Session 3447

An RF Communications Laboratory Capstone Electronic Design Experience

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Abstract

A direct conversion short wave receiver is used as a laboratory capstone electronic design experience in the Topics of Electronic Communication Laboratory offered to Electrical Engineering Technology students at the University of Cincinnati. The direct conversion receiver is used to illustrate the reception of continuous wave (CW) and single-sideband (SSB) signals in the 40-41 meter (7.0-7.3 MHz) short wave bands. The receiver is implemented with a low cost, readily available, printed circuit board and two commonly available integrated circuit chips. Electronic assembly time is approximately six hours with a total project cost, excluding resistors and capacitors, under $25. At the outset of the laboratory course, students are given a schematic diagram and are required to develop a project parts list to include component cost and supplier. Students are also required to develop and implement assembly, test, and calibration procedures for the project. Project journals and reports are used to record student ideas and experiences throughout the project.

Introduction

Time and effort spent experimenting with a properly designed double-sideband direct conversion receiver is an integral part of receiver design education. This experimentation experience is considered a fundamental educational building block by receiver experimenter's worldwide. Moreover, a simple direct conversion receiver serves as an important benchmark for comparison and it is useful for designers to periodically design, and re-design based on advances in technology, simple direct conversion receivers for applications where relaxed selectivity requirements or better sounding audio are the design objectives. "The Neophyte Receiver," an original classic work by Dillon [1], on which this paper is based, is the ultimate in simplicity and serves as an ideal starting point for students and faculty interested in exploring simple short wave receiver design concepts.

This paper presents Dillon's classic design, with slight component modification, of a direct conversion high-frequency short wave receiver. The design is of ultimate simplicity employing only two integrated circuit (IC) devices namely, a Signetics NE602A balanced modulator and an LM386 audio amplifier. The paper starts by outlining the advantages and disadvantages of direct conversion receivers. Solutions are given for most of the direct conversion design flaws. A functional block diagram describing the receiver subsystems is presented. A high-pass filter design is presented to eliminate amplitude modulation (AM) broadcast interference. The NE602A balanced mixer is introduced and the difference between “singly balanced” and “doubly balanced” modulators is explained. A singly tuned band-pass filter, attached to the input of the NE602 mixer, is designed to cover the frequency range between 7.0-7.3 MHz. The oscillator “tank circuit” components are selected to support the oscillator circuit contained in the NE602A chip. The output of the mixer is applied to a two-section audio low-pass resistor capacitor (RC) filter. A brief technical description of the LM386 audio amplifier IC is also presented.

A complete schematic of the receiver is given and a parts list is arranged in tabular form. The remainder of the paper presents a “test as you go” construction philosophy for the receiver. An assembly procedure guides construction starting with regulated dc voltages to the printed circuit board (PCB) followed by the audio circuitry. The completed LM386 circuitry is tested using a student built “twin-tee” audio oscillator. The oscillator is constructed over ground-plane using “Manhattan-Style” building techniques on a scrap piece of PCB material [2]. A low cost ($18) high-precision, 1-30 MHz, Analog Devices AD9850 Direct Digital Synthesis (DDS) chip configured as a radio frequency generator is used for calibration of the NE602A portion of the receiver circuitry.

Direct Conversion Receiver Concept

This section presents an overview of a direct conversion receiver specifically highlighting the advantages and disadvantages of the design. Some of the important advantages of the direct conversion receiver are simplicity of architecture, limited spurious responses, and compatibility with digital signal processing (DSP) based receiver architectures. Direct conversion receivers have only one frequency conversion stage as shown in Figure 1. This mixing operation happens before significant receiver gain occurs and hence mixer distortion does not significantly contribute to in-band inter-modulation. Therefore the quality of the recovered audio is almost entirely determined by the distortion properties of the audio amplification chain. Thus one can apply current audio engineering techniques yielding a sound quality that is quite remarkable given the simplicity of the receiver architecture. Moreover, improvements in DSP hardware will soon provide for rapid development and implementation of current "software defined radio" concepts.

