Topics:
Link Design

Satellite Communications

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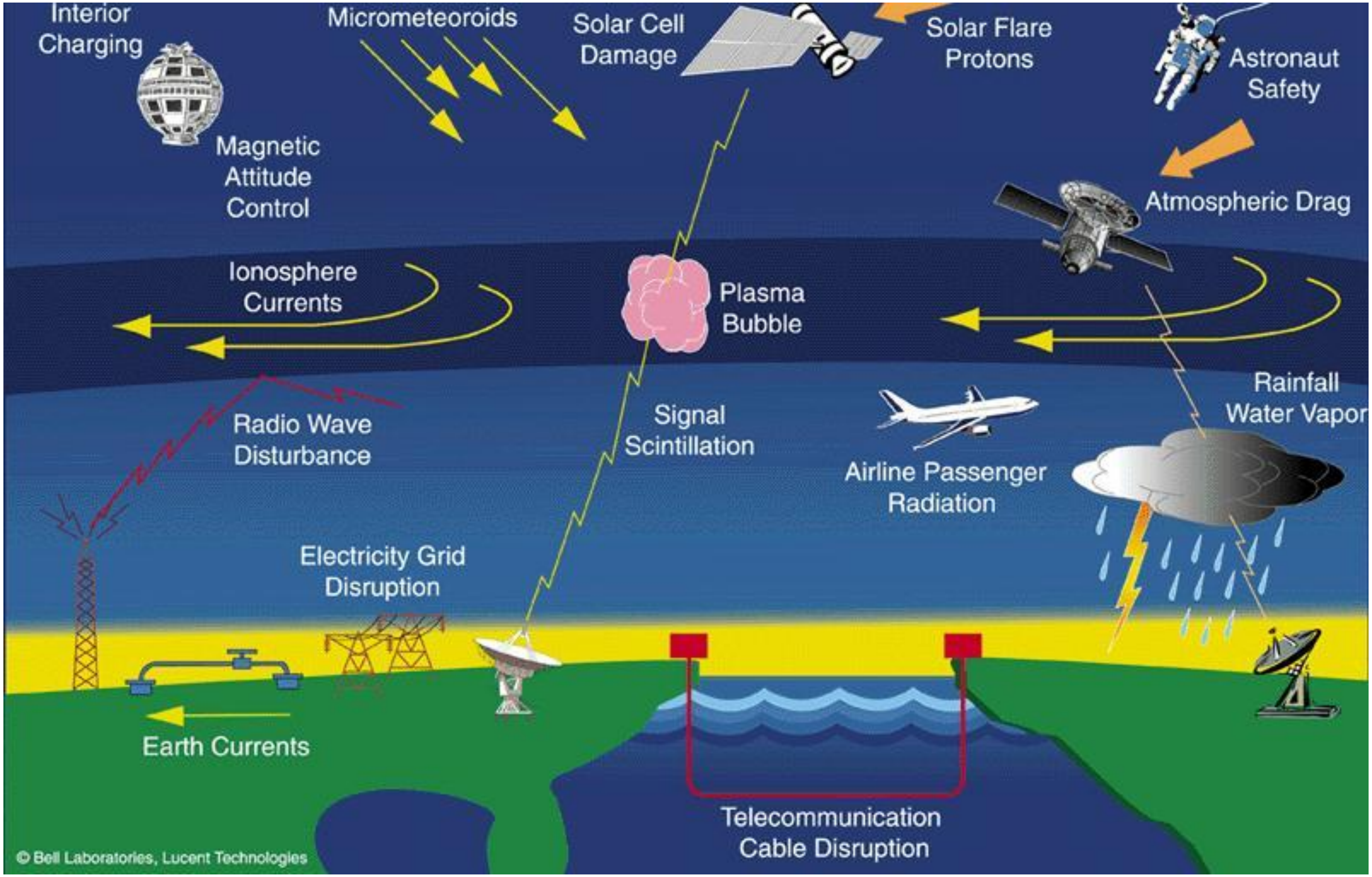
Satellite Link Design



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Agenda

- ***Performance Criteria***
- ***Basic Transmission Theory***
- ***Review of Decibel***
- ***Link Budget***

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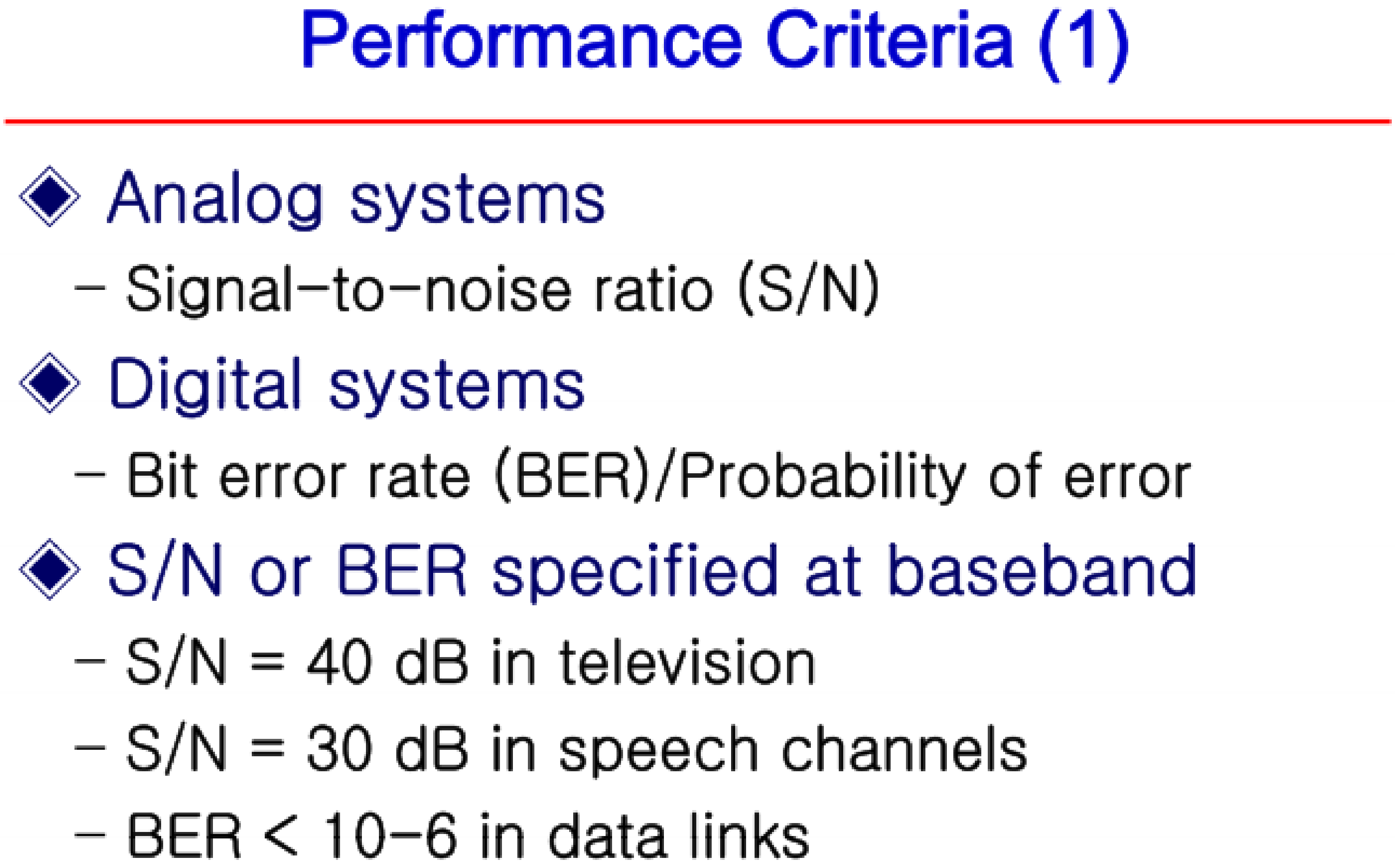

Performance Criteria (1)

- Analog systems
  - Signal-to-noise ratio (S/N)
- Digital systems
  - Bit error rate (BER)/Probability of error
- S/N or BER specified at baseband
  - S/N = 40 dB in television
  - S/N = 30 dB in speech channels
  - BER < 10−6 in data links

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Performance Criteria (2)

- S/N or BER is specified
  - Measured at demodulator output
  - At baseband
- Sets requirement on C/N at demodulator input
  - At IF section of receiver
  - S/N = 36−40 dB => C/N = 8 – 12 dB (television)
  - BER = 10−6 => C/N = 12 dB (QPSK modulation)

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Link Budget parameters

- Transmitter power at the antenna
- Antenna gain compared to isotropic radiator
- EIRP
- Flux density at receiver
- Free space path loss
- System noise temperature
- Figure of merit for receiving system
- Carrier to thermal noise ratio
- Carrier to noise density ratio
- Carrier to noise ratio

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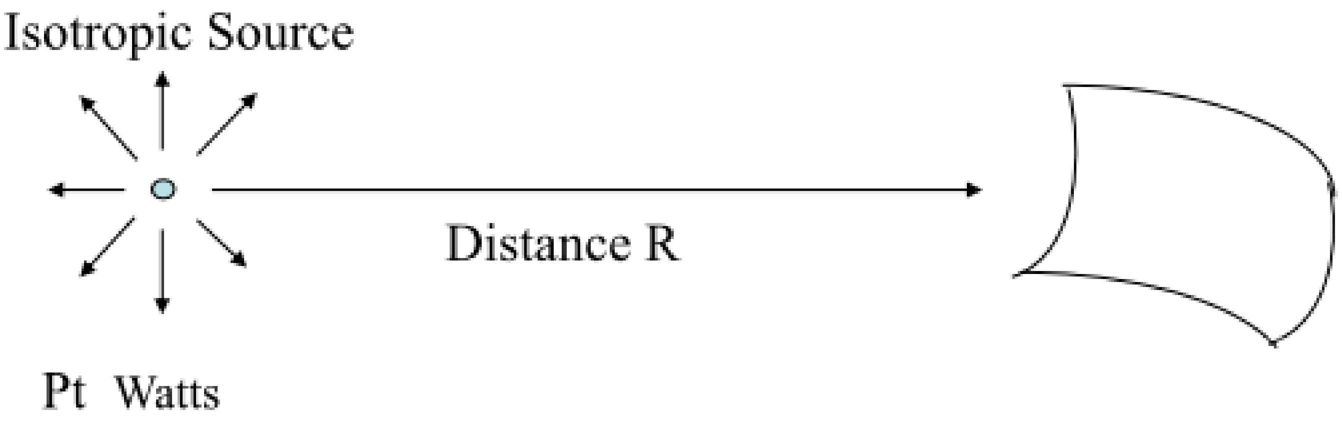
Isotropic Radiator



Surface Area of sphere

$= 4\pi R^2$

encloses Pt.

