EE 440
Fall
2012

Antennas and Propagation

[Good source = D.M. Pozar "Microwave & RF Design of Wireless Systems"]

Take a systems viewpoint rather than an E+M viewpoint. Antenna params of interest in comm. systems are:

- pattern
- directivity
- gain
- efficiency
- polarization

Antenna is an impedance converter:

guided wave — antenna — free space

Antenna properties are bidirectional — same parameter values for transmit and receive. (Said to be reciprocal).

Antenna Pattern

Consider antenna as a transmitter (but be aware of reciprocity). Ant. pattern is

$$w(\theta, \phi) = \text{power trans. per unit solid angle in the direction } (\theta, \phi)$$

θ: elevation, ϕ: azimuth

(Solid angle of a cone enscribed on a sphere of radius D is = surface area of cone's spherical cap$/D^2$ ... total solid angle of sphere is 4π steradians)

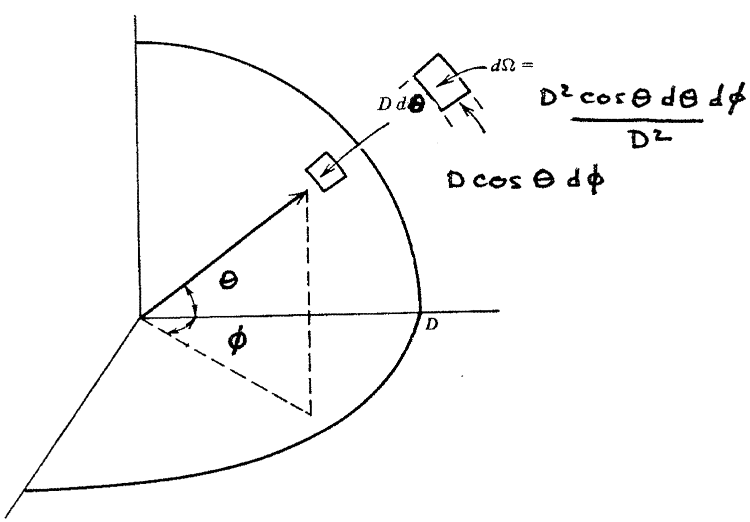

Figure 3.9. Antenna geometry.

$$d\Omega = \text{differential solid angle}$$
$$= \cos\theta \, d\theta \, d\phi$$

<u>Antenna Gain Function</u> is normalized antenna pattern:

$$g(\theta, \phi) = \frac{w(\theta, \phi)}{\text{power per unit solid angle of an isotropic radiator with same total transmitted power.}}$$

Isotropic radiator is a hypothetical antenna which radiates equally in all directions.

(ie radiated)

P_T = total transm. power of an antenna

$$= \int_{\text{unit sphere}} w(\theta,\phi)\, d\Omega = \int_{-\pi}^{\pi}\int_{-\pi/2}^{\pi/2} w(\theta,\phi) \cos\theta \, d\theta \, d\phi$$

$\therefore$ power per unit solid angle of isotropic $= P_T/4\pi$

$$\Longrightarrow \quad g(\theta, \phi) = \frac{w(\theta,\phi)}{P_T/4\pi}$$

Observation: Area under $g(\theta,\phi)$ always equals 4π. Thus if increased in one direction, it must be decreased somewhere else to maintain area $= 4\pi$.

Usually antenna designed to transmit preferentially along one ray line ... such called <u>antenna main lobe</u>. Transmissions in other directions called sidelobes. Often plot as one dim. functs hold the other angle constant .... planer gain functs or patterns.

For example: $g(\phi) = g(\theta,\phi)\Big|_{\theta=0}$

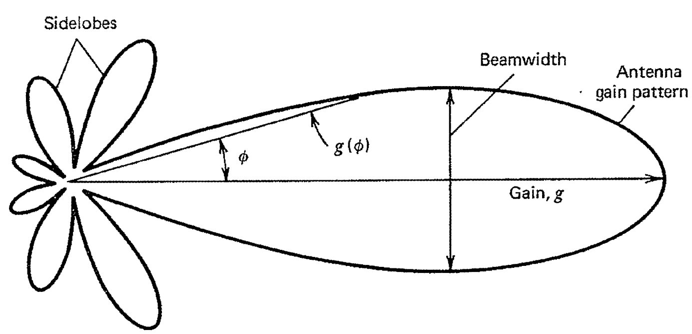

Figure 3.11. Antenna planar gain function $g(\phi)$.