The disadvantages of direct conversion receivers include hum, microphonics, poor dynamic range, low output power levels, and unwanted detection of AM broadcast signals. Poor dynamic range and low output power levels can be controlled by chip selection. NE602A or NE612 devices with improved dynamic range now replace the standard NE602. The LM386 audio amplifier is capable of producing power output levels ranging between 250-750 mW depending on device selection. Microphonics at 7.0 MHz is virtually non-existent and becomes most notable in receivers at frequencies above 20 MHz. In addition, rigid mechanical construction greatly minimizes microphonics at higher frequencies.

The problem of detection of AM broadcast signals is minimized by placing the receiver in a shielded enclosure, and by employing a high-pass filter at the input to the receiver as described in the next section of this paper. The remaining problem of "hum" is caused by a poorly designed dc power supply.

The problem of hum, when it occurs, normally overwhelms the receiver and reception is greatly degraded. The hum problem is isolated by replacing the power supply with a battery or battery pack. Improvements to the power supply design include using two 0.01µF ceramic capacitors, rated at 1 KV, to bypass both the hot and neutral input lines to ground at the primary winding of the transformer. On the secondary side of the transformer, each rectifier diode is shunted with a 0.01 µF ceramic capacitor. The capacitor working voltage should be rated to handle the peak inverse voltage (PIV) rating of the diode. A final improvement to the power supply includes a bifilar-wound toroidal choke using 12 turns of no.18 enamel wire on an Amidon FT-82-43 ferrite toroid. One of the bifilar-windings is placed in series with the positive power supply lead. The other winding lead is grounded at one end and the other end is used as the negative power supply lead at the output [3].

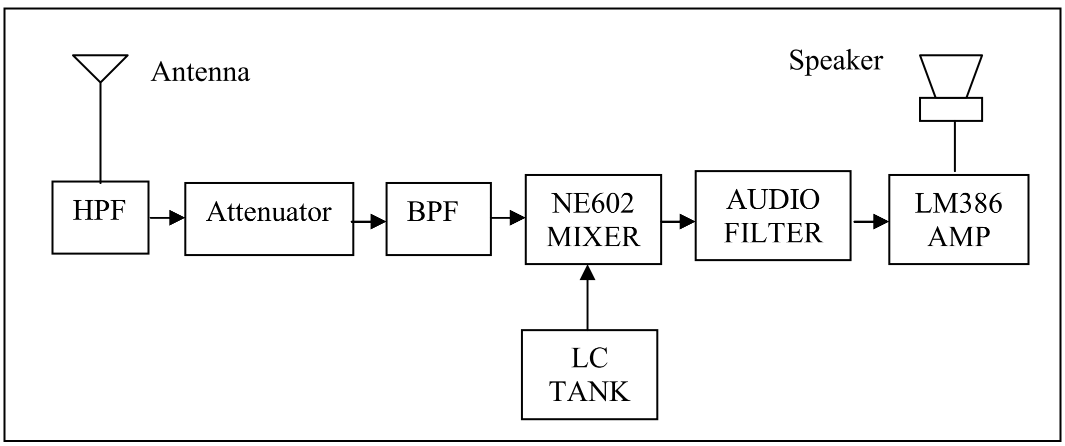

Figure 1. Block Diagram of Direct Conversion Short wave Receiver

High-Pass Filter and Attenuator

In the United States the AM broadcast band occupies frequencies ranging from 535-1705 kHz. This frequency range, starting at 540 kHz, is divided into 117 channels, designated by an assigned carrier frequency. Each channel is 10 kHz wide and contains the station carrier together with its upper and lower sidebands. Many of these stations operate with 1,000-10,000 watts of output power. A few stations are designated "clear channel" and can operate with 50,000 watts, 24 hours a day.

Serious reception problems often exist if a short wave receiver is located near an AM broadcast station. Unfortunately, the short wave receiver can only accommodate a limited amount of radio frequency energy in its front-end circuits. Technically, this level is expressed as the dynamic range specification of the receiver.