Power Flux Density:

$$F = \frac{P_t}{4\pi R^2} \quad \mathrm{W/m^2}$$

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Numerical Example 1

- Transmit power at satellite = **10** W
- Distance to earth, d = **40,000** km
- Flux density = $\mathbf{P}/4\pi R^2 = \mathbf{4.97 \bullet 10^{-16}}$ W/m2
- Note: This is a very small amount of power

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Antenna Gain

◆We need directive antennas to get power to go in wanted direction.

◆Define Gain of antenna as increase in power in a given direction compared to isotropic antenna.

$$G(\theta) = \frac{P(\theta)}{P_0 / 4\pi} \quad \text{(Eqn 4.2)}$$

- $P(\theta)$ is variation of power with angle.
- $G(\theta)$ is gain at the direction θ.
- P_0 is total power transmitted.
- sphere $= 4\pi$ solid radians

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Antenna Gain

- Antenna has gain in every direction! Term gain may be confusing sometimes.
- Usually "Gain" denotes the maximum gain of the antenna.
- The direction of maximum gain is called "boresight".
- Gain is a ratio:
- It is usually expressed in *Decibels* (dB)

$G\ [dB] = 10 \log_{10} (G \text{ ratio})$

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EIRP

- An isotropic radiator is an antenna which radiates in all directions equally
- Antenna gain is relative to this standard
- Antennas are fundamentally passive
  - No additional power is generated
  - Gain is realized by focusing power
  - Similar to the difference between a lantern and a flashlight
- Effective Isotropic Radiated Power (EIRP) is the amount of power the transmitter would have to produce if it was radiating to all directions equally
- Note that EIRP may vary as a function of direction because of changes in the antenna gain vs. angle

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EIRP

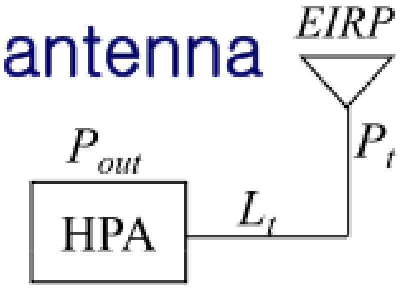
- The output power of a transmitter HPA is:

  P_{out} watts

- Some power is lost before the antenna:

  $P_t = P_{out} / L_t$ watts reaches the antenna

  P_t = Power into antenna



- The antenna has a gain of:

  G_t relative to an isotropic radiator

- This gives an effective isotropic radiated power of:

  $EIRP = P_t G_t$ watts relative to a 1 watt isotropic radiator

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Power Flux Density

- We now want to find the power density at the receiver
- We know that power is conserved in a lossless medium
- The power radiated from a transmitter must pass through a spherical shell on the surface of which is the receiver
- The area of this spherical shell is $4\pi R^2$
- Therefore spherical spreading loss is $1/4\pi R^2$

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Power Flux Density

- Power flux density (**p.f.d.**) is a measure of the power per unit area
- This is a regulated parameter of the system
  - CCIR regulations limit the p.f.d. of any satellite system
  - CCIR regulations are enforced by signatory nations
  - Allowable p.f.d. varies w.r.t. elevation angle
  - Allows control of interference
  - Increasing importance with proliferation of LEO systems

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Received Power

- We can rewrite the power flux density now considering the transmit antenna gain:

$$F = \frac{EIRP}{4\pi R^2} = \frac{P_t G_t}{4\pi R^2} \ \text{W/m}^2 \qquad \text{(Eqn. 4.3)}$$

◆The power available to a receive antenna of area A_r m^2 we get:

$$P_r = F \text{ x } A_r = \frac{P_t G_t A_r}{4\pi R^2} \quad \text{(Eqs. 4.4, 4.6)}$$

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Effective Aperture

- ◆Real antennas have effective flux collecting areas which are LESS than the physical aperture area.
- ◆Define Effective Aperture Area Ae:

$$A_e = A_{phy} \text{ x } \eta \qquad \text{(Eqn. 4.5)}$$

Where A_{phy} is actual (physical) aperture area.

$$\eta = \underline{\text{aperture efficiency}} \quad \begin{cases} \text{Very good: 75\%} \\ \text{Typical: 55\%} \end{cases}$$

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Effective Aperture

- Antennas have (maximum) gain G related to the effective aperture area as follows:

$$Gain = \frac{4\pi A_e}{\lambda^2}$$

Where:

A_e is effective aperture area.

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Aperture Antennas

- Aperture antennas (horns and reflectors) have a physical collecting area that can be easily calculated from their dimensions:

$$A_{phy} = \pi r^2 = \pi \frac{D^2}{4}$$

- Therefore, using Eqn. 4.7 and Eqn. 4.5 we can obtain the formula for aperture antenna gain as:

$$Gain = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi A_{phy}}{\lambda^2} \times \eta$$

$$Gain = \left(\frac{\pi D}{\lambda}\right)^2 \times \eta$$

Typical values of η:
-Reflectors: 50-60%
-Horns: 65-80 %

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Aperture Antenna Types

◆HORN
  - Efficient, Low Gain, Wide Beam

◆REFLECTOR
  - High Gain, Narrow Beam, May have to be deployed in space

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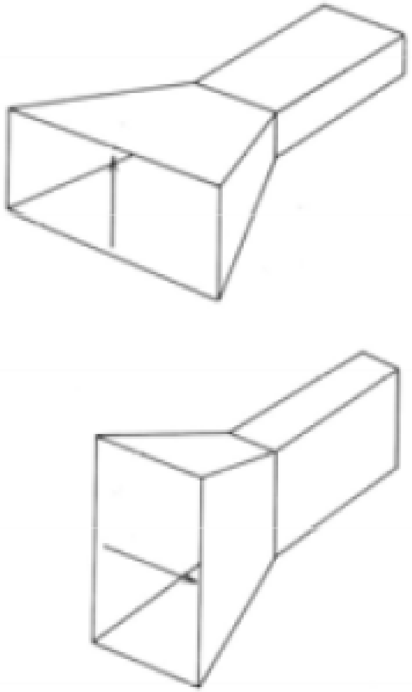
Horn Types



Orthogonally polarized waveguide horn antennas

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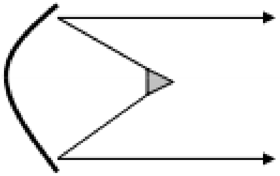
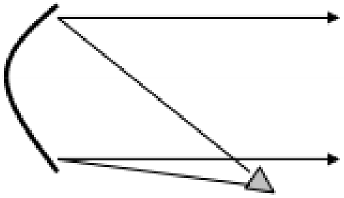
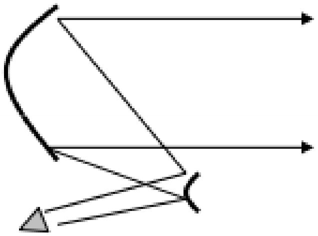
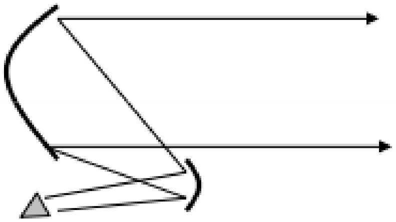
Reflector Types


Symmetrical, Front-Fed


Offset, Front-Fed


Offset-Fed, Cassegranian


Offset-Fed, Gregorian

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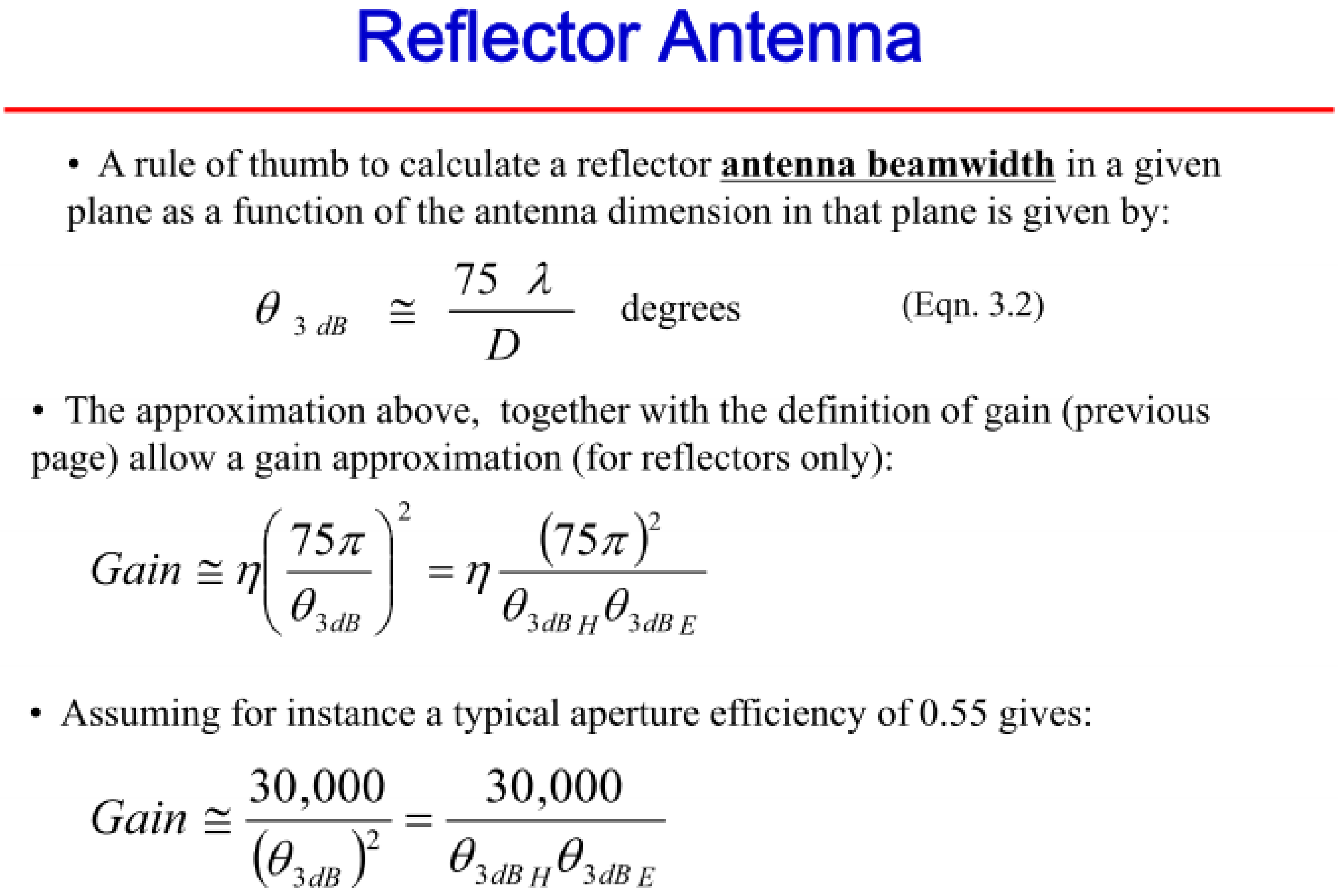