(Also called: directivity)

<u>Gain</u> of an antenna

$$G \triangleq \max_{\theta,\phi} g(\theta,\phi)$$

<u>Field of view</u> Antenna solid angle

Field of view is a measure of the solid angle into which most of transmitted power is concentrated ... Several definitions

3dB FoV, 6dB FoV, mainlobe FoV.

For a symmetrical gain pattern with planar 3dB beamwidth ϕ_B can show

$$\Omega_{FOV} = 2\pi\left(1 - \cos\frac{\phi_B}{2}\right) \approx \frac{\pi}{4}\phi_B^2 \qquad \phi_B \ll 1$$

Property of Antennas

ϕ_B = 3 dB beamwidth, A = antenna aperture cross-sectional area

$$\begin{cases} G = \left(\dfrac{4\pi}{\lambda^2}\right)\rho A \\ \phi_B = K\dfrac{\lambda}{D\sqrt{\rho}} \end{cases}$$

λ = wavelength of carrier

$\rho \triangleq$ antenna aperture loss factor

K = const. of proportionality depending on type of antenna.

$D \triangleq$ diameter of antenna aperture.

$G \propto A, f_c^2$

$\phi_B \propto D^{-1}, f_c^{-1}$ $\Longrightarrow$ larger antenna or higher freq. the larger is gain and narrower is beamwidth.

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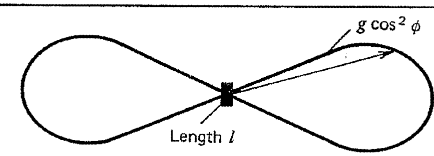
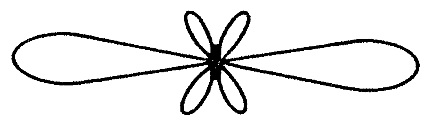
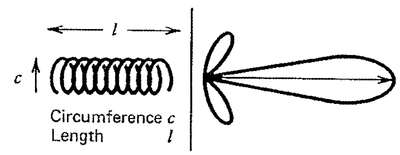
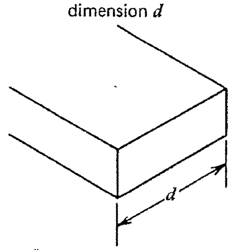
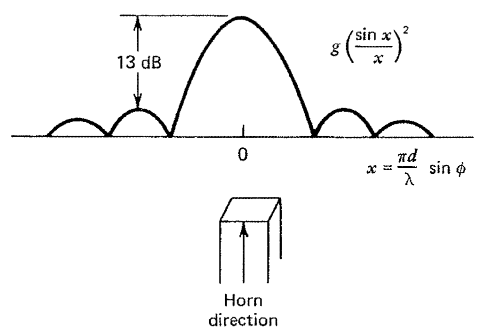
Antenna type	Pattern	Gain g	Half-power beamwidth
Short dipole $l \ll \lambda$		1.5	90°
Long dipole $l \gg \lambda$ $l = \lambda/2$		1.5 1.64	47° 78°
Helix		$15\left[\frac{cl}{\lambda^2}\right]$	$52°\left[\frac{\lambda}{c\sqrt{l}}\right]$
		$\frac{4\pi d^2}{\lambda^2}$	$\frac{0.88\lambda}{d}$ rad

Figure 3.12. Common antenna characteristics.