The interference problem, simply stated, is that a strong out-of-band broadcast station signal takes up so much of the receiver's dynamic range that only a small amount is left for the desired signal. The objective is to filter out or otherwise attenuate the strong out-of-band signal. Two standard interference reduction techniques are normally employed: a high-pass filter, and an in-line attenuator. In the design presented, an in-line attenuator in the form of a 1.0 KΩ audio-taper potentiometer is used to reduce all the signals to the front-end enough to drop the overall energy to a level that can be accommodated by the NE602A mixer without overload or intermediation occurring at significant levels.

A high-pass filter is attached external to the receiver and in-line with the coaxial feed from the antenna. The selected filter is a 5 pole Chebyshev design taken from reference [4]. High-pass filter no.61 was selected from the design table with a cutoff frequency of 3.49 MHz. A Chebyshev filter was chosen over elliptic because the Chebyshev design does not require tuning of the inductors. Typical attenuations for the selected filter: 3 dB at 3.05 MHz, 20 dB at 2.28 MHz, and 40 dB attenuation at 1.55 MHz. The resulting high-pass filter is shown in Figure 2 and is constructed using standard E24 series capacitors. Component selection consists of two 820 pF capacitors, and one 470 pF capacitor together with two 1.6 µH inductors. The inductors are wound on T37-2 toroidal cores. About 20 turns of no. 26 enameled magnet wire, evenly spaced around the core, yields the required inductance. The filter is built "Manhattan style" on a scrap piece of printed circuit board and enclosed in a metal container. Standard Bayonet Neill Concelman (BNC) connectors are placed on each end of the enclosure.

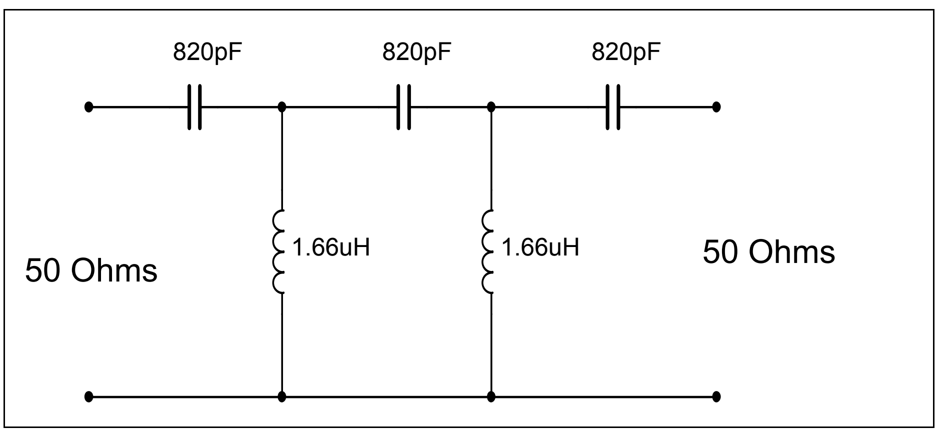

Figure 2. Chebyshev 5 Element, 50 Ω High-Pass Filter

NE602A Doubly Balanced Mixer

The terms "singly balanced" and "doubly balanced" are often used to describe mixers or balanced modulators. Mixer outputs generally include the input signals together with signals containing frequencies of the sum and differences of the inputs. The term singly balanced refers to a mixer where the local oscillator output signal has been suppressed. The output from a doubly balanced mixer is even more desirable because both the local oscillator and the incoming signal are nulled out. Thus the only signals present at the output are signals containing the sum and difference frequencies of the input signals. The clear advantage of the doubly balanced mixer is that the stages following the mixer are not contaminated by unwanted signals. Also, balanced mixers generally tend to have a higher dynamic range than non-balanced configurations [5]. The NE602A is an example of a low cost doubly balanced mixer that is commonly used in direct conversion receiver applications. The NE602A features good noise rejection and reasonable third-order intermodulation performance. The noise figure is 5 dB at 45 MHz, and the third-order intercept point is on the order of -15 dBm referenced to a matched input. The NE602 is capable of providing 0.2 µV sensitivity in receiver circuits without external radio frequency (RF) amplification.

