Improving the immunity of sensitive analogue electronics

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Introduction

The art of good analogue electronics design has appeared to decline in the face of the digital microprocessor revolution. Many products, however, continue to utilise analogue electronics, even if only to condition signals prior to being sampled into a digital form. The blame for many RF immunity test failures may be attributed to the sensitive analogue circuitry within that product.

The signal levels employed in analogue circuitry are frequently measured in micro-volts if not millivolts. It is hardly surprising therefore, that when subjected to a radiated field at 3 or 10 volts per metre most circuits misbehave. The usual test house fixes of ferrite clamps and in-line filters are often not enough to ensure compliance. To be sure of passing with a healthy margin a systematic approach to re-engineering is recommended.

In this article, a systematic evaluation, analysis and corrective action to greatly improve RF immunity is described. To many this may appear radical and expensive, but practical experience has shown that the method cost justifies itself in the vast majority of cases. More than 50% of the products I have re-engineered our clients' money has been saved by improving manufacturability and reducing assembly costs at the same time. In one case the investment was recovered on just six weeks of production!

If nothing else, adding an EMC analysis and re-engineering stage to your product prototyping programme affords another opportunity for design faults and oversights to be identified and rectified.

RF Propagation

The main culprits for introducing spurious RF signals into a product are the connecting leads and cables. Once the leads have introduced the unwanted signals, they readily cross couple between internal leads tracks and components (whether real or parasitic). As these signals couple with susceptible nodes within a circuit, they disturb that circuits normal operation. Special housings and RF gaskets on their own will not stop this mechanism.

The solution is two-fold:

1. To improve the immunity of susceptible nodes
2. To de-couple susceptible nodes from sources of unwanted signals

In order to achieve either, one must first know where the susceptible nodes within a circuit are. The trained eye can often pick out potential culprits by inspecting circuit diagrams, but a far more effective method is to test each significant node in turn by direct RF injection.

Significant Nodes

It would be pointless testing all the nodes within a circuit, as many adjacent nodes will yield the same results. The trick is to determine which nodes are significant and therefore worth investigating. Take for example, the circuit shown in Figure 1.