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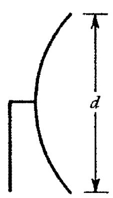
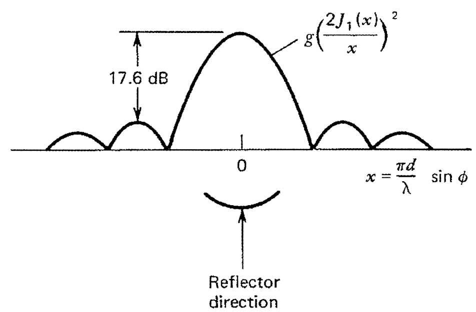
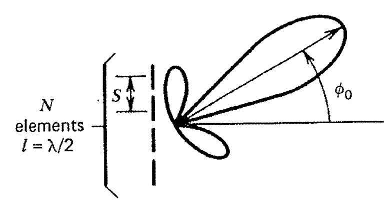
Circular reflector 		$\left[\frac{\pi d}{\lambda}\right]^2$	$\frac{1.02\lambda}{d}$ rad
Phased array, phase difference $= \frac{2\pi s}{\lambda} \cos \theta_0$		$\left[\frac{N\pi s}{1.4\lambda}\right]^2$	$50^\circ\left[\frac{\lambda}{Ns}\right]$ $\theta_0 = 0$

Figure 3.12 (*continued*).

Antenna Efficiency Etc

The gain G previously defined is sometimes called the directivity and denoted D ... it is a mathmotical idealization, obtainable by computation from an ideal geometry. It does <u>not</u> account for:

- resistive or dielectric losses in an actual antenna.
- inefficiencies associated with antenna feed (which might partially block the aperture, etc).
- deviation in manufacture from idealized geometry ... ie a real parabolic reflector will not have a perfect parabolic shape.

$$\therefore \quad G_{actual} = \overset{\text{radiation efficiency}}{\rho}\, G_{idealized} \qquad \rho = \frac{\text{Power radiated}}{P_{input}} = \frac{P_{input} - P_{loss}}{P_{input}}$$

$0 < \rho < 1$ to model all of these losses.

For example some antennas are aperture antennas (horns, parabolic) and have a well-defined aperture area $A_{aperture}$. For these

$$G_{idealized} = \frac{4\pi}{\lambda^2} A_{aperture}$$

e.g. rect. horn $2\lambda \times 3\lambda \implies G_{idealized} = 24\pi \quad (= 18.8\text{ dB})$

<u>Effective Area</u> By reciprocity the prev. results for a transmitting antenna also apply to a receiving antenna.

Reasonable that received power captured by an antenna is prop. to the power density of the incident wave (W/m^2) ... so prop. constant must have units m^2 or area.

If power density is approx. constant in vicinity of receive antenna

$$P_R = A_{effective} \cdot (\text{Power Density})$$

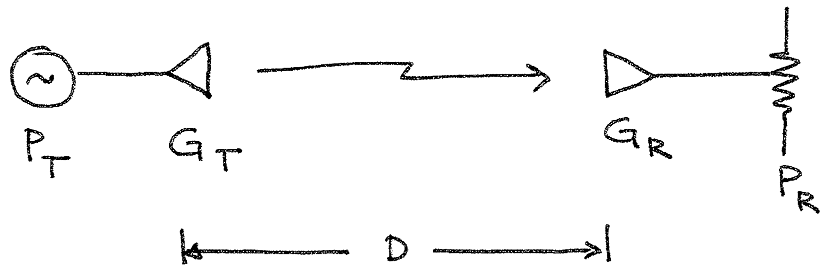
It can be shown that

$$A_{effective} = \frac{G_{idealized}\,\lambda^2}{4\pi} \quad (*)$$

These are max. values ie assuming antennas are <u>aligned</u>. To account inefficiencies use G_{actual} in place of $G_{idealized}$ in (*)

Eq. (*) can also be used to <u>define</u> an effective area for antennas not having well defined aperture, such as dipoles, etc.

The Friis Equation



P_T = total power radiated by Tx ant.

P_R = received power delivered to a matched load.

Imagine a hypothetical isotropic radiator. In such a case the power density at distance D:

$$S_{isotrop} = \frac{P_T}{4\pi D^2} \quad W/m^2$$

By definition of transmitter antenna gain (which is gain relative to isotropic) the power density in preferred direction (ie the max power density) would be

$$S = G_T S_{isotropic} = \frac{G_T P_T}{4\pi D^2} \quad W/m^2$$

Power captured by receive antenna of effective area A_e is

$$P_R = A_e S = \frac{G_T P_T}{4\pi D^2} A_e$$

Relating A_e to receive antenna gain

$$P_R = \frac{G_T P_T}{4\pi D^2} \frac{G_R \lambda^2}{4\pi} = G_T G_R \left(\frac{\lambda}{4\pi D}\right)^2 P_T \quad W$$

Observations

- Should use actual gains to account for various antenna loss factors (those internel to antenna).
- Other losses assoc. with syst. typically not included here. Examples are

  impedance mismatch
  polarization "
  non-free space attenuation effects
  multipath

- Received power decreases as $1/D^2$

  Seems large but is actually better than distance lossed in a wired link which are always decreasing exponential in D; $e^{-2\alpha D}$

  For long distance wireless always better even compared to fiber ... assuming long is very long and no chance for repeaters.

