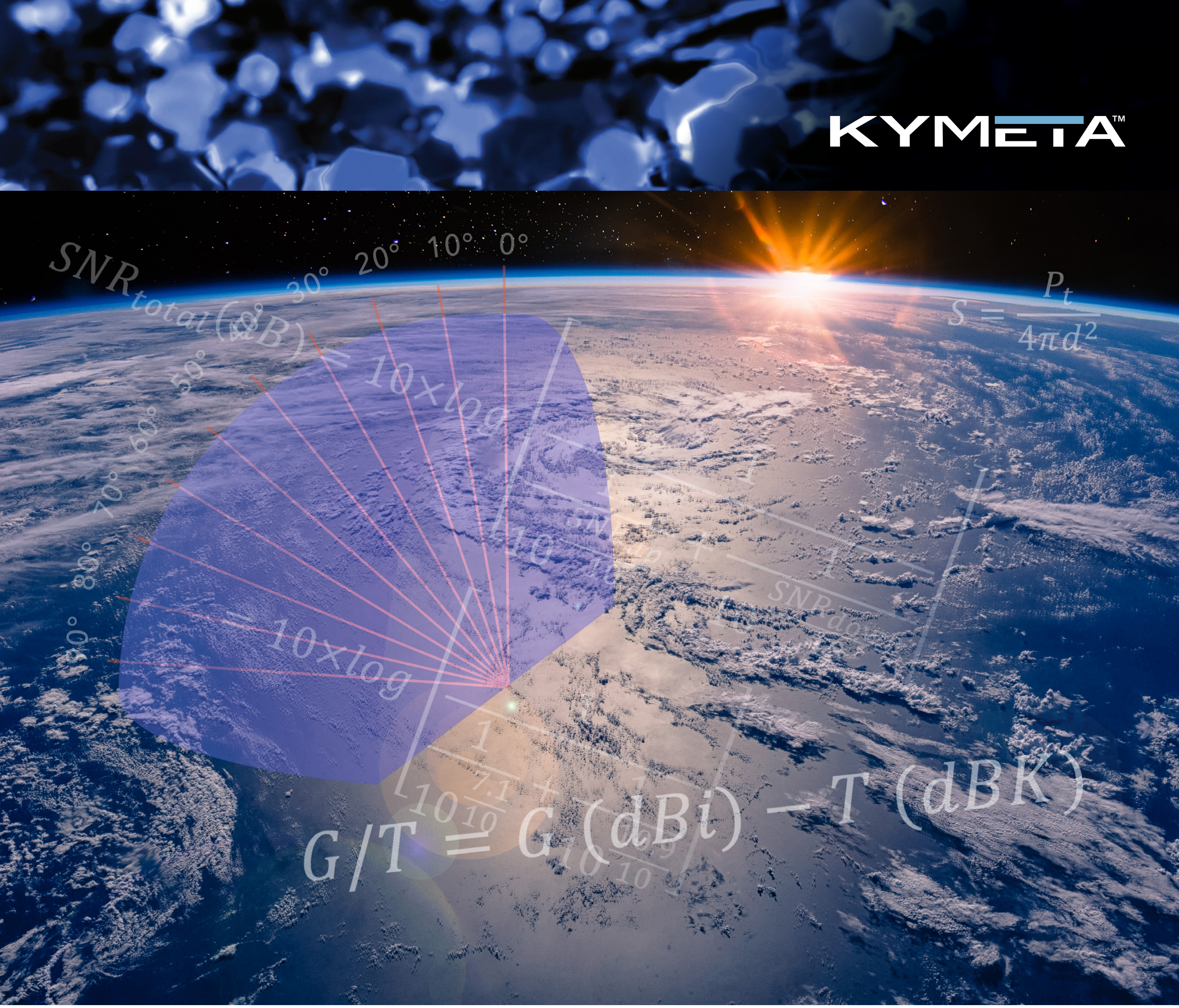

LINK BUDGET CALCULATIONS FOR A SATELLITE LINK WITH AN ELECTRONICALLY STEERABLE ANTENNA TERMINAL

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1 | INTRODUCTION

When designing a telecommunications system, one of the first and most important steps is to calculate a link budget (also called a link analysis). The link budget is a theoretical calculation of the end-to-end performance of the communications link. It accounts for all the gains and losses of the link under a specific set of conditions, and the result of the analysis is a set of figures of merit that characterizes the quality of the link. The most common figures of merit are:

- SNR (signal-to-noise ratio)
- Spectral efficiency (bits per second/Hz)
- Throughput (bits per second)

This paper shows you how to calculate the link budget for a satellite link that uses a flat panel, electronically steerable antenna (ESA) at the user terminal in mobility and fixed configurations. Before performing some example calculations, we'll first look briefly at the differences between a traditional parabolic dish antenna and an ESA, define three basic types of link budgets, and then identify the basic components of a satellite link and their associated gains and losses.

2 | THE ESA COMPARED TO THE PARABOLIC DISH

The conventional method of communicating with a geostationary satellite uses a parabolic dish antenna, which consists of a feed system and a passive parabolic reflector (Figure 1). The feed antenna is positioned in front of the reflector and illuminates it with radiation. The parabolic shape of the reflector ensures that the paths of the radiation from the feed antenna to the reflector and outwards from the reflector are all the same length, so that they combine in phase to produce a plane wave. Also, the paths from the reflector outward are all in parallel. The result is an accurate, highly directional beam. The directivity of the dish antenna also applies to incoming signals, greatly reducing the received power of signals coming from satellites or other sources that the antenna is not pointed at.

FIGURE 1. PARABOLIC DISH ANTENNA

The combination of high directivity and high radiation efficiency results in a high gain for the dish antenna. The gain can be further increased by increasing the size of the dish.

In stationary installations, the dish antenna can be set up, pointed at the satellite, and calibrated just once. But if used in mobility applications, such as on a vehicle, it must be repositioned whenever the vehicle moves to keep it pointed at the satellite. This requires a motorized mount, which adds bulk

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and weight, often making the dish antenna slow and cumbersome, or simply impractical for use, especially on smaller vehicles. The costs of manufacturing an accurate paraboloid reflector and a stable, precise gimbal mount can be high. Furthermore, the mount is subject to wear and mechanical failure from movement and from dirt intrusion.

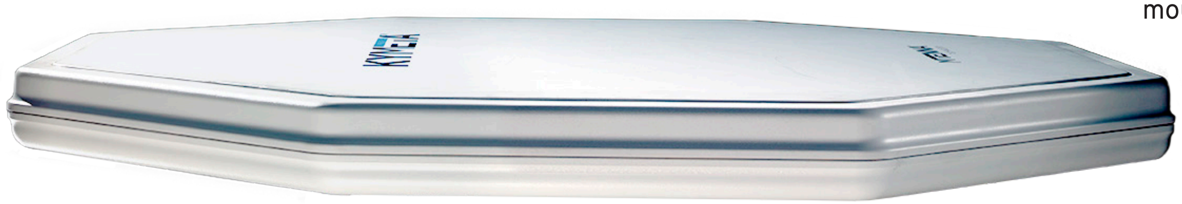

FIGURE 2. ELECTRONICALLY SCANNED ANTENNA (KYMETA)

Flat panel antennas that electronically steer (scan) their beams to track satellites are an increasingly popular alternative to dish antennas (Figure 2). Although there are various technologies in use, most ESAs use electronic control of the relative phase of the signals emitted from up to thousands of small antenna elements in a planar array to produce constructive and destructive interference, forming a beam that can be steered to track a satellite much more quickly than mechanical systems.

