AC 2008-2489: DESIGN OF A HARDWARE PLATFORM FOR ANALOG COMMUNICATIONS LABORATORY

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Design of a Hardware Platform for Analog Communications Laboratory

Introduction

In the typical electrical engineering curriculum, analog communications is usually a junior or senior year elective. Such a course typically focuses on analog radio, covering the topics of amplitude modulation (AM) and frequency modulation (FM). Also included is the study of noise effects in communication systems and other related concepts in signals and systems. Increasingly, the laboratory portion of an analog communications course has migrated to simulation-based experiments using MATLAB\(^1\) or to quasi-simulation methods based on the capabilities of LabVIEW\(^2\). The motivation for this move has been to sidestep the difficulties associated with having the students construct analog communications circuitry where often the communications experimentation is undesirably dominated by analog hardware build and debug. While simulation is a useful supplement, the move away from hardware does not fully satisfy the desire of students to experiment with “real” signals and systems.

Fortunately, with the increase of integration of communications circuitry towards stand alone ICs the difficulty associated with constructing analog communications circuits has been greatly reduced. It is thus possible to quickly assemble and begin experimenting with analog communications. Our approach has been to combine several of these circuits onto an all-in-one communications board that can be simply configured for a variety of experiments. The communication circuits, along with filtering and amplification stages, are connected in various configurations to allow for the emulation of a full communications system, including modulation, transmission, reception under the conditions of noise, tuning and demodulation. Furthermore, these circuits allow for experimentation at relatively low frequencies, thus avoiding higher frequency measurement issues while requiring only standard medium-range laboratory test equipment.

Our communications board allows for the emulation of modulation and demodulation for both AM and FM. AM is generated using the MC1496 balanced modulator\(^3\), with demodulation achieved via envelope detection. FM modulation is achieved through the use of the VCO ICL838 IC\(^4\). Alternatively, FM generation is also achieved through the use of a modified Colpitts Oscillator\(^5\) circuit. FM Demodulation is performed through a bandpass discriminator combined with an envelope detector. Filtering and buffering stages are included, along with an audio output circuit and signal multiplexor. Other circuitry includes a tunable broadcast quadrature detector FM receiver based on the TDA7000 IC\(^6\). Furthermore, other similar complexity circuits, which could optionally be used for this type of platform, are described including AM DSB-SC modulation using the SA602\(^7\) and PLL-based FM demodulation using the LM565C\(^8\). The communications
board also includes the ability to jumper around sections of the circuitry, or to add in additional circuitry if desired.

**Communications Board Circuitry**

The communications board block diagram is shown in Figure 1. As shown in the figure, there are two modulation/demodulation blocks for each of AM and FM, along with support circuitry for filtering, summing and buffering. In order to allow a variety of experiments, the blocks can be configured in various permutations using simple jumpers. It is assumed that the user supplies the carrier signal and the message (information) signal, while using bench equipment to sense and display output signals. These input and output signals are applied through BNC connectors, with power supplied from a DC supply of ±10 V/+5 V. The functionality of the blocks is described in the following subsections.

![Figure 1: Communications Board Block Diagram](image)

The communications board was implemented on a 4"×7" four layer PCB. The layout of the board showing the approximate location of circuitry is shown below in Figure 2.

**Inputs, Signal Paths and Outputs**

The inputs to the board include the message signals, the carrier signals (not required for all circuits) and an optional noise signal. The board allows for the application of up to two carrier signals (for frequency division multiplexing experiments), to be connected at the high-frequency portion of the circuit. Similarly, two message signals may be applied, at the lower-frequency portion of the circuit. All four inputs include basic line protection and are buffered via an Op-Amp follower circuit. If so desired, the carrier and/or message signals can be filtered by a second-order LPF. These filters have an adjustable corner frequency, such as 2.6–15 kHz for the message signal.

