EMI-RFI Considerations in Precision Linear Circuits

By Thomas Kuehl – Senior Applications Engineer
Precision Analog – Linear products

EMIRR content based on work by
Chris Hall – Applications Engineer
Precision Analog – Data Conversion products
and
John Caldwell – Applications Engineer
Precision Analog – Linear Products

EMI–RFI
first things first

- TI's interest in EMI-RFI is simply one of providing assistance to our customers who must prevent or resolve EMI-RFI issues affecting the performance of our products in their circuit application

- I would like to acknowledge the contributions of some of the people who have provided industry a wealth of information about EMI-RFI

  - *The Designers Guide to Electromagnetic Compatibity, EDN -William D. Kimmel, PE, and Daryl D. Gerke, PE, - Kimmel Gerke Associates, Ltd*
  - *Electromagnetic Compatibility Engineering – A Wiley and Sons Publication - Henry W. Ott – Henry Ott Consultants*
  - *Audio Systems Group, Inc. – Jim Brown*

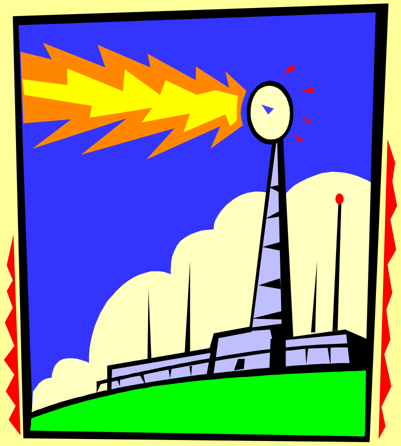
EMI–RFI

EMI – Electromagnetic Interference

RFI – Radio frequency Interference

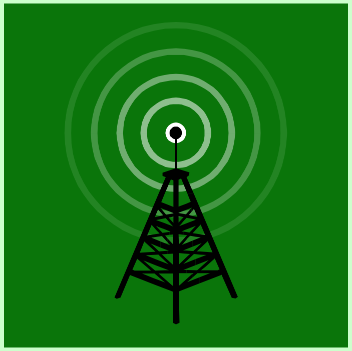
Why are EMI and RFI a concern?

- Radio spectrum pollution
- Compatibility within circuits
- System disturbance, malfunction or possibly damage
- Regulatory conformance

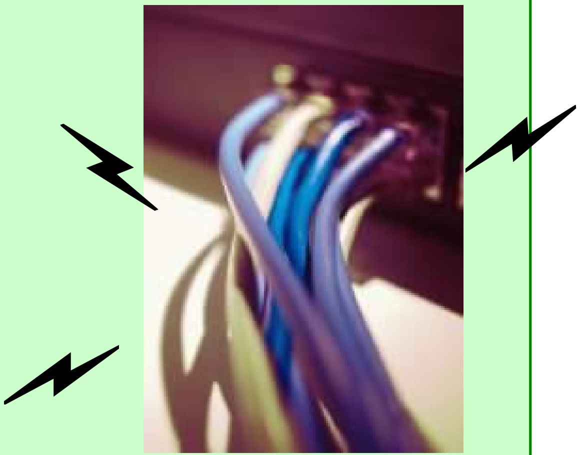


EMI or RFI?

Both are sources of radio frequency (RF) disturbance

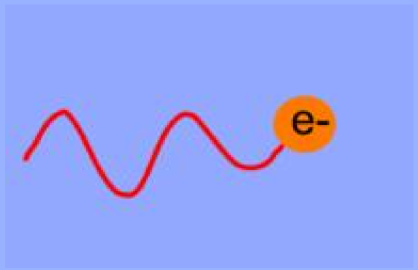


- RFI – radio frequency interference
  - Often a narrowband RF source
  - RF is often intentionally radiated
- EMI – electromagnetic interference
  - Often a broadband RF source
  - RF is often unintentionally radiated
- Terms are often used interchangeably



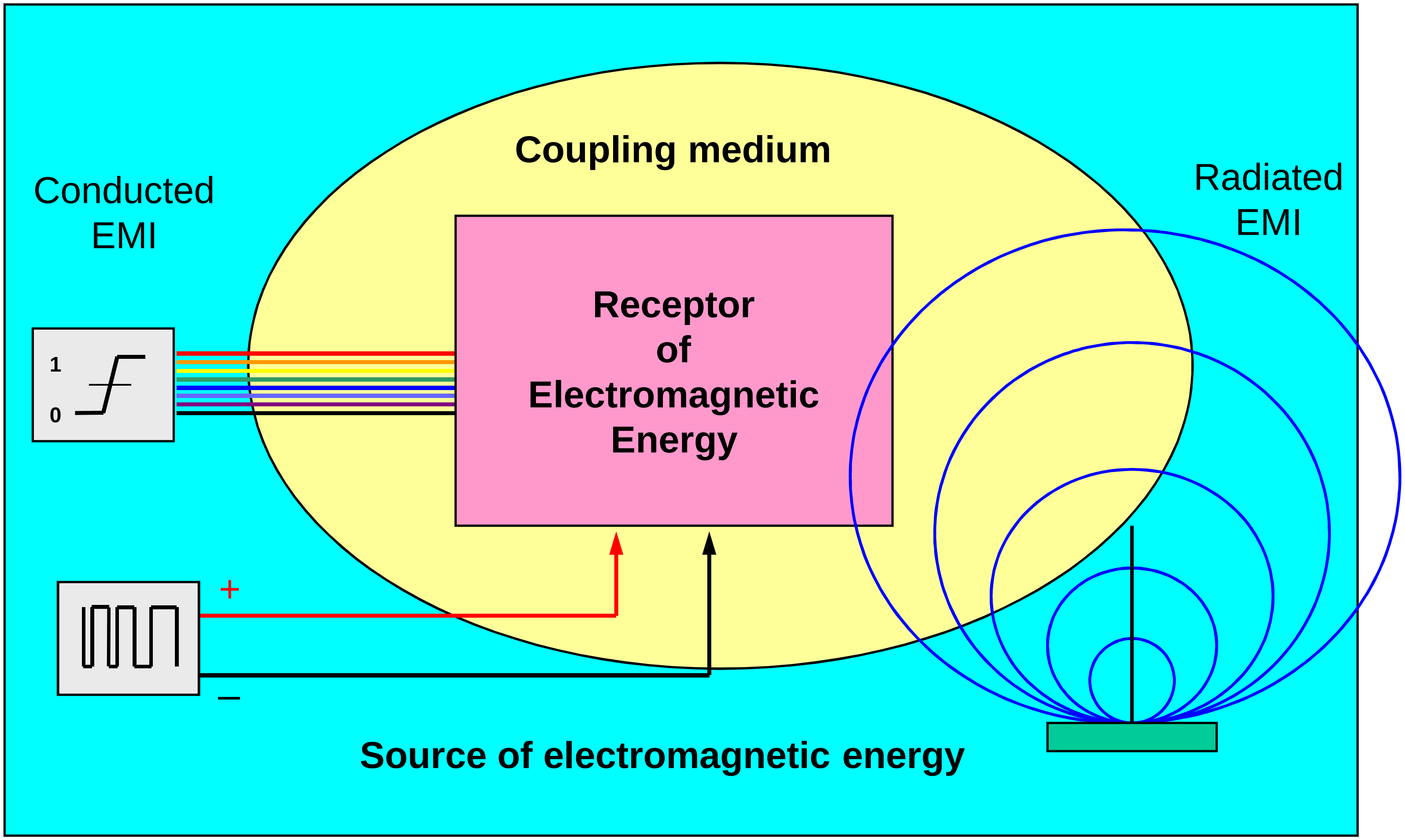
EMI can propagate by one or more types of fields

- Electric Field (E) – Force created by uneven charge distribution
- Magnetic Induction Field (H) – Force created by moving charges
- Electromagnetic Field – Created whenever charges are accelerated



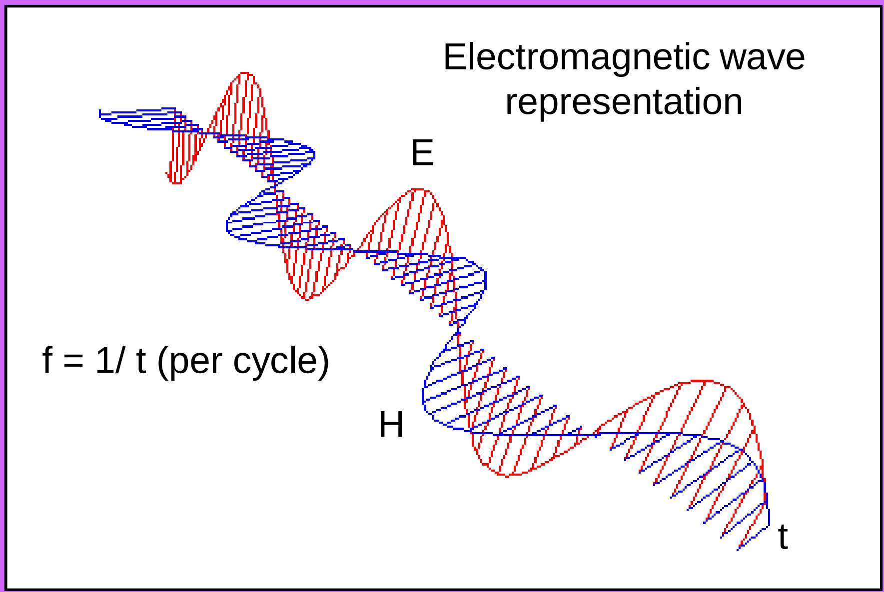
Source http://www.w8ji.com/radiation_and_fields.htm

The necessary elements for EMI



Radiated EMI will be converted to conducted EMI when it is intercepted by conductors!

Sources of electromagnetic energy



RF generating sources

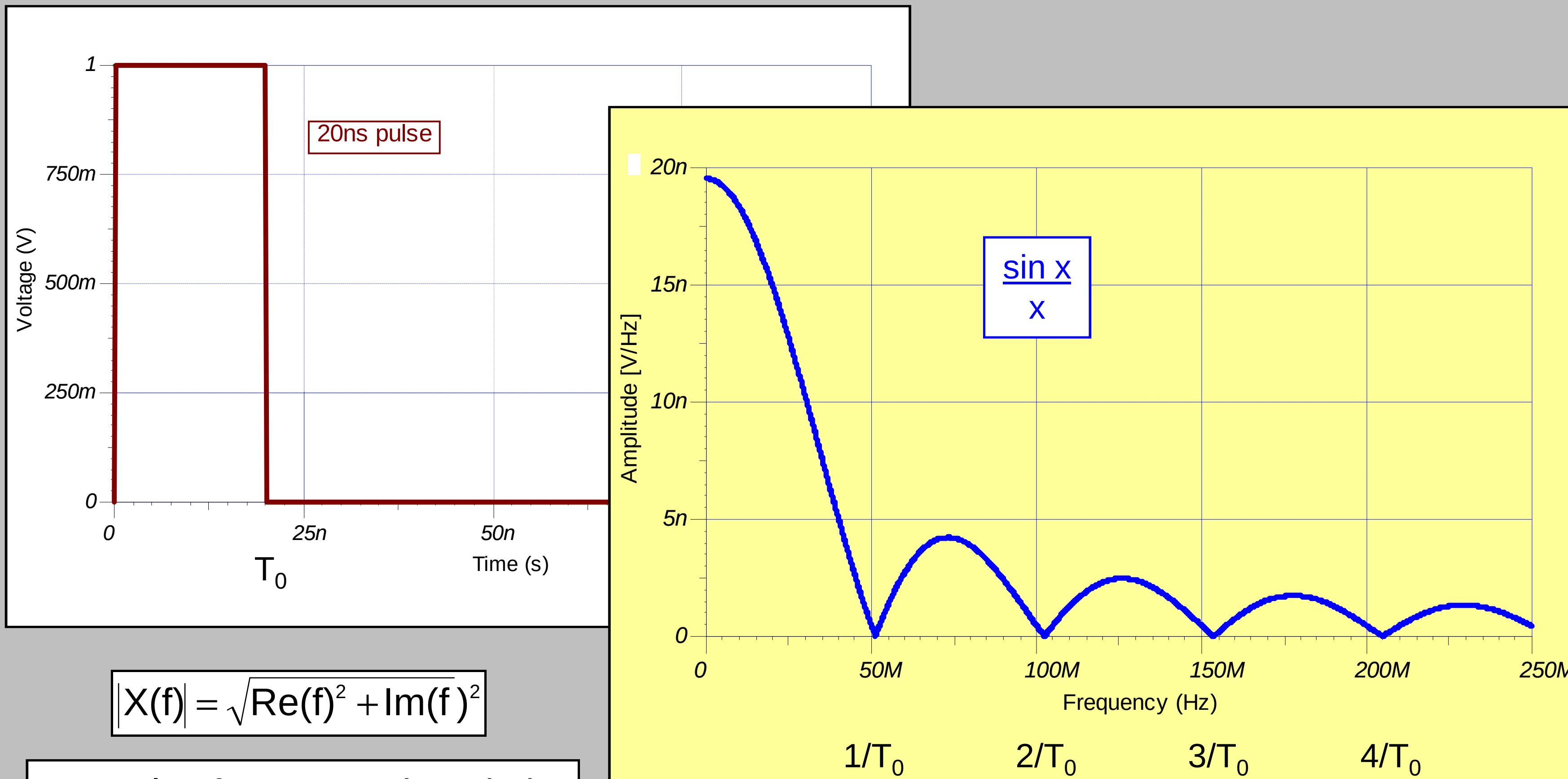
Intentional radiators

- Cell phones & personal electronics
- Transmitters & transceivers
- Wireless routers, peripherals
- Wireless instrumentation

Unintentional radiators

- System clocks & oscillators
- Processors & logic circuits
- Switching power supplies
- Switching amplifiers
- Electromechanical devices
- Electrical power line services