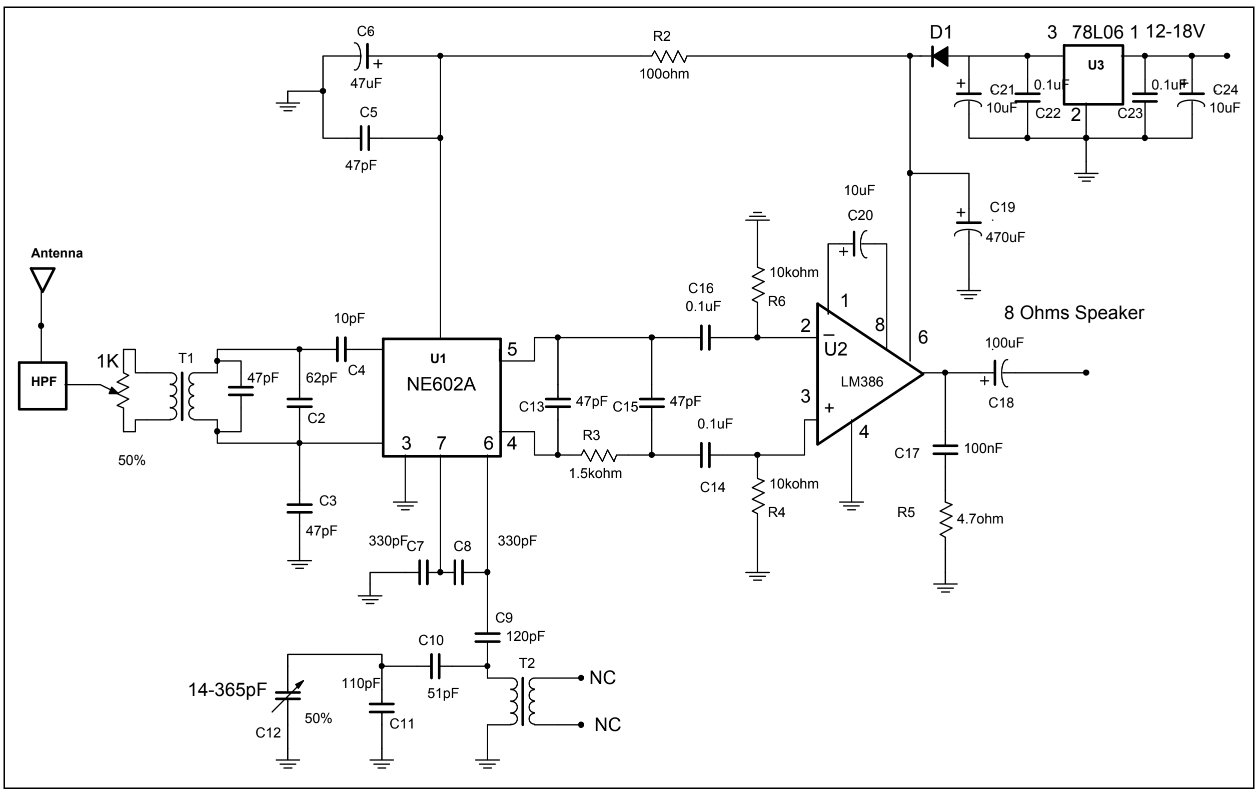

Figure 3. Schematic of Direct Conversion Receiver

Band-Pass Filter

The band-pass filter is a "singly tuned" LC circuit with a center frequency of 7.0 MHz. A bandwidth of 0.6 MHz was selected so that the filter 3 dB frequencies would span the range from 6.7-7.3 MHz. Thus, the loaded Q of the resonator is 7/0.6 or 11.67. The inductor used for the resonator is a standard 10.7 MHZ intermediate frequency (IF) transformer with and internal capacitance of 47 pF as shown in Figure 3. The transformer, T1, has a 7:1 turns ratio and a 14T secondary winding with an inductance of 4.5 μH and an unloaded $Q_u = 95$. The external loading is defined by Q_e and satisfies the relation $Q_L^{-1} = Q_e^{-1} + Q_u^{-1}$. After substitution $Q_e = 13.3$.

