Laboratory Course in Communications Engineering

Measurement in Wireless Communications

Contents

Abbreviations

FM	Frequency Modulation
GSM	Global System for Mobiles¨
VCO	Voltage Controlled Oscillator
RDS	Radio Data System
OFDM	Orthogonal Frequency-Division Multiplexing
LTE	Long Term Evolution
LAN	Local Area Network
DVB-T	Digital Video Broadcast, Terrestrial
FFT	Fast Fourier Transform
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
WLAN	Wireless Local Area Network
FHSS	Frequency-Hopping Spread Spectrum
GFSK	Gaussian Frequency Shift Keying
CDMA	Code Division Multiple Access
UMTS	Universal Mobile Communication System
W-CDMA	Wideband CDMA
DS-CDMA	Direct Sequence CDMA
ITU	International Telecommunication Union
IQ	In phase - Quadrature

1. Introduction

This laboratory exercise could be categorized into different parts:

- Using spectrum analyzer different wireless technologies are identified based on frequency and shape of the spectrum. These technologies are: WLAN, Bluetooth, FM, GSM, 3G, LTE.
- Examination of path loss and fading. Transmitting signal generator is moved on the hallway apart from the measurement point. Measured signal level as function of distance is compared to the theoretical path loss model derived in the preliminary exercise.

With pre and post reports, these are the learning objectives:

- To get familiar with the equipment and working methods in laboratory.
- Get an idea on which frequencies different technologies operate and outline the reasons why the spectrum of the technology is shaped as it is.
- Get a view of path loss models, fading types and link budget calculations. How measured signal strength behaves as a function of distance/time in reality.
- Understand the concept of receive diversity and why it improves the signal strength against fast fading.

The assumption is that the topics of this exercise are already familiar. One objective of this exercise is to observe these topics in "reality". This paper is a short presentation to review the issues which will be dealt with in the exercise.

The content of this paper is the following. Different transmission or modulation methods are introduced shortly to outline the key factors affecting to the spectrum shape and bandwidth of the transmission. The effect of path loss and fading are introduced with link budget calculations. Receive antenna diversity concept is also shortly introduced for overcoming the negative effect of fast fading.

2. Transmission methods and technologies

This chapter gives a brief overview on the issues related to examination of frequency spectrum, encountered in the exercise. After reading this chapter, understanding spectrum shape and bandwidth of different technologies should be easier.

3.1 Pulse shaping

In communications systems, two important requirements of a wireless communications channel demand the use of a pulse shaping filter. These requirements are: generating band limited channels and reducing inter symbol interference. Both requirements can be accomplished by a pulse shaping filter which is applied to each symbol. As the symbol rate increases, the signal’s bandwidth increases. Especially in wireless communication this is a problem because of the tight specified frequency bands. The signal spectrum is determined partially by the pulse shaping in the transmitter. In this example rectangular and sync pulse shaping is used to illustrate the effect of pulse shaping.

In many communication systems the pulse shaping filter is a rectangular pulse, illustrated in left hand side of figure 4. The frequency response of rectangular pulse is a sync pulse; right hand side of figure 4. If sync pulse is used for pulse shaping, the frequency response is rectangular. This example shows that the frequency response of sync pulse is narrow while the rectangular pulse creates side lobes.

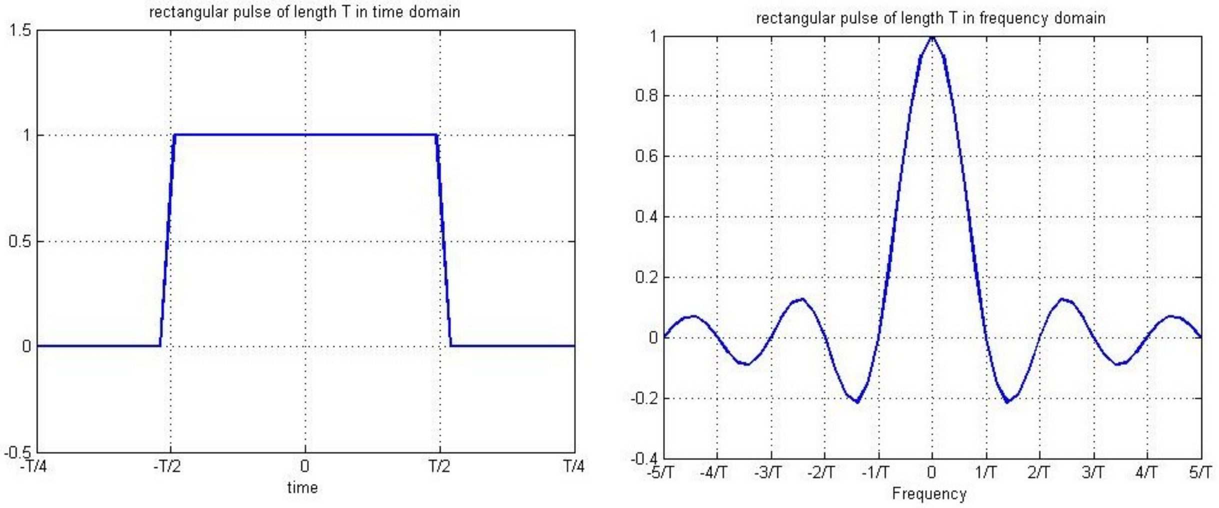

Figure 1. Rectangular and sync pulses.