Reflector Antenna

- A rule of thumb to calculate a reflector **antenna beamwidth** in a given plane as a function of the antenna dimension in that plane is given by:

$$\theta_{3\ dB} \cong \frac{75\ \lambda}{D} \quad \text{degrees} \qquad \text{(Eqn. 3.2)}$$

- The approximation above, together with the definition of gain (previous page) allow a gain approximation (for reflectors only):

$$Gain \cong \eta\left(\frac{75\pi}{\theta_{3dB}}\right)^2 = \eta\frac{(75\pi)^2}{\theta_{3dB\ H}\theta_{3dB\ E}}$$

- Assuming for instance a typical aperture efficiency of 0.55 gives:

$$Gain \cong \frac{30{,}000}{(\theta_{3dB})^2} = \frac{30{,}000}{\theta_{3dB\ H}\theta_{3dB\ E}}$$

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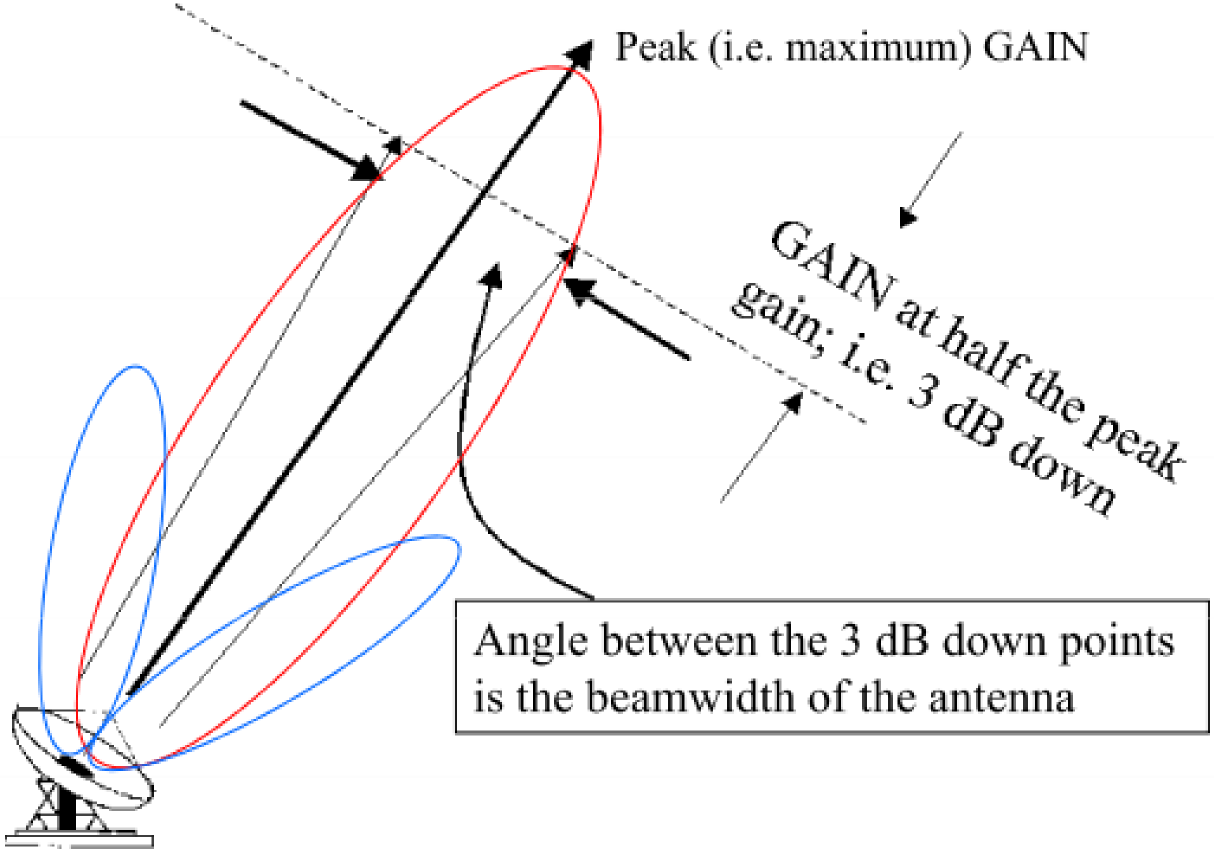
Antenna Beamwidth



Angle between the 3 dB down points is the beamwidth of the antenna

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Back to Received Power…

- The power available to a receive antenna of effective area $A_r = A_e$ m^2 is:

$$P_r = F \text{ x } A_r = \frac{P_t G_t A_e}{4\pi R^2} \qquad \text{(Eqn. 4.6)}$$

Where A_r = receive antenna effective aperture area = A_e

- Inverting the equation given for gain (Eq. 4.7) gives:

$$G_r = \frac{4\pi A_e}{\lambda^2} \xrightarrow{\text{Inverting…}} A_e = \frac{G_r \lambda^2}{4\pi}$$

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- Substituting in Eqn. 4.6 gives:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

Friis Transmission Formula

(Eqn. 4.8)

- The inverse of the term at the right referred to as “Path Loss”, also known as “Free Space Loss” (Lp):

$$L_p = \left(\frac{4\pi R}{\lambda} \right)^2 \xrightarrow{\text{Therefore…}} P_r = \frac{P_t G_t G_r}{L_p}$$

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More complete formulation

- Demonstrated formula assumes idealized case.
- Free Space Loss (L_p) represents spherical spreading only.
- Other effects need to be accounted for in the transmission equation:
  - L_a = Losses due to attenuation in atmosphere
  - L_{ta} = Losses associated with transmitting antenna
  - L_{ra} = Losses associates with receiving antenna
  - L_{pol} = Losses due to polarization mismatch
  - L_{other} = (any other known loss – as much detail as available)
  - Lr = additional Losses at receiver (after receiving antenna)

$$\boxed{P_r = \frac{P_t G_t G_r}{L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r}}$$

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Transmission Formula

◆ Some intermediate variables were also defined before:

$P_t = P_{out} / L_t$ $EIRP = P_t G_t$

Where:

- P_t = Power into antenna
- L_t = Loss between power source and antenna
- $EIRP$ = effective isotropic radiated power

- Therefore, there are many ways the formula could be rewritten. The user has to pick the one most suitable to each need.

$$\boxed{\begin{aligned} P_r &= \frac{P_t G_t G_r}{L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r} \\ &= \frac{EIRP \text{ x } G_r}{L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r} \\ &= \frac{P_{out} G_t G_r}{L_t L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r} \end{aligned}}$$

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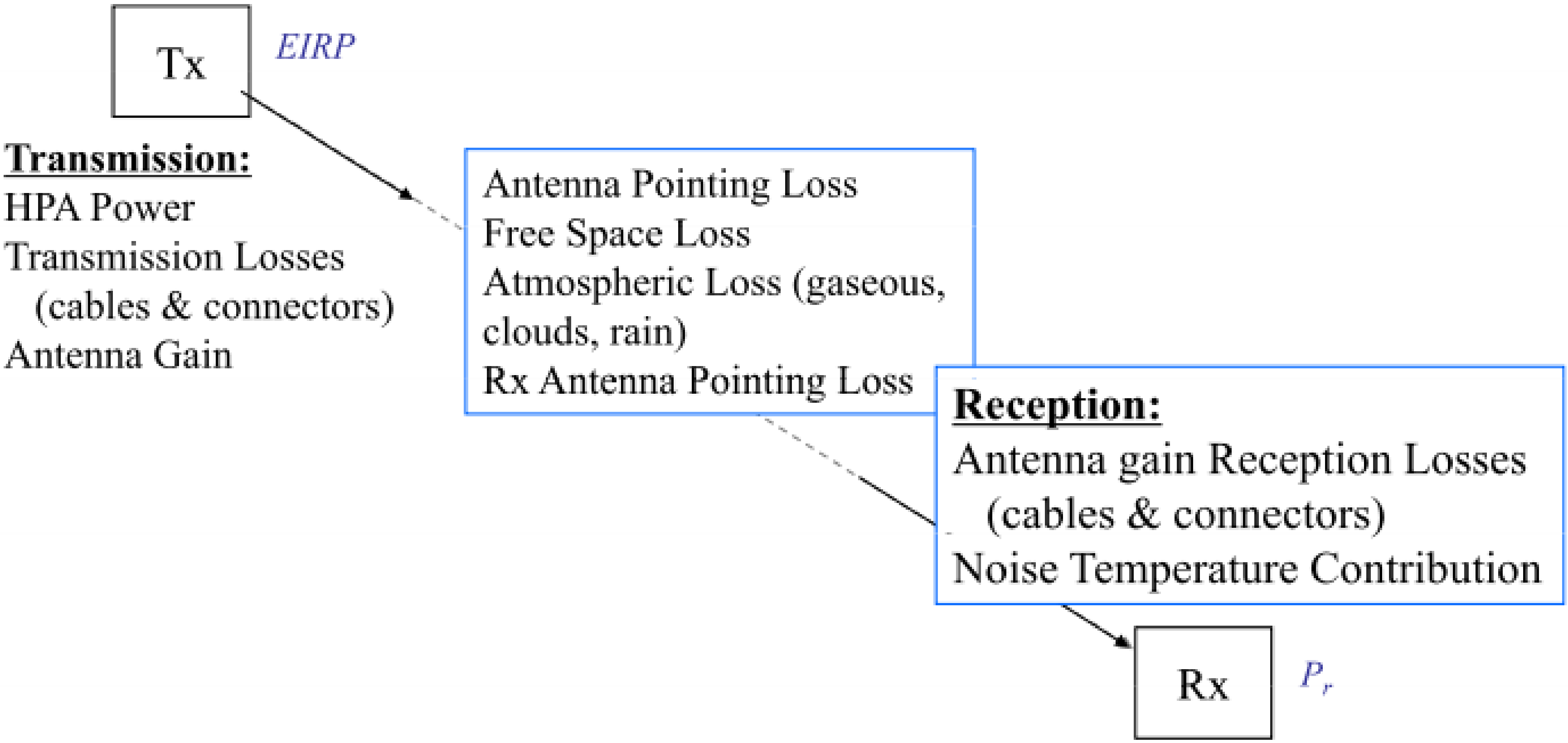
Link Power Budget



