INTRODUCTION

Consider the magic of radio. Portable, even hand-held, short-wave transmitters can reach thousands of miles beyond the horizon. Tiny microwave transmitters aboard space probes return data from across the solar system. And all at the speed of light. Yet before the late 1800s there was nothing to suggest that telegraphy through empty space would be possible even with mighty dynamos, much less with insignificantly small and inexpensive apparatus. The Victorians could extrapolate from experience to imagine flight aboard a steam-powered mechanical bird or space travel in a scaled-up Chinese skyrocket. But what experience would even have hinted at wireless communication? The key to radio came from theoretical physics. Maxwell consolidated the known laws of electricity and magnetism and added the famous displacement current term, \( \partial D/\partial t \). By virtue of this term, a changing electric field produces a magnetic field, just as Faraday had discovered that a changing magnetic field produces an electric field. Maxwell’s equations predicted that electromagnetic waves can break away from the electric currents that generate them and propagate independently through space with the electric and magnetic field components of the wave constantly regenerating each other.

Maxwell’s equations predict the velocity of these waves to be \( 1/\sqrt{\varepsilon_0\mu_0} \) where the constants \( \varepsilon_0 \) and \( \mu_0 \) can be determined by simple measurements of the static forces between electric charges and between current-carrying wires. The dramatic result is, of course, the experimentally known speed of light, \( 3 \times 10^8 \) m/s. The electromagnetic nature of light is revealed. Hertz conducted a series of brilliant experiments in the 1880s in which he generated and detected electromagnetic waves with wavelengths very long compared to light. The utilization of Hertzian waves (the radio waves we now take for granted) to transmit information developed hand-in-hand with the new science of electronics.

Where is radio today? AM radio, the pioneer broadcast service, still exists along with FM, television, and two-way communication. Now radio also includes radar, surveillance, navigation and broadcast satellites, cellular telephones, remote control devices, and wireless data communications. Applications of radio frequency (RF) technology outside radio include microwave heaters, medical imaging systems, and cable television.
Radio occupies about eight decades of the electromagnetic spectrum, as shown in Figure 1-1.

RF CIRCUITS

The circuits discussed in this book generate, amplify, modulate, filter, demodulate, detect, and measure ac voltages and currents at radio frequencies. They are the blocks from which RF systems are designed. They scale up and down in both power and frequency. A six-section bandpass filter with a given passband shape, for example, might be large and water cooled in one application but subminiature in another. Depending on the frequency, this filter might be made of sheet metal boxes and pipes, of solenoidal coils and capacitors, or of piezoelectric mechanical resonators, yet the underlying circuit design remains the same. A class-C
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amplifier circuit might be a small section of an integrated circuit for a wireless data link or the largest part of a multimegawatt broadcast transmitter. Again, the design principles are the same.

NARROW-BAND NATURE OF RF SIGNALS

Note that most of the RF allocations have small fractional bandwidths, that is, the bandwidths are small compared to the center frequencies. The fractional bandwidth of the signal from any given transmitter is less than ten percent – usually much less. This means that the RF voltages throughout a radio system are very nearly sinusoidal. An otherwise purely sinusoidal RF “carrier” voltage must be modulated (varied in some way) to transmit information. Every type of modulation (audio, video, pulse, digital coding, etc.) works by varying the amplitude and/or the phase of the carrier. An unmodulated carrier has only infinitesimal bandwidth; it is a pure spectral line. Modulation always broadens the line into a spectral band, but the energy clusters around the carrier frequency. Oscilloscope traces of the RF voltages in a transmitter on a transmission line or antenna are therefore nearly sinusoidal. When modulation is present, the amplitude and/or phase of the sinusoid changes but only over many cycles. Because of this narrow-band characteristic, elementary sine wave ac circuit analysis serves for most RF work.