The value of the capacitance required to resonate the 4.5 μH inductance of the secondary winding at 7.0 MHz is given by the formula $C = 1/\omega^2 L = 114.87$ pF. Also, the corresponding inductive reactance at 7.0 MHz is $X_L = 197.92\ \Omega$. The equivalent parallel resistance that must load the resonator externally is given by $Rp= X_L Q_e$ and is 2632.34 Ω. Half of the external resistance loading must come from each side of the doubly terminated filter [6]. As a consequence, each resistive end loading must appear as 2Rp or 5264.68 Ω in parallel with the LC resonator. Figure 4 is an equivalent representation of the loaded resonant circuit. With some elementary simplification the circuit can be shown to be equivalent to an RLC parallel network with R= 2632.24 Ω, L= 4.5 μH, and C= 114.87 pF. The parallel RC network consisting of 6.8418 pF and 5264.68 Ω can be transformed to an equivalent series network consisting of 9.57 pF and 1500 Ω. The 1500 Ω represents the input resistance between pins 1 and 2 of the NE602A. The capacitor is rounded to 10 pF and labeled as C4 in Figure 3. The 47 pF capacitor is internal to the 10.7 MHz IF transformer and is in parallel with the secondary winding of T1 as shown in the figure. Transformer T1 has a 7:1 turns ratio and the resistance 2Rp transforms to 107.44 Ω (5264.68 $\Omega/7^2$) at the primary input. This is not the best match to 50 Ω but is adequate given the turn's ratio limitation of the transformer. The remaining 61.035 pF capacitor is rounded to 62 pF and is labeled C2 in Figure 3. Capacitor C3 is a bypass capacitor.

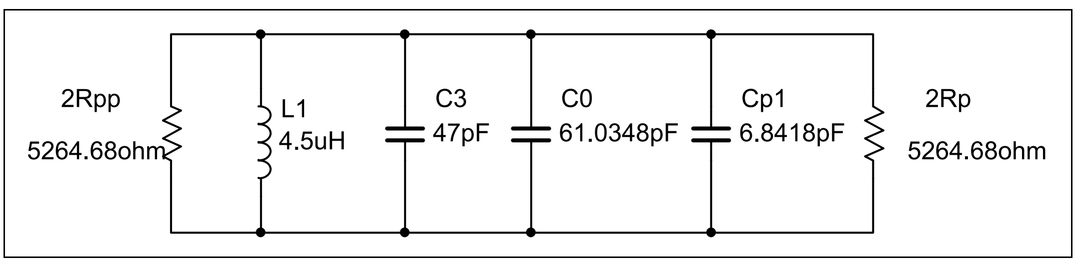

Figure 4. Singly Tuned Doubly terminated Band-Pass Filter

NE602A External Oscillator Components

Simplicity of design dictates a standard LC variable frequency oscillator for the short wave receiver. This approach is popular in the literature because the NE602A mixer IC already has a built-in oscillator that includes separate input and output pins to accommodate an external LC resonant tank circuit. This design implements a parallel-tuned Colpitts oscillator as shown in Figure 3. The NE602A oscillator contains a bipolar junction transistor (BJT) with its collector tied to the positive supply voltage. The base of the transistor is available at pin 6 while pin 7 goes to the emitter. The internal bias resistors set the oscillator quiescent collector current to approximately 0.25 mA. The feedback capacitors are placed between pins 6 and 7 and from pin

7 to ground. A 120 pF capacitor, C9, couples the base of the transistor to the rest of the tuned circuit.

Capacitors C7 and C8 are generally chosen larger in value than capacitors C9 and C10. Thus only a small fraction of the total "tank voltage" is applied to the BJT circuit, and the BJT is considered to be only lightly coupled to the tank circuit. The BJT is driven by the sum of the voltages across C7 and C8, while the BJT circuit, in turn, drives the voltage across C7 alone. Thus, the LC tank circuit functions as a resonant voltage step-up transformer and therefore compensates for the less than unity voltage gain of the voltage follower amplifier [7].

