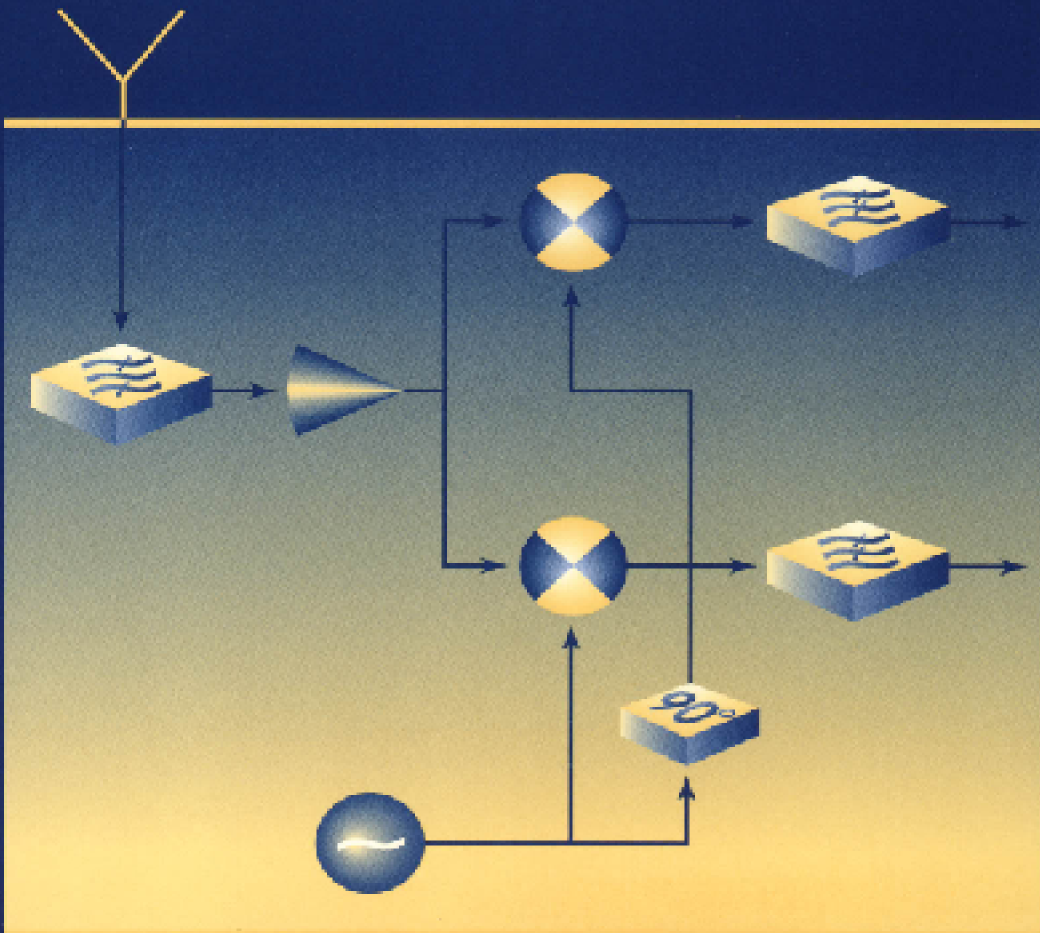
SOLUTIONS MANUAL

MICROWAVE AND RF DESIGN OF WIRELESS SYSTEMS



DAVID M. POZAR

Solutions Manual

for

Microwave and RF Design of Wireless Systems

This manual contains solutions for the end-of-chapter problems in **Microwave and RF Design of Wireless Systems**. Hopefully there is a good selection of theory versus design-type of problems, but the instructor should be able to use these as starting points to generate additional problems for homework assignments and exams. Many of the tuning, filter, amplifier, and oscillator problems will be facilitated if the reader has access to a commercial microwave CAD package, such as HP-MDS, Ansoft Serenade, or similar, but this is not essential.

Many of the solutions given here have been verified with known results, with independent solutions by others, or by computer simulation. Answers to these problems are indicated with a small check mark. Nevertheless, there likely are errors that have slipped through, and the author will be grateful if these are brought to his attention.