How radio frequency energy comes about in circuits



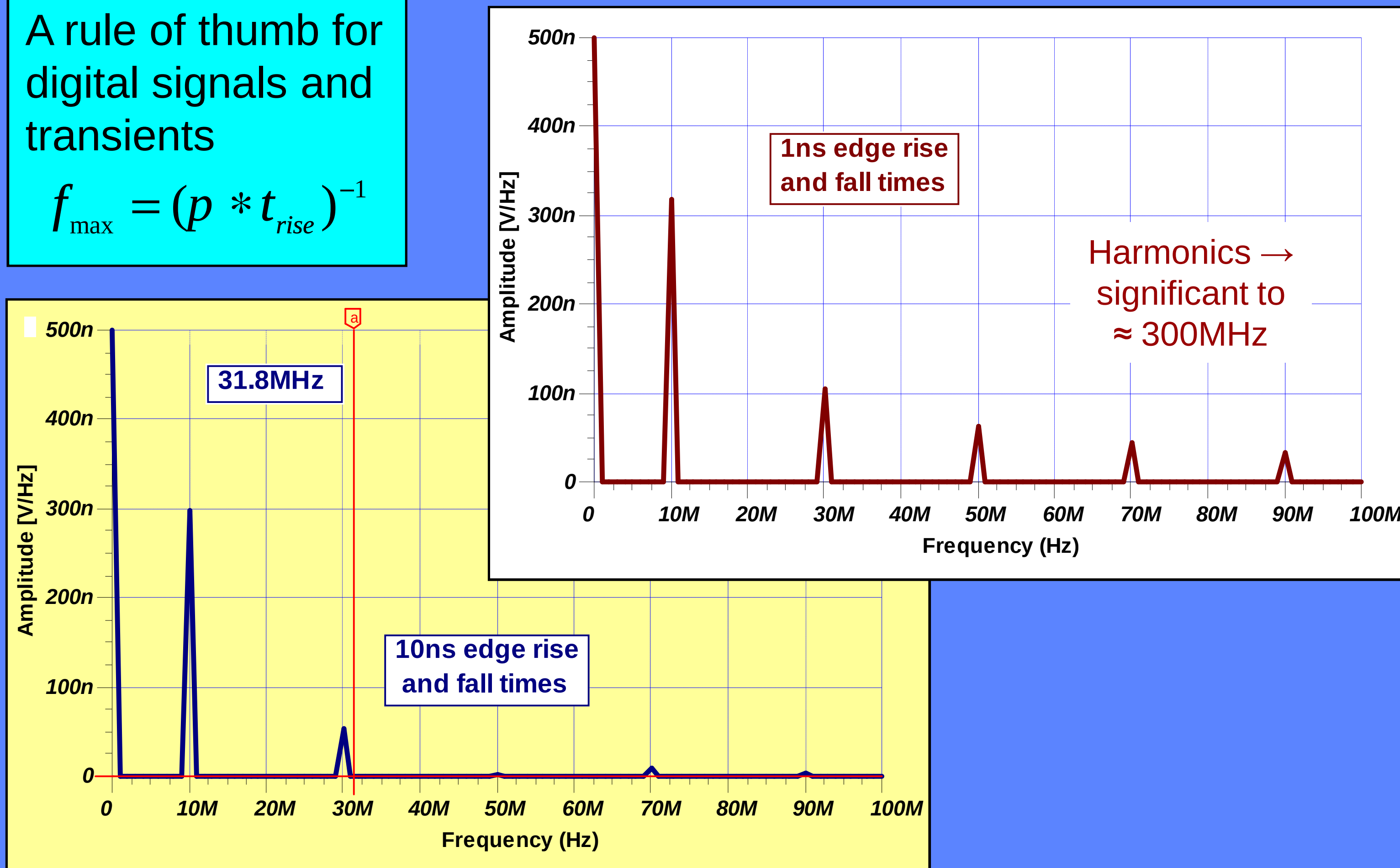
$$|X(f)| = \sqrt{Re(f)^2 + Im(f)^2}$$

Complex frequency domain in Polar form

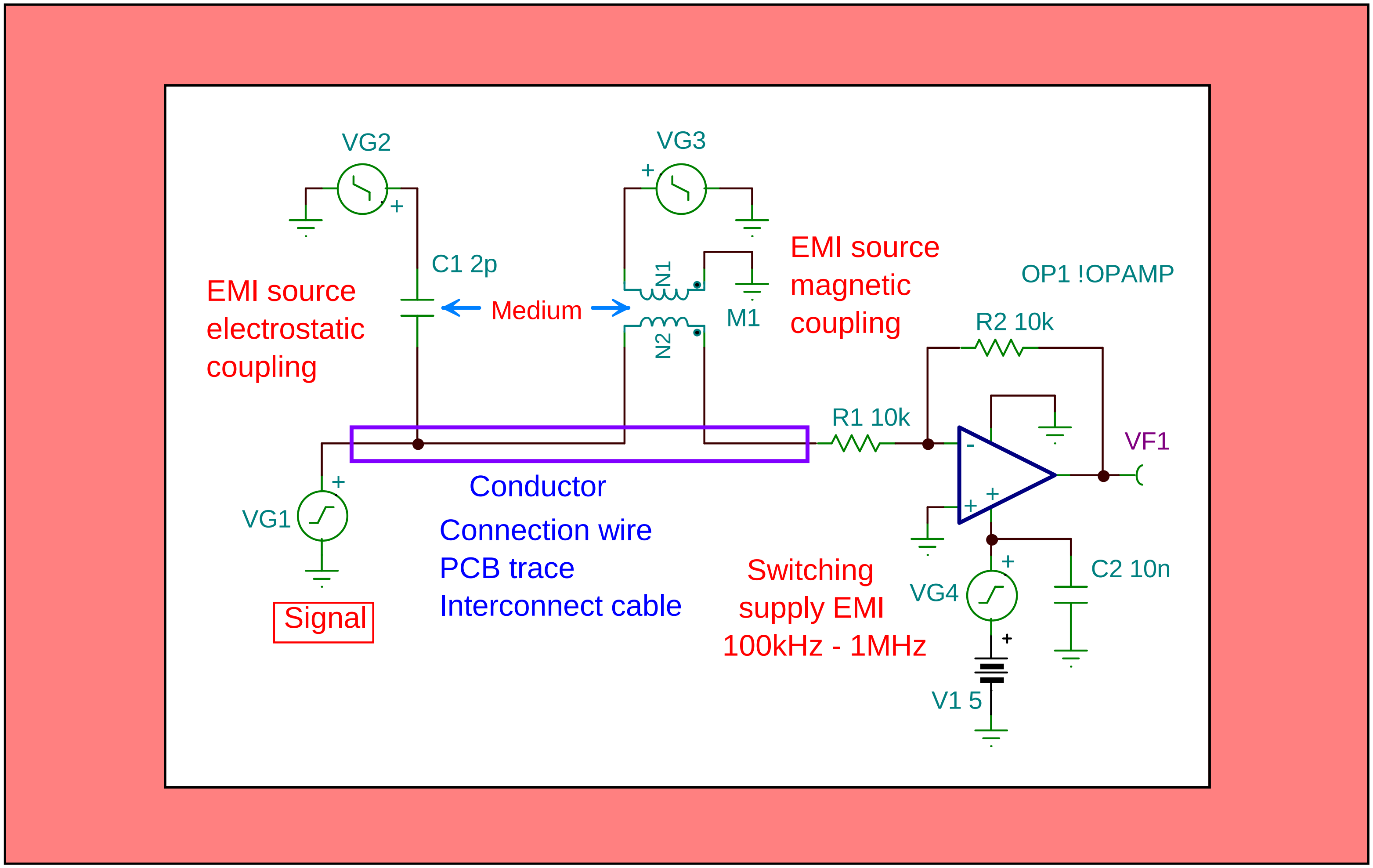
It’s about edge rates

A rule of thumb for digital signals and transients

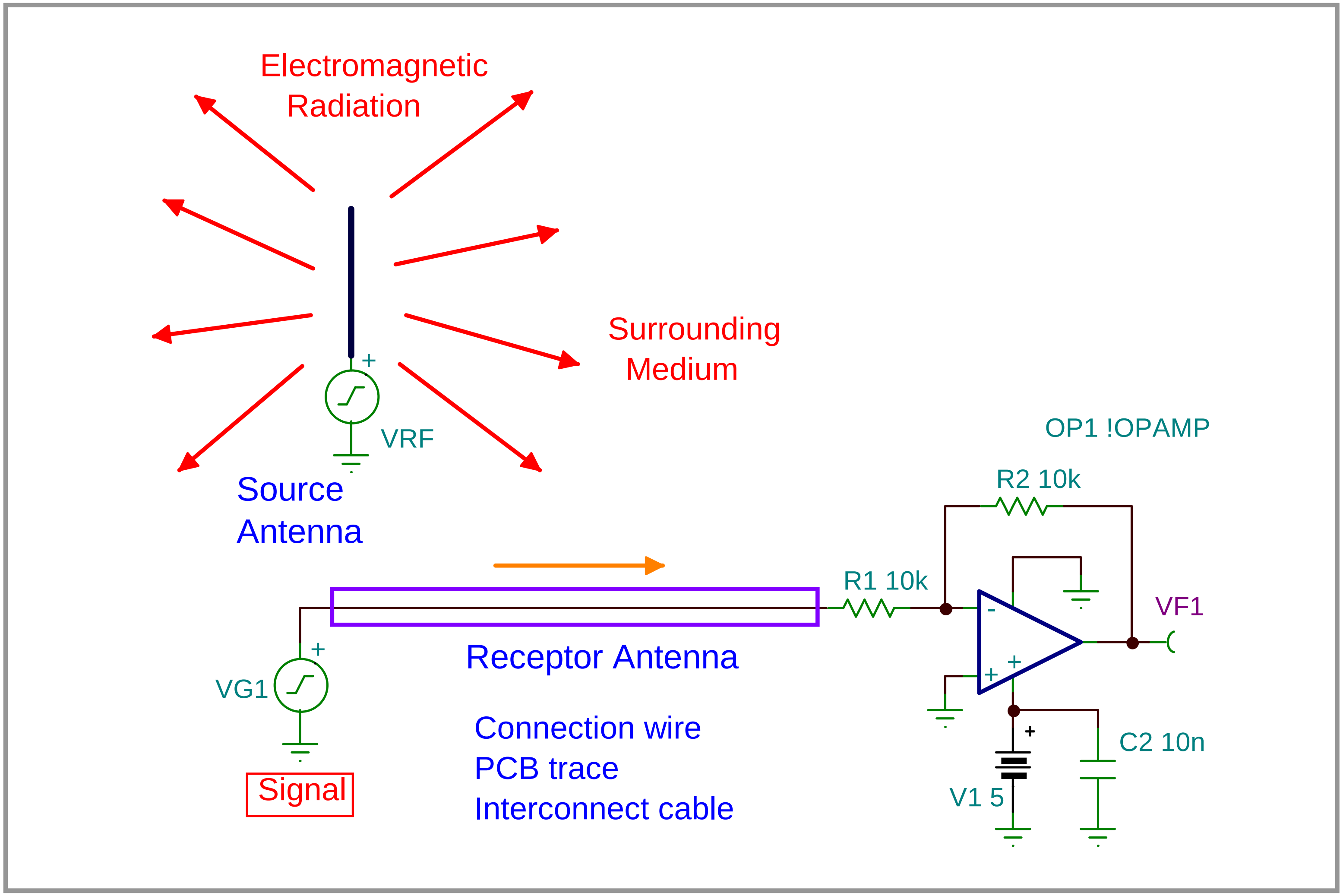
$$f_{\max} = (p * t_{rise})^{-1}$$



The coupling medium for conducted emissions



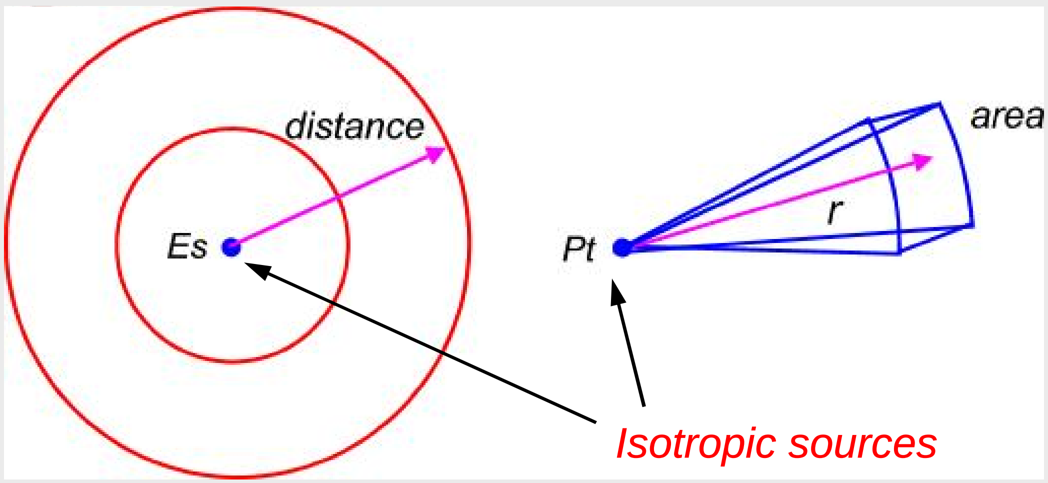
The coupling medium for radiated emissions



Electric-field strength and power density

EMI - electric-field strength units

Communications - power density units



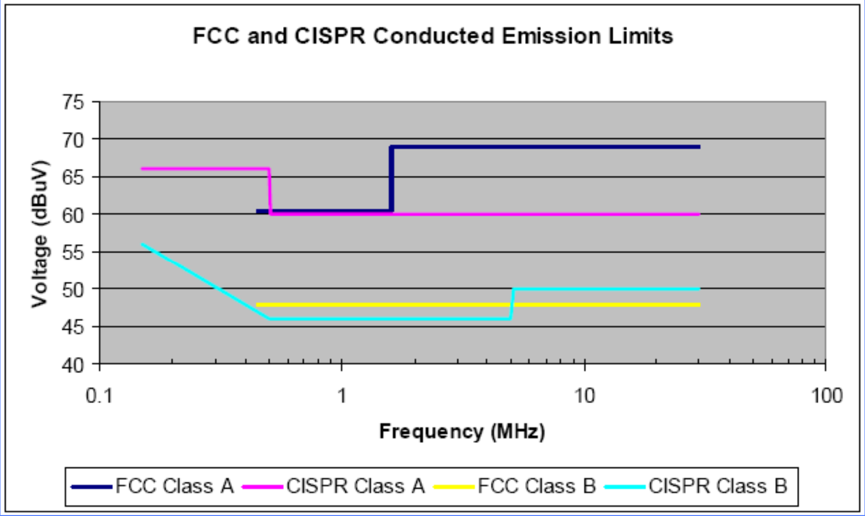
$E\ (V/m) = 61.4\ [P(mW) / cm^2]^{1/2}$

$P_d = P_t / 4\pi \cdot r^2 \quad (W/m^2 \text{ or } mW/cm^2)$

100V/m = 2.65mW/cm²	**10mW/cm² = 194V/m**
10V/m = 26uW/cm²	**1mW/cm² = 61V/m**
1V/m = 0.26uW/cm²	**0.1mW/cm² =1.9V/m**