Tx *EIRP*

Transmission:
HPA Power
Transmission Losses
(cables & connectors)
Antenna Gain

Antenna Pointing Loss
Free Space Loss
Atmospheric Loss (gaseous, clouds, rain)
Rx Antenna Pointing Loss

Reception:
Antenna gain Reception Losses
(cables & connectors)
Noise Temperature Contribution

Rx P_r

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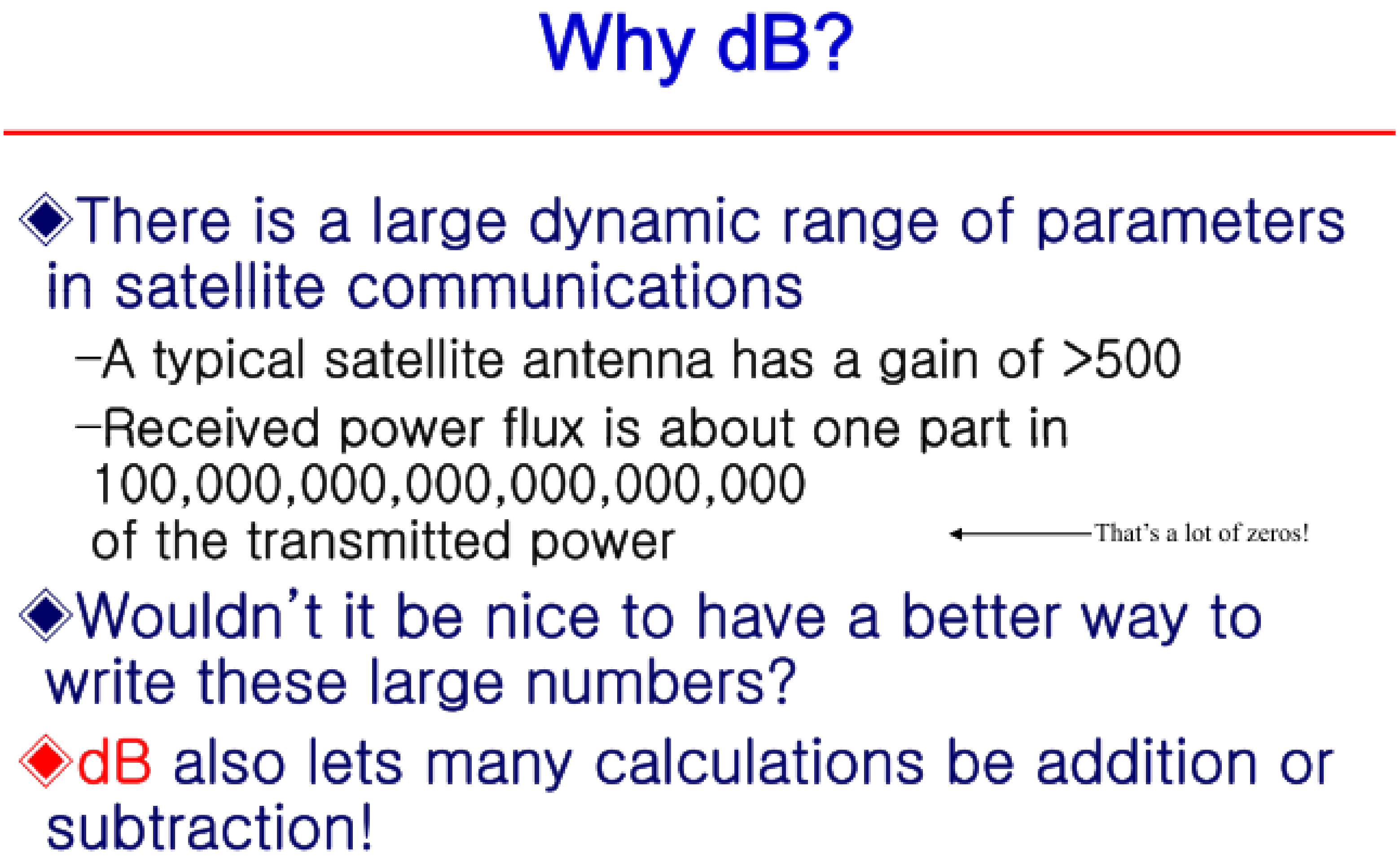

Why dB?

- There is a large dynamic range of parameters in satellite communications
  - A typical satellite antenna has a gain of >500
  - Received power flux is about one part in 100,000,000,000,000,000,000 of the transmitted power

← That's a lot of zeros!

- Wouldn't it be nice to have a better way to write these large numbers?
- dB also lets many calculations be addition or subtraction!

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What is a dB?

- Decibel (dB) is the unit for 10 times the base 10 logarithmic ratio of two powers
- For instance: gain is defined as P_{out}/P_{in} (where P_{out} is usually greater than P_{in})
- in dB: $G = 10 \cdot \log\left(\frac{P_{out}}{P_{in}}\right) \mathrm{dB}$
- Similarly loss is: $L = 10 \log\left(\frac{P_{in}}{P_{out}}\right) \mathrm{dB}$

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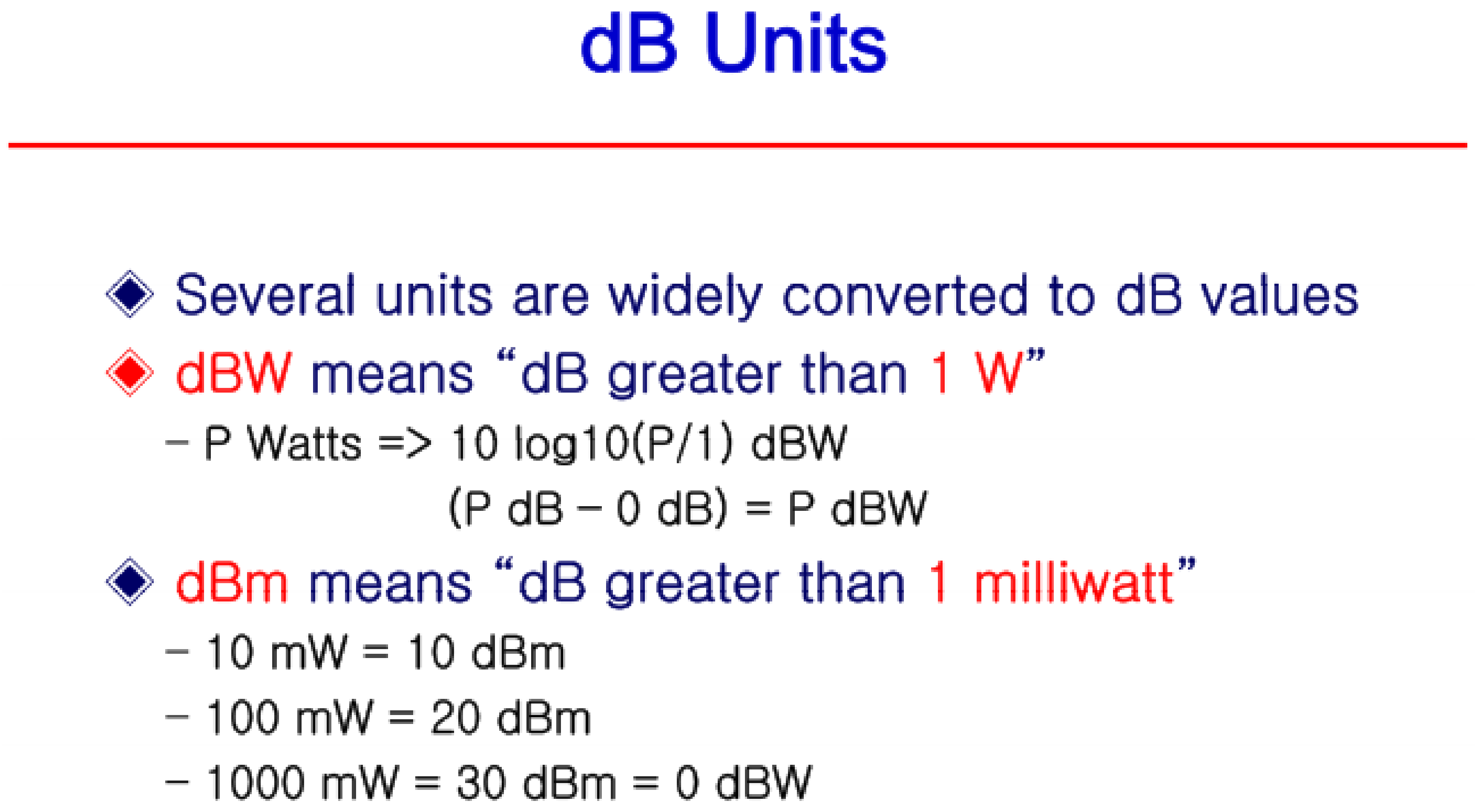

dB Units

- Several units are widely converted to dB values
- dBW means "dB greater than 1 W"
  - P Watts => 10 log10(P/1) dBW
    (P dB – 0 dB) = P dBW
- dBm means "dB greater than 1 milliwatt"
  - 10 mW = 10 dBm
  - 100 mW = 20 dBm
  - 1000 mW = 30 dBm = 0 dBW

