Chapter 1

Radio Propagation

This chapter aims at establishing the link budget of a radio transmission. The objective is to link the cell coverage and the useful throughput of a wireless system with the transmission power. These calculations are performed based on the transmission power, and using an accurate model of the power scattering in the space between the transmitter and the receiver. This radio space is then called the propagation channel. Its definition may be complex, as we may, in some cases, choose to integrate some elements of the transmission and reception chains in it (especially the antenna systems). Consequently, the most important elements, which will be introduced in an incremental way in the proposed exercises, are mainly: the transmission power, the antenna gain, the noise power spectral density, the useful throughput and the communication channel's capacity.

In an environment with obstacles, the radiocommunication channel undergoes lots of attenuations. It is modeled by propagation losses, also called path losses. Given that the same signal is transmitted, the average power of the received signal decreases as a function of the distance, according to a distribution that depends on the environment, called the path loss model. The path loss models are empirical and are obtained using radio measurements. We can distinguish between the urban environment model, the rural environment model or indoor environment models that are used inside buildings.

The radio channel also undergoes a shadowing effect. In the multipath case, it introduces fading phenomena into the signal spectrum. The multipath channel may also create inter-symbol interference.

Inter-symbol interference occurs depending on the channel selectivity. A radio channel is frequency-selective if its channel bandwidth is large with respect to its coherence bandwidth or, equivalently, if the maximum transmission delay introduced by the channel is large with respect to the modulation symbol time. In this case, equalization techniques must be used at the receiver in order to recover the transmission symbols.

The channel is time-selective if it varies faster than the modulation symbol time. This phenomenon is due to the mobile's speed and is called the Doppler effect. It happens when the coherence time of the channel is small with respect to the symbol time. The channel is then a "fast fading" channel. If the channel varies during the training sequence, it is no longer possible to estimate the channel impulse response, and equalization can no longer be performed.

1.1. Free-space loss link budget and capacity

In this first simple introductory problem, we consider free-space propagation for an earth-to-satellite radio link. The carrier frequency is equal to 6 GHz, the transmitter power is equal to 4 W, the transmission bandwidth is equal to 200 kHz, the earth station antenna is a parabolic antenna with a diameter equal to 80 cm, the satellite antenna is a parabolic antenna with a diameter equal to 40 cm and both antennas have an efficiency $\eta = 0.5$.

We consider only the free-space loss. The distance between the Earth and the satellite is equal to 36,000 km.

Modulation requires a + 20 dB E_b/N_0 ratio.

The utilized constants will be:

– $k = 1.38 \times 10^{-23}$ JK^{-1}, Boltzmann constant;

– T = 300 K, receiver noise temperature.

1) Calculate the equivalent isotropic radiated power (EIRP) of the earth station.

2) Calculate the free-space loss.

3) Calculate the satellite-received power; the result should be in dBW.

4) Calculate the signal to thermal noise power ratio in the receiving band.

5) Calculate the maximal throughput of this link, considering only the E_b/N_0 constraint.

6) Now considering the communication channel capacity, what could you conclude for this transmission?

7) How could we calculate the electric field from the received power?

Solution

1) The transmitted power is equal to Pe = 4 W, it is often easier to give this power in dBW. For this purpose, we just have to consider $10 \times \log_{10}(\ )$ of the linear value of the power. In this case, we obtain:

$$P_{e,dBW} = 10 \times \log_{10}(4) \approx 6 \text{ dBW}$$

Another unit, often used, is the dBm: then we have to consider the logarithm of the power in mW:

$$P_{e,dBm} = 10 \times \log_{10}(4{,}000) \approx 36 \text{ dBm}$$

The antenna gain G_e is given, for a parabolic antenna with a diameter equal to D_e, by:

$$G_e = \eta \left(\frac{\pi D_e}{\lambda}\right)^2$$

As for the power, it can be useful to give this gain in dB, we obtain then:

$$G_{e,dBi} = 10 \times \log_{10}(G_e) = 31 \text{ dBi}$$

The EIRP, defined by the $P_e G_e$ product, is then equal to:

6 dBW + 31 dBi = 37 dBW

2) The free-space loss, at a distance d distance from the transmitter, for a link with a carrier frequency with a wavelength λ is defined by (see problem 1.2):

$$\frac{1}{L} = \left(\frac{\lambda}{4\pi d}\right)^2$$

This corresponds, always in dB, to:

$$L_{dB} = -10 \times \log_{10}\left(\frac{\lambda}{4\pi d}\right)^2 = 199.1 \text{ dB}$$

3) The receiving antenna gain is equal to $G_r = \eta \left(\frac{\pi D_r}{\lambda}\right)^2$, it corresponds to 25 dBi. The received power is then given by:

$$P_r = \frac{P_e G_e G_r}{L}$$

Finally, doing the derivation in dBW, we obtain:

$$P_{r,dBW} = 6 \text{ dBW} + 31 \text{ dBi} + 25 \text{ dBi} - 199.1 \text{ dB} = -137.1 \text{ dBW}$$

4) The thermal noise power spectral density, given in W/Hz, is defined by:

$$N_0 = kT$$

Given in dB, in this case, we obtain:

$$N_{0,dBJ} = 10 \times \log_{10}(N_0) = -203.8 \text{ dBJ}$$

The transmission bandwidth is equal to $B = 200$ kHz, and the thermal power in this band is then equal to N_0B = kTB.

The signal-to-noise power ratio $\Gamma = \frac{P_r}{N_0 B}$ given in dB, is then equal to:

$$\Gamma_{dB} = 10 \times \log\left(\frac{\mathrm{P_r}}{\mathrm{N_0 B}}\right)$$

This yields to:

$$\Gamma_{dB} = -137.1 \text{ dBW} + 203.8 \text{ dBJ} - 53 \text{ dBHz} = 13.7 \text{ dB}$$

5) The useful throughput R_b corresponding to the received power and to the thermal noise power can then be obtained as follows:

$$P_r = R_b E_b$$

In this last equation, E_b stands for the useful received bit energy just before the decision process.

We can then calculate the $\frac{P_r}{N_0}$ ratio, giving:

$$\frac{P_r}{N_0} = \frac{R_b E_b}{N_0} = \frac{P_e G_e G_r}{kTL}$$

We obtain then the maximum useful throughput of the link:

$$R_b = \frac{P_e G_e G_r}{kTL} \frac{1}{E_b / N_0}$$

Given in dBHz, this throughput is equal to:

$$R_{b,dBHz} = 10 \times \log_{10}(\mathrm{R_b})$$

then:

$$R_{b,dBHz} = -137.1 \text{ dBW} + 203.8 \text{ dBJ} - 20 \text{ dB} = 46.7 \text{ dBHz}$$

This corresponds to a throughput (the similarity between the throughput in dB and in linear is due to the values used in this exercise):

$$R_b = 46.7 \text{ kbits/s}$$

6) The channel capacity C is defined as follows:

$$C = B \times \log_2\left(1 + \frac{R_b E_b}{B\, N_0}\right)$$

leading to:

$$C = 923 \text{ kbits/s}$$

We can note that the channel capacity is higher than the maximal throughput given by the link budget. The solution proposed in this exercise is then correct and could be implemented. When the channel capacity is lower than the maximal throughput given by the link budget, some parameters of the system have to be changed. It could typically be the case with a narrow transmission bandwidth associated with a high throughput.