Emission source limits

Conducted Emissions - 10kHz to 30MHz

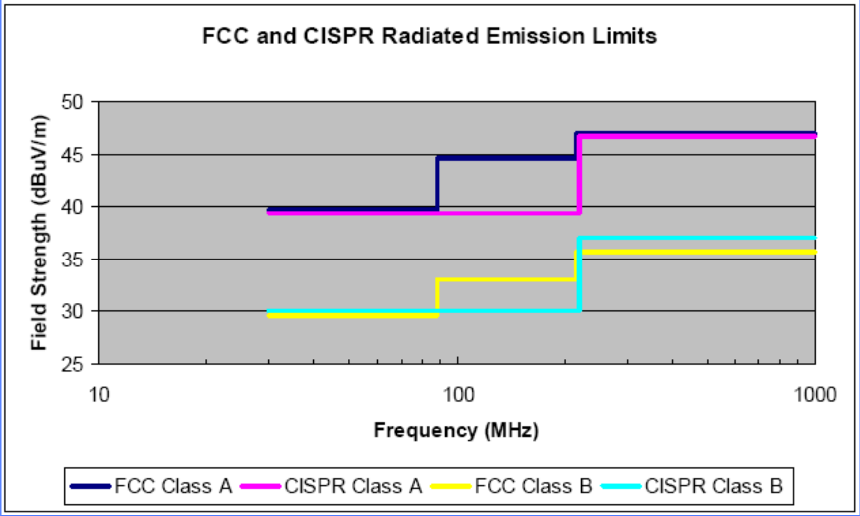


Freq (MHz)	Class A dBuV	Class B dBuV
0.45 - 1.6	60	48
1.6 - 30	69.5	48

Sources: SynQor app. note 00-08-02 Rev. 04
& www.cclab.com/engnotes/eng290.htm

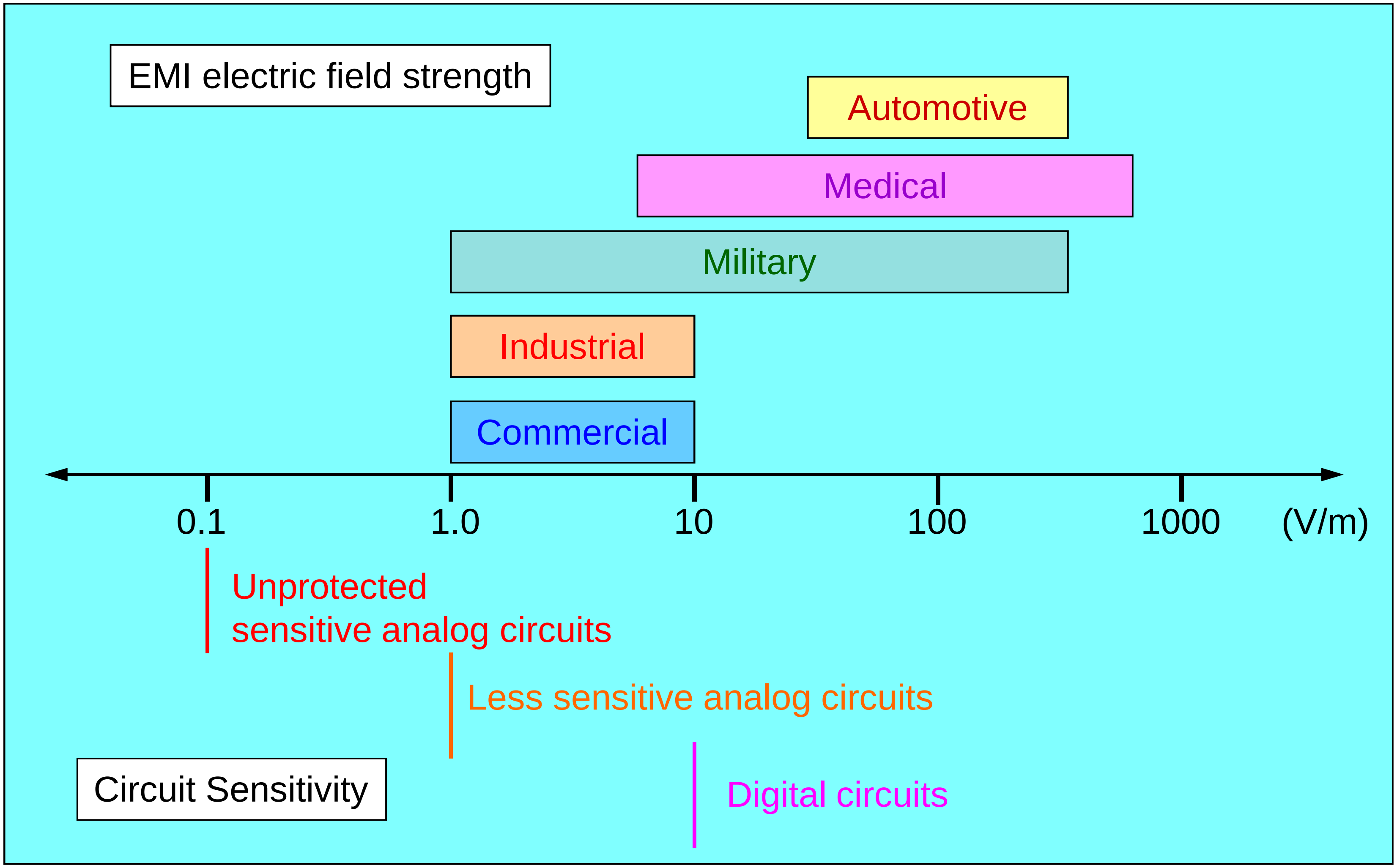
Radiated Emissions - 30MHz to 1GHz

measurement distance 10m

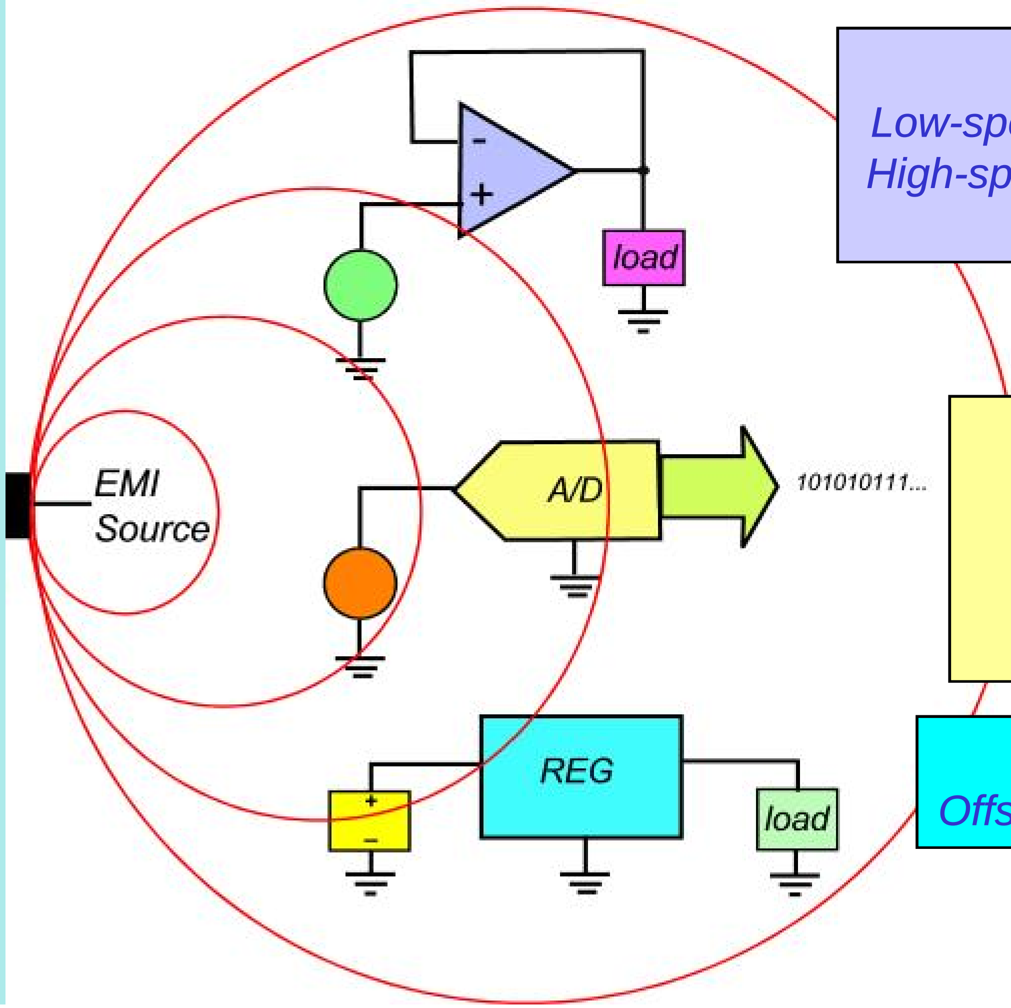


Freq (MHz)	Class A dBuV/m	Class B dBuV/m
30 - 80	39	29.5
88 - 216	43.5	33
216 - 960	46.4	35.6
960 - 1000	49.5	43.5

Typical RF field levels



Analog receptors of electromagnetic energy



Op-amps

Low-speed: offset shift, RF noise

High-speed: linear and non-linear amplification

Converters

EMI aliased into passband

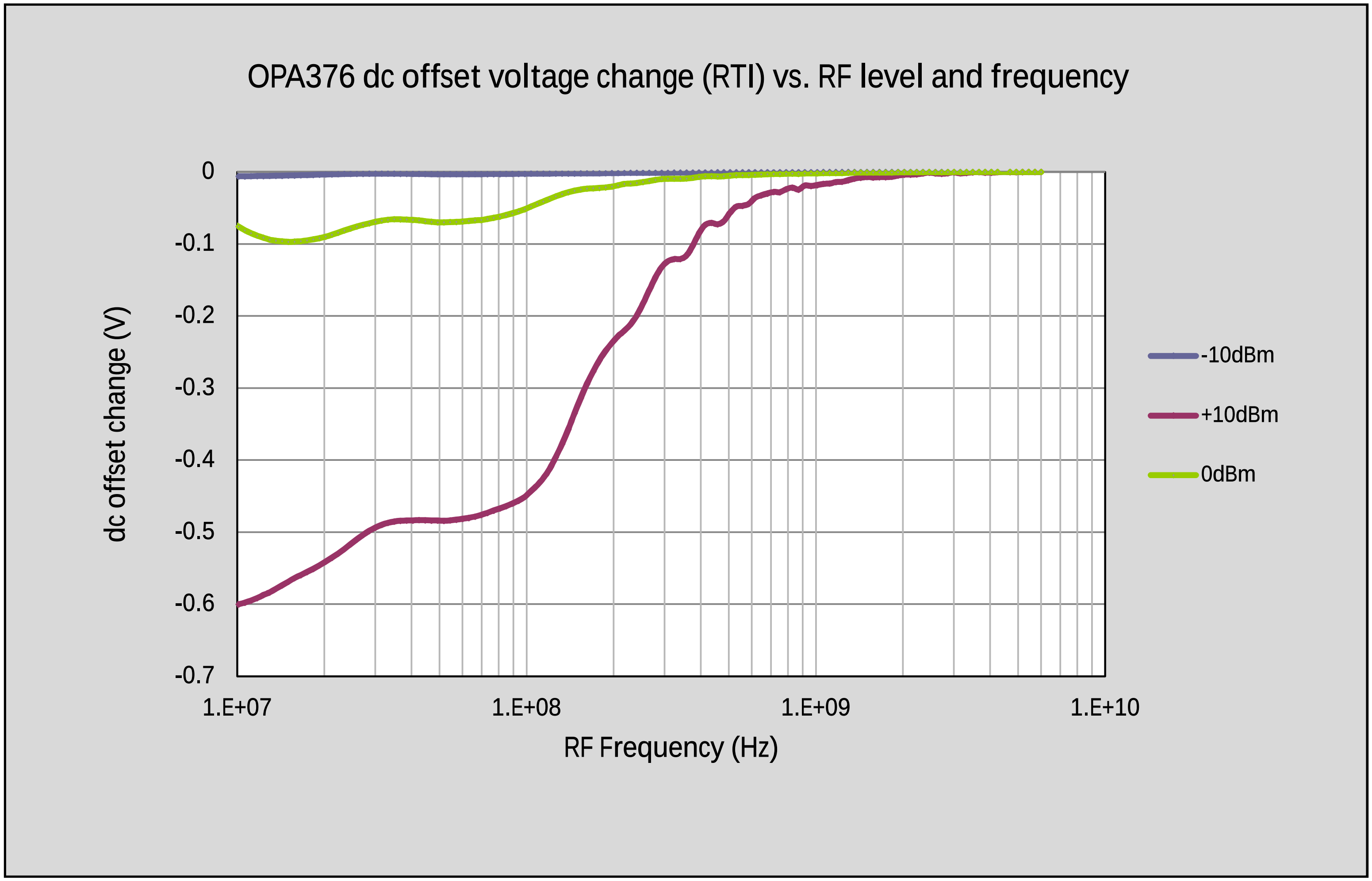
corrupted output levels or codes

offset shifts

Regulators

Offset - output voltage error

Operational amplifier voltage-offset shift resulting from conducted RF EMI



in a 50Ω system	**-10dBm = 100mV$_{pk}$**	**0dBm = 318mV$_{pk}$**	**+10dBm = 1.0V$_{pk}$**

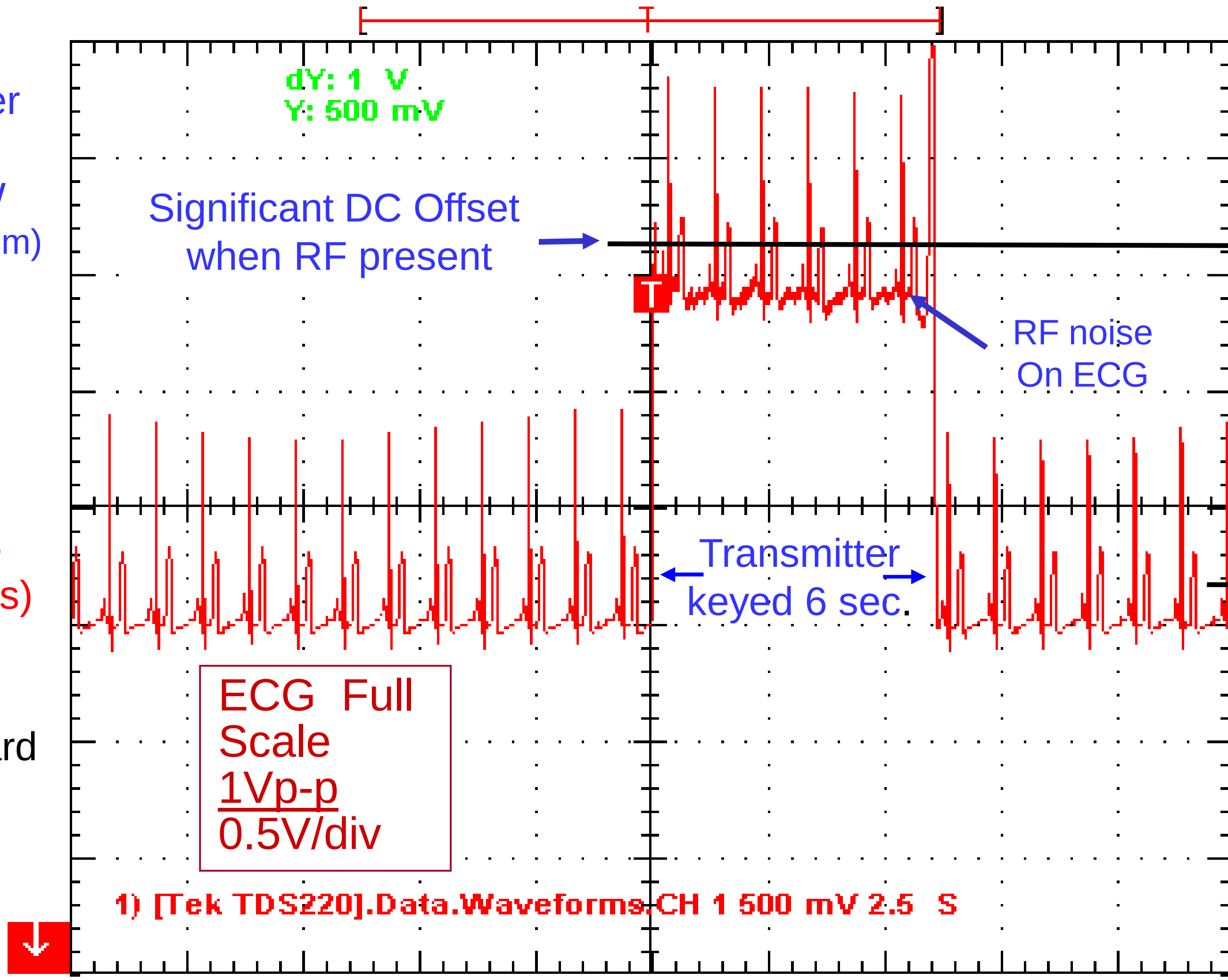
Radiated EMI and its affect on an ECG EVM

($V_{in} \approx 1mV_{p-p}$ G = 2500V/V)

Transmitter
470MHz
P_{out} 0.5W
d ≈1.5 ft (46cm)

Single
Supply
CMOS
INA326
OPA335(s)

Fly wire
Proto board



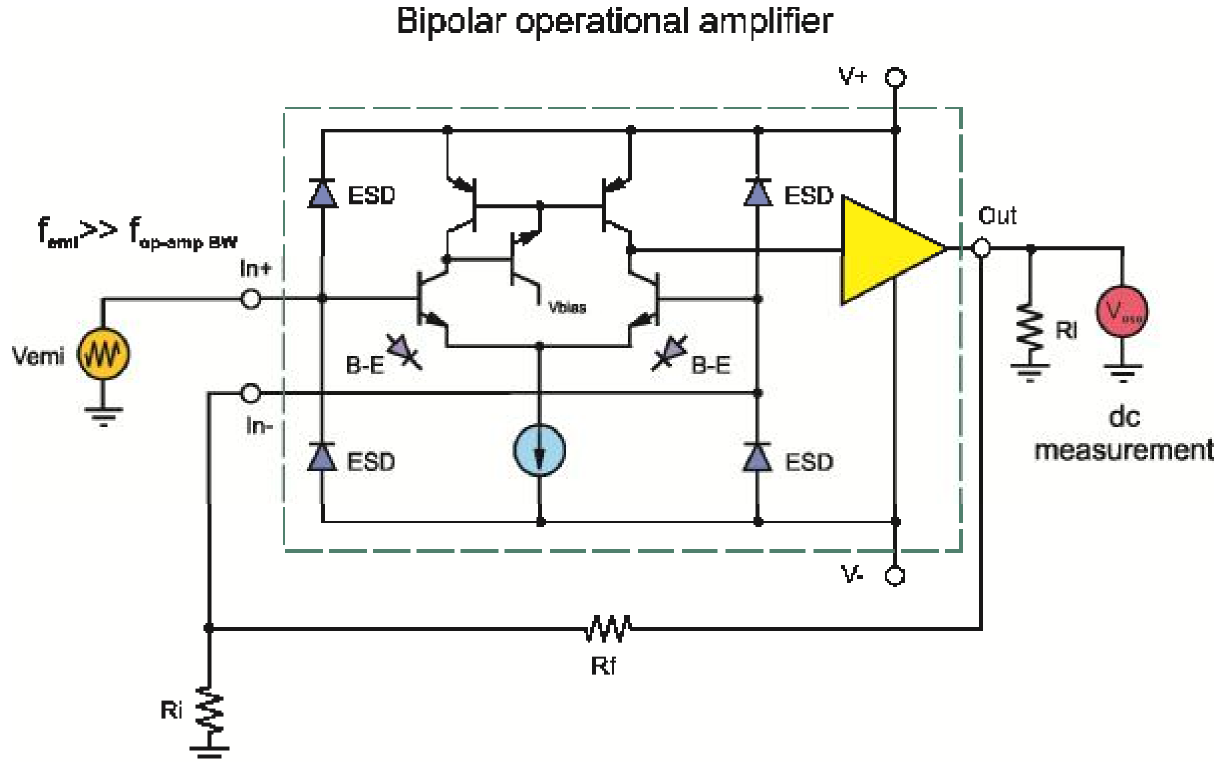
+4.0V offset RF present

D1.5V
Due to RFI

+2.5V offset normal

EMI slide
Information
by John Brown

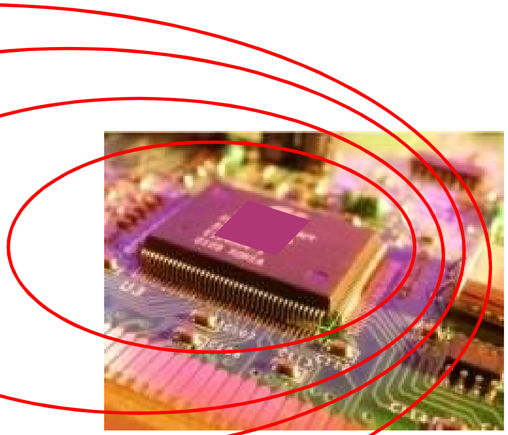
dc rectification by op-amp junctions can produce a voltage offset shift

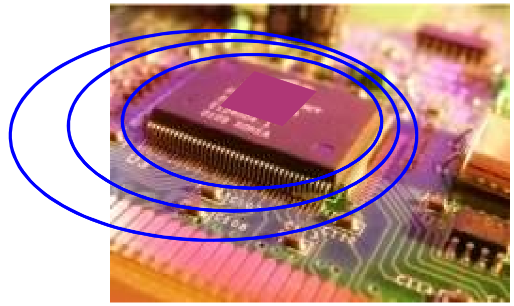


- Op amp ESD cell and transistor junctions can rectify RFI-EMI
- Resulting dc level is within the bandwidth of the amplifier
- The pulsating dc is filtered by the op-amp bandwidth
- Bandwidth of the op amp is too low to amplify RFI-EMI

Taming the EMI environment

- Minimize EMI radiation from the source
- Reduce the coupling medium's effectiveness
- Reduce receptor circuit's susceptibility to EMI



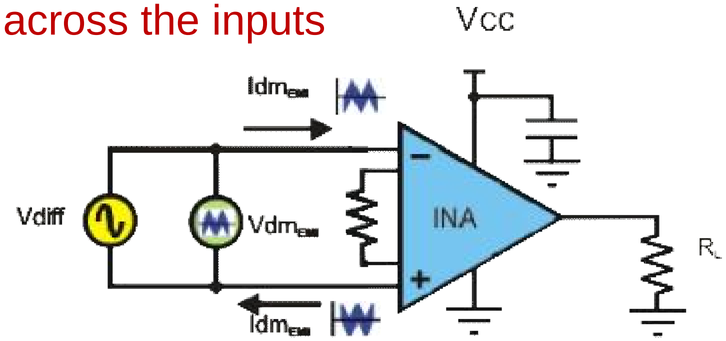


Normal (differential) and common-mode EMI

Normal mode EMI

- normal mode EMI propagates via unintentional loop antennas developed within circuits and wiring
- current level, EMI frequency and loop area determine the antenna's effectiveness
- The EMI induced current is proportional to the loop area

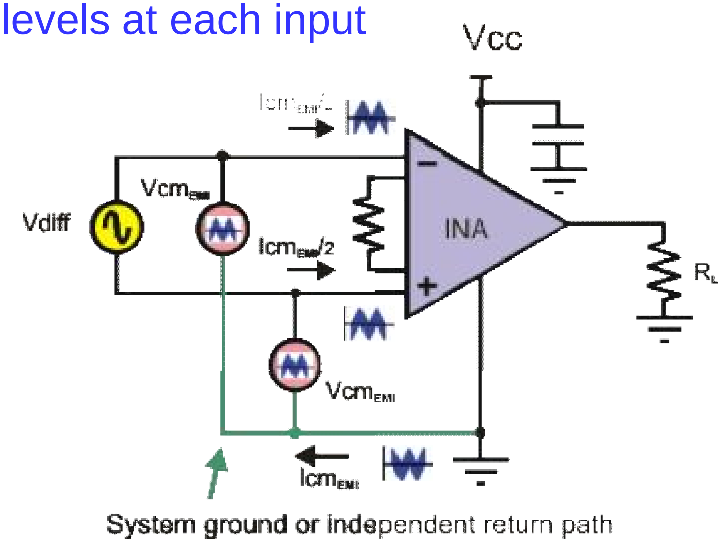
Normal mode EMI appears as a differential signal applied across the inputs



