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Radiated Interference in Audio Circuits

Abstract

The proliferation of wireless transceivers in portable applications has created a need for increased attention to an electronic circuits' ability to operate in the vicinity of high frequency radio transmitters. This Application Note will investigate an application using an op amp for the voice band audio in close proximity to a high frequency source. In gigahertz radio systems, the close proximity of the radio antenna to low frequency amplifier sub-assemblies, can result in the demodulation of the radio signal causing a disruptive interference in the receiving circuit. This Application note presents a simple method of producing a controllable test platform suitable for testing and characterizing Radio Frequency Interference (RFI) in op amp audio circuits. A comparison between Intersil's ISL28291 (bipolar input) and EL5220 (MOS input) dual precision amplifiers susceptibility to RF interference is investigated using this test platform. Research findings related to this topic will also be discussed with new information suggesting, in today's wireless hand held products, that radiated interference as well as conductive interference needs to be considered.

Introduction

Several studies, experiments and calculations have shown the propensity for operational amplifiers to demodulate RF signals principally at the emitter-base junction of the input differential pair[1, 2, 3] [8]. Demodulation occurs even though the amplifiers bandwidth is much lower than the RF's out-of-band signal. As long as the RF voltage at the junction is not significantly greater than 26mV, the rectified offset voltage follows the square-law relationship and is proportional to the absorbed power. Under these conditions, the audio interference will follow the envelope of the RF signal.

Our study of this phenomenon began when a customer reported their Bluetooth signal was being demodulated in the amplifier and showing up as audio noise on the output audio amplifier. The customer evaluated three opamps in their system and reported the ISL28291 is the worst of the three, National's LMV722 was in the middle and the EL5220 was the best. Even through the EL5220 was rated the best, all three parts exhibited the demodulated signal to some degree at their outputs.

Although the noise caused by the Bluetooth transmitter was readily observed at the amplifier output of the ISL28291, (EL5220 was clean) the frequency hopping and complex encoded modulation of the Bluetooth signal made it impossible to get consistent results. A test platform to quantitatively measure a circuit's susceptibility to RF signals was constructed using standard equipment found in most high frequency analog labs. This platform is capable of generating a swept carrier frequency for 100kHz to 6GHz with an external modulated signal. The platform uses an HP8753D network analyzer and a simple function generator to modulate the signal [4]. The swept modulated carrier frequency was connected to a simple antenna as shown in Figure 1. The output power of the carrier frequency was adjusted to 0dbm to match the standard Bluetooth signal. Consistent readings and, even more importantly, the ability to sweep the carrier frequency from 100kHz to 6GHz was now possible. This allowed the ability to investigate the sensitivity of the circuit as a function of carrier frequency and to focus on a specific frequency to study the demodulated signal.

This Application Note will:

1. Define the difference between conductive and radiated interference for this discussion.
2. Present new data suggesting that radiated interference needs to be considered for portable wireless applications where the antenna is in close proximity to audio circuits.
3. Present lab results comparing ISL28291 and EL5220.
4. Draw conclusions based on this study and other papers to give suggestions for applications and design engineers for operating in the vicinity of high frequency transmitters.
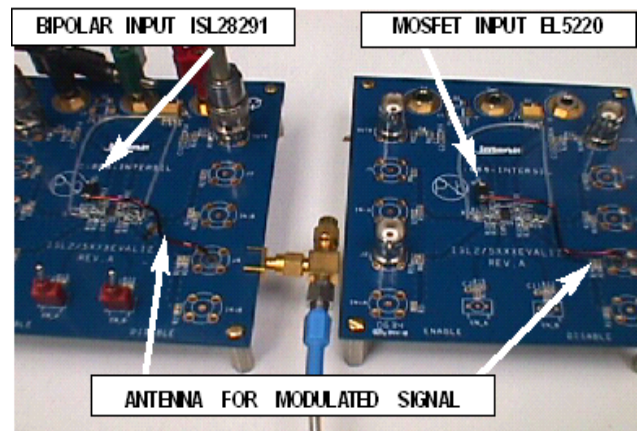
FIGURE 1. MODIFIED EVALUATION BOARD TO SIMULATE CUSTOMERS CIRCUIT

Conductive And Radiated Interference

Conductive interference is defined as the modulated RF signal collected by cables, PCB traces and external components and fed directly into the input pins of the audio amplifier. Radiated interference is defined as the combination of conducted interference plus the

interference collected by the package lead frame and bond wires and fed directly into all pins of the audio amplifier.