Since they have no external feed antenna or moving parts, ESAs can have a low profile of only a few inches and a relatively low weight. They can be simply mounted on the roof or other external surface of a vehicle (Figure 3).

The accuracy and speed of electronic beam steering means that ESAs, in comparison with dish antennas, can more easily stay connected to a satellite while the vehicle is moving. They can also be more easily sealed against weather and contamination than dish antenna assemblies. These advantages make them ideal for use on mobile platforms of almost any size, including buses, first responder vehicles, cars, construction vehicles, airplanes, and ships. Also, an ESA-based satellite terminal can be built into a rugged, transportable case for quick setup and use anywhere there is satellite coverage.

FIGURE 3. ESA MOUNTED ON THE ROOF OF A COMPACT SUV

The main disadvantages of ESAs compared to dish antennas are lower gain, and the variation in gain as the location and orientation are changed. For example, at high latitudes under geostationary satellites, a horizontal ESA will have less aperture area facing the satellite, resulting in lower efficiency than a dish, which can be mechanically pointed at the satellite for maximum gain. However, as non-geostationary LEO (Low Earth Orbit) and MEO (Medium Earth Orbit) satellite constellations become available, this problem will diminish, since the satellites are moving, so that there will always be a satellite overhead. Even with a fixed terminal, an ESA will have an advantage over a dish when using non-geostationary satellites, since it can track them without a gimballed tracking pedestal.

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3 | THE THREE TYPES OF LINK BUDGETS

Satellite links are named according to the flow of information on them. On the forward (FWD) link, information flows from the hub (earth station) to the user terminal. On the return (RTN) link, information flows from the user to the hub. Figure 4 shows the hub, satellite, and user terminal and the direction of data flow for the FWD and RTN paths. The FWD link budget is usually easiest to calculate, since good assumptions can be made to simplify the calculations. For example, the output power of the satellite can be assumed to be constant for the downlink to the terminal, since the hub has sufficient power to keep the satellite's high power amplifiers (HPAs) operating at saturation (or at the maximum power set by the operator). However, with a small aperture antenna such as an ESA, the uplink power from the terminal received by the satellite varies with antenna orientation and is not typically high enough to drive the HPAs to saturation, resulting in variable output power from the satellite. This means the RTN link budget calculations are usually more complicated.

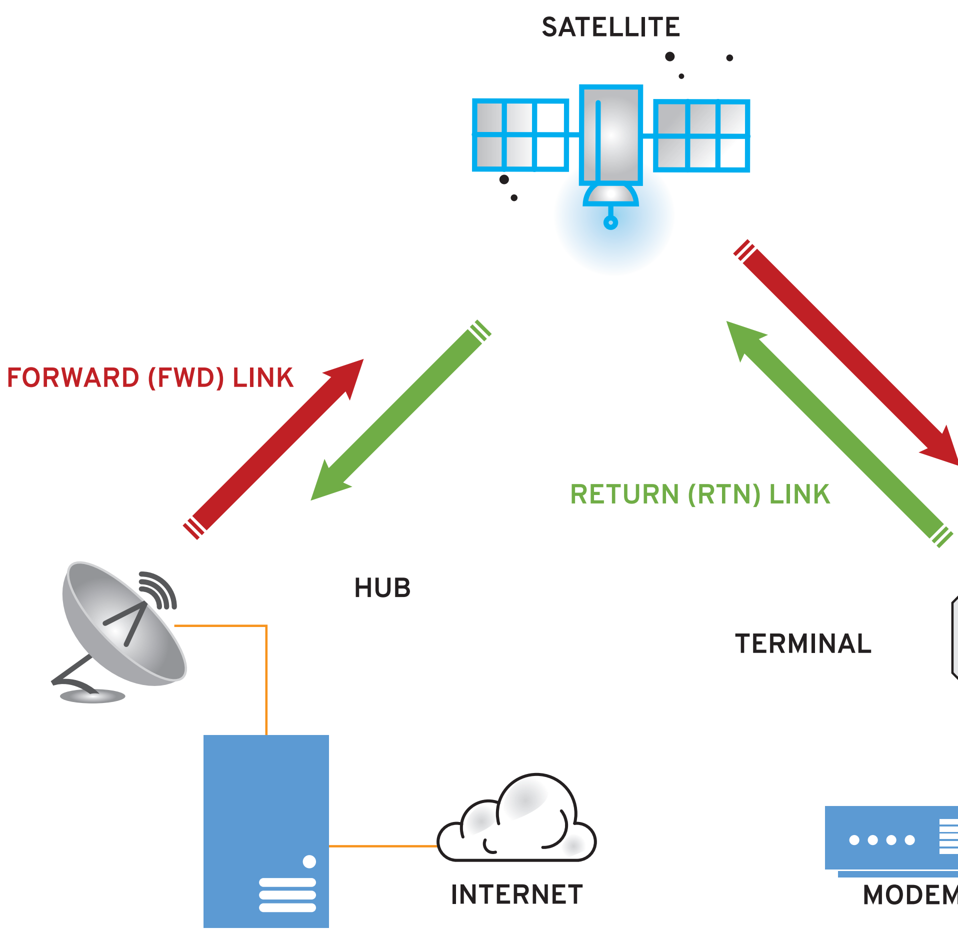

FIGURE 4. FORWARD (FWD) AND RETURN (RTN) LINKS

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3.1 FWD LINK: HUB TO TERMINAL

As explained above, the FWD link budget is the simplest to calculate, because the hub can be assumed to have sufficient uplink power to drive the FWD carrier up to the limits of the satellite transponder, ensuring constant output power. This means that our FWD analysis need only consider the portion of the link that connects the satellite and the user terminal.

3.2 SIMPLE RTN LINK: TERMINAL TO SATELLITE

The simple version of the RTN link budget considers only the uplink from the user terminal to the satellite, and so does not require knowledge of certain satellite and hub parameters, which can be difficult to obtain.

3.3 COMPLEX RTN LINK: TERMINAL TO SATELLITE AND SATELLITE TO HUB

Since the power from the user terminal received by the satellite varies with antenna orientation, and because this power is not enough to drive the satellite output power to the maximum level, additional noise is introduced into the link from satellite to hub. Therefore, an accurate calculation of the SNR for the entire RTN link must consider:

1. the SNR of the terminal-to-satellite link
2. the SNR of the satellite-to-hub link

When the output power of the satellite is at a maximum, SNR #2 is typically at least an order of magnitude greater than SNR #1, so it can be disregarded. But since the power density produced by the ESA terminal at the satellite is not high enough to yield maximum transponder output power, SNR #2 must be calculated and combined with SNR #1 to find the SNR of the complete RTN link.