The effect of pulse shaping to the transmission spectrum shape and bandwidth is demonstrated in figure 5. Using rectangular and sync pulse shaping, 1000 random symbols modulated with BPSK (taking values -1 and 1) are transmitted with 1 Hz symbol rate. In the left hand side of figure 5, the first 20 symbols are presented in time domain after pulse shaping each symbol. In the right hand side is the frequency response of the whole 1000 symbol transmission. Sharp transitions in a signal result in high-frequency components. By applying sync pulse-shaping the sharp transitions are smoothed and the resulting signal is limited to more narrow frequency band. This effect is visible in ride hand side of figure 5. In this example 1 Hz symbol rate results in approximately 1 Hz occupied bandwidth when sync pulse shaping is used, while the transmission bandwidth of rectangular pulse shaping is wider. The shapes of the frequency responses are sync and rectangular, as mentioned sync pulse shaping results in rectangular spectrum and rectangular pulse in sync spectrum. Roughly said, single carrier transmission signals frequency spectrum will resemble the response of the pulse shaping filter. Other used pulse shaping methods are for instance: Gaussian filter (GSM, Bluetooth) or raised cosine filter (WCDMA). [4]

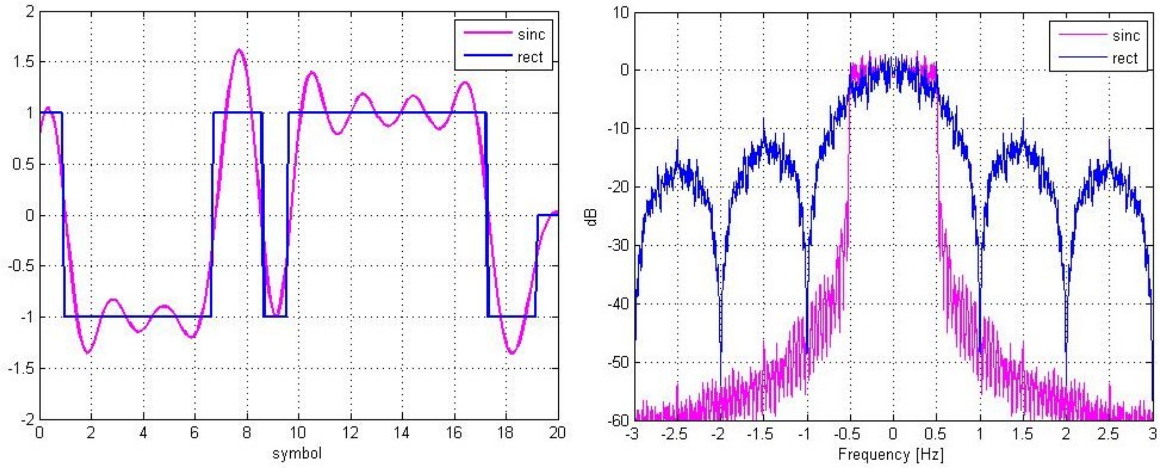

Figure 5. Transmission with rectangular and sync pulse shaping. Time and frequency domain plots.

3.2 FM

Frequency modulation (FM) conveys information over a carrier wave by varying its instantaneous frequency. The simplest approach to generating FM signal is to apply the message signal $m(t)$ directly to a voltage-controlled oscillator (VCO). The output is a constant amplitude sinsuoidal carrier wave whose frequency is ideally a linear function of its control voltage. The instantaneous frequency of the output signal $x_{fm}(t)$ varies above and below the center frequency:

$$f(t)=f_c+K_{vco}m(t) \qquad (1)$$

Where $K_{vco}$is the voltage-to-frequency gain of the VCO expressed in units of Hz/V. The quantity $K_{vco}m(t)$ is the instantaneous frequency deviation around the carrier frequency. The amplitude variation of the input signal transforms to variation of frequency. If the input signal is i.e. voice, loud sounds (high amplitude) generate high frequencies and quiet sounds low frequencies. The output of the frequency modulator is:

$$x_{fm}(t)=A_c\cos\left(2\pi f_c t+2\pi K_{vco}\int_0^t m(t)dt\right) \qquad (2)$$

The message signal of FM-radio broadcasting consists of several frequencies including music and data services. Therefore, the mathematical analysis of the output spectrum is difficult. To estimate the bandwidth of an FM signal, a single tone message signal is used as shown below:

$$m(t) = A_m \cos(2\pi f_m t) \tag{3}$$

Where, A_m is the amplitude and f_m is the frequency of the message signal. Substituting message signal (3) into (2), the output signal becomes:

$$x_{fm}(t) = A_c \cos\left(2\pi f_c t + \frac{\Delta f}{f_m} \sin(2\pi f_m t)\right) \tag{4}$$

Where the ratio called modulation index, $\beta = \frac{\Delta f}{f_m} = K_{vco} A_m$, represents the ratio of peak frequency Δf deviation and maximum instantaneous frequency f_m. In FM broadcast the peak frequency deviation is 50 or 75 kHz. The FM signal in frequency domain is presented in (5). The result is derived from (4) by dividing it into parts after which it is wrote as Bessel-function. Finally, taking Fourier-transform the FM-signal is obtained in frequency domain. The result is discrete FM output spectrum with magnitude coefficients as a function of modulation index β.

$$x_{fm}(f) = \frac{A_c}{2} \sum J_n(\beta) [\delta(f - f_c - n f_m) + \delta(f + f_c + n f_m)] \tag{5}$$

The number of sidebands of an FM signal and its associated magnitude coefficients can be found with the help of Bessel function tables such as table 1. The sidebands are multiples of f_m. If the message signal would be for example music, the sidebands would be multiples of every frequency in the song. Good approximation for the FM signal bandwidth is the Carson's rule:

$$BW_{fm} = 2(\beta + 1) f_m = 2(\Delta f + f_m) \tag{6}$$

The modulation index determines the bandwidth and the quality of transmission. For example, if the maximum message signals frequency is 15 kHz or 75 kHz and the frequency deviation is 75 kHz (as in Finland). The signals vary 75 kHz above and below the carrier frequency. The difference is that 15 kHz signal has modulation index five and 75 kHz signal has modulation index one. Therefore, 15 kHz has five times more space to vary than the 75 kHz signal. [5, 6]

Table 1. Magnitude coefficients of Bessel function.