7) The received power can be obtained by calculating the flow of the Poynting vector through the equivalent area of the receiving antenna. By definition, we have:

$$\vec{S} = \vec{E} \wedge \vec{\mathrm{H}}$$

Far from the transmitting antenna, $\vec{E}$ and $\vec{H}$ fields are linked by:

$$\frac{E}{H} = 120\pi$$

The equivalent area A_{eq} of an antenna is linked to its gain G_r by:

$$A_{eq} = \frac{\lambda^2}{4\pi} \mathrm{G_r}$$

We can then obtain the electric field from the received power with:

$$P_r = \|\vec{\mathrm{S}}\| \times A_{eq} = \frac{\|\vec{\mathrm{E}}\|^2}{120\pi} \times \frac{\lambda^2}{4\pi} \mathrm{G_r}$$

1.2. Link budget and free-space loss

From the propagation formula giving the received power, P_r, with respect to the transmitted power, P_e, calculate the free-space loss in dB, provide the loss in L_{dB} and show that it is equal to:

$$L_{dB} = 32.44 + 20 \times \log_{10}(\mathrm{d}) + 20 \times \log_{10}(\mathrm{f})$$

where f is the frequency of the transmission in MHz and d is the transmitter–receiver distance in km.

Solution

The power density transmitted by an isotropic antenna is uniformly spread over a sphere surrounding the antenna.

At a distance d from this antenna, this power density (1 W/m^2) is given by:

$$\Phi(d) = \frac{P_e}{4\pi d^2}$$

Knowing that the equivalent area A_{eq} of an antenna is linked to its gain G_r by the following formula [PIC 09]:

$$G_r = \frac{4\pi}{\lambda^2} A_{eq}$$

where λ is the wavelength of the transmitted signal ($\lambda f = c$, c is the light speed), integrating the antenna gain G_e, we obtain:

$$P_r = \frac{P_e}{4\pi d^2} A_{eq} = \frac{P_e G_e G_r}{\left(\frac{4\pi d}{\lambda}\right)^2} = \frac{P_e G_e G_r}{d^2 \left(\frac{4\pi f}{c}\right)^2}$$

The free-space loss term L is then equal to:

$$L = d^2 f^2 \left(\frac{4\pi}{c}\right)^2$$

Having $c = 3 \times 10^8$ m/s $= 300$ m/µs $= 0.3$ km/µs, we can express L with the following equation:

$$L = d^2 f^2 \left(\frac{4\pi}{0.3}\right)^2$$

with f in MHz and d in km.

Converting this result in dB, we obtain:

$$L_{dB} = 10 \times \log_{10}\left(\mathrm{d}^2\mathrm{f}^2\left(\frac{4\pi}{0.3}\right)^2\right)$$

$$L_{dB} = 20 \times \log_{10}(d) + 20 \times \log_{10}(f) + 20 \times \log_{10}\left(\frac{4\pi}{0.3}\right)$$

$$L_{dB} = 20 \times \log_{10}(d) + 20 \times \log_{10}(f) + 32.44$$

REMARK 1.1.– This free-space loss equation is correct if the line of sight between the transmitter and the receiver is not obstructed by any obstacles. But it is also necessary to have no obstacle in the first Fresnel ellipsoid between the transmitter and the receiver. This first ellipsoid has a small diameter equal to $\sqrt{\lambda d}$.

For instance, if $d = 1$ km, we need to have a 18 m free-space area around the line of sight between the transmitter and the receiver for a transmission with a carrier frequency equal to 900 MHz and 13 m for 1,800 MHz. We notice these requirements are not often verified and we have frequently a ground diffraction to consider.

1.3. Linear expression of the Okumura–Hata model

The Okumura–Hata propagation model is a very common model because it easily and rapidly gives reliable results. It was defined by Hata in 1980, from empirical measures done by Okumura in 1968 in Tokyo area.

In an urban area, the loss L can be approximated by the following formula (without considering the mobile height):

$$L_{dB} = 69.55 + \left(44.9 - 6.55 \times \log_{10}(h_b)\right) \times \log_{10}(d)$$
$$+26.16 \times \log_{10}(f) - 13.82 \times \log_{10}(h_b)$$

The validity assumptions for this model are the following: the base station antenna height h_b is expressed in m and is between 30 and 200 m; the distance d between the transmitter and the receiver is expressed in km and is between 1 and 20 km; the carrier frequency f is expressed in MHz and is between 150 MHz and 1.5 GHz.