In the section below, we'll identify the key components of the FWD and RTN links, and define the associated parameters and assumptions used for the calculation of SNR. This paper does not cover all potential sources of loss in satellite links, but it does include those that are common to all links.

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4 | LINK COMPONENTS AND THEIR PARAMETERS

4.1 | TERMINAL

4.1.1 | ANTENNA SCAN ANGLE AND COSINE ROLL-OFF

To determine the gain of an ESA terminal, we must know its scan angle. The scan angle is one of two angles that define the direction of the satellite beam (known as the bores-ight vector) relative to the antenna in a spherical coordinate system (Figure 5):

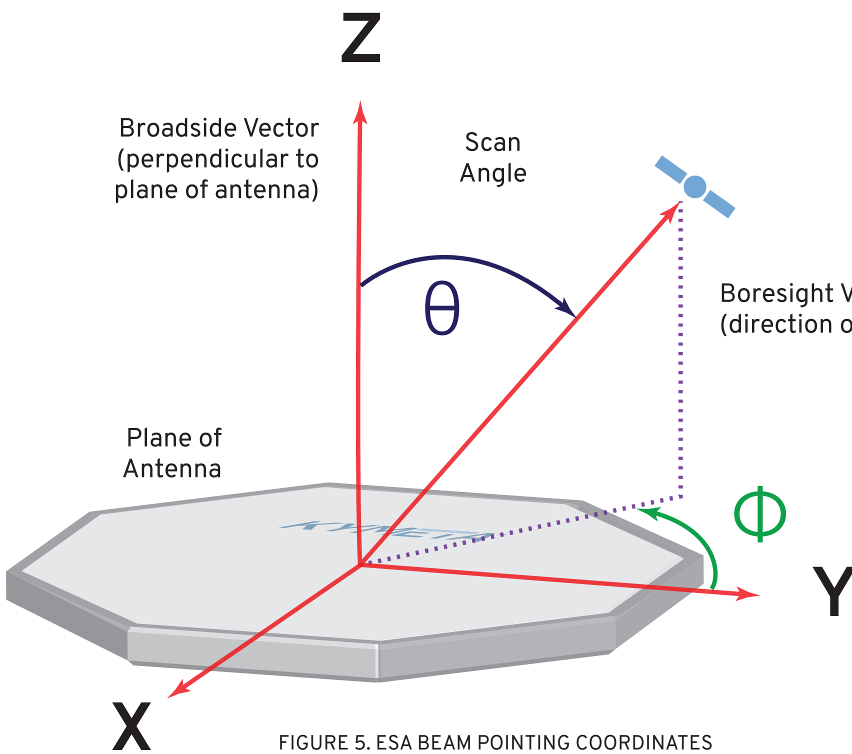

FIGURE 5. ESA BEAM POINTING COORDINATES

1. Theta (θ) is the scan angle. This is the angle between the boresight vector and the broadside vector (the axis that is perpendicular to the plane of the antenna). If the plane of the antenna panel is horizontal, the broadside vector is vertical.
2. Phi (ϕ) is the second angle coordinate that determines the direction of the boresight vector. It is measured in the plane of the antenna from a reference direction, which can be different for various antennas. For the Kymeta u7 antenna, the reference is a line connecting the center with the midpoint of the right side (the y-axis in Figure 5), and phi is measured.

For our calculations of SNR, we only need to consider theta, the scan angle.

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In fixed applications, the broadside vector is normally pointed at the satellite, so the angle between the broadside and boresight vectors (theta) is zero. In mobility scenarios, however, the antenna is typically mounted horizontally, so that the broadside vector is always vertical, but since the boresight vector must always point at the satellite, theta is positive (unless the satellite is directly overhead). Since less antenna area (aperture) is available to the beam in the case of a positive scan angle, the effective gain of the antenna is reduced. The reduction in gain with increasing theta is called the cosine (or scan) roll-off, discussed below.

4.1.2 | GAIN, NOISE TEMPERATURE, AND G/T

The gain (G) of the terminal is easily calculated for both fixed and mobility installations:

$$G(dBi) = Peak\ Gain\ (dBi) - cosine\ roll\text{-}off \times 10 \times log\ (cos\ \theta)$$

Where:

Peak Gain (dBi) = Peak gain of the antenna when the broadside and boresight vectors are aligned (θ = 0), so that there is no loss of gain caused by a reduction in the effective area of the antenna as seen by the satellite. This is typically specified by the antenna manufacturer.

Cosine roll-off = An antenna coefficient for the reduction in gain caused by scan angle (θ). Also called scan roll-off. This is also provided by the manufacturer.

However, the calculation of SNR requires that we determine a quantity called the gain-to-noise-temperature ratio, G/T, of the terminal. This ratio is a critical figure of merit for the terminal, and a peak value (for θ = 0) is usually provided by the manufacturer. T is the equivalent noise temperature (in kelvins) of the receiving system, which includes the antenna itself and the RF chain, ending at the output of the LNB (low noise block downconverter), assuming there is sufficient gain to make any noise contribution after the LNB negligible. The next section shows how terminal noise temperature is determined.

4.1.2.1 | TERMINAL NOISE TEMPERATURE

There are three main contributors to the noise temperature of the terminal:

1. Noise temperature of the antenna aperture
2. Loss of passive components (such as a diplexer)
3. Noise of active units (such as the LNB)

The additional gain from the LNB allows us to disregard the thermal noise following the LNB (including the modem), since it will not significantly impact the total noise temperature.

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Measuring the noise temperature of the antenna itself is difficult, but manufacturers typically determine it for you. Kymeta calculates antenna noise by measuring the peak directivity in the near field and the peak gain in the far field. The difference between directivity and gain is the ohmic loss of the antenna, from which the temperature can be calculated. The value for the Kymeta u7 antenna is approximately 170 K.

The noise temperature of a passive component is calculated using this equation:

$$T_p = T_e \times (A - 1)$$

Where:

T_p = noise temperature of the passive component

T_e = ambient temperature of the component (a good assumption is 290 K)

A = linear attenuation of the component

The only passive component in the RF chain between the antenna and the LNB in the Kymeta u7 terminal is the diplexer. A diplexer with 0.15 dB of loss (a typical value) introduces the following amount of noise into the system:

$$T_p = 290 \times \left(10^{\frac{0.15}{10}} - 1\right) = 11 \text{ K}$$

An active component is anything that introduces gain to the system (such as the LNB). Since these devices are not perfect, the SNR of the input signal is degraded when it reaches the output. The ratio of the input SNR to the output SNR is called the noise factor of the component. The noise figure (NF) is simply the noise factor expressed in dB and is a figure of merit for the component.