	Sideband								
β	Carrier	1	2	3	4	5	6	7	8
0.00	1.00								
0.25	0.98	0.12							
0.5	0.94	0.24	0.03						

1	0.77	0.44	0.11	0.02					
1.5	0.51	0.56	0.23	0.06	0.01				
2.0	0.22	0.58	0.35	0.13	0.03				
2.41	0	0.52	0.43	0.20	0.06	0.02			
2.5	– 0.05	0.50	0.45	0.22	0.07	0.02	0.01		
3.0	– 0.26	0.34	0.49	0.31	0.13	0.04	0.01		
4.0	– 0.40	– 0.07	0.36	0.43	0.28	0.13	0.05	0.02	
5.0	– 0.18	– 0.33	0.05	0.36	0.39	0.26	0.13	0.05	0.02

3.2.1 FM broadcasting

FM broadcasting is a broadcasting technology using frequency modulation to provide high-fidelity sound over broadcast radio. Throughout the world, the FM broadcast band fall within the VHF part of the radio spectrum. Usually 87.5 to 108.0MHz is used. Nowadays, FM broadcasts are compatible with stereo and mono receivers. The figure below describes how FM broadcast channels are multiplexed. The audio is suppressed to 15 kHz. Frequency band from 30Hz to 15kHz is the L + R (*left* + *right*) audio for mono-receivers. Stereo sound is achieved by the L – R (*left* – *right*) channel which is modulated by 38 kHz double-sideband suppressed carrier (DSBSC) in the 23 to 53 kHz region of the baseband spectrum. To achieve stereo sound, the receiver will add the difference signal to sum signal to recover left channel, and subtract the difference signal from the sum signal to recover the right channel. The 19 kHz pilot tone is added to the signal to enable FM stereo receiver to detect and decode the stereo left and right channels. RDS (*Radio Data System*) is for small amount of digital information carried by the FM-modulation e.g. time, station identification and program information. [5]

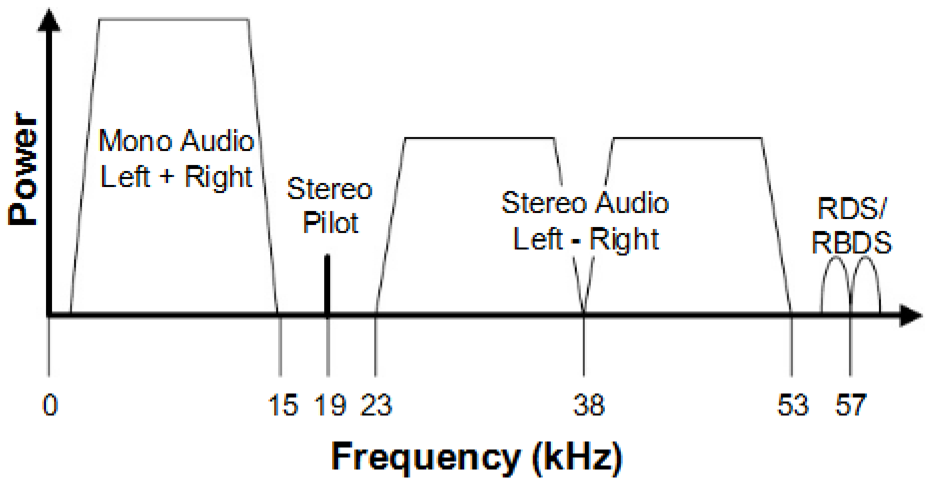

Figure 6. FM broadcast multiplex.

3.3 OFDM

OFDM (Orthogonal *frequency-division multiplexing*) is used in many modern communication systems i.e. LTE (Long Term Evolution), WLAN (*Wireless Local Area Network*) and DVB-T

(*Digital video broadcast, Terrestrial*). The basic principle of OFDM is to split a high-rate data stream into a number of lower rate streams that are transmitted simultaneously over a number of orthogonal subcarriers. The symbol duration increases for lower rate parallel subcarriers, so the relative amount of dispersion in time caused by multipath delay spread is decreased. Intersymbol interference is eliminated almost completely by introducing a guard time in every OFDM symbol. In OFDM design, a number of parameters are up for consideration, such as the number of subcarriers, guard time, symbol duration, subcarrier spacing, and modulation method for subcarriers. The choice of parameters is influenced by system requirements such as available bandwidth, required bit rate, tolerable delay spread, and Doppler values.