AC CIRCUIT ANALYSIS – A BRIEF REVIEW

The standard ac circuit theory that treats voltages and currents in linear networks is based on the linearity of the circuit elements. When a sinusoidal voltage or current generator drives a circuit, the resulting steady-state voltages and currents will all be perfectly sinusoidal and will have the same frequency as the generator. Normally we find the response of driven ac circuits by a mathematical artifice. We replace the given sinusoidal generator by a hypothetical generator whose time dependence is $e^{jwt}$ rather than $\cos(\omega t)$ or $\sin(\omega t)$. This source function has both a real and an imaginary part since $e^{jwt} = \cos(\omega t) + j \sin(\omega t)$. Such a nonphysical (because it is complex) source leads to a nonphysical (complex) solution. But the real and imaginary parts of the solution are separately good physical solutions that correspond to the real and imaginary parts of the complex source. The value of this seemingly indirect method of solution is that the substitution of the complex source converts the set of linear differential equations into a set of easily solved linear algebraic equations. When the circuit has a simple topology, as is often the case, it can be
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reduced to a single loop by combining obvious series and parallel branches. Several computer programs are available to find the currents and voltages in complicated ac circuits. Most versions of SPICE will do this steady-state ac analysis (which is much simpler than the transient analysis which is their primary function). Special linear ac analysis programs for RF and microwave work such as COMPACT, TOUCH- STONE, and MMICAD include circuit models for strip lines, waveguides, and other RF components. You can write a simple program to analyze ladder networks (see Problem 3) that will analyze most filters and matching networks.

IMPEDEACE AND ADMITTANCE

The coefficients in the algebraic circuit equations are functions of the complex impedances (V/I), or admittances (I/V), of the RLC elements. The voltage across an inductor is \( L \frac{di}{dt} \). If the current is \( I_0 e^{j\omega t} \), then the voltage is \( (j\omega L)I_0 e^{j\omega t} \). The impedance and admittance of an inductor are therefore respectively \( j\omega L \) and \( 1/(j\omega L) \). The current into a capacitor is \( C \frac{dv}{dt} \), so its impedance and admittance are \( 1/(j\omega C) \) and \( j\omega C \). The impedance and admittance of a resistor are just \( R \) and \( 1/R \), respectively. Elements in series have the same current, so their total impedance is the sum of their separate impedances. Elements in parallel have the same voltage, so their total admittance is the sum of their separate admittances. The real and imaginary parts of impedance are called resistance and reactance while the real and imaginary parts of admittance (the reciprocal of impedance) are called conductance and susceptance.

SERIES RESONANCE

A capacitor and inductor in series have an impedance \( Z_s = j\omega L + 1/j\omega C \). This can be written as \( Z_s = j(L/\omega)(\omega^2 - 1/LC) \), so the impedance is zero when the (angular) frequency is \( 1/\sqrt{LC} \). At this resonant frequency, the series LC circuit is a perfect short circuit (Figure 1-2). Equal voltages are developed across the inductor and capacitor but they have opposite signs, and the net voltage drop is zero. At resonance and in the steady state there is no transfer of energy in or out of this combination. (Since the overall voltage is always zero, the power, IV is always zero.) However, the circuit does contain stored energy, which simply sloshes back and forth between the inductor and the capacitor. Note that this circuit, by itself, is a simple bandpass filter.
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Figure 1-2. Series resonant LC circuit.

PARALLEL RESONANCE

A capacitor and an inductor in parallel have an admittance \( Y_p = j\omega C + 1/j\omega L \), which is zero when the (angular) frequency is \( 1/\sqrt{LC} \). At the resonant frequency, the parallel \( LC \) circuit is a perfect open circuit – a simple bandstop filter (Figure 1-3). Like the series \( LC \) circuit, the parallel \( LC \) circuit stores a fixed quantity of energy for a given applied voltage. These two simple combinations are important building blocks in RF engineering.

Figure 1-3. Parallel resonant LC circuit.

NONLINEAR CIRCUITS

Many important RF circuits, including mixers, modulators, and detectors, are based on nonlinear circuit elements such as diodes and saturated transistor switches. Here we cannot use the linear \( e^{jwt} \) analysis but must use time domain analysis. Usually the nonlinear elements can be replaced by simple models to explain the circuit operation. Full computer modeling can be used for accurate circuit simulations.