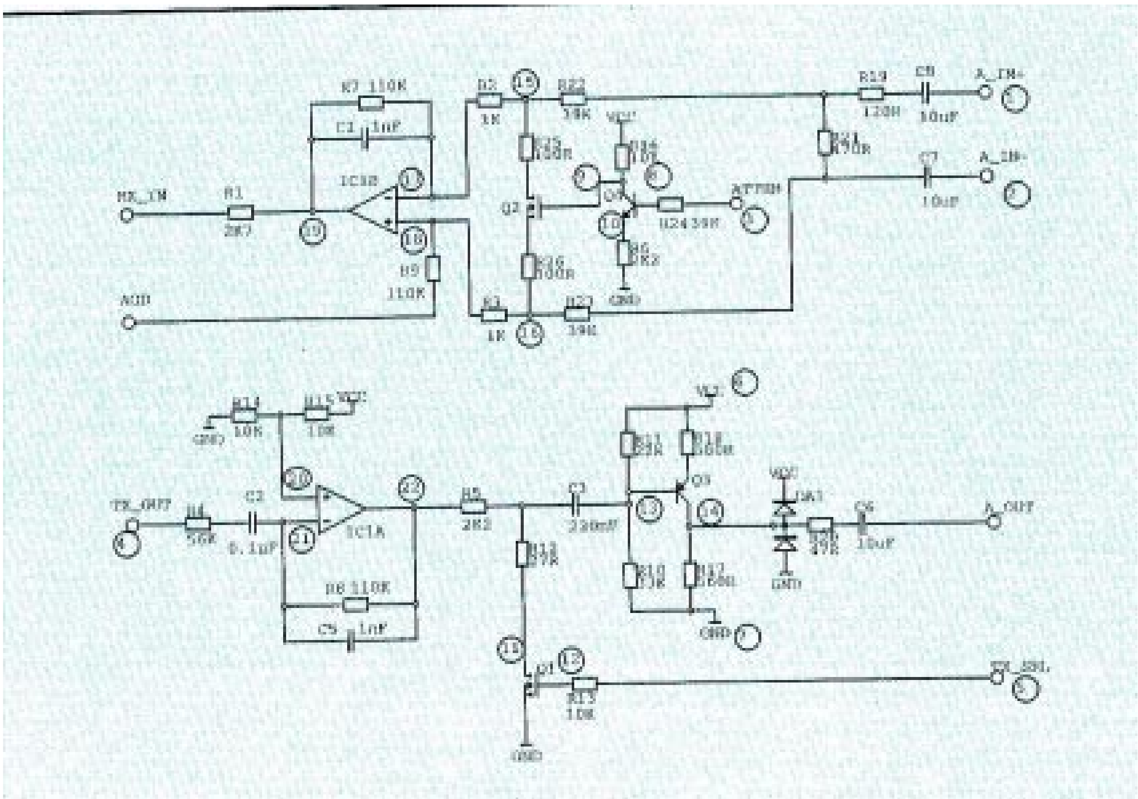

Figure 1: Example Circuit (Before)

The significant nodes are shown ringed. These are the inputs to and outputs from the circuit; the analogue power rails; the transistors and op-amp inputs and outputs. The power supply rails and any split analogue grounds are always worth investigating, because they go everywhere ad therefore pick up unwanted RF easily. Transistors amplify RF and so are worth investigating. Most op-amps are susceptible both at their inputs and outputs. All the other nodes in this example are passively coupled to at least one of the significant nodes and are unlikely therefore to yield any new information.

Test Arrangement

Each significant node must be investigated by direct RF injection. To do this the following test equipment is required:

1. Injection probe
2. RF amplifier
3. RF signal generator
4. An oscilloscope

The injection probe can be constructed as shown in Figure 2. The absolute value of the two components is not critical. The resistor has been chosen to be roughly equivalent to a nominal PCB track impedance. The capacitor to be small enough not to disturb the normal operation of a node under test. The values given yield a 3dB frequency of 3MHz. Below this point, RF injection is progressively attenuated.

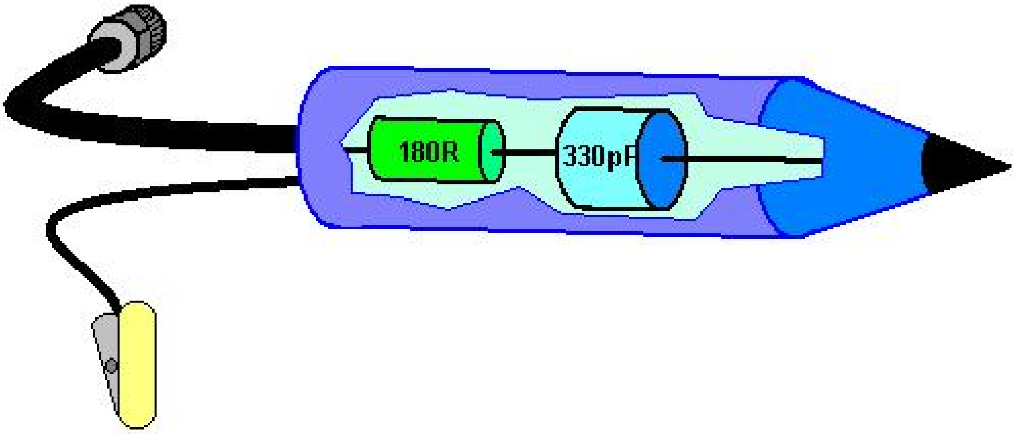

Figure 2 Injection Probe

The RF amplifier may be purchased, or home constructed with a further cost saving. It should be capable of generating about 3 Volts RMS into 50 load over the bandwidth 150kHz to 250 MHz. The generic standards require testing to 1GHz, but in practice the injection probe arrangement is only useful to the end of the VHF range. Beyond this spurious inductances in the probe and its earth lead dominate. In practice it has been found that if a circuit fails above 250MHz it will also fail at some lower frequency.