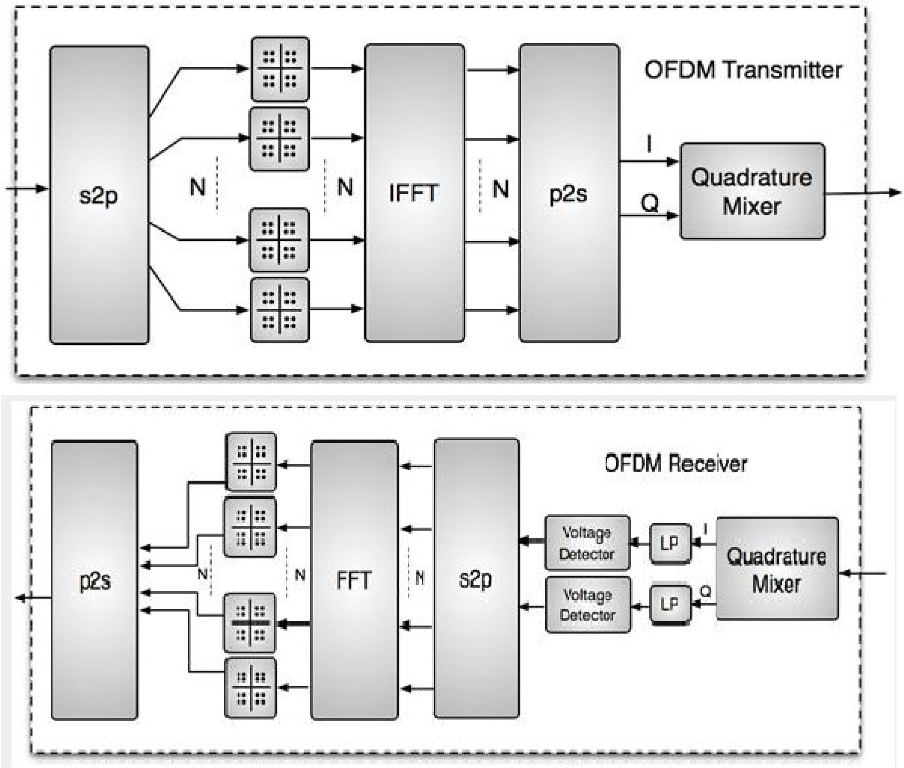

Figure 7. block diagram of OFDM transmission and reception

A simple block diagram of OFDM transmitter and receiver is presented in figure 7. Data is divided into N parallel data streams or channels. Each channels data is then modulated with a conventional modulation scheme, at low symbol rate. Data rate and bandwidth is maintained similar to conventional single carrier modulation scheme, with the exception of lower symbol rate. An inverse FFT (Fast Fourier transform) is computed on each channel resulting N orthogonal sub-carriers. Finally the orthogonal sub-carriers are summed up for the transmission. At the receiver, the procedure is similar but in reverse order. The OFDM symbol $s(t)$ is generated as follows:

$$s(t)=\frac{1}{\sqrt{T}}\sum_{k=0}^{N-1} a_k e^{j2\pi kt\,\Delta f} w(t) \qquad (7)$$

where

$a_k = data \; w(t) = pulse\ shaping\ window \; N = number\ of\ subcarriers$

$\Delta f = subcarrier\ spacing$

The OFDM symbol length is $T = \frac{1}{\Delta f}$ and contains N orthogonal subcarriers with $\Delta f = \frac{1}{T}$ frequency spacing, resulting occupied bandwidth of $N \Delta f$. In figure 8, the OFDM symbol is illustrated in time and frequency domain with two different cases. The upper figures are in time domain and the figures below are in frequency domain. The data stream is modulated with BPSK (taking values +1 or -1), and with 100 Hz carrier spacing, resulting $\frac{1}{100\,Hz} = 10\,ms$ symbol duration. In the left hand figures, 20 BPSK symbols are transmitted using 20 subcarriers, and in the right hand figures 3 BPSK symbols are transmitted using 3 subcarriers. The colored lines are the individual subcarriers, and the blue line is the OFDM symbol which is the sum of the subcarriers. The orthogonality of the subcarriers is visible in the frequency domain figures. The transmitted symbols are pulse shaped with rectangular pulse, which frequency domain response is a sync function. Sync function with frequency Δf is zero after every integer multiple of Δf, which is the spacing of the subcarriers. Therefore, the subcarriers are orthogonal and do not interfere each other at correct sampling points.