$c = \lambda f_c$

<u>Example</u> Geo sat. $D = 36{,}900$ km

$P_T = 2W$ $\quad G_T = 37$ dB $\quad G_R = 45.8$ dB $\quad f_c = 20$ GHz $\left(\lambda = 0.02\ \mathrm{m}\right)$

$$P_R(\mathrm{dB}) = G_T(\mathrm{dB}) + G_R(\mathrm{dB}) + \underbrace{20\log_{10}\left(\frac{\lambda}{4\pi D}\right)}_{-209.8\ \mathrm{dB}} + \underbrace{P_T(\mathrm{dB})}_{3.01\ \mathrm{dBW}}$$

$$= -124.0\ \mathrm{dBW} = -94.0\ \mathrm{dBm}$$

<u>Effective Isotropic Radiated Power (EIRP)</u>

$$\mathrm{EIRP} = P_T G_T \quad \mathrm{W.}$$

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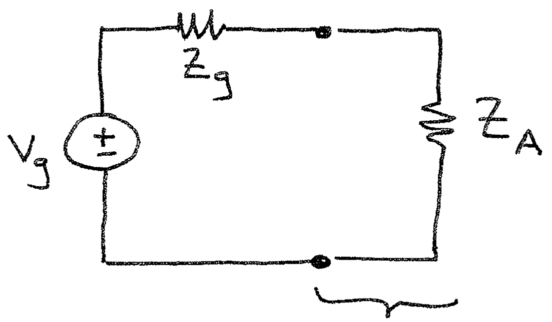
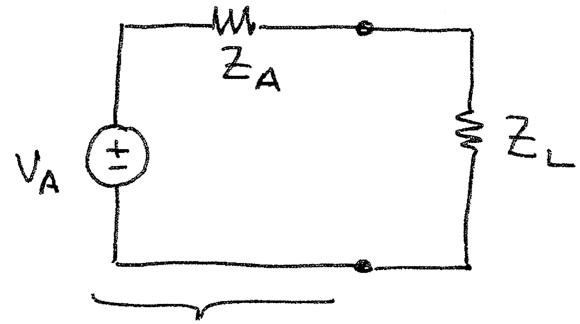
Circuit Model for Antenna



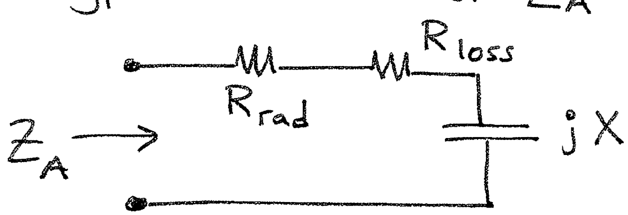
" As a transmitter "



" As a receiver "

Z_A is a property of the antenna. Reciprocity will indicate that Z_A is same for transmit or receive.

Typical models for Z_A look like:



For a short dipole ($L < \lambda/2$) of length L, wire radius a and center-fed

$$R_{rad} = 20\pi^2 (L/\lambda)^2 \ \Omega$$

$$R_{loss} = \sqrt{\frac{2\pi f \mu_0}{2\sigma}} \frac{L}{6\pi a} \ \Omega$$

$$X = -\frac{60\lambda}{\pi L}\left[\ln(L/a) - 1\right] \ \Omega$$

Antenna Noise Temperature

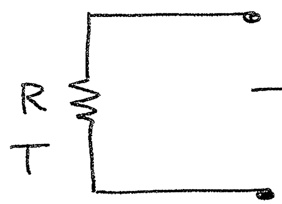
Antenna noise from two sources:

1. external environment (generally outside engineers control)
2. thermal noise due to losses in antenna itself.