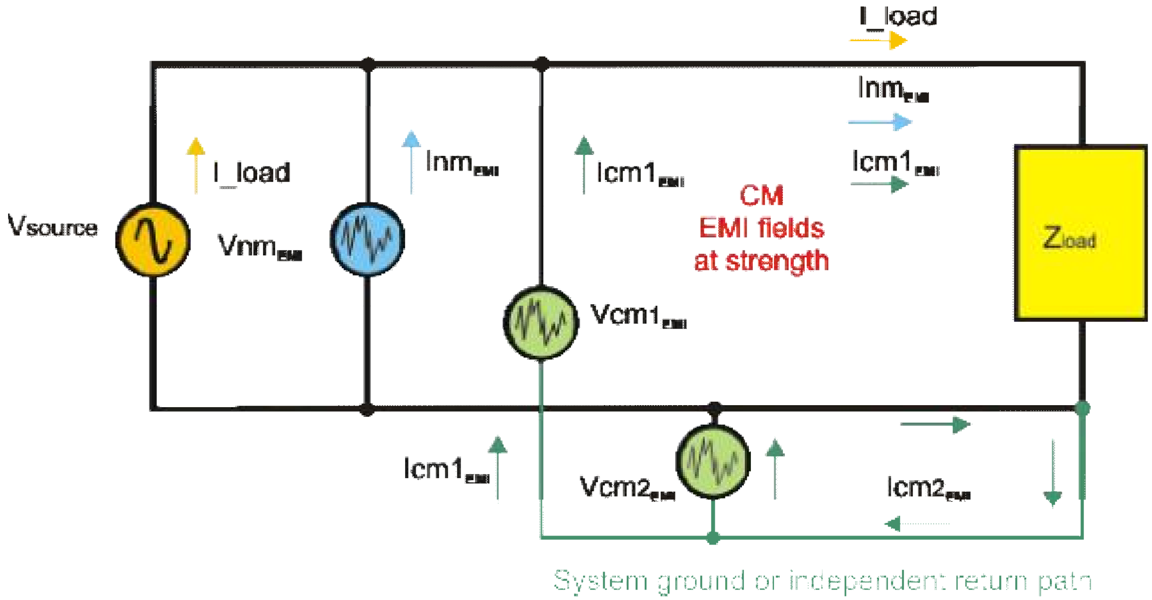
Common-mode EMI

- the majority originates from capacitively coupled (conducted) normal mode EMI
- the higher the frequency the greater the coupling between conductors
- may propagate directly via cabling acting as monopole antennas.
- power chords commonly can act as antennas
- electronic equipment is 10 to 100x more sensitive to common-mode EMI than normal mode EMI

Common-mode EMI produces equal signal levels at each input



Normal and common-mode current flow within a circuit

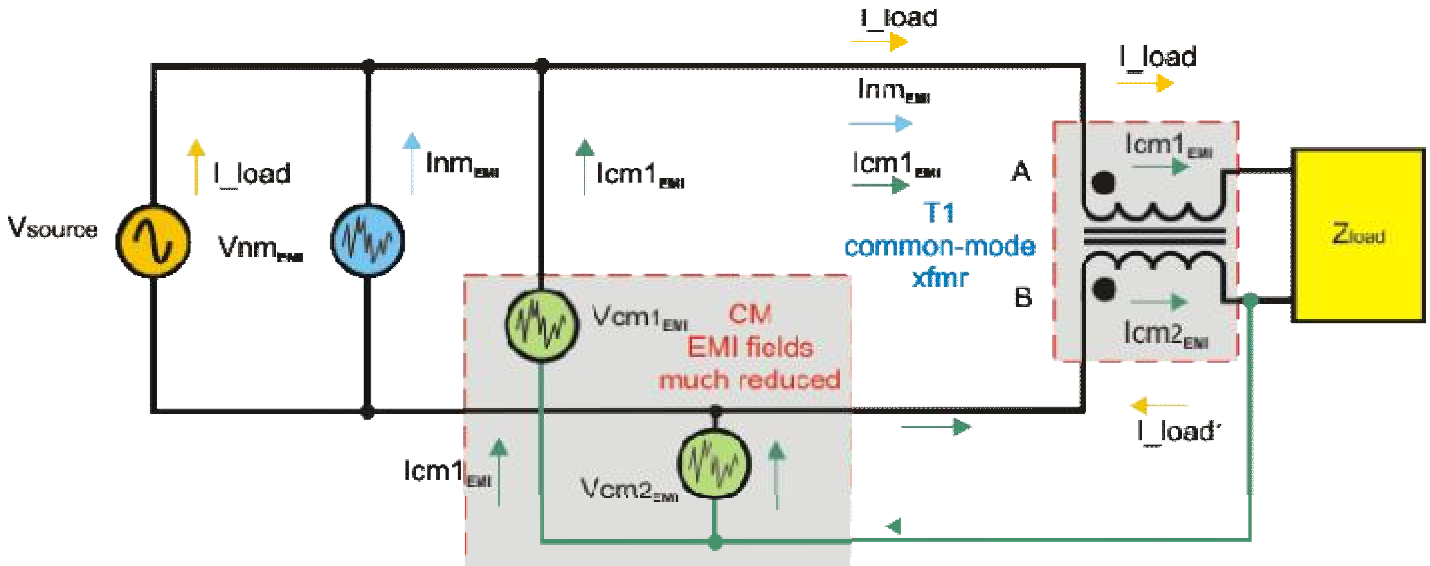


- The load, common-mode EMI current Icm1$_{emi}$ and normal mode EMI current Inm$_{emi}$ all flow through the Z**load**
- Icm2$_{emi}$ circulates through the source return line and the system ground, but not through the Z**load**
- The EMI fields develop at strength and reciprocity is applicable

Basis adopted from Butler Winding, "*Common Mode Choke Theory for Our Custom Built Coils"*

The common-mode transformer

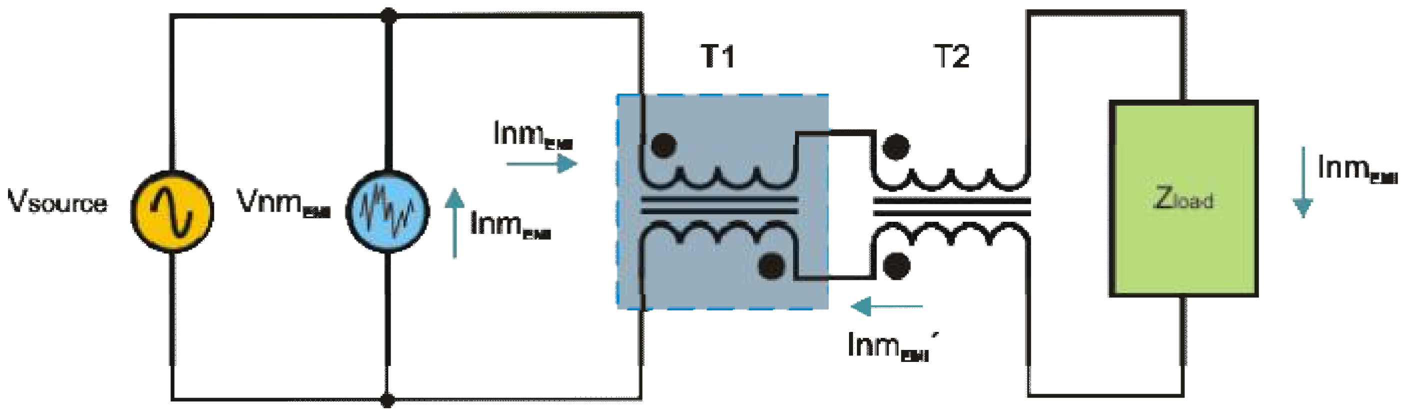
an effective common-mode EMI filter



- The common-mode transformer is a balanced structure having equal turns and winding sense
- The magnetomotive force created by I_load is equal and opposite to that created by I_load ′. Therefore, I_load flows through the transformer with no cancelation. This applies to Inm_{emi} as well.
- $Icm1_{emi}$ and $Icm2_{emi}$ flow through windings A and B in the same direction and encounter the same level of inductive reactance greatly reducing their amplitude.
- The reduction in Icm_{emi} currents results in a corresponding reduction the EMI fields

Normal mode and common-mode filtering

T1 - normal mode transformer
T2 - common-mode transformer



Inm$_{EMI}$ and Inm$_{EMI}$´ encounter the winding impedance

- The common-mode transformer functions as described previously
- Normal mode EMI cancelation in a specified frequency range may be needed
- The normal mode transformer windings are wound such that normal currents encounter inductive reactance restricting normal model current flow
- Some common-mode transformers are intentionally designed to have high flux leakage inductance. The leakage inductance acts in series with the load providing inductive reactance and normal mode EMI filtering

Common-mode transformer styles

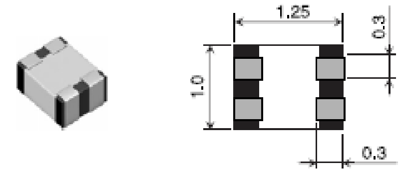
Power line application

BW Butler Winding
Custom Electronic Transformers & Inductors

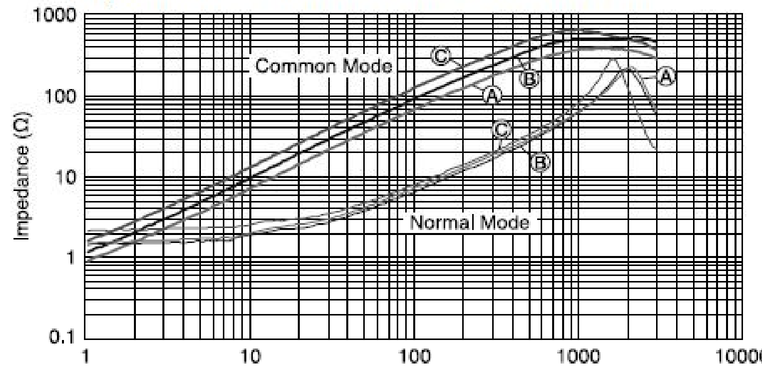
Common Mode Choke	
Typical Design:	Toroid
Core Types:	Toroid, Split Core
Core Materials:	Ferrite, Si steel tape wound core
AC Current:	Up to 20 Amps, rms
DC Current:	Up to 20 Amps
Voltage:	Up to 500 Vrms
Line Frequency:	Typically 50/60 Hz.
EMI Frequency Range:	Application specific
Inductance	Application specific
Leakage Inductance:	Application specific
Hipot	Up to 2,500 Vac, 1-sec
Mounting:	Thru Hole, SMT, Bracket

Signal path application

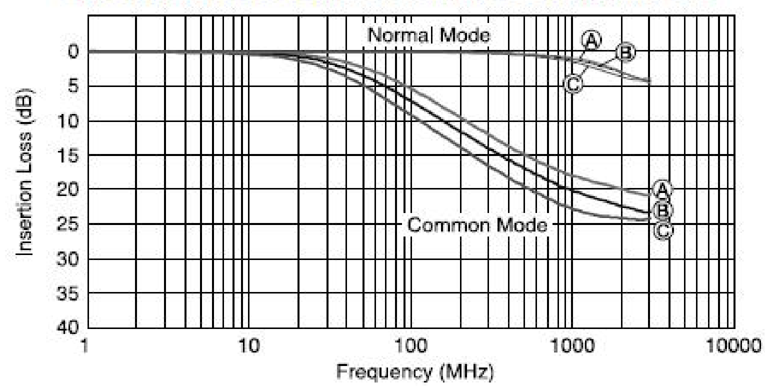
TOKO
NTM1210 TYPE



Impedance Characteristics of NTM1210

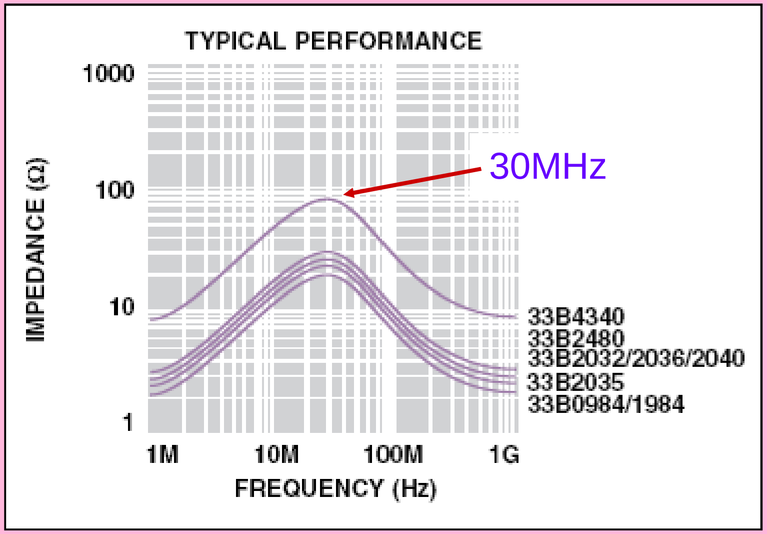


Insertion Loss Characteristics of NTM1210



Ferrites for EMI suppression

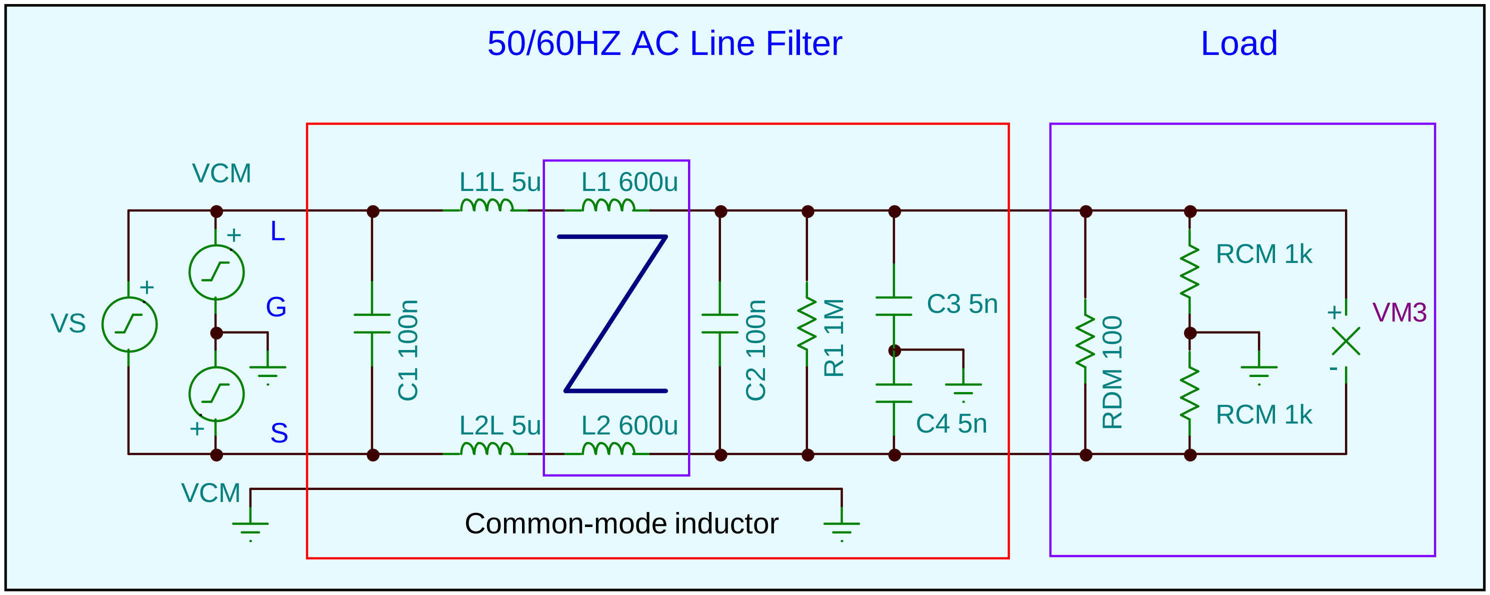
Ferrite surrounding the cable actually forms a common-mode transformer