The design objective is to select capacitors to cover the tuning range from 7.0 -7.3 MHz. This segment of frequencies contains CW, SSB, and AM broadcast stations, thus illustrating the detection of several modulation techniques presented in lecture portion of the course. As an aid to selecting the external capacitors, a spreadsheet program was used to fine-tune the combinations. Capacitors C7, C8, and C9 are in series and exhibit a total capacitance of 69.47 pF. Capacitor C12 varies from 14-365 pF and is in parallel with C11. Employing standard circuit theory techniques, the total capacitance in parallel with the 4.5 μH inductor varies from a maximum of 115.53 pF to a minimum of 105.61 pF. Thus, the oscillator tuning range varies from 6.98 MHz, at the low end of the 40 meter band, to 7.30 MHz at the top end. Mechanical rigidity and component selection are the keys to successful oscillator construction. Traditionally silver-mica fixed capacitors have been used extensively in oscillators.

Audio Filter

The output of the balanced mixer consists of audio signals, which are the sum and difference of the radio frequencies input at the antenna and the local oscillator. A low-pass filter removes the summation frequency components allowing only the difference frequencies to be amplified. The audio filter is a two stage RC filter consisting of components C13, C15, and R3 as shown in Figure 3. Setting resistor R3 at 1500 Ω and C13 and C15 equal to 47 pF yields a cutoff frequency of 845 Hz which is ideal (nominally 750 Hz) for CW reception. SSB and AM reception is more robust and requires a larger bandwidth. Hence, capacitors C13 and C15 are reduced to 15 pF. The smaller capacitance widens the filter 3dB bandwidth to 2.65 kHz, providing a more pleasant listening experience. Capacitors C14 and C16 remove the dc component of the voltage from the input of the LM386 audio amplifier and thus stabilize the amplifier against changes in the device's bias point. The 10 KΩ resistors, R4 and R6, establish the actual bias point of the LM386.

LM386 Audio Amplifier

The audio gain requirements in a direct conversion receiver tend to be very high in order to compensate for the low output level of the mixer. The audio amplifier increases the signal level by an amount that creates a comfortable listening with a pair of headphones or small speaker. The frequency response of the amplifier also tailors the band-pass characters of the audio response. The LM386 is a low power "audio system on a chip" that requires a minimum of external components. The IC chip includes both an audio preamplifier and power amplifier capable of producing between 250-750 mW of audio power to drive a small 8 Ω speaker. The IC chip is available in several power variations given by the -1 to -3 after the part number. The -3 indicates that the IC will supply up to 750 mW to the load. The device can operate between 4-12 volts and has 50 KΩ input impedance. The amplifier is driven in the differential rather than single-ended mode, which greatly eliminates AM broadcast breakthrough common to many direct conversion designs. The series combination of C17 and R5 at the output is a "snubber" eliminating high-frequency oscillations at the output. The nominal gain of the amplifier is set at 20 (26 dB). The addition of a 10μF capacitor, C20, between pins 1 and 8 provides for a gain of 200 or 46 dB for the amplifier.

Receiver Construction

A complete parts list for the receiver is provided in Table 1. The NE602A specification limits the device supply voltage to 8.0 volts. A simple but not necessarily cost effective solution is to us a standard 8 volt regulator. For this receiver simplicity reigns and a 78L08 IC voltage regulator was selected for the design as shown in Figure 3. A standard dc coaxial power jack is mounted to the enclosure and serves as an interface to an external dc source. Reverse polarity protection is a must for second year engineering technology students; thus a silicon diode is placed in the positive power supply lead at the output of the regulator. Experience also indicates that when developing a prototype that IC chips should be placed in sockets whenever possible, allowing devices to be easily replaced during construction and testing.

Once the regulator and IC sockets are in place a dc voltage check is made on the printed circuit board. Data are recorded in student notebooks and compared with values established by the instructor. Out of tolerance voltages are noted and problems corrected at the outset. The components associated with the LM386 are then attached to the board with particular attention focused on capacitor polarity. To test the audio amplifier a standard "twin-tee" audio oscillator was built by the students using "Manhattan-Style" building techniques on a scrap piece of PCB material. The oscillator is powered by a 9 volt battery and is implemented using both 2N3904 and 2N3906 transistors [8]. The oscillator signal is injected at pin 3 of the LM386 and the output of the amplifier is connected to a small speaker available on laboratory trainers. Students are generally quite happy when an amplified tone emanates form the speaker. They also become confident that if subsequent problems exist that they must reside in the mixer circuit.

