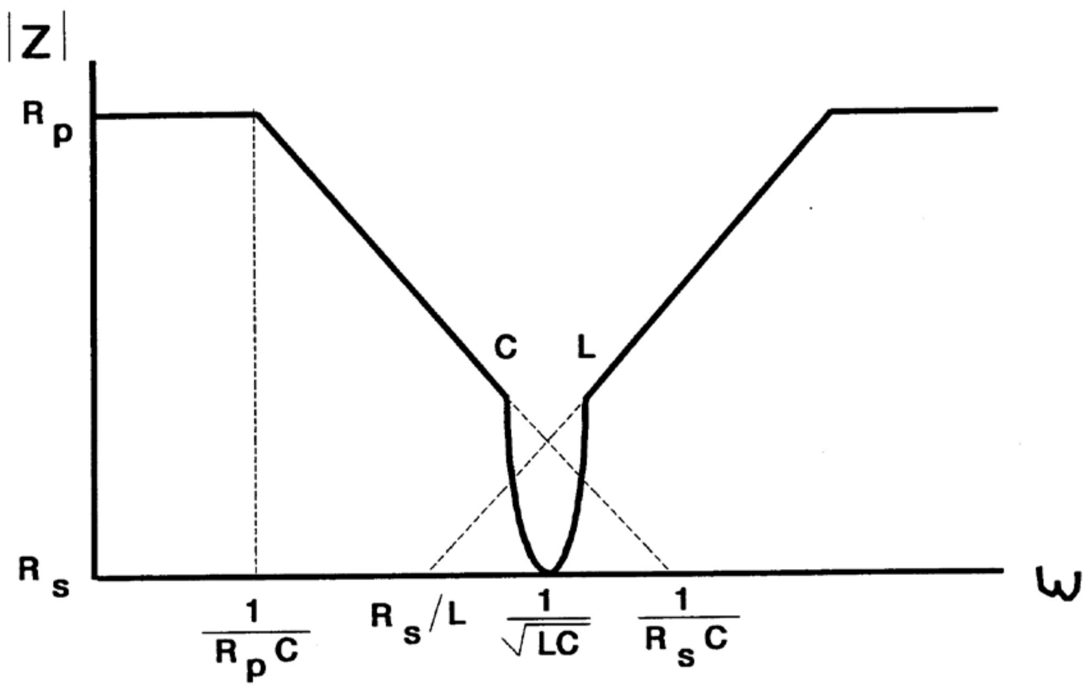
L is the series inductance
Rs is the series resistance
Rp is the shunt resistance
ρ is the resistivity of the dielectric
ε is the dielectric constant

$R_pC = \rho\varepsilon$

Temp Characteristics of R_pC



Impedance of a Cap for a Low-Loss Case

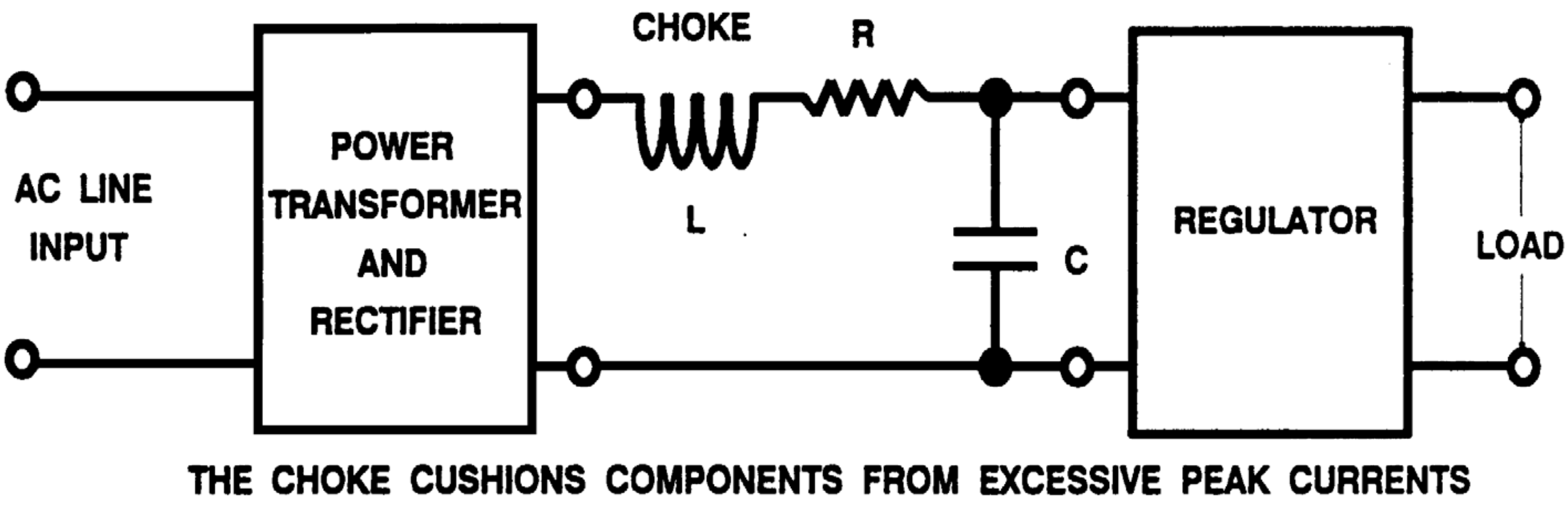


- A cap has a maximum useable frequency range between $1/R_pC$ and $1/R_SC$.

Filter Chokes

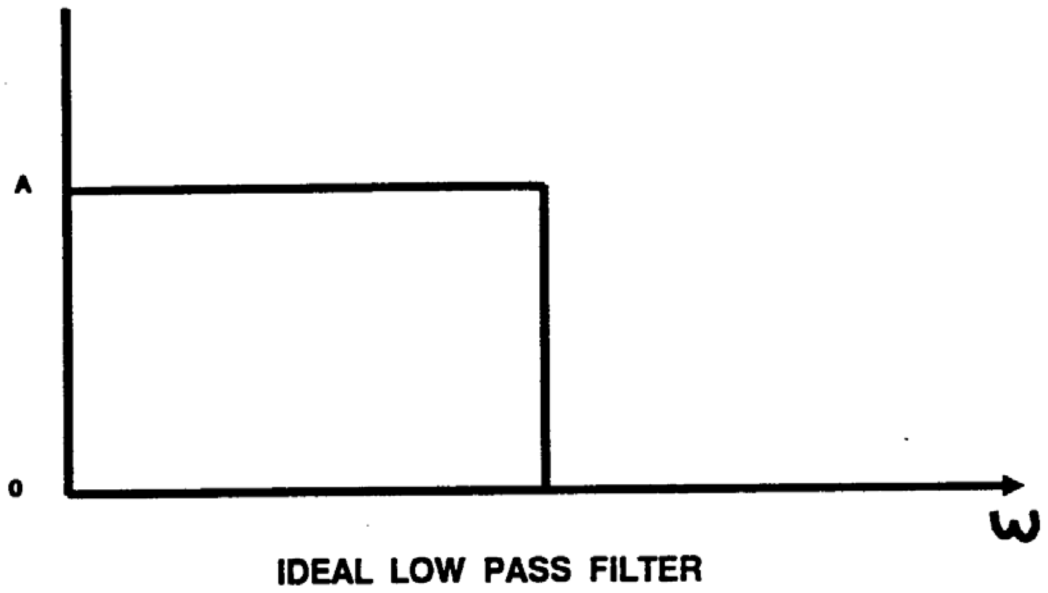
- Because input filter chokes help reduce the stresses applied to-power supply components, they are commonly used in this type of design.
- Their use avoids the excessive peak currents typical of capacitor input filters, thus reducing stress on the power transformer, rectifier circuit, and filter capacitor.

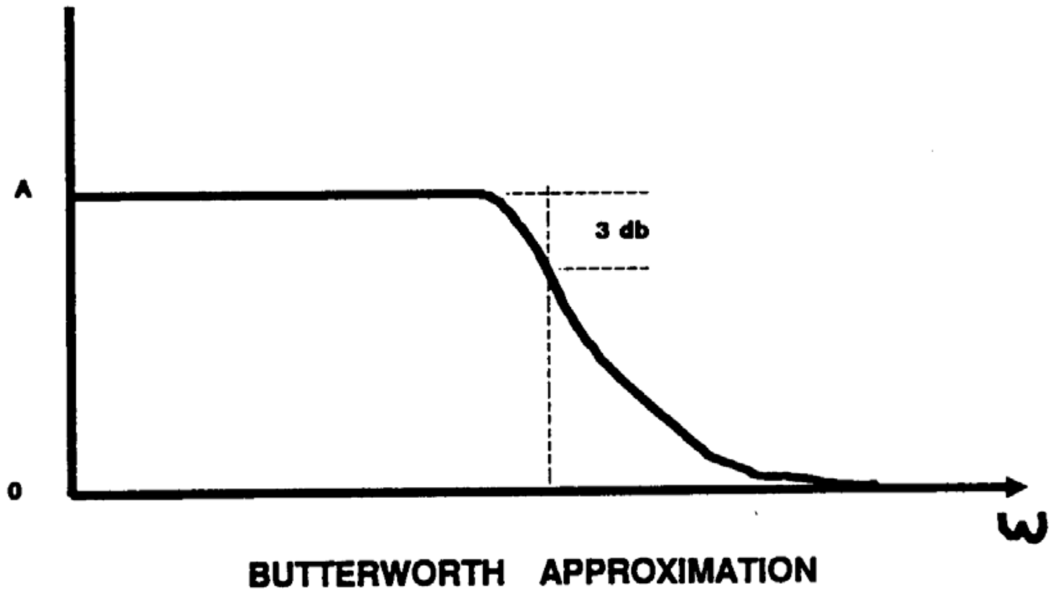
Choke Input Filter



Emission Control Guidelines

- Emission controlled applications normally require low pass filters
- Low pass filters have a second classification related to their roll-off characteristics. the three major response types are Butterworth, Tchebycheff, and Elliptic



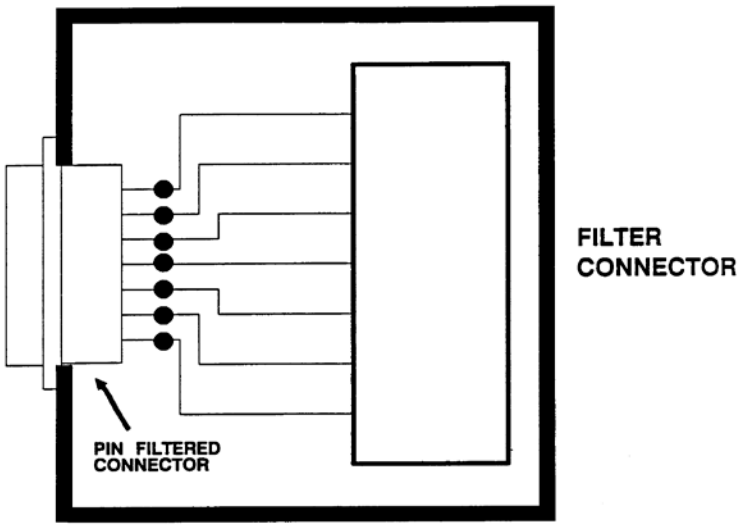


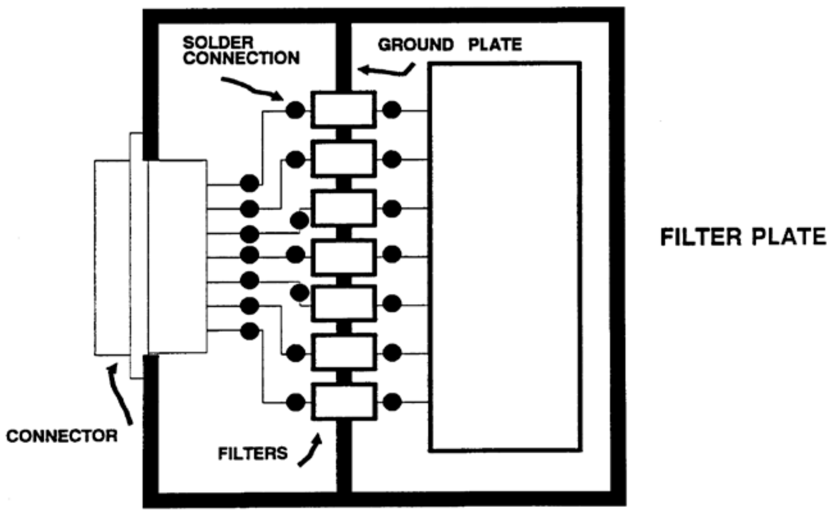
Of the three response types, Butterworth is the most common for emission controlled applications since the curve is extremely flat in the pass band

Filter Installation

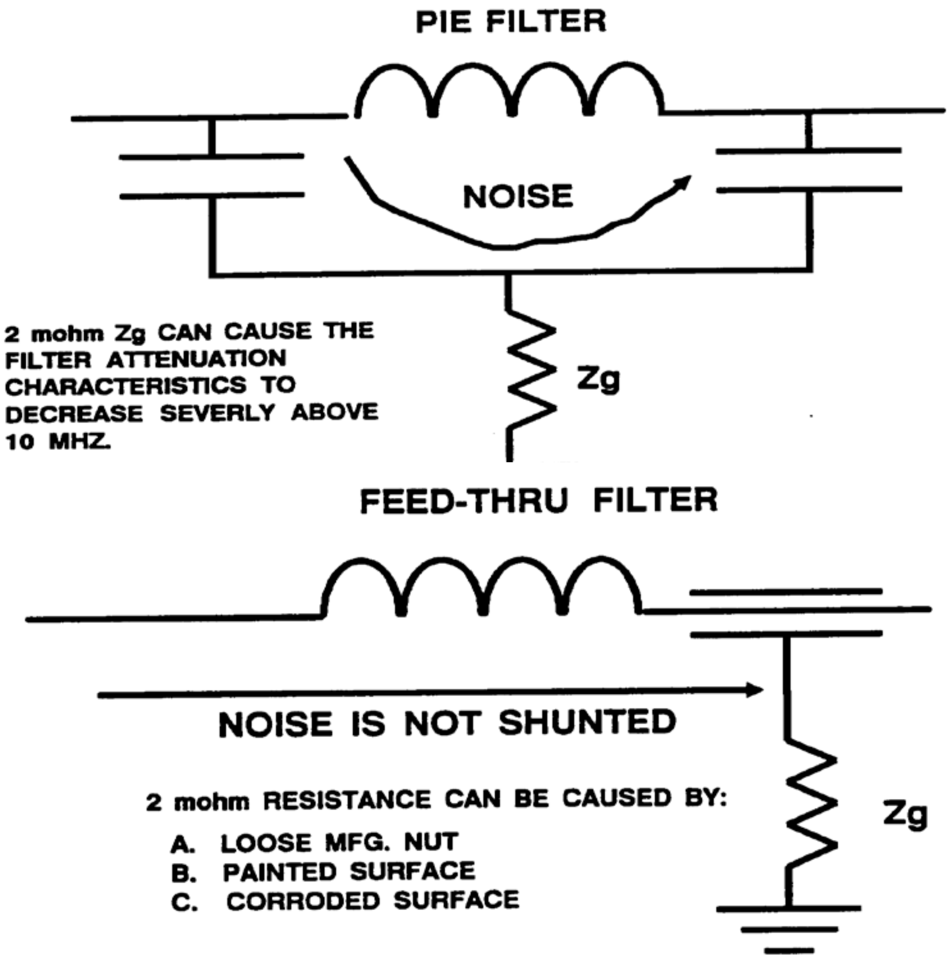
- Passive filters must be mounted (referenced) to the physical point where you want the return current to flow
- Filters can also drive ground noise into the signal line being filtered
- A solid metal to metal contact is necessary for good ground coupling
- Filters must be located such that a coupling path around the filter is not available

Filter Connector & Filter Plate

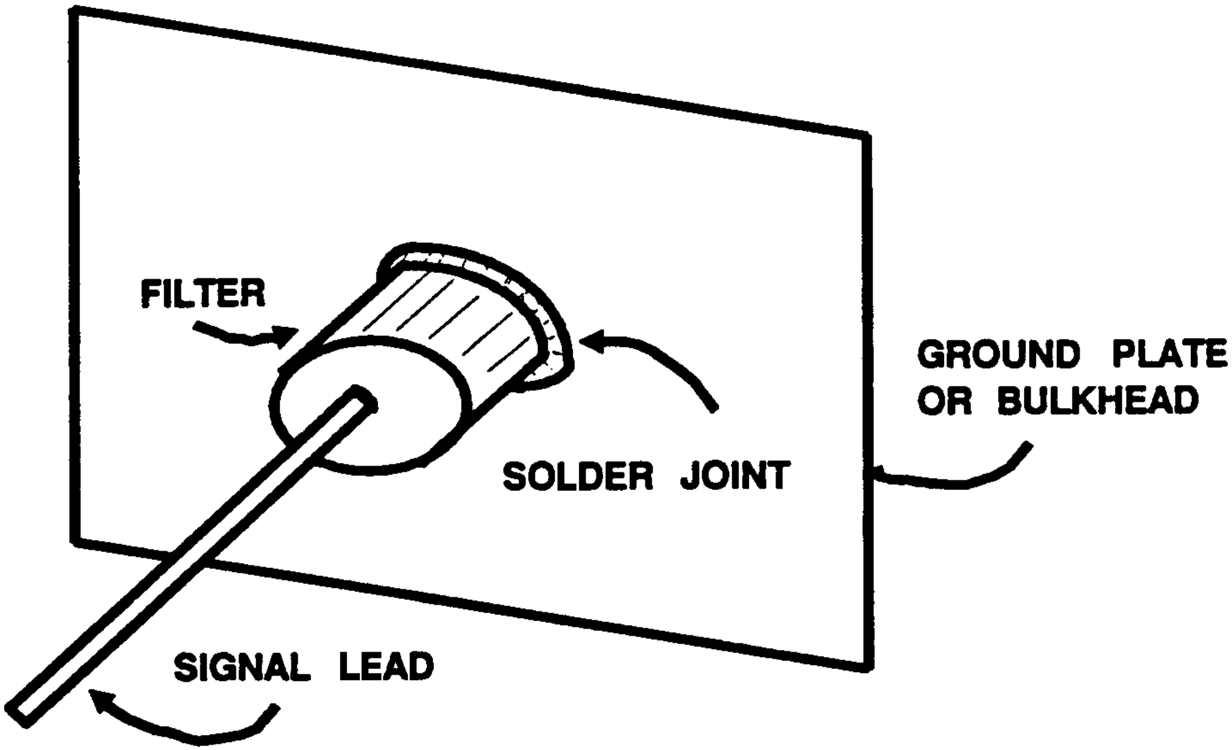




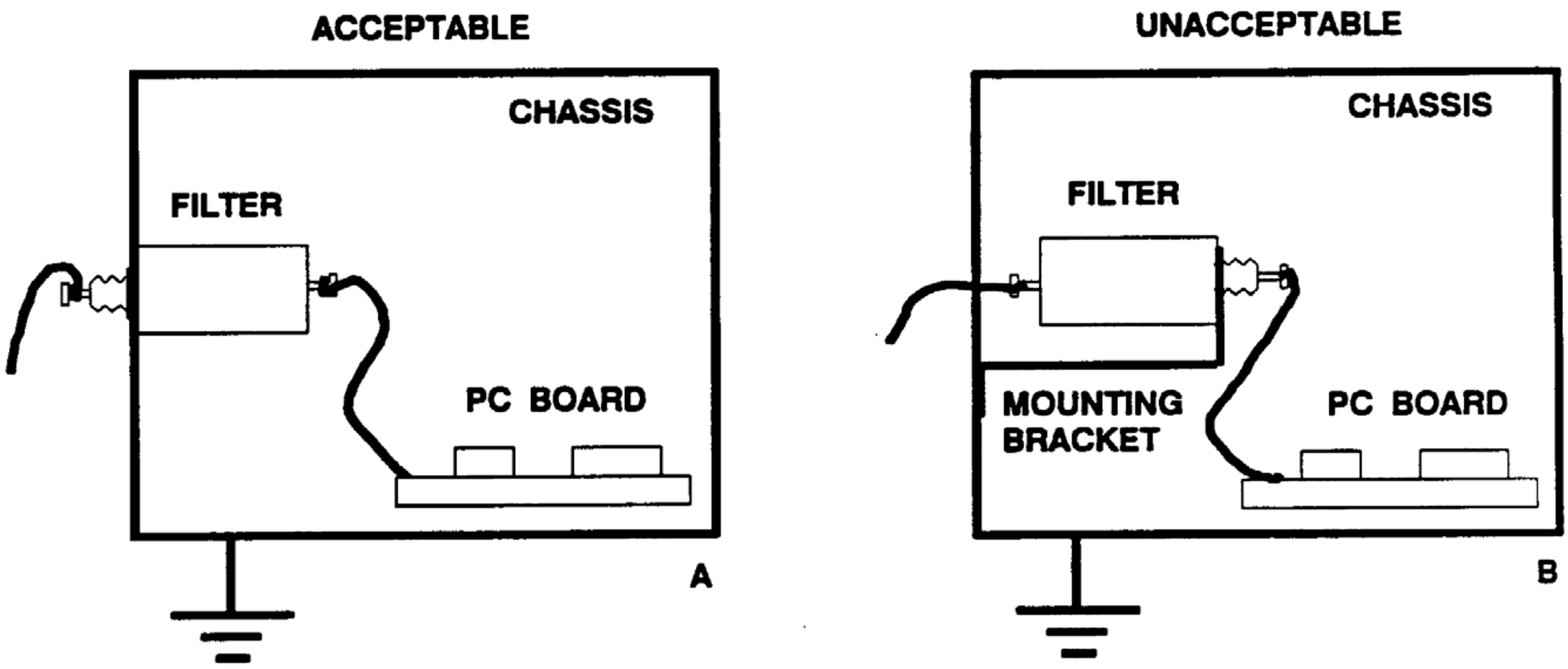
Filter Bonding Effects



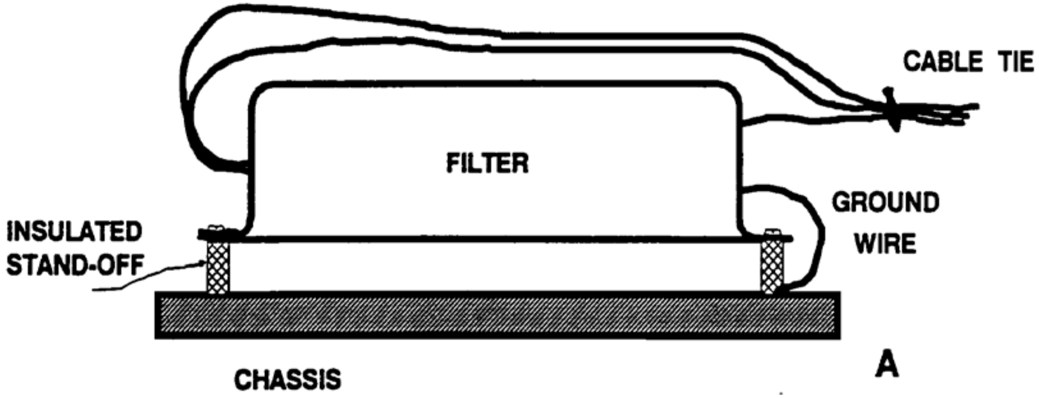
Soldered Feed-Thru



Good & Bad Installation



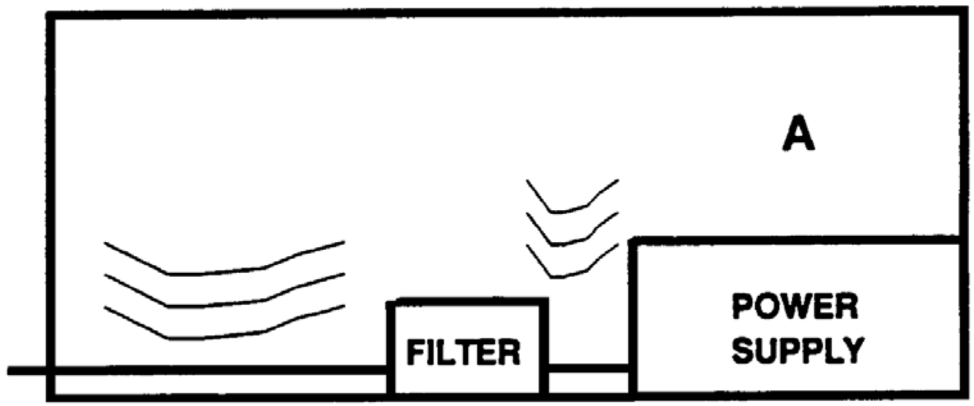
Common Mounting Techniques



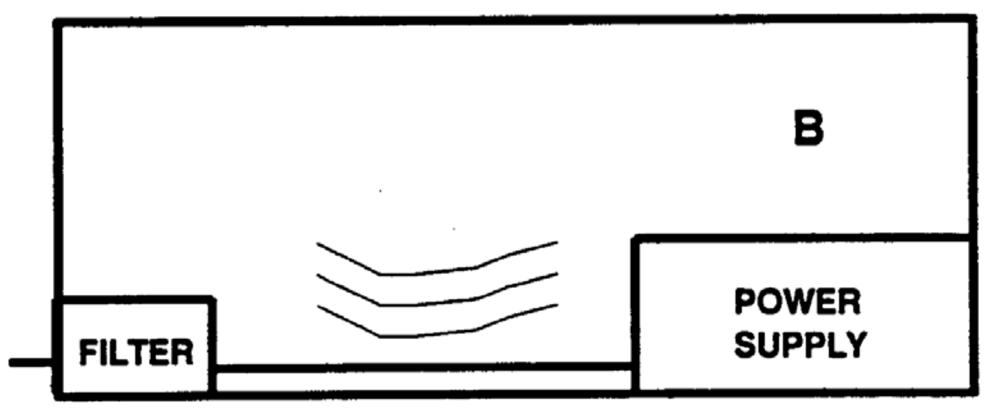
INCORRECTLY MOUNTED POWERLINE FILTER

CORRECTLY MOUNTED POWERLINE FILTER

Bad Filter Locations in a Box



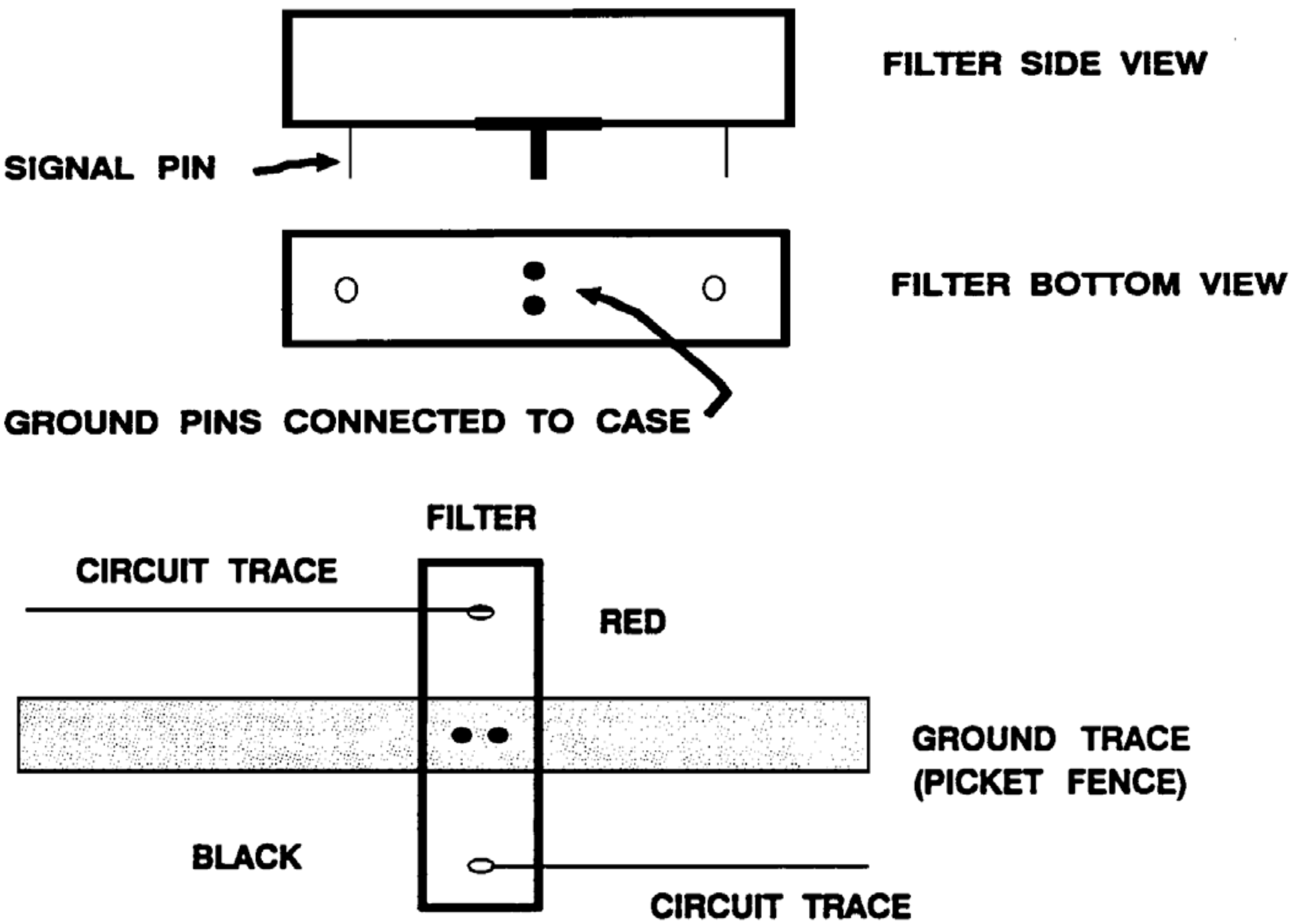
POOR FILTER LOCATION



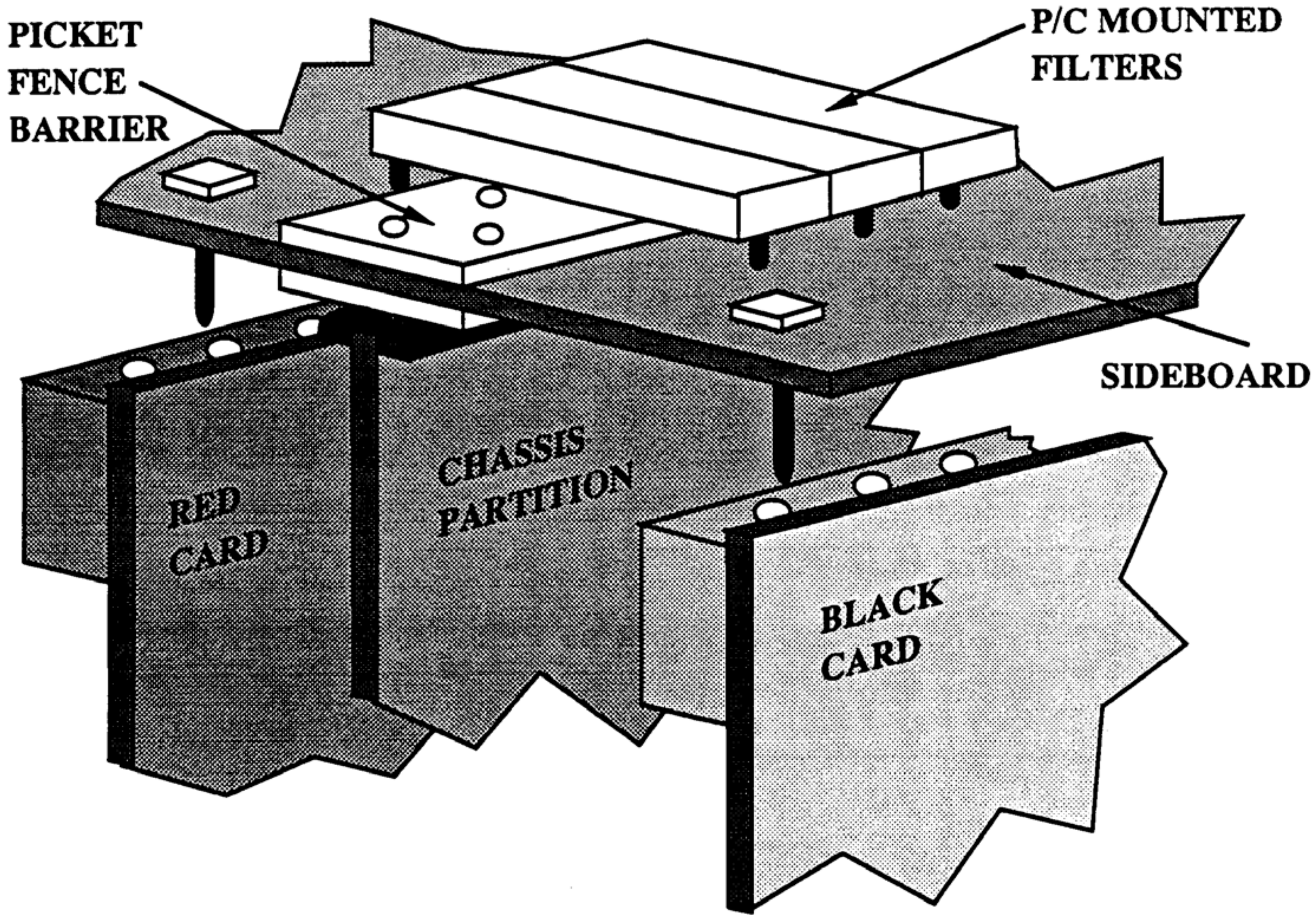
Filter Grounding

- Primary powerline installation concern is the maintenance of a low impedance to ground.
- Mount powerline filters through a wide metal flange directly to the outside bulkhead and physically close to the power supply.
- PC mounted filters are provided with two wide pins connected to the middle of their case for mounting to the ground plane.

