Path Loss and Link Budget

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Path Loss

A fundamental concept in planning any type of radio communications link is the concept of *Path Loss*. Path Loss describes the amount of signal loss (attenuation) between a receive and a transmitter.

As GSM operates in frequency duplex on uplink and downlink, there is correspondingly an *Uplink Path Loss* from MS to BTS, and a *Downlink Path Loss* from BTS to MS. Both need to be considered.

It is possible to compute the path loss in a theoretical ideal situation, where transmitter and receiver are in empty space, with no surfaces anywhere nearby causing reflections, and with no objects or materials in between them. This is generally called the *Free Space Path Loss*.

Path Loss

Estimating the path loss within a given real-world terrain/geography is a hard problem, and there are no easy solutions. It is impacted, among other things, by

- the height of the transmitter and receiver antennas
- whether there is line-of-sight (LOS) or non-line-of-sight (NLOS)
- the geography/terrain in terms of hills, mountains, etc.
- the vegetation in terms of attenuation by foliage
- any type of construction, and if so, the type of materials used in that construction, the height of the buildings, their distance, etc.
- the frequency (band) used. Lower frequencies generally expose better NLOS characteristics than higher frequencies.

The above factors determine on the one hand side the actual attenuation of the radio wave between transmitter and receiver. On the other hand, they also determine how many reflections there are on this path, causing so-called *Multipath Fading* of the signal.

Radio Propagation Models

Over decades, many different radio propagation models have been designed by scientists and engineers. They might be based on empirical studies condensed down into relatively simple models, or they might be based on ray-tracing in a 3D model of the terrain.

Several companies have developed (expensive, proprietary) simulation software that can help with this process in detail. However, the results of such simulation also depend significantly on the availability of precise 3D models of the geography/terrain as well as the building structure in the coverage area.

In absence of such simulation software and/or precise models, there are several models that can help, depending on the general terrain:

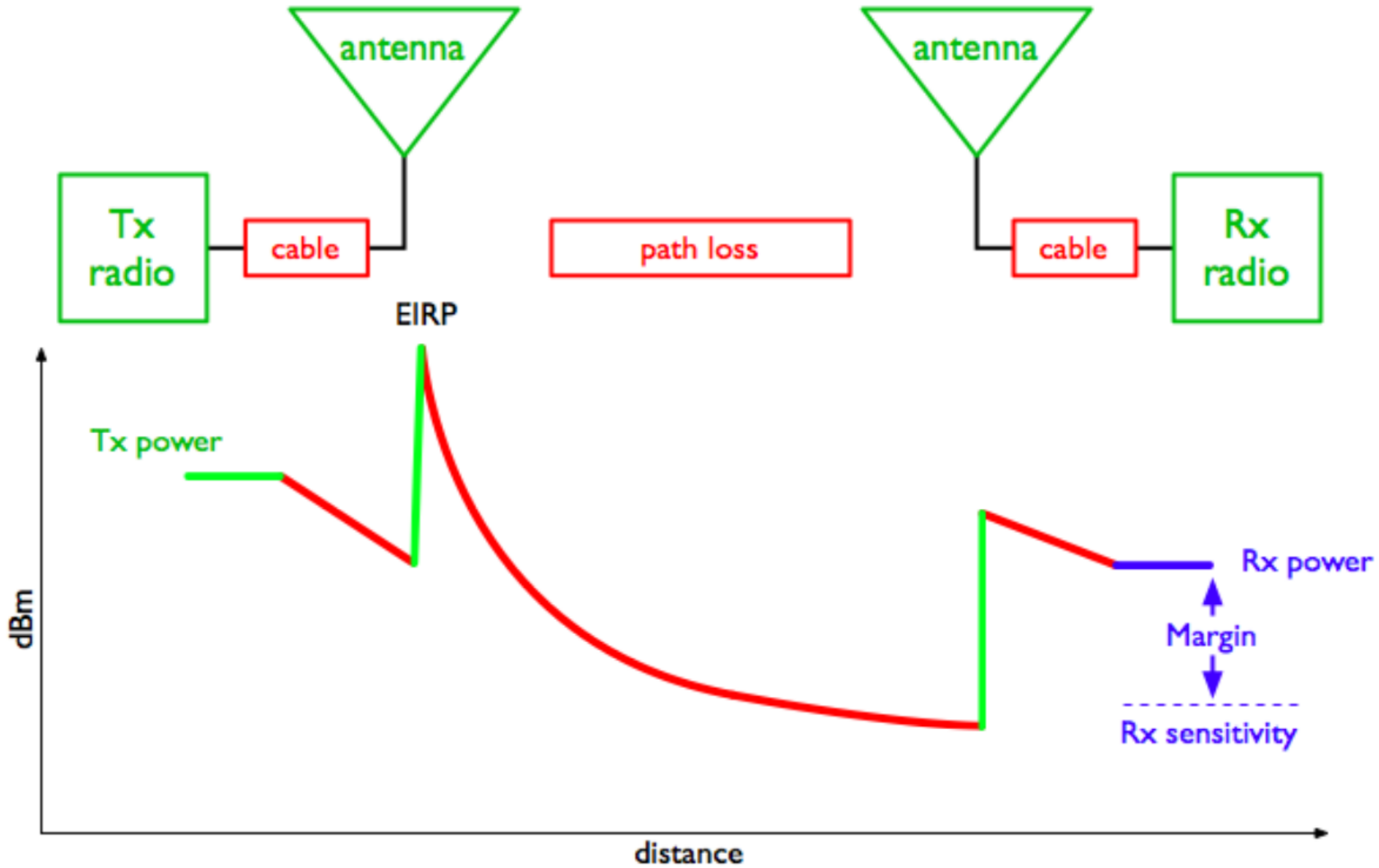
Common Path Loss Models

Table 1. List of common path loss models

Type	Sub-Type	Bands	Name
Terrain	-	850, 900, 1800, 1900	ITU terrain model
Rural	Foliage	850, 900, 1800, 1900	One woodland terminal model
City	Urban	850, 900	Okumura-Hata Model for Urban Areas
City	Suburban	850, 900	Okumura-Hata Model for Suburban Areas
City	Open	850, 900	Okumura-Hata Model for Open Areas
City	Urban	1800, 1900	COST-231 Hata Model
Indoor	-	900, 1800, 1900	ITU model for indoor attenuation

In [path-loss-models] you can see a list of commonly-used path loss models. They are typically quite simple equations which only require certain parameters like the distance of transmitter and receiver as well as the antenna height, etc. No detailed 3D models of the terrain are required.

RF Power in a Wireless Link



Link Budget

The link budget consists of the total budget of all elements in the telecommunication system between BTS and MS (and vice-versa).

This includes

- antenna gains on both sides
- coaxial cabling between antenna and receiver/transmitter
- losses in duplexers, splitters, connectors, etc
- gain of any amplifiers (PA, LNA)
- path loss of the radio link between the two antennas

Simplified Link Budget Equation

The simplified link budget equations looks like this:

```
Rx Power (dBm) = Tx Power (dBm) + Gains (dB) - Losses (dB)
```

Gains is the sum of all gains, including

- Gain of the transmitter antenna
- Gain of the receiver antenna
- Gain of any PA (transmitter) or LNA (receiver)

Losses is the sum of all losses, including

- Loss of any cabling and/or connectors on either side
- Loss of any passive components like duplexers/splitters on either side
- Path Loss of the radio link