The noise figure specification for the LNB in the Kymeta u7 terminal is 1.0 dB. The ambient temperature, Te , is widely accepted to be 290 K for earth terminals. Using the same equation as for the passive noise temperature:

$$T_p = 290 \times \left(10^{\frac{NF}{10}} - 1\right) = 290 \times \left(10^{\frac{1}{10}} - 1\right) = 75 \text{ K}$$

To find the overall terminal noise temperature, we simply add the individual noise temperature contributions. For the Kymeta u7 terminal, we have:

$$\text{T} = 170 + 11 + 75 = 256 \text{ K} = 24.1 \text{ dBK}$$

Now that we have the terminal noise temperature, we can compute the G/T of the terminal in dB/K by subtracting the noise temperature from the antenna gain (which includes the cosine roll-off):

$$G/T = G\ (dBi) - T\ (dBK)$$

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4.1.3 EIRP AND EIRP DENSITY

The Equivalent Isotropic Radiated Power (EIRP) of the terminal is a measure of the transmitted power. It is computed from the BUC (block upconverter) operating power, the passive losses following the BUC, and the antenna gain.

The BUC converts the IF (intermediate frequency) signal from the output of the modulator to the higher frequency required for satellite band transmission and boosts the power of the signal before it reaches the antenna. BUC operating power is the power at the output of the BUC. Typically, the specified output power of a GaAs BUC is the maximum output power at which operation is linear, which is usually 1 dB below the saturated power (called the P1dB point). For example, if the BUC is specified to have an output power of 8 W, then it can operate linearly up to a maximum of 9 dBW:

$$\textit{maximum BUC operating power} = 8\ W = 9.03\ dBW$$

The passive losses can be assumed to be only the loss of the diplexer that connects the output of the BUC to the antenna feed (the diplexer allows the same antenna to be used for both transmit and receive paths). The antenna gain, which includes the cosine roll-off, was computed above. The EIRP of the terminal is the sum of these terms:

$$\textit{EIRP of terminal} = \textit{BUC operating power} + \textit{passive losses} + \textit{antenna gain}$$

The diplexer loss is typically small (~0.15 dB), so we will ignore it for these link budget calculations.

When computing the RTN link budget, it is easiest to compare the EIRP to the noise floor in a 1 Hz bandwidth (BW). This can be called the EIRP density at the output of the terminal, and is calculated as follows:

$$\textit{EIRP density of terminal} = \textit{EIRP} - 10 \times \log\ (\textit{channel BW} \,/\, 1\ Hz)$$

4.2 TRANSMISSION MEDIUM

The losses experienced by the signal as it propagates through space between the ground and the satellite are significant for link budget calculations. These propagation losses would be the same for the FWD and RTN links if the carrier frequencies were the same. However, the carrier frequencies are typically different for the up and down links, which results in slightly different losses. In this section, we will look at the main contributors to propagation loss and their dependence on signal frequency.

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4.2.1 FREE-SPACE PATH LOSS (FSPL)

Free space means a vacuum, space, or air, free of any obstructions that might hinder the propagation of electromagnetic waves. Free-space path loss (FSPL) is the loss in strength of an electromagnetic signal as it travels through free space in a line-of-sight path from a transmitting antenna to a receiving antenna.

The calculation of FSPL includes two effects:

- The diminishing of power density as the signal spreads through space in all directions
- The efficiency of an antenna in receiving power from an incoming electromagnetic signal

To account for the first effect, we imagine an antenna that propagates energy uniformly in all directions (this is called an isotropic radiator). The regions of equal power density form spheres around the radiator, and the power density at the surface of a sphere is inversely proportional to the surface area of the sphere. This means that the density is also inversely proportional to the square of the distance (d) from the radiator, which is the radius of the sphere. This relationship is known as the inverse square law:

$$S = \frac{P_t}{4\pi d^2}$$

Where:

S = power density in W/m2 at a distance d

P_t = transmitted power in W

d = distance in m between antennas

The efficiency of the receiving antenna's aperture is a function of the frequency (or wavelength) of the signal:

$$P_r = \frac{S\lambda^2}{4\pi}$$

Where:

P_r = received power in W/m2

λ = wavelength of the signal in m

By combining these two expressions we arrive at the expression for free-space path loss:

$$FSPL = \frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi df)^2}{c^2}$$

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Where:

f = signal frequency

c = speed of light in a vacuum = 3×108 m/sec

Converting to logarithmic (decibel) format:

$$FSPL = 20 \times log\ (d) + 20 \times log\ (f) - 20 \times log\ (4\pi/c)$$

For simplicity when dealing with satellite communications, this can be expressed in units of GHz for frequency and km for distance:

$$FSPL = 20 \times log(d) + 20 \times log(f) + 92.45$$

4.2.2 ATMOSPHERIC LOSS

As the signal travels through the atmosphere, the different molecules that compose the air absorb energy at different rates depending on frequency (Figure 6).

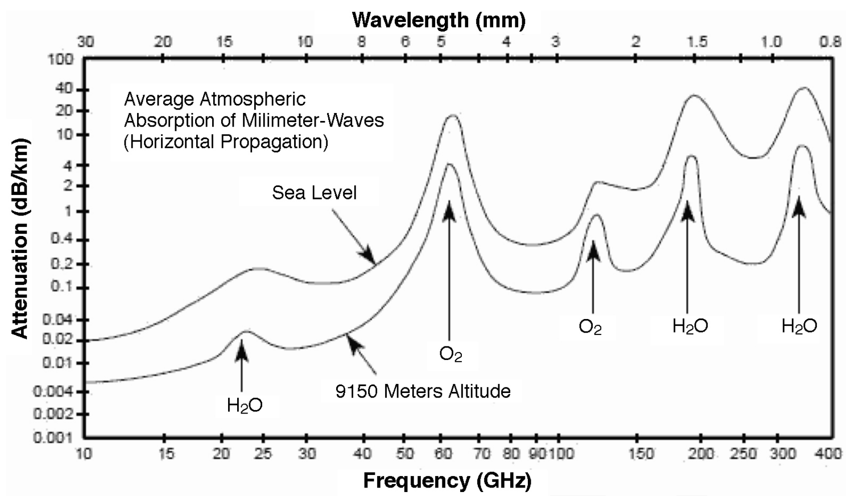

FIGURE 6. ATMOSPHERIC ABSORPTION OF MILLIMETER WAVE ENERGY [1]

Different molecules have different absorption (excitation) frequencies over the range of 10 to 400 GHz, and some have more than one absorption frequency. For example, the oxygen molecule (O2) has a large absorption peak at about 60 GHz and a smaller one at about 119 GHz. Therefore, transmitting a 60 GHz signal through the atmosphere would be nearly impossible, as the loss is extremely high (about 10 dB per km before reaching cloud level). However, a 60 GHz signal could be transmitted between satellites without severe attenuation, since there is no atmosphere at orbit altitude.

There is a significant absorption peak for water at approximately 22 GHz, which is why the IEEE K band is divided into three sub-bands:

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Ku band (12–18 GHz): Used mainly for satellite communications, direct broadcast satellite television, and terrestrial microwave communications.