An RF signal generator capable of automatically sweeping a wide range of frequencies (chirp signal) will improve the testing time over a generator that has to be manually tuned.

The oscilloscope doesn’t have to be anything special. A bottom end 20 MHz scope will be good enough to check a circuit is operating correctly although it wont be possible to observe the RF signal directly.

Finding Susceptible Nodes

Each node is tested by direct injection using the probe described. The earth clip should be attached to ground as near as possible to the node under test. The probe earth lead should be no more than about 2 or 3 inches long. If the circuit uses more than one ground reference (As many mixed mode circuits do), then testing with reference to each in turn is recommended. Where the reference point may have a voltage offset with respect to the test equipment ground, then be sure to operate the equipment under test via a mains isolating transformer.

Once the probe is secured (solder it on if you have to), fairly rapidly sweep the generator through the RF range whilst observing the downstream effect using an oscilloscope and other normal operational checks. Note the level at which a disturbance has effect. When a susceptible node has been found attenuate the test signal by 20 dB and see if the node is still susceptible. If it is, it is likely to be a problem node that will need special attention.

It may not always be straightforward to identify misfunctions in a circuit. This happens when RF injection acts to inhibit a circuit performing some function, such as detecting an over temperature or over current condition. The condition may not normally be present and the RF injection will appear to have no adverse effect. I call these nodes, inhibitor nodes. If it is important that the circuit should detect and act on abnormal conditions then it will be necessary to check that the RF injection does not inhibit the required detection. Designers of safety shut down equipment should take note!

Once all the susceptible nodes have been tested and marked on a circuit diagram, a pattern usually emerges.

Analysing the Results

Problem (highly susceptible) nodes have to be considered first. The other susceptible nodes may or may not need attention depending on:

(i) Whether they are close to inputs, outputs or RF sources, such as digital electronics. In this context, close does not just mean physically close, but electrically, i.e. connected via only a few components, particularly low impedance components.

(ii) Whether the nodes are clustered indicating a whole circuit board, or section there of, is susceptible. Circuits with susceptible clusters must be isolated as a whole, an EMI barrier is always used to achieve this.

(iii) Whether a node is poorly sited, i.e. with long or circuitous connections to its electrically adjacent circuitry. Poorly sited susceptible nodes will require relaying a PCB and re-siting components so that all tracks comprising the node are shortened to a minimum and do not run through ‘dirty’ areas of the board

(iv) Whether a node is part of a closed loop circuit. Closed loop circuits such as power regulators and amplifiers employing negative feedback can be particularly problematic. This is usually because feedback is negative over the operating frequency range but becomes positive at some higher frequency. The positive feedback then causes sympathetic oscillations

Nodes not satisfying the above are usually safe to leave alone. For example the base of a transistor or op-amp input will usually prove susceptible but if that node is connected using only short PCB tracks and is part of a circuit that is otherwise insensitive, it is unlikely to cause a failure during EMC testing.

Corrective Action

As stated earlier, there are two basic solutions for dealing with all susceptible nodes:

(i) improve immunity

(ii) increase isolation

For clusters of susceptible nodes and nodes close to inputs, outputs and other RF sources improving the isolation from interference sources is usually the only viable option. For isolated nodes and closed loop problem nodes, improving the immunity is usually the best approach.

The relative merits and applicability of a number of techniques that can be used to improve the immunity of a product are as follows. The list is not exhaustive.