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Chapter 1

1.1 US cellular telephone statistics are given in the table below, from the CTIA annual survey.

Yearly subscriber growth can be estimated as:

97-98 subscriber growth = (69.2 - 55.3)/55.3 = 25%

98-99 subscriber growth = (86.0 - 69.2)/69.2 = 24%

Then we estimate year 2000 subscribers at

86.0M (1.24) = 106.6 M

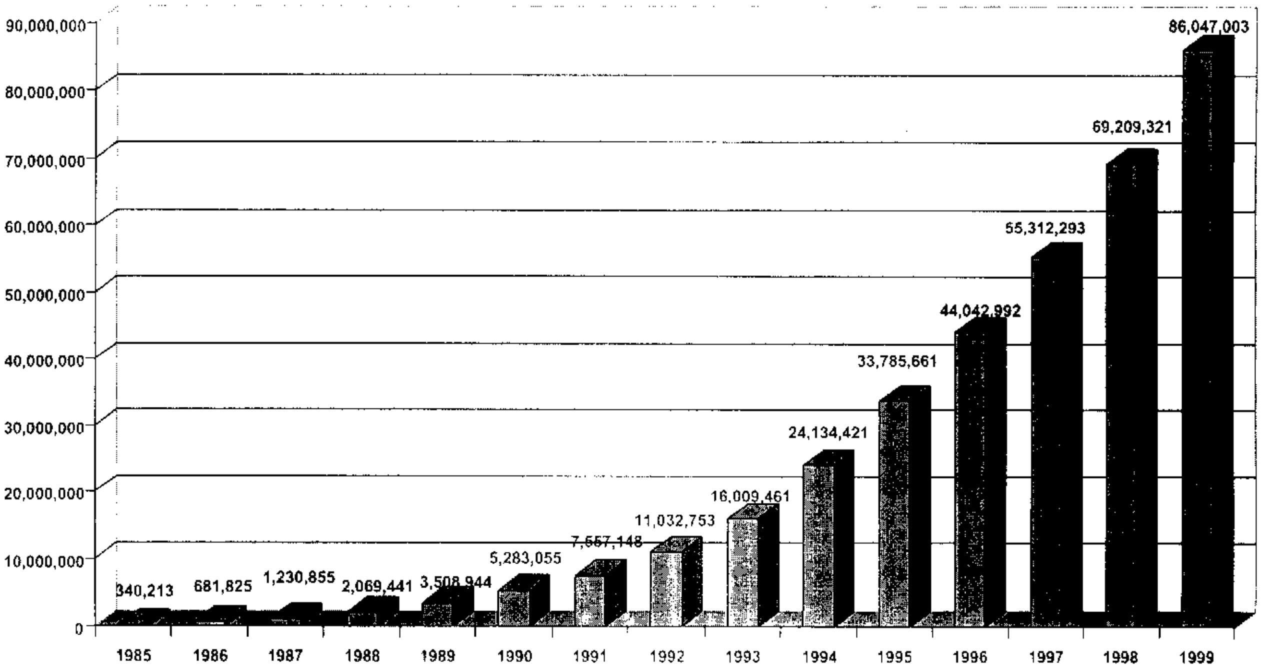
Graphs showing subscriber growth and average monthly bills are shown on the following page.

THE CELLULAR TELECOMMUNICATIONS INDUSTRY ASSOCIATION'S ANNUALIZED WIRELESS INDUSTRY SURVEY RESULTS
December 1985 to December 1999