PROBLEMS

1. A generator has a source resistance \( r_s \) and an open circuit rms voltage \( V_0 \). Show that the maximum power available from the generator is given by \( P_{\text{max}} = V_0^2/(4r_s) \) and that this maximum power will be delivered when the load resistance, \( R_L \), is equal to the source resistance, \( r_s \).

2. A passive network, for example a circuit composed of resistors, inductors, and capacitors, is placed between a generator with source resistance \( r_s \) and a load resistor \( R_L \). The power response of the network (with
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respect to these resistances) is defined as the fraction of the generator’s maximum available power that reaches the load. If the network is lossless, that is, contains no resistors or other dissipative elements, its power response function can be found in terms of the impedance $Z_m$, seen looking into the network with the load connected. Show that the expression for the power response of the lossless network is given by

$$P(\omega) = \frac{4r_i R}{(R + r_i)^2 + X^2}$$

where $R = \text{Re}(Z_m)$ and $X = \text{Im}(Z_m)$.

3. Most filters and matching networks take the form of the ladder network shown below. Write a program that reads a circuit file specifying the series and shunt elements and finds the power response function as defined in Problem 2. (This problem will be of use in many later problems and will be expanded in scope several times.)

**Hints:** One approach is to begin from the load resistor and calculate the input impedance as the elements are added, one by one. When all the elements are in place, the formula in Problem 2 gives the power response — as long as none of the elements are resistors. The process is repeated for every desired frequency.

A better approach, which is no more complicated and which allows resistors, is the following: Assume a current of $1 + j0$ amperes is flowing into the load resistor. The voltage at this point is therefore $R_i + j0$ volts. Move to the left one element. If this is a series element, the current is unchanged but the voltage is higher by $IZ$, where $Z$ is the impedance of the series element. If the element is a shunt element, the voltage remains the same but the input current is increased by $VY$ where $Y$ is the admit-
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tance of the shunt element. Continue adding elements, one at a time, updating the current and voltage. When all the elements are accounted for, you have the input voltage and current, and could calculate the total input impedance of the network terminated by the load resistor. Instead, however, go one more step, treating the source resistance, $r_s$, as just another series impedance. This gives you the voltage of the source generator, from which you can calculate the maximum power available from the source. Since you already know the power delivered to the load, $(I)^2R_L$, you can find the power response. Repeat this process for every desired frequency.

The ladder elements (and the start frequency, stop frequency, and frequency increment if you like) can be treated as data, that is, they can be located together in a block of the program or in a file so they can be changed easily. For now the program only needs to deal with six element types: series and parallel inductors, capacitors, and resistors. Each element in the circuit file must therefore have an identifier such as “PL,” “SL,” “PC,” “SC,” “PR,” and “SR” or 1, 2, 3, 4, 5, 6, or whatever, plus the value of the component in henrys, farads, or ohms. Organize the circuit file so that it begins with the element closest to $R_L$ and ends with some identifier such as “EOF” (for “end of file”) or some distinctive number.

An example of this program, written in Microsoft QBaasic, is shown here, together with some output data from an example circuit file (line number 600). Use this circuit and data to check your own program. You will want to add some headings for the print-out, and maybe graphing capability.
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Qbasic program to calculate transmission through an RCL ladder network
RESOURCE= 1000: RLOAD = 50
FOR F=1E6 TO 2E6 STEP 5E4
OMEGA=2 * 3.14159 * F
IR=1: II=0: VR= IR*RLOAD: VI=II*RLOAD 'assume 1 amp into load.'
READ TYPES "PC" IS parallel capacitor, "SL" is series inductor, etc.
DO UNTIL TYPES = "EOF" 'EOF denotes end of circuit file.
READ VALUE
IF TYPES = "PC" THEN B= OMEGA * VALUE: G=0: GOSUB 400 'to update I.
IF TYPES = "SC" THEN X= -1/(OMEGA * VALUE): R=0: GOSUB 500 'to update V.
IF TYPES = "PL" THEN B= 1/(OMEGA * VALUE): G=0: GOSUB 400 'to update I.
IF TYPES = "SL" THEN X= OMEGA * VALUE: R=0: GOSUB 500 'to update V.
IF TYPES = "PR" THEN G= 1/VALUE: B=0: GOSUB 400 'to update I.
IF TYPES = "SR" THEN R= VALUE: X=0: GOSUB 500 'to update V.
READ TYPES
LOOP
R=RESOURCE X=0: GOSUB500 'to get generator voltage.
'calculate fraction of maximum possible power transfer.
FRAC= (1^2*RLOAD)/((VR*VR+VI*VI)/(4*RESOURCE))
PRINT F, FRAC, 10/LOG(10)*LOG(FRAC)'freq, frac & frac in decibels
RESTORE 600 'rewind data.
NEXT F
END
400 ' subroutine to update real and imaginary parts of I.
IR=IR+(VR*G - VI*B): II=II+(VI*G + VR*B): RETURN
500 ' subroutine to update real and imaginary parts of V.
VR=VR+(IR*R - II*X): VI=VI+(II*R + IR*X): RETURN
'example circuit file: a 463 pF parallel capacitor and
a 23.1 microhenry series inductor
600 DATA SL,23.1E-6,PC,463E-12,EOF