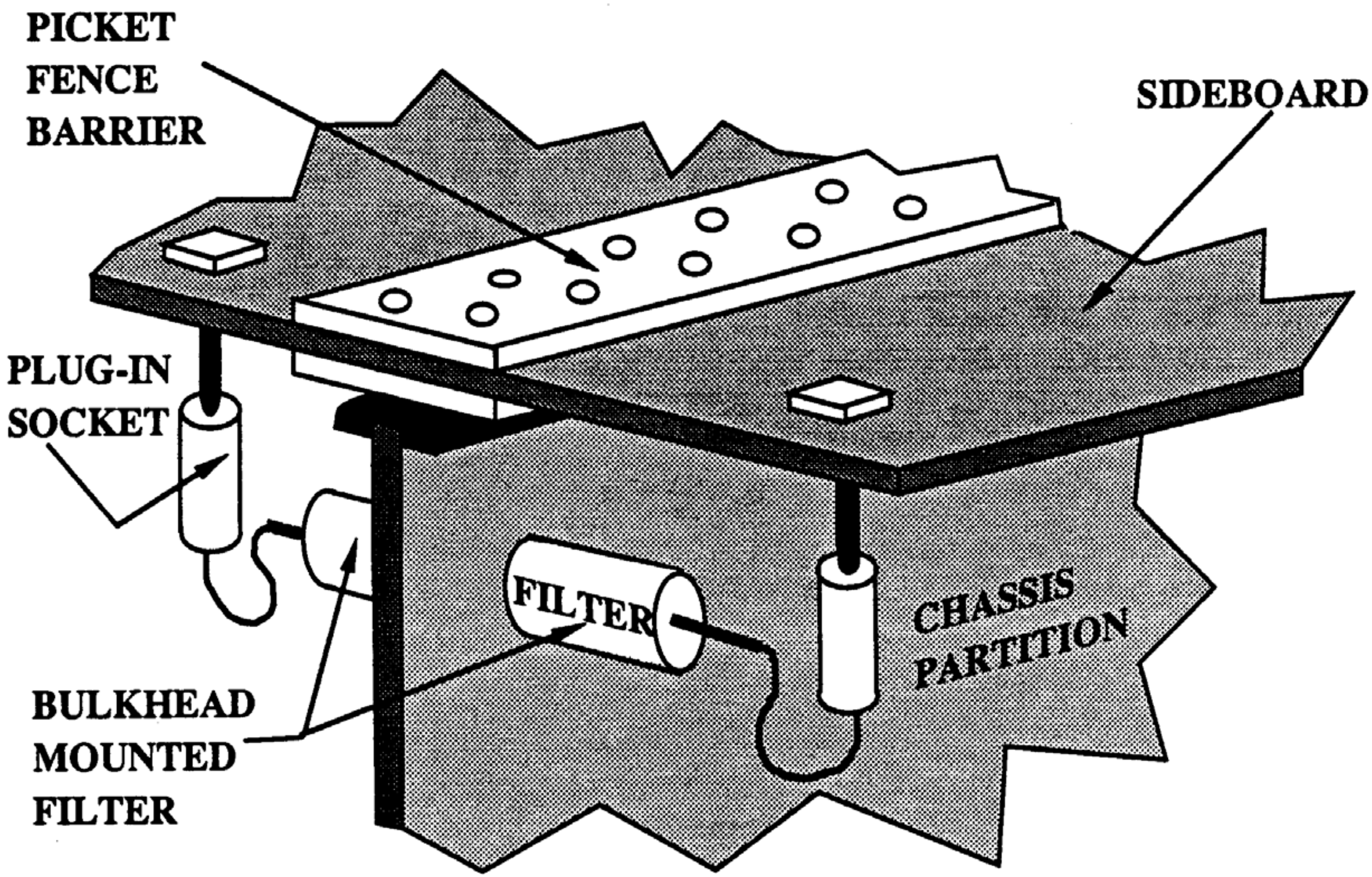
PC Mounted Filters



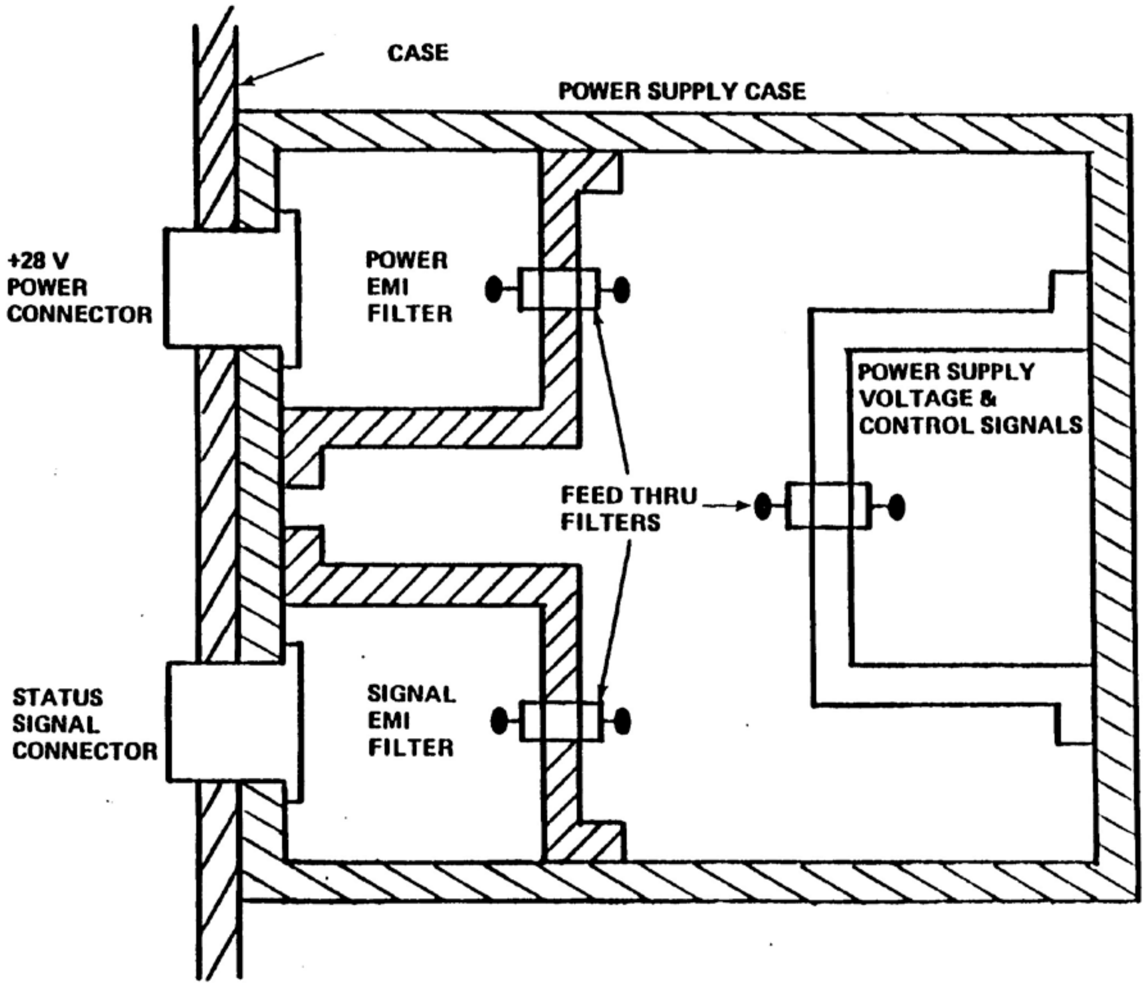
Backplane Filtered Compartment



Bulkhead Filtered Compartment



Power Supply Isolation Using Feedthrough Filters



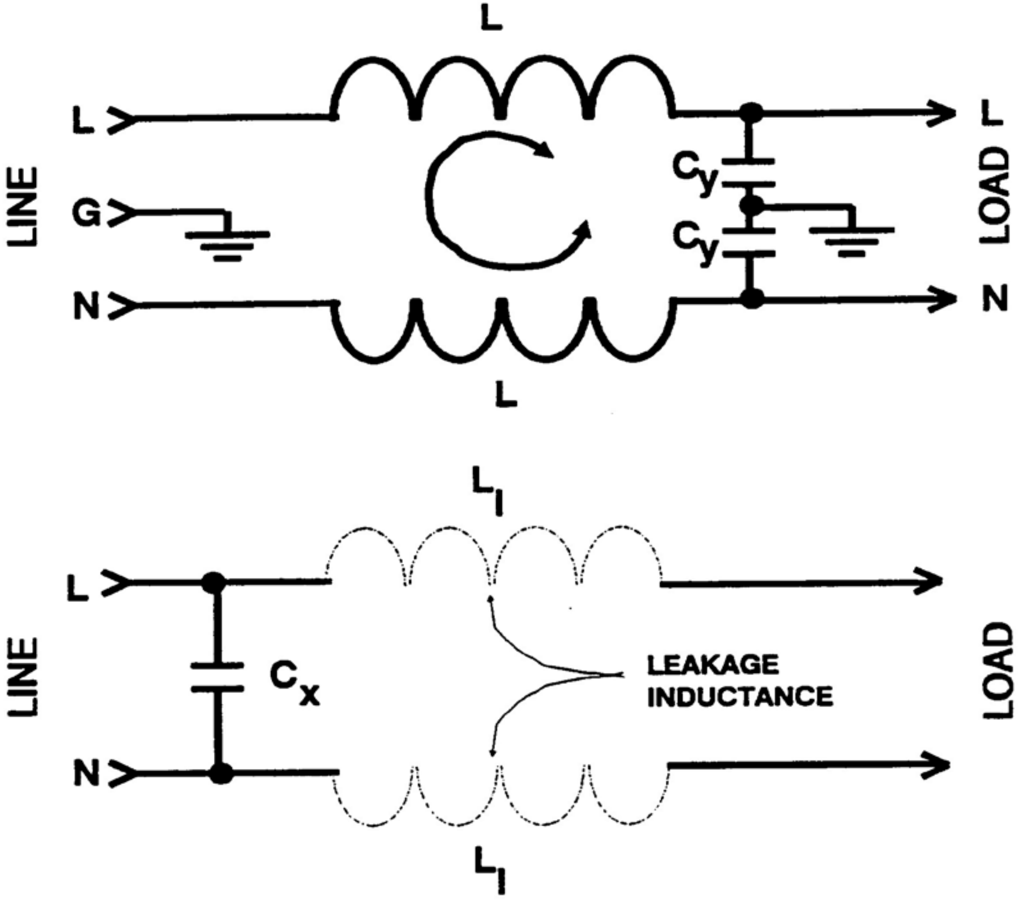
Powerline Filtering

- Facility filtering only required when average power consumption is less than 100 KVA.
- Filters are used at both the box (preferred) and system level.
- In no case should a combination of bulk and individual powerline filtering be used on the same equipment.

Neutral Filtering

- Needs depends on voltage level of ground system at the location of egress to the controlled area.
- If the difference in facility ground potential is less than 1 volt, neutral filtering is probably not required.

Powerline Filter Assembly

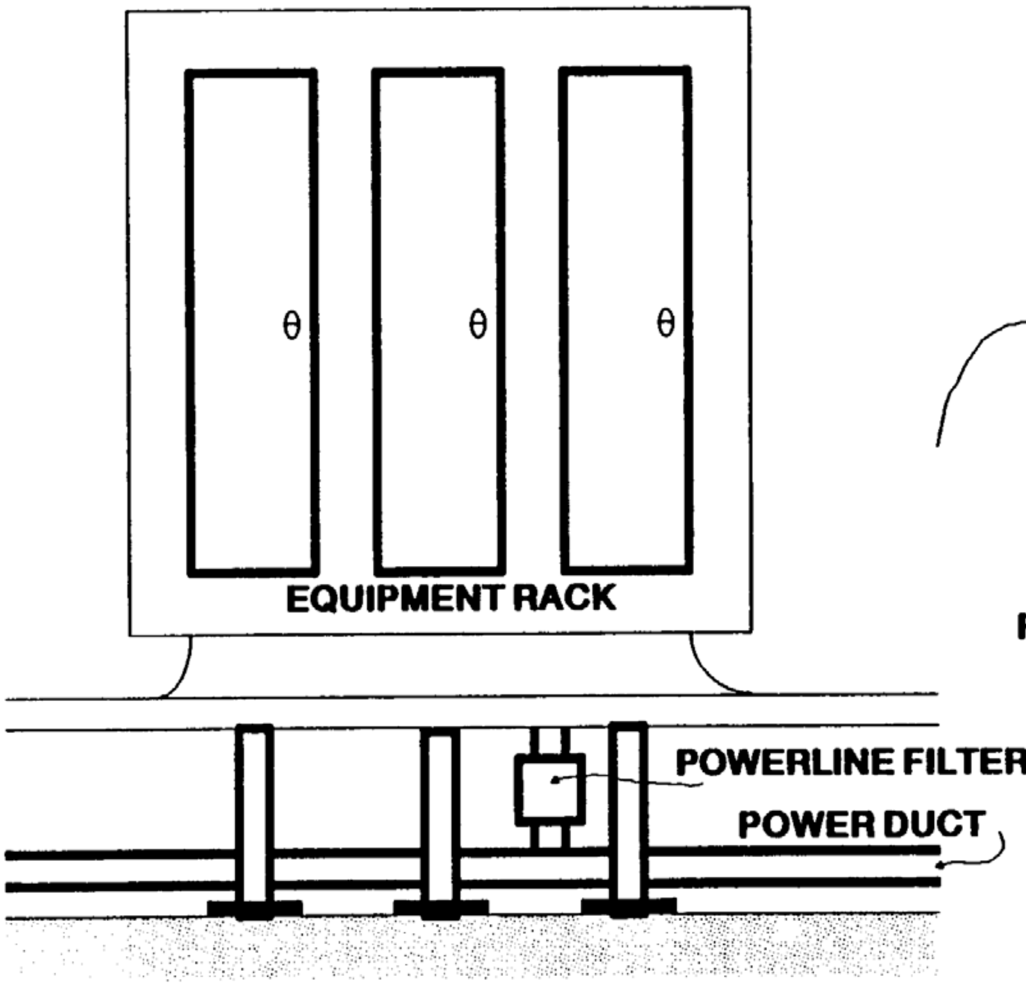


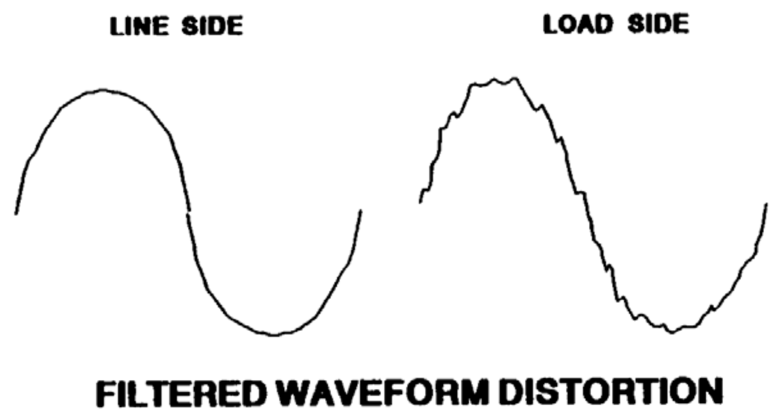
(Top - Common-Mode & Bottom Differential-Mode)

Common mode noise is attenuated by the combination of L and C_y.

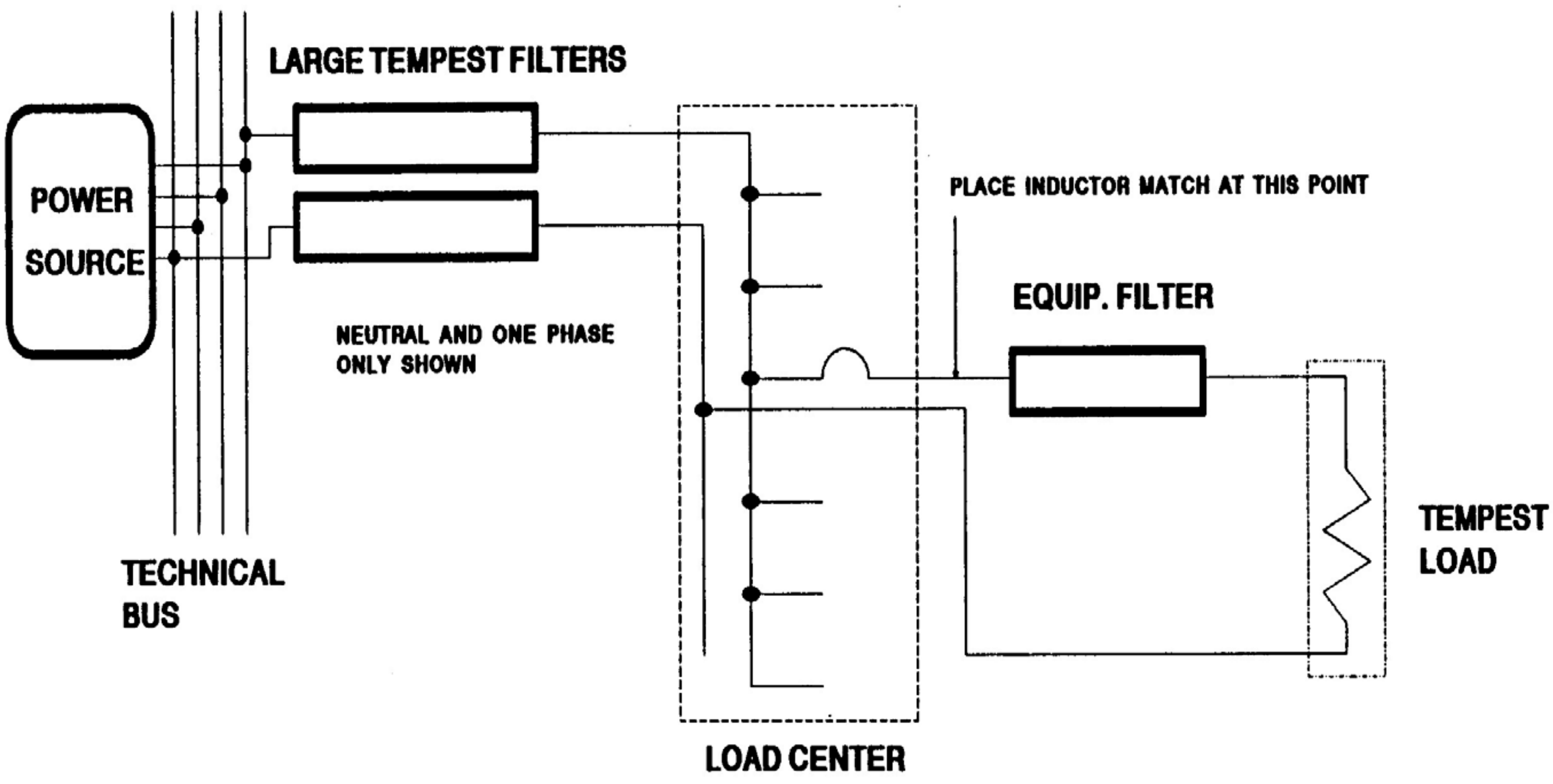
Differential mode noise is controlled by C_x and the leakage inductance (L_i) of the common mode inductor assembly

Preferred Method of Equipment Filtering

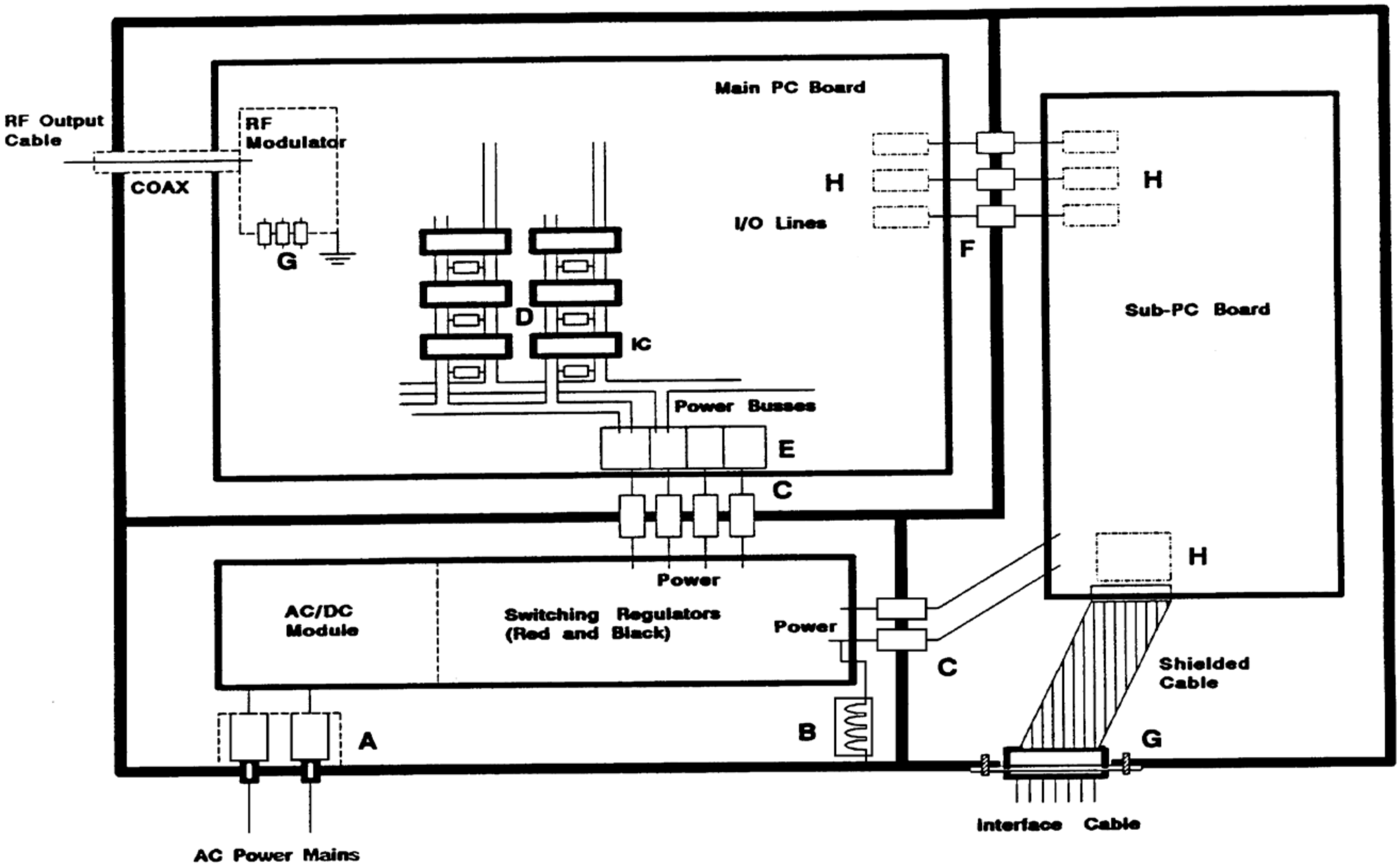




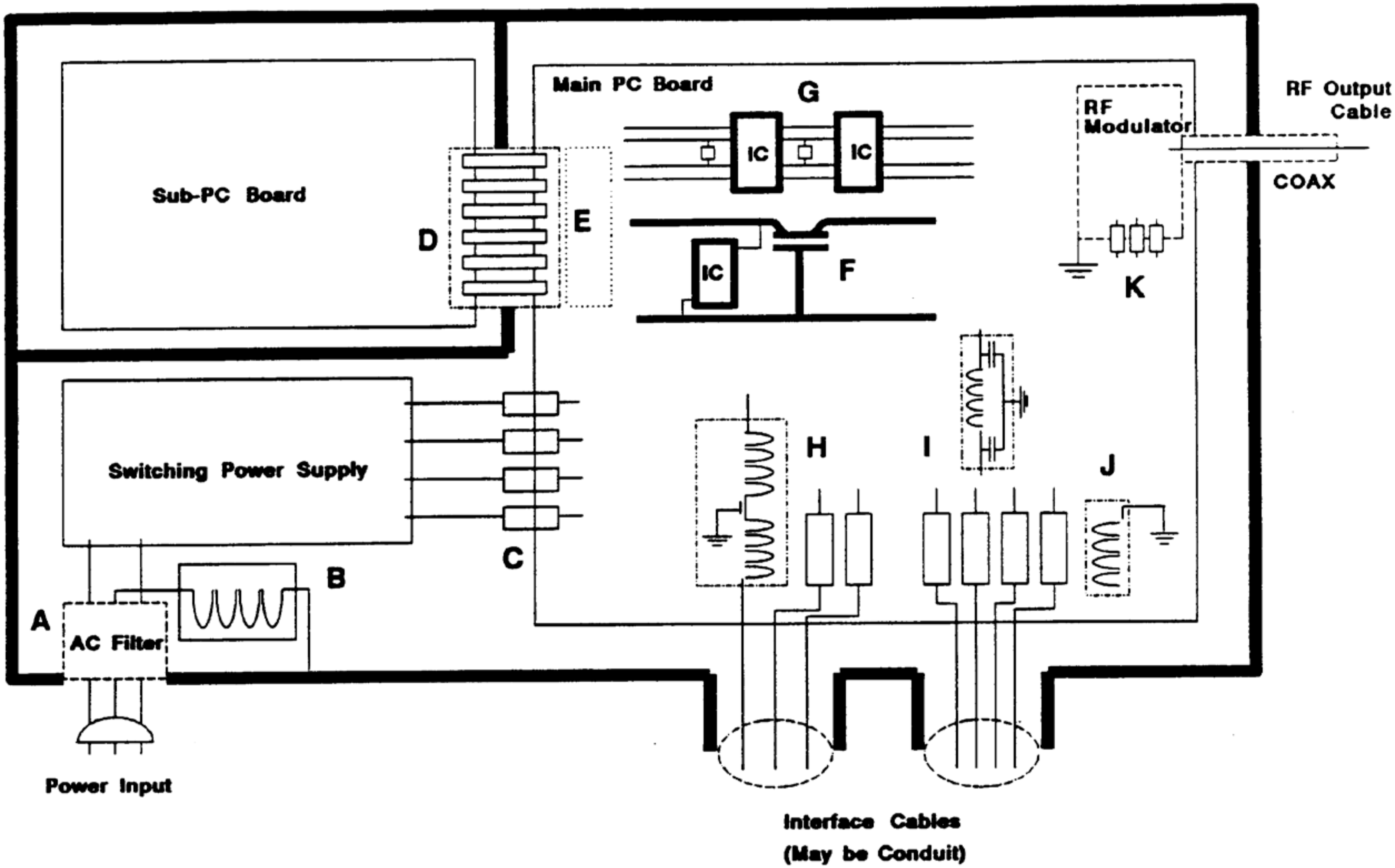
Double Filtered Power System



Typical Military Example



Typical Digital Application



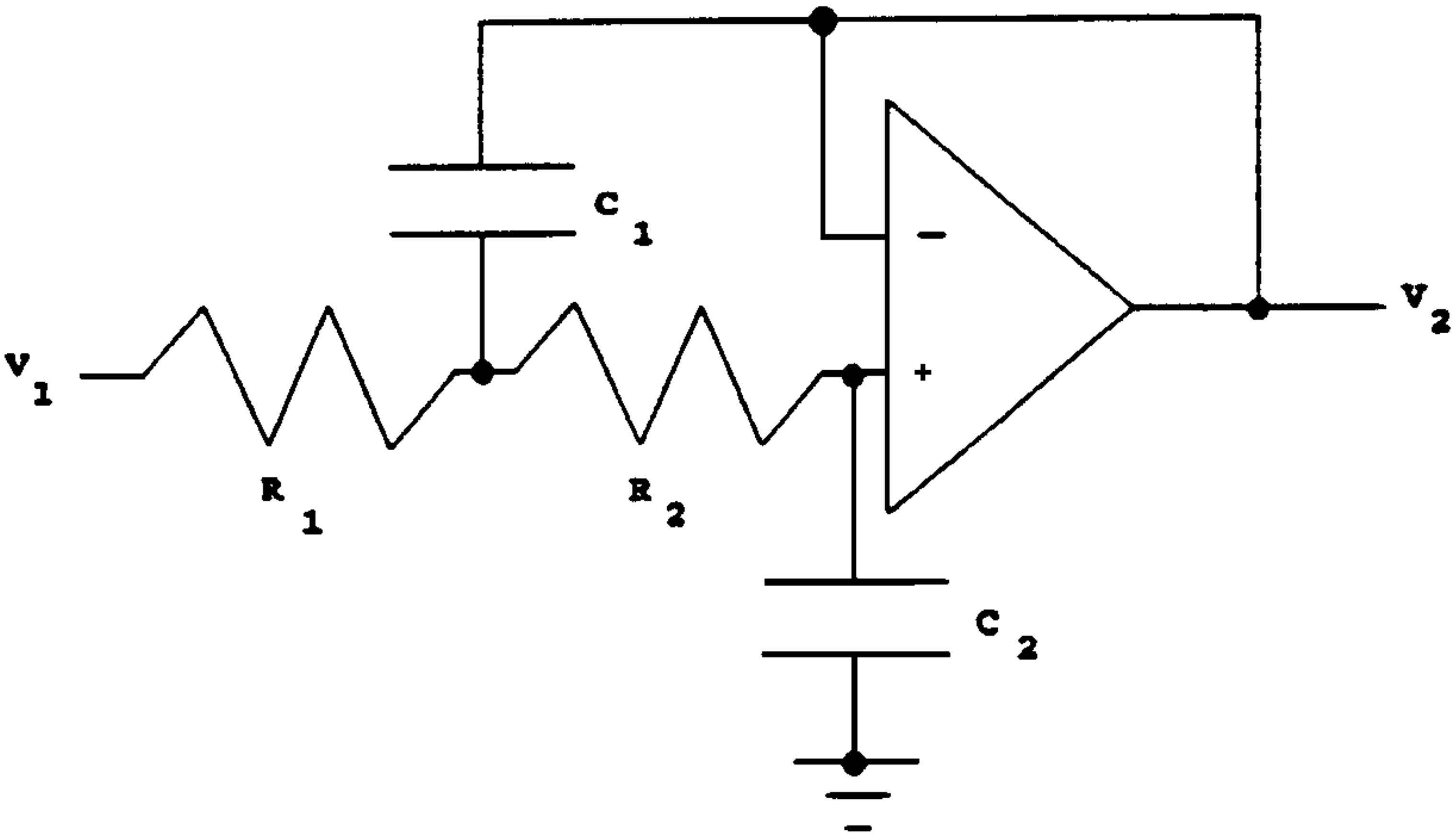
Active Filters Advantages/Problems

- The big advantage is their ability to increase line impedance using RC rather then LC components
- The big problem is their stability and susceptibility to signal coupling
  - High frequency oscillations can act as carriers to propagate coupled signals outside the TEMPEST container

Active Filter Usage

- Active filters find their greatest use as line driving circuits in emission controlled applications
  - Offset voltage becomes the major problem in line driver applications
  - Physical isolation and power decoupling are critical

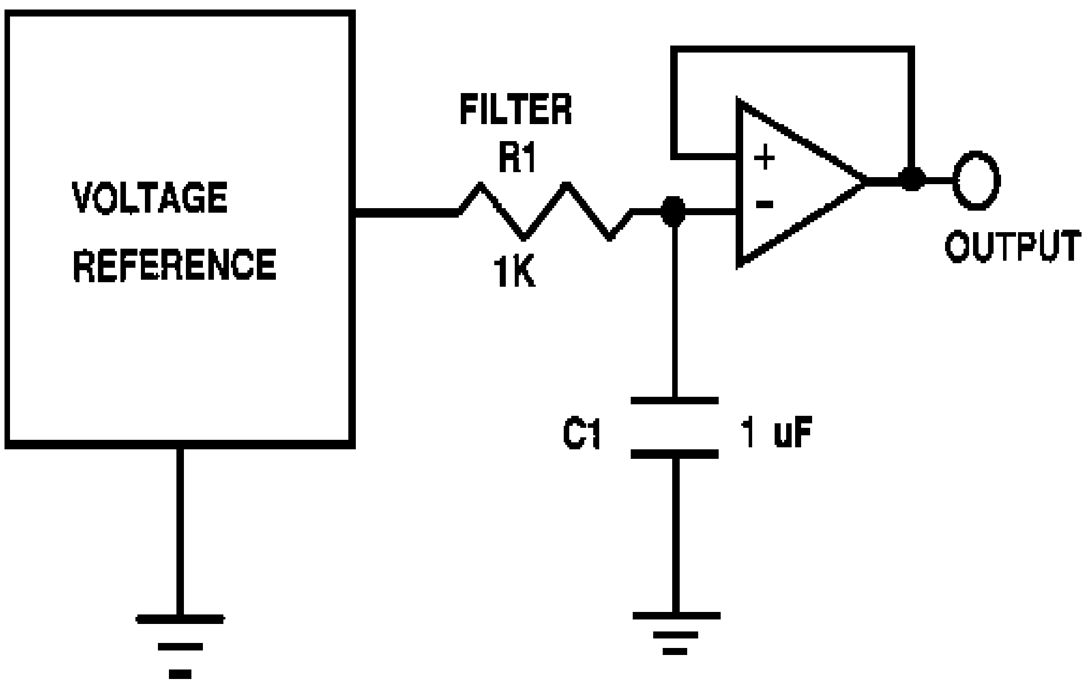
Single Op-Amp 2nd Order Filter



Single Op-amp Second Order Filter Response Problems

- Susceptible to signal coupling
- Only limited gain-bandwidth product available
- Increased gain near the natural frequency of the filter can cause ringing on driven lines
- A downshift in the calculated natural frequency of the filter occurs due to the excess phase shift of the amplifier
- Q is maximized at low frequencies due to finite amplifier gain

Noise Filter



- A conventional voltage reference circuit consists of a voltage reference unit, followed by a single-pole filter, and a unity-gain buffer
- The buffer provides low output impedance

Op-amp Characteristics - CMRR

- Common-mode noise appears as the offset voltage between each input and the op-amp ground
  - Up-amp common-mode rejection ratio is defined as: $$CMRR = 20\log\left|\frac{A}{A_{cm}}\right|$$
  - In general, CMRR is greatest at DC

Op-amp Characteristics – PSRR

- Op-amp power supply rejection ratio is defined as the ratio of the equivalent change at the input of the amplifier to a change in the supply voltage on the B+ input
- PSRR (lowest) best at DC and deteriorates with increasing frequency of ripple
- While both overshoot and settling time may be acceptable in a specific op-amp application, they may cause severe emission control problems as sources for unwanted HF emanations

Passive & Active Summary

- Passive filters more applicable to emission controlled applications because of stability and sensitivity to noise
  - Problems with passive filters include variable insertion loss, inductor nonlinearity and response output gain near the break frequency.
  - Problems with active op-amp filters relate to their significant amplification and/or modulation of noise in high Q circuit designs. for TEMPEST applications, active filters are best used at very low frequencies (such as voice circuits).