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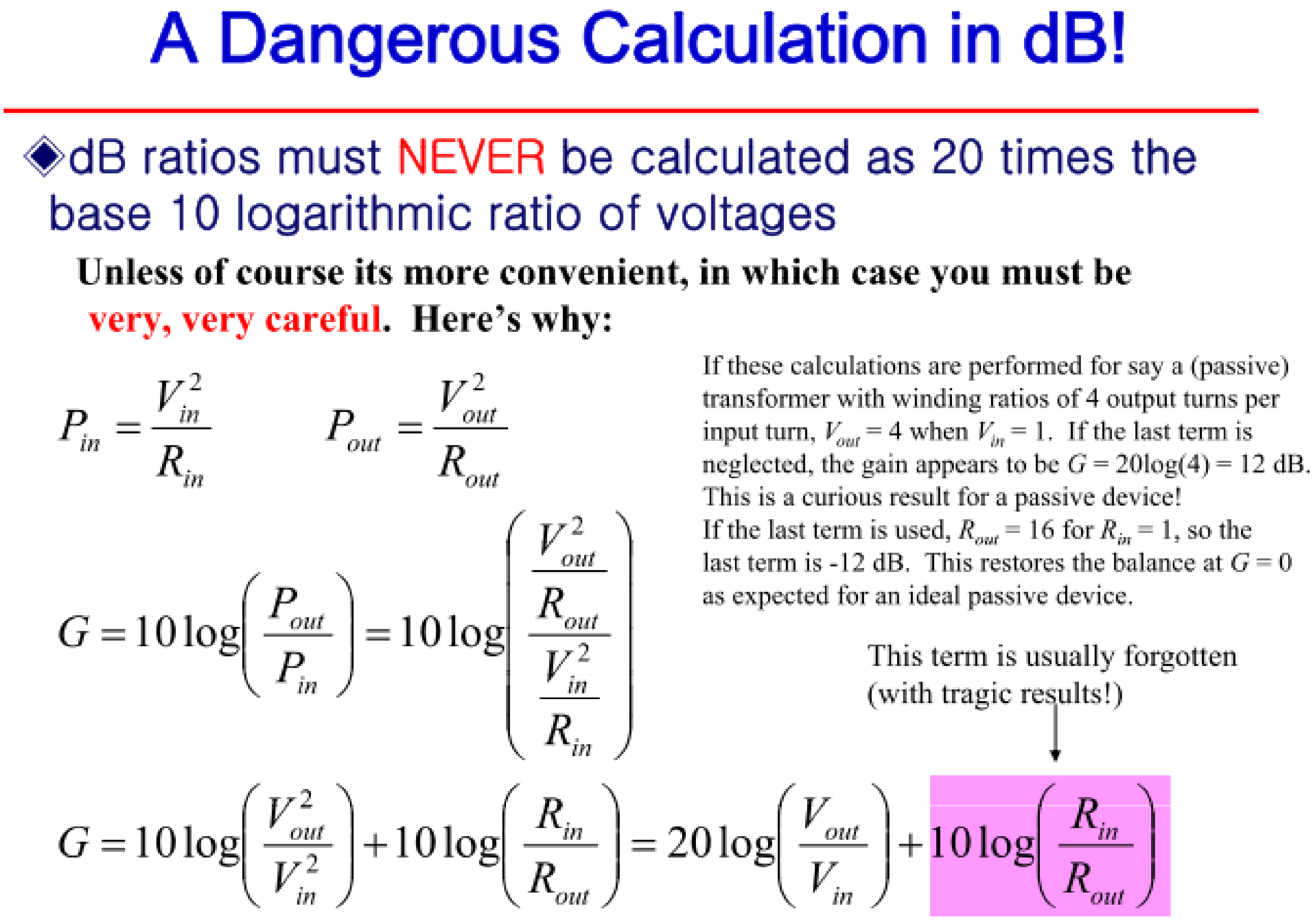

A Dangerous Calculation in dB!

- dB ratios must NEVER be calculated as 20 times the base 10 logarithmic ratio of voltages

Unless of course its more convenient, in which case you must be very, very careful. Here's why:

$$P_{in}=\frac{V_{in}^{2}}{R_{in}} \qquad P_{out}=\frac{V_{out}^{2}}{R_{out}}$$

If these calculations are performed for say a (passive) transformer with winding ratios of 4 output turns per input turn, $V_{out}=4$ when $V_{in}=1$. If the last term is neglected, the gain appears to be $G = 20\log(4) = 12$ dB. This is a curious result for a passive device! If the last term is used, $R_{out}=16$ for $R_{in}=1$, so the last term is -12 dB. This restores the balance at $G=0$ as expected for an ideal passive device.

$$G=10\log\left(\frac{P_{out}}{P_{in}}\right)=10\log\left(\frac{\dfrac{V_{out}^{2}}{R_{out}}}{\dfrac{V_{in}^{2}}{R_{in}}}\right)$$

This term is usually forgotten (with tragic results!)

$$G=10\log\left(\frac{V_{out}^{2}}{V_{in}^{2}}\right)+10\log\left(\frac{R_{in}}{R_{out}}\right)=20\log\left(\frac{V_{out}}{V_{in}}\right)+10\log\left(\frac{R_{in}}{R_{out}}\right)$$

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Using Decibels

Rules:

◆ Multiply A x B:

(Add dB values)

$$
\begin{aligned}
&10\log_{10}(A \text{ x } B)\\
&\quad = 10\log_{10}(A) + 10\log_{10}(B)\\
&\quad = A\text{dB} + B\text{dB}\\
&\quad = (A + B)\text{dB}
\end{aligned}
$$

- Divide A / B:

(Subtract dB values)

$$
\begin{aligned}
&10\log_{10}(A / B)\\
&\quad = 10\log_{10}(A) - 10\log_{10}(B)\\
&\quad = A\text{dB} - B\text{dB}\\
&\quad = (A - B)\text{dB}
\end{aligned}
$$

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Using Decibels

Rules:

◆ **Squares:**

(Multiply by 2)

$$10\log_{10}(A^2)$$
$$= 2 \text{ x } 10\log_{10}(A)$$
$$= 20\log_{10}(A)$$
$$= 2 \text{ x } (A \text{ in dB})$$

- Square roots:

(Divide by 2)

$$10\log_{10}(\sqrt{A})$$
$$= \frac{10}{2}\log_{10}(A)$$
$$= \frac{1}{2} \text{ x } (A \text{ in dB})$$

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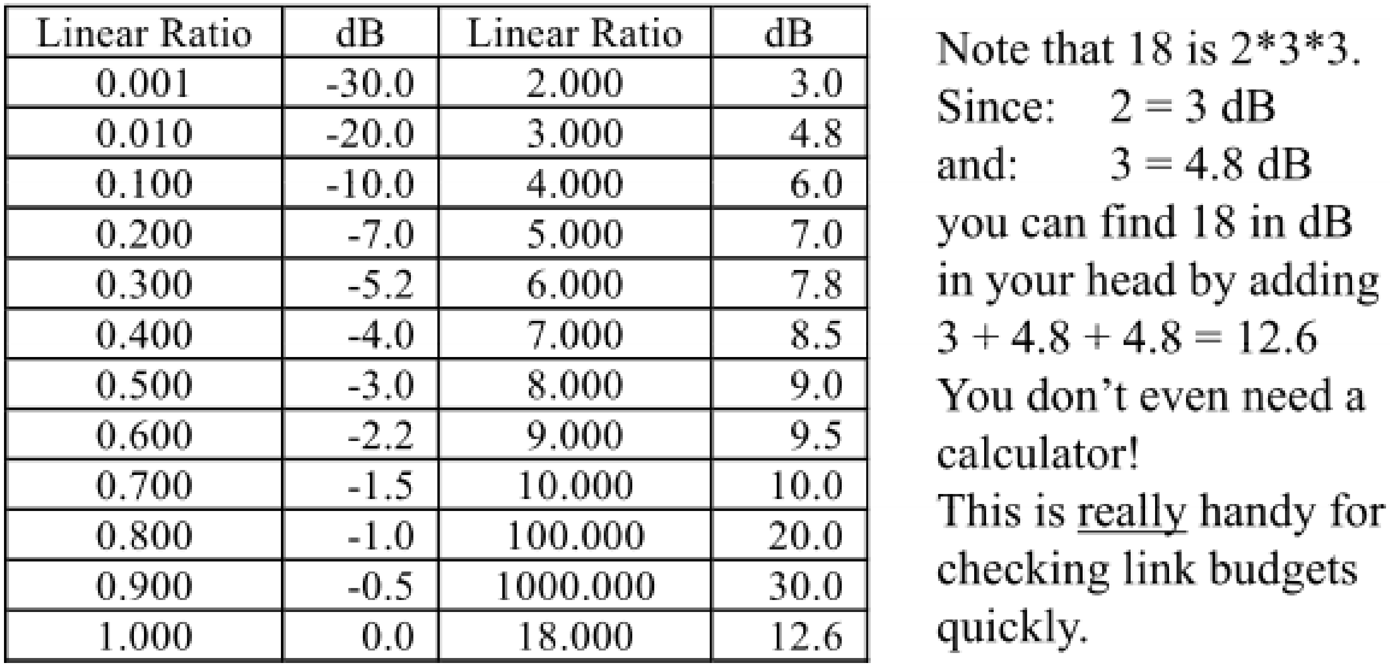
- Its useful to be able to think in dB



Linear Ratio	dB	Linear Ratio	dB
0.001	-30.0	2.000	3.0
0.010	-20.0	3.000	4.8
0.100	-10.0	4.000	6.0
0.200	-7.0	5.000	7.0
0.300	-5.2	6.000	7.8
0.400	-4.0	7.000	8.5
0.500	-3.0	8.000	9.0
0.600	-2.2	9.000	9.5
0.700	-1.5	10.000	10.0
0.800	-1.0	100.000	20.0
0.900	-0.5	1000.000	30.0
1.000	0.0	18.000	12.6

Note that 18 is 2*3*3.
Since: 2 = 3 dB
and: 3 = 4.8 dB
you can find 18 in dB in your head by adding 3 + 4.8 + 4.8 = 12.6

You don't even need a calculator!