The basic concept of the board is that by configuring the proper set of jumpers, the user will be able to select a signal path incorporating the desired circuitry blocks. There are two main signal paths, where each path can contain the desired combination of the modulation/demodulation schemes and/or the injected noise. The signal path then terminates at the audio output, which is driven by the recovered message signal. A composite signal is formed by summing the signal pathways (for frequency division multiplexing experiments). The composite signal is then demultiplexed and routed to the proper demodulator for final delivery to the audio output. At all jumper points on the
board, the signal can easily be probed for further investigation with a 1× or 10× oscilloscope probe at the outputs of the various stages. The card was designed to keep message, carrier, and modulated signals in the 3 \( V_{rms} \) range.

![Figure 2: Communications Board Layout](image)

**AM Modulation**

There are two independent, but identical, AM modulation circuits, both based on the MC1496 Balanced Modulator/Demodulator. The circuit for AM modulation is shown below in Figure 3. This circuit generates the AM signal \( x_{AM}(t) \) according to

\[
x_{AM}(t) = A(1 + \mu m(t))\cos(\omega_c t),
\]

where \( m(t) \) is the message signal (bandlimited by the action of the input low-frequency LPF), \( \mu \) is the AM modulation index with \( 0 < \mu \leq 1 \) and \( c(t) = A\cos(\omega_c t) \) is the carrier signal at radian frequency \( \omega_c \) and amplitude A.

The MC1496 works best if the signal frequencies and levels do not exceed certain limits. Specifically, the carrier frequency is to be kept below 300 kHz, with 100 kHz recommended. The message bandwidth can likewise go up to 300 kHz, but the circuit works best for a baseband bandwidth limited to 10 kHz. The message signal is typically pre-filtered by the input LPF to enforce this limit.

The MC1496 IC is designed to use very low-level signals. To maintain operation in the linear region of the device, it is necessary to keep these signals below 25 m\( V_{rms} \) (both
message and carrier). This limit is quite restrictive, but higher level signals (up to 1 \( V_{\text{rms}} \)) may be used, with the issue that the MC1496 is no longer performing linear modulation. Fortunately, the non-linearity manifests itself via a series of spectrum copies centered at even harmonic multiples of the carrier frequency, which can be filtered out through the on-board BPF.

The AM modulation index is chosen by varying an on-board potentiometer (R63), effectively accomplished by adjusting the amplitude of the message signal input. Furthermore, minor adjustments to the AM modulation circuit are necessary to set the device bias for this application using another potentiometer (R76). Tuning of R76 is best accomplished during circuit operation. Finally, in order to tune the device output voltage level, another potentiometer is included (R77).

![AM Modulation Circuit](image)

**Figure 3: MC1496 AM Modulation Circuit**

**AM Demodulation**

AM demodulation is accomplished using an amplifier and envelope detection circuit. There are independent identical envelope detectors on each of the signal paths. Envelope detection is a non-linear process by which the AM signal is half-wave rectified and then lowpass filtered (along DC offset removal). These actions recover the envelope of the AM signal, which is directly proportional to the original message signal. The envelope detector circuit is shown below in Figure 4.

The envelope detector must be adjusted to suit the signal parameters. First of all, a diode based half-wave rectifier suffers from the problem of a non-linear voltage response such that the input must exceed the diode turn-on voltage in order for any current to flow. For an AM signal where the modulation index is near unity, the diode turn-on voltage effect causes clipping in the recovered message signal. To circumvent the problem, an adjustment is provided to inject a DC bias into the rectifier amplifier using potentiometer
R109. Typically, this bias (denoted $V_{\text{injection}}$) will need to be near 0.5 V, and is governed by the relationship

$$V_{\text{injection}} = \left(1 + \frac{R62}{R67 + R45}\right) \cdot V_{\text{in}} + 10V \cdot \left(\frac{R135 + R109}{R135 + R109 + R134}\right).$$

The envelope detector LPF corner frequency must also be tuned. The corner frequency is controlled by the potentiometer R99. To properly filter out the carrier following the rectifier, the LPF is used, where the corner frequency must be chosen according to $W < f_{\text{corner}} < f_c$, where $W$ is the bandwidth of the message signal and $f_c$ is the carrier frequency. Practically, the filter should be tuned as low as possible without affecting the message signal. This corner frequency varies from $2.6kHz < f_{\text{corner}} < 15kHz$.