The EMI Barrier

One of the most powerful and often used techniques is to create an EMI barrier within a product. An internal EMI barrier can usually be created far more effectively than an external barrier. Most engineers will be familiar with a external barrier comprising a shielding housing and in-line filtering of connecting leads. The internal barrier operates on the same principal. A circuit is split into two sections; a 'clean' and 'dirty' section. The dirty section contains circuitry interfacing to external leads and connectors and may also contain known RF noise sources such as digital processors. The 'clean' section contains the susceptible nodes. The dirty section may not contain susceptible nodes unless the have bee designed to be sufficiently immune.

An example of an EMI barrier can be seen in Figure 3. This is the circuit of Figure 1, with a dotted line representing the barrier and additional filtering components. The dirty section is to the left of the line and the clean section to the right. All the susceptible nodes are in the clean section. The circuit's inputs, outputs and power rails connect to the dirty side.

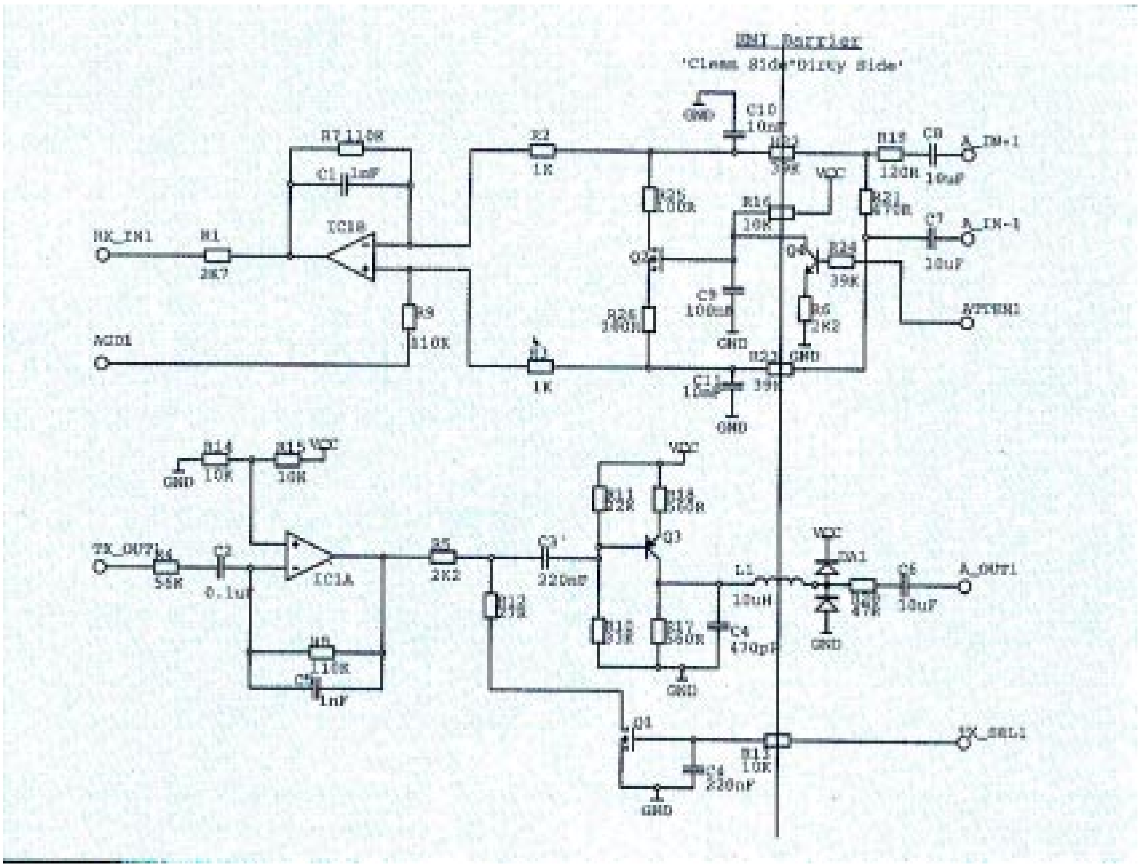

Figure 3 Example Circuit (after)

An example of how a PCB containing an EMI barrier might be laid out, is shown in Figure 4.