Passive Filter Summary

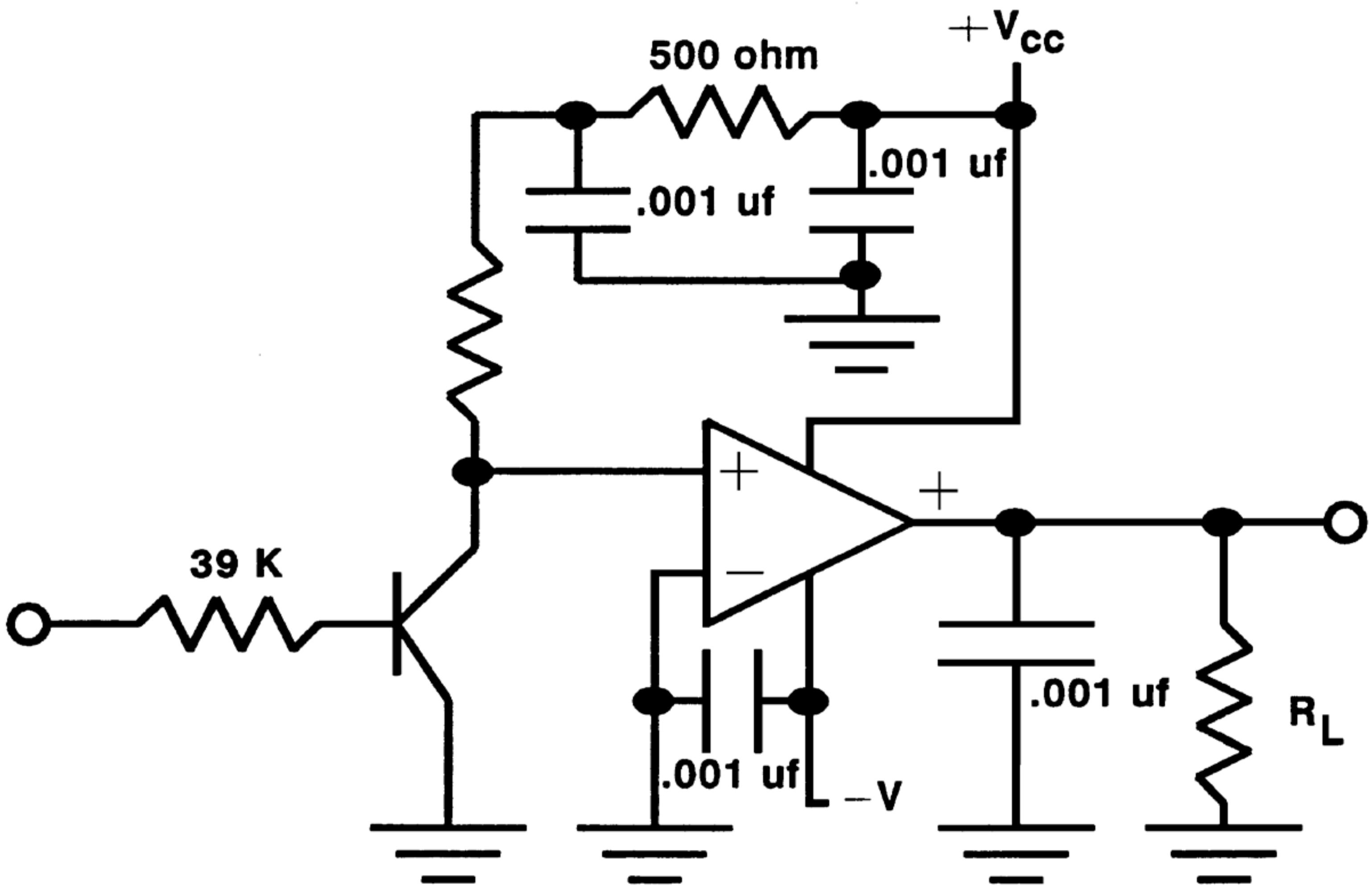
- Have a variable insertion loss
- Inductor nonlinearity creates harmonic and intermodulation distortion products that are a function of signal amplitude
- Tank circuits (pi filters) ring at a natural resonant frequency with a shock excitation more than L and much more than T circuits
- Capacitors turn inductive at high frequency

Active Filter Summary

- Input noise is amplified significantly in high Q designs
- When a single amplifier is used to generate two poles the relative amplification factor of noise is proportional to the square of the filter Q
- Bi-quad or state variable filter has a relative noise amplification factor proportional to Q
  - Noise is created by the basic amplifier design and by power supply noise transformed by the B+ rejection of the amplifier

Active Filter Summary

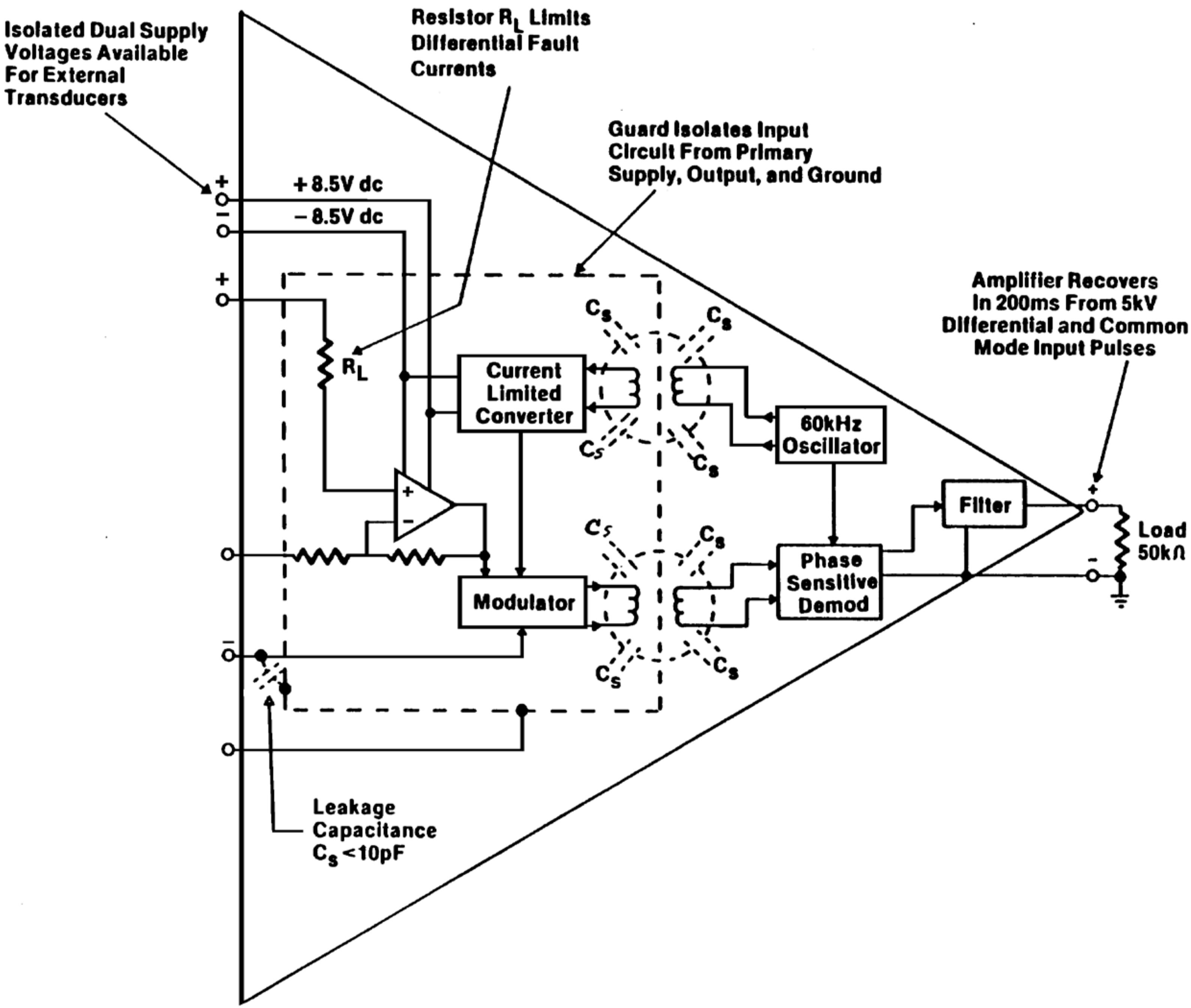
- Are best used at frequencies below 100 Hz
- Distortion products usually below 80 Db



Op-amps attenuate from 35 dB to 50 dB of unwanted input signals. By using .001 uf capacitors on the power leads to an input drive transistor, the attenuation can be increased to 80 dB or more.

Isolation Amplifiers

- A two port isolation amplifier is an instrumentation amplifier with its signal-input circuit isolated from signal output and power inputs
- A three port isolator has, in addition, isolation between signal output and power inputs
- Only useful for TEMPEST applications in the low kHz range.



Isolated Dual Supply Voltages Available For External Transducers
Resistor R_L Limits Differential Fault Currents
Guard Isolates Input Circuit From Primary Supply, Output, and Ground
+8.5V dc
−8.5V dc
R_L
Current Limited Converter
60kHz Oscillator
Modulator
Phase Sensitive Demod
Filter
Amplifier Recovers In 200ms From 5kV Differential and Common Mode Input Pulses
Load 50kΩ
C_s
Leakage Capacitance C_s <10pF

Eliminating Ground Loops

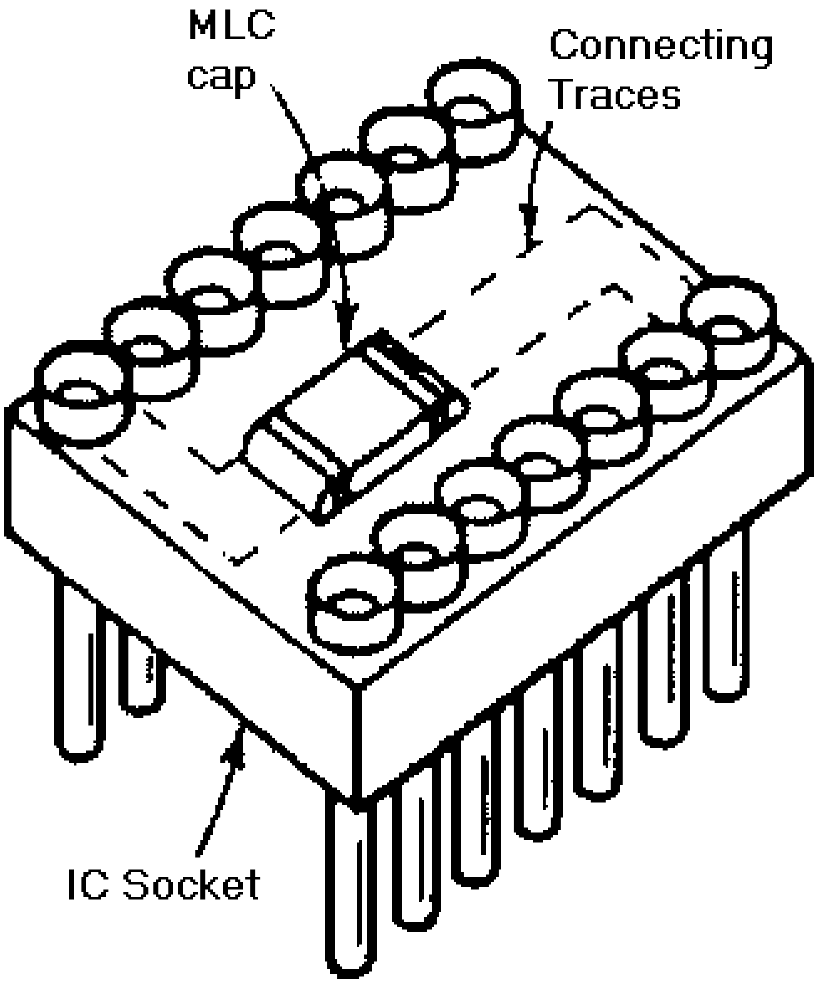
- Isolation amps used to eliminate ground loops - an isolator with a "fully-floating" front end, requires zero net bias current, permitting two-wire hook-up to signal sources, thereby eliminating coupled connections through source ground

Eliminate Noise Problems

- Isolation amps used when systems operate in noisy environments
- Interference arising from RFI and EMI radiation from motors, relays and power lines is reduced to negligible levels by the excellent common mode rejection (CMR) performance of the isolation amplifier

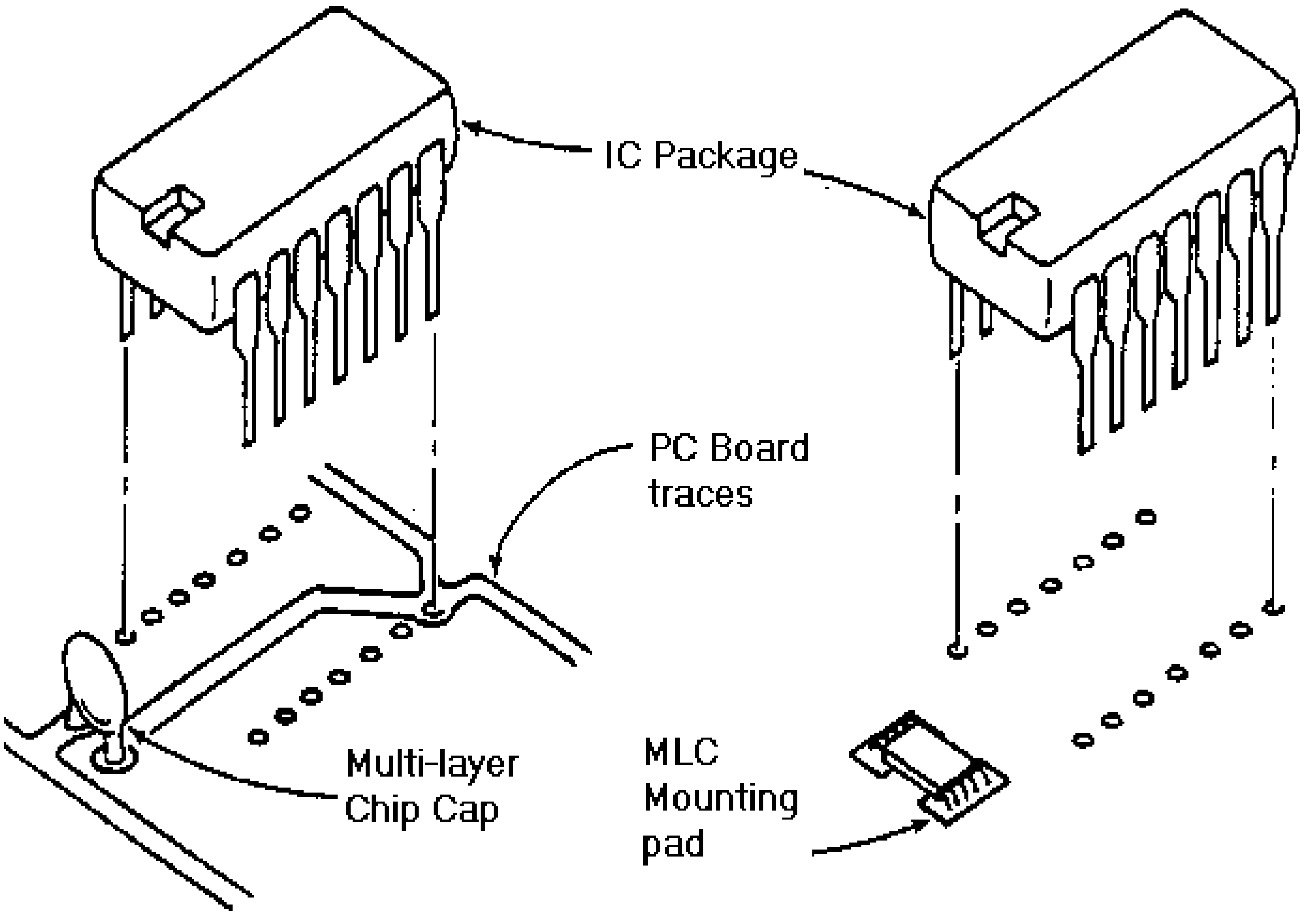
Filter Caps

Decoupled Sockets



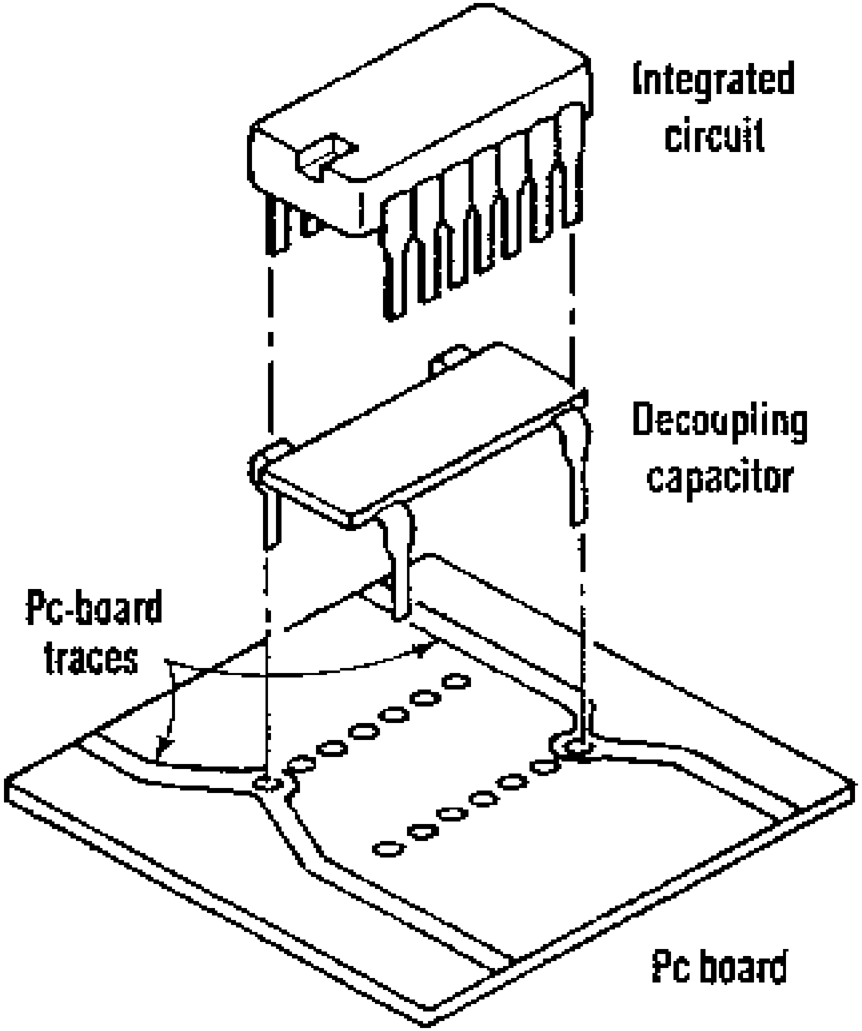
- Sockets with internal caps connected between voltage an ground pins are common.

On-Board Decoupling



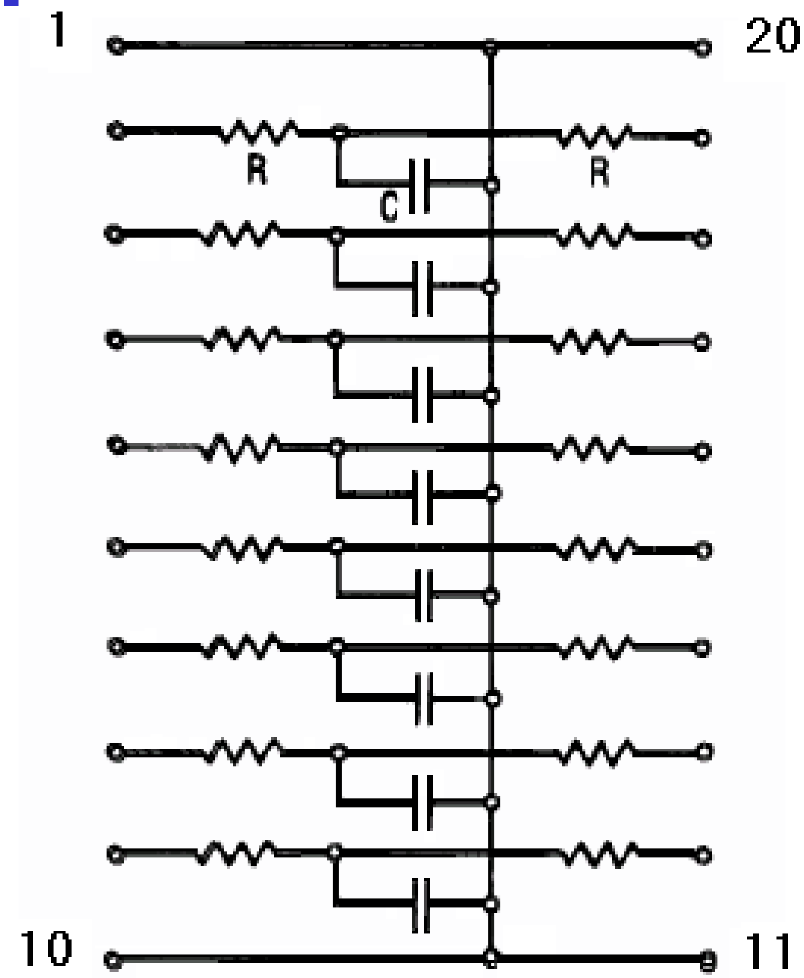
- Chips or pads connected to power & ground planes.

Under IC Decoupling



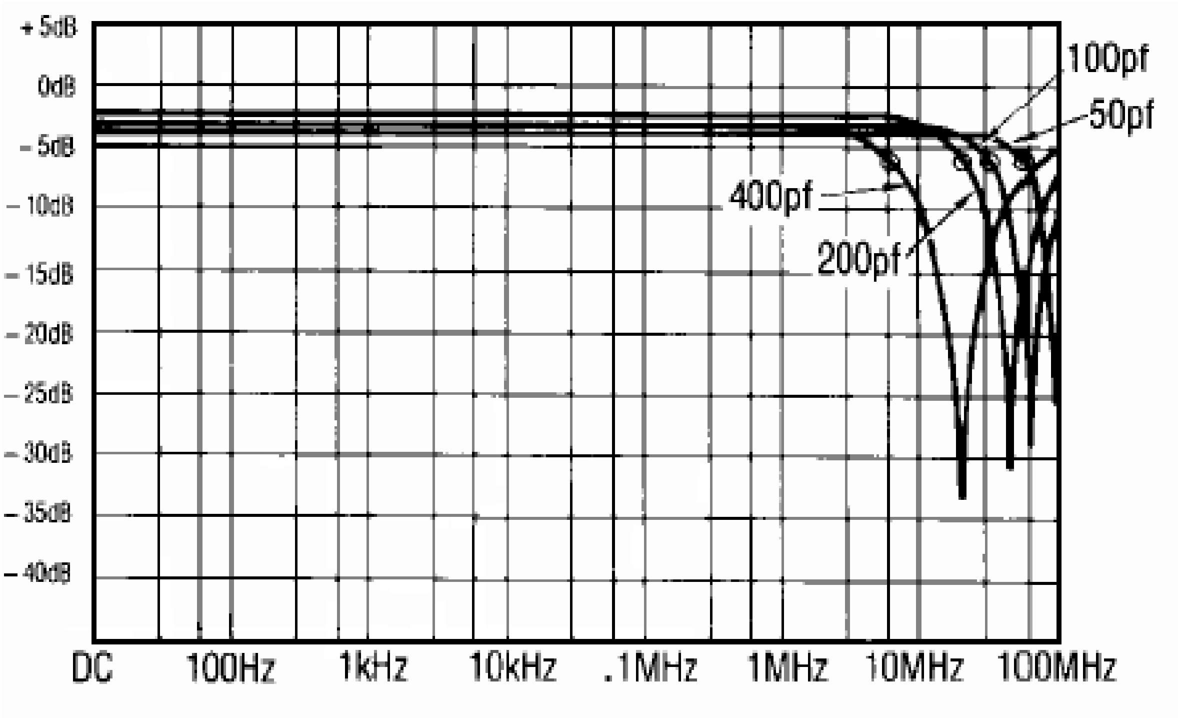
- Flat, thin caps are often installed under the IC to provide better decoupling.

RC Filter Package



- Dip-type RD filter packages are commonly used for wave shaping.

Typical RC Response Curves



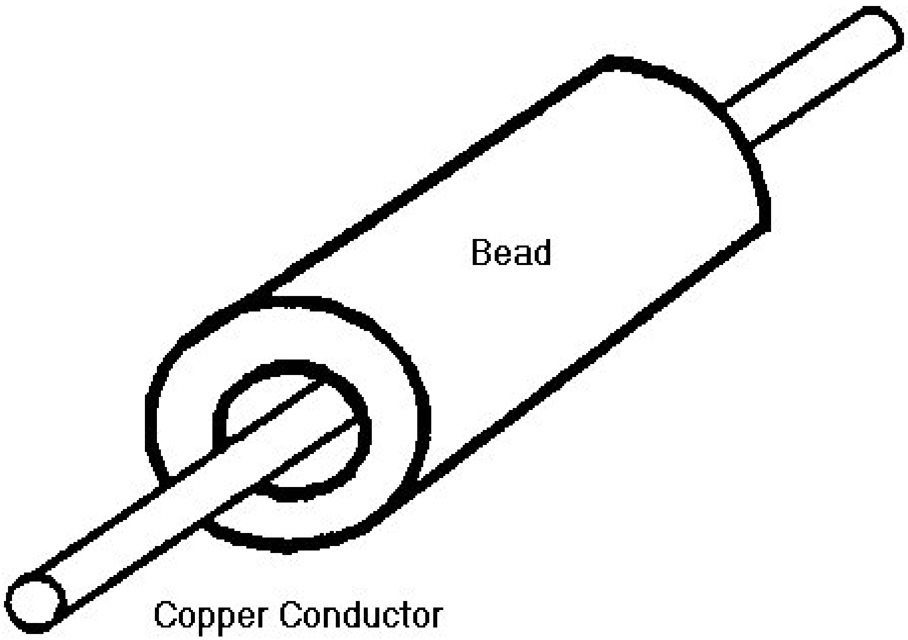
- Note general attenuation resonance between 10 and 100 MHz.

Ferrites

Ferrite Applications

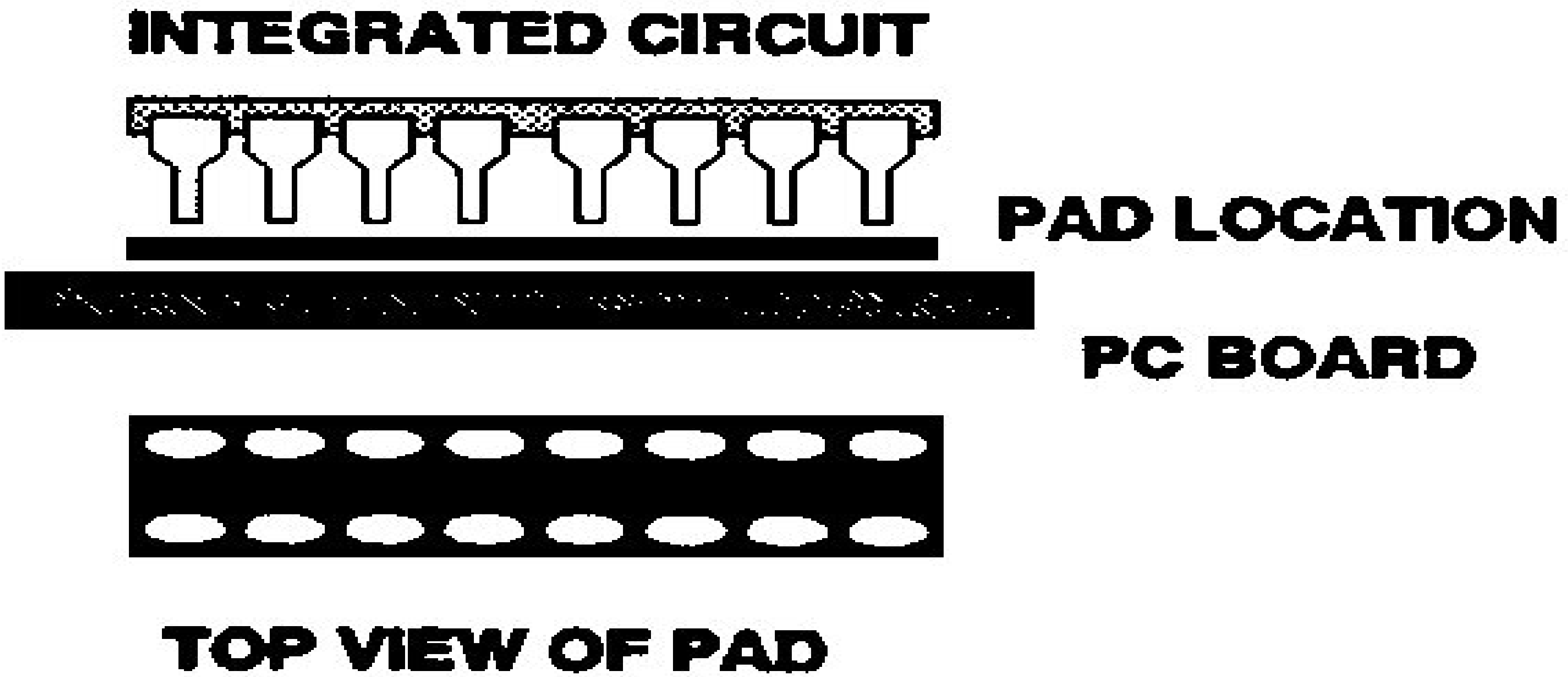
- Only suppression component that can be added without effecting normal circuit operation.
- Bead introduces a small inductance to low frequency current that increases with frequency through a sharp reduction in magnetic permeability.
- The signal suppression capability is also useful in decoupling high frequency circuits and in reducing parasitics in fast switching devices.

Single Ferrite Bead on Wire

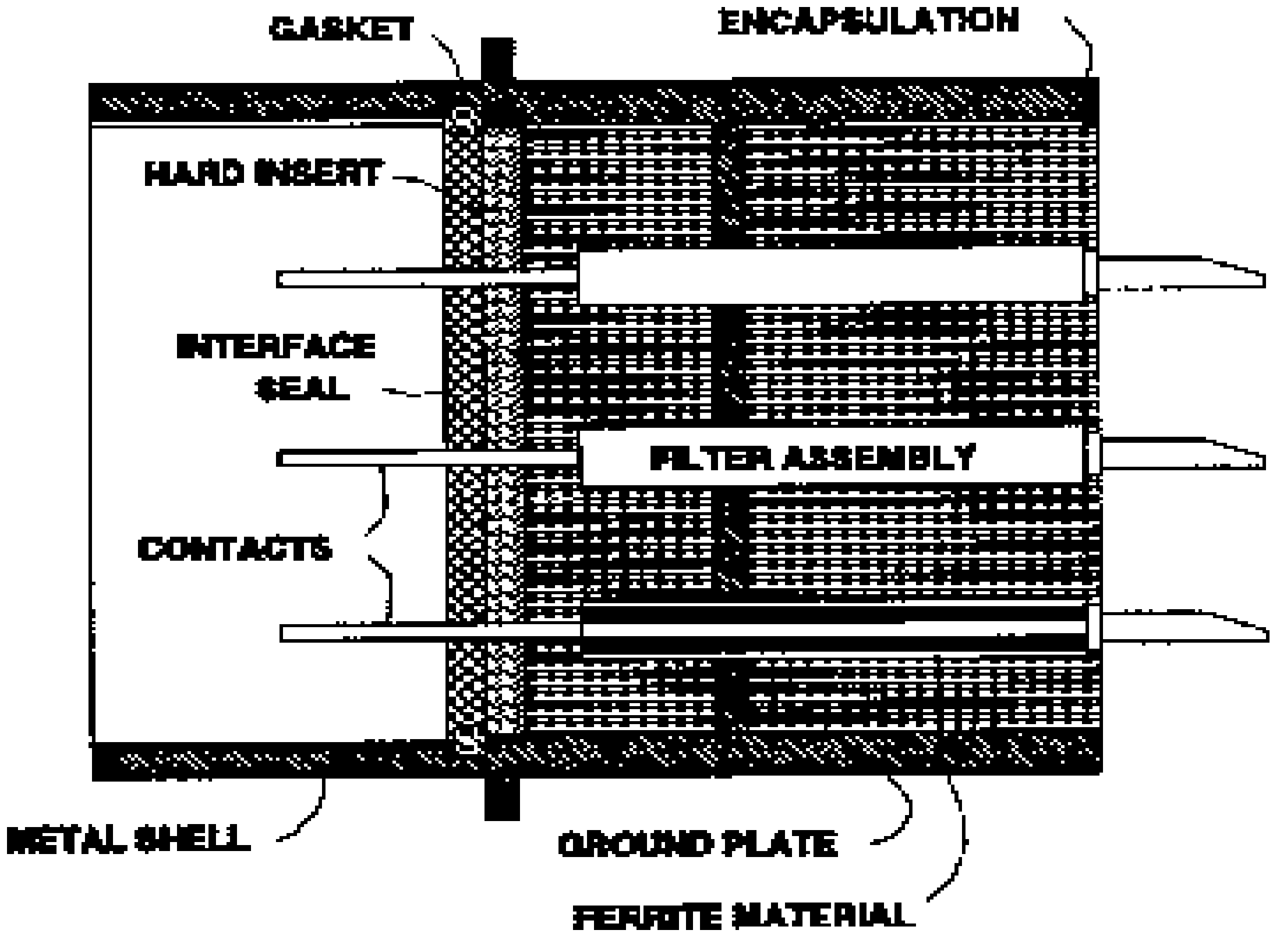


- Installs under IC, around component pin, and on or around interface pin connector.