Previous studies have focused on interference that is collected by cables and PCB traces while interference collected by package lead-frame and bond wires was considered negligible [5] and therefore not investigated. As a result, these studies coupled the modulated RF signal directly into the inputs of the amplifier. This method, did not account for the radiated effects found in real world customer environments. Using the test platform described above, this application note investigates the additional RF interference radiated through the air and compares the results to previous work published.

Previous Published Conducted Interference Analysis Results

Several papers have been written about conductive interference and the effects on RF demodulation by the op amp [1, 5, 6, 7]. Once again, these experiments injected the RF modulated signal directly into the amplifiers input pins. Experimental results are indicated in the following:

1. RFI effects are more pronounced when RF power is injected into either of the two op amp signal input terminals 1 (The experimental procedure involves injecting RF power directly into one op amp terminal and monitoring all the other op amp terminals voltages. After injecting RF power into all the op amp terminals (one at a time), it was determined that the most susceptible terminals were those for the inverting and non-inverting input, the offset inputs, and the output terminal, in that order) [1].

2. Experimental results showed that increasing the values of the input and feedback resistors improves the RFI immunity of the inverting op amp circuit due to the increase in series resistance and parasitic capacitances [6].

3. Experimental results showed that parasitic capacitances C_{IN} (between the inverting and non-inverting inputs and CR1 (shunted across R1) cause the inverting op amp circuit to have better RFI immunity than the non-inverting op amp circuit [7].

4. MOS transistors can be considered less susceptible than bipolar transistors, since RFI induces in a bipolar transistor a variation of collector current higher than that induced in the drain current of a MOS transistor. As a matter of fact, field-effect transistors are inherently less susceptible to RFI than bipolar transistors because of their smoother nonlinearity [5]. Also, most audio band operational amplifiers are made in large geometry higher voltage CMOS processes that have much lower RF bandwidth than similar voltage bipolar processes.

Interference Models

Figure 2 shows a concept model for the RF interference test set. The HP8753D network analyzer and modulating generator produce an AM modulated wave that is radiated on to the circuit under test. This model illustrates how the RF carrier is stripped off by the circuit under test leaving behind the low frequency signal.
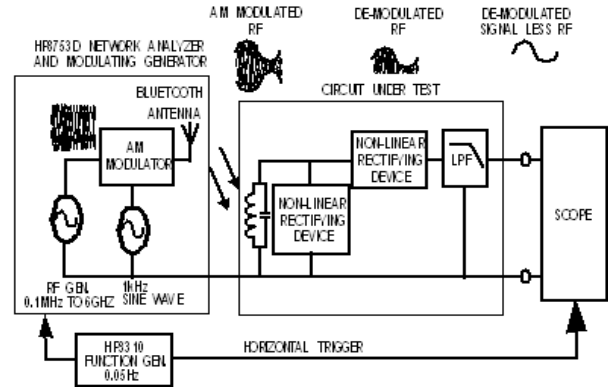

FIGURE 2. CONCEPT MODEL FOR THE RFI

Figure 3 is a behavioral model and equivalent circuit for the IC in close proximity of a high frequency source. Antenna theory states that a trace length less than ¼ wavelength of the carrier frequency makes an efficient antenna. Thus, for 1Ghz carrier frequencies - PCB traces up to 7.5cm (2.95 in.) become efficient antenna. External components (i.e. caps, resistors) on the evaluation board are also receiving antennas for RF frequencies.

The PCB interconnect close to the amplifier (between the feedback resistors and the package) as well as the amplifiers pins and bond wires start to become efficient antennas.

Without the series resistance of the PCB traces and feedback resistors to form the low pass filter, the RF signal is picked up on the lead-frame and conducted directly into the emitter-base junction of the input differential pair. This results in the demodulated signal appearing at the amplifiers output.
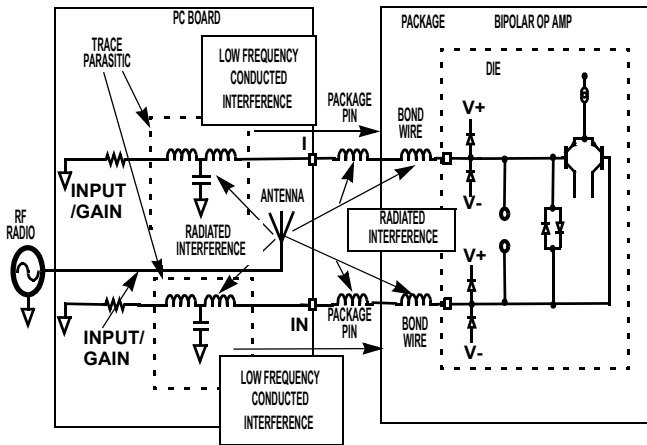
**FIGURE 3. BEHAVIORAL MODEL FOR EQUIVALENT CIRCUIT**

Comparison Between ISL28291 (Bipolar) and the EL5220 (M) Experiment

The following investigation compared the radiated interference immunity of the ISL28291 and the EL5220.

