Log-Normal Fading, Link Budgets

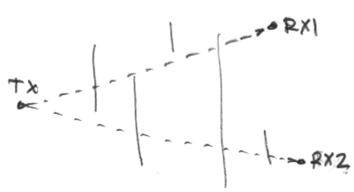
Log-Normal Fading (Shadowing)

Statistical path loss models provide us with an estimate of the mean path loss as a function of distance and other parameters such as frequency and antenna heights. Since these models treat the path loss as a random variable, it is useful to know not just the mean but also the distribution of this random variable. This would allow us to predict how much variability we can expect and compensate for this variability by providing additional margin so as to provide reliable coverage.

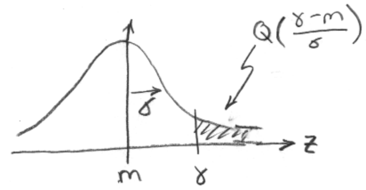
Experimentally it has been found that the path loss in cluttered multipath environments is log-normally distributed. This means that the log of the path loss (for example, the path loss expressed in dB) has a normal distribution. A normal distribution is defined by two parameters: the mean, which is provided by the statistical path loss models and the variance which is typically estimated based on the type of propagation environment (WLAN, rural cellular, etc).

An explanation for the log-normal shadowing distribution is that for any path there are many factors contributing to the overall path loss (combinations of free space loss, diffraction, reflection, transmission, etc). Each of these losses is a random variable. The total loss expressed in dB will be sum of all of these losses (each in dB). The central limit theorem states that the distribution of the overall loss (in dB) will trend to a normal distribution.

Another name for this effect is "log-normal shadowing". This refers to a model where the signal "shadowed" by a variable number of objects and this results in the observed log-normal distribution.



This variation can be modelled as a random variable, X_σ, whose logarithm has a normal (Gaussian) distribution. When X_σ is expressed in dB, is has zero mean and standard deviation σ dB.



The probability that a normal random variable, z, with mean m and standard deviation σ will exceed the value γ is:

$$\Pr[z > \gamma] = Q(\frac{\gamma - m}{\sigma}) = \frac{1}{2}\text{erfc}\left(\frac{\gamma - m}{\sqrt{2}\sigma}\right)$$

Exercise 1: A cellular system is designed so that users on the cell edge have an average SNR of 16 dB. The system requires that users have a minimum SNR of 8dB to place a call. The standard deviation of the log-normal fading is 8dB. What fraction of users at the cell edge will be able to place calls?

Link Budgets

A link budget is the most important tool for system-level design of wireless systems. Link budgets are used both by companies and standards organizations developing new wireless systems as well as by by companies deploying individual wireless links.

A link budget is a "budget" similar to an accountant's budget but instead of adding profits and losses it adds signal gains and losses as the signal travels through the different portions of the system. The link budget has to demonstrate that the system will provide satisfactory performance. The performance metric will depend on the type of system and could include SNR (analog satellite TV), BER or PER (a digital point-to-point link), or outage probability (a cellular phone system).

The link budget includes all gains (and losses) from baseband input to baseband output. It is more convenient to add values expressed in dB instead of multiplying and dividing.

Gains/Losses Included

The following are the basic quantities included in a link budget:

(a) transmitter output power
(b) transmit antenna gain
(c) path loss
(d) receive antenna gain
(e) receiver noise power
(f) link margin

Depending on the type of wireless system, other factors such as interference, may need to be taken into account and these may involve other calculations.

When a wireless communication system is designed many design options will need to be considered (antennas, transmit powers, data rates, ...) each of which affects one or more of the above gains/losses.

The difference between the required SIR/SNR and what the link budget predicts is the "margin".

Exercise 2: Which of the quantities above will be in dBm and which will be in dB?

The objective of the system design phase is to "close the link" (end up with a positive margin) with the lowest (dollar) cost.

Link budgets are usually prepared with a spreadsheet so that various system design options can be easily explored.

The basic link budget shown above is seldom sufficiently detailed to capture all of the parameters of a real system.

Bi-directional systems usually need different link budgets for the two directions (forward and reverse or downlink and uplink).

Many systems can operate at various data rates, modulation types, antennas or propagation environments and the link budget will have to include the calculations for each of these options.

Some values may be random and may only be known in terms of their statistics (e.g. mean path loss and shadowing standard deviation). In this case the mean value plus an additional value for the desired probability is used to achieve a performance criteria that is also defined in terms of its statistics. For example, the performance criteria could be that the BER will be less than 10^{-2} over 90% of the service area.

Examples of Typical Link Budget Elements

- transmitter output power: cost will be affected by transmitter output power and power amplifier efficiency. Battery consumption may limit the maximum output power and regulatory or safety considerations may limit the EIRP.

- transmitter feedline losses: low-loss cable or waveguides are more expensive

- transmit antenna gain: higher-gain antennas are more expensive and may not be practical for portable or mobile users

- path loss: this may be fixed (e.g. a geostationary satellite) or may be a system design parameter (e.g. cell size). For free-space systems we can use the Friis equation, for land-mobile applications we can use statistical models such as Hata-Okumura.