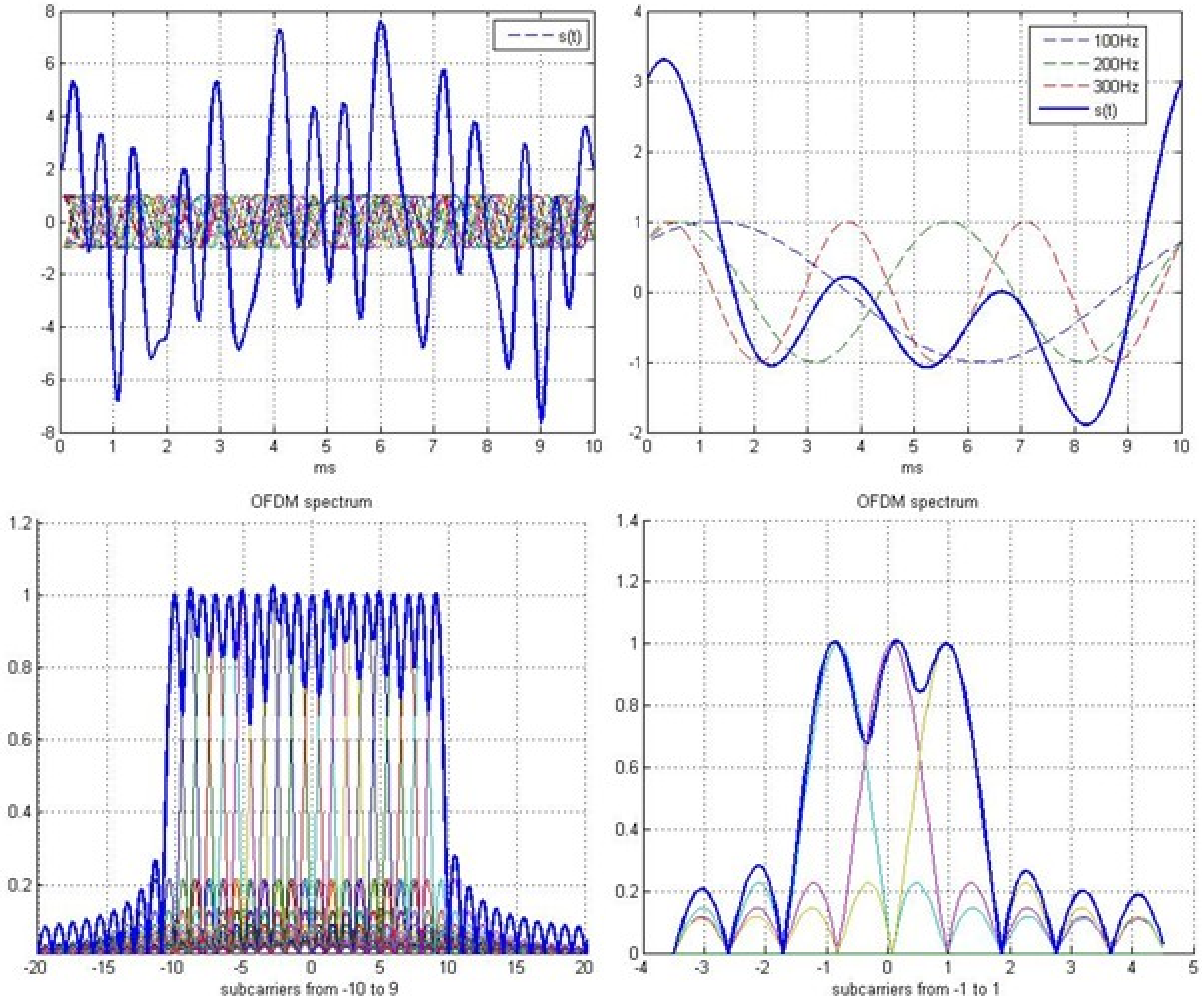

Figure 8. OFDM symbols in time and frequency domain.

As mentioned, OFDM is used in many modern wireless technologies with different parameters. For example in DVB-T the possible subcarrier modulation scheme are QPSK, 16QAM or 64QAM. The possible transmission schemes are called 2K or 8K-mode. In 2K-mode, 1705 subcarriers are used with 4.464 kHz spacing resulting 7.6 MHz bandwidth. In 8K-mode, 6817 subcarriers are used with 1.116 kHz spacing, resulting approximately the same 7.6 MHz bandwidth. Another example is WLAN standard IEEE 802.11a that uses 52 subcarriers with 312.5 kHz subcarrier spacing, resulting approximately 16.25 MHz bandwidth. The used modulation schemes are BPSK, QPSK, 16-QAM or 64-QAM. [7, 8]

3.4 Bluetooth

Bluetooth is a wireless technology standard for exchanging data over short distances. It uses radio technology called frequency-hopping spread spectrum (FHSS), which transmits radio signals by rapidly switching carrier among many frequency channels, using a pseudorandom sequence known to both transmitter and receiver. The data is send over 1MHz carriers and the frequency hops from 2.4 to 2.48GHz resulting 79 different carrier frequencies for the FHSS. The frequency hopping rate is 1600 hops per second. The modulation of single carrier is GFSK (*Gaussian frequency shift keying*) and the symbol rate is 1Ms/s. Bluetooth 2 EDT standard (*Enhanched Data Rate*) uses n/4 DQPSK and 8DPSK modulations to achieve higher data rates. [9]

3.5 DS-CDMA

In DS-CDMA (*Direct Sequence – Code Division Multiple* Access) systems, the narrowband message signal is multiplied by a very large-bandwidth signal called the spreading signal. All users in a DS-CDMA system use the same carrier frequency and may transmit simultaneously. Each user has its own spreading signal, which is approximately orthogonal to the spreading signals of all other users. The receiver performs a correlation operation to detect the message addressed to a given user. The signals from other users appear as noise due to de-correlation. For detecting the message signal, the receiver requires the spreading signal used by the transmitter. Each user operates independently with no knowledge of the other users. Figure nine illustrates an example of spreading. The symbol is multiplied by spreading code which symbol duration is eight fold less. Resulting eight fold higher symbol rate. As mentioned in 3.1, when the bandwidth of transmission increases, the symbol duration decreases. Therefore, in this example the resulting bandwidth would be approximately eight fold the bandwidth before spreading.

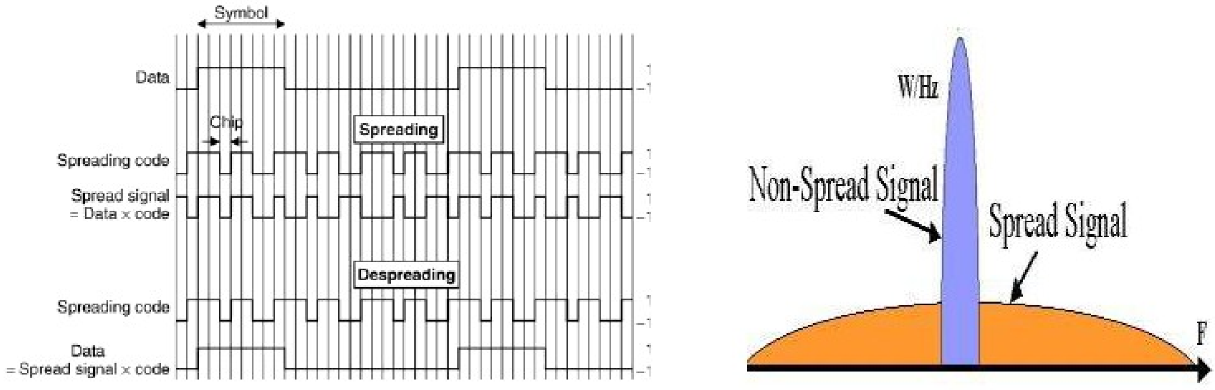

Figure 9. Example of spreading

UMTS W-CDMA is an air interface standard found in 3G mobile telecommunication networks. It deploys DS-CDMA where user information bits are spread over wide bandwidth by multiplying the user data with pseudorandom bits (called chips) derived from CDMA spreading codes. The chiprate in W-CDMA is 3.84 Mcps. [10, 11]

3. Link budget and fading

This chapter briefly introduces fading and path loss models together with link budget calculations that are used to estimate the signals attenuation. In addition, receiver diversity combining methods are introduced to improve the signal level in a fast fading channel.