Figure 1 shows the two customer evaluation boards that were modified to match the customers single-ended to differential circuit (Figure 4). Care was taken during the modification of the two boards to make them as identical as possible. One board has the ISL29291 and the other the EL5220. Note: Placement of our antenna was much closer than the customer's test. This was done to achieve the best signal for evaluation. Demodulation did occur with the antenna as far away as 2 inches with about only 50% drop in measured signal amplitude.
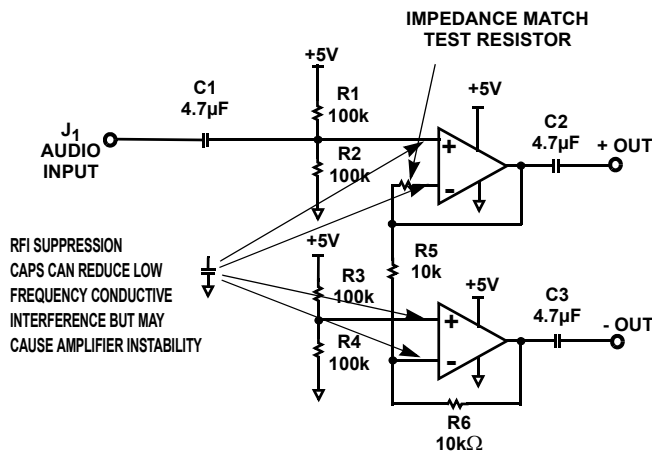
FIGURE 4. CUSTOMERS APPLICATION CIRCUIT
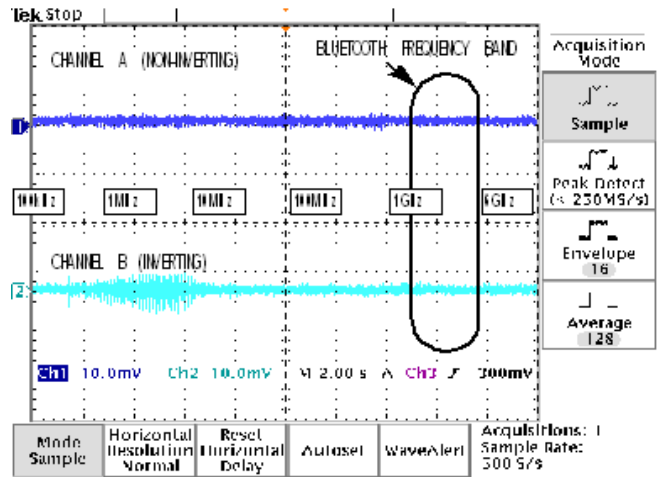
FIGURE 6. EL5220 MOSFET INPUT OPAMP SWEEP J_1 GND
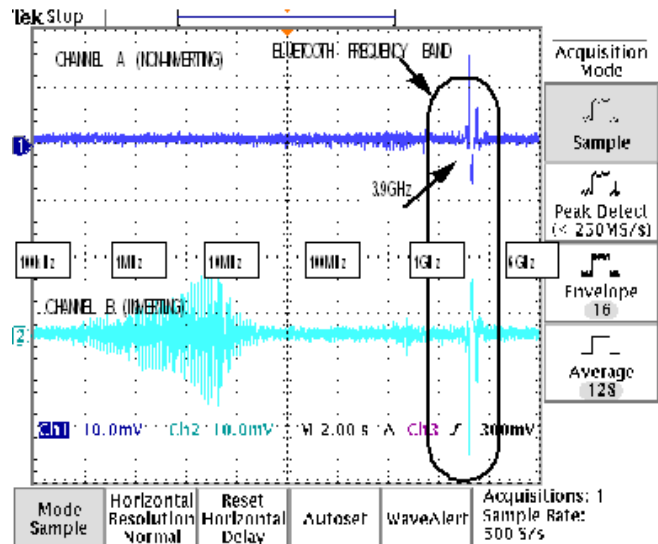
FIGURE 5. BIPOLAR INPUT OPAMP SWEEP J_1 GND

Figure 6 shows the result of a frequency sweep from 100kHz to 6GHz of the EL5220. Across the frequency sweep, the output of Channel "A" (unity gain configuration) shows a total peak-to-peak voltage of less than $3mV_{P-P}$ with J_1 input grounded (Figure 4). The lower trace shows the output of channel "B" (inverting gain of one) with a maximum of $10mV_{P-P}$ in the frequency band of 500kHz to ~5MHz. From 5MHz to 6GHz the total peak-to-peak voltage <3mV.