Considering a carrier frequency set at 900 MHz and a base station height at 40 m, give the value for L (in linear) as a function of d.

Solution

Starting from the formula giving L_{dB}, we insert the known inputs, f and h_b:

$$L_{dB} = 69.55 + \left(44.9 - 6.55 \times \log_{10}(40)\right) \times \log_{10}(d)$$

$$+26.16 \times \log_{10}(900) - 13.82 \times \log_{10}(40)$$

$$L_{dB} = 131.36 + 34.4 \times \log_{10}(d)$$

As $L_{dB} = 10 \times \log_{10}(\mathrm{L})$, we have $L = 10^{\frac{\mathrm{L_{dB}}}{10}}$ and then:

$$L = 10^{\frac{131.36+34.4\times\log_{10}(d)}{10}}$$

$$L = 10^{13.13} \times 10^{3.44\times\log_{10}(d)}$$

$$L = 10^{13.13} \times d^{3.44}$$

$$L = 1.35 \times 10^{13} \times d^{3.44}$$

The power of d is often called "propagation coefficient" (denoted as γ). Here, we have $\gamma = 3.44$. In free space, $\gamma = 2$.

1.4. Frequency, distance and propagation model

A mobile terminal transmits with an EIRP equal to 21 dBm toward its base station. The Okumura–Hata model is used as a propagation model for an urban area, for small- to medium-sized cities. We consider the following parameters:

– transmission frequency: 900 MHz (global system for mobile communications (GSM));

– base station antenna height: 30 m;

– mobile antenna height: 1.5 m.

1) Calculate the *path loss* in dB if the distance between the mobile and the base station is 500 m or 1 km. Calculate the average received power.

2) Do the same calculation with a transmission frequency equal to 2 GHz (universal mobile telecommunications system (UMTS)). Compare them and conclude.

REMARK 1.2.– In Hata's formula, the frequency is expressed in MHz. This formula should normally not be used for frequencies more than 1.5 GHz. Nevertheless, we allow this approximation in this exercise, for the purposes of comparison.

Solution

The Hata propagation model in urban area, for small- to medium-sized cities, is given by [GOL 05]:

$$L_{dB}(d)=A+B\times \log_{10}(d)-a_1$$

where the parameters are defined as follows:

$$A = 69.55 + 29.16\times\log_{10}(f_c) - 13.82\times\log_{10}(h_b)$$

$$B = 44.9 - 6.55 \times \log_{10}(h_b)$$

$$a_1 = \left(1.1 \times \log_{10}(f_c) - 0.7\right) \times h_m - \left(1.56 \times \log_{10}(f_c) - 0.8\right)$$

where d is the distance between the transmitter and the receiver in km, f_c is the central carrier frequency, expressed in MHz, and h_b and h_m are the respective heights of the base station and the mobile, expressed in m.

1) For $f_c = 900$ MHz, we get $A = 126.42$; $B = 35.22$ and $a_1 = 0.016$; consequently, the *path loss* equation in dB is:

$$L_{dB} = 126.43 + 35.22 \times \log_{10}(d)$$

Thus, the *path loss* at 500 m is equal to $L_{dB}(0.5) = 115.80$ dB and the *path loss* at 1 km is equal to $L_{dB}(1) = 126.43$ dB.

The received power is equal to the EIRP minus the *path loss*:

$$P_{r,dBm} = \text{EIRP}_{dBm} - L_{dB}(0.5) = 21 - 115.8 = -94.8 \text{ dBm}$$

for a distance of 500 m and:

$$P_{r,dBm} = \text{EIRP}_{dBm} - L_{dB}(1) = 21 - 126.4 = -105.43 \text{ dBm}$$

for a distance of 1 km.