External environment — Sources of natural and man-made background noise include

- Cosmic background noise
- Sun + stars
- thermal noise from ground
- lightening
- high voltage lines
- auto ignition
- building lighting
- interference gen. by computer equip.
- Other radio transmissions

Model these background sources and their interaction with an antenna in thermal equillibrium and impedance matched to the receiving circuit as

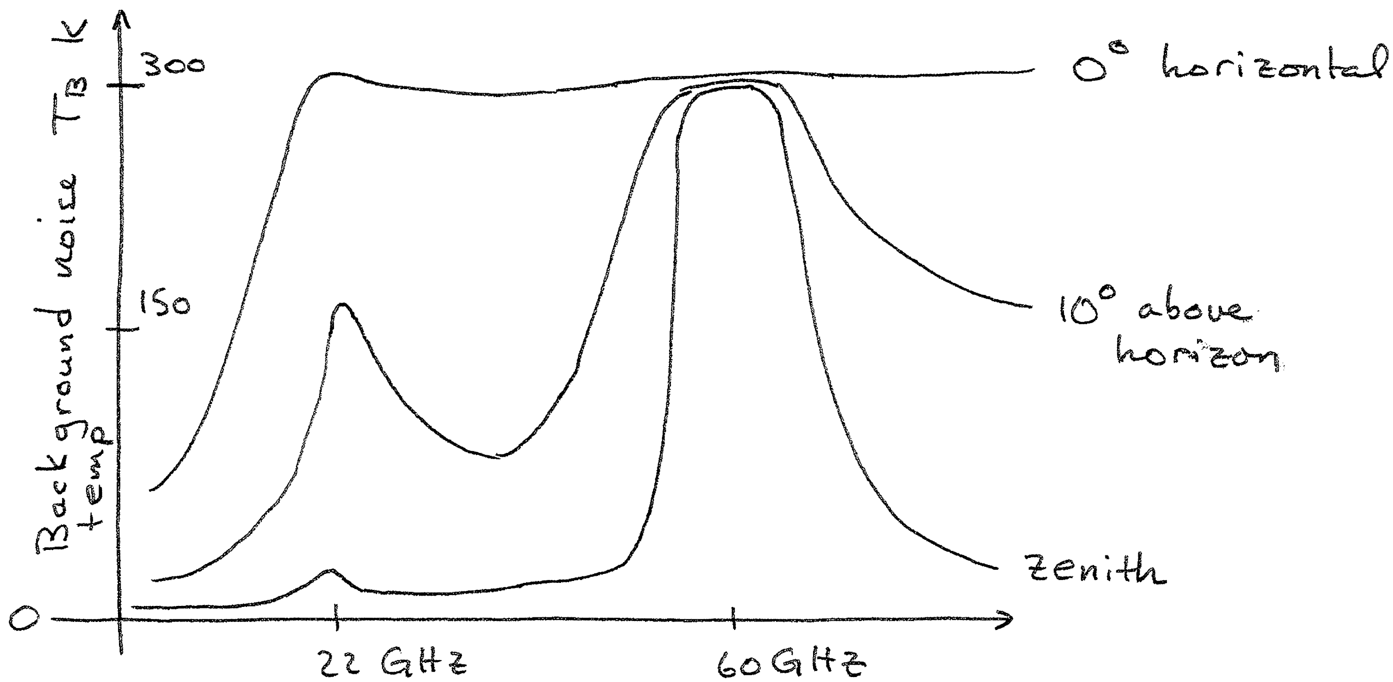


$\longrightarrow N_{background} = kTB$ (one-sided BW).

Background temp. of sky: 3 – 5K toward zenith
50 – 100K toward horizon
290 – 300K toward ground

There are freq. dependent effects also primarily due to resonances due to atmospheric water (22 GHz) and oxygen (60 GHz). At these freqs. the sky background temp. peaks

From Pozar:



Via various calculations can arrive at an antenna noise temp. T_A which is reference to output

kT_AB = power input to rest of receiver due to antenna.

G/T Figure of Merit for a Receive Antenna

$$\frac{G}{T}(\text{dB}) = 10 \log_{10}\left(\frac{G}{T_A}\right) \quad \text{dB/K}$$

Turns out that signal-to-noise ratio at input to receiver is proportional to G/T_A.