From Figure 6, it is obvious why the EL5220 did not have a problem with the Bluetooth application.

Figure 5 shows the result of a frequency sweep from 100kHz to 6GHz of the ISL28291. Across the frequency sweep, the output of Channel "A" (unity gain configuration) shows an interference peak of $25mV_{P-P}$ at ~2GHz with J_1 input grounded (Figure 4). The lower trace shows the output of Channel "B" (inverting gain of one) with a maximum of $30mV_{P-P}$ in the frequency band of 500kHz to ~30MHz. From 30MHz to 6GHz there is a $5mV_{P-P}$ interference peak at ~800MHz and a series of peaks of ~$25mV_{P-P}$ over the 1.8 to 3GHz range.

Interference below 30MHz is conductive and within the bandwidth of the both the ISL28291 and the EL5220. The Interference in the GHz range correlates with the reported customer problem.

From Figure 5, it is obvious why the ISL28291 has a problem with the Bluetooth application.

Figure 7 shows the interference on channel A and channel B outputs with a fixed carrier frequency of 3.9GHz and a 1kHz 100% modulation. 3.9GHz was chosen because there is an interference peak at this frequency. The signals shown are the 1kHz demodulated signal. The non-symmetry in the 1kHz signal is from our lab equipment generating the modulated signal and not the amplifiers.
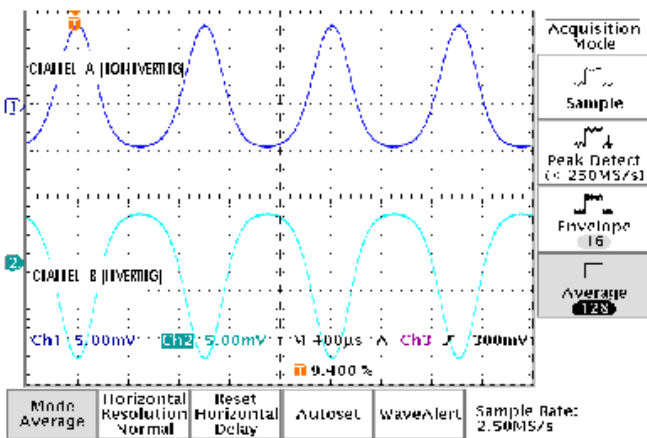
FIGURE 7. INTERFERENCE WITH FIXED CARRIER FREQUENCY

Radiated Interference Investigation Results

Previous studies determined that higher value feedback resistors, the addition of RFI caps and the use of inherently more liner MOSFET input devices reduce RFI. These improvements techniques are compared using the radiated test platform.

Figure 8 shows an improved test setup to investigate radiated interference. The antenna is terminated in 50Ω and the end of the antenna loop is bent to have a width approximately equal to the width of the IC's package. Figure 9 shows the placement of the antenna and layout symmetry of the external components. Both amplifiers were configured for differential gains of 10, so that the impedance at both inputs were identical. Channel "A" has 5k/500Ω resistors and Channel "B" has 500k/50k, two orders of magnitude higher value resistors.

Experimental results, using the setup in Figure 8 and a swept frequency measurement from 100kHz to 6GHz, showed concentrations of interference in the 1.4GHz to 2.8GHz range and a second in the 3.8GHz to 5GHz range (see Figure 10).

FIGURE 8. IMPROVED ANTENNA DESIGN TO EVALUATE RADIATED INTERFERENCE
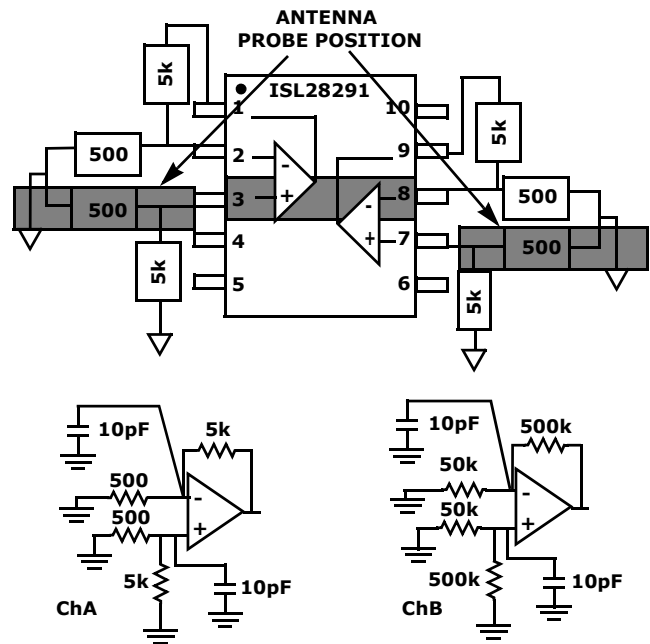
FIGURE 9. PLACEMENT OF ANTENNA OVER DIE AND OPAMP SCHEMATIC FOR CHANNELS A AND B