2) For $f_c = 2{,}000$ MHz, we obtain $A = 135.49$, $B = 35.22$ and $a_1 = 0.047$. The *path loss* equation in dB is then:

$$L_{dB} = 135.44 + 35.22 \times \log_{10}(d)$$

Thus, the *path loss* at 500 m is equal to $L_{dB}(0.5) = 124.84$ dB and the *path loss* at 1 km is equal to $L_{dB}(1) = 135.44$ dB. Consequently, the received power is:

$$P_{r,dBm} = \text{EIRP}_{dBm} - L_{dB}(0.5) = 21 - 124.84 = -103.84 \text{ dBm}$$

for a distance d = 0.5 and:

$$P_{r,dBm} = \text{EIRP}_{dBm} - L_{dB}(1) = 21 - 134.91 = -113.91 \text{ dBm}$$

for a distance d = 1.

To conclude, the *path loss* increases when the carrier frequency increases. As a consequence, radio propagation is less effective when the carrier frequency increases, thus generating lower received power levels.

1.5. Link budget and diffraction

We consider a microwave link transmission. The carrier frequency is equal to 6 GHz, we consider 20 cm diameter parabolic antennas with efficiencies equal to 0.5. Only the free-space loss is taken into consideration. The distance between the transmitter and the receiver is equal to 40 km, and the antennas are located on 25 m high "mats". At an equal distance between the transmitter and the receiver, we find a 20 m high narrow "obstacle". The transmitted power is P_e = 100 mW.

1) Does the obstacle interfere with the transmission?

2) What is the impact of this obstacle on the link budget? Calculate the received power in dBm.

3) Same questions for a 30 m high obstacle.

Solution

1) A radio link is not obstructed if the line of sight is free of obstacles and if the first Fresnel ellipsoid has no interference. The maximal "rayon" ρ_{max} of this first Fresnel ellipsoid is observed at equal distance between the transmitter and the receiver. Its value depends on the

distance d of the radio link and on the wavelength λ of the transmission [LAV 97]:

$$\rho_{max} = \frac{1}{2}\sqrt{\lambda d}$$

In this problem, we have $f = 6$ GHz, then $\lambda = \frac{c}{f} = 5$ cm and we have $d = 40$ km, then:

$$\rho_{max} = 22.36 \text{ m}$$

The obstacle interferes with the first Fresnel ellipsoid. The link cannot be considered as corresponding to a free-space loss context.

2) To calculate the diffraction impact due to a narrow obstacle, we have to calculate the parameter v defined by:

$$v = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)}$$

In this expression, h stands for the distance between the line of sight and the top of the obstacle. This distance is negative if the top of the obstacle is under the line of sight and positive in the other case.

Here, we find $v = -0.31$. When the parameter v is greater than -1, we can approximate the diffraction fading with the function $J(v)$:

$$J(v) = 6.4 + 20 \times \log_{10}\left(\sqrt{v^2+1}+v\right)$$

In our case, we will find:

$$J(v) = 3.7 \text{ dB}$$

This value has to be subtracted from propagation losses in the link budget. The received power is then equal to:

$$P_{r,dBm} = P_{e,dBm} + G_{e,dBi} + G_{r,dBi} - L_{dB} - J(v)$$

The transmission parabolic antenna gain is given by:

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

We obtain then:

$$G_{e,dBi} = G_{r,dBi} = 19 \text{ dBi}$$

The free-space propagation loss at 40 km is equal to L_{dB} = 140 dB, then finally:

$$P_{r,dBm} = -85.7 \text{ dBm}$$

3) If we consider now a 30 m high obstacle, the term $J(v)$ becomes:

$$J(v) = 9.1 \text{ dB}$$

The received power is then equal to $P_{r,dBm}$ = –91.1 dBm.