Additionally, an adjustable gain to control the overall amplitude of the recovered message signal is implemented by varying R45.

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**Figure 4: Envelope Detector for AM Demodulation**

**FM Modulation**

As described earlier, there are two approaches to FM modulation on the communications board. The first uses the ICL8038 VCO circuit, with the second based on a discrete implementation using a modified Colpitts Oscillator design. These circuits generate an FM signal $x_{FM}(t)$ according to

$$x_{FM}(t) = A \cos \left(\omega_c t + \kappa_f \int_{-\infty}^{t} m(\tau)d\tau\right),$$
where, similarly to AM, \( c(t) = A \cos(\omega_t t) \) is the carrier signal at radian frequency \( \omega_c \), \( m(t) \) is the message signal (also frequency limited by the input LPF) with \( \kappa \) the FM gain constant.

The schematic of the ICL8038 VCO is shown below in Figure 5. This device generates its own carrier signal, controlled via capacitor C22. In the current design, the carrier frequency is approximately 100 kHz.

![Figure 5: ICL8038 VCO FM Modulation Circuit](image)

The VCO will generate an FM signal with the message signal present on the first processing path. The bandwidth of the message signal controls the modulation index of the FM signal.

Obviously, with a carrier frequency of 100 kHz, the message signal bandwidth should be considerably less, with a recommended setting of 10 kHz. Additionally, the message signal amplitude should be less than 1 \( V_{rms} \), which is consistent with limits required by the MC1496.

A potentiometer (R15) is available to remove distortion in the FM output of the ICL8038. Using no message signal, the unmodulated FM output (a sinusoidal waveform) should be observed. If distortion is present, the potentiometer is varied until the distortion is minimized. Furthermore, capacitors C35 and C36 are used to decouple the message and output signals and remove any DC bias. The select resistor, R26, is an optional component recommended by the IC datasheet. Its value is selected based on the signal levels desired. The value selected for R26 will also affect the choice in value for the DC blocking cap (C35).

The second FM modulation method, present on the second signal path, is a discrete Colpitts Oscillator design. The schematic for this circuit is shown in Figure 6. Like the VCO circuit just described, this oscillator also generates its own carrier signal. The circuit operates due to the action of the message signal driving the bias point of the oscillating transistor. As the amplitude of the message signal varies, the oscillation frequency varies proportionally, thus creating an FM signal. To operate, this circuit
requires an appropriately High-Q inductor-capacitor pair (L1 and C2). Additionally, the variable capacitor C2 controls the oscillator frequency, which roughly supports a center frequency range of 80–120 MHz.

This circuit uses a fairly low-level message signal amplitude of less than 100 \( V_{rms} \). If so desired, the output level of the FM signal can be varied by adjusting the input to the circuit via the message LPF stage.

**FM Demodulation**

There are two approaches to FM demodulation on the communications board. The first is intended for the FM signal as generated on-board using the VCO. The second FM demodulation method is intended to demonstrate reception of commercial FM broadcast signals or the Colpitts Oscillator generated FM signal.

**Figure 6: Colpitts Oscillator FM Modulation Circuit**

The first FM demodulator, intended for on-board generated FM, is designed to demodulate an FM signal centered near 100 kHz. The FM signal is first processed by the bandpass discriminator that effectively converts the FM signal to an AM signal. Following the conversion to AM, the signal is passed to one of the envelope detectors to recover the message signal.

The bandpass discriminator operates on the approximately linearly rising slope of a BPF, as shown in Figure 7. With an FM signal, the frequency varies linearly with the message signal. As applied to the discriminator, the filter output amplitude is linearly proportional to the distance between the instantaneous frequency and the carrier frequency \( f_c \). That is, when the frequency is above the carrier, the amplitude is larger; when it is less, the amplitude is less. Hence, an FM signal is converted to an AM signal.