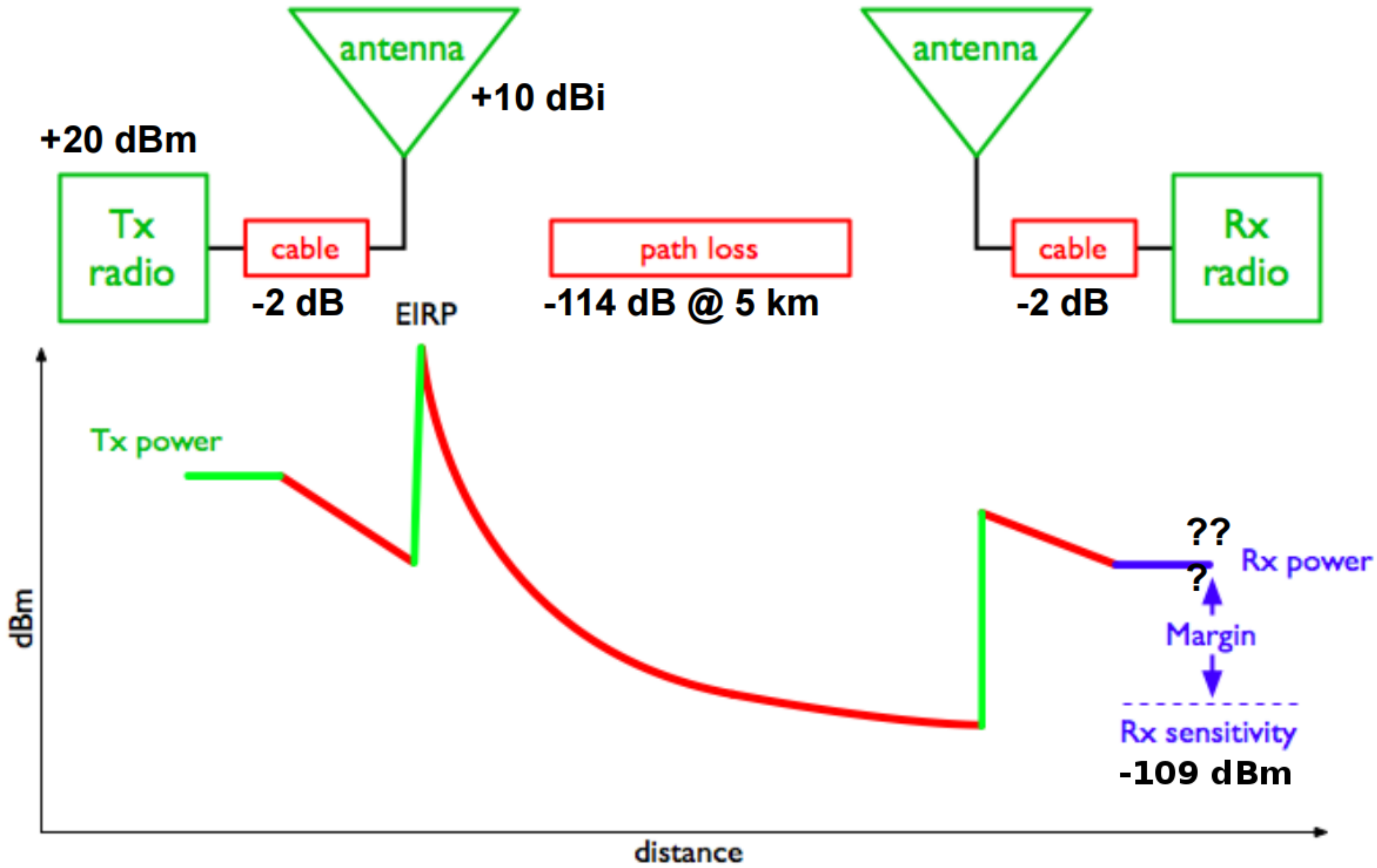
Link Budget Equation vs. Path Loss

- Using the Link Budget equation and resolving it for the path loss will give you an idea of how much path loss on the radio link you can afford while still having a reliable radio link.
- Resolving the path loss into a physical distance based on your path loss model will then give you an idea about the coverage area that you can expect.

NOTE

The Rx Power substituted in the Link budget equation is determined by the receiver sensitivity. It is customary to add some some safety margin to cover for fading.

RF Link


antenna
+10 dBi
antenna
+20 dBm
Tx
radio
cable
path loss
cable
Rx
radio
-2 dB
EIRP
-114 dB @ 5 km
-2 dB
Tx power
??
?
Rx power
Margin
Rx sensitivity
-109 dBm
dBm
distance

Uplink Link Budget

The transmit power of a MS depends on various factors, such as the MS Power Class, the frequency band and the modulation scheme used.