3.1 Path loss and fading

The path loss is the power difference between receive and transmission antennas. There are many reasons for the signal attenuation, for example:

- Free space loss: the signal travels through space without any other effects attenuating the signal.
- Absorption losses: the radio signal passes into a medium which is not totally transparent to radio signals.
- Diffraction losses: an object appears in the signal path.
- Multipath attenuation: signals will be reflected and they will reach the receiver via number of different paths.

When transmitter or receiver is moving, the signal strength varies due different reasons, which may be categorized to three different attenuation types: path loss, slow fading and fast fading. Path loss denotes the attenuation caused by the distance between transmitter and receiver, while fading is caused by the change in the environment. Slow fading or shadowing is the attenuation when an obstacle (cars, buildings, walls) is between the transmitter and receiver. The signal strength increases and decreases depending on whether there are obstacles or not on the signal path. Fast fading is caused by the multipath propagation, where multiple copies of the signals arrive with different delays and attenuations. The multipath propagation will cause fast variations to the received signal strength. If the delayed signal arrives in phase with the direct signal, then the reflected signal will tend to reinforce the direct signal. If they are out of phase, then they will tend to cancel the signal. For example, wavelength of 2GHz signal is approximately 15 cm; therefore, 7.5cm difference between the multipath components would sum the direct and reflected signal out

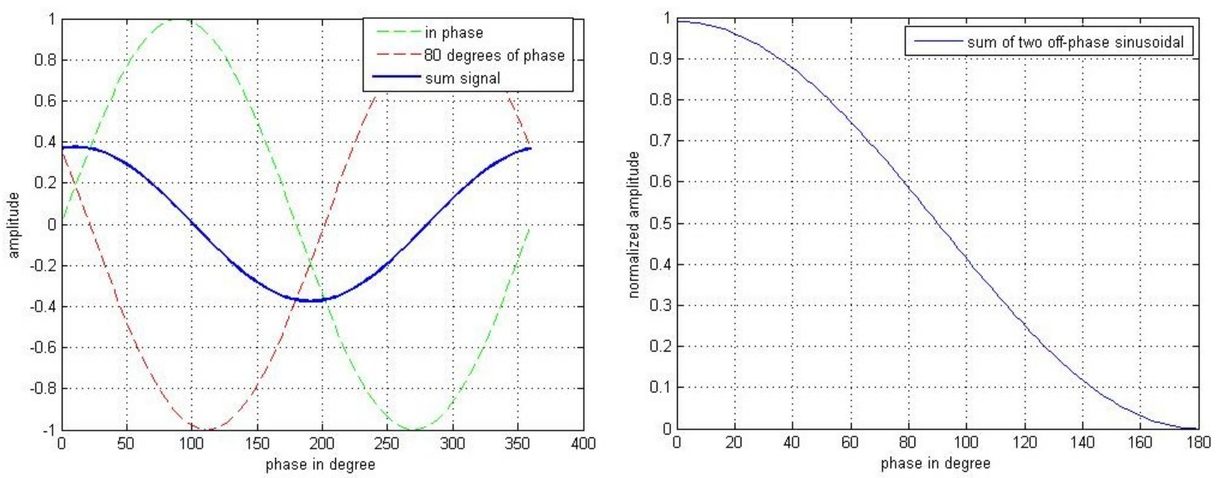

Figure 10. Affect of single multipath component.

of phase. This is illustrated in figure 10. Left hand figure is the sum of direct path and one multipath signal with 80 degrees off-phase. The right hand figure illustrates the attenuation when phase difference goes from zero to half the wavelength. In reality the situation is far more complicated with signals being received via many paths. However, this gives an indication of the distances involved to change from an in-phase to an out of phase situation.

Including path loss and fading, the measured signal power as a function of distance could look like in the figure 11. Green line is the theoretical free space path loss curve. Red line is the path loss combined with slow fading, where signal power varies slowly above and below the theoretical curve. Blue curve is combination of all the mentioned scenarios. The signal strength varies rabidly due the delayed signals arriving off and in-phase.

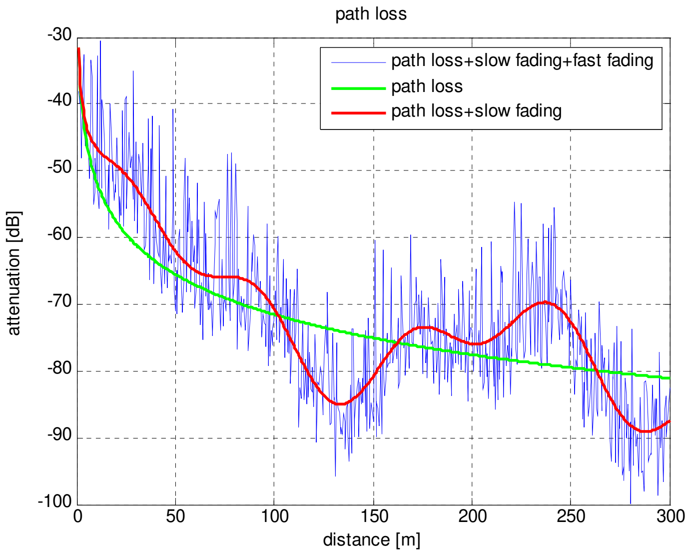

Figure 11. Example of the effect of path loss and fading.