The bandpass discriminator consists of two 2-pole adjustable BPF in series. This choice allows for a steep (i.e., high gain) discriminator response. Following processing by the discriminator, the signal must be connected to one of the envelope detectors to complete the demodulation.
The second FM demodulation method utilizes the TDA7000 IC for reception of commercial FM radio stations (mono only). Broadcast FM for this application is received via a wire attached to the circuit card to act as an antenna. The output from the Colpitts Oscillator FM circuit can also be demodulated using this circuit. The circuit for the TDA7000 IC is given in Figure 8.

The TDA7000 employs quadrature FM demodulation\textsuperscript{11}, with the RF, IF, demodulation and audio stages largely integrated onto the IC. In order to use this circuit to receive over-air signals, a 2 inch or longer wire is to be soldered to the antenna pad on the circuit card. Alternatively, an RF range FM signal can be routed on the board through high frequency BPF (adjustable 3–120 MHz center frequency) into the TDA7000 input. The TDA7000 can be tuned to receive stations over the whole FM range of 88 to 108 MHz utilizing the adjustable capacitor C5. The demodulated audio (message) signal is to then be routed to the audio section for output to headphones.
Support Circuitry

The communications board includes an audio amplifier to drive a mono headphone jack. This amplifier can sum all or any of the outputs from each of the envelope detectors and the TDA7000 IC, allowing the user to easily listen to the demodulated signals. A potentiometer is used to control output volume.

To allow for frequency division multiplexing experiments, the communications board includes a summing amplifier for creating an emulated transmission channel. This circuit sums any desired combination of the two AM and two FM modulated signals and places them onto a single output, made available to a BNC connector, with characteristic impedance of $50 \, \Omega$, capable of driving a matched load up to $3 \, V_{\text{rms}}$. Additionally, it is possible to independently scale the amplitude of each summing amplifier input. Unused channel inputs to the summing amplifier should be grounded via jumper settings.

In keeping with the intent of the transmission channel summing amplifier, the communications board includes two 2-pole adjustable BPF. These amplifiers are used to frequency select the channel a user wishes to demodulate. The center frequency range of one filter is 80–120 kHz, allowing the user to tune all of the on-board generated modulation signals, except for the Colpitts Oscillator FM. The second BPF has an 80–120 MHz range, allowing tuning of the Colpitts Oscillator section or other manually injected modulated signals. This stage may be selected in before sending the output of the channel to the demodulator sections.

Noise

The ability to add noise into the modulation path is provided on the communications board. The injection of noise is useful for studying the effect it has on the performance of different modulation schemes. The communications board provides an input to apply an external wideband noise signal. The wideband noise can be added into the summed transmission channel, or it can be first filtered by a nearly flat-passband BPF in order to create a bandpass random process $^{13}$ (BRP). This flat passband BPF is composed of a 1-pole LPF and 1-pole HPF in series. Alternately, the BRP will be created when the multiplexed communications signal is filtered by the receiver BPF.

Alternative Circuits

PLL-based FM Demodulation

Demodulation of FM via a Phase-Locked-Loop (PLL) is commonly used. A simple circuit, based upon the LM565C PLL, is given in Figure 9. This circuit demodulates an FM signal with a carrier frequency of 100 kHz, and is compatible with the other circuit elements on the communications board.
Double Sideband–Suppressed Carrier (DSB-SC)\textsuperscript{12} is one of the flavors of AM described by the equation

\[ x_{DSB-SC}(t) = Am(t)\cos(\omega_c t), \]

where \( m(t) \) is the message signal and \( c(t) = A\cos(\omega_c t) \) is the carrier signal at radian frequency \( \omega_c \) and amplitude \( A \). As can be seen from the above equation, the message signal and carrier sinusoid are multiplied (or mixed) to create the DSB-SC signal. The SA602 mixer IC performs the multiplication function and can be used to generate a DSB-SC AM signal, as shown in the circuit in Figure 10. The input signal impedance needs to be balanced to match the circuit input impedance using the variable inductor \( L_1 \). Balancing the output to the isolation transformer is done by varying \( C_4 \).