The following tests were performed with a single carrier frequency within the above mentioned concentrations of interference. The results are as follows:

1. **Higher feedback resistor values vs lower feedback resistor values:** Placing the antenna directly over the higher value resistors resulted in a lower level of interference then when placed over the lower value resistors. The higher the frequency the lower the level of interference. This observation is in agreement with the results reported by Ghadamabadi [6]. Placing the antenna over the IC

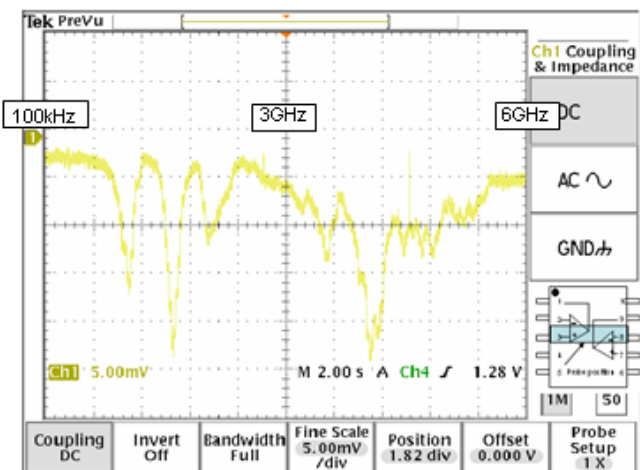resulted in minimal interference for both sets of resistors.

2. **Adding RFI capacitors:** Placing the antenna directly over the higher value resistors resulted in lower level of interference then when placed over the lower value resistors. The higher the frequency the lower the level of interference. This observation is in agreement with the results reported by Ghadamabadi [7]. However, placing the antenna directly over the IC package resulted in much higher levels of interference at the outputs of both amplifiers, regardless of resistor values, than observed when the antenna was placed over the resistors.

3. **MOSFET input amplifiers are less susceptible than bipolar:** Placing the antenna directly over the die or resistors showed the EL5220 to have much less interference than the ISL28291. This observation is in agreement with the results reported by Fiori [5].

The increase in interference after adding the RFI capacitors was not reported in prior studies, because it was considered negligible [5]. In the authors opinion, in Bluetooth applications where the antenna is in close proximity to a sensitive audio circuit, the effect of radiated interference should not be ignored. The radiated RF appears all over the PCB and is picked up on component leads, PCB traces and IC lead-frames/bondwires. The results of these findings may not apply to all circuits but serve as a reminder that additional awareness of the antenna location and radiation pattern needs to be considered in the final design.

FIGURE 10. CARRIER FREQUENCY SWEEP FROM 100KHZ TO 6GHZ, BOARD IN FIGURE 8 AND SCHEMATIC FIGURE 9

Conclusions

The test platform presented in this paper is an effective tool for generating radiated interference and measuring RFI. Previous studies were focused primarily on conductive interference and the demodulation of the RF signal in the emitter-base junction. From these studies basic rules of thumb were established to mitigate the effects of RFI in the receiving circuit. Among the many preventative measures a designer could take to reduce RFI, this investigation looked at changing feedback resistors [6], adding RFI capacitors [7], and bipolar vs. MOSFET input amplifiers [5] when exposed to a radiated interference source. Another precaution / best practice, although not proven in this study, would be to specify an amplifier (preferably MOS input) with just enough bandwidth for the application.

The main result of this study showed the use of RFI capacitors could result in an increase in interference depending upon the placement of the antenna. It is therefore recommended that the system designer become aware of the antenna placement before using RFI caps to increase the immunity of their design. Other results of this study are in agreement with published results, showing that higher value feedback resistors and MOSFET input amplifiers are effective techniques to improve a circuits' immunity to RFI.

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