Impedance of wire passing through FerriShield® ribbon cable ferrite

Filtering conducted RF-EMI

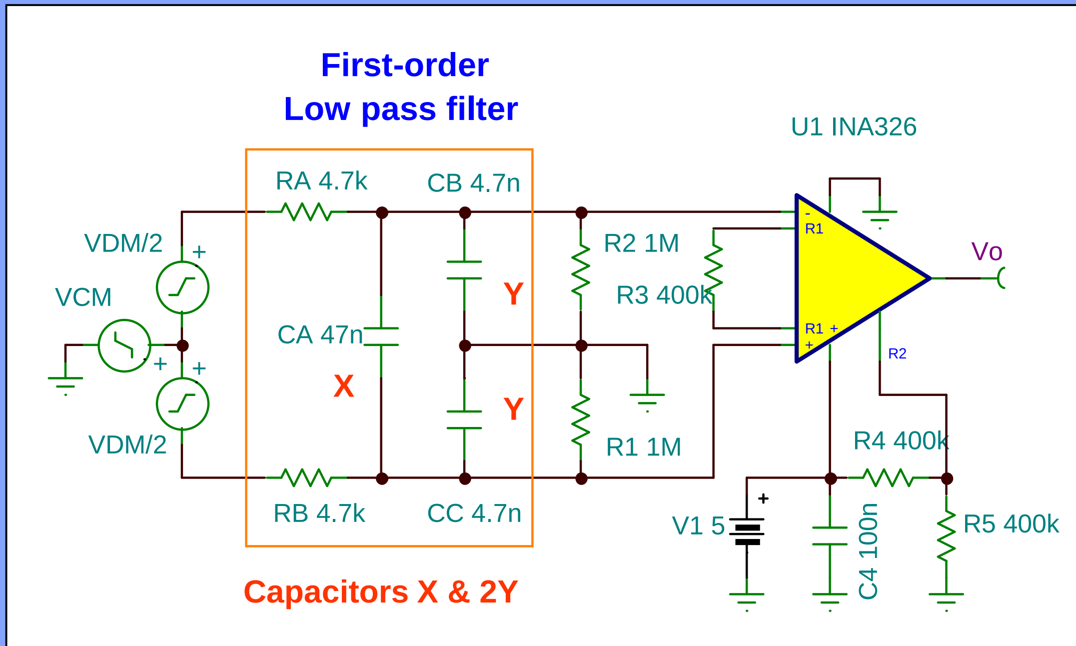
50/60Hz ac line filter example



Mode	150kHz	500kHz	1MHz	5MHz	10MHz	20MHz	30MHz	
Common	6	20	28	42	45	45	48	dB
Differential	10	13	30	50	50	40	40	dB

Attenuation characteristics for ac line filter (SAE GA1B-10)

Input RC filtering as applied to an instrumentation amplifier



Differential Mode

$$f_{-3dB} = [2\pi(R_A + R_B)(C_A + C_B/2)]^{-1}$$

let $R_B = R_A$ and $C_C = C_B$

$$f_{-3dB} = 343\text{Hz}$$

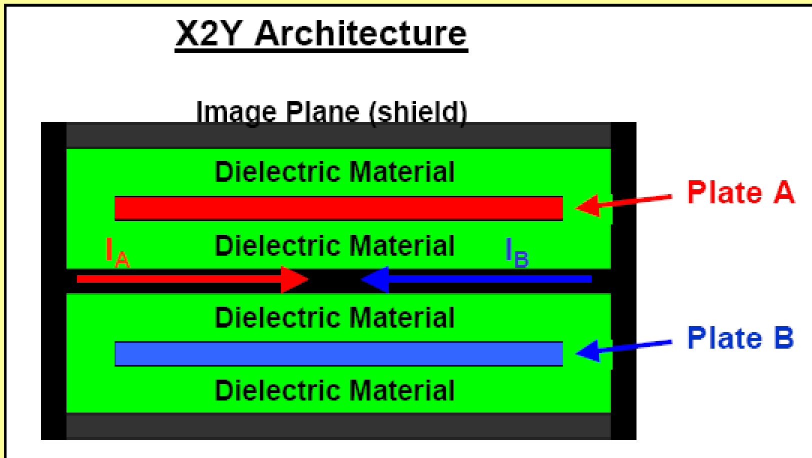
Common Mode

$$f_{-3dB} = [2\pi \cdot R_A \cdot C_B)]^{-1}$$

let $R_B = R_A$ and $C_C = C_B$

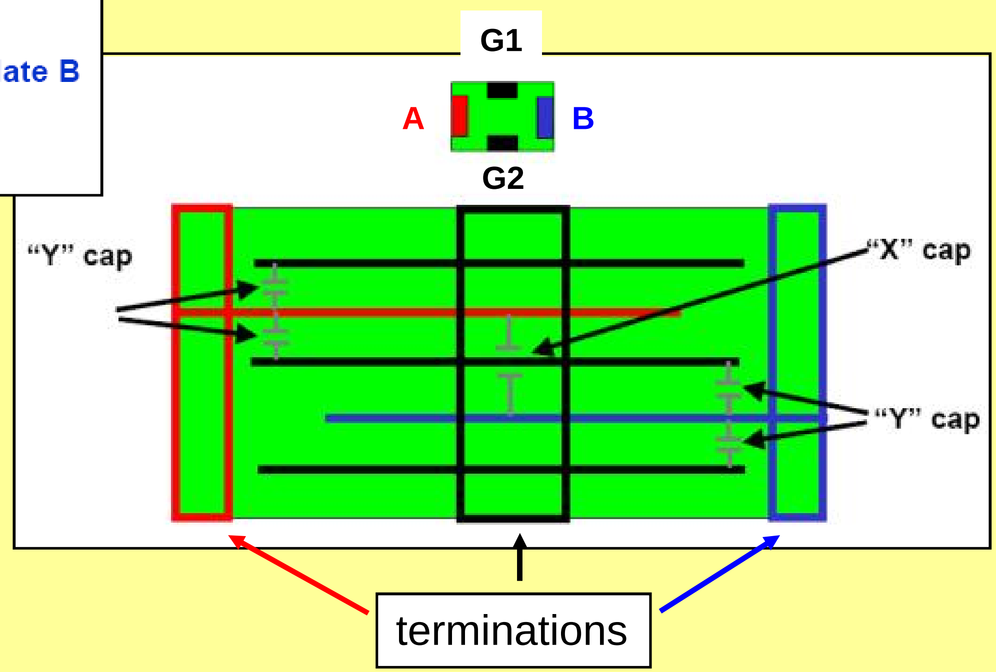
$$f_{-3dB} = 7.2\text{kHz}$$

X2Y® Capacitor Architecture



<u>The X2Y capacitor</u>

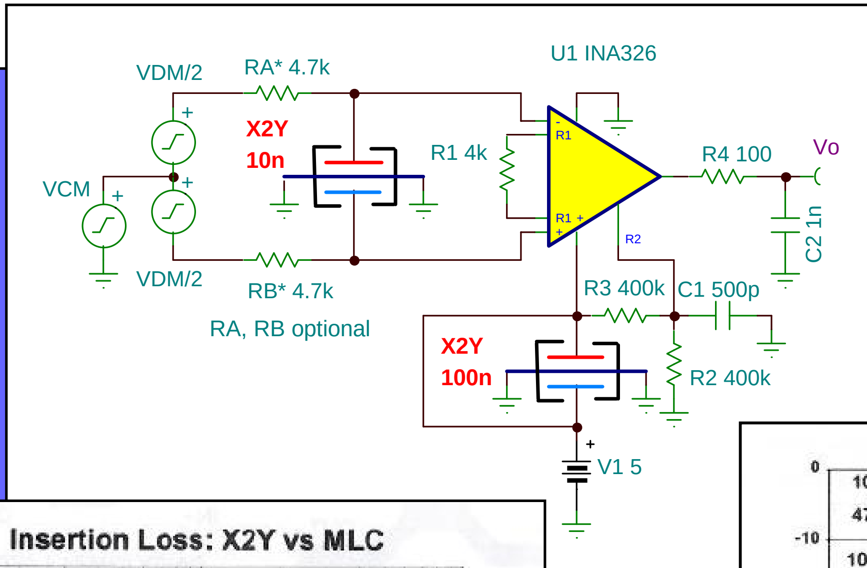
- 1 'X' capacitor, 2 'Y' capacitors
- Effective for both common-mode and differential-mode filtering
- Excellent capacitance matching



$C_x = ½ C_y$

From Yageo.com website

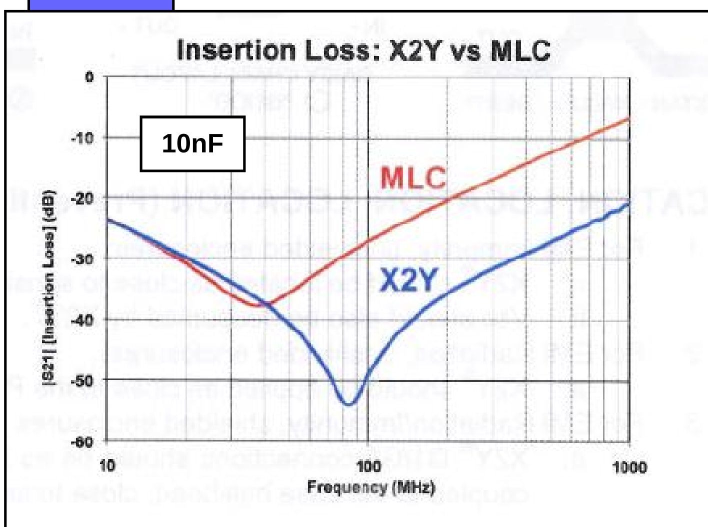
The X2Y® capacitor in application

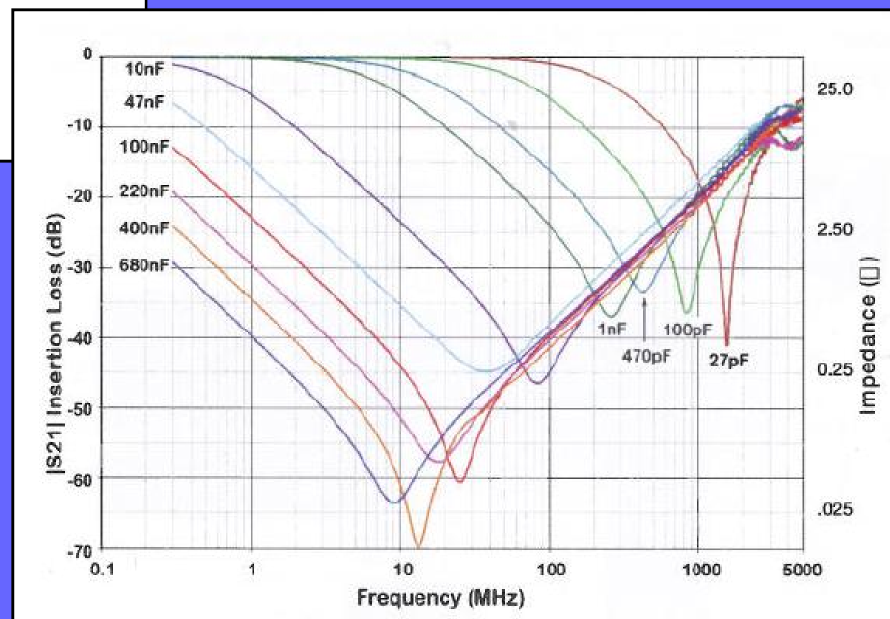


JOHANSON DIELECTRICS

X2Y® Filter & Decoupling Capacitors

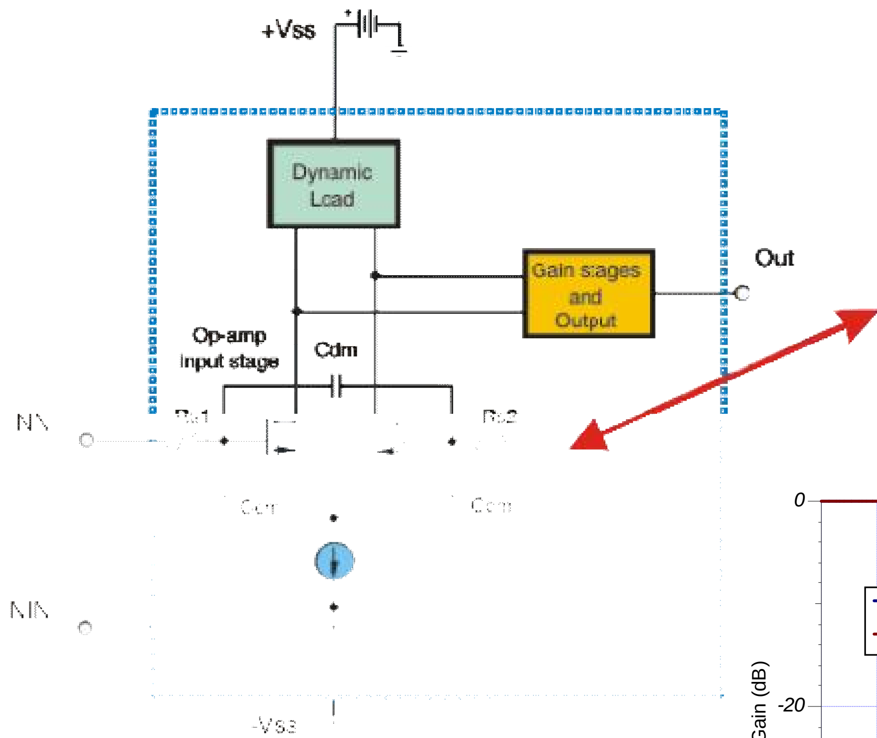
Input filtering s21
Signal-to-Ground



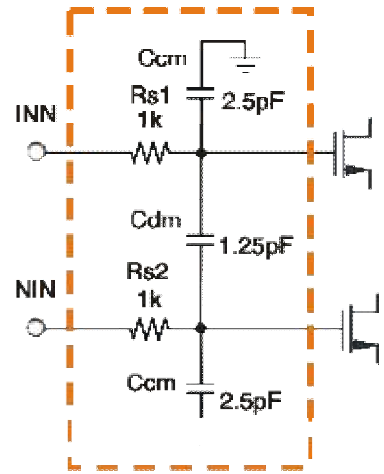


Newer op-amps have built-in EMI filtering

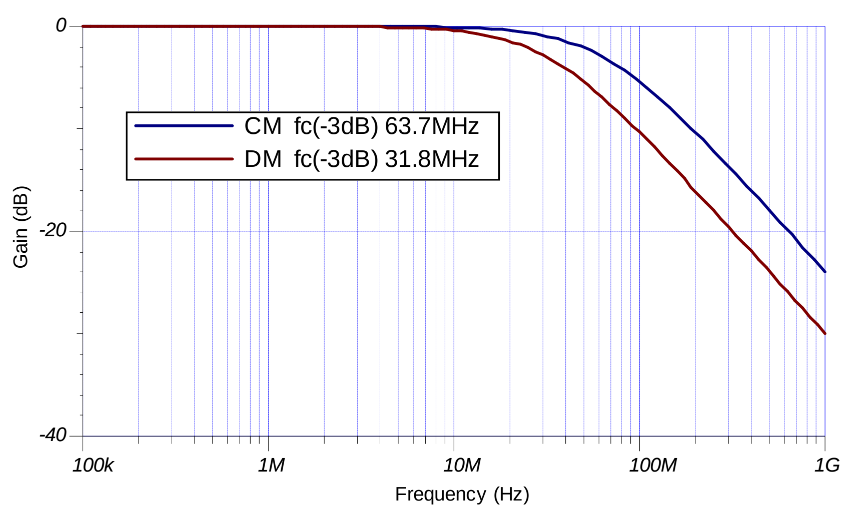
Simplified CMOS Op-amp



Built-in input EMI Filter

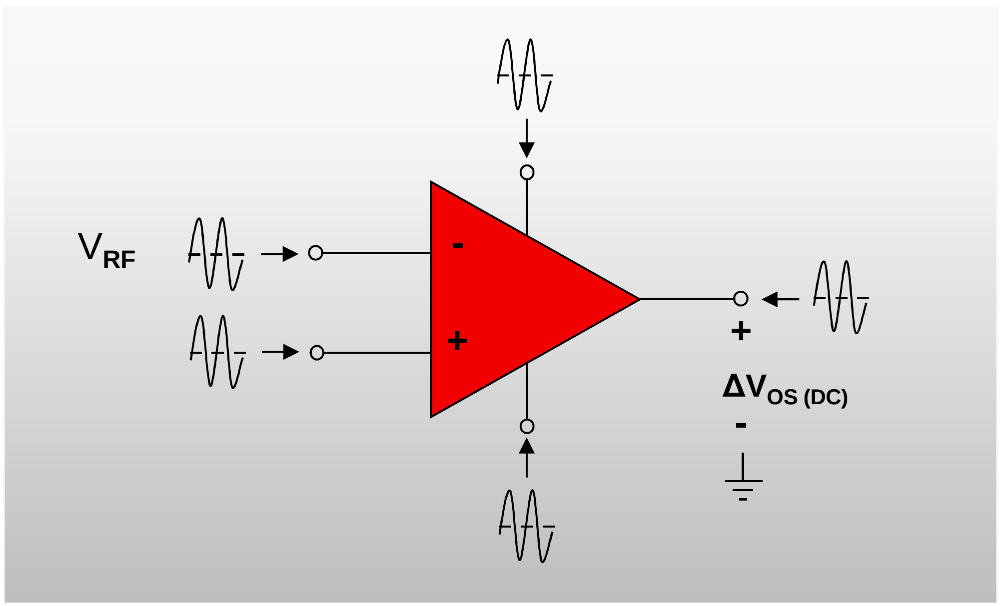


Filter response



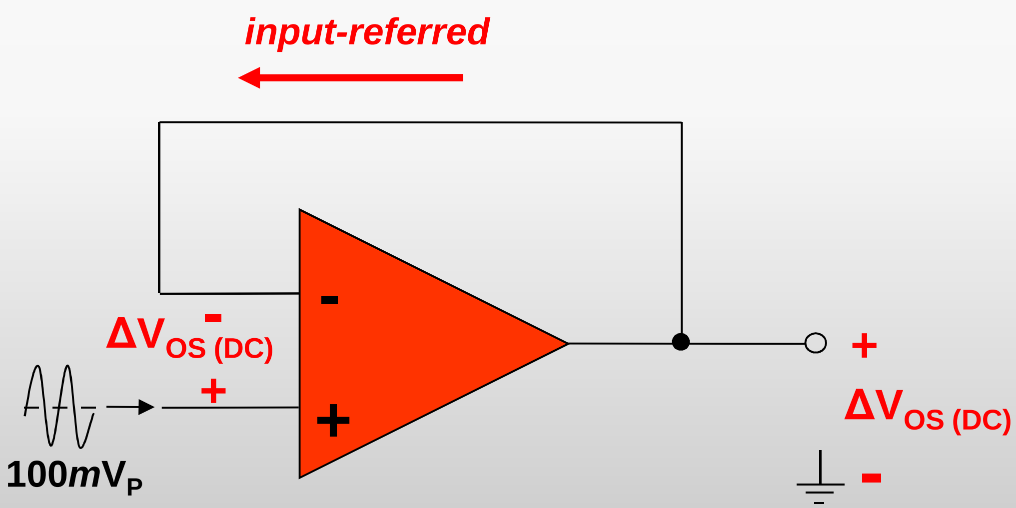
EMIRR- a measure quantifying an operational amplifier's ability to reject EMI