One of the key reasons for understanding the elements affecting the path loss; is to be able to calculate the loss for a given path. Calculations can be fairly accurate in free space scenarios, but in real life scenarios accurate prediction might not be possible due various effects affecting the signal. For fading there are mathematical models such as: Rayleigh fading, Rician fading and Log-normal shadow fading. Fading margins are calculated using these models, to estimate the worst case attenuation of the signal path. Most path loss models are produced using techniques outlined below:

- Statistical/empirical models calculate the signal path loss based on measurements.
- Deterministic methods utilize the basic laws of physics as the basis for the calculations. These kinds of methods are complex but accurate.
- Semi-deterministic models are based on empirical and deterministic models together.

An example of deterministic model is the mentioned free space path loss model, describing the signal attenuation (dB scale) as a function of distance and frequency:

$$L = 20\log_{10}(d) + 20\log_{10}(f) - 27.55$$

where

$$d = distance \in meters\, f = frequency \in MHz$$

Modeling indoor propagation is complicated by the large variability in building layout and construction materials. The indoor environment is considerably different from the typical outdoor environment and in many ways is more hostile. The environment can change radically by the simple movement of people, closing of doors, and so on. For these reasons, deterministic models are not often used. An example of indoor propagation model is the ITU indoor propagation model. This model is computed statistically via measurements:

$$L = N \log_{10}(d) + 20 \log_{10}(f) + P_f(n) - 28$$

Where N is the distance power coefficient and P_f is the floor loss penetration factor. The formula is similar to the free space path loss model but with the two additional parameters. The parameter values are presented in table 2. [12, 13, 15]

Table 2. ITU Indoor Path Loss Model parameters

Frequency	Residential	Office	Commercial
900 MHz	-	33	20
1.2 – 1.3 GHz	-	32	22
1.8 – 2 GHz	28	30	22
4 GHz	-	28	22
5.2 GHz	-	31	-

Frequency	Residential	Office	Commercial
900 MHz	-	9 (1 floor) 19 (2 floors) 24 (3 floors)	-
1.8 – 2.0 GHz	4n	15+4(n-1)	6+3(n-1)
5.2 GHz	-	16 (1 floor)	-

3.2 Link Budget

As the name implies, a link budget is an accounting of all the gains and losses in a transmission system. The link budget looks at the elements that will determine the signal strength arriving at the receiver. A simple link budget equation is in formula 10 (dB scale).

$$Receiver\ power = Transmitted\ Power + Gains - Losses \qquad (10)$$

Gains could include antenna and diversity gain. Losses could include cable and connector losses, transmission loss trough walls and path loss. More detailed link budget equation might look like in (11).

$$P_{rx} = P_{tx} + G_{tx} - L_{tx} - L_{pl} - L_M + G_{rx} - L_{rx} \tag{11}$$

where

$$P_{rx} = Received\ power\,(dBm)\,P_{tx} = Trasmitted\ power\ output\,(dBm)\,G_{tx} = Transmitted\ antenna\ gain\,(dBi)$$

$$L_{tx} = Losses\,\text{¿}\,transmitter\,(cable\,, connectors\,etc\,.)\,(dB)\,L_{pl} = Pathloss\,(dB)$$

$$L_M = Misc\,.\,Losses\,(fade\ margin\,, polarization\ misalignment\ etc\,.)\,G_{rx} = Receiver\ antenna\ gain\,(dBi)$$

$$L_{rx} = Losses\,\text{¿}\,receiver\,(cable\,, connectors\,etc\,.)\,(dB)$$

The path loss model used for link budget calculation should be suitable for the situation. For example, the free space path loss model might not be accurate for indoor situation. [14, 15]

3.3 Diversity

Diversity techniques can be used to improve system performance in fast fading channels. Instead of transmitting and receiving the desired signal through one channel, we obtain multiple copies of the desired signal through different channels. The idea is that while some copies may undergo deep fades, others may not. There are several different kinds of diversity which are commonly employed in wireless communication systems:

- Frequency diversity: The same information signals are transmitted on different carriers, the frequency separation between them being at least the coherence bandwidth, so that the different frequencies undergo independent fading.
- Time diversity: the information signal is transmitted in different periods of time i.e. symbol is transmitted multiple times. The intervals between the transmissions of the same symbol should be at least coherence time of the channel, so that the different copies of the same symbol undergo independent fading.
- Angle diversity: directional antennas are used to create independent copies of the transmitted signal over multiple paths.
- Space diversity: multiple antennas are used to receive or transmit the signal. The antennas should be spaced far enough apart, so that different received copies of the signal undergo independent fading.

3.3.1 Receive diversity combining methods

The fundamental principle of diversity is to combine several copies of the transmitted signal, which undergo independent fading, resulting increase on the average received power level. In this example the diversity is achieved with space diversity using multiple receive antennas.

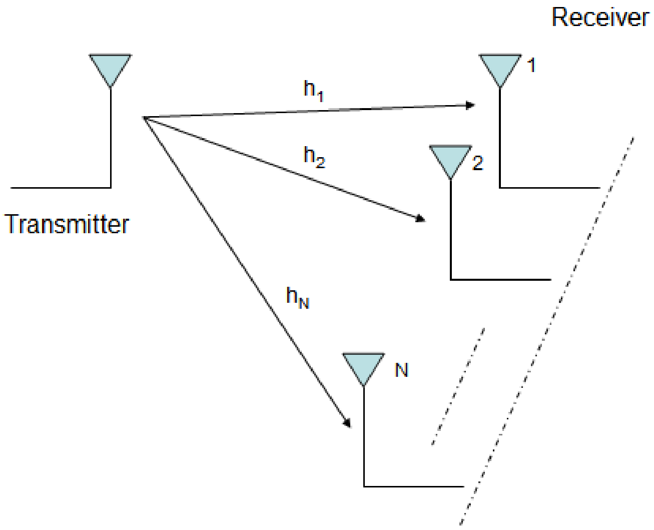

Figure 12. Multiple receive antennas

To achieve independent fading for each receive antenna, the spacing between antennas should be enough. Increasing the spacing between the antennas decreases the correlation between the signals. If the antennas are fully correlated, the paths do not experience independent fading and the diversity gain disappears. In practice zero correlation is almost impossible to achieve. When the correlation is below 0.5 the channels are practically independent. The correlation of mutual channels as a function of distance between the antennas is given by the relation:

$$\rho = J_0^2\left(\frac{2\pi d}{\lambda}\right) \quad (10)$$

Where

$$\rho = correlation \, J_0(.) = bessel\ function\ of\ zero\ order \wedge first\ kind$$

$$d = distance\ between\ antennas \, \lambda = wavelength$$

Figure 13 presents the antenna correlation as a function of $\frac{d}{\lambda}$.