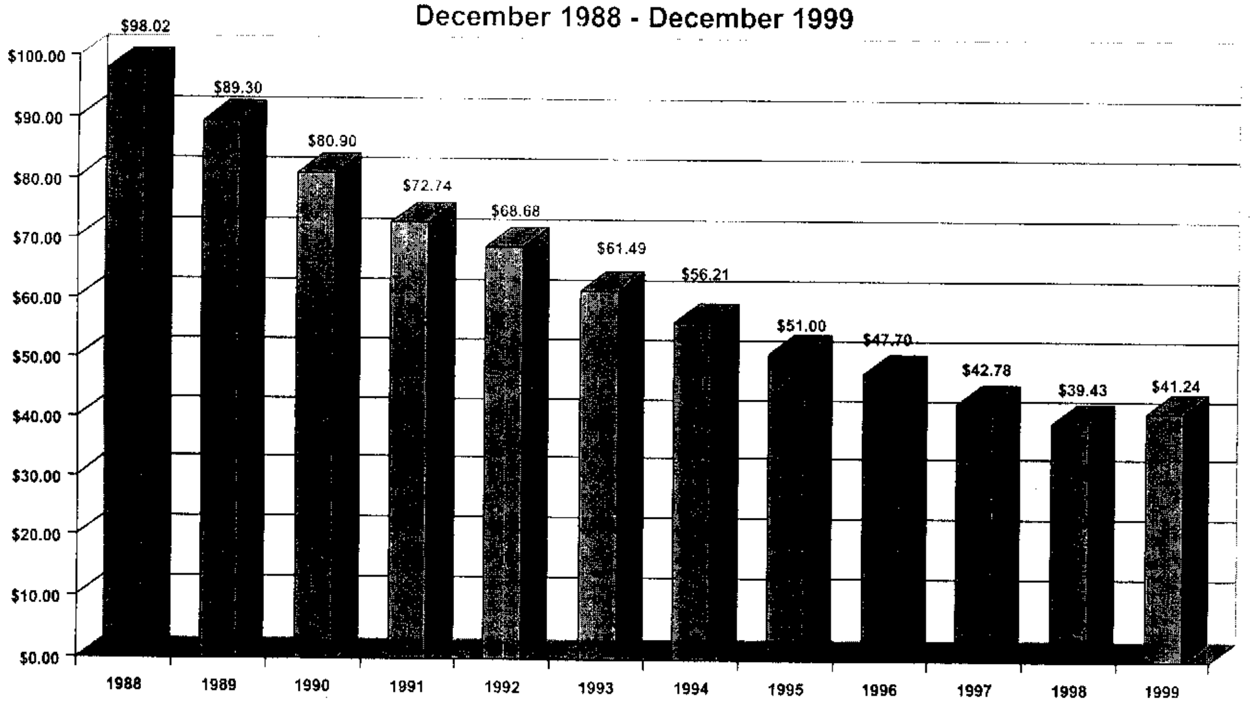
Reflecting Domestic U.S. Commercially-Operational Cellular, ESMR and PCS Providers

Date	Estimated Total Subscribers	Annualized Total Service Revenues (in 000s)	Annualized Roamer Revenues (in 000s)	Cell Sites	Direct Service Provider Employees	Cumulative Capital Investment (in 000s)	Average Local Monthly Bill	Average Local Call Length
1985	340,213	482,428	N/a	913	2,727	911,167	N/a	N/a
1986	681,825	823,052	N/a	1,531	4,334	1,436,753	N/a	N/a
1987	1,230,855	1,151,519	N/a	2,305	7,147	2,234,635	$96.83	2.33
1988	2,069,441	1,959,548	N/a	3,209	11,400	3,274,105	$98.02	2.26
1989	3,508,944	3,340,595	294,567	4,169	15,927	4,480,142	$89.30	2.48
1990	5,283,055	4,548,820	456,010	5,616	21,382	6,281,596	$80.90	2.20
1991	7,557,148	5,708,522	703,651	7,847	26,327	8,671,544	$72.74	2.38
1992	11,032,753	7,822,726	973,871	10,307	34,348	11,262,070	$68.68	2.58
1993	16,009,461	10,892,175	1,361,613	12,824	39,810	13,956,366	$61.49	2.41
1994	24,134,421	14,229,922	1,830,782	17,920	53,902	18,938,678	$56.21	2.24
1995	33,785,661	19,081,239	2,542,570	22,663	68,165	24,080,467	$51.00	2.15
1996	44,042,992	23,634,971	2,780,935	30,045	84,161	32,573,522	$47.70	2.32
1997	55,312,293	27,485,633	2,974,205	51,600	109,387	46,057,910	$42.78	2.31
1998	69,209,321	33,133,175	3,500,469	65,887	134,754	60,542,774	$39.43	2.39
1999	86,047,003	40,018,489	4,085,417	81,698	155,817	71,264,865	$41.24	2.38