The NE602 double balanced mixed circuit is preceded by a band-pass filter attached to the antenna at one end and the NE602 pins 1 and 2 on the other. The inductive component of the band-pass filter is a standard, commercially available, 10.7 MHz intermediate-frequency (IF) transformers with a built in 47 pF capacitor across its secondary winding. The transformer together with a collection of silver-mica capacitors forms the singly tuned doubly terminated band-pass filter. This filter has a center frequency of 7.0 MHz and a bandwidth of 0.6 MHz. Standard value capacitors are chosen and the filter is easily attached to the PCB board.

The external oscillator tank circuit consists of only the secondary winding of the IF transformer with the internal capacitor removed. The series-parallel collection of capacitors forming the tank

Table 1. Parts list for Direct Conversion Receiver

Qty	Component	Description	Designator	Supplier	Part Number	Unit	Cost
1	PCB	Circuit Board	N/A	Far Circuits	QST 84	$4.50	$4.50
1	NE602AN	Mixer	U1	Ocean State	NE602AN	$2.49	$2.49
1	LM3869	500 Mw Amp	U2	Ocean State	LM386N	$0.99	$0.99
1	78L08	8V Regulator	U3	Ocean State	78L08	$0.59	$0.59
1	Air-dielectric Cap.	14-365 pF	C12	Ocean State	BC-14400	$10.95	$10.95
2	IF Transformer	10.7 MHz	T1, T2	Mouser	42 IF 123	$0.79	$1.58
2	IC Socket	8 Pin	U1, U2	Mouser	575-193308	$0.26	$0.52
1	Power Connector	2.1 mm Coaxial	P1	Mouser	163-5004	$0.63	$0.63
1	Ant. Connector	BNC	J1	Mouser	523-31-5538-10-RFX	$1.11	$1.11
1	Diode	Polarity Protect	D1	Ocean State	1N4001	$0.10	$0.10
1	Silver Mica	62 pF	C2	Ocean State	CSM62	$0.55	$0.55
1	Silver Mica	10 pF	C4	Ocean State	CSM10	$0.55	$0.55
4	Ceramic Disc	47 pF	C3, C5, C13, C15	Ocean State	CD47-5	$0.12	$0.48
2	Silver Mica	330 pF	C7, C8	Ocean State	CSM330	$0.65	$1.30
1	Silver Mica	120 pF	C9	Ocean State	CSM120	$0.65	$0.65
1	Silver Mica	51 pF	C10	Ocean State	CSM51	$0.55	$0.55
1	Silver Mica	110 pF	C11	Ocean State	CSM110	$0.65	$0.65
5	Ceramic Disc	0.1 μF	C14, C16, C17, C22, C23	Ocean State	CD104-5	$0.20	$1.00
1	Electrolytic	47 μF	C6	Ocean State	CER10-25	$0.17	$0.17
1	Electrolytic	470 μF	C19	Ocean State	CER10-25	$0.17	$0.17
1	Electrolytic	100 μF	C18	Ocean State	CER10-25	$0.17	$0.17
1	Electrolytic	10 μF	C20,C21,C24	Ocean State	CER10-25	$0.17	$0.17
1	Audio Taper	1KΩ Pot.	R1	Mouser	31VM301	$1.72	$1.72
1	Resistor	100 Ω, 1/4 W	R2	Mouser	291-100	$0.07	$0.07
1	Resistor	1.5 KΩ, 1/4 W	R3	Mouser	291-1.5K	$0.07	$0.07
2	Resistor	10 KΩ, 1/4 W	R4, R6	Mouser	291-10K	$0.07	$0.14
1	Resistor	10 KΩ, 1/4 W	R5	Mouser	291-4.7K	$0.07	$0.07
						Total	**$23.37**