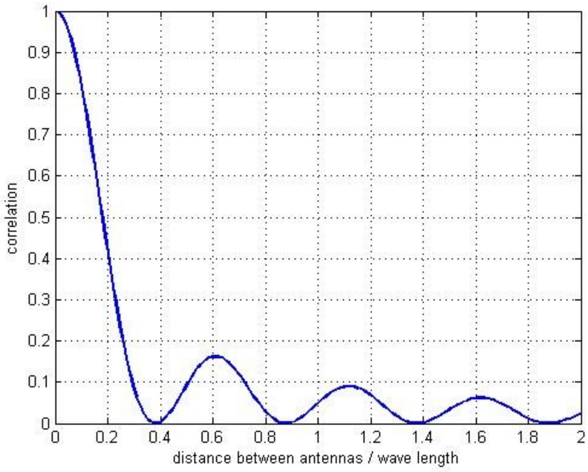

Figure 13. correlation between receive antennas as a function of distance

Next, three different diversity combining methods are briefly introduced: selection combining, maximum gain combining, and equal gain combining. In selection combining method, the receiver selects the antenna with the highest received signal power and ignores observations from the other antennas. Assuming that each received signal experiences independent Rayleigh fading, the gain in linear scale is according to following formula

$$G=\sum_{k=1}^{M}\frac{1}{k} \tag{11}$$

Where M is the number of receive antennas. An example of selection combining method is illustrated in figure 14. Two antennas experiences independent Rayleigh fading channel and the receiver selects the antenna with higher received power. As seen from the figure, at times the deep fades of single antenna reception is avoided. With more antennas, the likelihood to experience a deep fade decreases as the number of antennas increase.

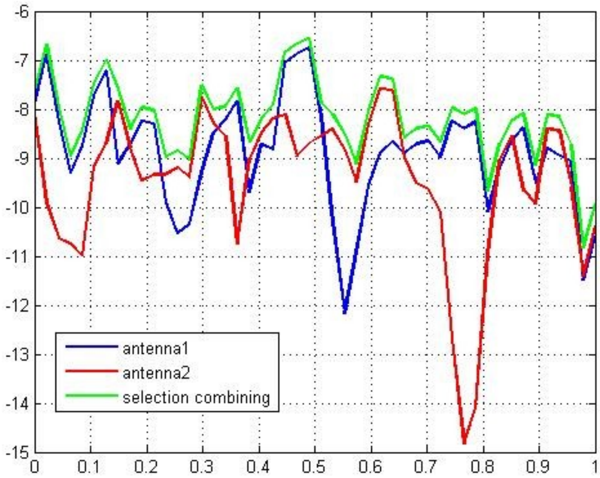

Figure 14. Selection combining with to receive antennas.

Another diversity method is maximum ratio combining. This method adds up all the received signals with weight factor proportional to signals SNR. This requires co-phasing so that the signals sum up in same phase and do not weaken each other as in figure 10. The gain of this method is the number of receive antennas used. For example; with two antennas, two similar signals are added up and the amplitude of the signal doubles, with three antennas the amplitude triples etc. Equal gain combining is similar to maximum ratio combining expect the signals are not weighted. This method is simpler but the gain is reduced approximately by factor of 0.8. The figure 15 illustrates the gain in dB of these methods. Selection combining is the worse but simples to implement, while maximum ratio combining has the best performance but the most complex implementation because of the co-phasing and weighting. It is good to keep in mind that this result is only exactly correct when the signals are not correlating and the fading is Rayleigh. In reality the given results are only illustrative. [13]

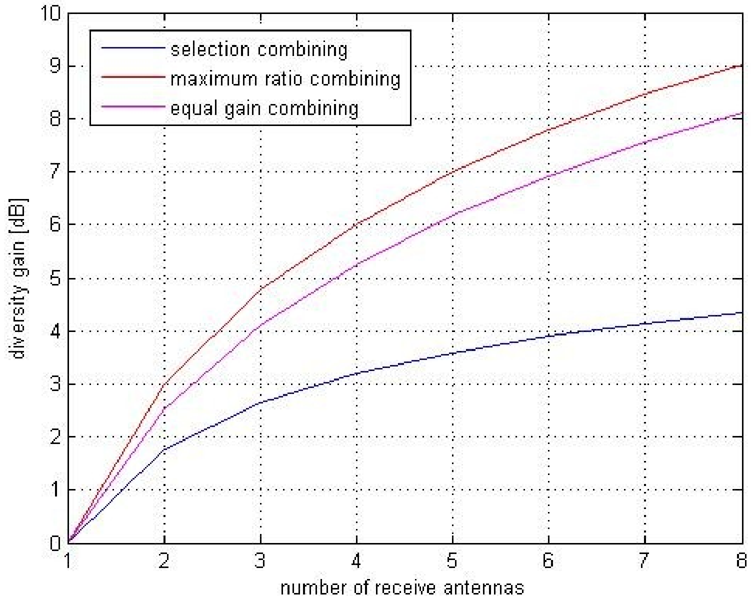

Figure 15. Gain of diversity as function of number of receive antennas.

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