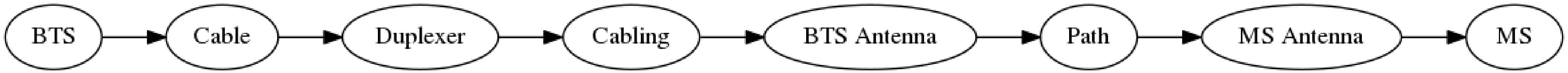
Table 2. Typical MS transmit power levels

Power Class	Band	Modulation	Power
4	850 / 900	GMSK	33 dBm (2 W)
1	1800 / 1900	GMSK	30 dBm (1 W)
E2	850 / 900	8PSK	27 dBm (0.5 W)
E2	1800 / 1900	8PSK	26 dBm (0.4 W)

The minimum reference sensitivity level of a normal GSM BTS is specified in 3GPP TS 05.05 and required to be at least -104 dBm. Most modern BTSs outperform this significantly.

FIXME: Example calculation (spreadsheet screenshot?)

Downlink Link Budget



The transmit power of the BTS depends on your BTS model and any possible external power amplifiers used.

The minimum reference sensitivity level of a GSM MS is specified in 3GPP TS 05.05 and can typically be assumed to be about -102 dB.

FIXME: Example calculation (spreadsheet screenshot?)

Optimization of the Link Budget

If the coverage area determined by the above procedure is insufficient, you can try to change some of the parameters, such as

- increasing transmit power by adding a bigger PA
- increasing antenna gain by using a higher gain antenna
- reducing cable losses by using better / shorter coaxial cables
- increasing the height of your antenna

Introduction into RF Electronics

Setup and Operation of a GSM network is not only about the configuration and system administration on the network elements and protocol stack, but also includes the physical radio transmission part.

Basic understanding about RF (Radio Frequency) Electronics is key to achieving good performance of the GSM network.

Coaxial Cabling

Coaxial cables come in many different shapes, diameters, physical construction, dielectric materials, and last but not least brands and types.

There are many parameters that might be relevant to your particular installation, starting from mechanical/environmental properties such as temperature range, UV resilience, water/weatherproofness, flammability, etc.

For the subject of this manual, we will not look at those mechanical properties, but look at the electrical properties instead.

The prime electrical parameters of a coaxial cable are:

- its attenuation over frequency and length
- its maximum current/power handling capability
- its propagation velocity (ignored here)
- its screening efficiency (ignored here)

Coaxial Cable Attenuation

The attenuation of a coaxial cable is given in dB per length, commonly in *dB per 100m*. This value changes significantly depending on the frequency of the signal transmitted via the cable. Cable manufacturers typically either provide tables with discrete frequency values, or graphs plotting the attenuation per 100m (x axis) over the frequency (y axis).

FIXME: Example.

So in order to estimate the loss of a coaxial cable, you need to

1. determine the frequency at which you will use the cable, as determined by the GSM frequency band of your BTS. Make sure you use the highest frequency that might occur, which is typically the upper end of the transmit band, see [gsm-bands]
2. determine the attenuation of your cable per 100m at the given frequency (check the cable data sheet)
3. scale that value by the actual length of the cable

A real cable always has connectors attached to it, please add some additional losses for the connectors that are attached. 0.05 dB per connector is a general rule of thumb for the frequencies used in GSM.

FIXME: Example computation

As you can see very easily, the losses incurred in coaxial cables between your antenna and the BTS can very quickly become significant factors in your overall link budget (and thus cell coverage). This is particularly relevant for the uplink power budget. Every dB you loose in the antenna cable between antenna and the BTS receiver translates into reduced uplink coverage.