This is really handy for checking link budgets quickly.

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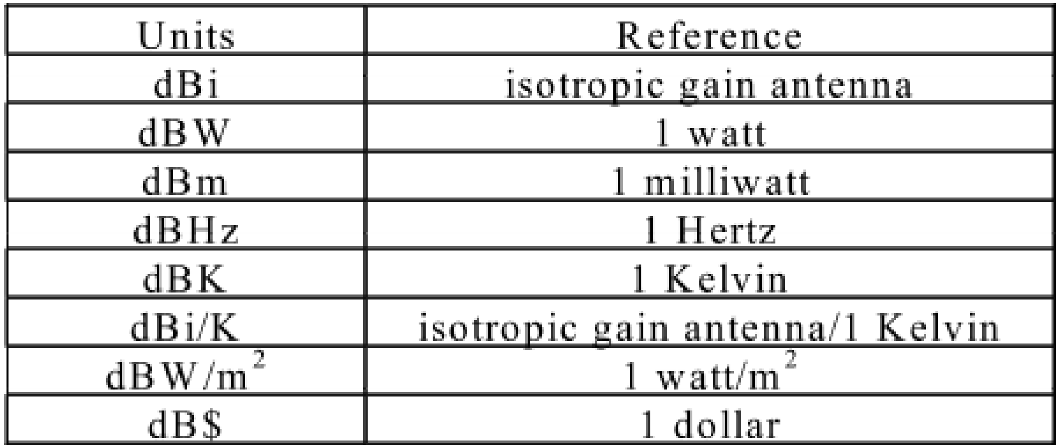
References in dB

- dB values can be referenced to a standard
- The standard is simply appended to dB
- Typical examples are:



Units	Reference
dBi	isotropic gain antenna
dBW	1 watt
dBm	1 milliwatt
dBHz	1 Hertz
dBK	1 Kelvin
dBi/K	isotropic gain antenna/1 Kelvin
dBW/m^2	1 watt/m^2
dB$	1 dollar

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Link Budget

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Translating to dBs

◆The transmission formula can be written in dB as:

$$P_r = EIRP - L_{ta} - L_p - L_a - L_{pol} - L_{ra} - L_{other} + G_r - L_r$$

◆This form of the equation is easily handled as a spreadsheet (additions and subtractions!!)

◆The calculation of received signal based on transmitted power and all losses and gains involved until the receiver is called "Link Power Budget", or "Link Budget".

◆The received power Pr is commonly referred to as "Carrier Power", *C*.

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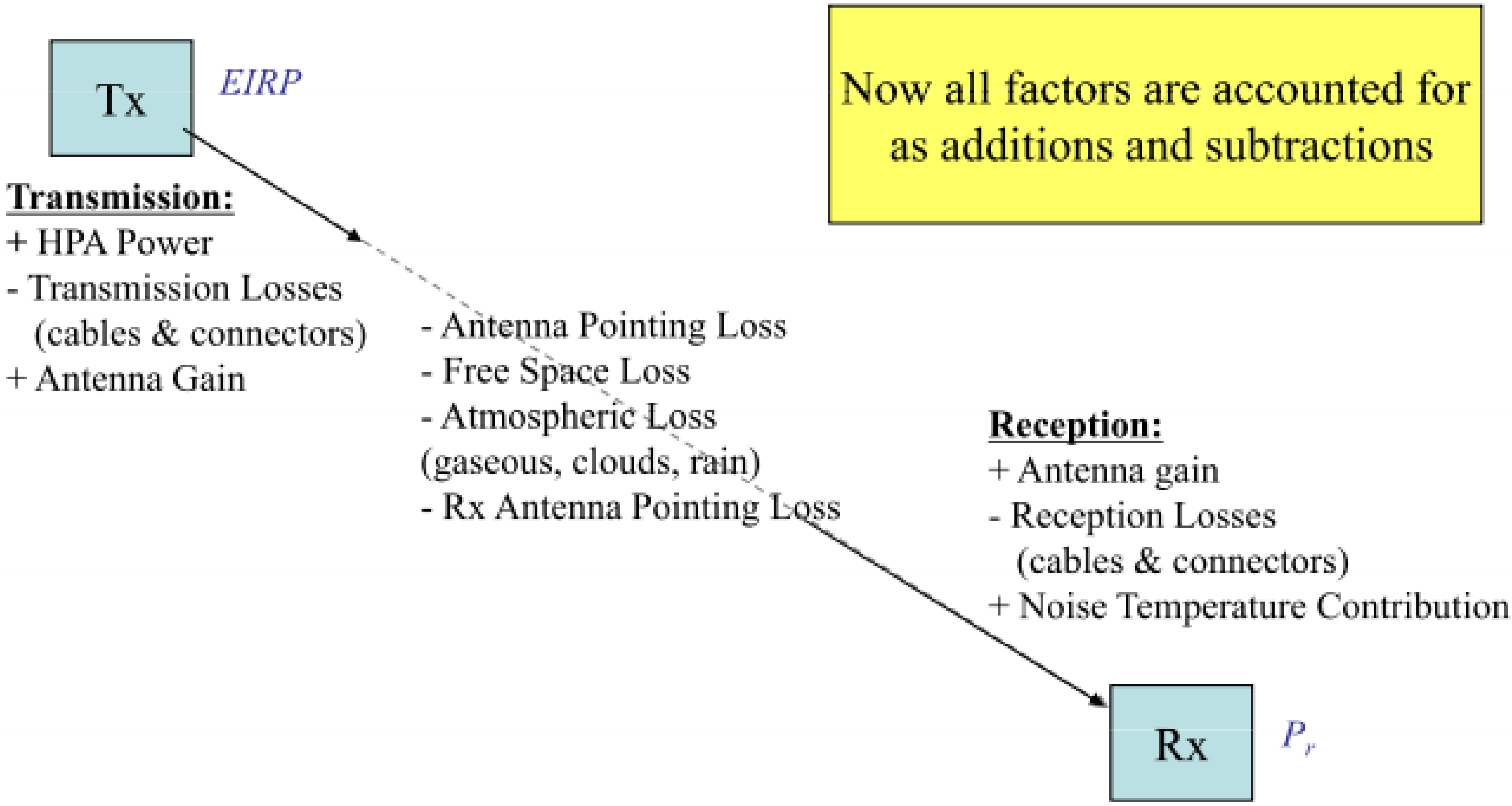
Link Power Budget



Transmission:
- \+ HPA Power
- \- Transmission Losses (cables & connectors)
- \+ Antenna Gain

Now all factors are accounted for as additions and subtractions

- \- Antenna Pointing Loss
- \- Free Space Loss
- \- Atmospheric Loss (gaseous, clouds, rain)
- \- Rx Antenna Pointing Loss

Reception:
- \+ Antenna gain
- \- Reception Losses (cables & connectors)
- \+ Noise Temperature Contribution

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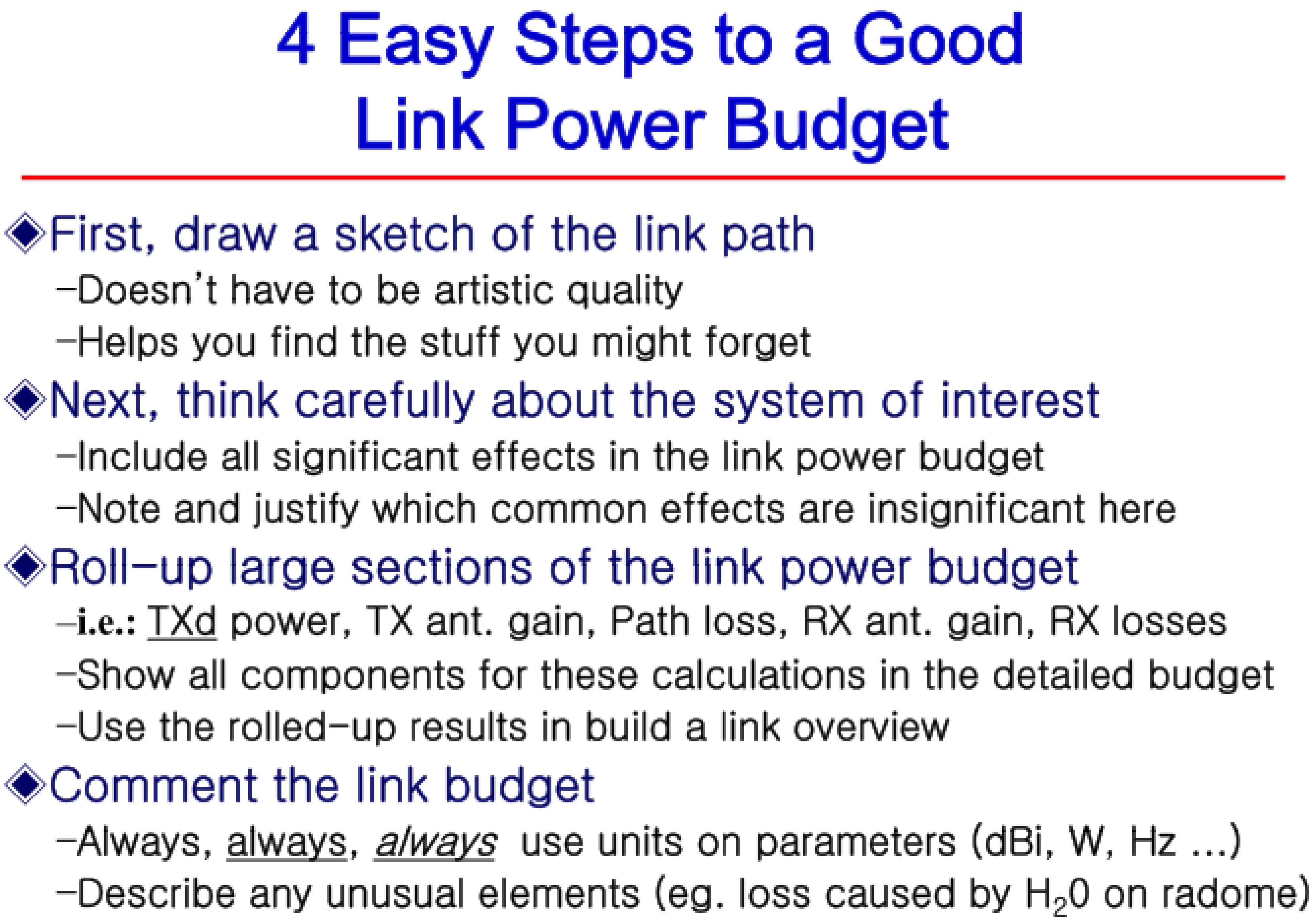