1.6. Link budget and refraction

We consider a microwave link transmission. The carrier frequency is equal to 6 GHz, and we have parabolic antennas located at h meters from the ground. The distance between the transmitter and the receiver is equal to 50 km.

We consider an index “gradient” g = –40 µN/km.

The earth “rayon” R_T is considered to be equal to R_T = 6,370 km.

What should be the antenna height in order to avoid the ground diffraction?

Solution

We first calculate the half rayon of the Fresnel ellipsoid at equal distance between transmitter and receiver:

$$\rho_{max} = \frac{1}{2}\sqrt{\lambda d}$$

here f = 6 GHz then $\lambda = \frac{c}{f}$ = 5 cm and d = 50 km, then:

$$\rho_{max} = 25 \text{ m}$$

We consider a horizontal propagation of electromagnetic waves. Then, we have to correct the earth rayon.

The "fictive" earth rayon R_f is given by $R_f = \frac{1}{\frac{1}{R_T}+g}$, we find then:

$$R_f = 8{,}548 \text{ km}$$

To avoid a contact between the first Fresnel ellipsoid and the ground, the distance x between the horizontal line of sight and the ground must be at least equal to ρ_{max}.

We simply write:

$$(R_f + h)^2 = \left(\frac{d}{2}\right)^2 + \left(R_f + x\right)^2$$

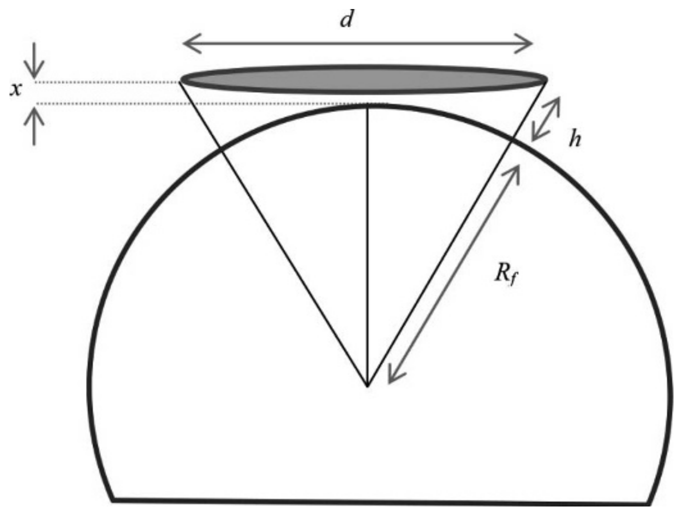

Figure 1.1. *First Fresnel Ellipsoid*

Considering that $R_f >> h$ and $R_f >> x$, second-order terms can be neglected, the equation becomes then:

$$R_f^2\left(1+2\frac{h}{R_f}\right)=\left(\frac{d}{2}\right)^2+R_f^2\left(1+2\frac{x}{R_f}\right)$$

$$2hR_f=\frac{d^2}{4}+2xR_f$$

In the limit case, we have $x = \rho_{max}$, then:

$$h=\frac{d^2}{8R_f}+\rho_{max}$$

we obtain:

$$h = 61.5 \text{ m}$$

Then, we have to locate antennas at high positions and use high pylons in order to reach this 61.5 m value.

1.7. Link budget and diffusion

We study a microwave link transmission, with a transmitter–receiver distance $d = 50$ km, and we consider Table 1.1 [BOI 83, LAV 97, MAR 98], representing the rain intensity (R) for an outage probability.

Probability (%)	Temperate area (R in mm/h)
0.001	78
0.002	62
0.005	41
0.01	28
0.02	18
0.05	11
0.1	7.2
0.2	4.8
0.5	2.7
1	1.8

Table 1.1. *Probability of exceeding a rain intensity*

This table should be analyzed as follows: a 0.1% probability for a temperate area means that the rain intensity will be higher than 7.2 mm/h for 0.1% of the time. This corresponds to 520 min per year.