K band (18–26.5 GHz): Because of the high atmospheric absorption at 22 GHz, this is only useful for short-range applications.

Ka band (26.5–40 GHz): Used primarily for radar and a limited number of satellite communications.

For Ku band, it is generally agreed that atmospheric absorption is between 0.01 and 0.02 dB/km. The thickness of the atmosphere is approximately 90 km, but since a satellite is not typically directly overhead, a path length of 100 km is a good approximation of the distance the signal must travel through the atmosphere. However, the atmosphere becomes less dense at higher altitude, so a total loss of 0.35 dB is a reasonable assumption, except in the case of a satellite at a very low elevation angle.

4.2.3 | RAIN FADE AND AVAILABILITY

A thorough discussion and method of calculating rain fade is provided in [2]. This section is a summary of the method.

When a signal travels through clouds, it will be attenuated by the high concentration of water vapor. This is called rain fade. The rate of attenuation will vary depending on factors including cloud height and density, rainfall rate, polarization, frequency, and the location on the Earth.

The Crane model (Figure 7), which is often used for rain fade computations, describes the estimated rainfall rate (mm/hr) for various climate zones of the world.

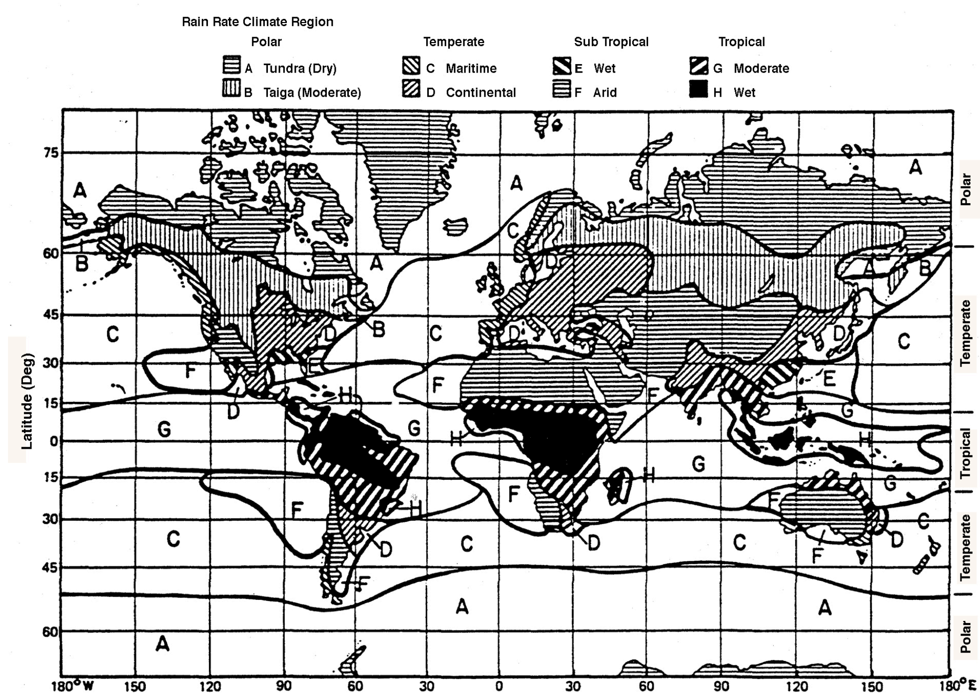

FIGURE 7. RAIN RATE CLIMATE REGIONS [2]W

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Each zone is assigned a rainfall rate coefficient (R) to help calculate the rain fade loss for a terminal in that region. Additional coefficients (k and a) to account for frequency and signal polarization are also used.

The other important factor in the calculation is a statistical one, called the availability. Availability is defined as the expected percentage of the time that the satellite link will be able to close. For example, an availability of 99.5% means that only 0.5% of the time will the rain cause enough signal degradation to destroy the link. The desired availability has a large effect on the calculated rain fade loss, as shown in Table 1, which relates the rainfall rate, R, to the percentage of time it is exceeded in any year for each climate zone.

TABLE 1. RAINFALL COEFFICIENTS BY REGION AND AVAILABILITY [2]

Percentage of time R exceeded	ZONE														
	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q
1.0	<0.1	0.5	0.7	2.1	0.6	1.7	3	2	8	1.5	2	4	5	12	24
0.3	0.8	2	2.8	4.5	2.4	4.5	7	4	13	4.2	7	11	15	34	49
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65	72
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105	96
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200	142
0.001	22	32	42	42	70	78	65	83	55	100	150	120	180	250	170

The equation for rain fade is:

$$Loss = kR^a \times D$$

Where R, a, and k are the coefficients described above, and D is the path length through the troposphere (the lowest region of the atmosphere, which contains approximately 99% of the water vapor). The following are example calculations of rain fade for different availability values for a terminal located on the ground in Seattle, WA (zone C) and operating at 12 GHz in the Ku band, and a geostationary satellite at an elevation of 40 degrees.

k = 0.0188

a = 1.217

R = 0.7

D = (height of rain)/sin(elevation)

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Where the height of the rain depends on the latitude of the terminal, which is 47 N for Seattle. For a latitude > 23 N the height is given by:

$$\text{Height of rain} = 5 - 0.075\times(47-23) = 3.2$$

Thus, for a satellite elevation of 40 degrees, simple trigonometry yields:

$$D = 3.2\times\sin(40) = 4.97 \text{ km}$$

Now we can compute the loss in this example for various values of availability threshold using the loss equation above. The results are shown in Table 2.

TABLE 2. RAIN FADE FOR DIFFERENT AVAILABILITY RATES

AVAILABILITY	LOSS FROM RAIN FADE
99%	0.06 dB (NEGLIGIBLE)
99.97%	1.35 dB
99.99%	8.83 dB

As this example shows, the assumed availability has a significant effect on the SNR margin that should be allowed for rain fade. Because of the extreme sensitivity of the margin to the desired availability, which is determined by customer expectations, a clear sky is assumed for the example calculations below.

4.3 | SATELLITE

4.3.1 | TRANSPONDER EIRP

Since geostationary satellites are static relative to any fixed location on the Earth, engineers can shape the satellite antenna to produce different levels of energy at different locations on the surface of the Earth. This distribution of energy is described by the satellite's EIRP footprint (or coverage) map, which shows the EIRP with the transponder operating at saturation (see section 4.3.2). The EIRP footprint map for Galaxy 18 is shown in Figure 8 [3].