Wireless Subscribership: December 1985 - December 1999

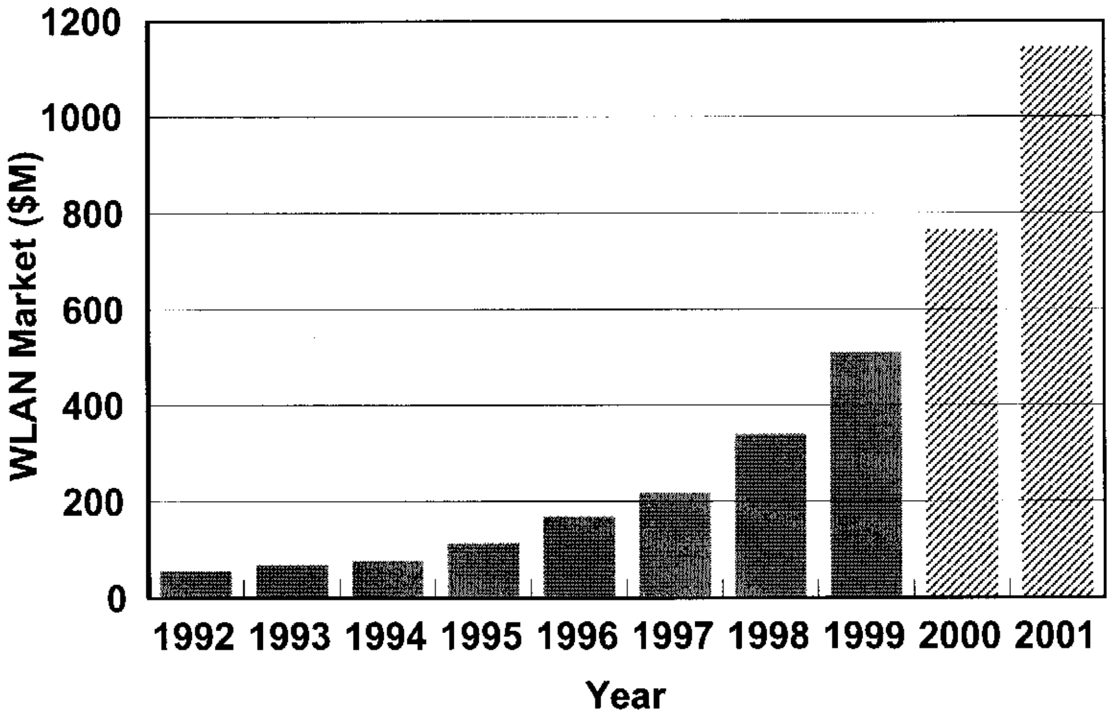


Average Local Monthly Bill: December 1988 - December 1999



1.2

WIRELESS LAN MARKET DATA WAS COLLECTED FROM SEVERAL SOURCES, INCLUDING THE YANKEE GROUP, THE GARTNER GROUP, AND OTHERS. VALUES WERE AVERAGED, AND PLOTTED BELOW. THE HASHED BARS ARE ESTIMATES FOR THE YEARS 2000 AND 2001.



1.3 THE MAJOR SPECTRUM ALLOCATIONS FOR 50 MHz to 2 GHz ARE LISTED BELOW:

BROADCAST RADIO AND TV:

FM:	88 - 108 MHz	→	20 MHz
TV:	54 - 72 MHz	→	18 MHz
	76 - 88 MHz	→	12 MHz
	174 - 216 MHz	→	42 MHz
	470 - 890 MHz	→	420 MHz
			512 MHz

WIRELESS SYSTEMS:

AMPS:	869 - 894 MHz	→	25 MHz
	824 - 849 MHz	→	25 MHz
PCS:	1710 - 1785 MHz	→	75 MHz
	1805 - 1880 MHz	→	75 MHz
PAGING:	931 - 932 MHz	→	1 MHz
ISM:	902 - 928 MHz	→	26 MHz
			227 MHz

We see that wireless systems occupy approximately half the bandwidth freely allocated to commercial radio and TV broadcasting.

Essays could take differing viewpoints. Useful information can be found in the following references:

[1] R. J. Orsulak, et al, U.S. Department of Commerce, NTIA TM-94-160, National Land Mobile Spectrum Requirements, January 1994.

[2] R. J. Mayher, et al, The SUM Data Base: A New Measure of Spectrum Use, U.S. Department of Commerce, NTIA TR-88-236, August 1988

[3] U.S. National Spectrum Requirements: Projects and Trends NTIA Special Publication 94-31, 1995.