Program output

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Fraction</th>
<th>dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.4179</td>
<td>-3.789</td>
</tr>
<tr>
<td>1.05</td>
<td>0.4601</td>
<td>-3.372</td>
</tr>
</tbody>
</table>
IMPEDEANCE MATCHING

Matching normally means the use of a lossless (nonresistive) network between an ac (here RF) source and a load in order to maximize the power transferred to the load. An antenna tuner, for example, is a device to match an antenna to a transmitter. The same circuit, if it is built into the transmitter, might be called an output tuner. In the direct current (dc) circuit of Figure 2-1, maximum power is transferred when the load resistance is equal to the source resistance. (You can verify that making the load resistance equal the source resistance maximizes the current × voltage product of the load.)

\[ R_L = R_S \]

**Figure 2-1.** Maximum power is transferred to \( R_L \) when \( R_L = R_S \).

TRANSFORMER MATCHING

In the case of an alternating current (ac) source, a transformer can make the load resistance match the source resistance (and vice versa), as shown in Figure 2-2. The ac situation often has a complication: the source and/or load may be reactive, that is, have an unavoidable built-in reactance. An example of a reactive load is an antenna; many antennas are purely resistive at only one frequency. Above this resonant frequency they usually look like a resistance in series with an inductor, and below the resonant frequency...
frequency they look like a resistance in series with a capacitor. An obvious way to deal with this is first to cancel the reactance to make the load and/or source impedance purely resistive and then use a transformer to match the resistances. In the circuit of Figure 2-3, an inductor cancels the reactance of a capacitive (but not purely capacitive) load. If we are working at 60 Hz we would say the inductor corrects the power factor of the load.

From the standpoint of the load, the matching network converts the source impedance, $R_s + j0$, into the complex conjugate of the load impedance. And in general, when a matching device is used between two devices, each device will look into an impedance that is the complex conjugate of its own impedance. Whenever the source and/or load has a reactive component, the match will be frequency-dependent, that is, away from the design frequency the match will not be perfect. In fact, with reactive sources and/or reactive loads, any lossless matching circuit will be frequency-dependent – a filter of some kind – whether we like it or not.

**L-NETWORKS**

More often than not, matching circuits use no transformers (i.e. no coupled inductors). Figure 2-4 shows a two-element L-network (a rotated letter “L”) that will match a source to a load resistor whose resistance is smaller than the source resistance. The trick is to put a reactor, $X_p$, in parallel with the larger resistance. We will consider a specific example: $R_s = 1000$ ohms and $R_L = 50$ ohms. The impedance of the left-hand side is given by

$$Z_{left} = R_{left} + jX_{left} = \frac{1,000jX_p}{1,000 + jX_p} = \frac{(1,000jX_p)(1,000 - jX_p)}{(1,000 + jX_p)(1,000 - jX_p)}$$

$$= \frac{1,000^2X_p^2 + 1,000X_p^2}{1,000^2 + X_p^2}. \quad (2-1)$$

We can pick the value of $X_p$ so that the real part of $Z_{left}$ will be 50 ohms, that is, equal to the load resistance. Using Equation (2-1), we find that