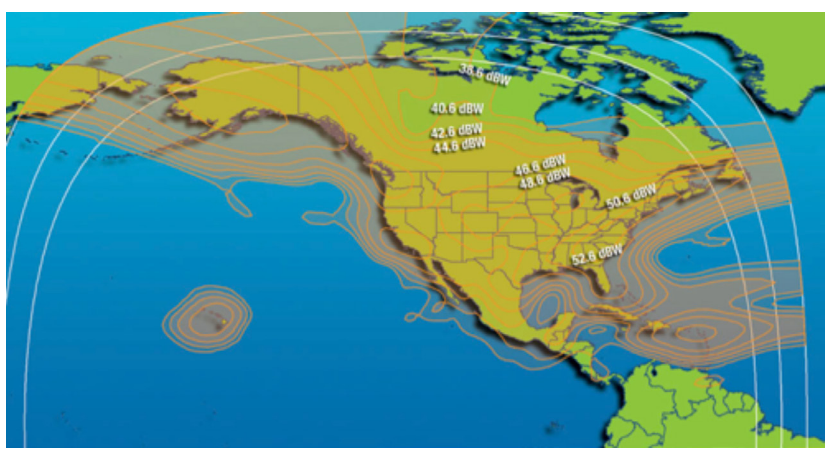

FIGURE 8. FOOTPRINT MAP FOR THE GALAXY 18 SATELLITE [3]

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The map shows contour lines for the satellite's saturated EIRP, which are analogous to the elevation contour lines of a topographical map. The EIRP is constant at the indicated value everywhere along the contour line, and for locations between the lines we can interpolate the values. Footprint maps simplify the complex internals of the satellite and allow the operator to keep confidential sensitive technical details, which otherwise would be needed to calculate link budgets. A similar map is usually generated for the satellite transponder's uplink (receive) G/T, where the contours show the reduction from peak G/T at various locations.

4.3.2 SATURATION FLUX DENSITY (SFD), HPA BACK-OFF, AND SATELLITE G/T

The Saturation Flux Density (SFD) is a satellite parameter required for calculating the complex RTN link budget. It represents the received power flux density (PFD) needed at the satellite antenna to saturate the high power amplifier (HPA) of the transponder and produce the maximum output power. Since the EIRP of the ESA terminal is generally lower than that of a terminal that uses a parabolic antenna, it typically cannot achieve the SFD value at the satellite antenna (except possibly in a very narrow channel bandwidth). The difference between the terminal PFD and the SFD of the transponder is called the input back-off to the HPA.

We can determine the PFD at the satellite using the equation for power density at a distance r to the satellite in meters:

$$Power\ Density\ (W/m^2) = \frac{P \times G}{4\pi r^2}$$

Where P = power (W) into antenna and G = antenna gain (as calculated above). Converting to dB:

$$PFD\ (dBW/m^2) = EIRP\ of\ terminal - 20\times log(r) - 10\times log(4\pi)$$
$$= EIRP\ of\ terminal - 20\times log\ (r) - 10.99$$

Typically, the SFD for the transponder you are assigned by the satellite operator is provided for a specified G/T contour (this is the G/T of the satellite looking toward the terminal) shown on the uplink coverage map; for example, SFD =−88 dBW/m2 at the 0 dB/K G/T contour. A lower G/T requires more transmitted power to achieve HPA saturation. For instance, if the terminal is at the −2 dB/K contour, then 2 dB more power must be transmitted, so the required SFD would be higher at −86 dBW/m2.

Once the difference between SFD and PFD is determined, this back-off value is subtracted from the value shown on the hub downlink EIRP contour map (Figure 8) when calculating the satellite-to-hub SNR, since

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the contour value of EIRP is for the entire transponder channel (typically 36 MHz) operating at or near saturation. Typically, wide-beam satellites have one coverage map for both FWD and RTN links, but HTS (High Throughput Satellite) satellites will have a dedicated antenna for the hub (gateway) downlink to maximize gain and SNR towards the hub.

4.3.2.1 | ADDITIONAL FACTORS AFFECTING BACK-OFF

The total signal back-off for the transponder is also affected by two other factors: channel bandwidth and HPA compression.

If the channel bandwidth is not the full transponder bandwidth, then only part of the SFD power is allocated to the terminal. The effective SFD, which accounts for the difference in bandwidths, is called the terminal SFD:

$$Terminal\ SFD = SFD - 10 \times \log\left(transponder\ BW / channel\ BW\right)$$

For example, if the transponder has a bandwidth of 36 MHz and the channel bandwidth is 3.6 MHz, so that our signal only occupies 10% of the transponder bandwidth, then the effective terminal SFD in the above example would be 10 dB less: that is, −96 dBW/m2 instead of −86 dBW/m2.

In addition, all amplifiers experience compression when operating near saturation. For a satellite HPA, this is typically about 2.7 dB. Therefore, when calculating the back-off of the signal with respect to saturation, this must be included. For example, if the delta between PFD and SFD is calculated to be 10 dB, then in practice it's at least 12.7 dB, because an additional 2.7 dB of power would have to be added to attain saturation.

4.4 | HUB

4.4.1 | G/T

The antenna gain-to-noise-temperature ratio for a specific hub used in a geostationary satellite service is not typically available to a user, but there are at least three techniques for calculating the G/T, which are covered in detail in [4]. These techniques account for the increases in noise temperature due to atmosphere and precipitation, and noise contributions from interfering ground and cosmic radiation sources. The gain is also dependent on the diameter of the dish.

For the example calculation of the complex RTN SNR below, we will use the following assumptions:

- G = 52 dBi for a 4.5 m dish operating at 12 GHz
- Antenna noise temperature = 100 K
- Additional noise from atmospheric loss and miscellaneous sources = 60 K

Hub G/T = 52 – 10×log(100 + 60) = 30 dB/K

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5 | CALCULATING SNR

Because of the sensitivity of rain fade to the desired link availability, which is determined by user expectations for quality of service (QoS), the SNR calculations presented below assume a clear sky.

5.1 | FWD EQUATION

The calculation of the signal-to-noise ratio of the FWD link (satellite to user terminal) is relatively simple, because the EIRP of the satellite is constant. The equation is:

$$SNR = satellite\ transponder\ EIRP\ (dBW) - transponder\ BW\ (dBHz) - FSPL\ (dB) - atmospheric\ loss\ (dB) + G/T\ of\ terminal\ (dB/K) - k(dBW/K/Hz)$$

Where k = Boltzmann's constant, the theoretical noise floor or minimum sensitivity of the receiver.

Subtracting the transponder bandwidth from the full satellite EIRP gives the satellite transmit power in a 1 Hz bandwidth. Subtracting the FSPL and atmospheric attenuation, and then adding the terminal G/T provides the power at the output of the LNB (also in a 1 Hz BW). Finally, subtracting k, the theoretical noise floor of the receiver, produces the overall signal-to-noise ratio in a 1 Hz BW.