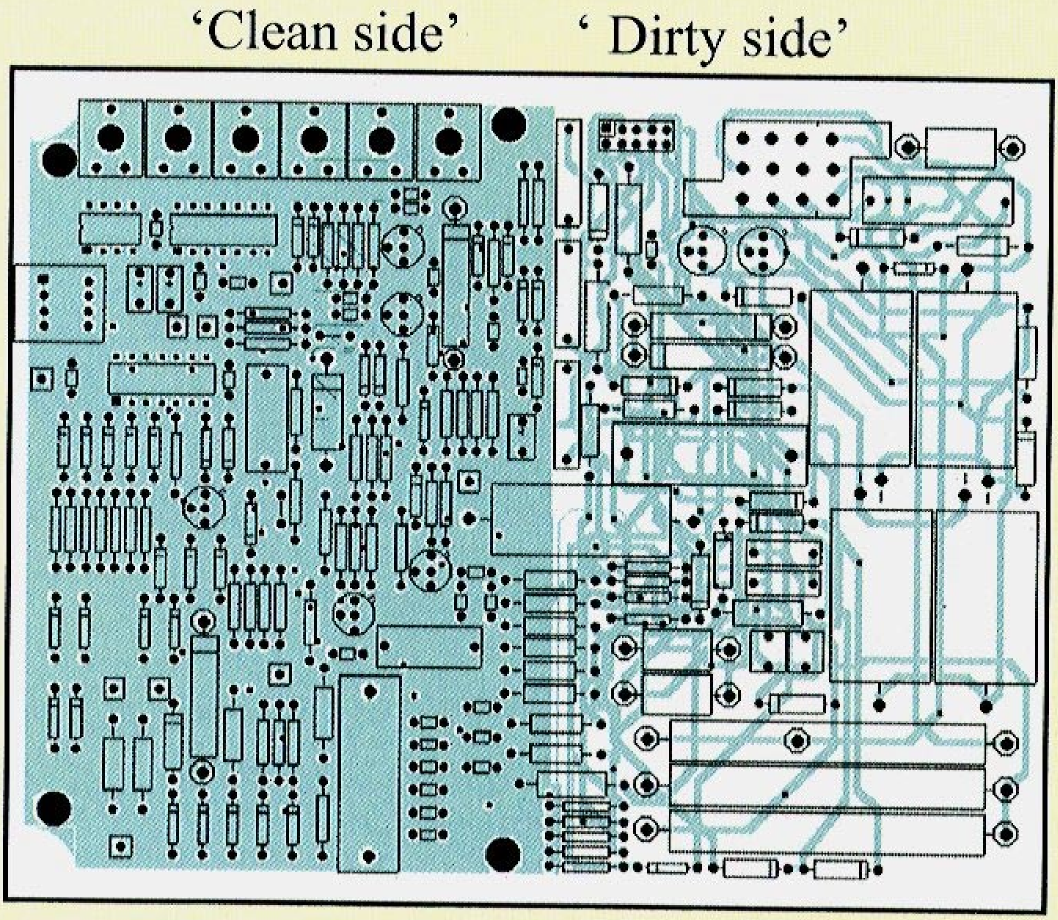

Figure 4 PCB Layout Example

The dirty half of the PCB has no ground plane, the clean side has one. There is only one point of contact of the analogue 0v signal on the dirty side and the ground plane on the clean side. All other lines crossing the halves are filtered by components straddling the boundary. No other components are allowed to straddle the boundary and tracks routed in one half cannot pass through the other half. This can be achieved by placing a void or ‘keep-out’ track across the board prior to auto-routing. If a ground plane were employed on both sides, they would need to be split to provide only a single interconnecting track.