4 Easy Steps to a Good Link Power Budget

- First, draw a sketch of the link path
  - Doesn't have to be artistic quality
  - Helps you find the stuff you might forget
- Next, think carefully about the system of interest
  - Include all significant effects in the link power budget
  - Note and justify which common effects are insignificant here
- Roll-up large sections of the link power budget
  - **i.e.:** TXd power, TX ant. gain, Path loss, RX ant. gain, RX losses
  - Show all components for these calculations in the detailed budget
  - Use the rolled-up results in build a link overview
- Comment the link budget
  - Always, always, *always* use units on parameters (dBi, W, Hz ...)
  - Describe any unusual elements (eg. loss caused by $H_2$0 on radome)

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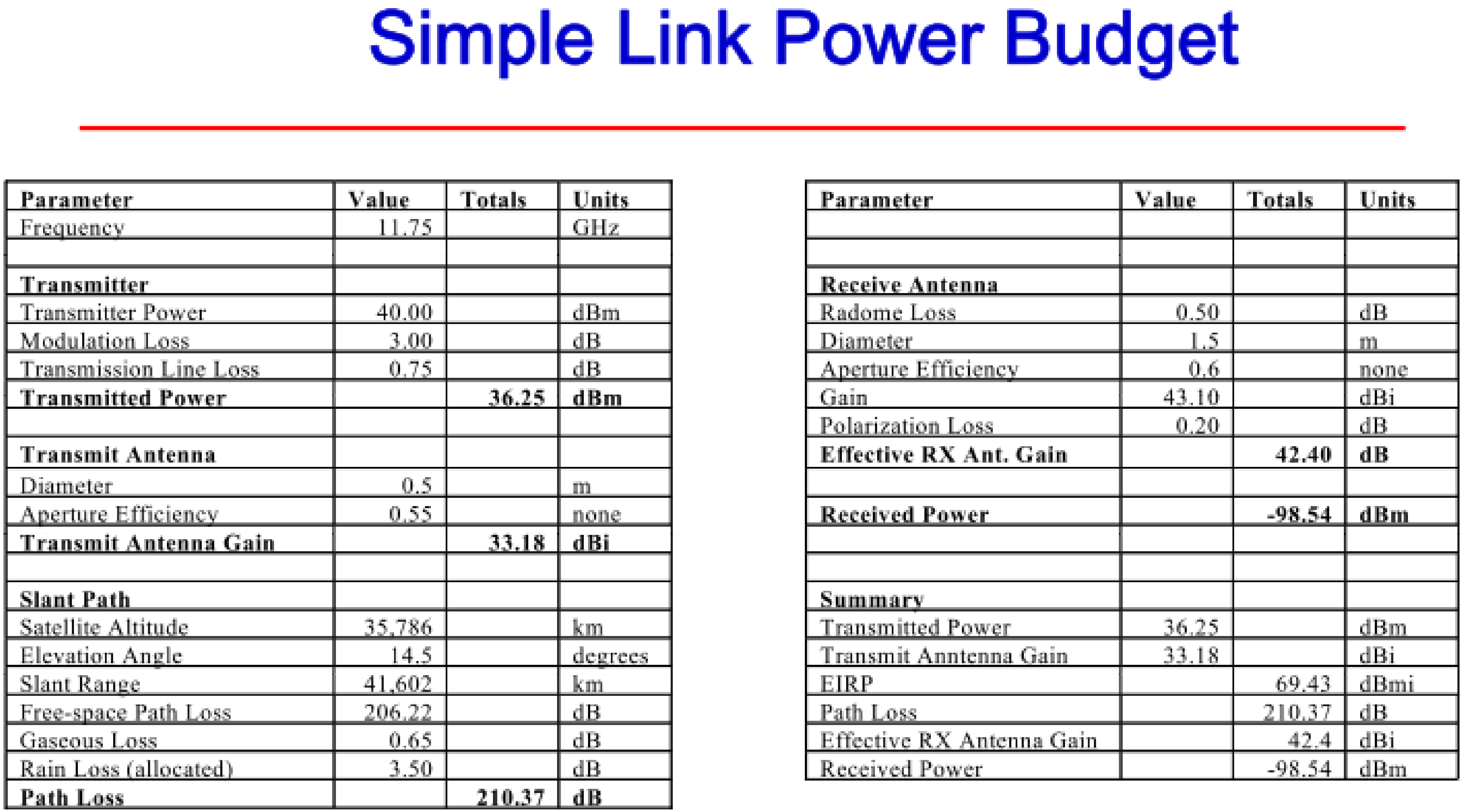

Simple Link Power Budget

Parameter	Value	Totals	Units
Frequency	11.75		GHz
Transmitter			
Transmitter Power	40.00		dBm
Modulation Loss	3.00		dB
Transmission Line Loss	0.75		dB
Transmitted Power		**36.25**	**dBm**
Transmit Antenna			
Diameter	0.5		m
Aperture Efficiency	0.55		none
Transmit Antenna Gain		**33.18**	**dBi**
Slant Path			
Satellite Altitude	35,786		km
Elevation Angle	14.5		degrees
Slant Range	41,602		km
Free-space Path Loss	206.22		dB
Gaseous Loss	0.65		dB
Rain Loss (allocated)	3.50		dB
Path Loss		**210.37**	**dB**

Parameter	Value	Totals	Units
Receive Antenna			
Radome Loss	0.50		dB
Diameter	1.5		m
Aperture Efficiency	0.6		none
Gain	43.10		dBi
Polarization Loss	0.20		dB
Effective RX Ant. Gain		**42.40**	**dB**
Received Power		**-98.54**	**dBm**
Summary			
Transmitted Power	36.25		dBm
Transmit Anntenna Gain	33.18		dBi
EIRP		69.43	dBmi
Path Loss		210.37	dB
Effective RX Antenna Gain		42.4	dBi
Received Power		-98.54	dBm

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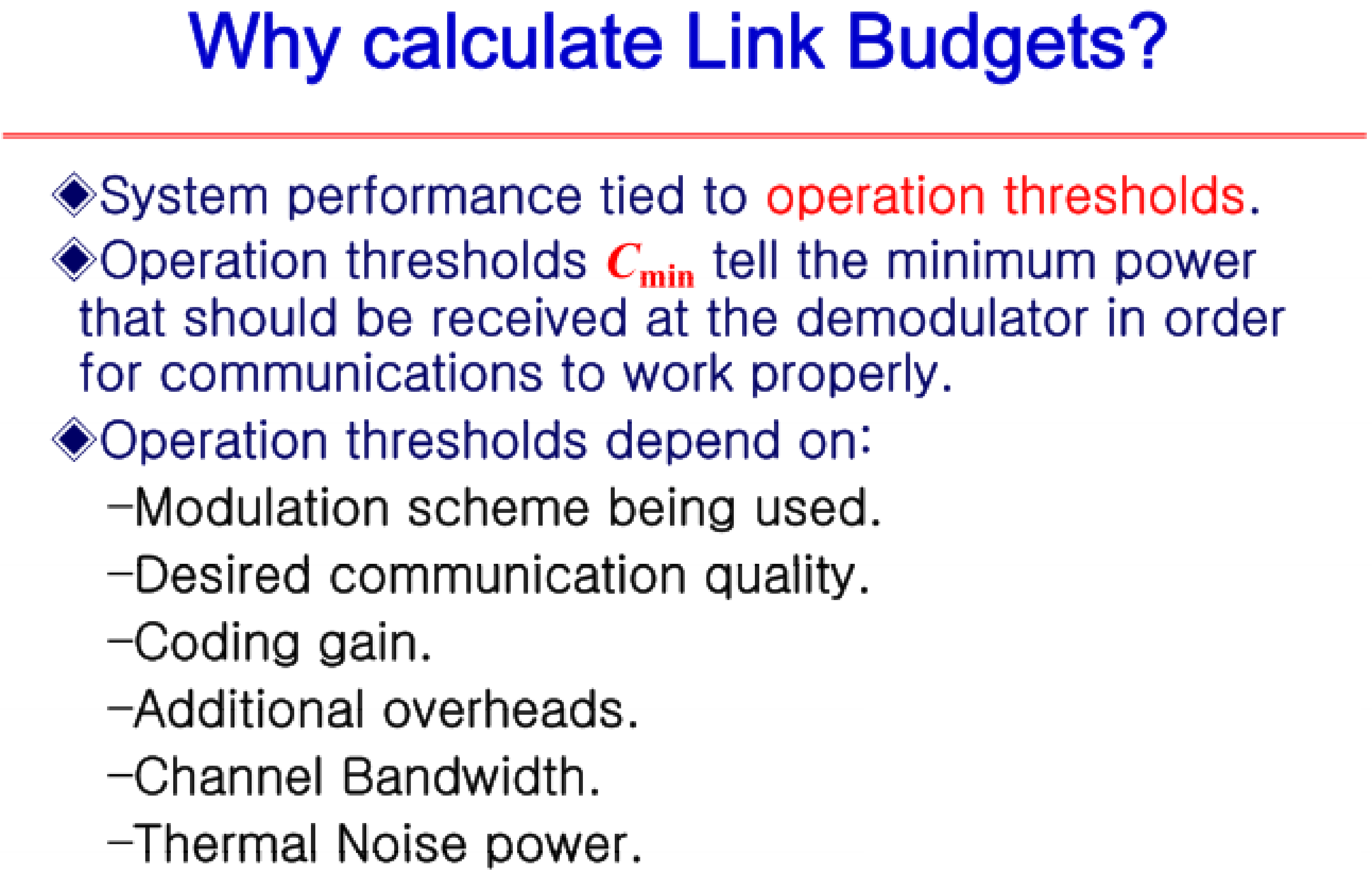

Why calculate Link Budgets?