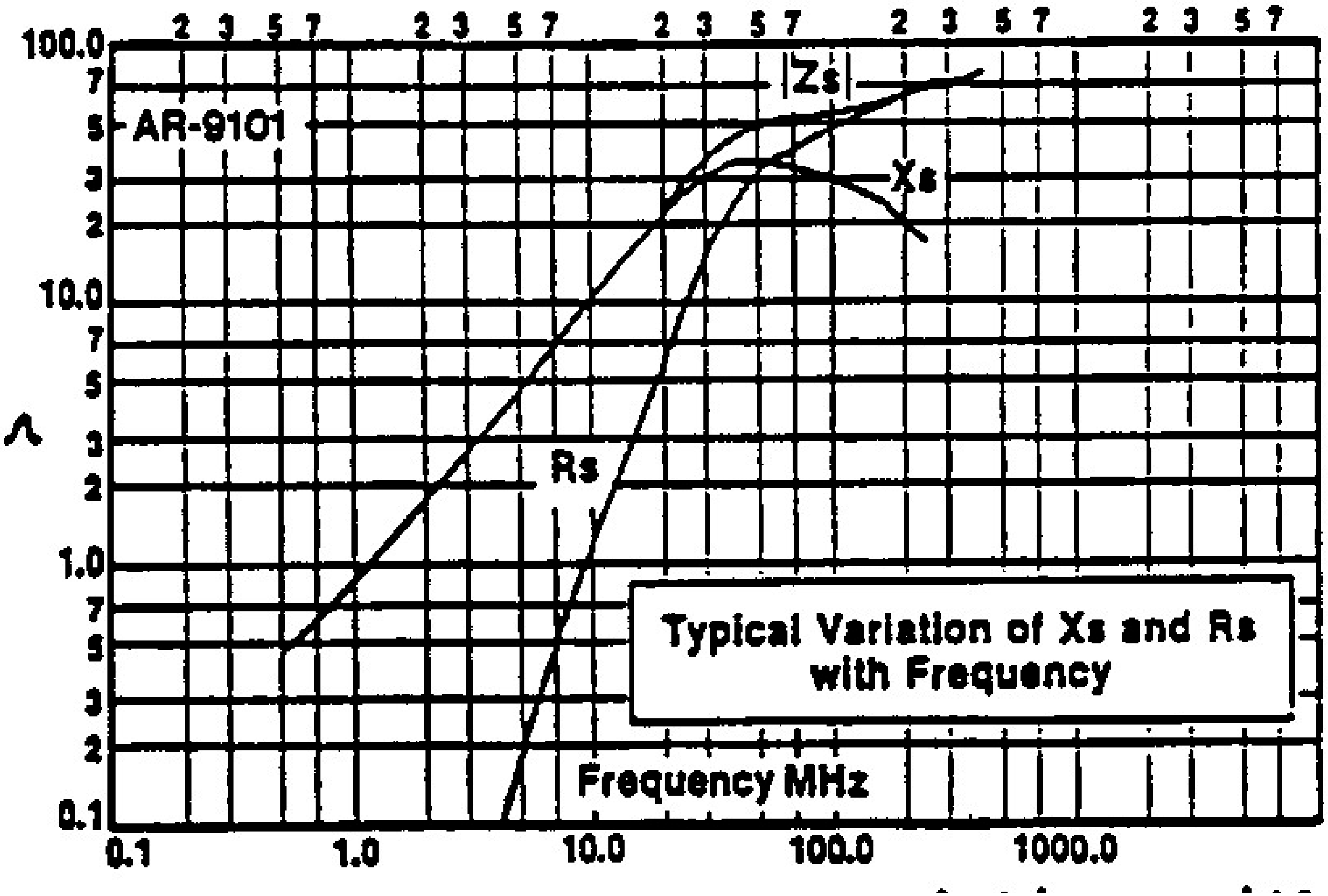
Ferrite Pad Used Under IC



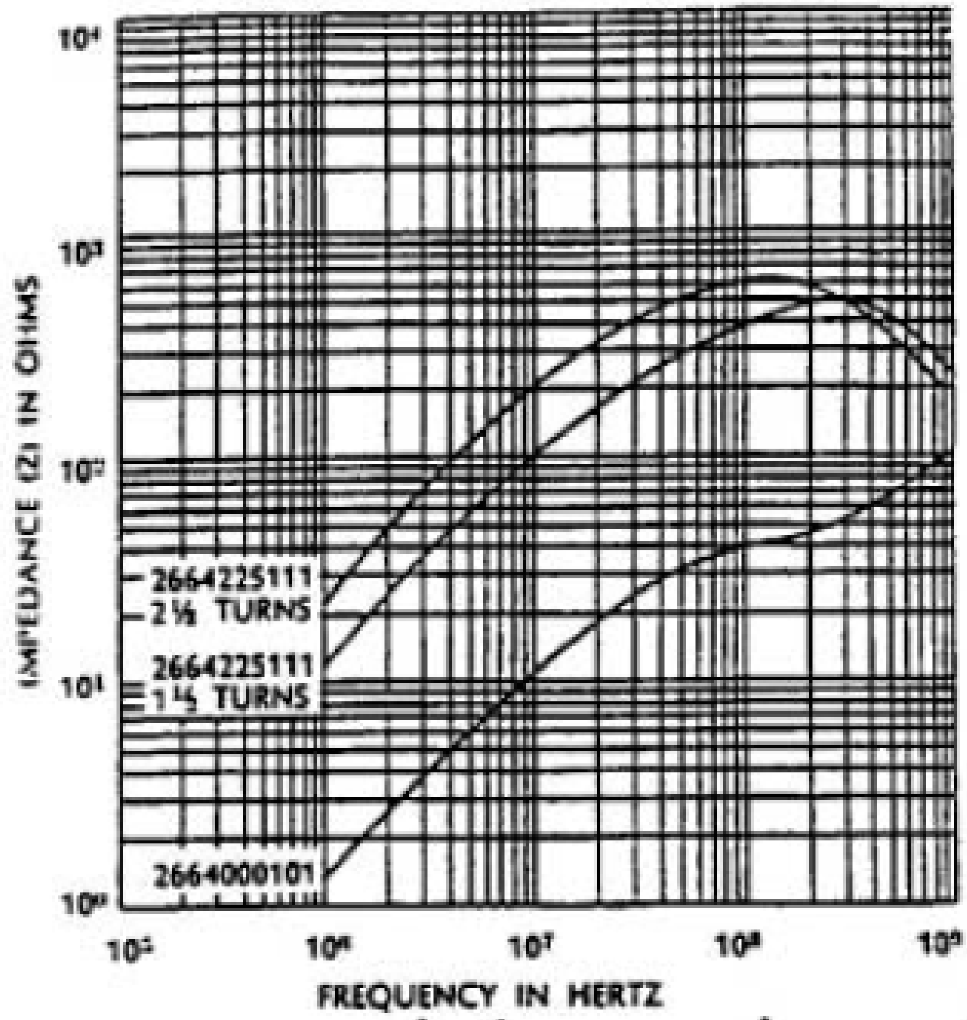
Shielded Pin Filtered Connector



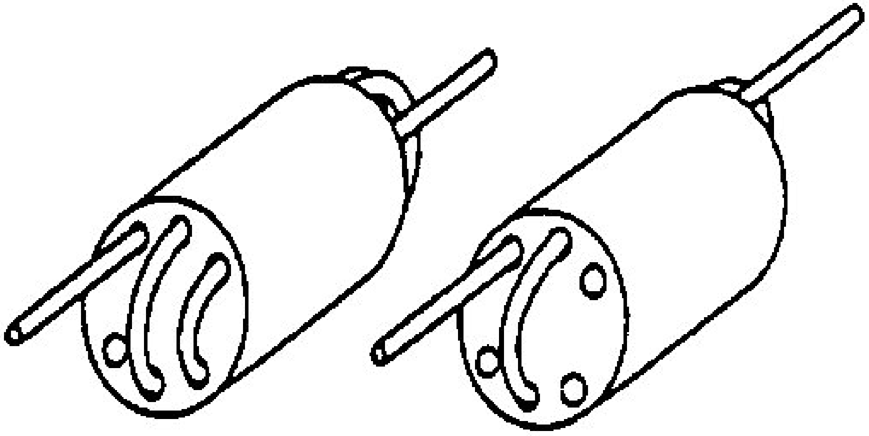
Impedance Variation With Frequency



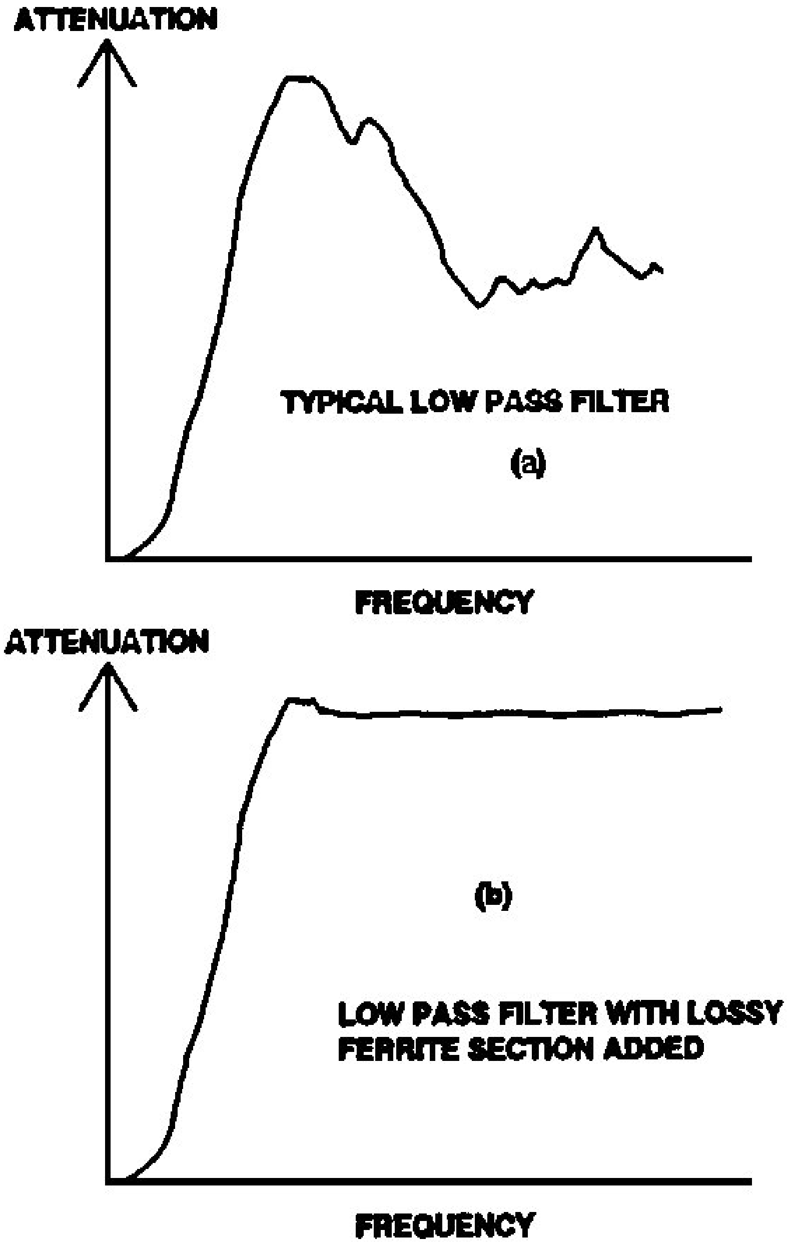
Decreasing Z With Multiple Turns



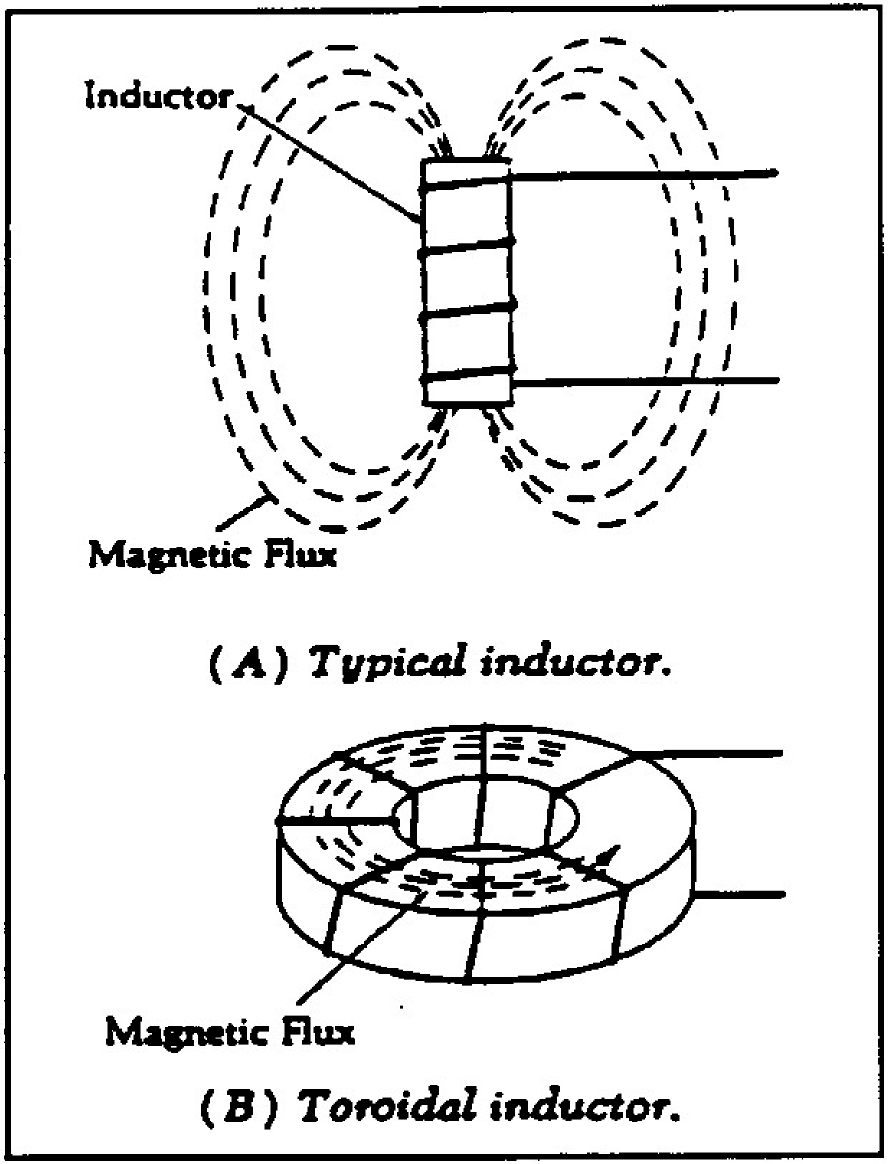
Multi-Hole Core



- Multiple turns of wire through the ferrite eventually saturate the ferrite's noise suppressing characteristics.
- A two and one-half turn loop seems to be the optimum for most applications.



- Low-pass filters loose their effectiveness when their wire wound inductors become capacitive and their capacitors become inductive due to lead length.
- Inserting a lossy ferrite bead in the filter will absorb excess energy at frequencies where the filter characteristics change.

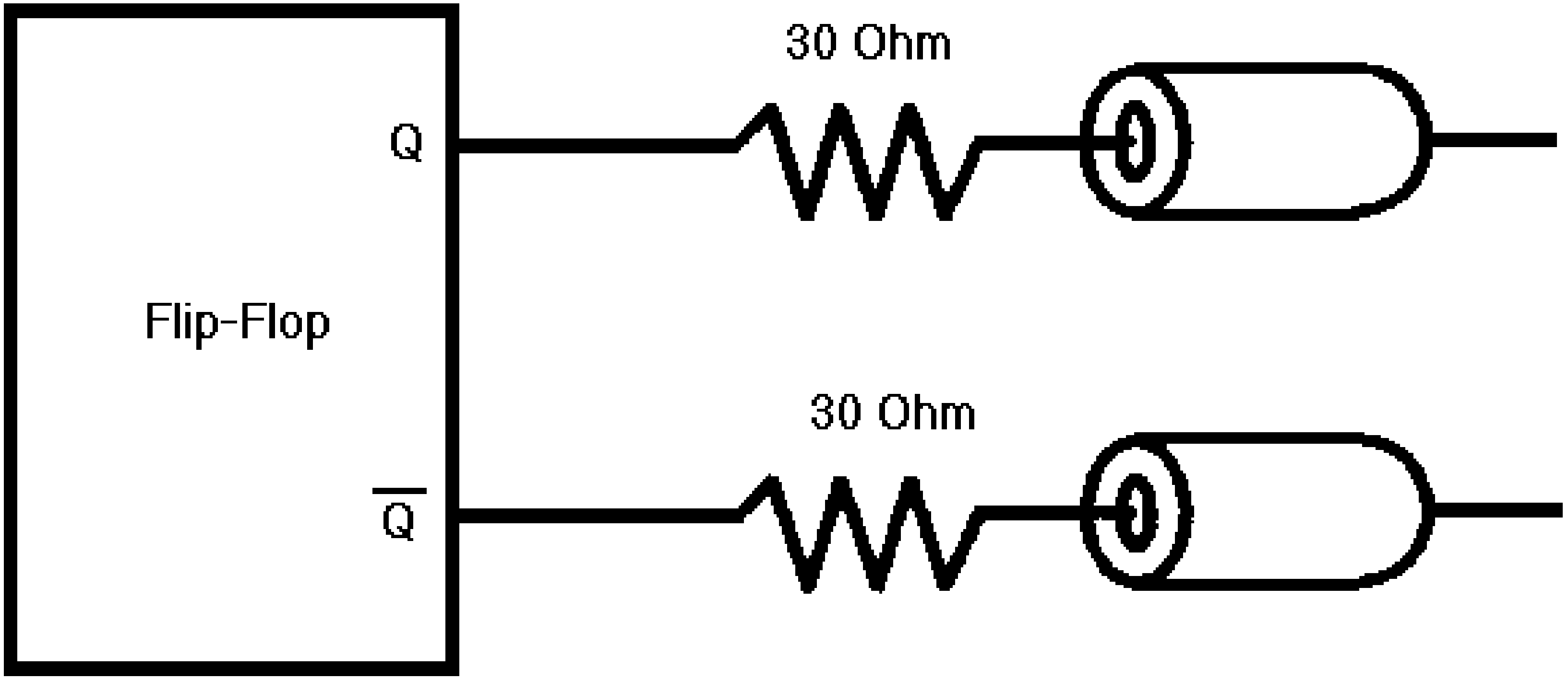


- Inductors wound on toroidal ferrite cores completely contain the lower frequency magnetic flux within the core, increase inductor Q, and allow less turns then would otherwise be required for the same inductance.

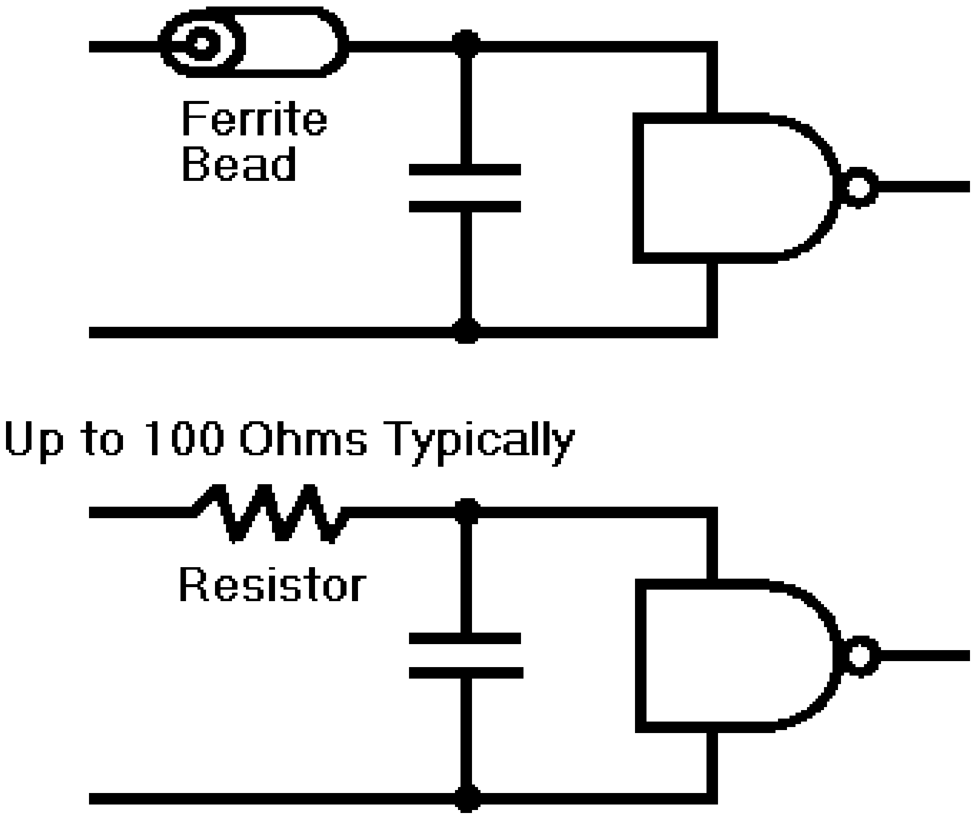
Larger Ferrite Cores

- Large ferrites work well to suppress common mode noise on powerline and on video cables
- When powerline current is high, high permeability toroids are required to increase the coupling between the leads for effective field cancellation.
- High Q inductors can cause ringing at higher frequencies and increase the radiated emission level on the transmission line.
- low Q inductors provide more uniform loading on the transmission line.

Typical Noise Suppression

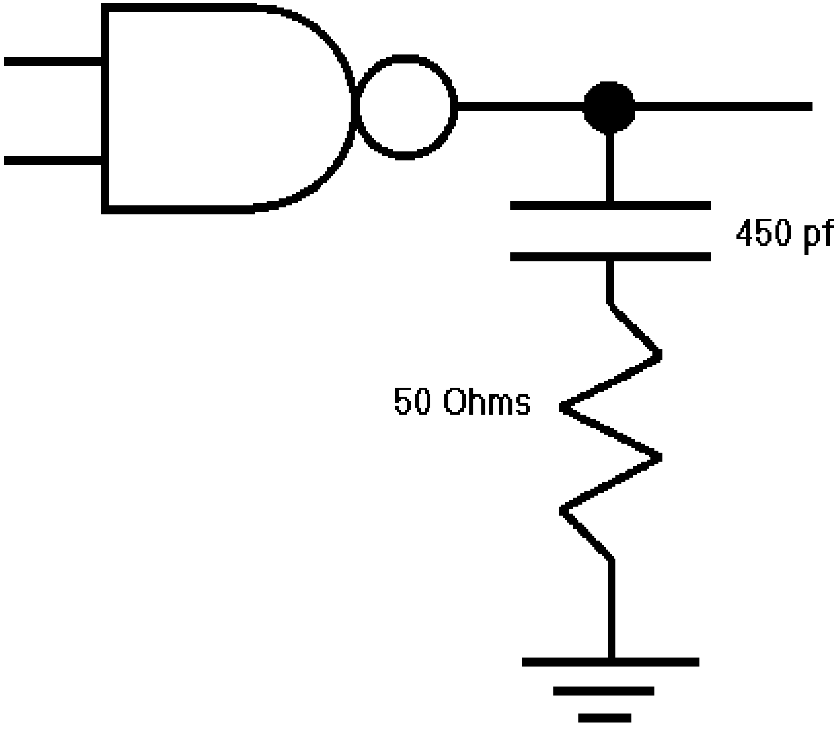


Power Decoupling



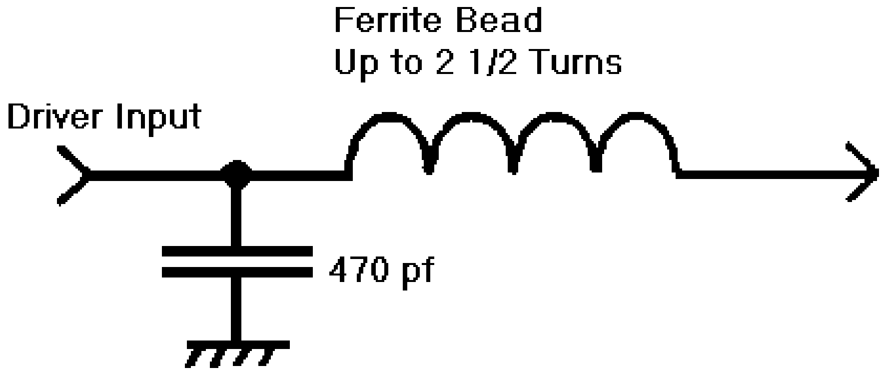
- Ferrites are used for damping as well as filtering.
- R-C filters are used primarily for filtering.

Waveshaper



- RC loading to reduce ringing and wave shape a digital output.

Ferrite Filter

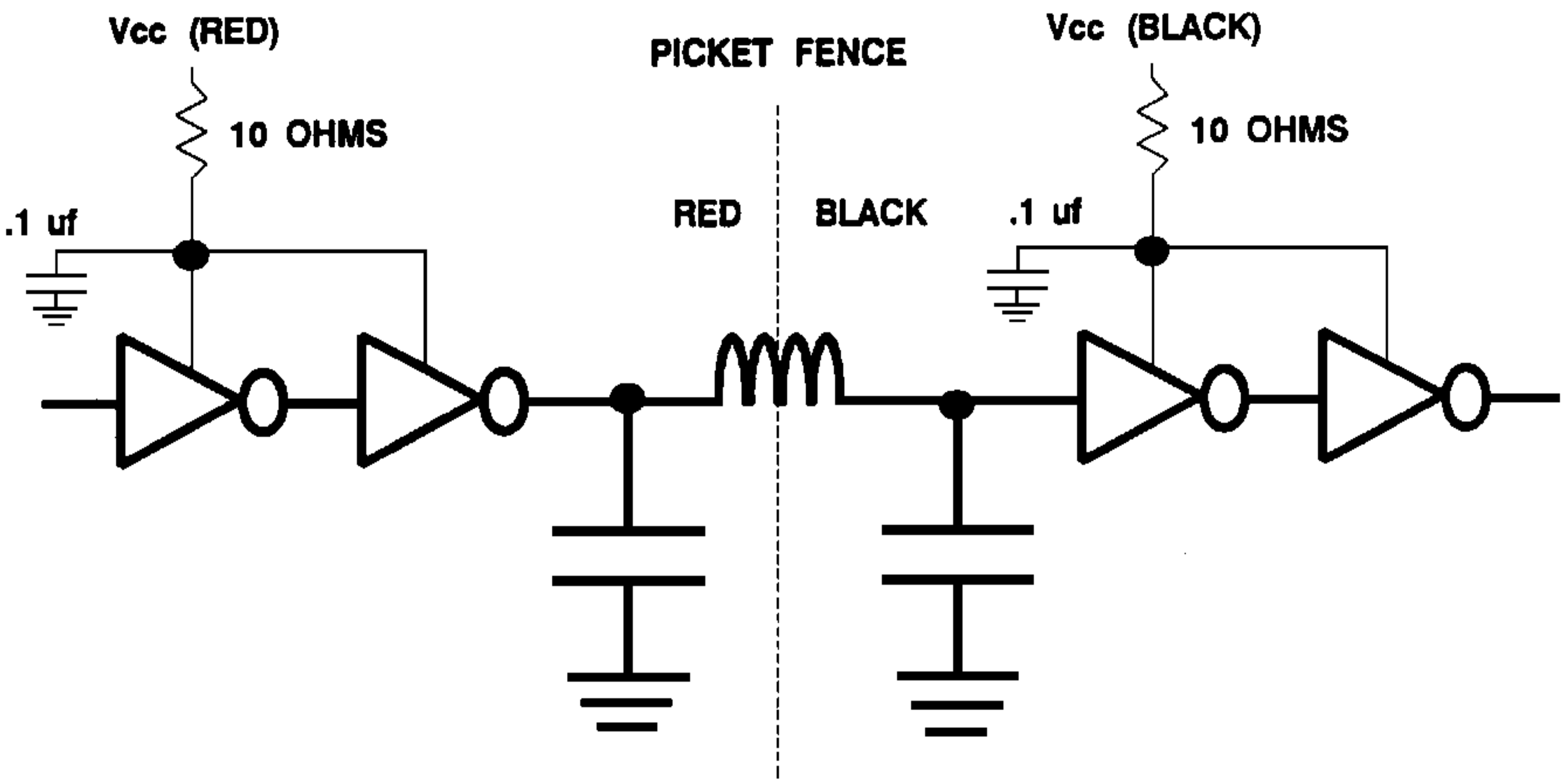


- The series ferrite filter is used to wave shape ringing circuit traces on commercial boards, with a size and value proportional to the frequency detected.

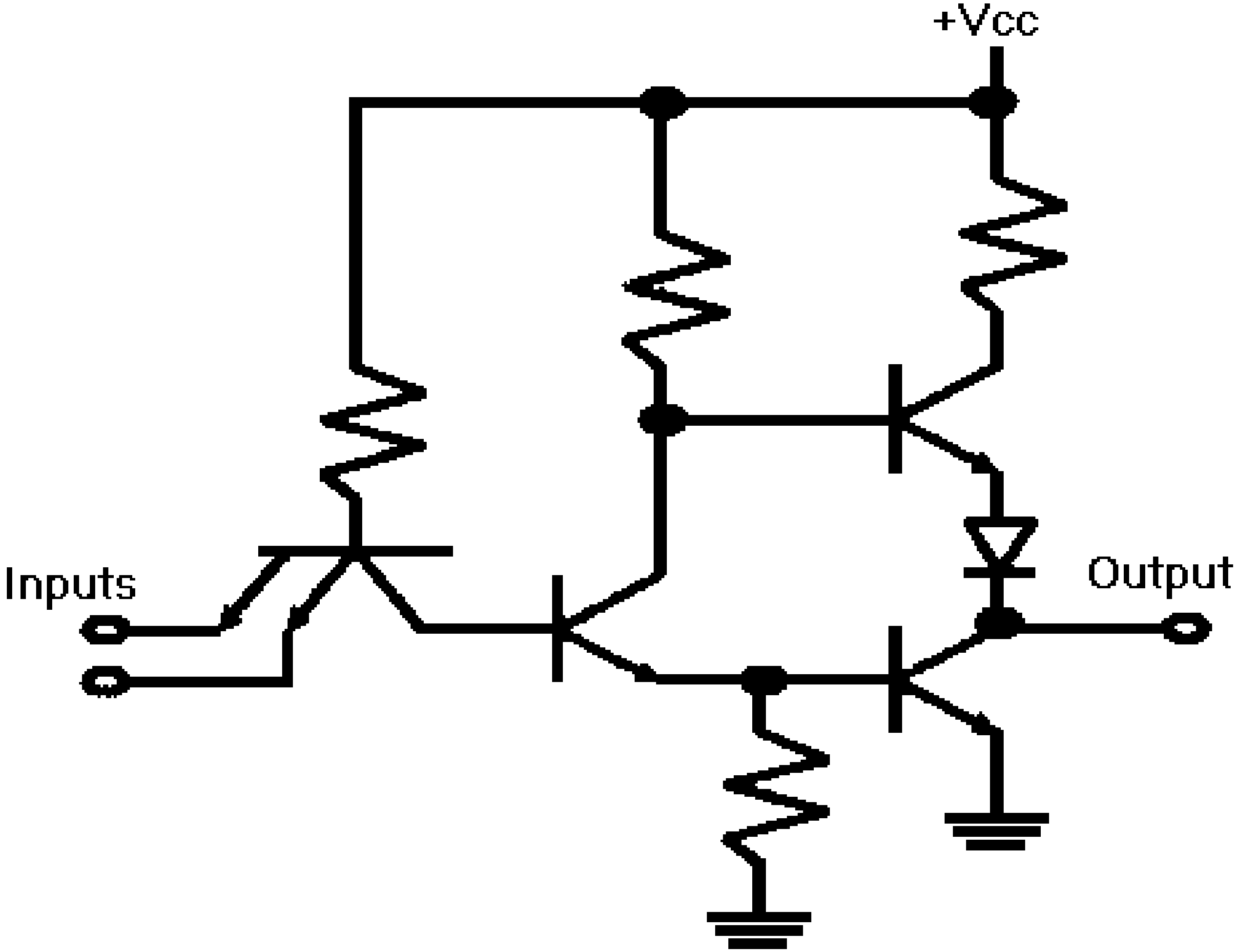
Digital Interface Filters

- Used when a control line crosses an interface between circuitry operating at two different levels of isolation protection.
- The possible conducted emanations must be stopped both directly on the line itself and on the power line driving the circuit.

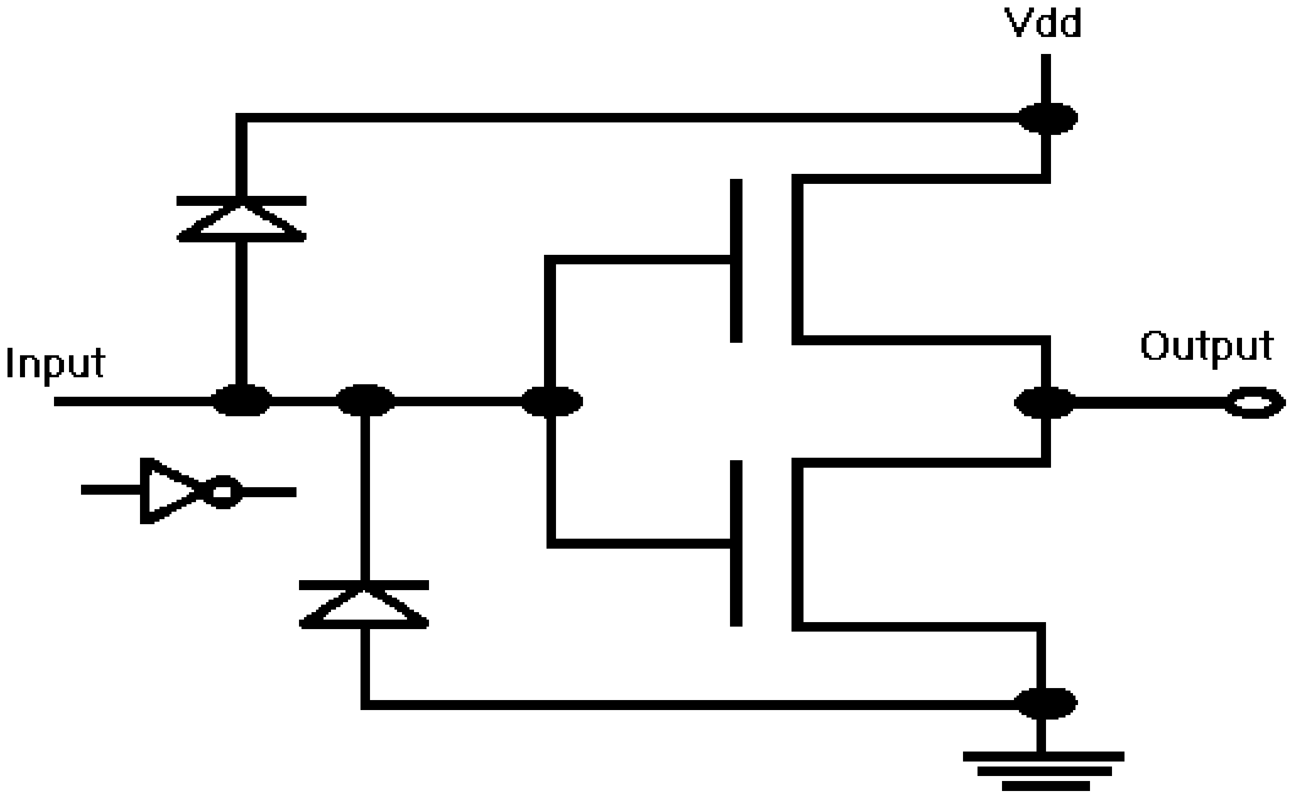
Digital Forward/Reverse Isolation for Digital Interfaces



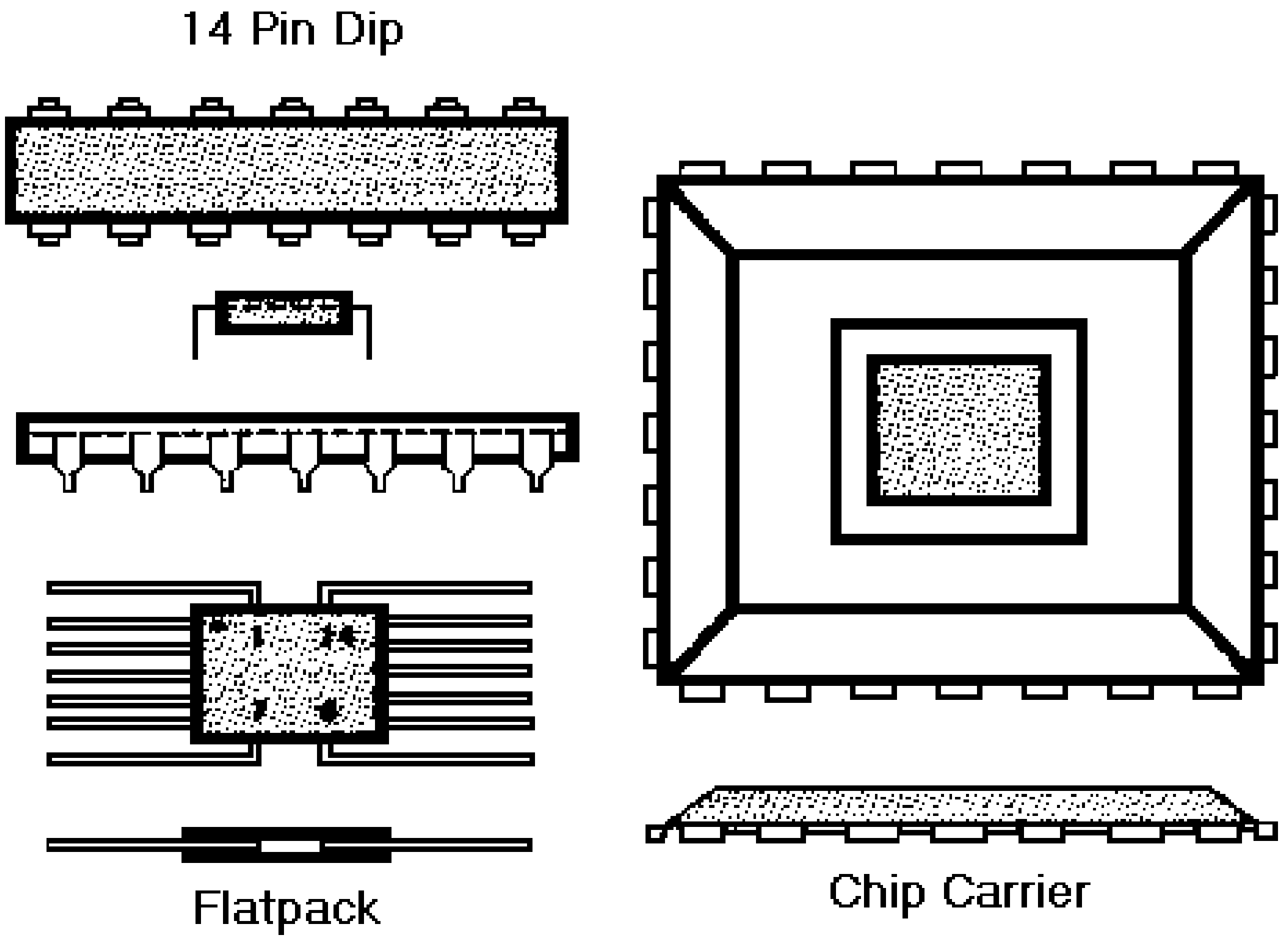
Saturating TTL Logic Prevents Direct Conduction



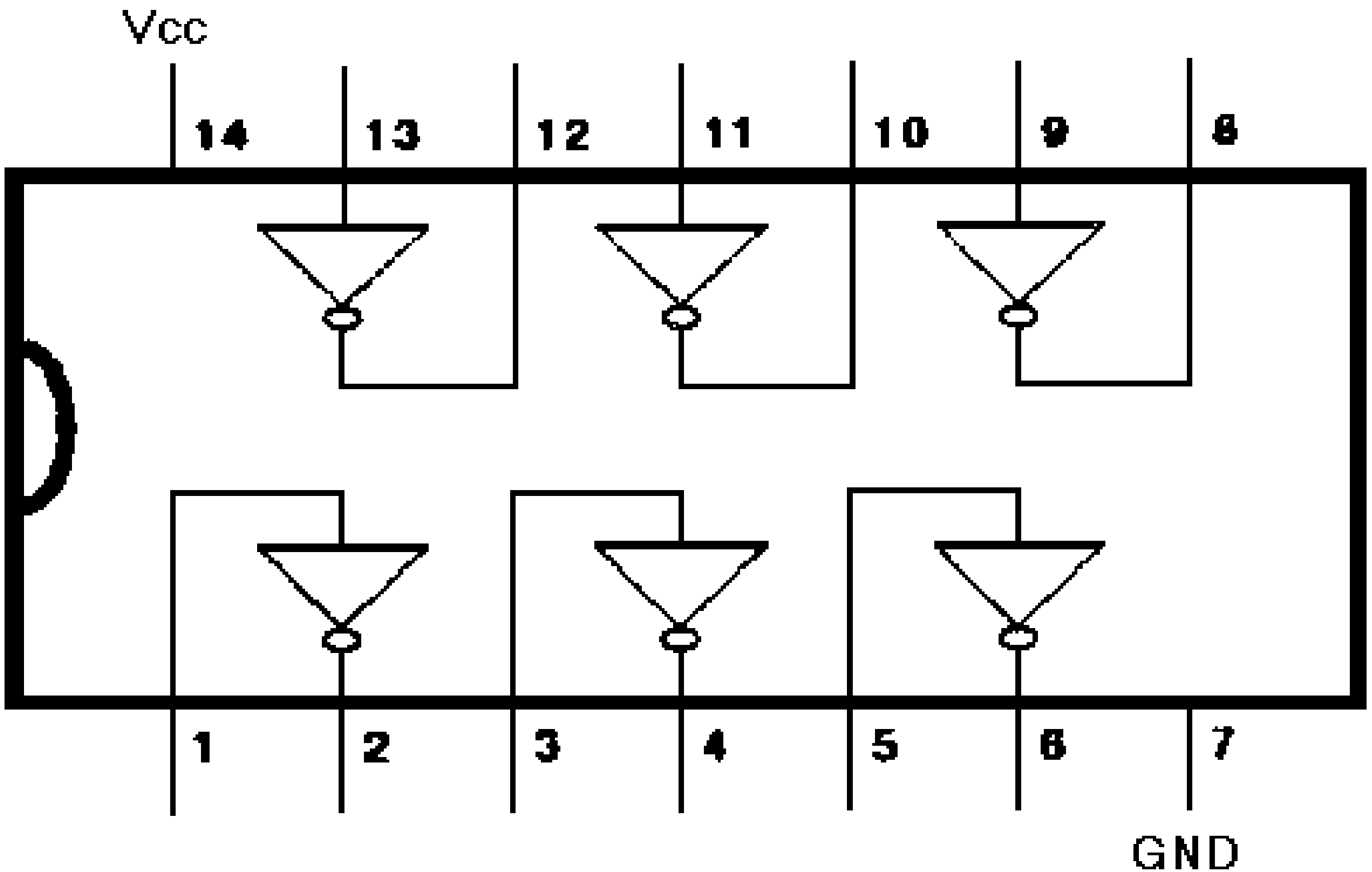
Non-Saturating CMOS Will Conduct an Emission