The center frequency and bandwidth of the DSB-SC signal will be determined by the carrier frequency, with a bandwidth of twice that of the message signal. In order to demodulate, the same circuit can be duplicated, where in this case the inputs are the DSB-SC modulated signal and again the carrier signal. Note that the delay (phase shift)
of the carrier from the application at modulation to that at demodulation will be insignificant (coherent demodulation is required for DSB-SC), although phase delay can be introduced to study the effect. When followed by a LPF, the message signal is recovered.

**Experiments**

The generic test equipment configuration for experimentation using the communications board is shown in Figure 11. Test equipment includes a function generator capable of generating the carrier sinusoid (at or near 100 kHz for AM), a function generator (or other audio signal player) to source the message signal and a wideband noise generator for noise performance experiments. For signal display, an oscilloscope and spectrum analyzer is recommended, both with bandwidths into the 200 MHz range. Additionally, the user may connect headphones to the audio jack in order to hear demodulated audio.

![Figure 11: Communications Board Test Equipment Configuration](image)

**AM**

The AM experiment is comprised of modulation via the MC1496, demodulation using the envelope detector and message signal recovery at the audio output, as shown in Figure 12. The user supplies the 100 kHz carrier tone and the message signal, which is to be either a sinusoid at frequency 10 kHz or less (sinusoidal modulation) or some baseband signal (it may be necessary to apply the input LPF to limit the signal bandwidth). Note that the MC1496 is followed by a BPF, tuned to the carrier signal frequency, in order to remove the harmonic images generated by the modulator.

![Figure 12: AM Experimental Setup](image)
An oscilloscope is used to display the signal at the output of the MC1496 modulator, demonstrating how the envelope of the AM signal is proportional to the message signal. The spectrum of the signal is also displayed, centered at the carrier, showing the upper and lower sidebands along with the carrier spectral line. The recovered message signal is displayed on the oscilloscope, indicating how it is recovered from the modulated waveform.

There are several interesting laboratory experiments in AM that can be accomplished with the communications board. Examples include:

- Varying the modulation index $\mu$ and observing the effect in the modulated waveform, the AM spectrum and the recovered message signal. Testing modulation indices greater than unity demonstrate the problem for message signal recovery, as shown in an oscilloscope screen capture in Figure 13.

- Use an audio signal as the message signal, and compare the quality of the audio output as compared to FM. Of further interest, observe the spectrum of the modulated waveform.

![Oscilloscope Capture of MC1496 Output with Overmodulation](image)

Figure 13: Oscilloscope Capture of MC1496 Output with Overmodulation

**FM**

There are two modulation/demodulation on-board choices for FM, yielding several variations for the FM experiment. The first is FM modulation using the ICL8038 VCO, along with demodulation with the bandpass discriminator/envelope detector combination, shown in Figure 14. The user supplies the bandlimited message signal, typically sinusoidal in order to best illustrate FM behavior, although audio signals may be used.
An oscilloscope is used to probe the output of the ICL8038 in order to display the FM modulated signal. Furthermore, this same signal is sent to the spectrum analyzer such that the student can observe the spectral lines present in the FM frequency plot. The output of the balanced discriminator is also displayed to show the conversion of the FM signal to AM. Finally, the recovered message signal is displayed, obtained from the output of the envelope detector.

With FM, there is a wide variety of experiments to perform. Examples include:

- Varying the FM modulation index $\beta$ and observing the effect to the FM spectrum (note: the modulation index is varied for the ICL8038 by adjusting the message signal level). With a sinusoidal message signal, it is demonstrative to observe the spectral line levels and compare to predicted levels using the Bessel functions of the first kind.

- Perform the Bessel NULL experiment in which the modulation index $\beta$ is varied until particular spectral lines no longer appear in the spectrum

- Observe the FM spectrum (for a sinusoidal input) and derive the FM gain constant $k_f$.

- Use an audio signal as the message, and compare demodulated quality to that of AM. Also observe the FM spectrum.