5.2 | SIMPLE RTN EQUATION

The simple RTN equation is like the FWD equation, but for the uplink direction (terminal to satellite). However, since the user can change the channel bandwidth, the terminal EIRP density (represented by the first three terms in the equation) can vary. The equation is:

$$SNR_{up}(dB) = BUC\ operating\ power\ (dBW) + G\ (dBi) - channel\ BW\ (dBHz) - FSPL\ (dB) - atmospheric\ loss\ (dB) + G/T\ of\ satellite\ (dB/K) - k(dBW/K/Hz)$$

As the channel BW decreases, the SNR increases, but the data throughput decreases. In the extreme case of a 1 Hz BW, throughput will be down to a few bits per second (bps), and little or no information can be encoded on the carrier. Increasing the BW allows a higher data rate, but decreases the SNR, and in the extreme case the power is distributed over such a wide BW that the signal is below the noise threshold and no data is received. Since all practical BWs yield SNRs above the noise threshold and are wide enough to transmit data, there must be a specific BW that optimizes the product of the spectral efficiency (bps/Hz) and the channel BW, which is the throughput. However, there is another constraint to consider: the available transponder bandwidth is a limited commodity. This means that the most cost-effective approach is usually

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to minimize the channel bandwidth (limited by regulatory channel masks).

5.3 | COMPLEX RTN EQUATION

The complex RTN equation includes both the uplink (terminal to satellite) and downlink (satellite to hub) paths. The equation for the SNR of the uplink path is the simple RTN equation given above. However, to calculate the downlink SNR we must know the satellite transponder SFD, BW, and HPA back-off (discussed above), as well as the G/T of the hub.

$$SNR_{down}(dB) = saturated\ satellite\ EIRP - (terminal\ SFD\ -\ PFD + 2.7)\ - 10 \times \log\left(transponder\ BW\right) - FSPL - atmospheric\ loss + G/T\ of\ hub - k$$

The two SNR values are then combined to account for the cascading noise contributions:

$$SNR_{total}(dB) = 10 \times log\left[\frac{1}{\frac{1}{10^{\frac{SNR_{up}}{10}}} + \frac{1}{10^{\frac{SNR_{down}}{10}}}}\right]$$

5.4 | IF SATELLITE AND HUB PARAMETERS ARE NOT AVAILABLE

Depending on the geostationary satellite service you are using, it might not be possible to obtain the hub G/T, saturated satellite EIRP for the hub location, satellite G/T looking at the terminal, transponder bandwidth, and SFD for calculating the SNR of the complete RTN link. In this case, you can use these approximations for rough budget calculations:

- Hub G/T: 30 dB/K (see section 4.4.1)
- Saturated EIRP: use highest EIRP from footprint map
- Satellite G/T: 6 dB/K
- Transponder BW: 36 MHz
- SFD: −88 dBW/m2 at the 0 dB/K G/T contour

Another approximation to simplify the complex RTN calculation is to assume a satellite-to-hub SNR of 25 dB at saturation. Then to find SNRdown we subtract (SFD – PFD + 2.7), the back-off for the HPA (section 4.3.2).

6 | CONVERTING SNR TO SPECTRAL EFFICIENCY AND THROUGHPUT

The goal of the link budget calculations is to determine figures of merit

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that describe the quality of our satellite link. The SNR is the key figure of merit for a link. Once it is calculated, and we know the available MODCODs for the modem we are using (see the MODCOD section below), we can select the most efficient MODCOD for our SNR. The selected MODCOD determines the other figures of merit that are part of a typical link budget analysis: spectral efficiency and data throughput.

6.1 MODCOD

Every satellite link is designed with a specific MODCOD (modulation and coding) scheme. Modulation is the method by which the carrier (an analog signal) is modulated, or varied, to encode digital information. This is typically done by shifting the phase of the carrier signal according to the value of the bit (1 or 0). At the receiving end, a demodulator extracts the data from the modulated carrier by detecting the phase shifts.

A popular modulation scheme now in widespread use is PSK (phase shift keying). The simplest form of PSK is binary phase shift keying (BPSK), which uses two phases separated by 180 degrees, and is also called 2-PSK. Quadrature phase shift keying (QPSK, or 4-PSK) uses four phases, and can therefore transmit twice the data rate in the same bandwidth as BPSK for the same error rate (but double the power is needed).

So that an independent reference signal is not required to determine the absolute phase change of the carrier, the transmitted signal itself is typically used as the reference, and the phase is shifted relative to the previous bit. This implementation of PSK is called DFSK (differential phase shift keying).

Coding refers to forward error correction (FEC), a technique for controlling errors in data transmission over noisy channels. The transmitter adds redundant data in the form of an error-correcting code that is generated from the information data using a predetermined algorithm. By analyzing the code, the receiver can perform a certain level of error correction without requesting a retransmission of the data via a reverse channel. However, this additional, non-informational data effectively reduces the effective bit rate in exchange for a lower error rate. The FEC scheme for a link is described by the code rate (or information rate), which is the ratio of the useful (non-redundant) information to the total number of bits. For example, a code rate of 2/3 means that one redundant bit is sent after every second useful bit.

As the SNR increases, more efficient MODCODs can be used, since there is less uncertainty of errors created by noise, and more useful information can be transmitted in a given bandwidth.

6.2 SPECTRAL EFFICIENCY (SE)

The spectral (or spectrum) efficiency of a communications link describes

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the amount of data that can be transmitted in a given bandwidth and is measured in bits per second per Hz (bps/Hz). It's usually defined as the net bit rate (the useful bit rate exclusive of error-correction codes) divided by the channel bandwidth.

There is a theoretical limit to spectral efficiency for a given bandwidth and system noise level, called the Shannon limit, derived from the Shannon-Hartley theorem [5]. Every modem has a set of available MODCODs, and the manufacturer can provide a table that shows the spectral efficiency for each MODCOD. The spectral efficiency for modems is slightly less than theoretically possible because of the difficulty of operating close to the Shannon limit. An example of a MODCOD table for a theoretical DVB (Digital Video Broadcasting) modem is shown in Table 3. The rightmost column shows the minimum SNR required for quasi error free (QEF) operation with a particular MODCOD. Note that the more efficient MODCODs require higher SNRs.

TABLE 3. MODCOD TABLE FOR A THEORETICAL DVB MODEM (BASED ON THE SHANNON LIMIT).

MODCOD	SPECTRAL EFFICIENCY bps/Hz	SNR for QEF (dB)
APSK 1/2	0.4	-2
CPSK 1/4	0.5	0
CPSK 1/2	0.6	1
CPSK 3/4	0.65	2
DPSK 1/4	0.75	3
DPSK 1/2	0.9	4
DPSK 3/4	1.05	6
DPSK 5/6	1.25	7
DPSK 7/8	1.5	9

Once the SNR for the link has been calculated, you can refer to the table for your modem to find the most efficient MODCOD that can be used with that SNR, and then find the corresponding spectral efficiency. This is also useful for determining how much channel bandwidth is required.

6.3 | THROUGHPUT (DATA RATE)

The final figure of merit we'll cover is the throughput, or data rate (bits/s or bps). This is the one users usually care about the most. It is calculated by multiplying the spectral efficiency by the channel bandwidth.

Typically, the channel bandwidth used for this calculation is what is called the usable channel bandwidth, which is the transmit bandwidth after the application of a regulatory channel (or spectral) mask. A digitally modulated carrier has (theoretically) an infinite bandwidth, which can cause adjacent-channel interference, so a raised-cosine roll-

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off filter is used at the output of the modulator (and at the input of the demodulator) to limit the bandwidth and ensure that it stays within the regulatory mask. This filtered bandwidth is called the usable channel bandwidth (or occupied bandwidth).