- EMIRR – Electromagnetic Interference Rejection Ratio
- Defined in National Semiconductor's application note AN-1698
- Measured as a dB voltage ratio of output offset voltage change in response to an injected RF voltage having a defined level
- Provides a definitive measure of EMI rejection across frequency allowing for a direct comparison of the EMI susceptibility of different operational amplifiers



EMIRR IN+

- EMI testing of operational amplifier pin functions has shown that the input pins are the most sensitive to EMI and produce the largest offset shift
- EMIRR IN+ is the EMI rejection ratio of the non-inverting input. The term EMIRR IN+ has become nearly synonymous with EMIRR
- The operational amplifier is connected as a unity-gain buffer during the test. An RF signal with a specified drive level is applied to the non-inverting input



Typical EMIRR IN+ Measurement Configuration

EMIRR IN+ equation

$$EMIRR\ IN+\ (dB) = 20 \cdot \log\left(\frac{V_{RF\_PEAK}}{|\Delta V_{OS}|}\right) + 20 \cdot \log\left(\frac{V_{RF\_PEAK}}{100mV_P}\right)$$

- V_{RF_PEAK} = peak amplitude of the applied RF signal @ op-amp input
- ΔV_{OS} = resulting "input-referred" DC offset voltage shift @ op-amp output
- 100*m*V_P = standard EMIRR input level (-10 dBm)

Higher EMIRR IN+ equates to lower amplifier EMI sensitivity

EMIRR IN+ equation solved for $|\Delta V_{OS}|$

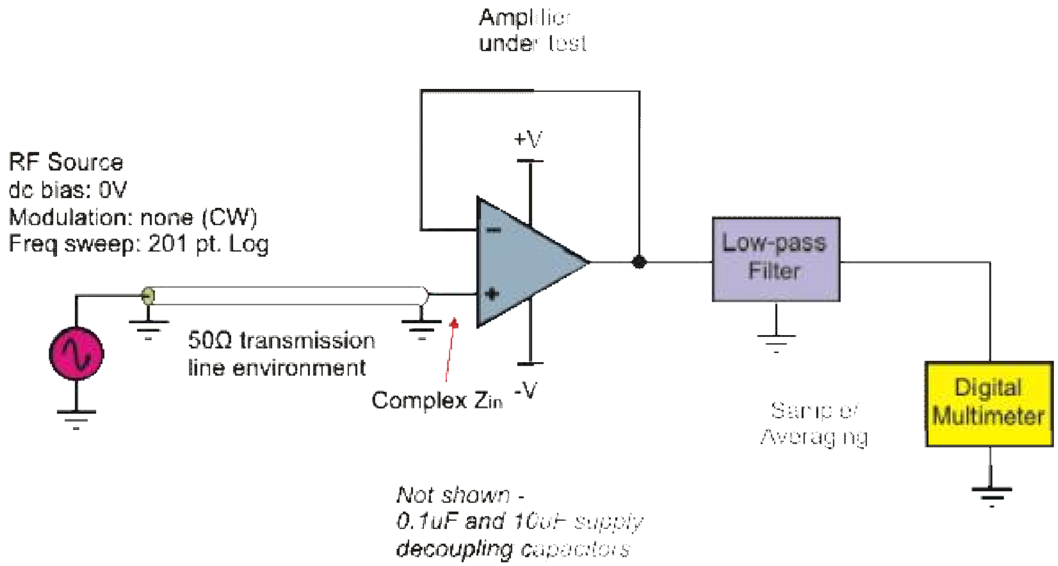
$$\left|\Delta V_{OS}\right| = \frac{1}{10^{\left(\frac{EMIRR\ IN+(dB)}{20}\right)}} \cdot \left(\frac{V_{RF\_PEAK}{}^{2}}{100mV_P}\right)$$

- Use this equation to solve for $|\Delta V_{OS}|$ of a unity gain amplifier if V_{RF_PEAK} and EMIRR IN+ are known such as when a plot is provided
- EMIRR IN+ is frequency dependant
- **Doubling V_{RF_PEAK} Quadruples $|\Delta V_{OS}|$!**
- For example: $100mV_P$ RF signal at 1.8GHz produces an EMIRR IN+ of 60 dB. The associated voltage offset shift would be 100uV

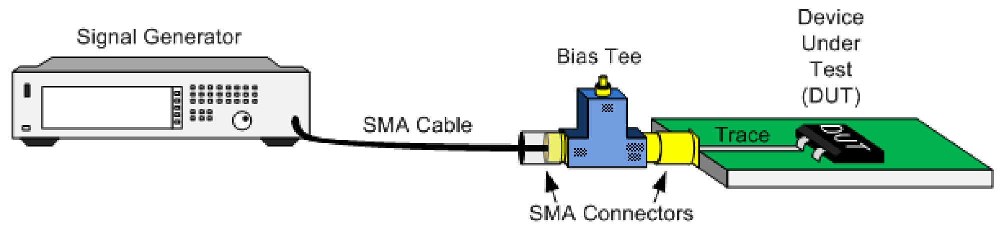
The EMIRR IN+ test set-up

See TI Application Report SBOA128 for details

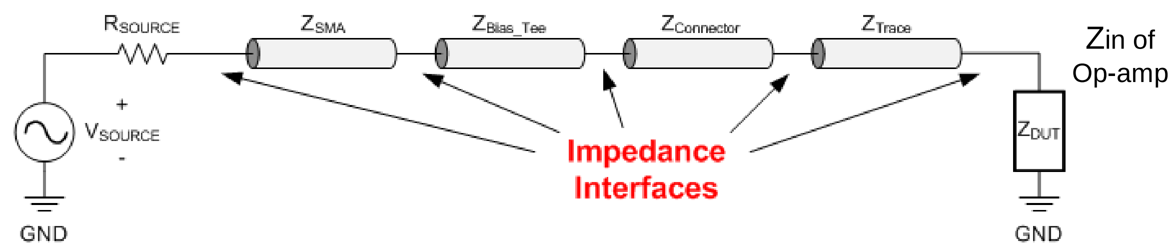
Simple schematic for EMIRR IN+ test



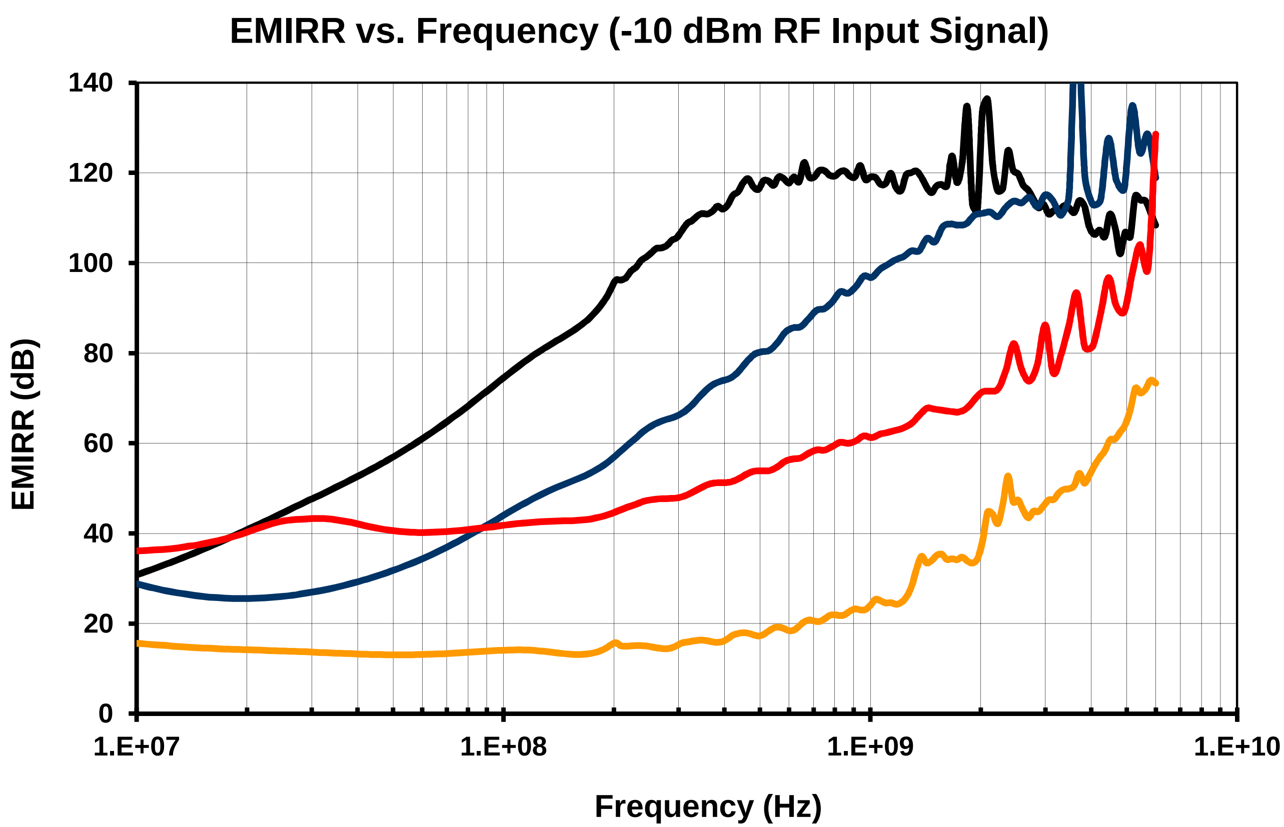
Practical implementation



The complex RF input environment



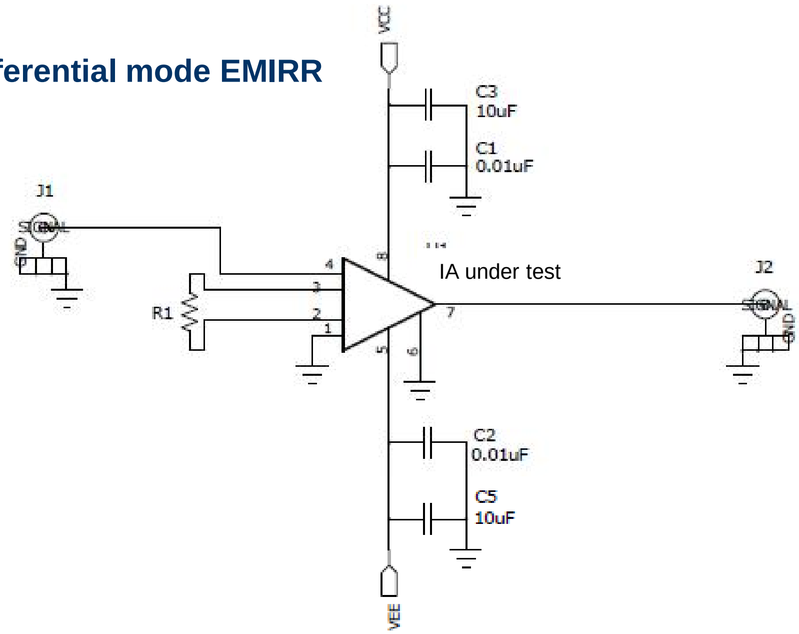
EMIRR IN+ measurement results for
TI CMOS rail-to-rail operational amplifiers



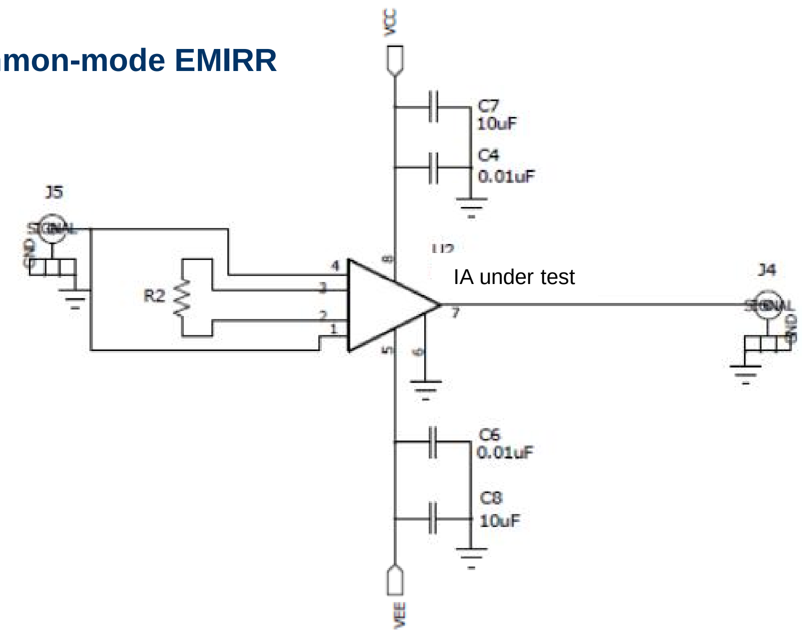
Model	GBW	Filter	Model	GBW	Filter
OPA333/2333	350kHz	Yes	OPA376/377	5.5MHz	Yes
OPA378	500kHz	Yes	OPA348/2348	1MHz	No

EMIRR testing applied to instrumentation amplifiers

Differential mode EMIRR



Common-mode EMIRR



Test Configuration

Bipolar supplies (+/-V), reference pin grounded, RF level -10dBm

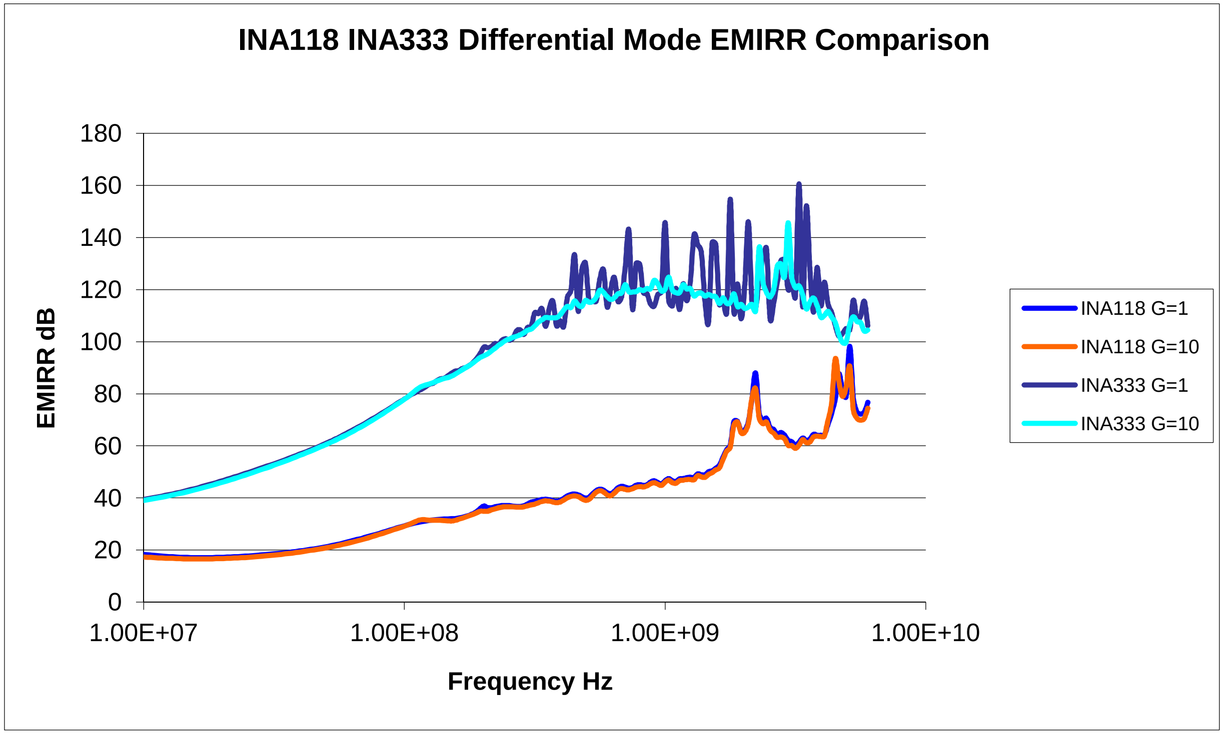
Differential measurement

- RF signal applied to non-inverting input
- Inverting input grounded

Common-mode Measurement

- RF signal applied to both inputs

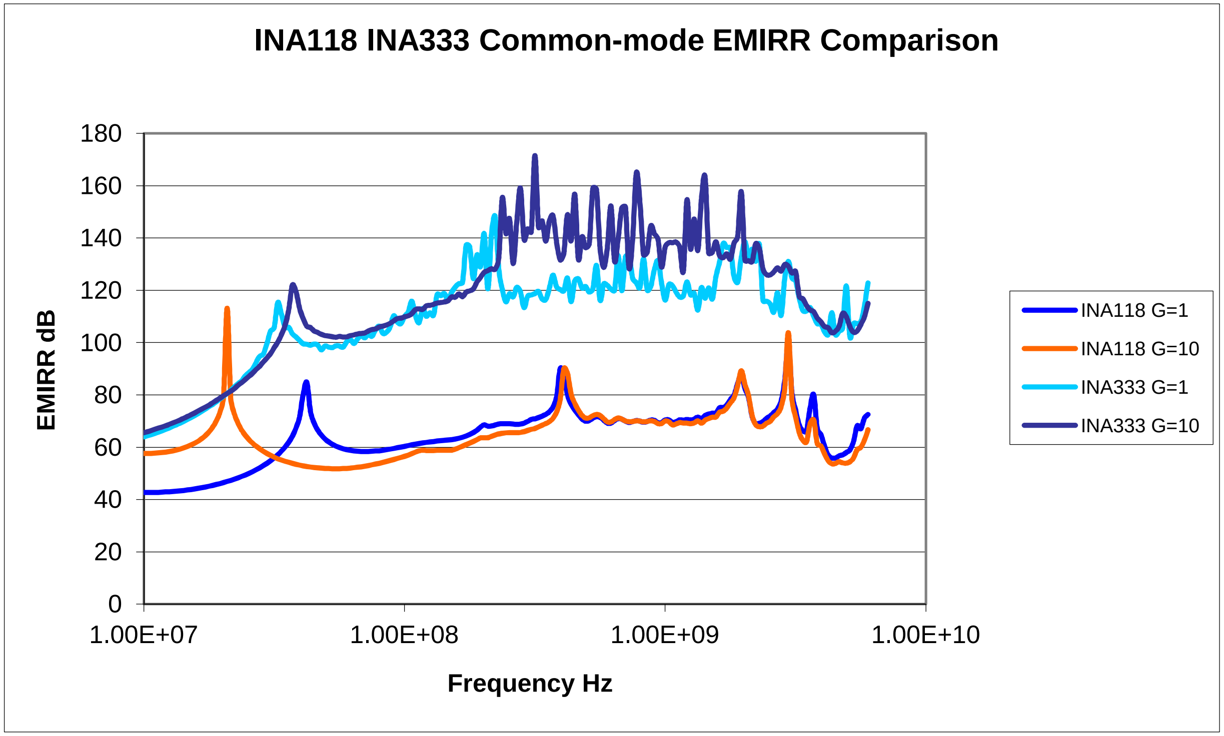
EMIRR testing applied to instrumentation amplifiers INA118 – INA333 differential mode comparison