![Figure 14: FM VCO Experimental Setup](image)

The second FM experiment utilizes the Colpitts Oscillator and the TDA7000 as shown in Figure 15. Again, the user sources the input message signal, bandlimited to 10 kHz. In this experiment, the FM can be generated on-board with the Colpitts Oscillator (as shown in the figure) using an injected message signal (again bandlimited 10 kHz). Alternatively, the user can attach an antenna (2 inch or greater length wire) and demodulated broadcast FM.

In either case, the TDA7000 must be tuned to the proper center frequency, which is approximately 100 MHz for the on-board oscillator and anywhere from 88–108 MHz for broadcast FM. Similar test equipment to that used for earlier experiments is recommended. Here, the student can observe the FM spectrum at higher center frequencies. Furthermore, the student can observe the frequency distribution of a commercially broadcast FM spectrum.
Figure 15: FM Experimental Setup using the TDA7000

**FDM**

The communications board is useful for conceptualizing Frequency Division Multiplexing (FDM). A recommended setup is given in Figure 16, where lab equipment is not shown for space considerations.

There are two modulation paths, one using AM modulation via the MC1496 and the other using FM modulation as generated by the ICL8038 VCO. In this experiment, the injected AM carrier frequency should differ from FM carrier frequency of 100 kHz. The two modulated signals are FDM by the action of the transmit sum block. At the output of this summing device, it is instructive to view the combined spectrum. The BPF is tuned to desired modulation path (AM or FM) and the jumpers must be configured such that the proper signal is demodulated and sent to the audio amplifier. Alternatively, the companion BPF can be used to simultaneously demodulate both waveforms.

Figure 16: FDM Experimental Setup

**AM/FM Noise Performance**

A setup for measuring noise performance is given in Figure 17, where the modulation/demodulation choice can be any of the AM/FM circuits. In this setup, the user supplies a wideband noise source, which is then filtered by the nearly flat noise BPF to create an easily analyzable bandpass random process (BRP). The student can then
observe the noise corrupted modulated waveform using the oscilloscope as well as the noise effect in the frequency domain using the spectrum analyzer. Using the oscilloscope following demodulation, the student can see the effect of the noise in the recovered signal. Finally, the noise effect can be heard in the recovered signal.

There is a wide variety of experiments to perform using noise. Examples include:

- Measurement of SNR for all modulation/demodulation schemes
- Observance of the AM SNR threshold effect.
- Observance of the dependence of FM SNR on modulation index $\beta$.
- Observance of the FM SNR threshold effect.

Figure 17: Noise Performance Setup

Implementation in the Laboratory

The course “Communication Systems” covering an introduction to analog and digital communications was delivered in FALL 2007, in which the above experiments were performed by the students in lab during the first half of the course. Unfortunately, due to PCB turnaround and assembly delays, only one platform was available for a set of five student teams. However, the described experiments were performed by all groups, but it was necessary for the majority of the groups to construct the circuits themselves on prototyping boards.

The anecdotal lesson from the experience was that the all-in-one analog communications board was a highly useful platform. Without the platform, students struggled to build and debug the circuits. Usually, at least half the lab period was consumed constructing the circuitry, complicated by secondary problems due to parasitic effects inherent with the prototyping boards. Despite these issues, the experimental setup and circuitry did an effective job of illustrating the underlying communications theory. For the group using the solitary platform, the frustration incurred by the other groups was avoided. Instead, as intended, this group was able to focus solely on the action of the hardware rather than the difficulty associated with constructing the hardware.

At the next offering of the course, sufficient communication board platforms will be available. As with our above mentioned experience, we expect a similar outcome in that
the students will experience less frustration in the lab. At that time, we expect to follow up this paper with a report describing our experiences.

**Conclusion**

The design of a low-cost, low-frequency all-in-one communications board was presented, including multiple circuits for the modulation and demodulation of AM and FM waveforms. Through the liberal use of jumper points on the circuit card, a series of analog communications experiments can be performed, including measuring noise performance. A key feature of this platform is that it allows the student to focus on the communication theory in the experiment rather than the potentially cumbersome hardware construction and debug.

**Bibliography**