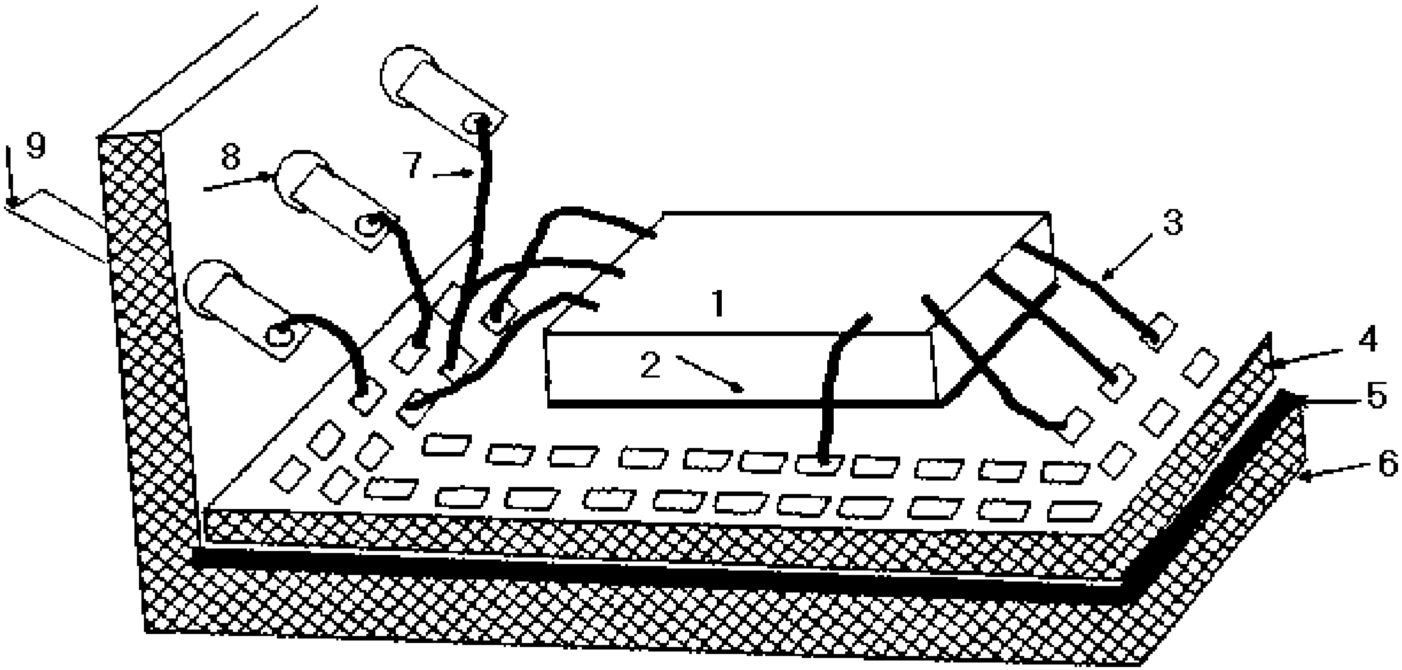


DIP and Flatpack Packages Will Still Couple Signals



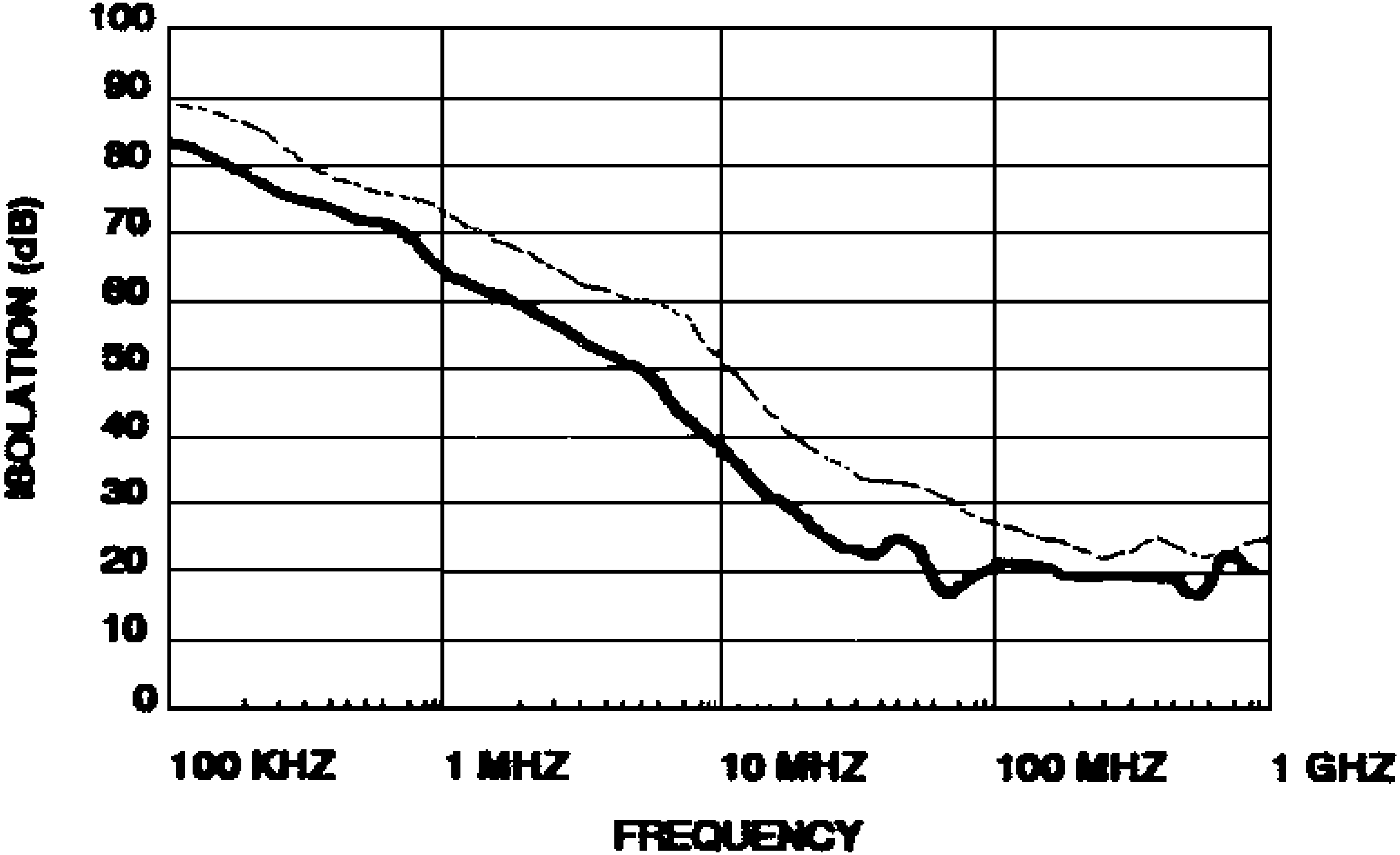
I/O Layout Pins on Packages





1. Chip
2. Die Attached Epoxy
3. Bond Wire
4. Programmable Silicon Circuit Board
5. Substrate Attached Epoxy
6. Package Base
7. Bond Wire
8. Glass Seal
9. Package Lead

Package Isolation



Controlling Signal Lines Drivers & Receivers

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Last Updated: 2002

Signal/Wire Transmission Characteristics

- Primary Characteristics include:
  - Cable Capacitance
  - Line Length
  - Signal Bit Rate/Width
  - Duty Cycle
  - Receiver Sensitivity
- The maximum bit rate per length of transmission wire is a function of the bit width and the duty cycle of the data stream.

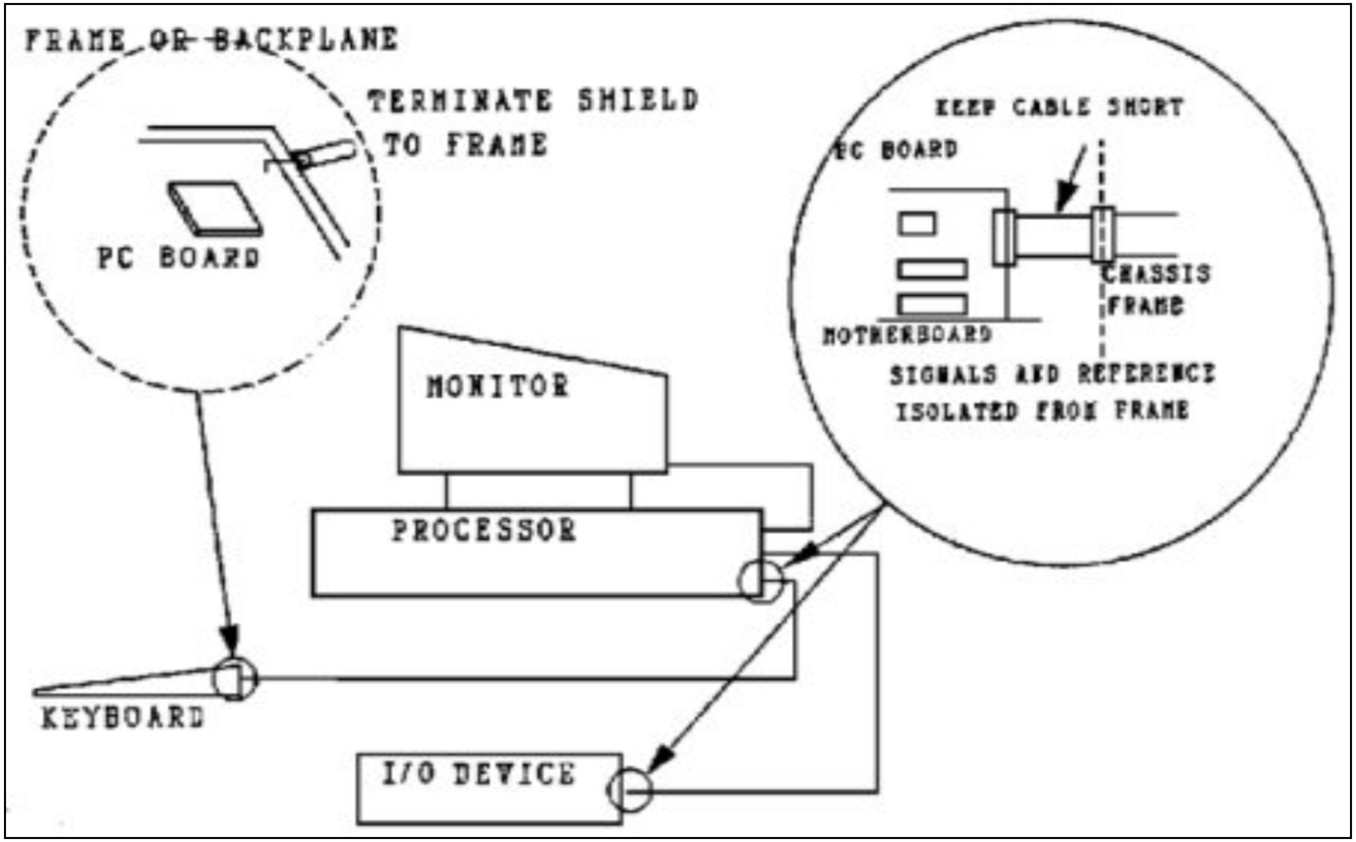
Emission Protected Transmission Lines

- Transmission lines are designed and available for maximum rather then minimum data transfers.
- There is sufficient capacity in the interface drivers and cabling that a significant amount of additional capacitive and resistive loading can be added in most applications without interference.

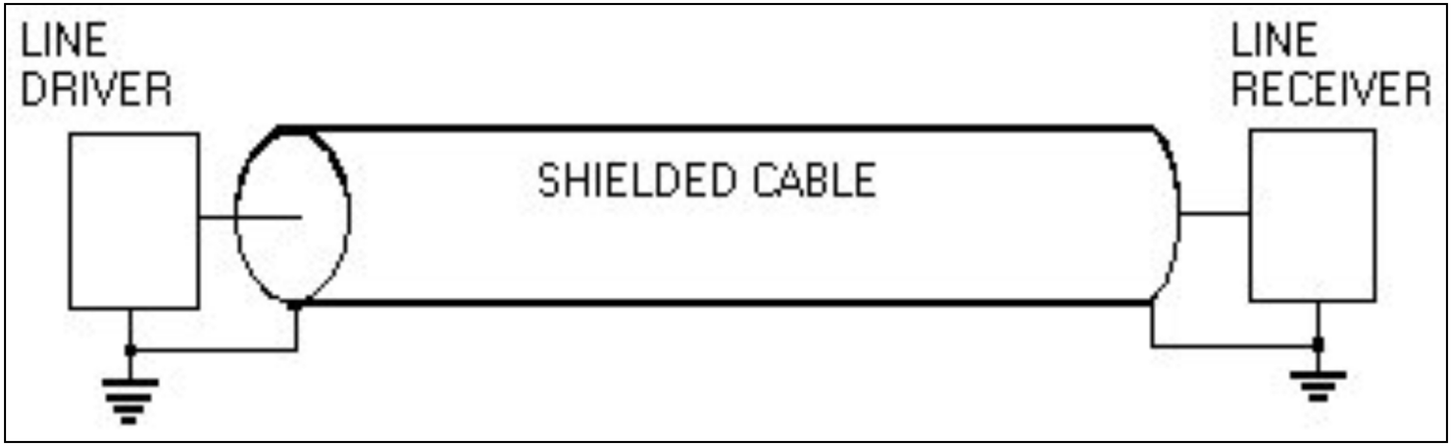
The Problem

- The greatest sources of system generated emissions escaping a security controlled medium is through cable radiation associated with improperly terminated transmission lines.
  - Wires are never matched at all frequencies and some level of reflected signals and associated standing waves nearly always exists.

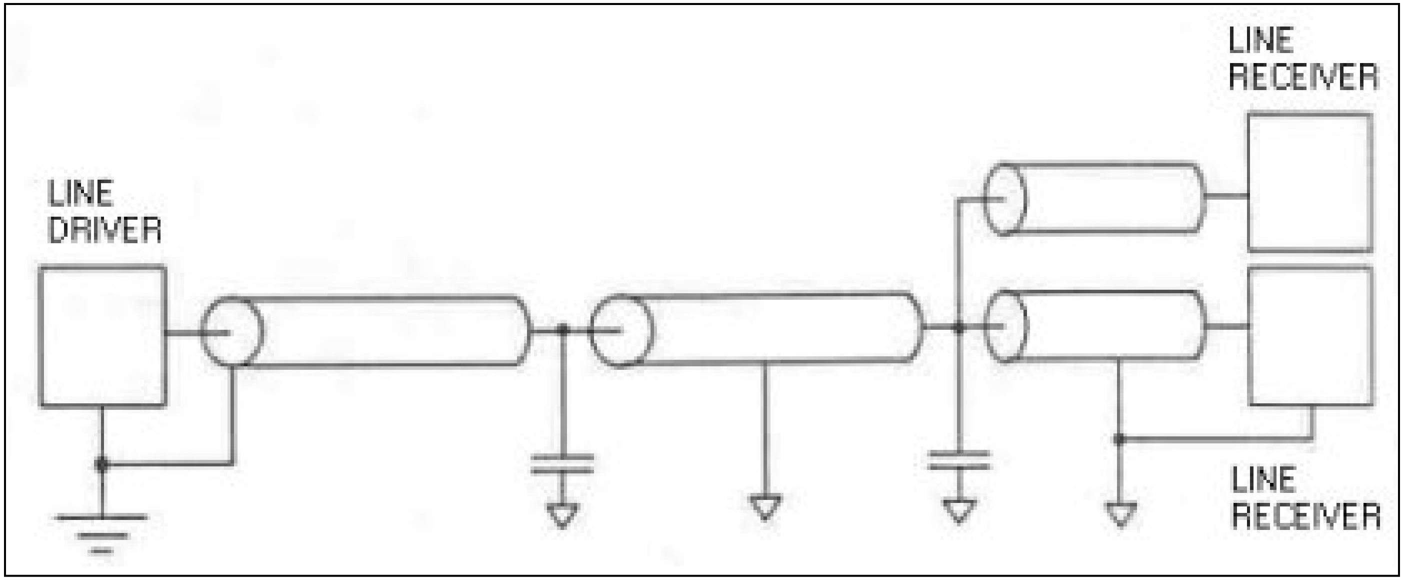
Low Noise and ESD Protection



The “Ideal” Interface



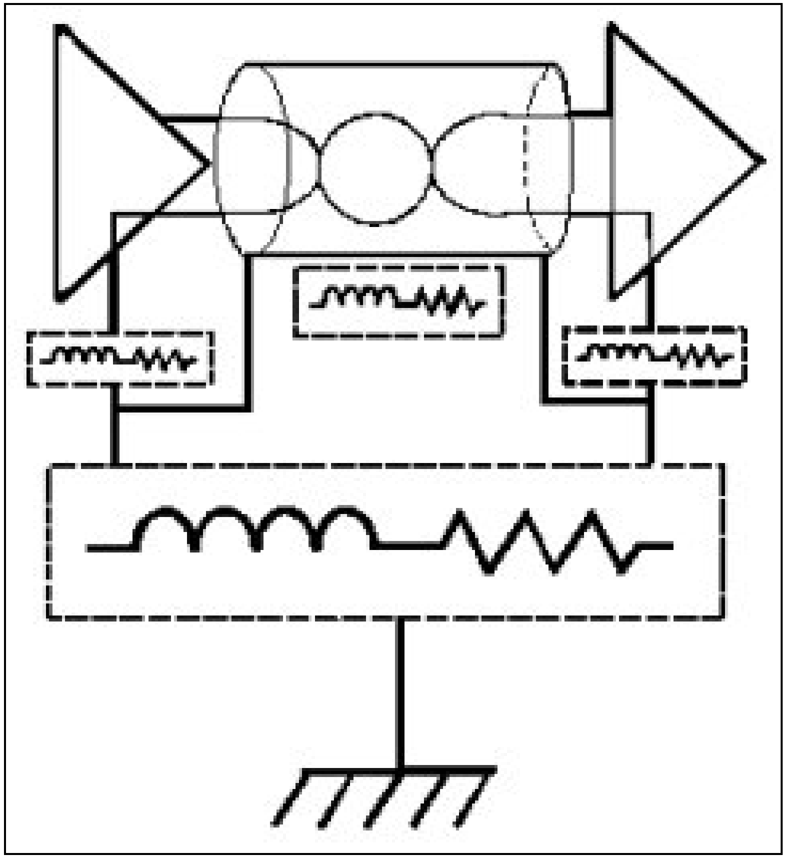
The "Typical" Interface



Single Point Ground Returns

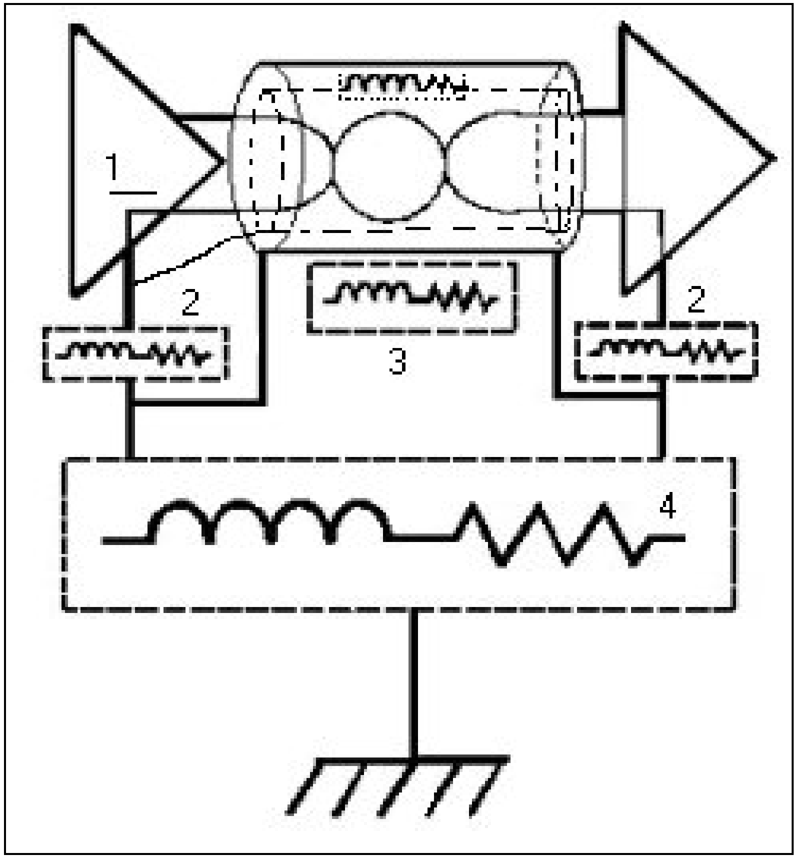
- The return conductors of circuits referenced to a single point are essentially floating circuits throughout the interference frequency spectrum.
- The "hot" conductor, and the return conductor which is returned to a single point ground, must be treated as a floating circuit that requires a balanced filter with a center-tap referenced to the structural ground plan.

Interconnect Showing Impedances



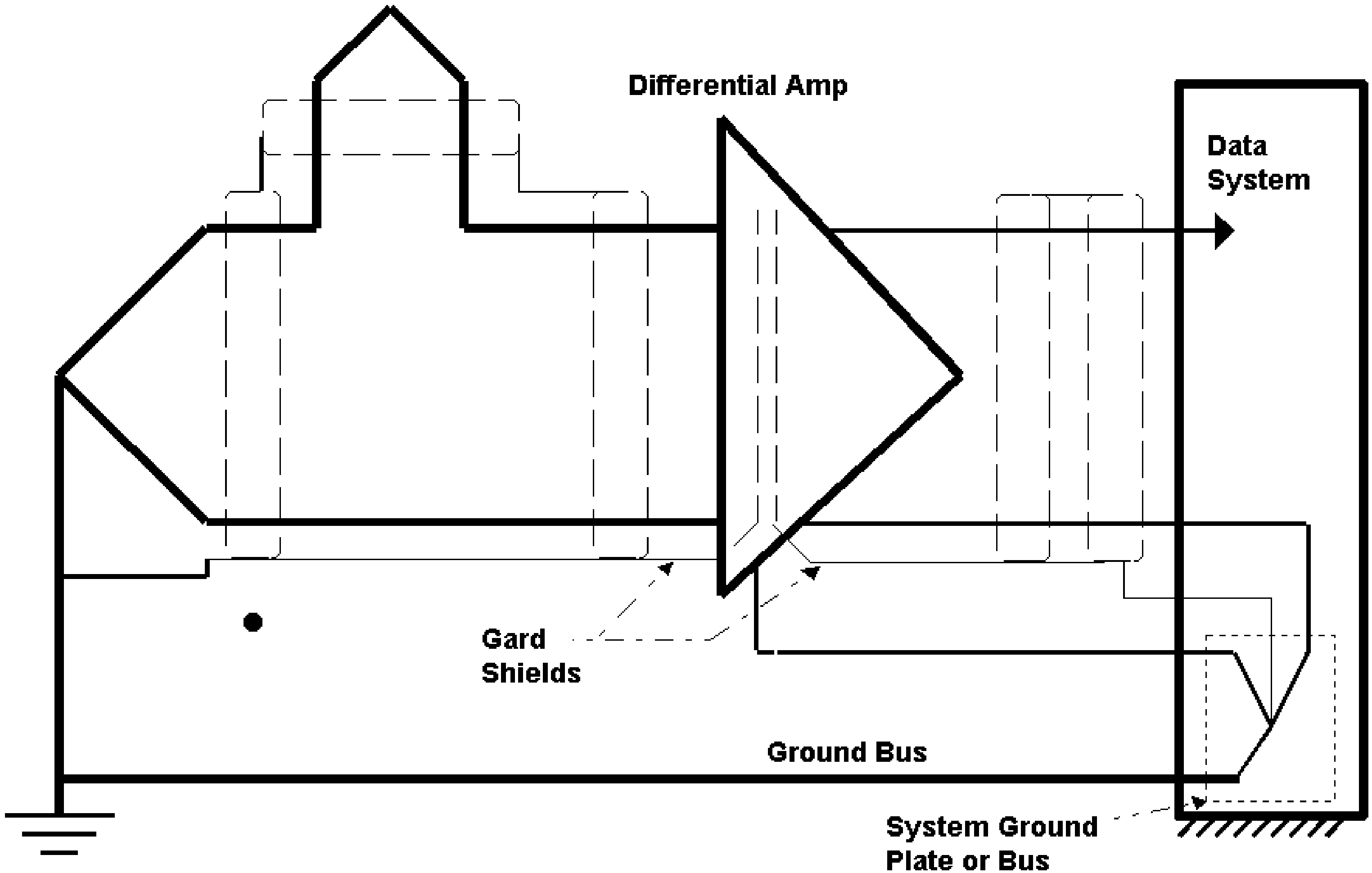
For a digital signal line connected to a line receiver through a shielded interface cable, the return signal reference sees a finite impedance between its board signal ground and the chassis ground connected to the shielded connector. The cable shield also sees a smaller (shown as a larger box) ground path through the structure of the platform.

Combination of All Grounds



Best low noise approach. Radiated energy from the inner wiring is absorbed to some extent by the inner shield and returned to the signal's source reducing energy escaping to the outer cable shield. The low impedance path through the structural ground becomes the principal common mode return path for the offset current from the digital line driver.

Typical Example

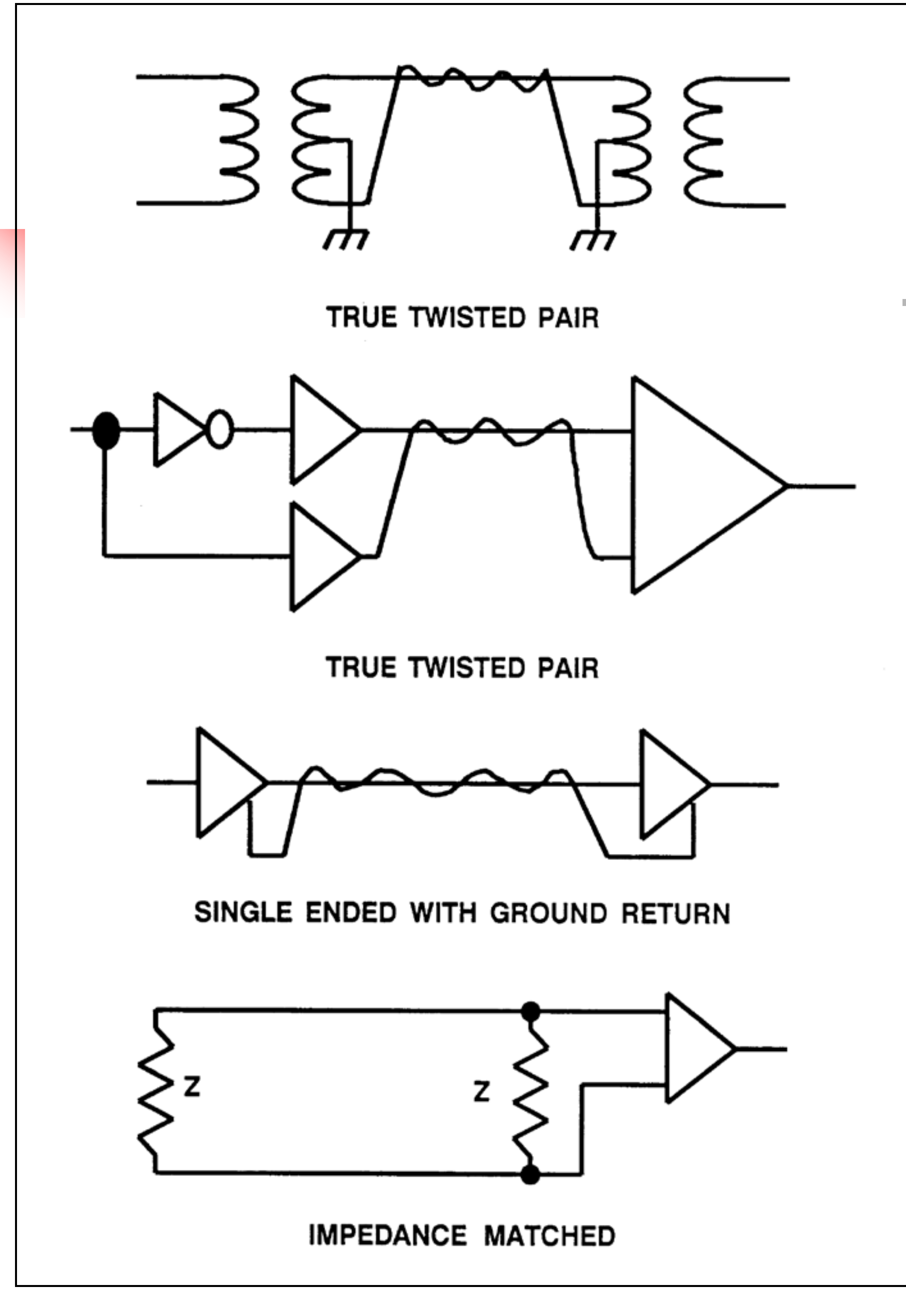


Summary of Interactive Grounds

- It’s always a good idea to reduce common-mode and differential-mode noise generation as early in the design as possible.
  - This consideration will nearly always save time and money.
- Cabling and wiring is very much a platform related problem highly dependent on other parts of the system design.
  - The technology selection, for example, has a major bearing on the cables and wires employed.

Balanced & Floating Circuits

- Balanced line-to-line filters require a structural ground plane reference through a capacitive (or inductive) center-tap to eliminate common mode interference.
- An ungrounded filter capable of eliminating line-to-line interference is not capable of eliminating line-to-ground plane interference.
  - Due to the lack of continuity between each line and the ground plane.

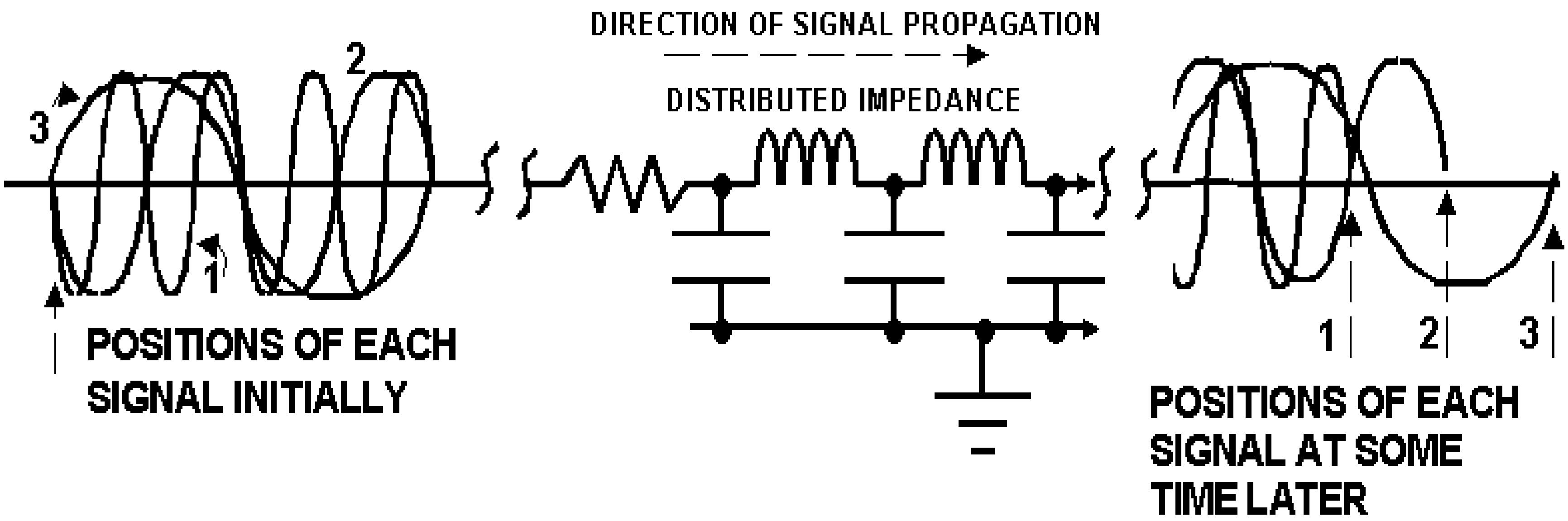


- Transmission line techniques always seek to return emissions to their source using the shortest path with lowest impedance.

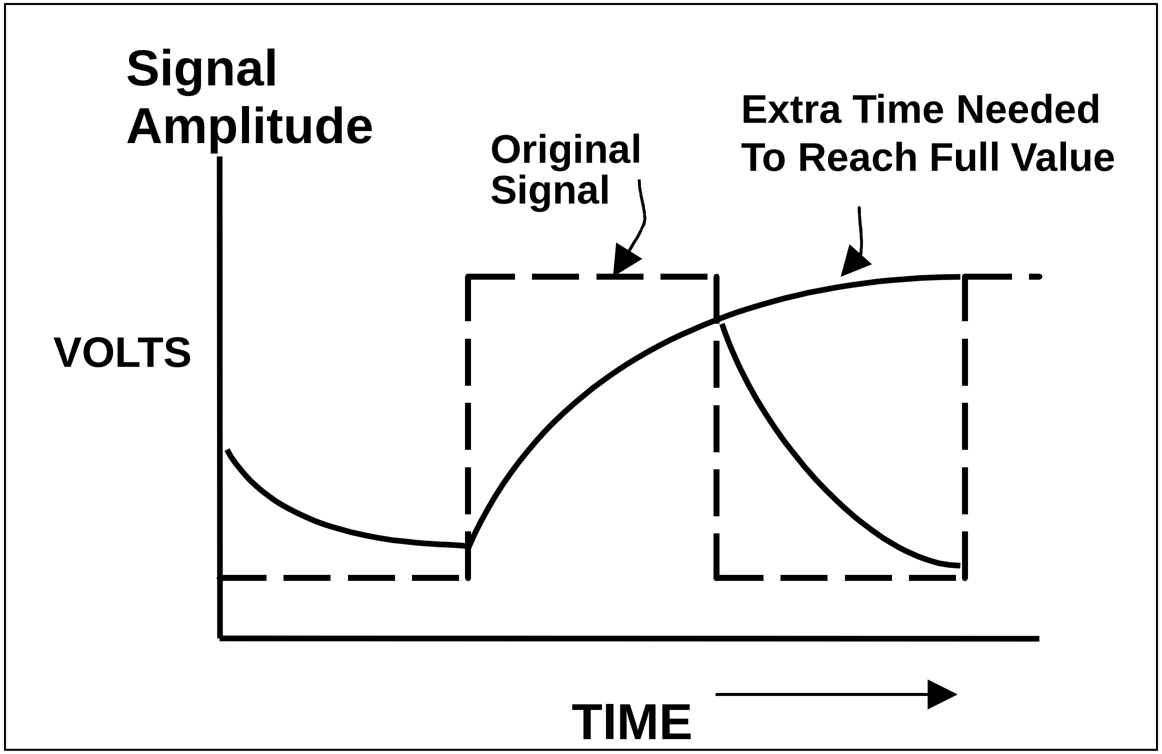
Signal Distortion

- The resistive component of a transmission line over a short distance is relatively small when compared to the input impedance of the line receiver in a typical application.
  - Distributed capacitance combines with the resistive component to produce a RC time constant that degrades the digital waveform.
  - The higher the capacitance, or the longer the transmission line, the more the signal is rounded off or otherwise degraded.