Filtering

Simple low cost filtering components have been added to electrically separate the clean and dirty sections of Figure 3. I have two standard filter designs, both are shown in Figure 5.

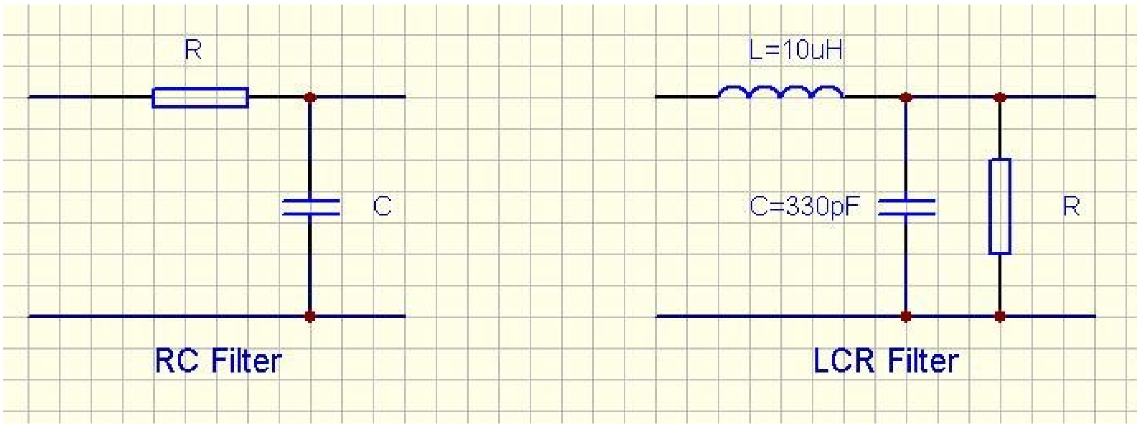

Figure 5 EMI Barrier Filters

The RC low pass is design to have a 3dB frequency at about 15kHz and provides effective isolation from 150 kHz up. The R value needs to be a component already present in the circuit, in our example R37 and R38. C is then calculated as:

$$C = \frac{1}{2\pi \cdot 15x10^{3} \cdot R}$$

C can be increased if required, but should not be decreased below this value.

This type of filter is effective against the signals injected during conducted immunity testing.

The LRC low pass filter is designed with a 3dB frequency at about 2.3MHz and provides effective isolation from 25MHz up. The R value is provided by the loading effect of adjacent circuitry and should not be more than a few kilohms.

This type of filter is effective against the signals injected during radiated immunity testing.

The PCB Ground Plane

A ground plane is a very effective mechanism for reducing inter-track coupling. Unwanted RF on a PCB track is electrically well coupled to the ground plane and less well coupled to other tracks. Furthermore provided that a given track doesn’t change layers too often, that track will act as a transmission line relative to the ground plane and will convey signals end-to-end with considerably less radiated loss.

For existing two-layer boards that don’t have a ground plane it is not always necessary to migrate to a 4 layer design. It may be possible to place a ground fill on one of the layers around a susceptible area. When doing this it is important to tightly couple added filters to this ground plane or they will be rendered ineffective.

Distributed Filtering

Distributed filtering is most commonly used with power rails. The capacitive smoothing of the rail is distributed as a number of parallel components spread around the PCB. What is effectively being created when this is done is complex multi-staging filter, where the stray inductance of the power rail tracking and each capacitor create a stage of that filter. In high gain RF applications where really quiet power rails are required, the power rail is broken using inductors at progressive stages back toward the RF front end.

Reducing and Damping Loop Gain

Excessive loop gain, particularly in power supply regulating circuits is a major cause of problems. Consider Figure 6.