Using the shortest possible coaxial cabling (e.g. by mounting the BTS high up on the antenna tower) and using the highest-quality cabling are the best strategies to optimize

> If you plan to assemble the coaxial connectors yourself, please make sure

Warning you ensure to have the right skills for this. Properly assembling coaxial connectors (whether solder-type or crimp-type) requires precision tools and strict process as described by the manufacturer. Any mechanical imprecision of connector assembly will cause significant extra signal attenuation.

Checking coaxial cables

If you would like to check the proper operation of a coaxial cable, there are several possible methods available:

- The more expensive method would be to use a *RF Network Analyzer* to measure the S11/S12 parameters or the VSWR of the cable.
- Another option is to use a TDR (time domain reflectometer) to determine the VSWR. The TDR method has the added advantage that you can localize any damage to the cable, as such damage would cause reflections that can be converted into meters cable length from the port at which you are testing the cable. Mobile, battery-powered TDR for field-use in GSM Site installation are available from various vendors. One commonly used series is the *Anritsu Site Master*.

Coaxial Connectors

A coaxial connector is a connector specifically designed for mounting to coaxial cable. It facilitates the removable / detachable connection of a coaxial cable to a RF device.

There are many different types of coaxial connectors on the market.

The most important types of coaxial connectors in the context of GSM BTSs are:

- The *N type* connector
- The *SMA type* connector.
- The *7/16* type connector

FIXME: Images

The above connectors are tightened by a screw-on shell. Each connector type has a specific designated nominal torque by which the connector shall be tightened. In case of uncertainty, please ask your connector supplier for the nominal torque.

> **Note** Always ensure the proper mechanical condition of your RF connectors. Don’t use RF connectors that are contaminated by dust or dirt, or which show significant oxidization, bent contacts or the like. Using such connectors poses significant danger of unwanted signal loss, and can in some cases even lead to equipment damage (e.g. in case of RF power at PA output being reflected back into the PA).

Duplexers

A GSM BTS (or GSM TRX inside a BTS) typically exposes separate ports for Rx (Receive) and Tx (Transmit). This is intentionally the case, as this allows the users to add e.g. additional power amplifiers, filters or other external components into the signal path. Those components typically operate on either the receive or the transmit path.

You could now connect two separate antennas to the two ports (one for Rx, one for Tx). This is commonly done in indoor installations with small rubber-type antennas directly attached to the BTS connectors.

In outdoor installations, you typically (want to) use a single Antenna for Rx and Tx. This single antenna needs to be connected to the BTS via a device that is called *Duplexer*.

The *Duplexer* is actually a frequency splitter/combiner, which is specifically tuned to the uplink and downlink frequencies of the GSM band in which you operate the BTS. As such, it has one port that passes only uplink frequencies between the antenna and that port, as well as another port that passes only downlink frequencies between antenna and that port.

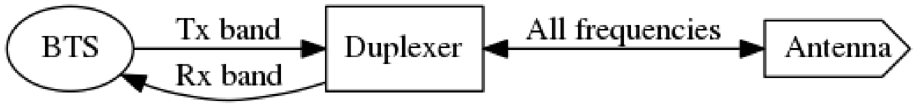


Figure 1. Illustration of the Duplexer functionality

Warning

The ports of a duplexer are not interchangeable. Always make sure that you use the Rx port of the duplexer with the Rx port of the BTS, and vice-versa for Tx.

RF Power Amplifiers

A RF Power Amplifier (PA) is a device that boosts the transmit power of your RF signal, the BTS in your case.

RF power amplifiers come in many different characteristics. Some of the key characteristics are:

Frequency range

A PA is typically designed for a specific frequency range. Only signals inside that range will be properly amplified

Gain in dB

This tells you how many dB the power amplifier will increase your signal. `Pout = Pin + Gain`

Maximum Output Power

This indicates the maximum absolute output power. For example, if the maximum output power is 40 dBm, and the gain is 10dBm, then an input signal of 30dBm will render the maximum output power. An input signal of 20dBm would subsequently generate only 30dBm of output power.

Efficiency

The efficiency determines how much electrical power is consumed for the given output power. Often expressed as Power Added Efficiency (PAE).