Delay Line Characteristics



What Happens



Designs Should Accommodate Not Overkill

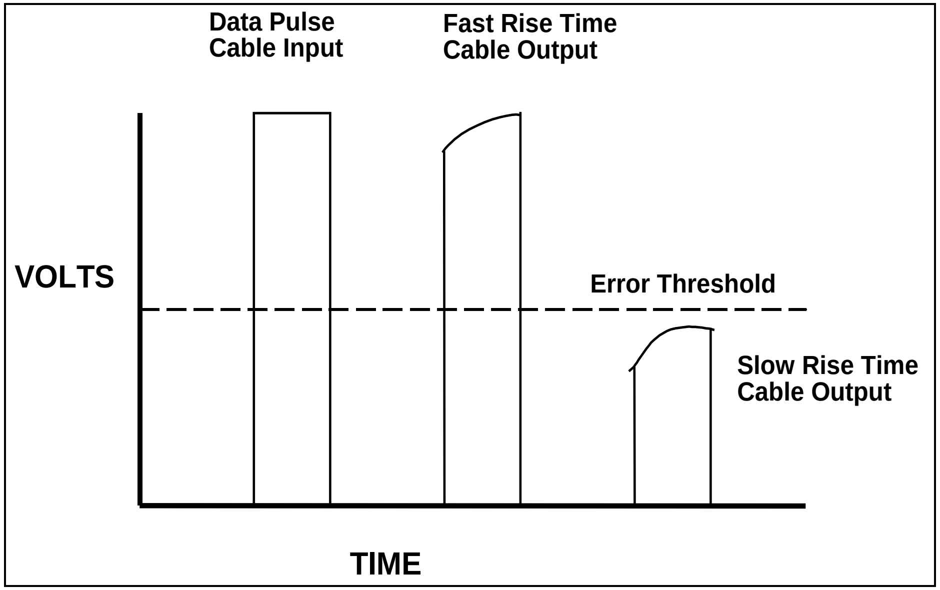
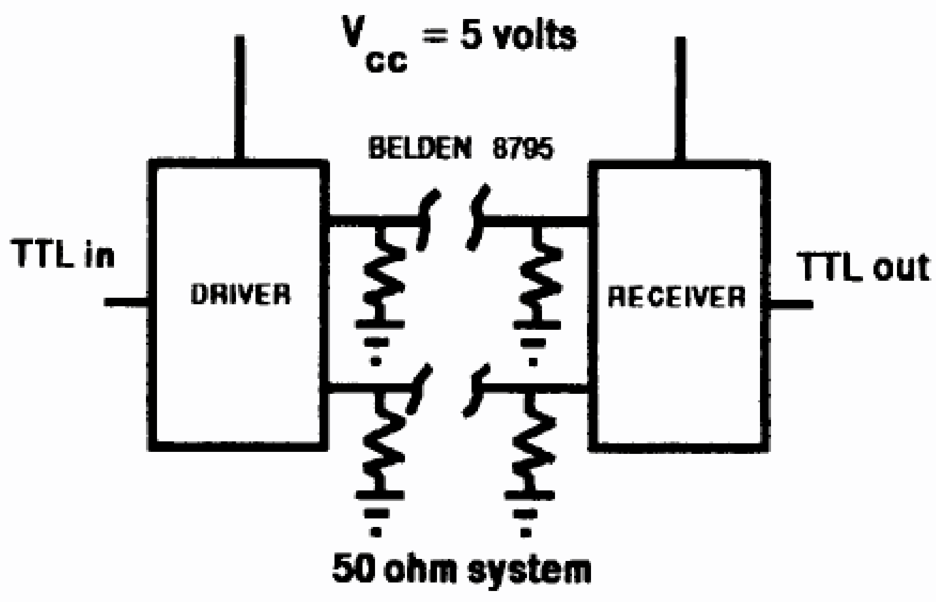
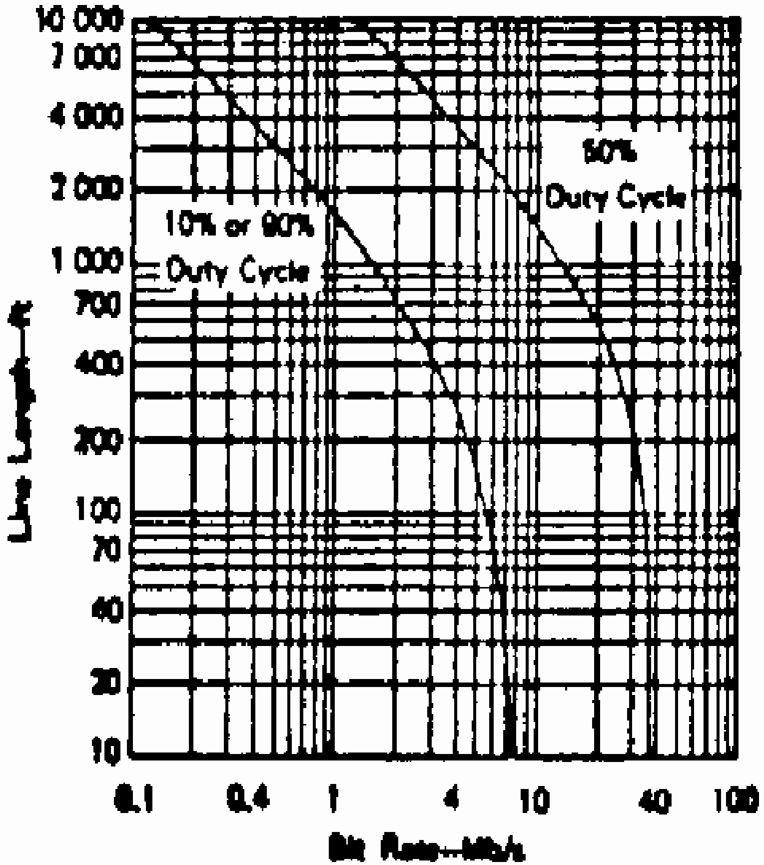


Table 2.1

Cable Dielectric	Time Delay (nanosec/ft)	Velocity % c
Solid Polyethylene	1.54	65.9
Foam Polyethylene	1.27	80.0
Foam Polystyrene	1.12	91.0
Air Sp. Polyethylene	1.15-1.21	84-88
Solid Teflon	1.46	69.4
Air Space Teflon	1.13-1.2	85-90

Driver/Receiver Combination





Driver Characteristics

- Important line driver characteristics:
  - Output impedance, output peak current capability, and frequency response.
- To reduce reflections, the line driver's output impedance should equal the characteristic impedance of the transmission line with the receiver attached.
  - Impedance matching/damping should continue at higher frequencies where square wave harmonics can cause transmission line reflections.

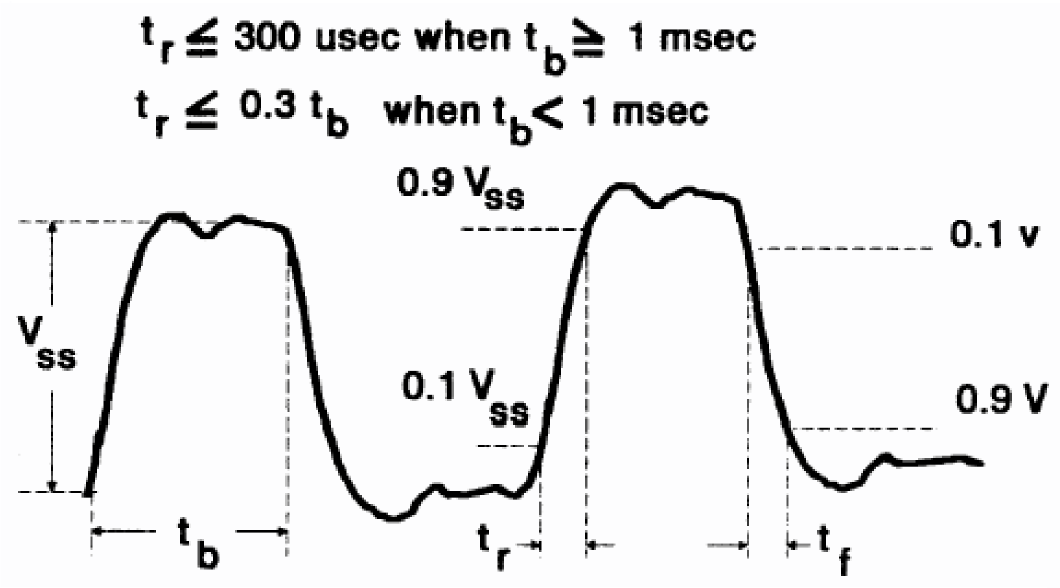
Always Wave Shape Drivers

- Wave shaping at the driver involves controlling and smoothing the signal rise time, which, in effect, decreases the reflection produced at the impedance mismatch, and controls the amount of signal crosstalk to adjacent lines.

Wave Shaping Points

- Protected emission signal lines are designed to pass the required signal and no more.
- The rule of thumb is to design the driver to pass the fundamental and the first three harmonics without distortion.
- For critical edge triggered receivers, do not overload the leading edge of the data bit.

Standard RS-423 Wave Shaping

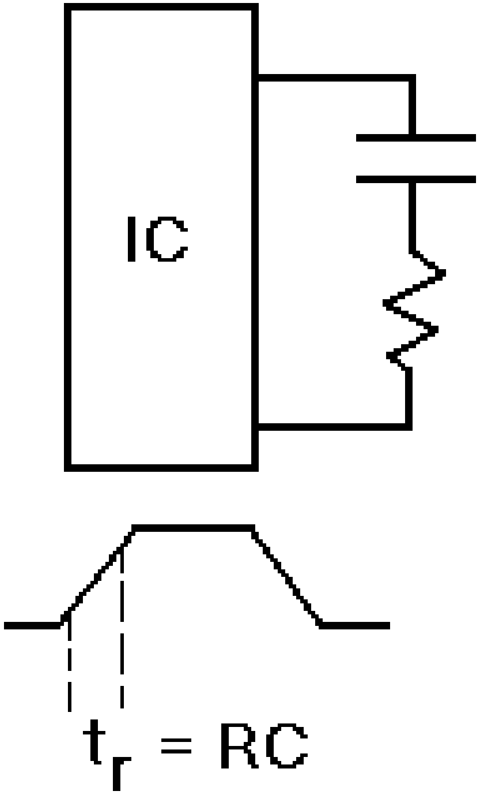


- Note that dedicated secure systems can usually conform to whatever is necessary for them to be operable.

Wave Shaping Techniques

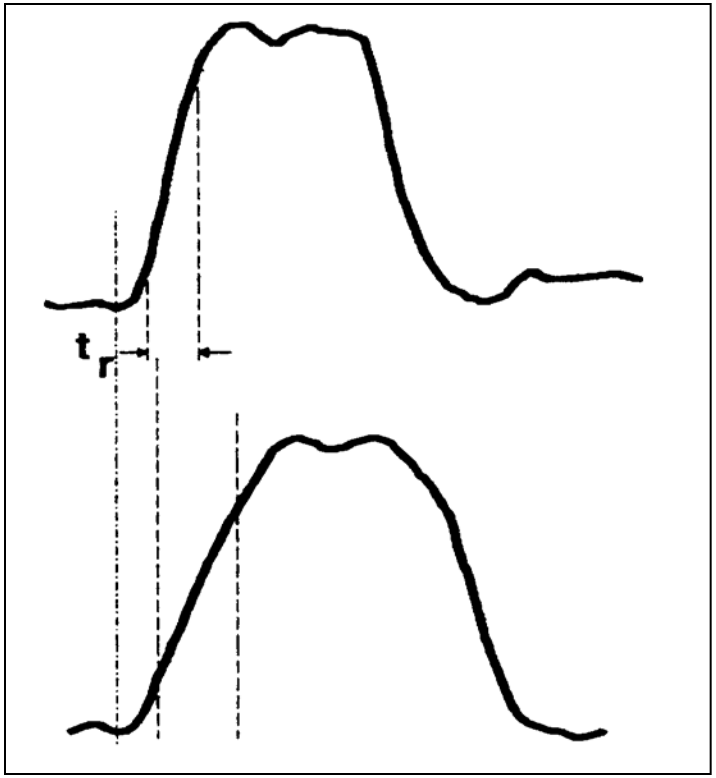
- Linear wave shaping is used for rise times of 100 μsec or more, but exponential is used for most rise times.
- For linear wave shaping, a resistor is connected between the wave shaping control pin and ground which can control the output to almost straight line rise and fall times.

Exponential Wave Shaping



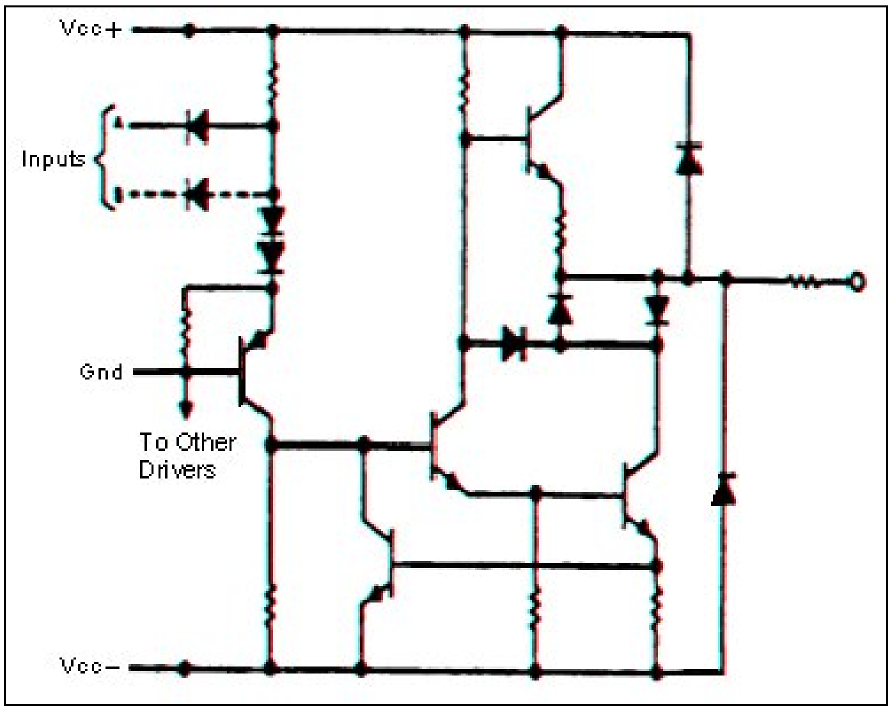
- A series resistor and capacitor are connected between the control pin and ground with the resultant RC time constant tuned to the desired response.

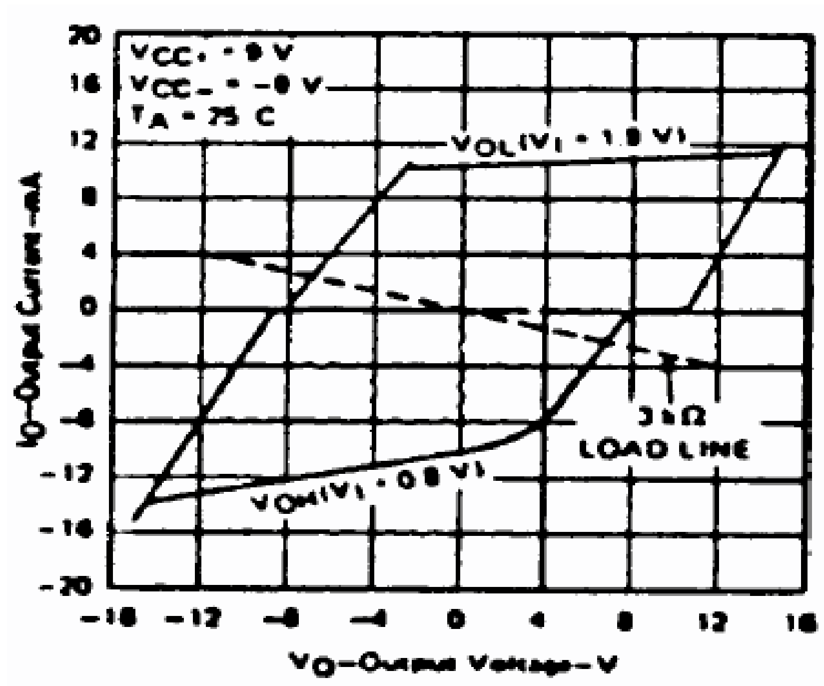
Exponential Shaped Wave



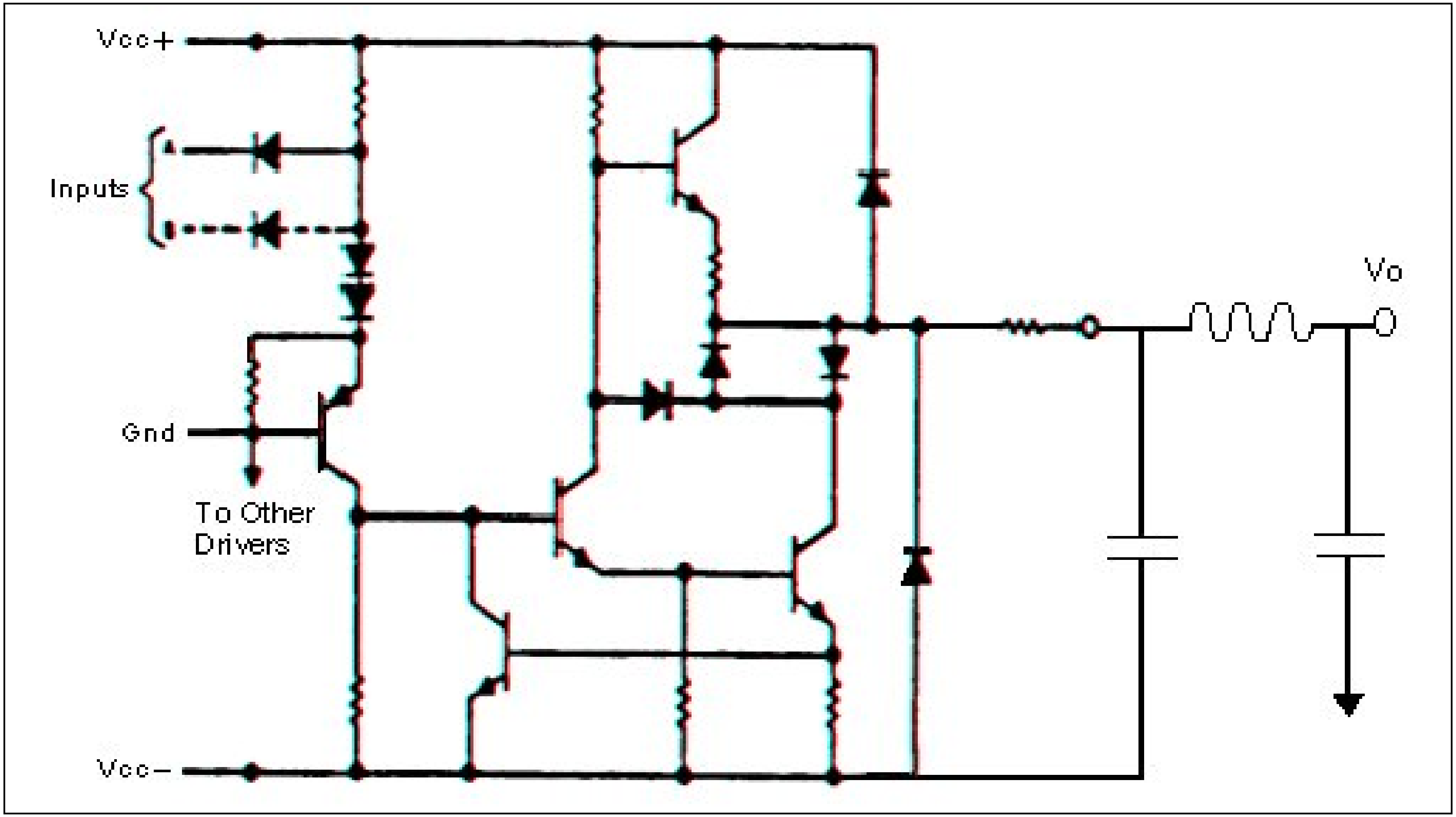
- Shaping has the effect of stretching the pulse slightly.
- For edge triggered devices, do not round off the signal beyond the maximum signal rise time required by the receiver.

Typical Line Driver (*SN75188*)

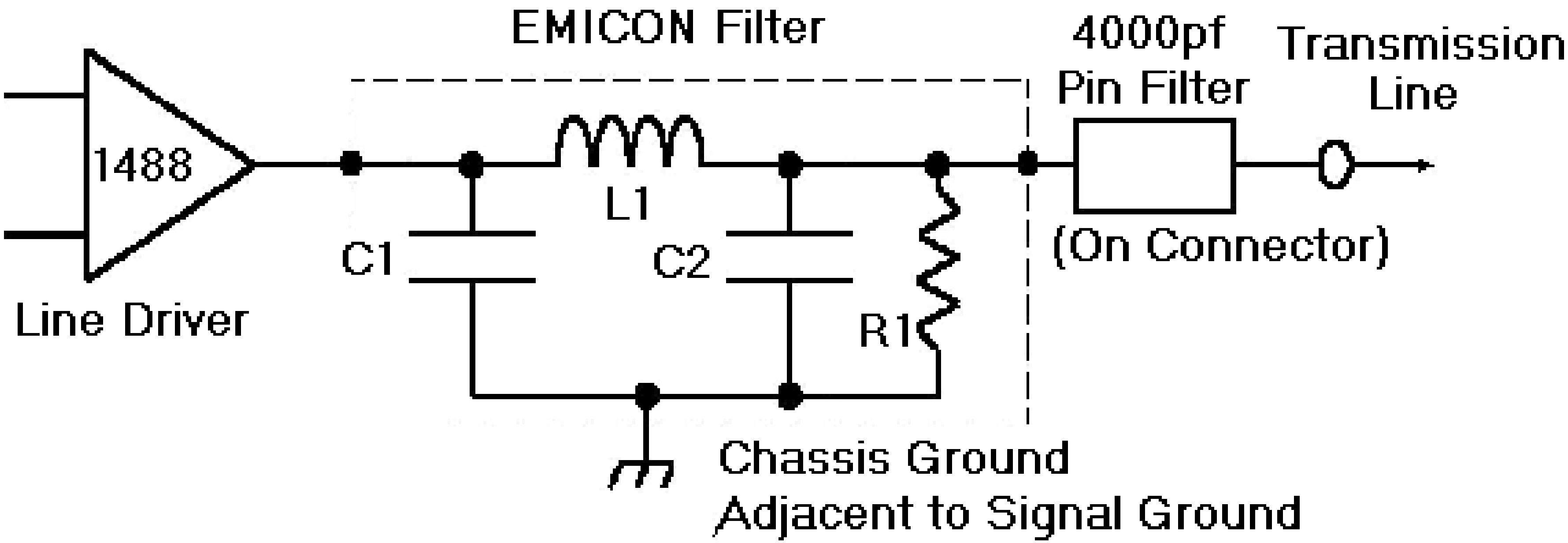




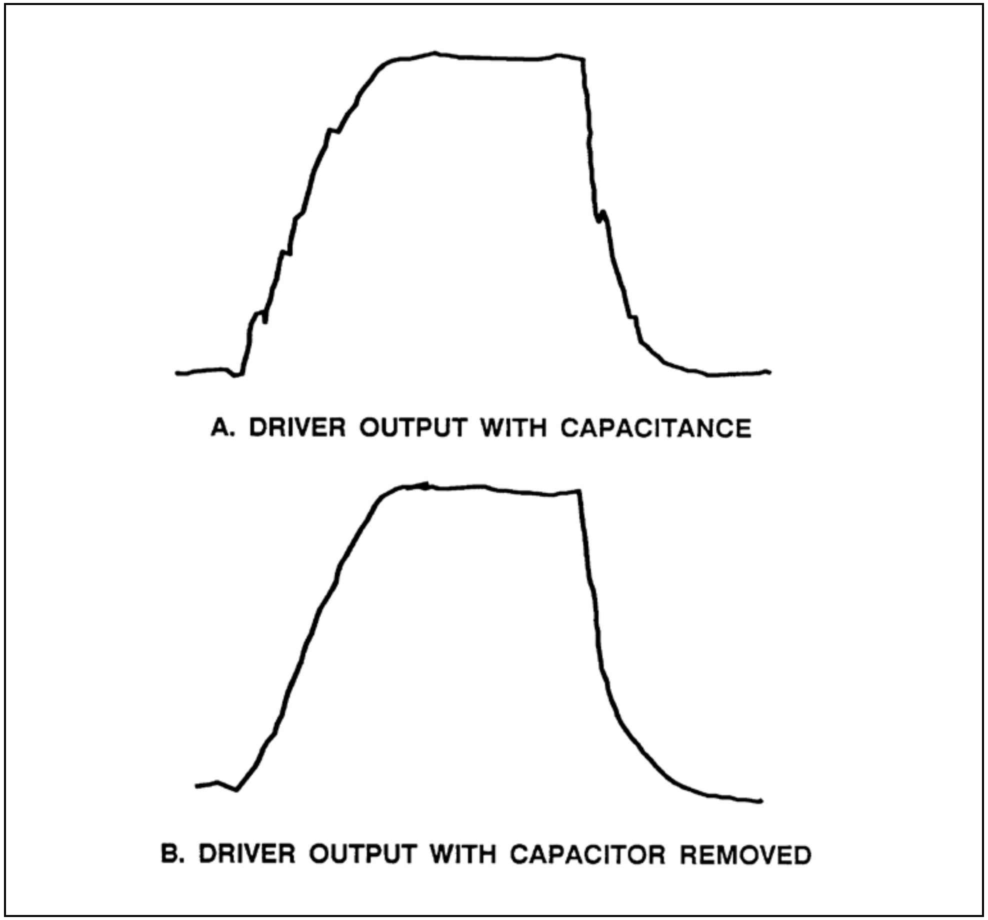
Possible Fixes



Line Driver Circuit With Pin Filtered Shaper

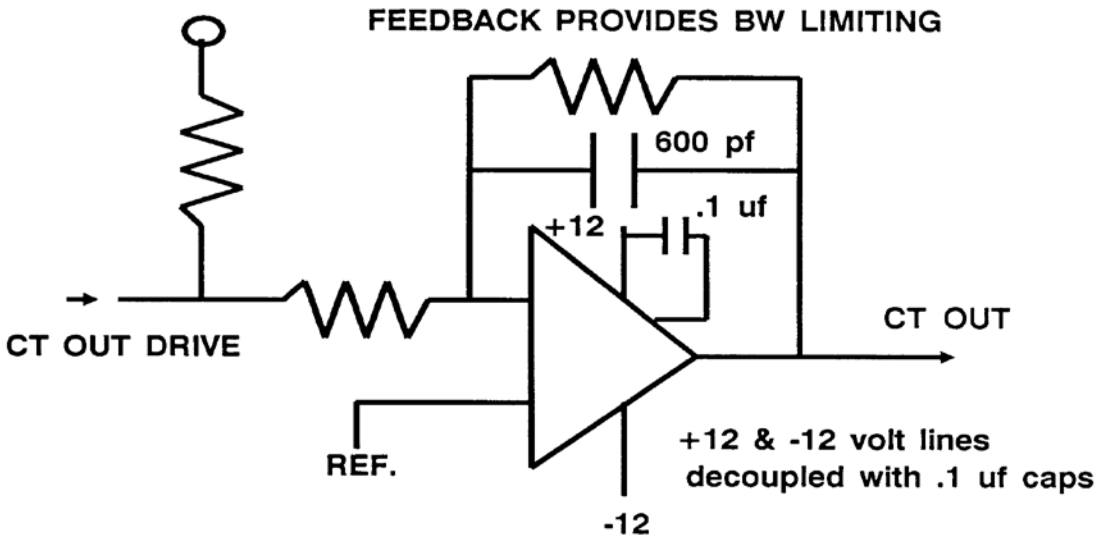


Problem With Too Much Capacitance



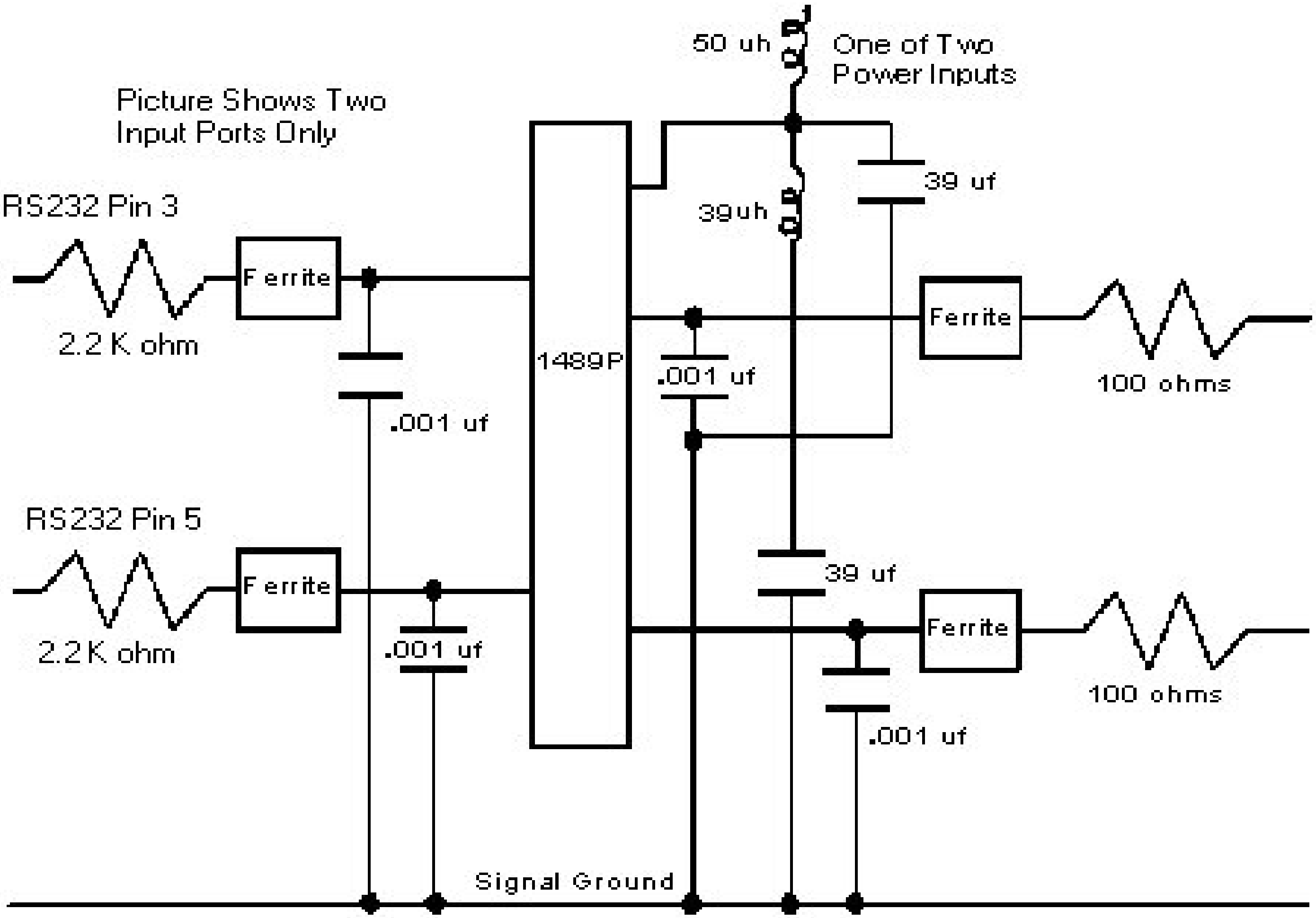
- To correct small spikes, remove C1 from the commercial filter.
  - Has the effect of increasing impedance at high frequency to the line driver, and results in smoother waveform.

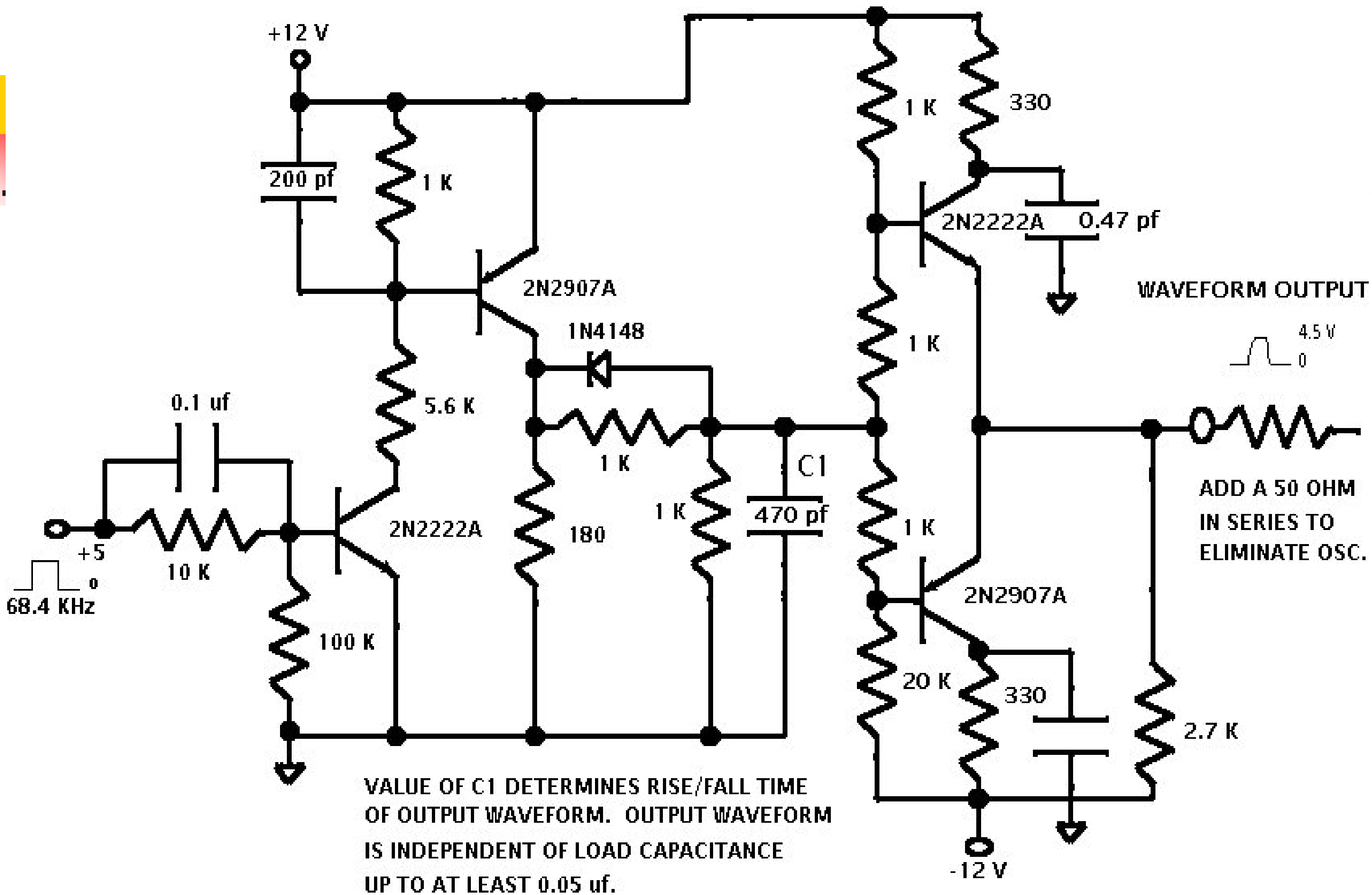
Op-Amp BW Limiting



- Reduce the problem of signal coupling to the Op-Amp input by bandwidth limiting.