1.4 We consider two different cell phones:

CASE A: NOKIA 232 ANALOG (AMPS) PHONE
$P_A = 0.6\,W$ (TALK POWER CONSUMPTION), 6V BATTERY

CASE B: NOKIA 2170 DIGITAL (CDMA) PHONE
$P_B = 0.2\,W$ (TALK POWER CONSUMPTION), 6V BATTERY

ENERGY PER MINUTE OF TALK-TIME:

$$E_A = P_A T = (0.6\,w)(60\,sec) = \underline{36\ W\text{-}sec} \quad (/\text{MIN T.T.})$$

$$E_B = P_B T = (0.2\,w)(60\,sec) = \underline{12\ W\text{-}sec} \quad (/\text{MIN T.T.})$$

TYPICAL SOLAR PANELS:

1.5v, 500 mA PANEL (6.2 cm × 12.0 cm) COST ~ $800!
FOUR OF THESE WILL PROVIDE 6.0V AT 500 mA IN FULL SUNLIGHT. SIZE WILL BE ABOUT 24 cm×12 cm, OR 9" × 4.7" (~ 6"×6" AREA)

500 mA WILL PROVIDE A "SLOW CHARGE" TO THE BATTERY. WITH A TYPICAL CHARGING EFFICIENCY OF 70%, THE ENERGY SUPPLIED TO THE BATTERY IN <u>ONE HOUR</u> WILL BE,

$$E_C = e \cdot P \cdot T = (0.7)(0.5)(6)(60)^2 = 7560\ W\text{-}sec.$$

RESULTING TALK TIME:

$$T_A = E_C/E_A = \frac{7560}{36} = 210\ sec = \underline{3.5\ min}$$

$$T_B = E_C/E_B = \frac{7560}{12} = 630\ sec = \underline{10.5\ min}$$

ALL DATA WAS OBTAINED FROM MANUFACTURER'S WEB SITES. THERE ARE SEVERAL VARIABLES THAT CAN AFFECT THIS RESULT, SUCH AS BATTERY TYPE, PHONE TYPE, SOLAR EFFICIENCY, CHARGING EFFICIENCY, AND SUNLIGHT VARIATION WITH TIME AND LOCATION.

MUCH MORE WORK COULD BE DONE ON THIS PROBLEM.

1.5

The Iridium satellite telephone system consisted of 66 satellites in low Earth orbit, and was advertised as providing worldwide coverage with a single handset. The system cost was about $5B. The satellites had an expected lifetime of about 5 years, after which the entire constellation would have to be replaced. The handsets were large and bulky, with a typical price tag of about $1000. Service charges ranged from about $1.40 to $3.00 per minute.

While the Iridium system was technologically sophisticated, it was doomed to failure for several reasons. First, the rapid growth of land-based cellular systems provided service to large percentage of the population at rates that typically were a tenth that of Iridium (Typically about $0.35 per minute during peak times, often with free talk time during off-peak hours. Handsets are usually free, or with a small nominal charge). Iridium claimed that their system was the only one to offer seamless coverage to people in lesser-developed countries, remote desert or mountainous regions, or even on the oceans. This was true, but they seemed to miss an important point – there are not many paying customers in those regions. Another serious problem with the Iridium system (and one that was never mentioned in their advertisements) is that Iridium handsets required a line-of-sight path to the satellite, meaning that it was rarely possible to use an Iridium phone in a building or vehicle. Land-based cellular systems, working at lower frequencies with better link margins and propagation properties, work quite well in buildings and vehicles. Iridium declared bankruptcy in August 1999, and the present plan is that the satellites will be de-orbited into the oceans. A sad outcome to well-engineered system, but one that was not unexpected.

The Globalstar satellite system consists of 48 LEO satellites, and is also designed to provide worldwide telephone coverage. Globalstar handsets typically cost about $750, and service charges are about $1 per minute. Satellite lifetime is expected to be about 7.5 years. Service began in late 1999, and at the present time (Spring 2000) the Globalstar system is struggling to meet its market projections. It, too, has trouble providing service to users in buildings or vehicles, and so suffers from the same type of problems as did Iridium. We expect it to suffer the same fate, but probably at a slower pace.