- other propagation losses: these effects may need to be considered in some applications

  - log-normal shadowing (land-mobile)
  - diffraction losses (obstructed paths)
  - atmospheric absorption (at high frequencies)
  - outdoor-to-indoor loss (base outside, user indoor)

- receiver antenna gain: the same gain/cost considerations as with transmitter antenna. In some cases using a higher-gain receiving antenna will also reduce interference.

- receiver noise figure: lower noise figure is more expensive. Many systems are interference limited (the performance is limited by the interference power which is much greater than the thermal noise power) so this may not be an issue. For other systems, designs using a low noise figure LNA (low noise amplifier) is the lowest-cost way of closing the link and the cost of the LNA may be a significant part of the system cost.

- receiver noise bandwidth: this will depend on the signal bandwidth which in turn depends on the data rate and modulation scheme

- coding gains: a system using FEC may include coding gain in the link budget
- implementation losses: some link budgets include an implementation loss to account for distortion, intermodulation, phase noise and other degradation introduced by real receivers and transmitters

Sample Link Budget (Geostationary TV Broadcast)

Increasing the transmit power or antenna gain (on the satellite) is relatively expensive, so the receiving antenna has more gain and low-noise figure LNAs are used instead of higher transmitter power.

a	transmitter power output	43	dBm (20 W)
b	transmit antenna gain	20	dB
c	frequency	4	GHZ
e	wavelength	7.5	cm
f	path distance	42,164	km
g	free-space path loss	197	dB
h	receiver antenna gain	45	dB
i	feedline loss	1	dB
j	received signal power	-90	dBm
k	kT	-174	(dBm/Hz)
l	receiver noise bandwidth	67	dB-Hz (5 MHz)
m	receiver noise figure	1	dB
n	received noise power	-106	dBm
m	IF SNR	16	dB

Exercise 3: Classify the likely origin for each of the values. For example, a physical constant, a system specification, a value chosen by the system designer or a value computed from other lines. Write the equation for each of the computed values in terms of the values of other lines.

Sample Link Budget (Cellular System)

The following page shows a link budget taken from the GSM specification. In this case there are separate link budgets for forward (base [transceiver] station (BTS) to mobile station (MS)) and reverse links. Other abbreviations are probability of service at the cell edge (Ps) and TU50 (median (50th percentile) path loss for a typical urban (TU) channel), and Ec/No (SNR). The channel bandwidth is 271kHz (54.3 dB-Hz).

This link budget is organized to separately compute the required received signal power (including margins) and the transmitted power. From these the maximum path loss and cell radius are derived.

The end result of this particular link budget is the maximum cell radius for a certain fraction of coverage since the other parameters are considered to be fixed. The cell radius is of interest to system operators because it is a factor that determines the cost of deploying a particular technology.

The GSM system was designed to be interference-limited in small cells and noise limited in large cells and a 3 dB interference degradation margin is included in this particular example.

Annex A.4: Example of RF-budget for GSM 900 Class4 (peak power 2 W) in a small cell

Propagation over land in urban and rural areas				
Receiving end: TX:		BTS MS	MS BTS	Eq. (dB)
Noise figure(multicoupl.input)	dB	8	10	A
Multipath profile		TU50	TU50	
Ec/No min. fading	dB	8	8	B
RX RF-input sensitivity	dBm	-104	-102	C=A+B+W-174
Interference degrad. margin	dB	3	3	D (W=54.3 dBHz)
Cable loss + connector	dB	2	0	E
RX-antenna gain	dBi	16	0	F
Diversity gain	dB	3	0	F1
Isotropic power, 50 % Ps	dBm	-118	-99	G=C+D+E-F-F1
Lognormal margin 50 % ->75 % Ps	dB	5	5	H
Isotropic power, 75 % Ps	dBm	-113	-94	I=G+H
Field Strength 75 % Ps		24	43	J=I+137 at 900 MHz
Transmitting end: RX:		MS BTS	BTS MS	Eq. (dB)
TX PA output peak power	W	-	12.6	
(mean power over burst)	dBm	-	41	K
Isolator + combiner + filter	dB	-	3	L
RF Peak power,(ant.connector)	dBm	33	38	M=K-L
1)	W	2	6.3	
Cable loss + connector	dB	0	2	N
TX-antenna gain	dBi	0	16	O
Peak EIRP	W	2	158	
	dBm	33	52	P=M-N+O
Isotropic path loss,50 % Ps 2)	dB	142	142	Q=P-G-9
Isotropic path loss, 75 % Ps	dB	137	137	R=P-I-9
Range km - 75 % Ps				
Urban, out of doors		1.3		
Urban, indoors		0.52		

1) The MS peak power is defined as:

a) If the radio has an antenna connector, it shall be measured into a 50 Ohm resistive load.

b) If the radio has an integral antenna, a reference antenna with 0 dBi gain shall be assumed.

2) 9 dB of the path loss is assumed to be due to the handheld MEG (-antenna/body loss) of –9 dBi.