We consider a vertical polarization with the parameters given in Table 1.2.

f (GHz)	a_v	b_v
6	0.00155	1.265
12	0.0168	1.2

Table 1.2. *Parameters for calculating the lineic attenuation for vertical polarization*

Using the Lin formula, calculate the margin that we should apply on the link budget in order to have a reliability of the link equal to 99.99%. Carry out the derivations for $f = 6$ GHz and $f = 12$ GHz.

Lin's formula:

$$k(L,R) = \frac{1}{1 + L\dfrac{R-6.2}{2636}}$$

where L is the effective distance where a rain intensity R is observed.

Solution

The 99.99% reliability requirement leads us to take very unlikely events into consideration. Then, we have to introduce important power margins into the link budget and overdesign the transmitter power amplifier.

Then, we have to consider the limit case of an important rain with an outage probability of 0.01% for a temperate area. The table analysis gives us $R = 28$ mm/h.

The Lin formula gives $k = 0.7$, the effective distance of the link is then equal to $d_e = \gamma \times d = a_v \times R^{b_v} \times d = 35.4\ \text{km}$.

For the 6 GHz frequency, we have $\gamma = 0.105$.

For the 12 GHz frequency, we have $\gamma = 0.916$.

Rain fadings are then equal to the following:

– For the 6 GHz frequency, *fading* = 3.7 dB;

– For the 12 GHz frequency, *fading*= 32.4 dB.

These two fadings represent margins that have to be taken into consideration in the link budget. If the 3.7 dB value can be envisaged, the 32.4 dB value will be more difficult to consider as a power back-off of the transmitter amplifier.

In conclusion, the required reliability will be difficult for the 12 GHz carrier frequency case.

1.8. Frequency and time selectivity

Let us consider a radio channel with the following parameters:

– the Doppler spread bandwidth is $B_d = 150$ kHz;

– the maximum multipath delay is equal to $T_m = 3$ µs.

1) Calculate the channel coherence bandwidth and coherence time.

2) Explain in which cases the channel is not frequency-selective.

3) Explain in which cases the channel undergoes slow fading.

Solution

1) The coherence time is approximately equal to $T_{co} = 1/B_d = 6.67$ µs. The coherence bandwidth is equal to $B_c = 1/T_m = 333$ kHz.

2) The channel is not frequency-selective if $B < B_c$, so the channel bandwidth is lower than 333 kHz.

3) The channel undergoes slow fading if $T_s < T_{co}$, so the symbol time is lower than 6.67 µs.

1.9. Doppler effect

A GSM system is operating at a central carrier frequency f_c = 1.8 GHz. It serves a mobile terminal that is located in a rural environment, where the multipath delay is equal to 10 μs.

1) Calculate the channel coherence bandwidth.

2) The GSM channel bandwidth is B = 200 kHz. Is the channel frequency-selective?

3) Calculate the coherence time for a mobile having a speed of 50 km/h.

4) The data rate in GSM is equal to $R = 271$ kbits/s. Calculate the corresponding symbol time.

5) Is it possible to recover the transmitted signal using equalization?

Solution

1) $B_c = 1/T_m$ = 100 kHz.

2) $B > B_c$, so the channel is frequency-selective. There will be intercell interference.

3) The maximum Doppler frequency is $f_d = f_c v / c$ = 83.33 Hz. The coherence time is approximately equal to $T_{co} = 1/(2f_d)$ = 6 ms.

4) The symbol time is $T_s = 1/R$ = 3.69 μs.

5) As $T_s < T_{co}$, the channel does not vary with respect to the time during the transmission of a symbol. Consequently, equalization can be used at the receiver in order to recover the transmitted signals by suppressing intercell interference. This is even more accurate as the channel remains constant over several consecutive symbols.

Starting from Chapter 2, some hardware characteristics are expressed in dB, according to the notation used in many industrial technical sheets. The reader should determine whether this is a power level (in which case dB means dBW) or a loss or a gain.