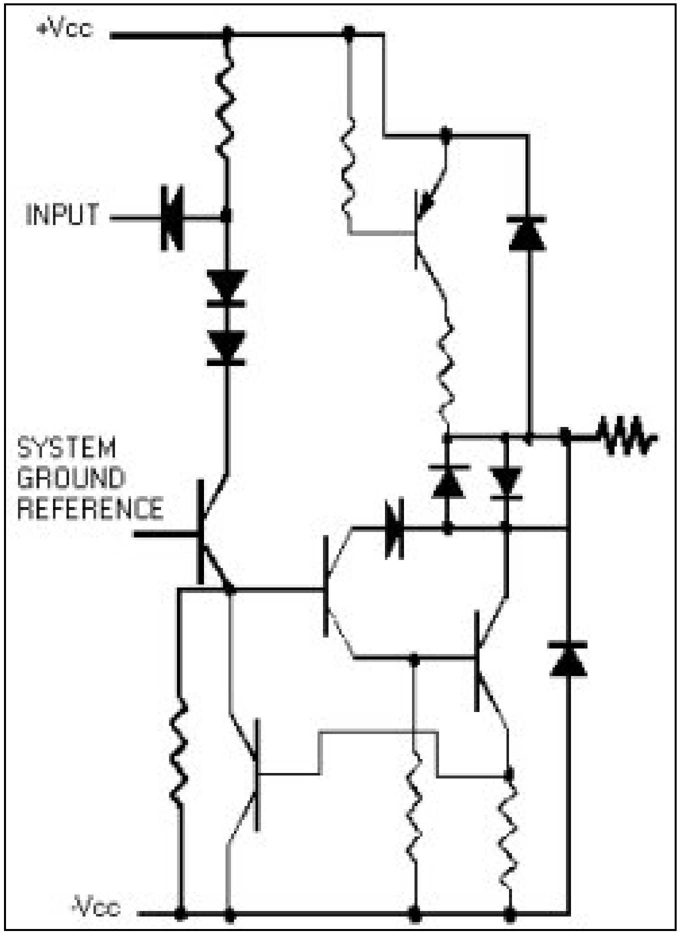
Modified MC1489P Line Driver





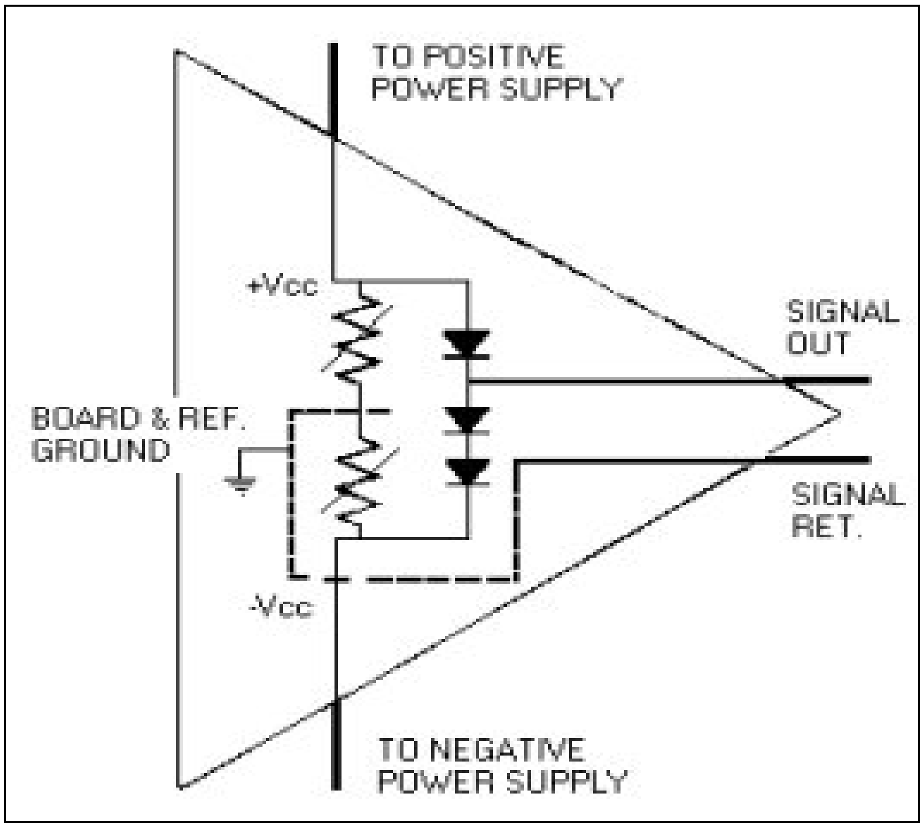
MIL-STD 188C WAVE/SHAPER DRIVER

SN5188 Line Driver



- Typical digital signal line driver. Notice that the output drive line is offset by .7 volts (one additional diode drop) from the center of the circuits plus and minus voltage sources.
- The system reference ground (the output used as the signal return) is not exactly referenced to the center of the power system.

Line Driver Bias Equivalent

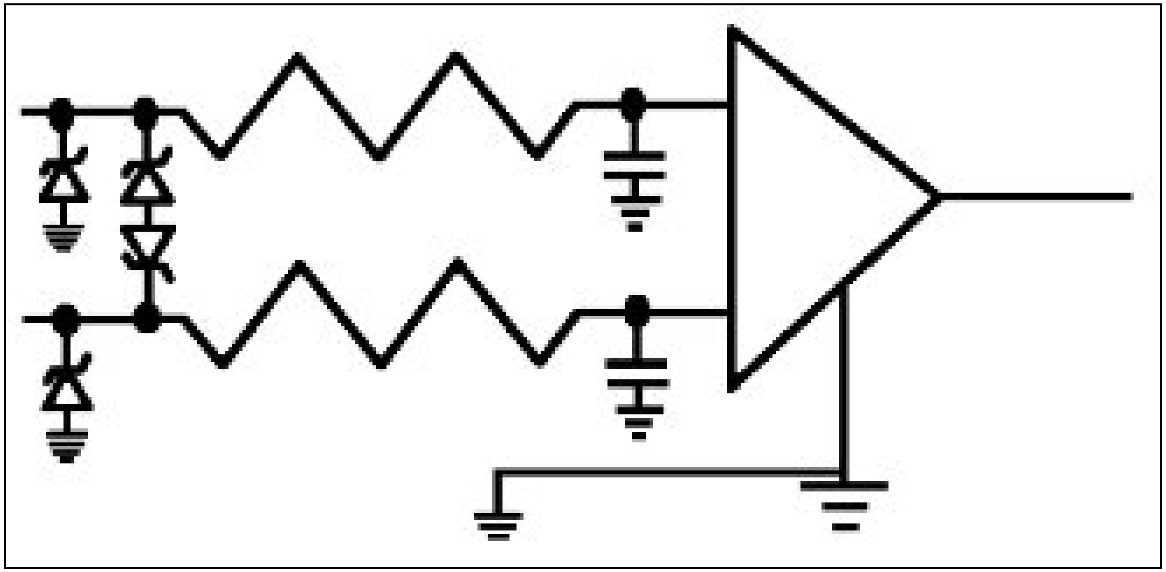


- Result is the equivalent biased driver shown driving a low level signal source into the ground system.
- This signal appears as a low level common mode voltage on all other boxes referenced to the same ground platform

Line Receiver Characteristics

- Primary Receiver Characteristics:
  - Input impedance, sensitivity, hysteresis, and input threshold.
- Designing a line receiver for the first of these characteristics, input impedance, is fundamental to the reduction of reflected signal noise.

Protected Differential Line Receiver



Also good for lightning, EMP, and low noise protection.

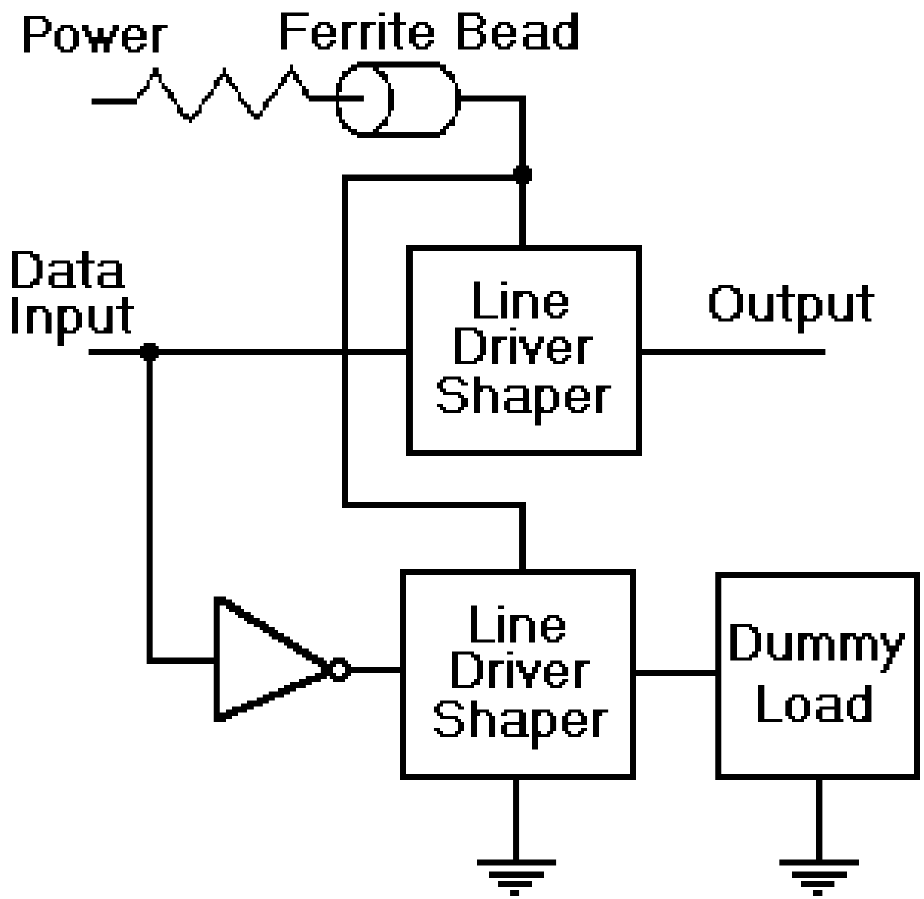
The Decoupling Solution

- The solution to decoupling problems is to provide differential and common mode decoupling for the critical interface lines as near to the device as possible.
- Differential decoupling should be accomplished using capacitors of very low inductance with loading appropriate for the switching frequencies required.

Separation of Line Driver & Receiver

- By placing the VO circuitry on a separate board from the rest of the circuitry, common mode and differential mode coupling problems can be effectively eliminated.
- Since less circuitry exists on the board
  - A solid ground plane can be employed
  - Grounds to the chassis can be controlled
  - Filtering can be applied directly between signal line and signal ground
  - Bypass capacitors will shunt return currents directly to their source

Masking



- Masking involves the generation of an "equal" but opposite signal in order to confuse a covert observer.

Masking Problem

- Technique may work when employed in a unique device with no production or parameter changes and at room temperature.
- Since component operational parameters vary slightly from part to part and since impedance line matching (including trace layouts) is not exact between each signal line, most making fails at some frequency.

Fiber Optic Solutions

Emission Freedom

- Susceptibility and emission coupling problems are overcome using fiber optic cables.
- Electrical ground loops are eliminated between communications equipment and between separate power systems.

Protected Emission Problems

- Fiber optic line drivers require current levels that generate strong emissions.
  - Driver generated emissions are difficult to suppress.
- In full duplex operation, crosstalk isolation may be defeated by physical light coupling on the board.
- LEDs on visible signal emitters are fast enough to re-generate true data impulses.

Quick Look Testing and Troubleshooting Your Design

Bruce Gabrielson, PhD

brucegabrielson@yahoo.com

Last Updated: 2002

Out of the Box

- Equipment manufacturers that don't perform their own emission reductions prior to sending their equipment to test labs still pay premium costs for troubleshooting.
- Usually these inhouse costs are considerably less than the cost associated with extensive laboratory troubleshooting.
- Troubleshooting inhouse is a common method for controlling emission reduction costs.

Troubleshoot Test Lab Costs

Basic Troubleshooting Equipment Set	
Suggested New or Used Equipment	**Appx. Cost**
Used Spectrum Analyzer to 1 GHz (HP 8568)	$15K to 25K
Used Pre-amps	$1200
Used Oscilloscope (400 GHz)	$5000 to $8000
E field Antenna Set	$3000
Tripod	$200
PLISN	$2500
Attenuator	$1000
Cables and Connectors	$500
Hand Probes	$400
Average Total (US Dollars)	$44,800

Full Certification Test Lab

- In addition to the troubleshooting costs, add the following new or used costs:
  - Shielded Enclosure — $20 K + Install
  - Tunable Receiver — $250 K-300 K
  - Oscilloscope (storage) — $10 K
  - PLISN — $2 K – 7 K
  - Scope Camera — $2 K
  - Impulse Generator — $5 k – 7 K
  - CW Signal Source(s) — $9 K
  - Attenuators — $1 K
  - 60 Hz Comb Notch Filter — $2 K
  - 3400A True RMS Voltmeter — $1 K
  - Misc. — $3 K

Test Equipment Specifications

Receiver/Spec Analyzer	50 Hz – 10 GHz
Oscilloscope (Dual Beam)	400 MHz (BW)
Oscilloscope (Storage)	400 MHz (BW)
E-Field Antennas	50 Hz – 10 GHz
H-Field Antennas	50 Hz – 30 MHz
PLISN	5 KHz – 10 GHz
CW Source(s)	50 Hz – 10 GHz
Impulse Generator	50 Hz – 1 GHz

Receiver Specifics

- Sensitivity achieved through noise figures in the order of 10 dB.
- Selectivity based on monotonic bandpass filtering with 60/6 shape factor of 4:1 and a selection scheme that approaches 3 dB between selectable filters.
- Frequency range of 100 Hz to greater than 12.4 GHz with incremental tuning of less than 100 Hz.

Facilities and Equipment

- Enclosures should meet NSA 65-6.
- Nontunable testing requires the use of an Electrometrics NTR 51B or a custom receiver with similar capabilities.
- The key to insuring adequate equipment is the capability to achieve wide band high frequency measurements.
  - Receivers are used for wider band measurements.
  - Spectrum analyzers are used for narrow band measurements.

Recording a DC Measurement

- D.C. coupled measurement of an impulsive signal:
  - Adjust scope to good reference level.
  - Substitute a CW source and adjust the level.
  - The recorded level is the amplitude of the CW source.

Recording an AC Measurement

- A.C. coupled measurement of an impulsive signal:
  - Adjust the scope to a good reference level.
  - Substitute 30% modulated CW source level and adjust the signal level measured.
    - Signal level = 20 log (.3A) dBμV
      - Assumes a linear detector.

Bandwidth Calculation

- To determine variations in signal levels for impulsive signals and to calculate Johnson noise levels, bandwidths in Hz must be transposed into decibel units.
  - For calculating noise floor levels, the power form is used:
    - BWdB = 10 log (BWHz)
    - BWHz = 500 MHz BWdB = 10 log (5×10^5)

= 10 x 5.7 = 57 dB

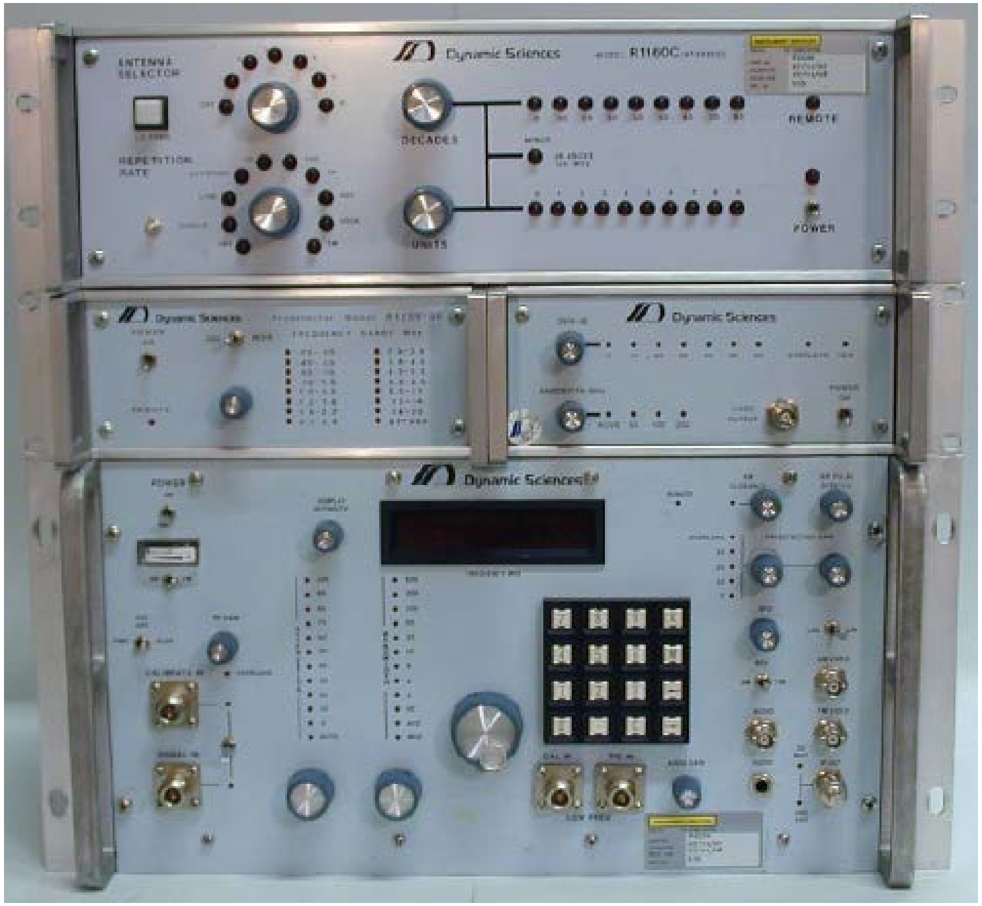
Johnson Noise

- Theoretical lowest receiver noise floor
- Johnson Noise = kTB
  - k = Boltzmann's Constant ($1.38x10^{23}$ J/deg Kelvin)
  - T = Standard baseline temperature (293 deg Kelvin)
  - B = Effective bandwidth (in Hz)

In a 50 ohm system:
Johnson Noise = kTB (1 Hz) + 10 log (bw)
Johnson Noise = -174 + 10 log (bw)

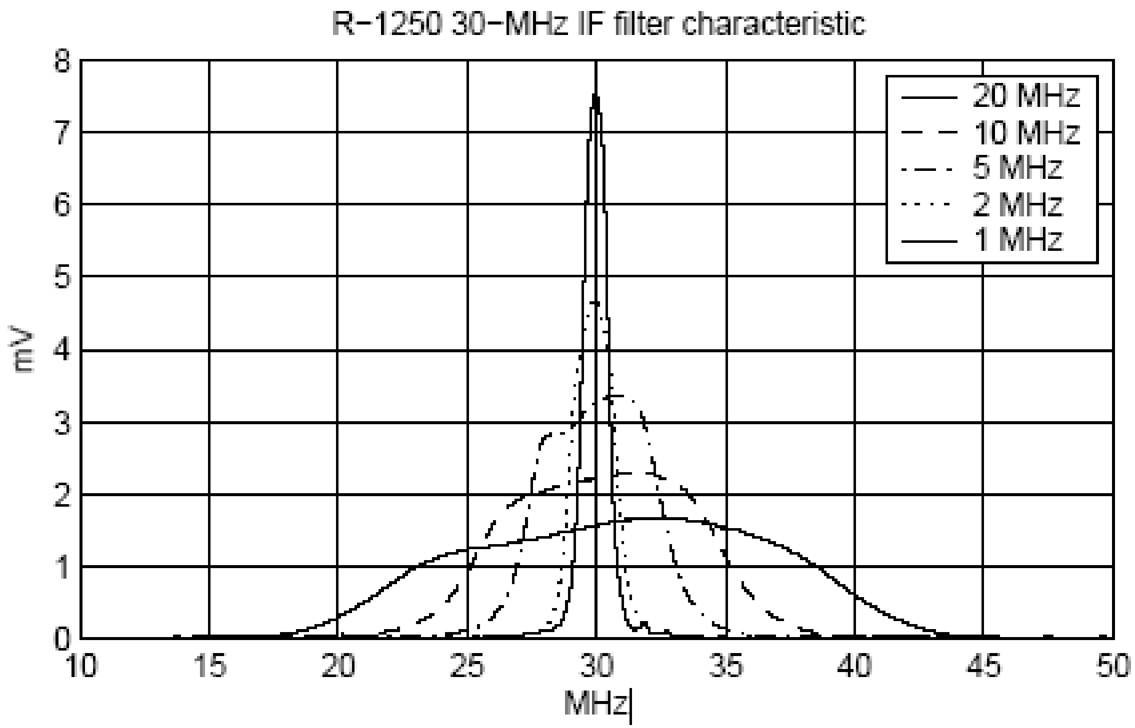
For a 10 kHz bandwidth:
-174 + 10 log (10^4) = -174 + 40 = -134 dbm = -27 dBμV

Tunable Receivers



Transfer Functions

- This shows the transfer function of an R-1250 receiver for five different 30-MHz IF filter bandwidth settings.
- The transfer function of a band-pass filter would be symmetric around its center frequency but isn't due to component tolerances.



CW Narrowband Field Strength Measurements

- Adjust the 3 dB IF-filter bandwidth of the receiver such that it entirely covers the bandwidth of the examined signal, but still suppresses any out-of-band noise.
  - Connect a sine wave generator adjusted to the tuning frequency of the receiver to its antenna input and then adjust its amplitude (usually expressed in µVrms or dBm) until the peak-to-peak voltages seen with an oscilloscope on the intermediate frequency (IF) output of the receiver are identical to those seen with the antenna.
  - The resulting amplitude setting on the sine-wave generator becomes the measured signal level at the antenna input.

Impulsive Signal Measurements

- When measuring impulsive signals, the apparent amplitude of the signal corresponds to the impulsive bandwidth of the IF being used to measure the signal.
  - The difference in amplitude between a 3 MHz and a 20 MHz IF bandwidth becomes critical for impulsive signals.
    - Measurement differential in dBμV at 20 MHz

      = 20 log (3 MHz/20 MHz) = -16.47 dB

Impulsive Corrections

- For calculating impulsive signal corrections, the voltage form is used:
  - IBWdB/MHz = 20 log (BWHz/1 MHz)

BWHz = 500 KHz

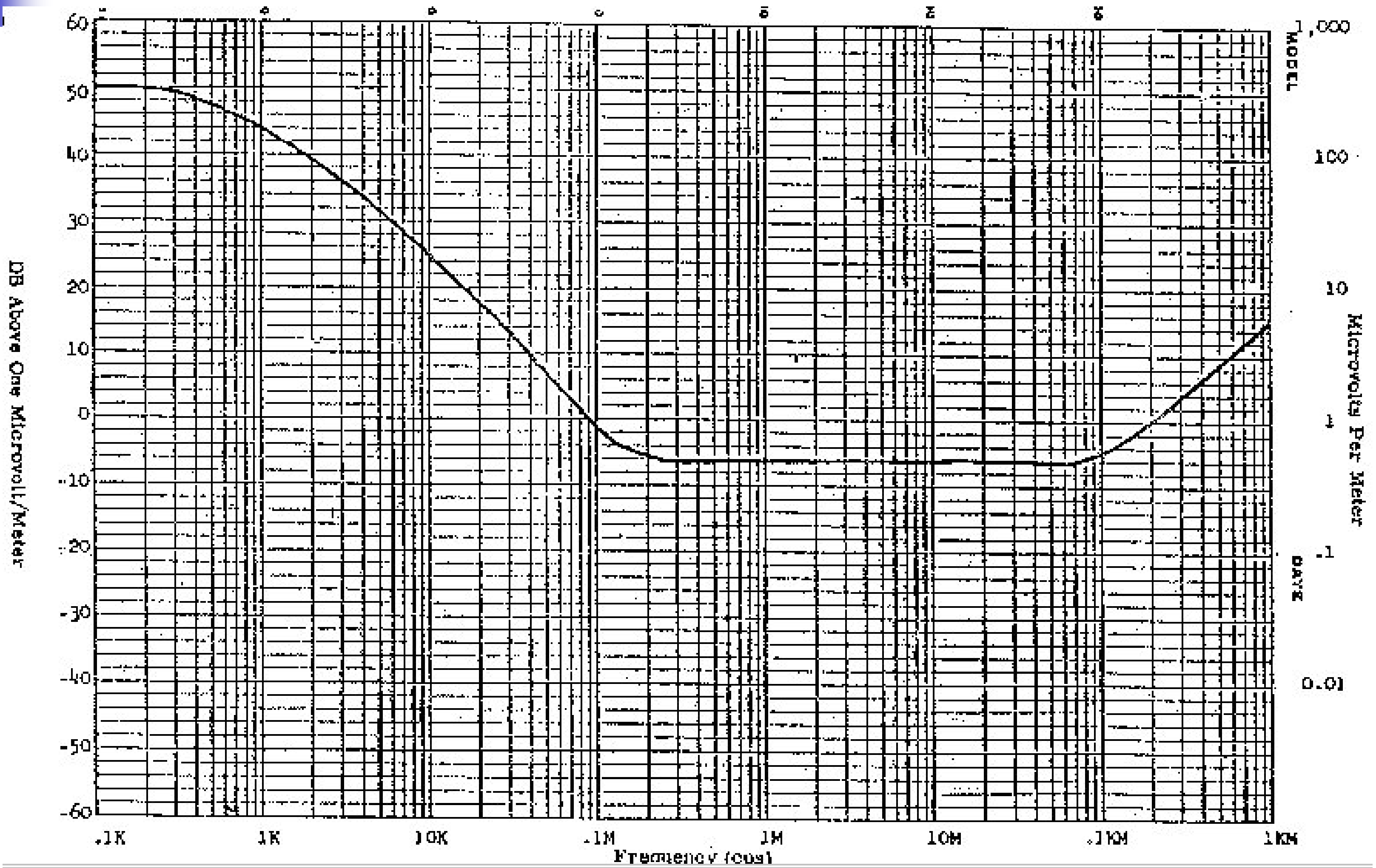
IBWdB/MHz = 20 log (500 KHZ/1 MHz)

= 20 log ($5x10^5/10^6$)

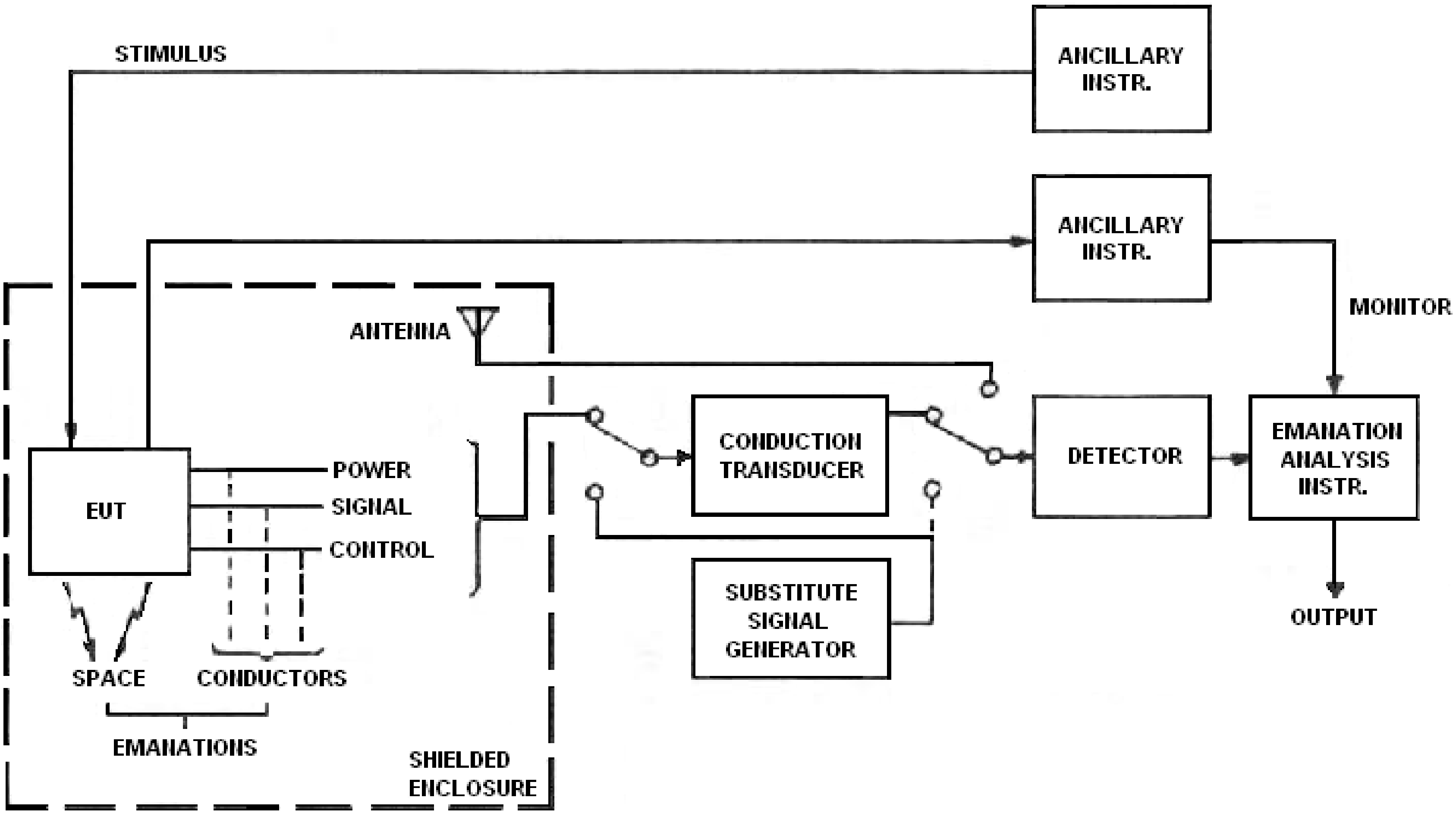
= 20 log (.5)

= -6.02 dB/MHz

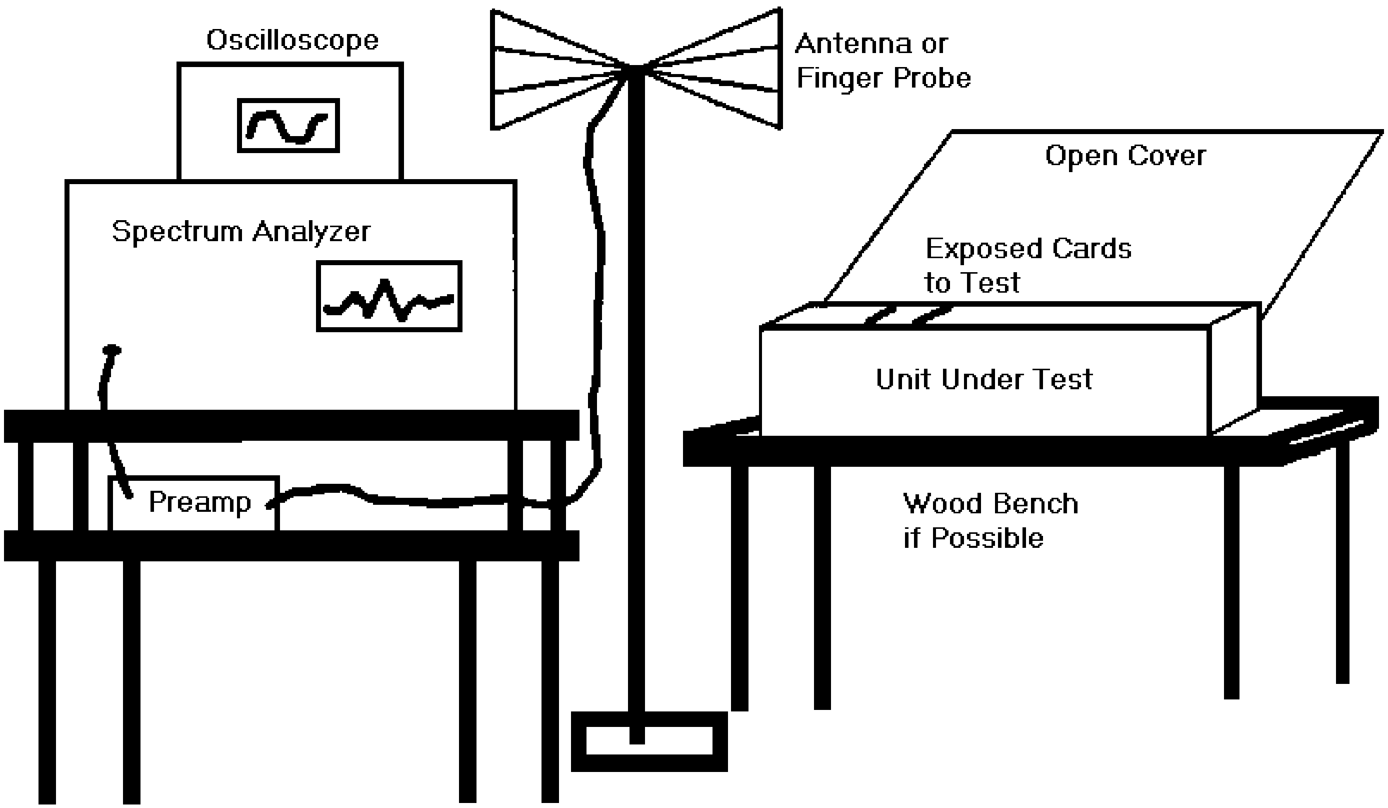
What Limits Look Like



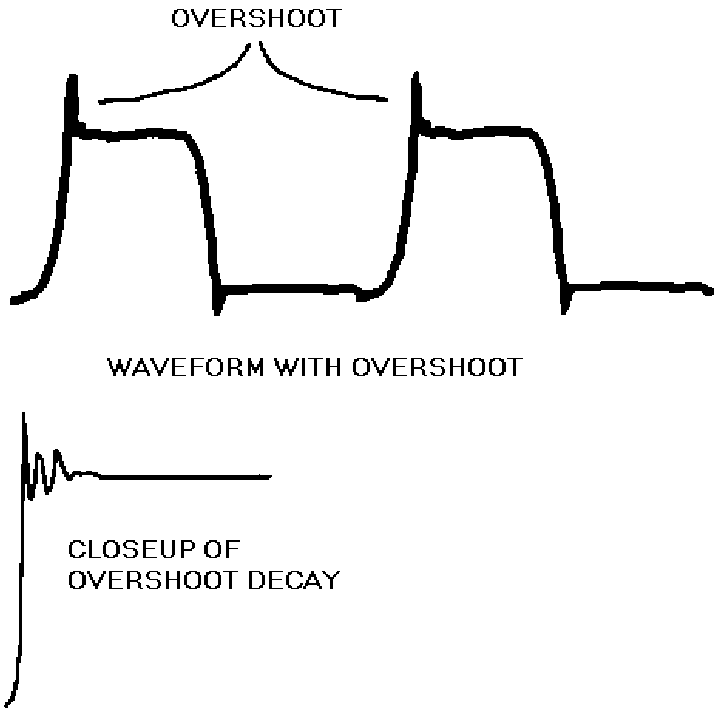
Real Test Set-up



Typical Troubleshooting Setup

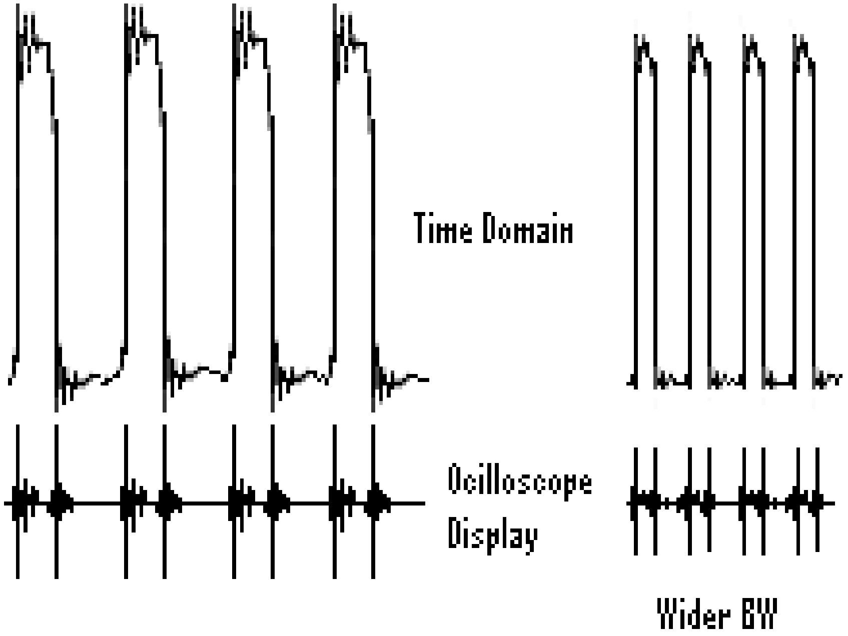


Time Domain Emission Source

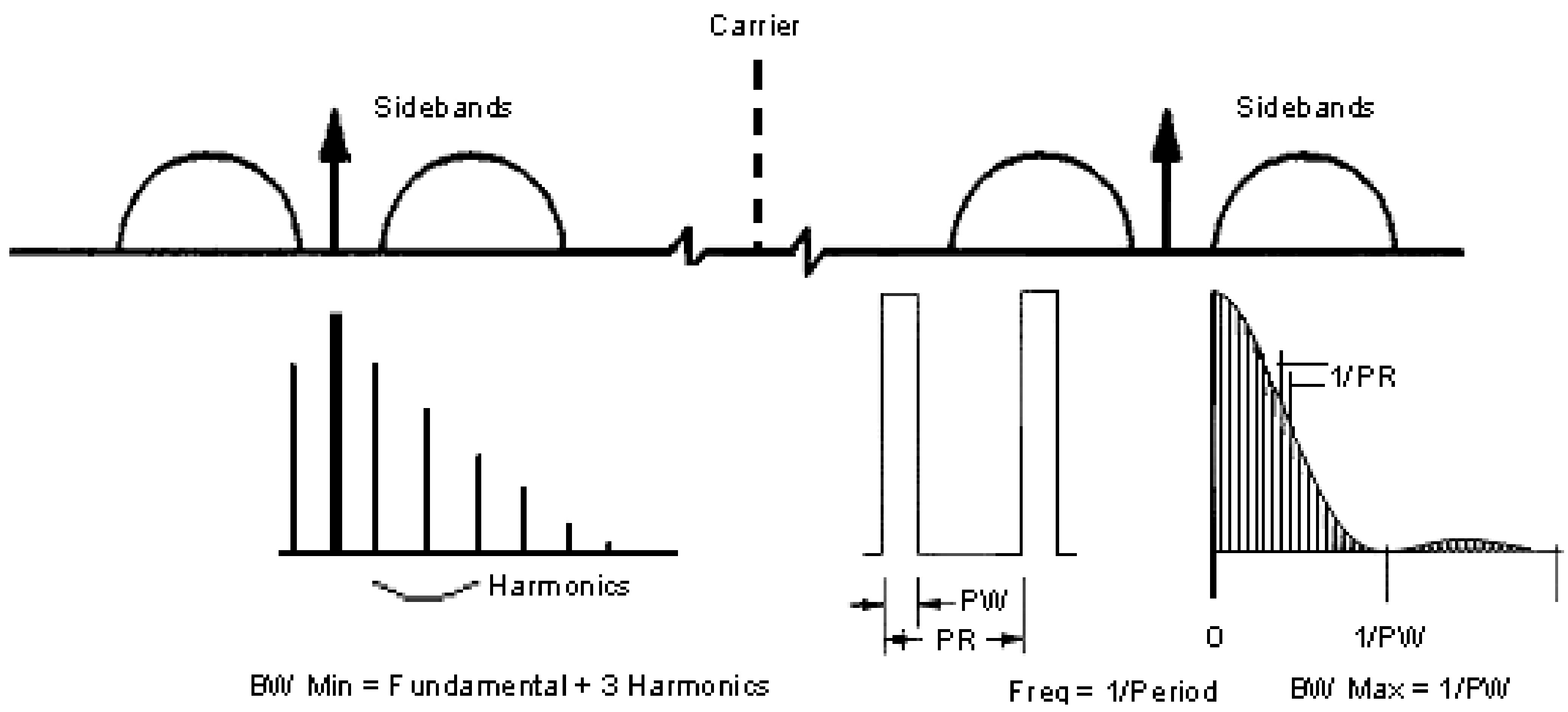


- Signal waveshape on a trace using an oscilloscope.
- The signal waveform will have ringing and overshoot as shown.