INA118
- **3 op-amp current feedback design**
- **Av range 1 to 10kV/V**
- **70kHz BW, G = 10V/V**
- **Iq 350uA**
- **circa 1994**
- **no internal EMI filter**

INA333
- **3 op-amp CMOS auto-zero design**
- **Av range 1 to 1kV/V**
- **35kHz BW, G = 10V/V**
- **Iq 50uA**
- **2008 introduction**
- **internal EMI filter**

EMIRR testing applied to instrumentation amplifiers INA118 – INA333 common-mode comparison



INA118
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- 1994 introduction
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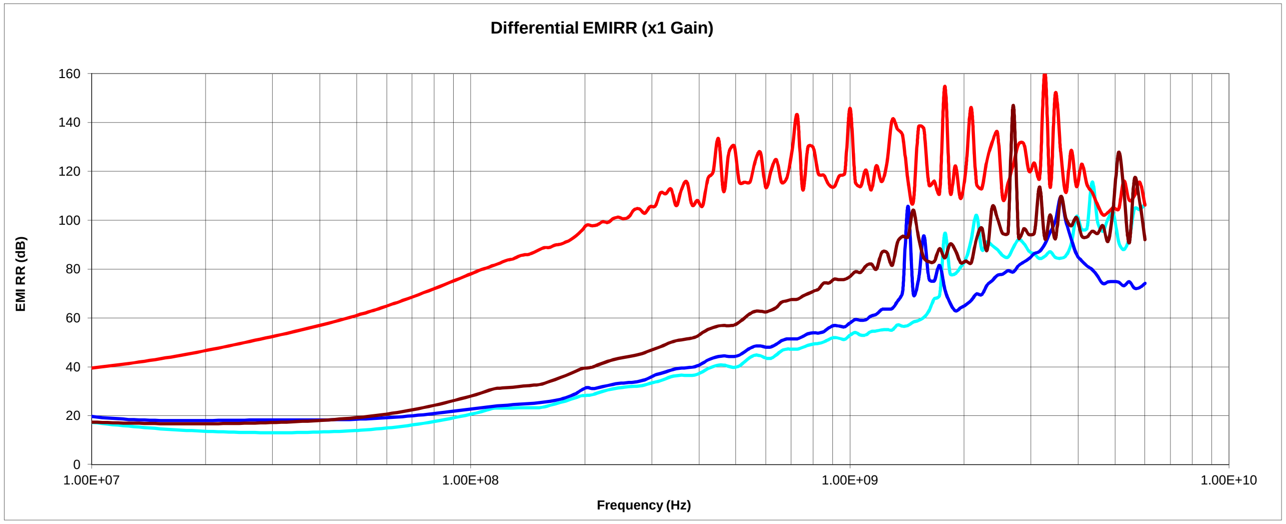
INA333
- 3 op-amp CMOS auto-zero design
- Av range 1 to 1kV/V
- 35kHz BW, G = 10V/V
- Iq 50uA
- 2008 introduction
- internal EMI filter

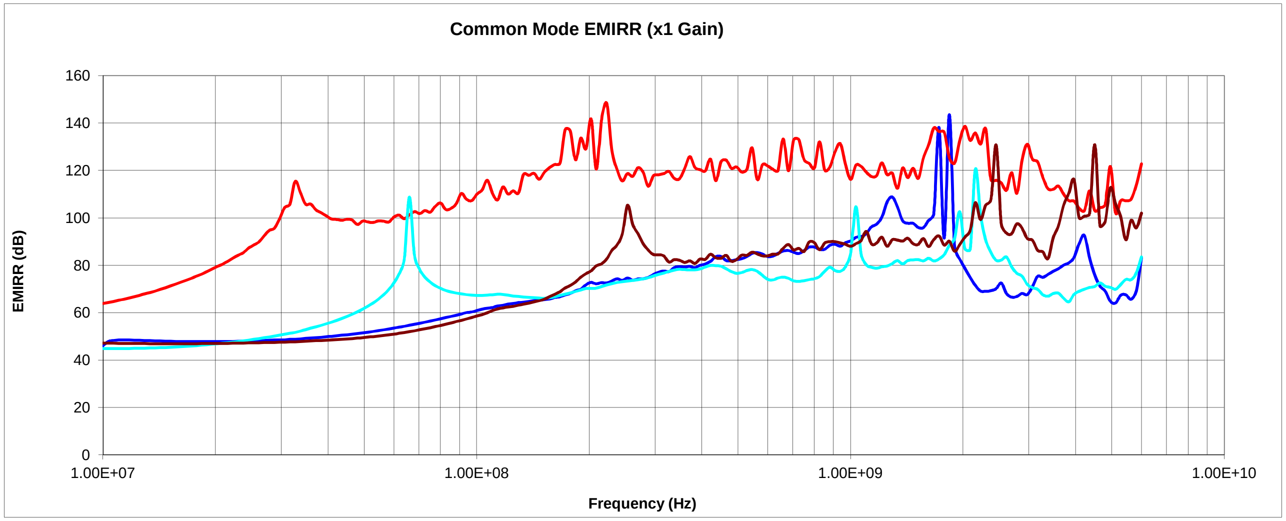
Instrumentation amplifier EMIRR performance comparison

TI - INA333
competitor A
competitor B
competitor C

Differential mode EMIRR

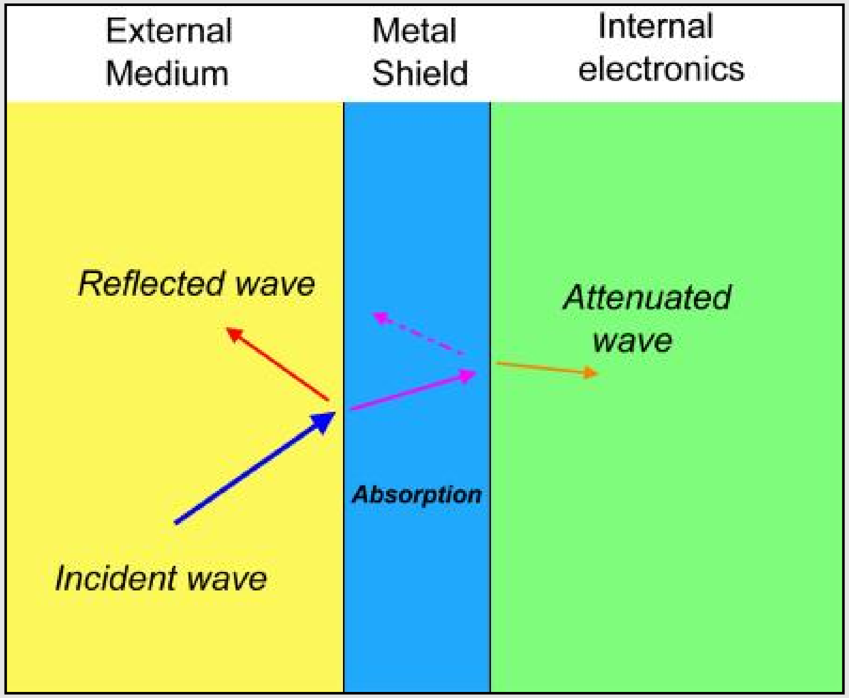


Common-mode EMIRR



Shielding and screening

Minimizing the medium's effectiveness



Derived from: *EDN – The Designer's Guide to Electromagnetic Compatibility*

Shielding Effectiveness *(S.E.)* of enclosed material

<u>Emission Suppression</u>

$S.E_{dB\ (Em.\ Supp.)} \approx A_{dB}$

<u>Susceptibility</u>

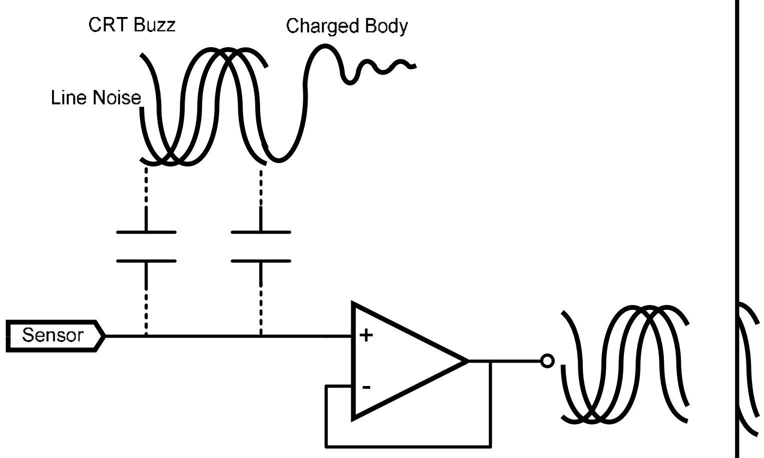
$S.E_{dB\ (Sus.)} \approx A_{dB} + R_{dB\ (appropriate)}$

where: A: absorption loss in dB
R: reflection loss in dB

From: COTS Journal, *January 2004 – "Design Considerations In Building Shielded Enclosures."*

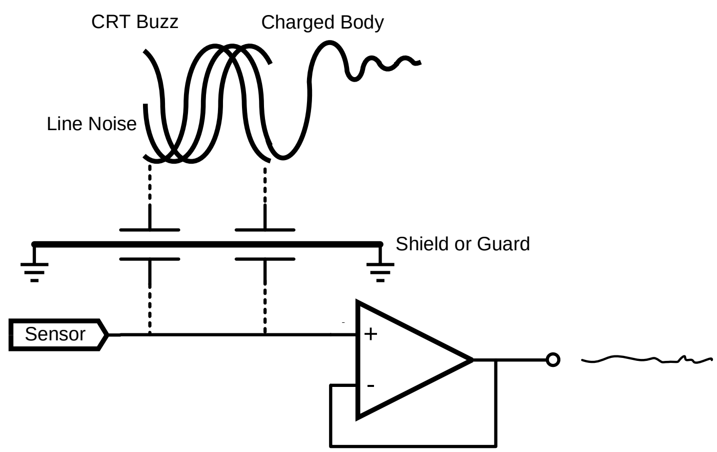
Noisy Neighbors - Electrostatic Noise

Without Shield



- Noise is capacitively coupled into high impedance node
- $I = C * (\Delta V / \Delta T)$
- Changing capacitance (distance) or voltage creates a current
- Circuit can "see" you moving
- Vibrations create ΔC

With Shield



- Inserting a "plate" between the two plates breaks the field path.
- Plate does not have to be ferrous, just conductive (aluminum).

Texas Instruments

Shielding and screening

Minimizing medium's effectiveness

Metal Shielding

Magnetic field   f < 20kHz

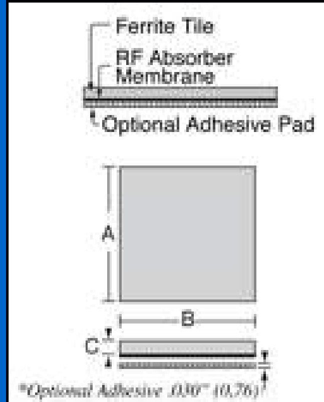
Ferrous metals
- steel
- Mu-metal – nickel, iron

RF fields   10kHz < f < 1GHz

Non-ferrous metals
- Al foil I_{Loss} > 90dB
- Cu, Ni I_{Loss} 40-60dB
- Vacuum plating
  I_{Loss} > 80dB
- Electroless deposition
  I_{Loss} > 80dB

From: EDN EMI/EMC guide

Ferrite shield



RF absorber shield

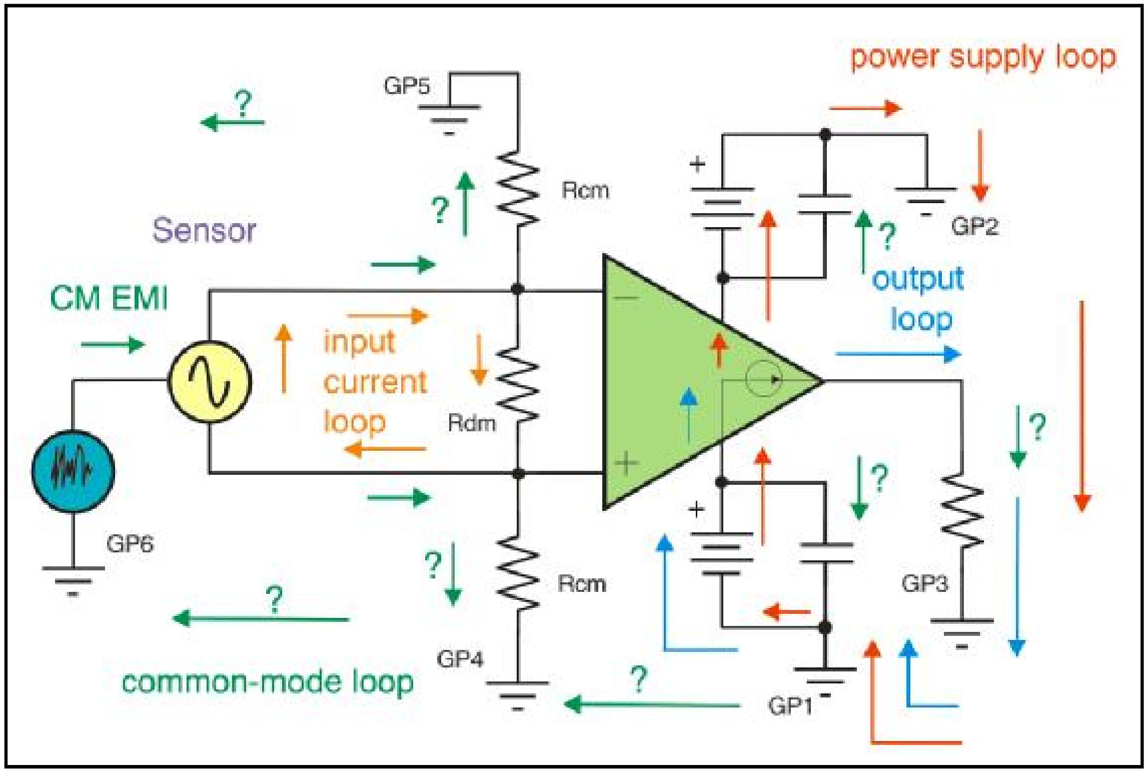
FerriShield, INC.
Interference Control Components

A loop – the path current follows

Loops

- dc, ac and EMI signal may share loop paths
- EMI-RFI will take the path of least impedance
- The current loop may act as a loop antenna coupling EMI/RFI in, or out, of the circuit

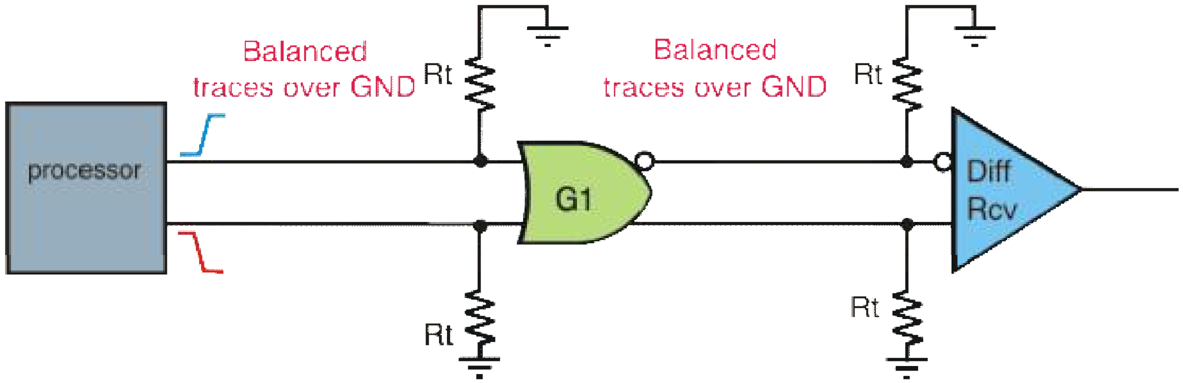
The common-mode return loop may be difficult to predict