> **Warning** If you add external power amplifiers to a GSM BTS or any other transmitter, this will invalidate the regulatory approval of the BTS. It is your responsibility to ensure that the combination of BTS and PA still fulfills all regulatory requirements, for example in terms of out-of-band emissions, spectrum envelope, phase error, linearity, etc!

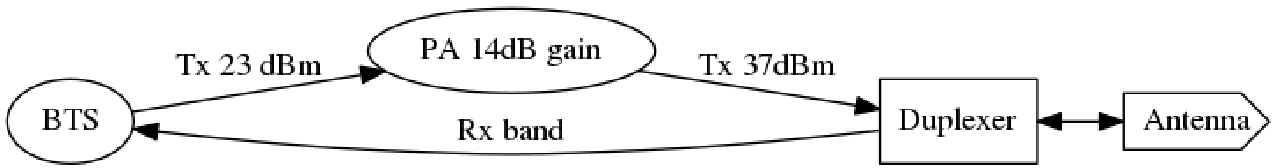


Figure 2. Addition of a RF Power Amplifier to a GSM BTS Setup

Antennas

The Antenna is responsible for converting the electromagnetic waves between the coaxial cable and the so-called *air interface* and vice-versa. The properties of an antenna are always symmetric for both transmission and reception.

Antennas come in many different types and shapes. Key characteristics distinguishing antennas are:

Antenna Gain

Expresses how much more efficient the antenna converts between cable and air interface. Can be expressed in dB compared to a theoretical isotropic radiator (dBi) or compared to a dipole antenna (dBd). Gain usually implies directivity.

Frequency Band(s)

Antennas typically have only a relatively narrow band (or multiple narrow bands at which they radiate efficiently. In general, the higher the antenna gain, the lower the usable frequency band of the antenna.

Directivity

Antennas radiate the energy in all three dimensions.

Mechanical Size

Mechanical Size is an important factor depending on how and where the antenna is mounted. Size also relates to weight and wind-load.

Wind Load

Expresses how much mechanical load the antenna will put on its support structure (antenna mast).

Connector Type

Your cabling will have to use a compatible connector for the antenna. Outdoor antennas typically use the 7/16 type connector or an N type connector. Indoor antennas either N type or SMA type.

Environmental Rating

Indoor antennas cannot be used outdoor, as they do not offer the level of protection against dust and particularly water / humidity / corrosion.

Down-tilt Capability

Particularly sector antennas are typically installed with a fixed or (mechanically / electrically) variable down-tilt in order to limit the radius/horizon of the antenna footprint and avoid excess interference with surrounding cells.

VSWR

The Voltage Standing Wave Ratio indicates how well the antenna is matched to the coaxial cable, and how much of the to-be-transmitted radio signal is actually converted to radio waves versus reflected back on the RF cable towards the transmitter. An ideal antenna has a VSWR of 1 (sometimes written 1:1). Real antennas are typically in the range of 1.2 to 2.

Side Lobes

A directional antenna never radiates only in one direction but always has certain side lobes pointing outside of the main direction of the antenna. The number and strength of side lobes differ from antenna to antenna model.

Note Whenever installing antennas it is important to understand that any metallic or otherwise conductive object in their vicinity will inevitably alter the antenna performance. This can affect the radiation pattern, but also de-tune the antenna and shift its frequency band outside the nominal usable frequency band. It is thus best to mount antennas as far as practically possible from conductive elements within their radiation pattern

Omni-directional Antennas

Omni-directional antennas are typically thin long dipole antennas covered with fiberglass. They radiate with equal strength in all directions and thus result in a more or less circular cell footprint (assuming flat terrain). The shape of the radiation pattern is a torus (donut) with the antenna located in the center of that torus.

Omni-directional antennas come with a variety of gains, typically from 0 dBd to 3 dBd, 6 dBd and sometimes 9 dBd. This gain is achieved by compressing the radiation torus in the vertical plane.

Sometimes, Omni-directional antennas can be obtained with a fixed down-tilt to limit the cell radius.

Sector Antennas

Sector antennas are used in sectorized cell setups. Sector antennas can have significantly higher gain than omni-directional antennas.