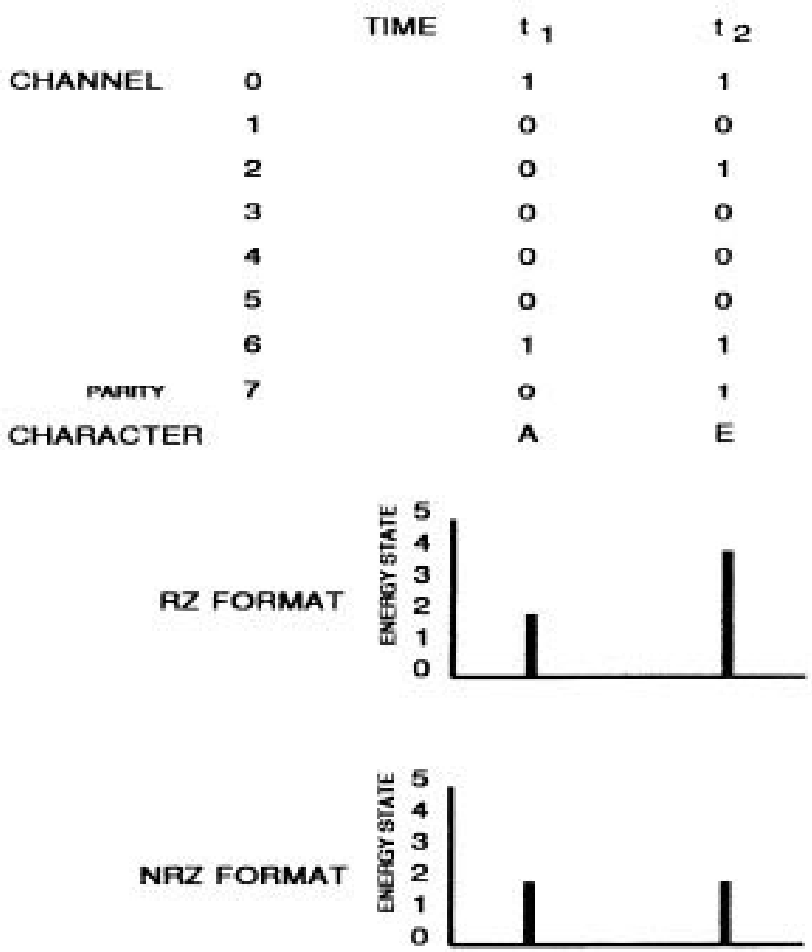
Detected Signal Display



Selecting the Test Bandwidth (Narrowband)



Visualization of the Information



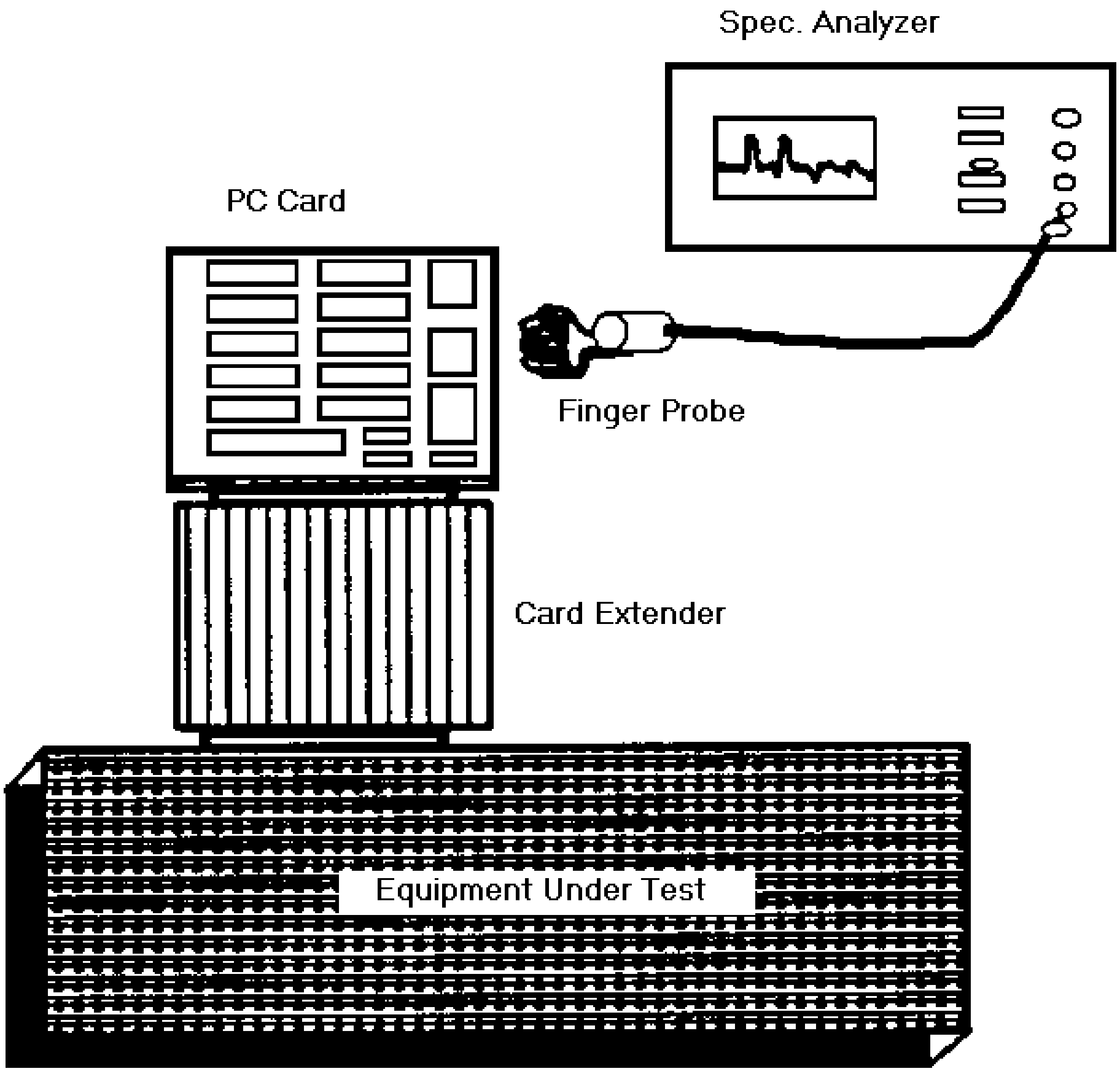
- Bit Energy States
  - **The amount of energy emitted is directly proportional to the number of bits changed from “1” to “0” or “0” to “1” states.**
  - **The energy is transmitted during the transition**
- Probability theory can be used to help predict the ASCII character associated with a particular energy pattern

TEMPEST Approach

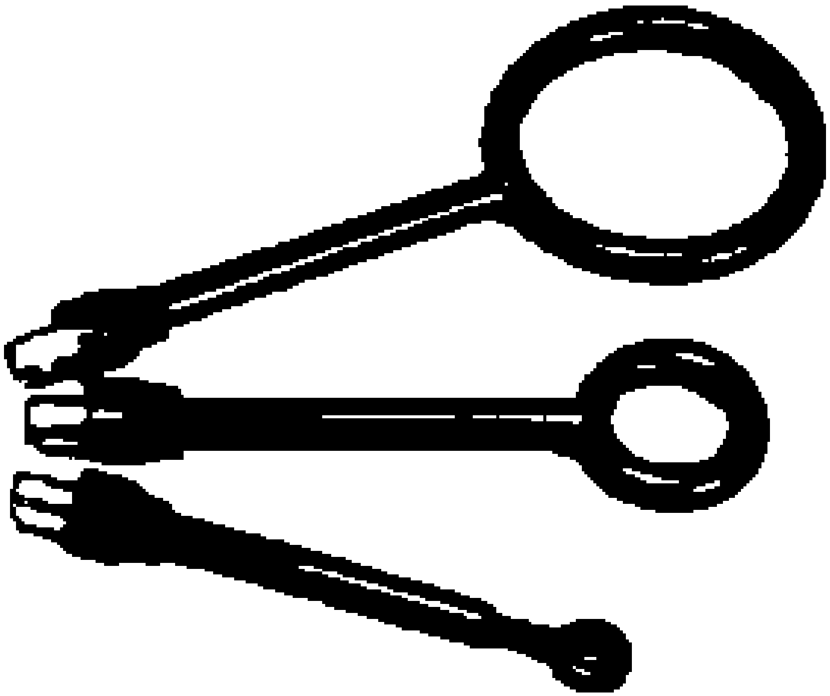
- Perform closed box level scan to determine major emission problem areas.
- Open box and perform specific radiated probe scans to identify source of problem.
  - Process often requires both schematics and board layout diagrams.
- Carefully evaluate extent of problem to determine best suppression or containment approach.
- Fix the problem and perform additional scans to see if solution worked or created new problems.

Troubleshooting Tips

- After identifying emissions, open the box and put card on extender.
- Find a sensitive signal so it can be easily identified.
- Map sensitive emission hot spots on each card.
- Unsolder IC and use ferrite pad initially to reduce emissions before more drastic activities.

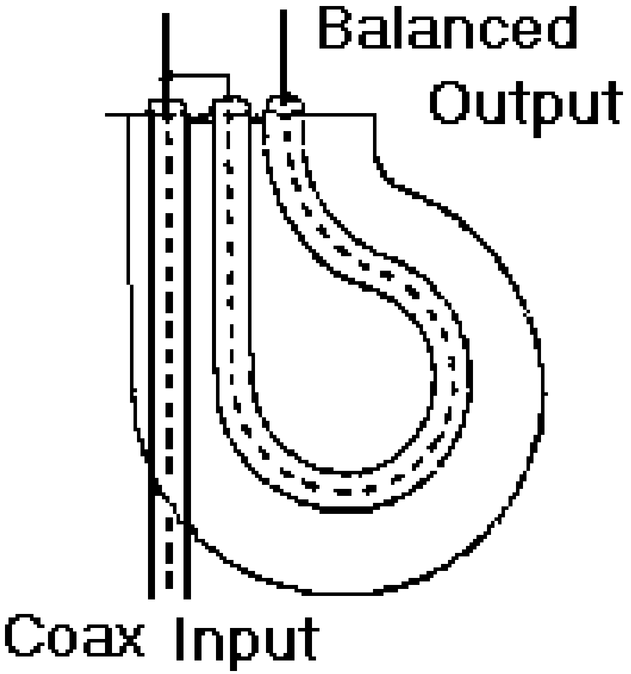

Spec. Analyzer
PC Card
Finger Probe
Card Extender
Equipment Under Test

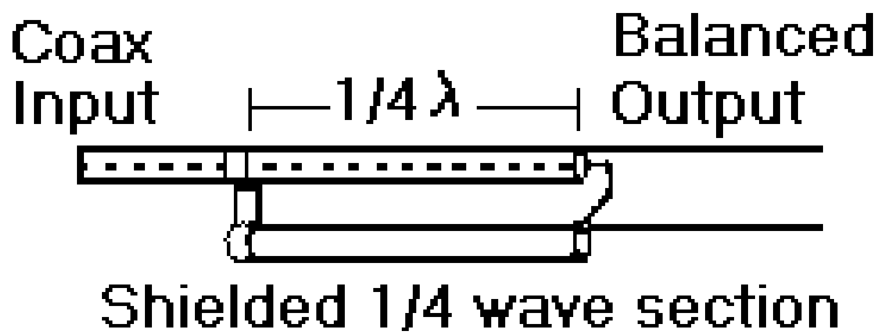
“Sniffer” Probes

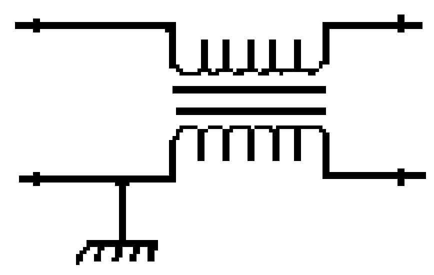


- Hand held sniffer probes are commonly used for detecting E-field or H-field emission sources.

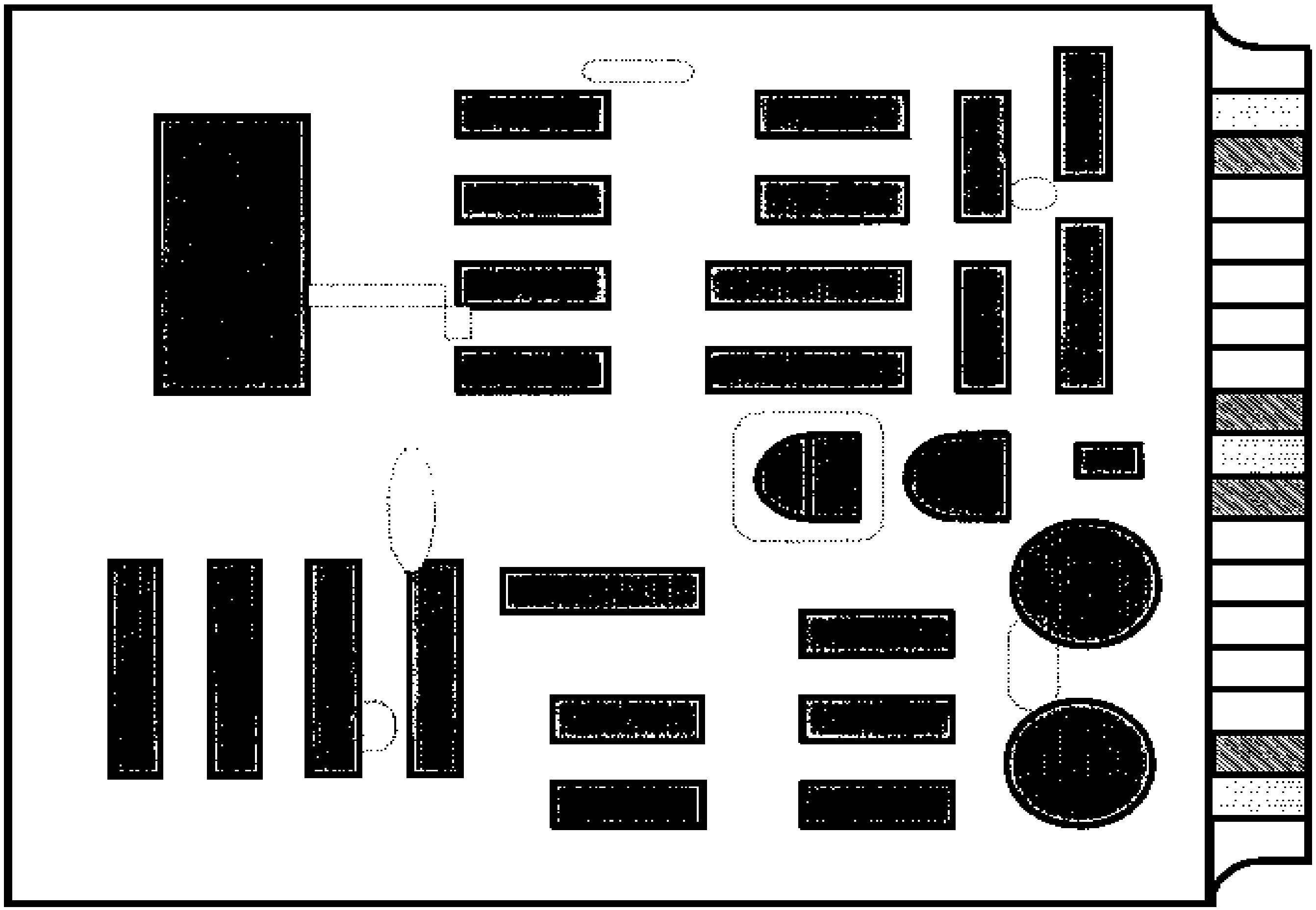
Balun Probe


Balanced
Output
Coax Input

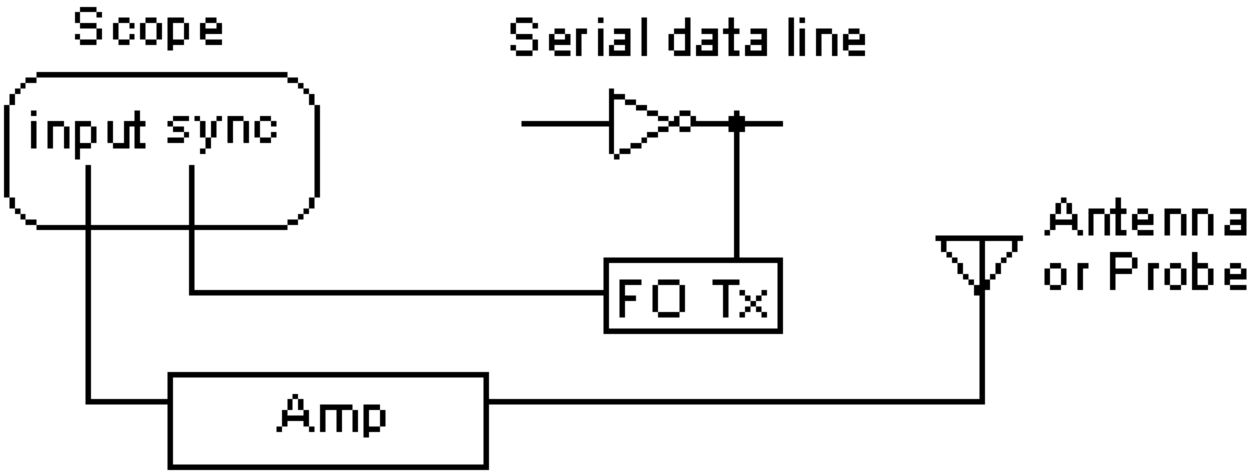

Coax
Input
1/4 λ
Balanced
Output
Shielded 1/4 wave section



Emission Mapped PC Card

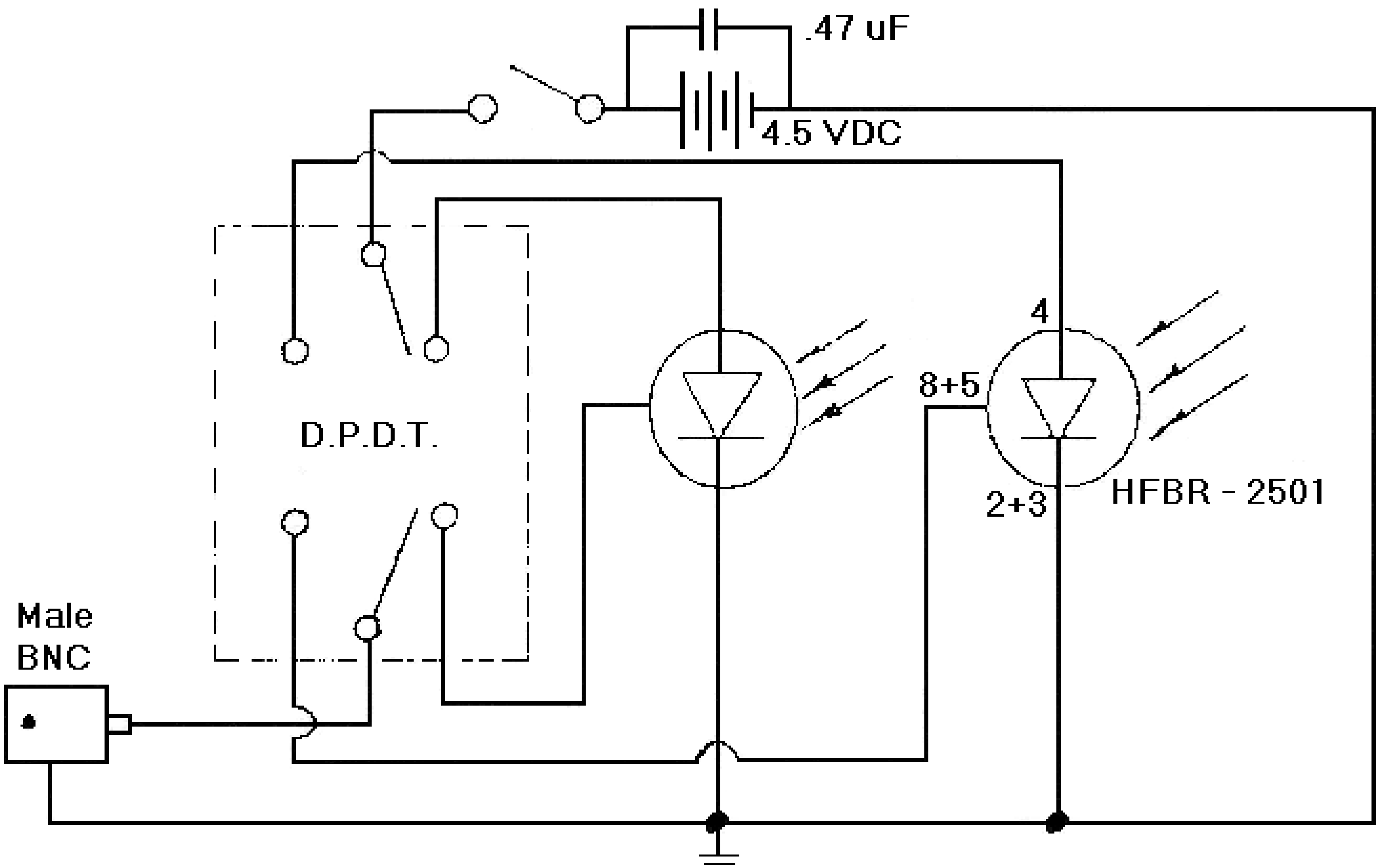


Triggering the Scope

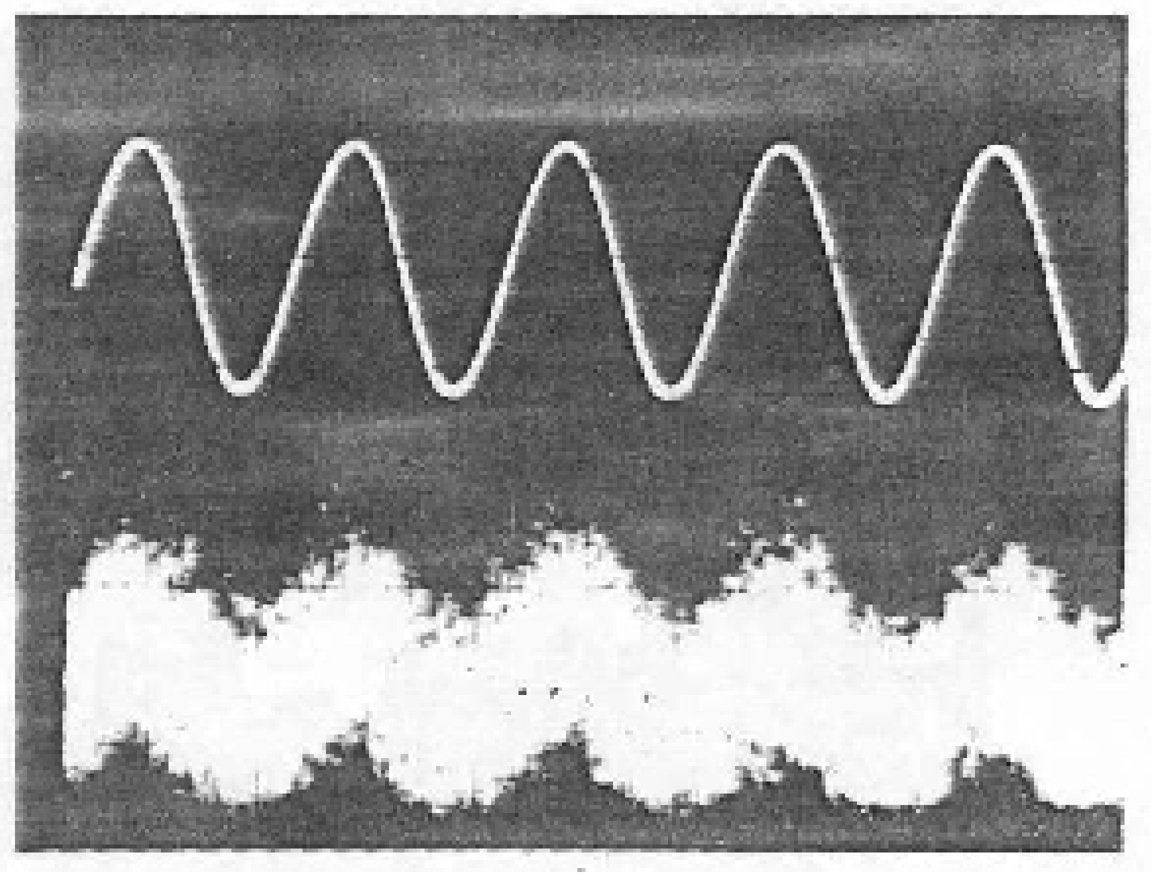


Note: The amplifier can be a receiver, spectrum analyzer or pre-amp.

Dual Fiber-Optic Coupler

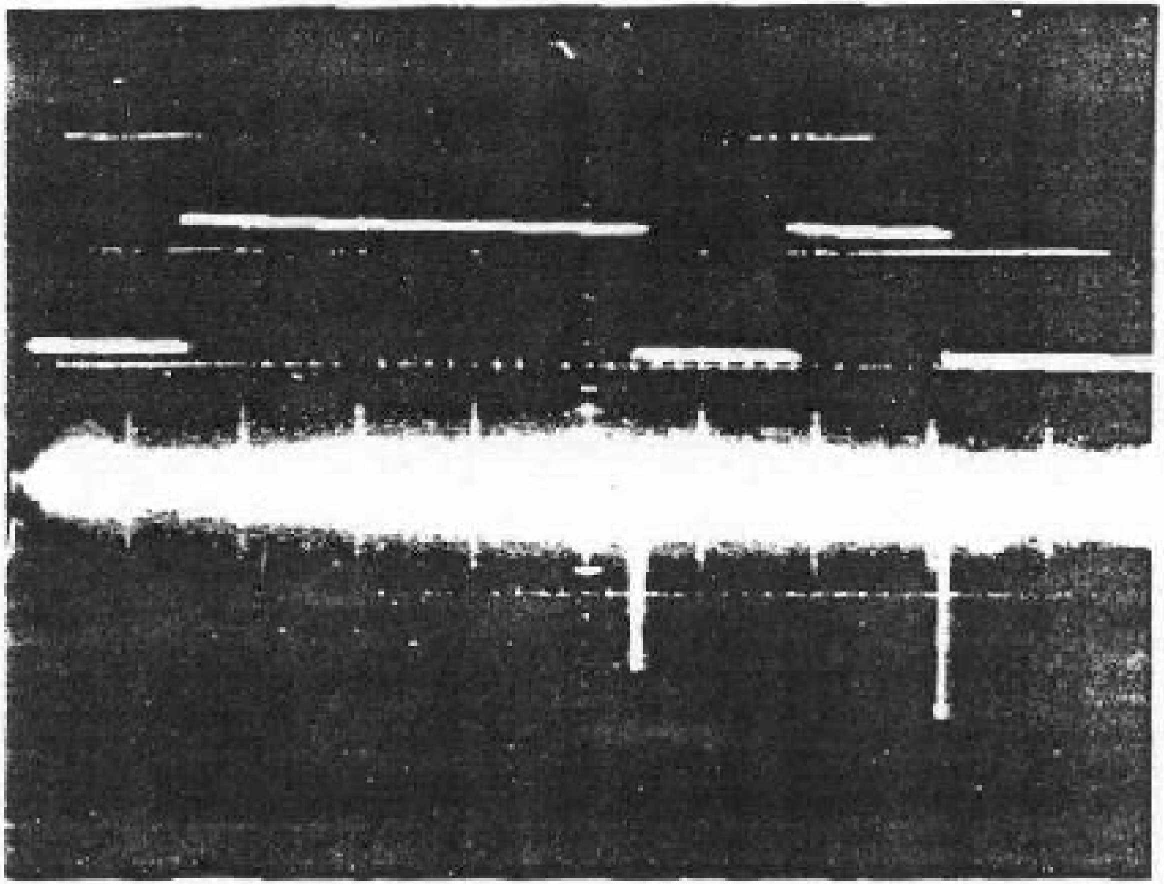


Clock or Analog Voice



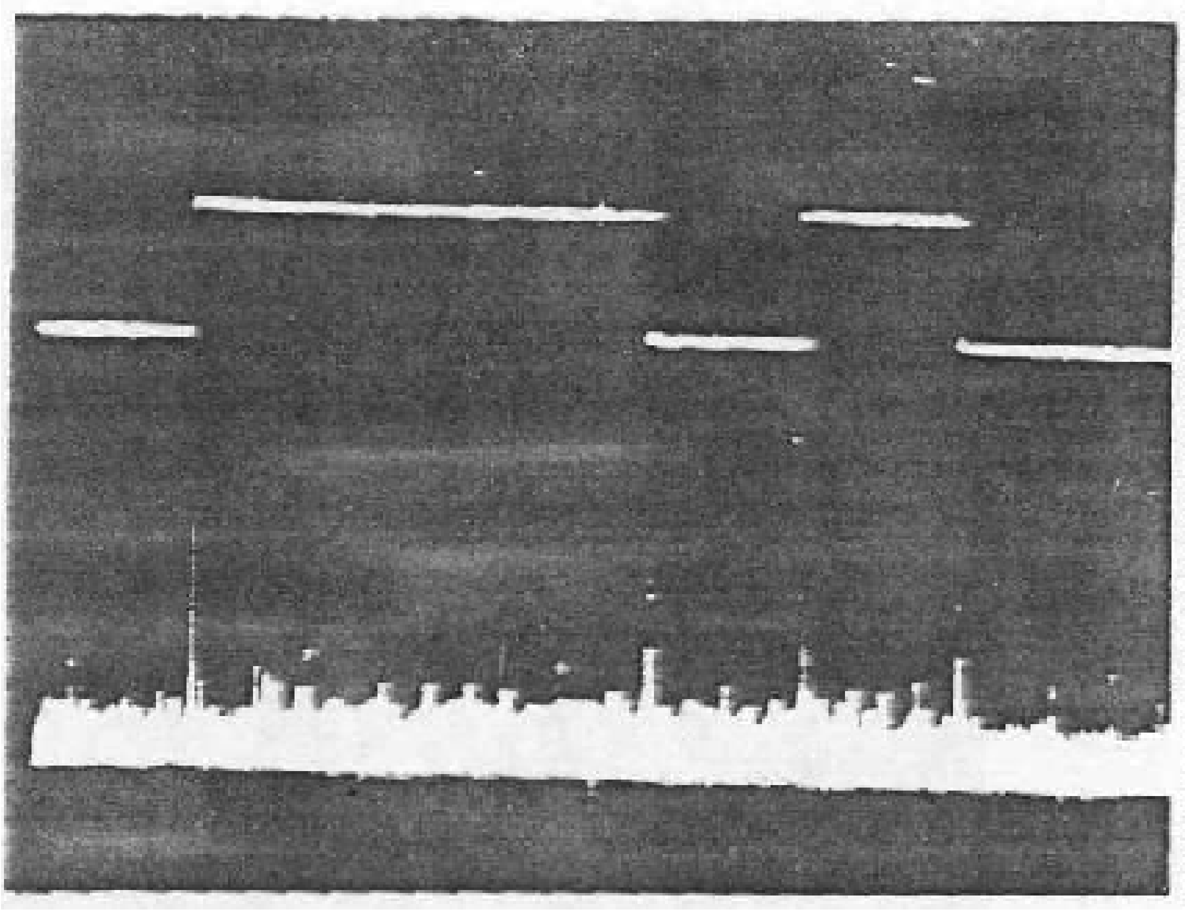
NACSIM 5000 TEMPEST Fundamentals

Clock With Signals



NACSIM 5000 TEMPEST Fundamentals

Signal Hidden in Noise



NACSIM 5000 TEMPEST Fundamentals

Typical Processor Redesign

- Conductive coated housing
- Powerline filters
- Pin filtered connectors
- Shielded internal cables with ferrites on flat cables
- Shielded AC power cable
- Controlled grounds
- If necessary, separate metal housing for power supply
- Gasket as necessary

Typical Keyboard Redesign

- Shielded cable to Processor
- Metal plane installed above and below circuitry
- Carefully controlled grounds
- Capacitive loaded or wave shaped clock circuit
- Conductive coated housing
- Twisted shielded pair (TSP) wiring wherever possible

Typical Monitor Redesign

- Conductive coated housing
- Fiber optic interface if possible
- Foil wrap CRT
- Mesh screen with gasketing
- TSP's on all internal video lines
- Liberal use of ferrites on signal lines
- Capacitor loading on overvoltage protection circuit in the CRT cathode circuit
- Braid ground connected between chassis and CRT cathode drive circuit card