The lesson here is that large constellations of LEO satellites simply cannot compete with land-based systems that provide essentially the same service. Land-based facilities are much cheaper to build, install, and operate than satellites, and they can be much more easily modified, upgraded, and repaired. In addition, the quality of service (including factors such as coverage in buildings and vehicles, handset size, weight, and battery life) of land-based telephone systems is significantly better than that provided by satellite systems. This is ultimately due to the difference in link loss between satellite systems and land-based cellular systems – a fact of nature that no amount of marketing can change. Users will not pay substantially more for inferior service, even if the system can work worldwide. The same conclusion applies to data-oriented LEO systems, such as the proposed Teledesic system.

Chapter 2

2.1 $L = 0.3\,\mu H/m$, $C = 450\ pF/m$, $R = 5\,\Omega/m$, $G = 0.01\ S/m$
$f = 880\ MHz$.

From (2.5), $\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \sqrt{(5 + j1659)(.01 + j2.49)}$

$$= \sqrt{(1659\angle 89.83^\circ)(2.49\angle 89.77^\circ)} = 64.3\angle 89.80^\circ$$

$$= 0.224 + j64.3 = \alpha + j\beta.$$

From (2.7), $Z_0 = \sqrt{\dfrac{R + j\omega L}{G + j\omega C}} = \sqrt{\dfrac{1659\angle 89.83^\circ}{2.49\angle 89.77}} = 25.8\angle 0.03^\circ$

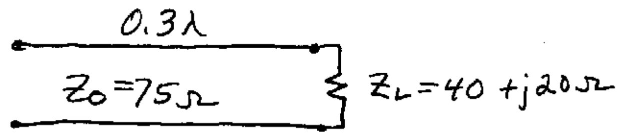
$$= 25.8 + j0.014\ \Omega$$

If $R = G = 0$, then $\alpha = 0$ and $\beta = \omega\sqrt{LC} = 64.2$ rad/m.

$$Z_0 = \sqrt{\frac{L}{C}} = 25.8\ \Omega$$

Note that β and Z_0 for the lossless case are very close to the corresponding values for the lossy (but low loss) case.

2.2



$z_L = \dfrac{Z_L}{Z_0} = 0.53 + j0.266$

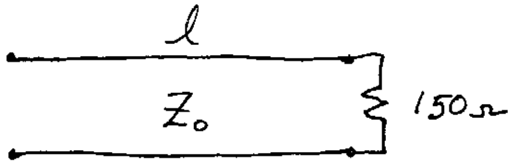
From a Smith chart, $z_{in} = 0.93 - j0.7$

So, $Z_{in} = Z_0 z_{in} = 69.8 - j52.5\ \Omega$ ✓

$SWR = 2.05$ ✓

$\Gamma = 0.34\angle 140^\circ$ ✓

2.3



SWR = 1.6

From (2.23), $SWR = \frac{1+|\Gamma|}{1-|\Gamma|}$ so $|\Gamma| = \frac{SWR-1}{SWR+1} = \frac{0.6}{2.6} = 0.231$

From (2.17), $\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$, so $|\Gamma| = \left|\frac{Z_L - Z_0}{Z_L + Z_0}\right|$

So either, $|\Gamma| = \frac{Z_L - Z_0}{Z_L + Z_0} \Rightarrow Z_0 = Z_L \frac{1-|\Gamma|}{1+|\Gamma|} = 150\left(\frac{1-.231}{1+.231}\right) = \underline{93.7\Omega}$ ✓

OR,

$-|\Gamma| = \frac{Z_L - Z_0}{Z_L + Z_0} \Rightarrow Z_0 = Z_L \frac{1+|\Gamma|}{1-|\Gamma|} = 150\left(\frac{1+.231}{1-.231}\right) = \underline{240.\ \Omega}$ ✓

(verified by Smith chart)

2.4 $Z_L = 80 + j40\ \Omega$, $Z_0 = 50\Omega$, $P_{in} = 30\ W$

From (2.17), $\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{30 + j40}{130 + j40} = \frac{50\angle 53°}{136\angle 17°} = 0.367\angle 36°$ ✓

$$P_{LOAD} = P_{INC}\left(1 - |\Gamma|^2\right) = 30\left[1 - (0.367)^2\right] = \underline{25.9\ W}$$ ✓