- System performance tied to operation thresholds.
- Operation thresholds $C_{\min}$ tell the minimum power that should be received at the demodulator in order for communications to work properly.
- Operation thresholds depend on:
  - Modulation scheme being used.
  - Desired communication quality.
  - Coding gain.
  - Additional overheads.
  - Channel Bandwidth.
  - Thermal Noise power.

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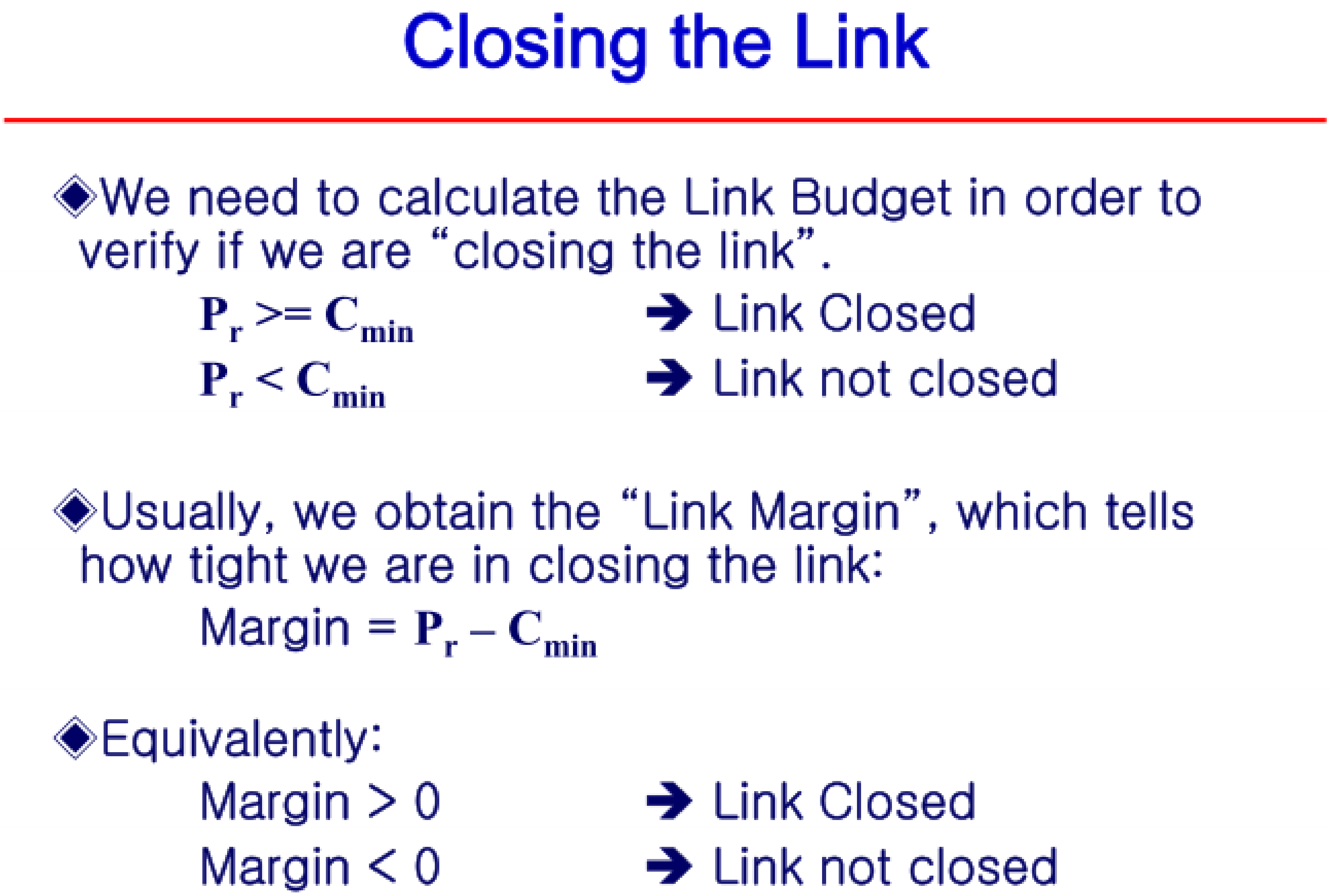


Closing the Link

- We need to calculate the Link Budget in order to verify if we are "closing the link".

  $P_r >= C_{min}$ ➔ Link Closed

  $P_r < C_{min}$ ➔ Link not closed

- Usually, we obtain the "Link Margin", which tells how tight we are in closing the link:

  Margin = $P_r - C_{min}$

- Equivalently:

  Margin > 0 ➔ Link Closed

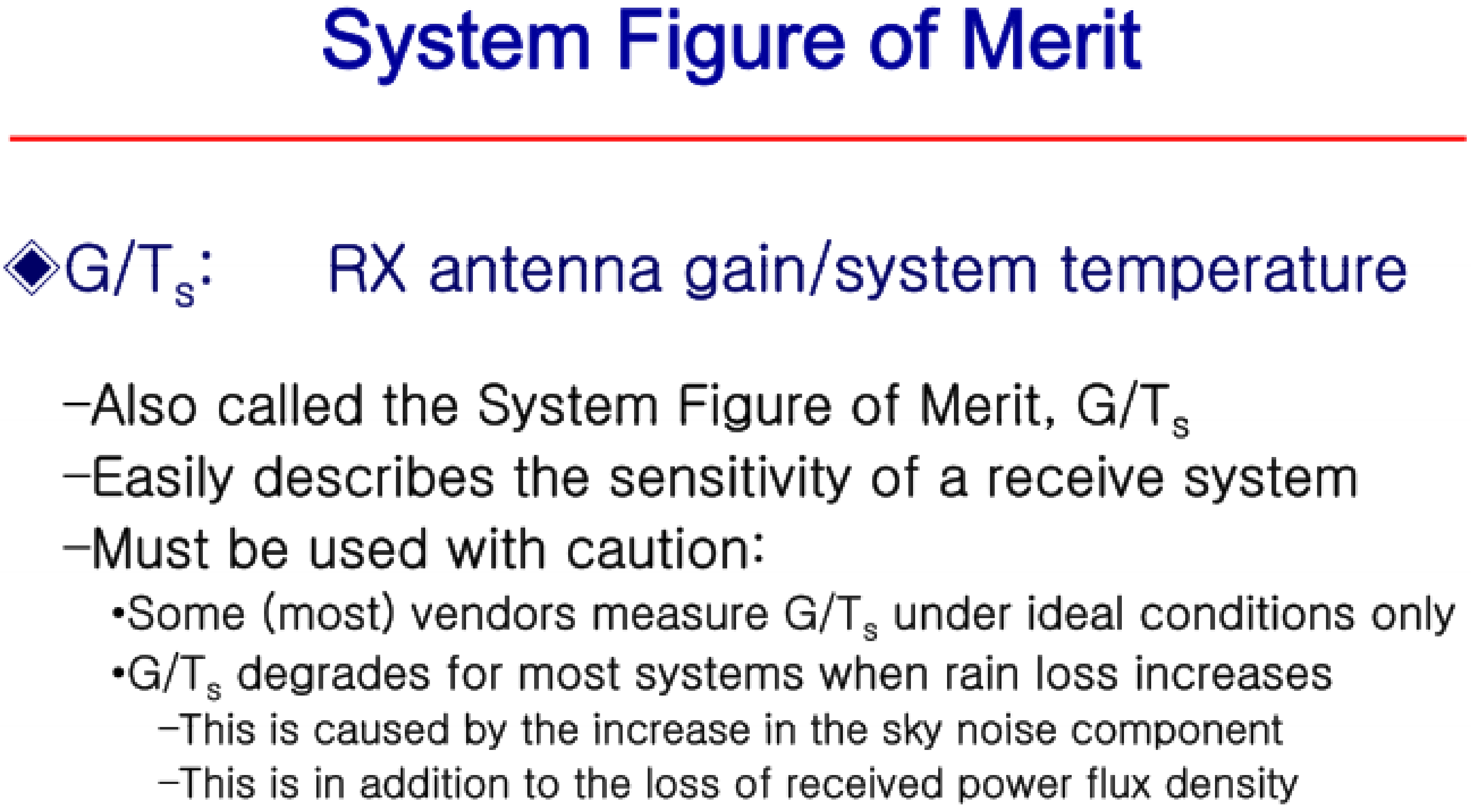
  Margin < 0 ➔ Link not closed

Satellite Link Design

Carrier to Noise Ratios

- C/N: carrier/noise power in RX BW (dB)
  - Allows simple calculation of margin if:
  - Receiver bandwidth is known
  - Required C/N is known for desired signal type
- C/N_o: carrier/noise p.s.d. (dbHz)
  - Allows simple calculation of allowable RX bandwidth if required C/N is known for desired signal type
  - Critical for calculations involving carrier recovery loop performance calculations

Satellite Link Design



System Figure of Merit

◆ G/T_s: RX antenna gain/system temperature

- Also called the System Figure of Merit, G/T_s
- Easily describes the sensitivity of a receive system
- Must be used with caution:
  - Some (most) vendors measure G/T_s under ideal conditions only
  - G/T_s degrades for most systems when rain loss increases
    - This is caused by the increase in the sky noise component
    - This is in addition to the loss of received power flux density

Radar!!

- Basic Principles
- Radar Equations
- Factors Affecting Radar Range
- Principles of Moving Target Indicator (MTI)