For example, if the SE is 0.9 bps/Hz and the usable channel bandwidth is 5 MHz, the throughput is 0.9 bps/Hz $\times 5\times 10^6$ Hz = 4.5 Mbps.

Typically, the link budget report summary would include SNR, MODCOD, SE, and throughput.

7 | EXAMPLE LINK BUDGET SNR CALCULATIONS

7.1 | FWD LINK

Example 1: A fixed Kymeta u7 Ku-band terminal in broadside orientation ($\theta = 0$) located in Seattle, using the Galaxy 18 (G-18) geosynchronous satellite.

Note: The interactive G-18 coverage map at the following URL was used to determine EIRP at Seattle and the distance to the satellite (d) in km: http://www.groundcontrol.com/Galaxy_18_Ku_North_America.php

- Satellite EIRP = 46.6 dBW
- Transponder BW = 36 MHz
- FSPL = $20\times\log(d) + 20\times\log(f) + 92.45 = 20\times\log(38.2\times 10^3) + 20\times\log(12) + 92.45 = 205.6$ dB
- Atmospheric loss = 0.35 dB
- Peak receive gain = 33.0 dB
    - o T = $10\times\log(256K) = 24.1$ dBK
    - o Terminal G/T = 33.0 dB – 24.1 dBK = 8.9 dB/K
- Boltzmann's constant = -228.6

SNR = $46.6 - 10\times\log(36\times 10^6) - 205.6 - 0.35 + 8.9 - (-228.6) = 3.15$ dB

If the modem has the MODCODs shown in Table 3, then the most efficient one that is supported by a SNR of 2.5 dB is DPSK 1/4, which provides a spectral efficiency of 0.75 bps/Hz. If the usable channel bandwidth (after filtering) is 5 MHz, then the throughput is 5 MHz × 0.75 bps/Hz = 3.75 Mbps.

Example 2: A Kymeta u7 Ku-band terminal in mobility mode in Seattle using G-18 with a scan angle of 55 degrees.

- Satellite EIRP = 46.6 dBW
- Transponder BW = 36 MHz
- Theta = 55 degrees
- Polarization: horizontal

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- Cosine roll-off = 1.2
- Peak receive gain = 33.0 dB

o Gain at θ = 55 degrees = 33.0 – 1.2 × 10×log(cos θ) = 30.1 dB

o T = 10×log(256K) = 24.1 dBK

o Terminal G/T = 30.1 dB – 24.1 dB = 6.0 dB/K

- FSPL = 20×log(d) + 20×log(f) + 92.45 = 20×log(38.2 × 10^3) + 20×log(12) + 92.45 = 205.6 dB
- Atmospheric loss = 0.35 dB

SNR = 46.6 – 10×log (36 × 10^6) – 205.6 – 0.35 + 6.0 – (-228.6) = -0.35 dB

If the modem has the MODCODs shown in Table 3, then the most efficient one that is supported by a SNR of -0.35 dB is APSK 1/2, which provides a spectral efficiency of 0.4 bps/Hz. If the usable channel bandwidth (after filtering) is 5 MHz, then the throughput is 5 MHz × 0.4 bps/Hz = 2.0 Mbps.

7.2 | SIMPLE RTN LINK

Example 1: A Kymeta u7 Ku-band terminal with a 16 W BUC in mobility mode in Seattle, using the Galaxy 18 (G-18) geosynchronous satellite with a scan angle of 55 degrees.

- BUC operating power = 16 W = 12 dBW
- Peak transmit gain = 33.5 dB
  - o Cosine roll-off = 1.2
  - o Gain at θ = 55 degrees = 33.5 + 1.2 × 10×log(cos 55) = 30.6 dB
- Uplink frequency = 14.25 GHz
- Path distance = 38,000 km
- Channel BW = 1.2 MHz with a filter roll-off of 20% = 1 MHz
- FSPL = 20×log(d) + 20×log(f) + 92.45 = 20×log(38 × 10^3) + 20×log(14.25) + 92.45 = 207.1 dB
- Atmospheric loss = 0.35 dB
- G/T of satellite transponder looking at a terminal in Seattle = 4 dB/K

SNRup = 12.0 + 30.6 – 10×log(10^6) – 207.1 – 0.35 + 4 – (–228.6) = 7.8 dB

7.3 | COMPLEX RTN LINK

Example 1: A Kymeta u7 Ku-band terminal with a 16 W BUC in mobility mode in Seattle, using the Galaxy 18 (G-18) geosynchronous satellite with a scan angle of 55 degrees.

We have calculated the uplink (terminal to satellite) SNR in the previous example, so we only need to calculate the downlink (satellite to hub) SNR, and them combine them to find the SNR for the complete RTN path.

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Downlink parameters:

- Downlink frequency = 11.45 GHz
- Path distance = 38,000 km
- Transponder BW = 36 MHz
- Transmit BW = 1.2 MHz with a filter roll-off of 20% = 1 MHz
- SFD = −88 dBW/m2
- HPA compression = 2.7 dB
- Transponder EIRP at saturation: 53 dBW
- FSPL = 20×log(d) + 20×log(f) + 92.45 = 20×log(38000) + 20×log(11.45) + 92.45 = 205.2 dB
- Atmospheric loss = 0.35 dB
- Hub G/T = 30 dB/K

Terminal EIRP = BUC operating power + antenna gain = 12.0 + 30.6 = 42.6 dB

PFD (dBW/m2) = Terminal EIRP – 20×log(path distance) – 10.99 = 42.6 – 20×log(38 × 10^6) – 10.99 = −120 dBW/m2

Terminal SFD = SFD – 10×log(transponder BW/transmit BW) = –88 – 10×log(36/1) = –103.6 dBW/m2

SNR_{down} = 53 – (–103.6 + 120 + 2.7) – 10×log(36×10^6) – 205.2 – 0.35 + 30 – (–228.6) = 11.6 dB

Combining the SNRs for the two paths using the complex RTN equation:

$$SNR_{total}(dB) = 10\times log\left[\frac{1}{\frac{1}{10^{\frac{SNR_{up}}{10}}}+\frac{1}{10^{\frac{SNR_{down}}{10}}}}\right]$$

$$= 10\times log\left[\frac{1}{\frac{1}{10^{\frac{7.1}{10}}}+\frac{1}{10^{\frac{10.9}{10}}}}\right]$$

= 6.3 dB

8 | CONCLUSION

The performance of a satellite link is described by standard figures of merit, including the signal-to-noise ratio, spectral efficiency, and throughput. These values are determined by performing a link budget analysis for both the forward (satellite to user terminal) and return (user

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terminal to satellite plus satellite to hub) links. The analysis starts with the calculation of path signal-to-noise ratios based on terminal, satellite, transmission medium, and hub parameters. Spectral efficiency (SE) and throughput (bps) are then determined from the MODCOD specifications of your modem.

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