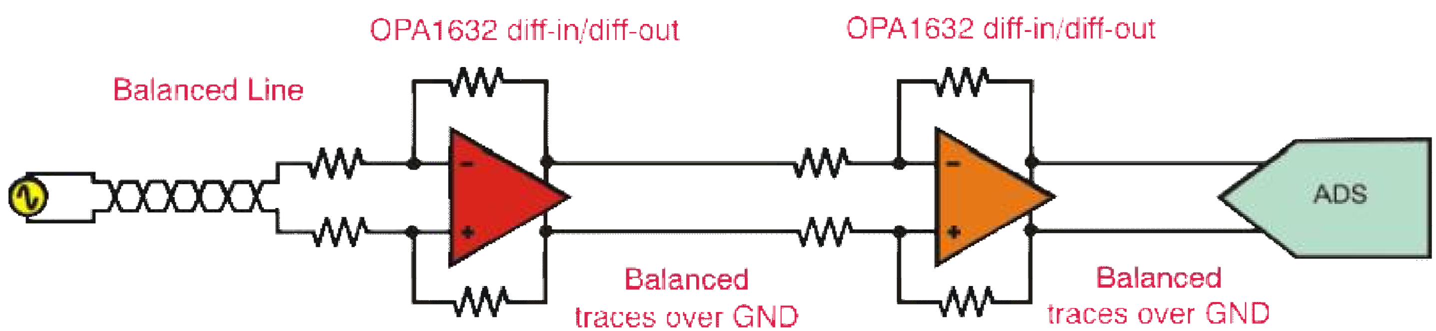
Balanced analog and digital circuitry

reduces common-mode response

Balanced digital logic: LVDS, PECL, HSTL

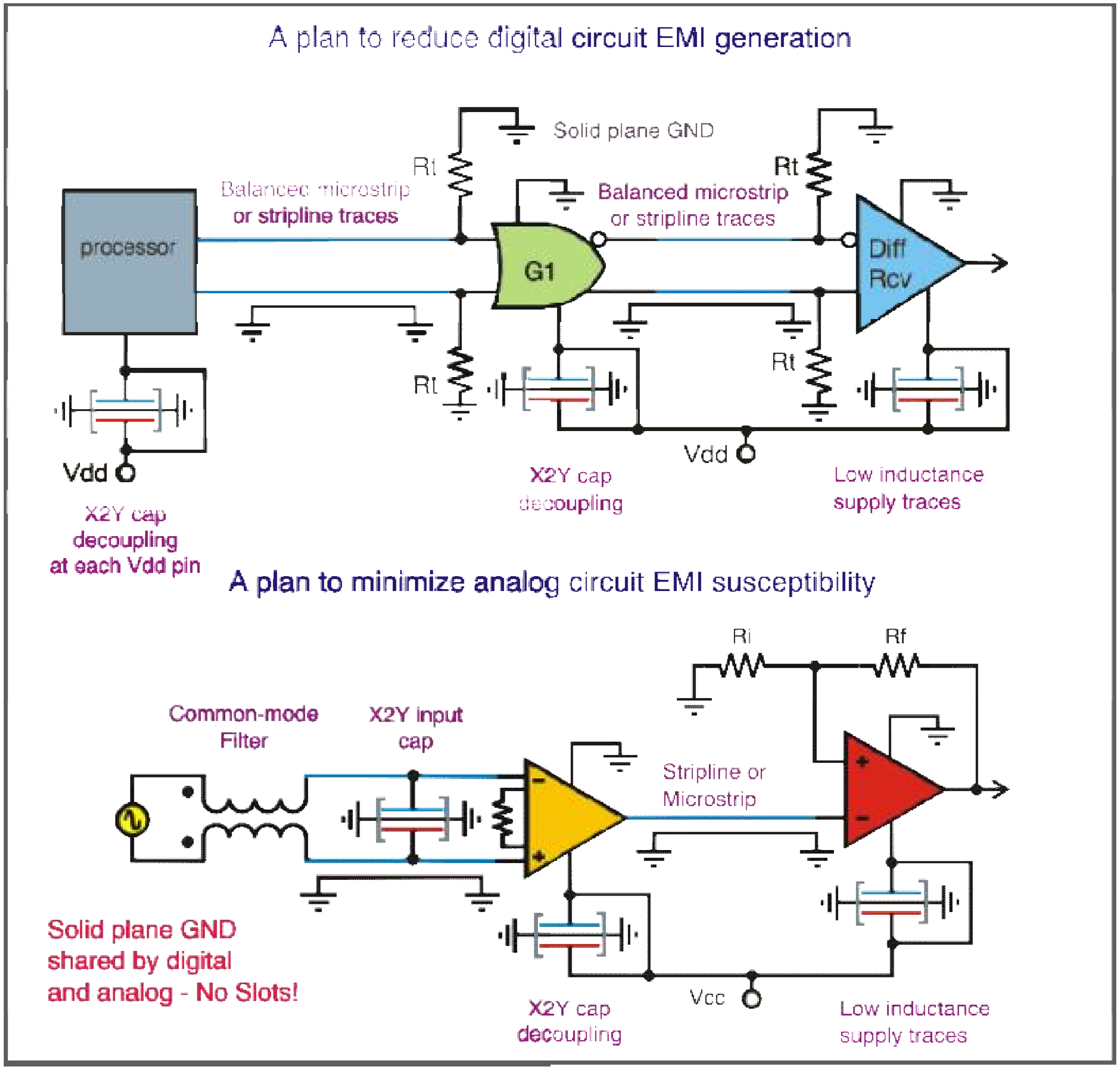


Balanced differential analog circuitry



Circuit plans to help minimize EMI

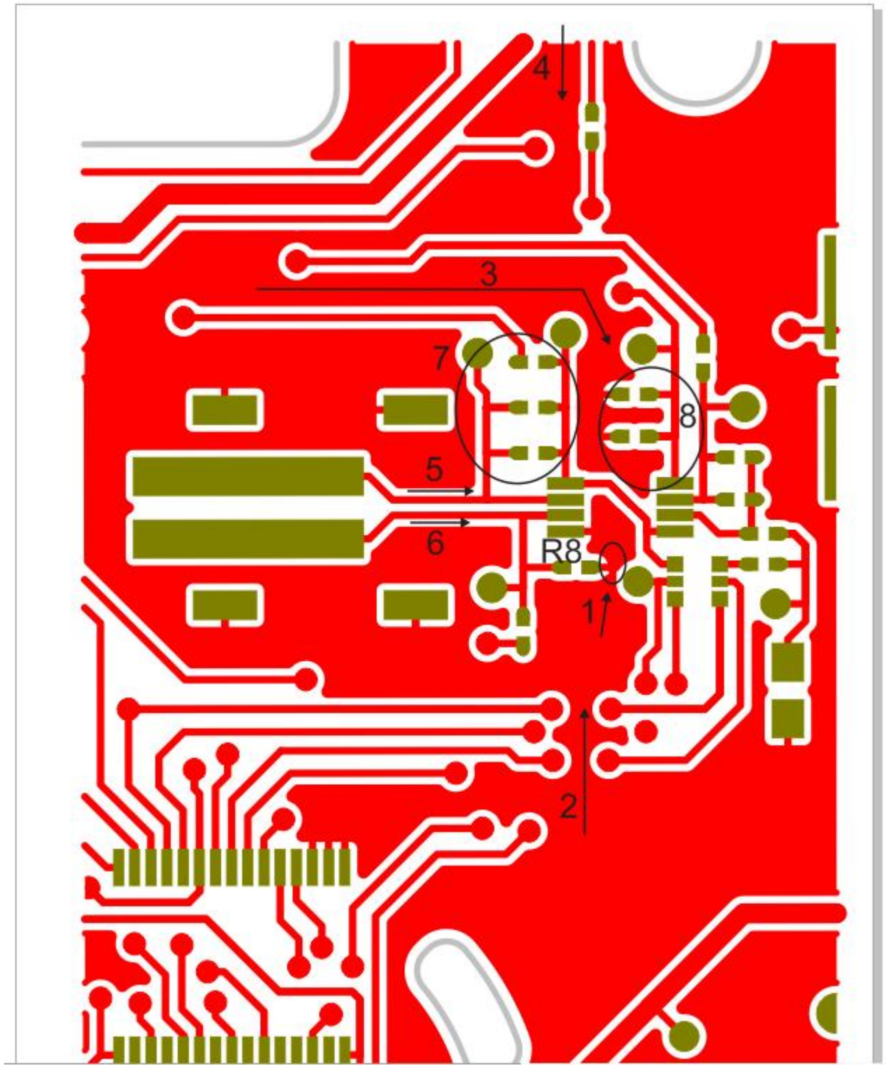
- Strive for a zero impedance ground
- Design for a differential signal environment, both logic and analog
- Minimize PCB loops that act as EMI antennas
- Use X2Y capacitors for filtering and decoupling
- Make use of common-mode transformers
- Use balanced lines and traces



PC board tips to help reduce EMI's affect in circuits

- Minimize path inductance, especially ground which may be the return for many signals.
- Use a continuous ground plane. Avoid slots in the plane. They increase path length increasing the inductance.
- Place potential EMI sources on one end of board, potential receptors on the other end.
- Extend balanced line concepts to the board; especially, in the low-level signal circuits.

A PB board that failed radiated EMI testing in several hundred MHz range



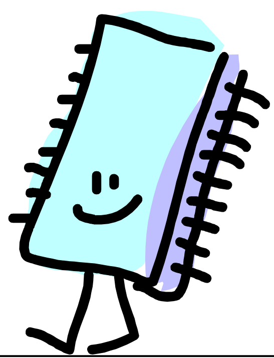
Board layout includes TI dual CMOS op amp

- 1-4 - long ground return paths increases return impedance and loop areas
- 5,6 – long, unbalanced input traces
- 7, 8 – Decoupling capacitors are too distant and have long traces
- No ground plane!
- RFI – EMI performance likely wasn't considered during board layout

In conclusion EMI/RFI

- May constitute an operational, regulatory or liability concern
- Is best considered as part of the design process
- Requires a source, medium and receptor
- Propagates by conduction and/or radiation
- Most often appears as a dc offset shift in precision linear circuits
- Can most often be resolved by reducing the effectiveness of an EMI source or medium and responsiveness of a receptor circuit

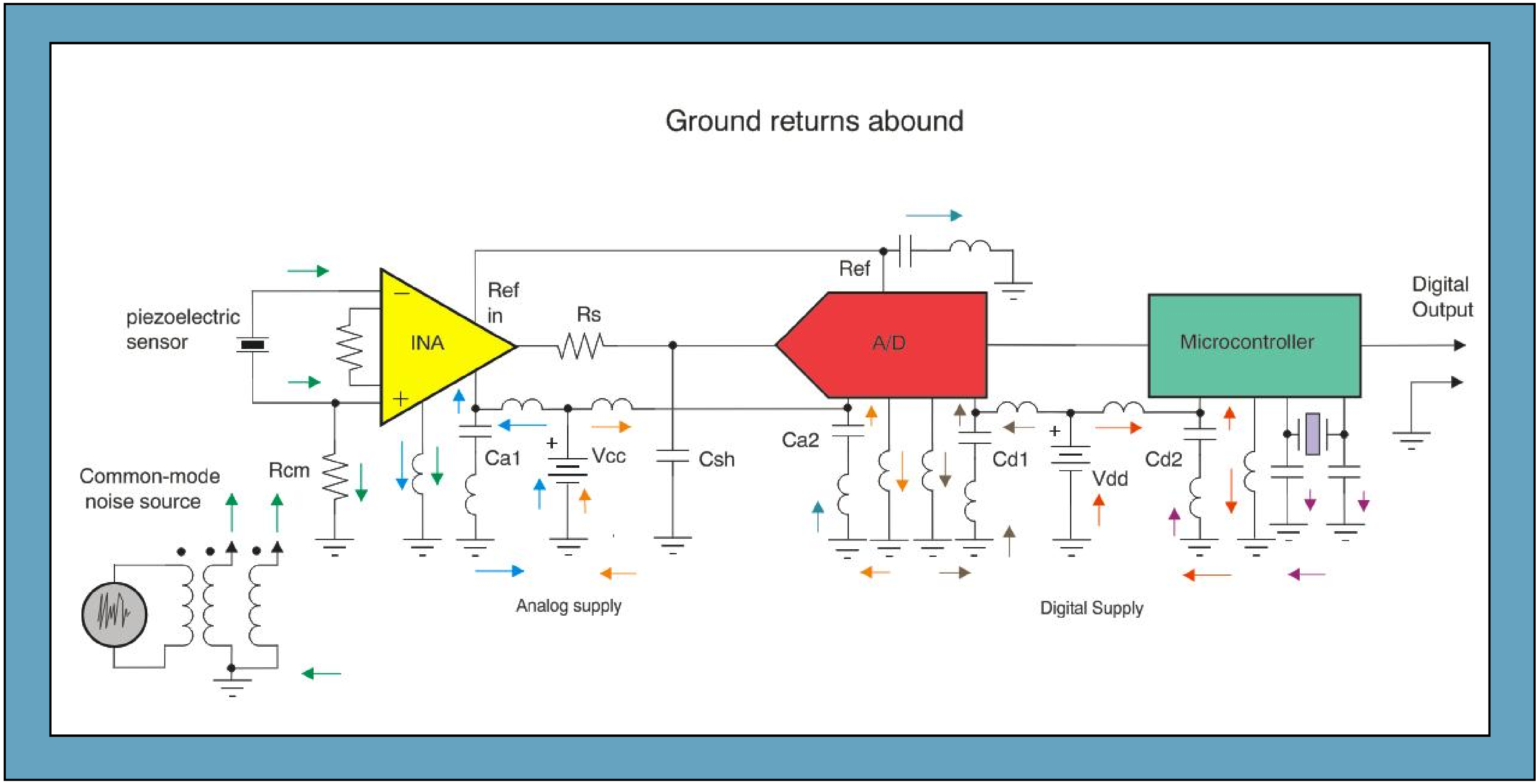
A happy IC - EMI free!



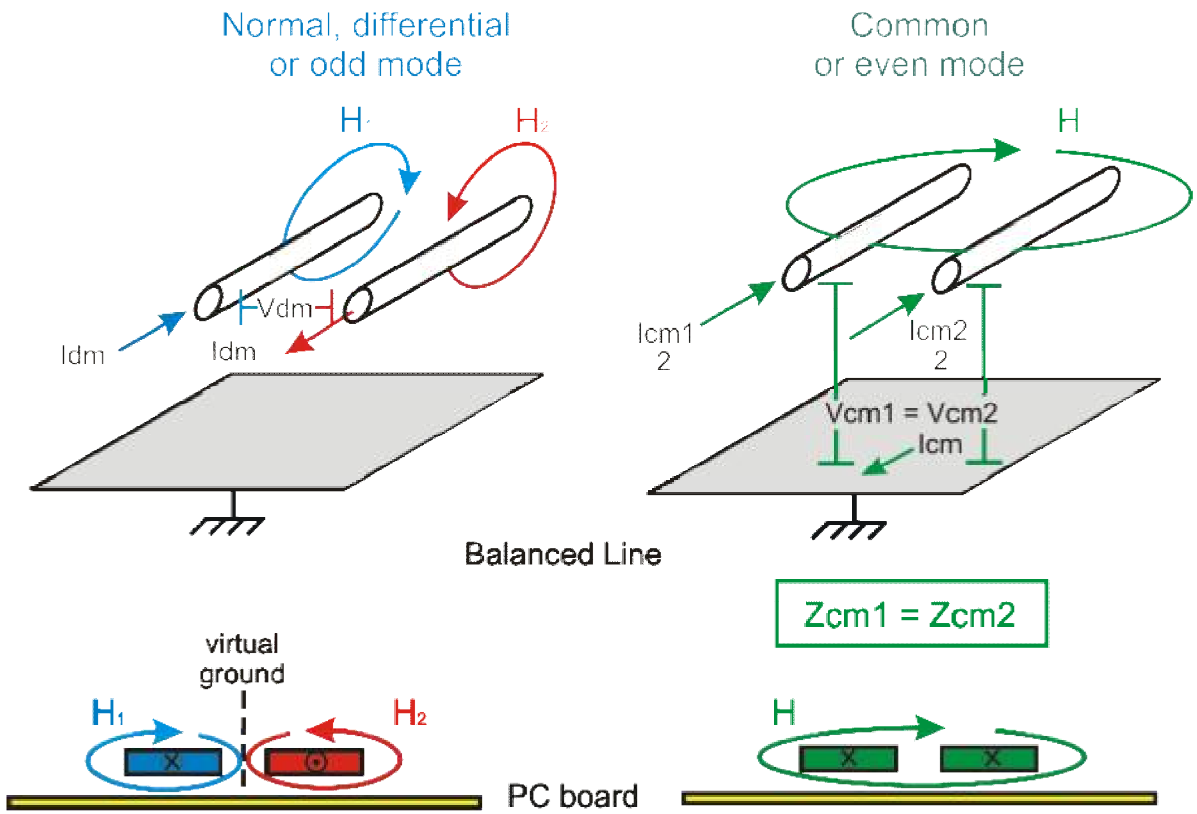
Appendix

The ground return environment may be complex

Current paths must be carefully considered to avoid long loops



Balanced line helps keep induced common-mode EMI from differential conversion



- balanced line presents induced EMI as an equal level, same phase signal to amplifier input
- the common-mode rejection of the amplifier or transformer will act upon the common-mode EMI
- twisting the line improves balance by equalizing the field exposure of both wires