Chapter 2
Communications Technologies

This chapter goes into some detail on how some of the modern radio technologies work. However, some of these technologies are not unique to the radio but are used across many different mediums of communications. There have been tremendous developments on many fronts of communications that make modern communications possible.

The signal in a modern communication system goes through a number of steps. First, there is the signal that needs to be communicated from a transmitter to a receiver. For a digital system it is a stream of bits. Some form of modulation is used to overlay the baseband signal into a carrier which is then transmitted through an antenna. Modern communication systems usually broaden the baseband signal before overlaying on a carrier. Broadening is done to mitigate the narrow band frequency distortion, multipath, ISI, etc. usually present in a channel.

An overview of technologies, such as coding, modulation, Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), multipath is provided. This is a vast area of knowledge and a number of references are provided for the interested reader to explore further.

Coding

Coding is used to mitigate a number of imperfections and disturbances that arise in a communications channel. Prime among them are: short burst error, fading, spreading, DC balance (8B/10B coding). Coding is an extensively researched area with many good books [1, 2]. Here, we will go over some of the codes used in wireless communications. There are a number of types of codes: block code, convolution code, turbo code, Low Density Parity Check (LDPC) code.

In essence, coding amounts to using more bits necessary than to transmit the data. Suppose the data consist of k bits, then coding maps the 2^k numbers to 2^n numbers. This is the (n, k) binary block code space. The Hamming distance

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between code words is the number of bits they differ. The minimum distance between the different code words is a significant number as that provides error detecting/correcting capability of the code. For example, in the (*k*, *k*), the minimum Hamming distance is one. The minimum distance, d_m, is the least distance between all code words and the zero code word. A block code is called perfect if every received word is exactly within distance *d* of exactly one code word (i.e. all received words, also called sense words, are not code words), and hence, can correct *t* or less bit errors (e.g., $d = 2^t - 1$). The (*n*, *k*) block is linear if the code words are closed under bitwise modulo-2 addition. So, if C_i and C_j are two n-bit linear code words, then their modulo-2 bitwise addition (i.e. $1 + 1 = 0$, $0 + 1 = 1$, $0 + 0 = 0$) is also an *n*-bit code word. The *n*-bit code word from the *k*-bit data words are generated through the use of Generator matrix.

A (*n*, *k*) block code generates n coded bits from k data bits. Two types of linear block codes exist: Cyclic and LDPC. Cyclic codes are linear block codes where a cyclic shift produces another code. So, if $(c_0c_1c_2c_3c_4c_5c_6c_7)$ is a cyclic code word then so is $(c_1c_2c_3c_4c_5c_6c_7c_0)$. Cyclic codes are simpler to implement, and hence, they are popular. Cyclic codes are generated through polynomials instead of matrices. The data word is also represented as a polynomial. The polynomial operations are binary or modulo-2 operations $(i.e.\ (X^1 + 1)\ (X^2 + X^1 + 1) = X^3 + X^2 + X^1 + X^2 + X^1 + 1 = X^3 + 1)$. If the generating polynomial is of degree $n - k$, it is expressed as $g(X) = X^{n-k} + g_{n-k-1}x^{n-k-1} + \cdots + g_2x^2 + g_1x^1 + 1$. Data bits of degree $k - 1$ is expressed as $i(X) = i_{k-1}x^{k-1} + i_{k-2}x^{k-2} + \cdots + i_2x^2 + i_1x^1 + 1$. Then, the code word of degree $n - 1$ is $b(X) = q(x)g(x)$, where *q(x)* is the dividend obtained from dividing $x^{n-k}i(x)$ by $g(x)$.

Bose–Chaudhuri–Hocquenghem (BCH) codes and Golay Codes are Cyclic codes. Both Hamming Codes and Reed-Solomon Codes are BCH codes. Some examples of perfect codes are Golay code and Hamming code.

The Hamming code is characterized by $d_m = 3$, and hence, can correct up to 1-bit error. Extended binary Golay code encodes 12 bits of data in a 24-bit word in such a way that any triple-bit error can be corrected and with $d_m = 7$.

Convolution codes use more than data bits to produce the code word. Each block of *k* bit is encoded into *n* bits. To produce the *n* bits, *K − 1* previous *k*-bit blocks are used. Hence, Convolution codes are known as memory codes. Convolution codes do not break the message stream into fixed-size blocks, instead redundancy is added continuously to the whole stream. Convolution codes are used in 802.11g.

Low Density Parity Check is a block code that was discovered in the 1960s, but did not gain in popularity till the 2000s due to the computational complexities involved. They approach Shannnon capacity for long code words. They are suitable for parallel decoding, and have the best known error correcting properties with large minimum distance between code words. They are used in a number of new protocols—WiMax or 802.16e, WiFi or 802.11n, and 10GE copper or 802.3an.

Turbo codes: they are used in communication protocols, such as HSPA, EV-DO, UMTS, and LTE. Turbo code is formed from the parallel concatenation of two encoders separated by an interleaver. The two encoders used are usually identical, the code is in systematic form (hence, the input bits also occur in the output), and the interleaver reads the input bits in the same fashion (could be pseudo-random). They compete with LDPC codes.