From Friis Equation the signal power delivered by the receive antenna to a matched receiver input is

$$S_i = \frac{G_R G_T P_T \lambda^2}{(4\pi R)^2}$$

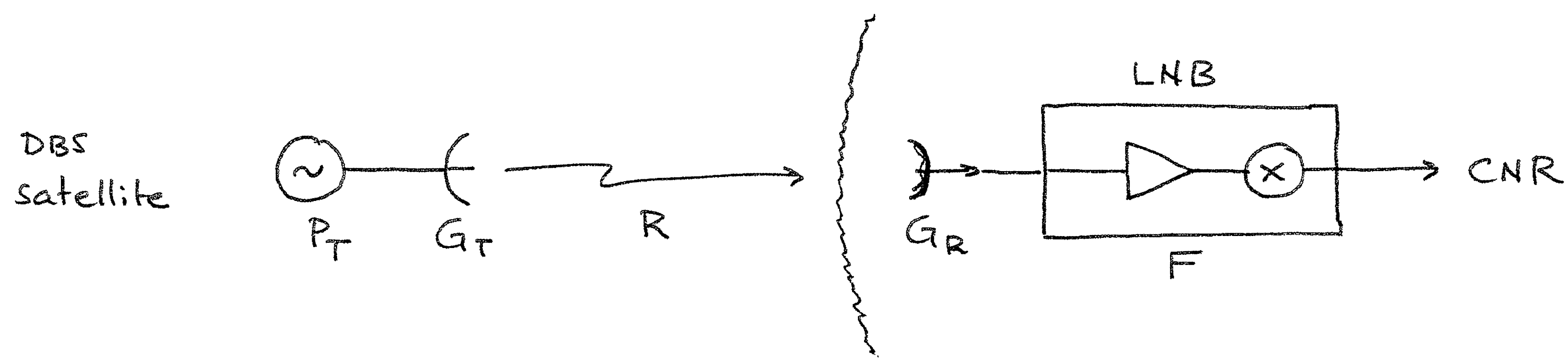
Noise input to receiver

$$N_i = k T_A B$$

Only param. controllable at receiver.

$$\Longrightarrow \quad \frac{S_i}{N_i} = \frac{G_R G_T P_T \lambda^2}{k T_A B (4\pi R)^2} = \left(\frac{G_R}{T_A}\right) \frac{G_T P_T \lambda^2}{k B (4\pi R)^2}$$

Example Calculation for Direct Broadcast System



12.2 - 12.7 GHz $\rightarrow$ pick 12.45 GHz
$\lambda = 0.0241$ m

$P_T = 120$ W
$G_T = 34$ dB $= 2512$
$B = $ IF BW $= 20$ MHz
$R = 39{,}000$ km
$G_R = 33.5$ dB $= 2239$ (18" dish)
$T_A = 50$ K
$F = 1.1$ dB $= 1.29$

Find:

(a) EIRP of transmitter
(b) G/T for combination of receive antenna + low noise block
(c) received carrier power at receive antenna terminals
(d) carrier-to-noise (CNR) ratio at output of LNB.

(a) $EIRP = P_T G_T = (120)(2512) = 3.01 \times 10^5 \text{ W} = 54.8 \text{ dBm}$

(b) To find G/T for antenna + LNB combo, find noise temp of cascade: antenna → LNB but referenced to the LNB input.

$$T_e = T_A + T_{LNB} = T_A + (F-1)\,290\text{K}$$
$$= 50\text{K} + (1.29-1)\,290\text{K} = 134 \text{ K}$$

$$G/T = 10 \log\left(\frac{2239}{134}\right) = 12.2 \text{ dBK}^{-1}$$ ← we do not include the LNB gain G_{LNB} in this calculation.

(c) $$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} = 1.63 \times 10^{-12} \text{ W} = -117.9 \text{ dBW}$$

(d) $$CNR = \frac{P_R \cancel{G_{LNB}}}{k T_e B \cancel{G_{LNB}}} = \frac{1.63 \times 10^{-12}}{(1.38 \times 10^{-23})(134)(20 \times 10^6)} = 44.1$$
$$= 16.4 \text{ dB.}$$

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