Instead of mounting a single BTS with an omni-directional antenna to a given antenna pole, multiple BTSs with each one sector antenna are mounted to the same pole. This results in an overall larger radius due to the higher gain of the sector antennas, and also in an overall capacity increase, as each sector has the same capacity as a single omni-directional cell. And all that benefit still requires only a single physical site with antenna pole, power supply, back-haul cabling, etc.

Experimentation and simulation has shown that typically the use of three sectors with antennas of an opening angle of 65 degrees results in the most optimal combination for GSM networks. If more sectors are being deployed, there is a lot of overlap between the sectors, and the amount of hand-overs between the BTSs is increased.

RF Low Noise Amplifier (LNA)

A RF Low Noise Amplifier (LNA) is a device that amplifies the weak received signal. In general, LNAs are combined with band filters, to ensure that only those frequencies within the receive band are amplified, and out-of-band interferers are filtered out. A duplexer can already be a sufficient band-filter, depending on its characteristics.

The use of a LNA typically only makes sense if you . have very long and/or lossy coaxial cables from your antenna to the BTS, and . can mount the duplexer + LNA close to the antenna, so that the amplification happens before the long/lossy coaxial line to the BTS

Key characteristics of a LNA are:

Frequency range

A LNA is typically designed for a specific frequency range. Only signals inside that range will be properly amplified

Gain in dB

This tells you how many dB the low noise amplifier will increase your signal. `Pout = Pin + Gain`

Maximum Input Power

This indicates the maximum RF power at the PA input before saturation.

Noise Figure

This indicates how much noise this LNA will add to the signal. This noise will add to the interference as seen by the receiver.

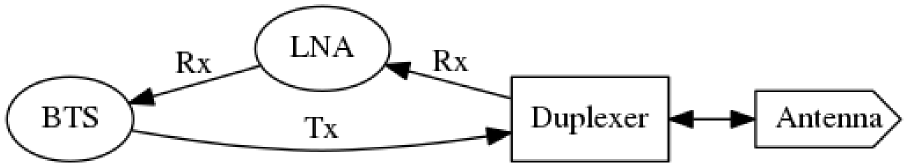


Figure 3. Addition of a RF Low Noise Amplifier to the GSM BTS Setup

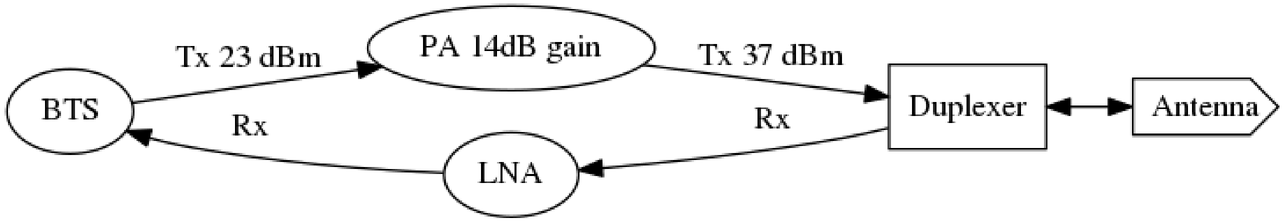


Figure 4. Addition of a RF LNA + RF PA to the GSM BTS Setup

As any LNA will add noise to the signal, it is generally discouraged to add them to the system. Instead, we recommend you to mount the entire BTS closer to the antenna, thereby removing the losses created by lengthy coaxial wire. The power supply lines and Ethernet connection to the BTS are far less critical when it comes to cable length.

Introduction into GSM Radio Planning

The main focus of the manual you are reading is to document the specifics of the Osmocom GSM implementation in terms of configuration, system administration and monitoring. That's basically all on the software part.

However, successful deployment and operation of GSM networks depends to a large extent on the proper design on the radio frequency (RF) side, including the right cabling, duplexers, antennas, etc.

Planning and implementing GSM deployment is a science (or art) in itself, and in most cases it is best to consult with somebody who has existing experience in the field.