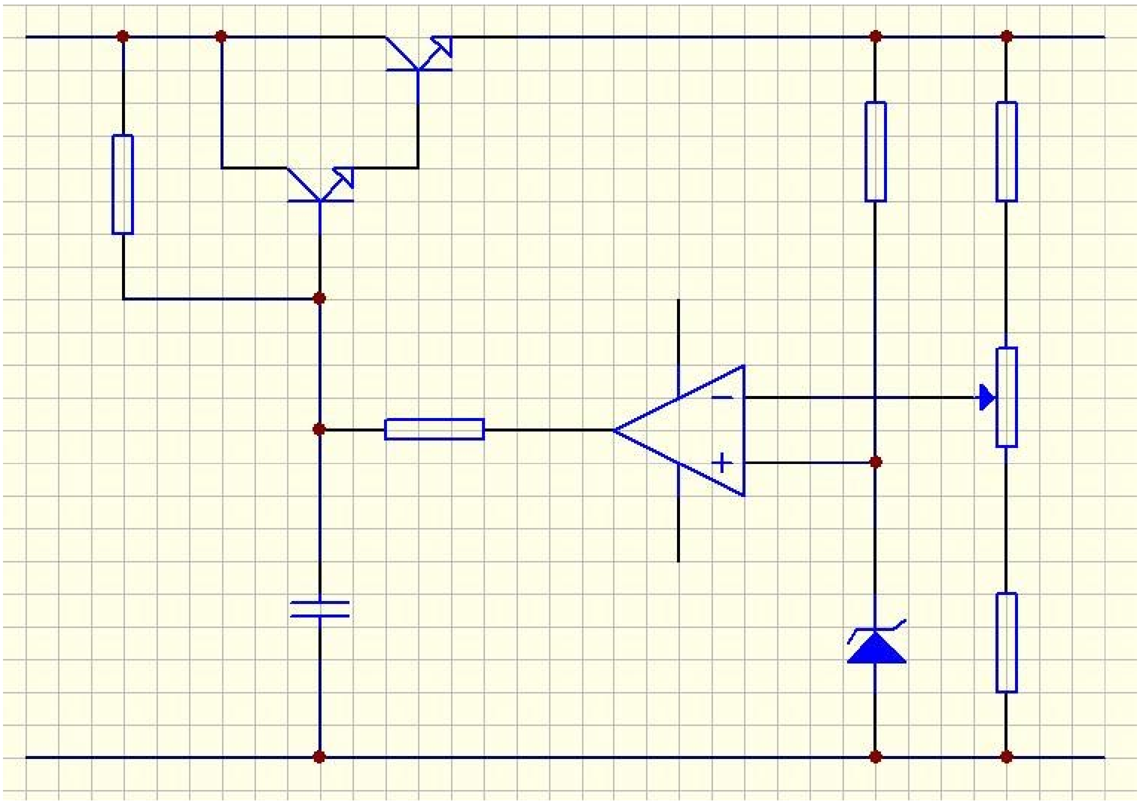

Figure 6 Linear Voltage Regulator

This is a classic closed loop voltage regulator. The regulated output voltage is set by the pre-set variable resistor. The open loop gain of this circuit is the product of the gain of the power Darlington and the operational amplifier. The gain will therefore be massive, probably several billion times. An RF disturbance picked up on the power rail (remember power rails are particularly susceptible to this) is injected straight into the closed loop. At some unfavourable frequency, the feedback in this loop is not negative (due to time delays in the op-amp and power Darlington) and the regulator oscillates! The capacitor has been added to reduce the high frequency gain but is ineffective because when combined with the stray and parasitic inductances within the loop, it simply acts to re-tune the oscillating frequency.

The only safe solution is to reduce the open loop gain in some way. Or, to replace the op-amp with a single transistor circuit a shown in Figure 7.