circuit extends the tuning range to cover the entire 40-41 meter short wave bands. The large variable tuning capacitor requires special mechanical considerations. The capacitor is normally mounted through a hole drilled in the front of the chassis or enclosure. An L-shaped bracket attached to the rear portion of the stator stabilizes the unit from rotating when the knob is turned. The NE602A is checked for proper operation by injection a small radio frequency (RF) signal at the antenna input. An RF signal at 7.020 MHz produces a 20 kHz audio signal at pin 5. Calibration of the receiver is achieved by injecting a small RF signal at 7.0 MHz at the antenna and adjusting the slug-tuning element in the oscillator inductor. The variable capacitor should be fully meshed providing maximum capacitance during calibration. A low cost ($18) high-precision, 1-30 MHz, Analog Devices AD9850 Direct Digital Synthesis (DDS) chip configured as a radio frequency generator is available as a surface-mount kit [9]. Please note that for surface mount soldering, Radio Shack 62/36/2 (0.015 inch diameter) silver-bearing solder is highly recommended. The serial port on of a computer is used to send a control word to the DDS chip to set the frequency.

Comments from Student Project Reports

To date four RF Communication Laboratory sections (48 short wave radio projects) have been taught using the Capstone Electronic Design Experience as a central theme for the laboratory. The following comments are extracted from student project reports. Overall, the comments are very encouraging [10]:

- "The Neophyte Receiver design and building experience diverged from my typical laboratory experience in several ways. Normally, the intent is for 'laboratory experiments' to enforce lecture topics. That said, a definite sense of compensation for hours spent in the lab could sometimes be lost, especially for an applied engineering technology student. A project such as building a short wave radio gives tangible purpose to time spent with hardware and serves to teach skills that might not otherwise be learned. More indefinable rewards were the ones that mattered most."

- "Attention to detail, clean solder joints, use of IC sockets, proper capacitor polarity; these are all must be enforced by the builder of the radio. Shortcuts in any of these areas are immediately evidenced as output that differs from expectations. As a capstone laboratory project, the receiver construction required circuit analysis skills, understanding of basic communications theory, and the ability to troubleshoot potentially non-working systems. More satisfying than any lab period up to this point in the curriculum, the radio, for lack of better terms, 'did something.' From the dc voltage for input, to the networking blocks of mixing, filtering and amplifying, to the clean audio output, the overall goal was not just gather data and calculate percent error. This more elusive goal was to build an electronic device that could pull waves out of the air and convert them to sound. Thus, a sense of pride in workmanship and follow-through were unintended skills that seemed most satisfying."

- “It is important to observe how electronic systems interface with the outside world. Finishing the PCB board was only half the battle. The board then had to be mounted to protect it from damage. Power and antenna connectors, tuning capacitor knob, indicator lights; these all had to be user friendly so that someone without an electronic background could operate the radio without damage. Consequently, on a small scale, aspects of design were being learned.”

- "Overall, The Neophyte Receiver project leaves the student with practical experience in building hardware, including cost effectiveness and feasibility. Arguably more important, is recognizing the value of lab time, attention to detail, and time-management. These are areas that are critical to success in an engineering discipline and are appreciated after an experience such as this is completed."

Conclusion

This paper describes a simple direct conversion receiver project that introduces students to the 40-41 meter short wave bands (7-7.3 MHz) and provides them with an opportunity to listen to CW, SSB and AM signals that were heretofore only described mathematically in the lecture. The course project relies heavily on skills previously learned in the electronics sequence and serves a vehicle to introduce system design concepts, elementary packaging, and subsystem specifications. Only a modest amount of construction, testing, and calibration skills are required for successful completion of the project.

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Biography

James O. Everly is an Associate Professor of Electrical and Computer Engineering Technology at the University of Cincinnati. He received a BSEE and MSEE from The Ohio State University in 1969 and 1970, respectively. He is and a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE) and a registered professional engineer in the state of Ohio. He is currently Vice-Chair of the IEEE Cincinnati Section, and in 1997 he received the IEEE Professional Achievement Award. He has held several research and management positions in industry working for such companies as Battelle's Columbus Laboratories, Rockwell International, and Claspan Corporation. He joined the University of Cincinnati in 1985.