There are three parts to this:

GSM Radio Network Planning

This includes an analysis of the coverage area, its terrain/geography, the selection of the right sites for your BTSs, the antenna height, a path loss estimate. As a result of that process, it will be clear what amount of transmit power, antenna gain, cable length/type, etc. you should use to obtain the intended coverage.

GSM Site Installation

This is the execution of what has been determined in the previous step. The required skills are quite different, as this is about properly assembling RF cables and connections, duplexers, power amplifiers, antennas, etc.

Coverage testing

This is typically done by driving or walking in the newly-deployed GSM site, and checking of the coverage is as it was expected.

Note This chapter can only give you the briefest overview about the process used, and cannot replace the experience and skill of somebody with GSM RF planning and site deployment.

GSM Radio Network Planning

In GSM Radio Network Planning, the number and location of sites as well as type of required equipment is determined based on the coverage requirements.

For the coverage of a single BTS, this is a process that takes into consideration:

- the terrain that needs to be covered
- the type of mobile stations to be supported, and particularly the speed of their movement (residential, pedestrians, trains, highways)
- the possible locations for cell sites, where BTSs and Antennas can be placed, as well as the possible antenna mounting height
- the equipment choices available, including
  - type and capabilities of BTS. The key criteria here is the downlink transmit power in dBm, and the uplink receive sensitivity.
  - antenna models, including gain, radiation pattern, etc.
  - RF cabling, including the key aspect of attenuation per length
  - RF duplexers, splitting the transmit and receive path
  - power amplifiers (PAs), increasing the transmit power
  - low noise amplifiers (LNAs), amplifying the received signal

For coverage of an actual cellular network consisting of neighboring cells, this process also must take into consideration aspects of *frequency planning*, which is the allocation of frequencies (ARFCNs) to the individual cells within the network. As part of that, interference generated by frequency re-use of other (distant) cells must be taken into consideration. The details of this would go beyond this very introductory text. There is plenty of literature on this subject available.

The Decibel (dB) and Decibel-Milliwatt (dBm)

RF engineering heavily depends on the Decibel (dB) as a unit to express attenuation (losses) or amplification (gain) impacted on radio signals.

The dB is a logarithmic unit, it is used to express the ratio of two values of physical quantity. You can thus not express an absolute value in dB, only relative.

Note | **Relative loss** (cable, connector, duplexer, splitter) **or gain** (amplifiers) are power **is expressed in dB**.

In order to express an absolute value, you need to use a unit like *dBm*, which is referencing a power of 1 mW (milli-Watt).

Note | **Absolute power** like transmitter output power or receiver input power **is expressed in dBm**.

Table 3. Example table of dBm values and their corresponding RF Power

dBm	RF Power	Comment
0	1 mW	
1	1.26 mW	transmit power of sysmoBTS 1002 when used with `max_power_red 22`
3	2 mW	
6	4 mW	
12	16 mW	
12	16 mW	
20	100 mW	
23	199 mW	Maximum transmit power of indoor sysmoBTS 1002
26	398 mW	
30	1 W	Maximum transmit power of a MS in 1800/1900 MHz band
33	2 W	Maximum transmit power of a MS in 850/900 MHz band
37	5 W	Maximum transmit power of 1 TRX in sysmoBTS 2050
40	10 W	Maximum transmit power of sysmoBTS 1100

GSM Frequency Bands

GSM can operate in a variety of frequency bands. However, internationally only the following four bands have been deployed in actual networks:

Table 4. Table of GSM Frequency Bands

Name	Uplink Band	Downlink Band	ARFCN Range
GSM 850	824 MHz .. 849 MHz	869 MHz .. 894 MHz	128 .. 251
E-GSM 900	880 MHz .. 915 MHz	925 MHz .. 960 MHz	0 .. 124, 975 .. 1023
DCS 1800	1710 MHz .. 1785 MHz	1805 MHz .. 1880 MHz	512 .. 885
PCS 1900	1850 MHz .. 1910 MHz	1930 MHz .. 1990 MHz	512 .. 810

The End

Questions?