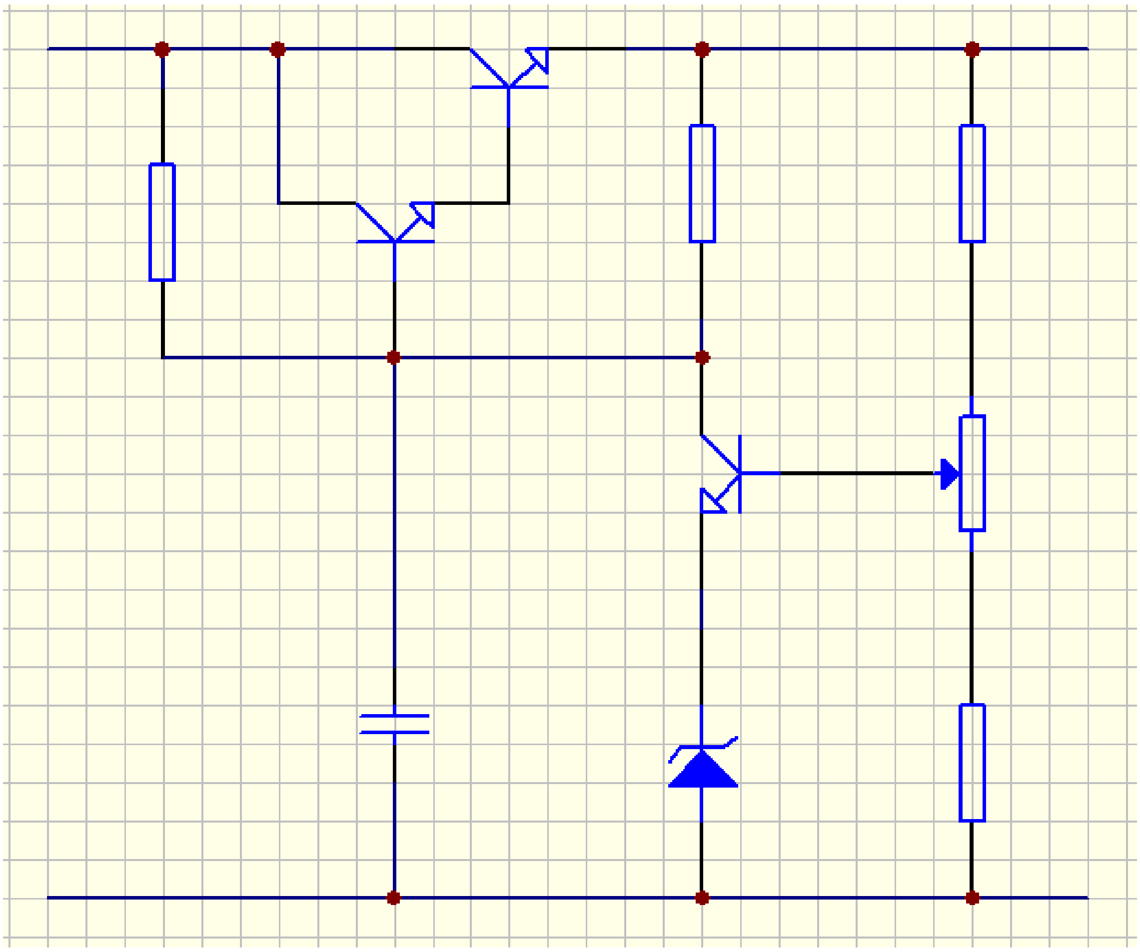

Figure 7 Modified Linear Voltage Regulator

Shielding and Bonding

It is often more cost-effective to have an internal metal shield covering or enclosing the clean area of a PCB than to invest in a custom made metal enclosure or enclosure metalisation and gasketting.

Folded metal screening sub-assemblies are now cost-effective for small production runs and at least one company is known to offer etched screening can technology with negligible tooling costs.

Whether solder tag or bolt down screens are employed, sufficient electrical points of contact between the screen and the PCB ground plane should be designed in to ensure that radiated signals do not leak in (or out for emissions) through the gaps.