Barker codes are short (13 bits or less) sequences that are normally used in spreading. Barker codes have auto-correlation of at most 1 [3]. The 11-bit Barker code, 11100010010, is used in 802.11b as the spreading code for the standard rate (1 and 2 Mbps) DSSS mode of 802.11. The start and end of a symbol is aligned with the ends of the 11-bit Barker sequence.

Complementary Codes [4, 5] are Polyphase Codes. Their auto-correlation is zero everywhere other than at zero shift. Complementary Code is used for spreading in the high date rate DSSS mode of 802.11 (5.5 and 11 Mbps). 8 bits of the input is converted into 8 complex chips (e.g., 1, −1, j, j, −j, j, −1, −1), which are then transmitted one after another. In essence, whereas, Barker code was just used for spreading a low bandwidth signal, CCK achieves the same amount of spreading by increasing the data rate.

Gold code is used in GPS and CDMA. It has high auto-correlation and low cross-correlation properties. Gold codes are not exactly orthogonal, but near orthogonal, which helps in distinguishing weak auto-correlation signals from strong cross-correlation signals.

Space–Time Code (STC) involves adding redundancy over both spatial and temporal domain. Essentially there are two types of STC, Space–Time Trellis Code (STTC) and Space–Time Block Code (STBC). In STTC, a stream of information is split into a number of substreams. Each such substream is then fed into a separate transmit antenna. In STTC, each substream is encoded via a number of convolution encoders. The complexity of decoding grows exponentially with the memory length of Trellis code. STBC on the other hand has low encoder/decoder complexity, and hence, is more inexpensive to implement. For a 2-antenna system, the Alamouti code is the only full rate and diversity gain STBC code. This is achieved by full orthogonality of the signals transmitted over the two antennas. For higher number of antennas, orthogonality is not achieved but approached, hence full rate and diversity gain are also approached. See the section on MIMO for a mathematical representation of Alamouti coding/decoding.

Modulation

The radio spectrum typically used for communication ranges from 0 to 3 GHz. Of course, if only the baseband signal is transmitted, then most of the 3-GHz spectrum is left unused. Modulation is a method to ride a lower frequency signal over a higher frequency signal called the carrier wave. Here, we will focus on

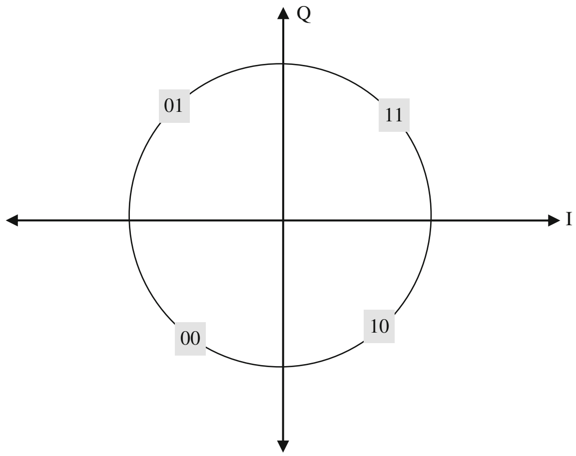


Fig. 2.1 I-Q diagram for QPSK constellation

digital modulation or modulation for digital bits. The following discussion is not intended to be either comprehensive or rigorous. A number of very good books on modulation are available [1, 6, 7].

There are primarily three types of digital modulations—amplitude, phase, and frequency. Pure amplitude modulation is used in AM radios. Most modern modulation schemes use a combination of the three.

Amplitude Shift Keying (ASK)/M-ary Pulse Amplitude Modulation (MPAM) encodes information only in amplitude.

Phase modulation is well represented by I (in-phase) and Q (quadrature) components. The I and Q components are sinusoids at a particular carrier frequency that are separated in phase by 90° (i.e. $\sin 2\pi f_c$ and $\cos 2\pi f_c$) and is based on the trigonometric identity $\sin(2\pi f_c + \varphi) = \cos 2\pi f_c \ \sin \varphi + \sin 2\pi f_c \ \cos \varphi = \mathrm{Q} \cos 2\pi f_c + I \ \sin 2\pi f_c$. Diagrammatically, the *I* component is plotted horizontally and the *Q* component is plotted vertically. Binary Phase Shift Keying uses two phases separated by 180° and encodes 1 bit per symbol period. Quadrature Phase Shift Keying (QPSK) uses four phases, 90° apart; and encodes 2 bits per symbol period. Offset QPSK (OQPSK) is a form of QPSK, where any 180° jump in phases is prevented, by offsetting the timing of even and odd bits of the symbol. Gray encoding is used with QPSK, which results in maximum one bit error for mistaking an adjacent symbol. Differential PSK encodes digit '1' by changing the phase and encodes '0' by leaving the phase unchanged. The general M-ary Phase Shift Keying (MPSK) encodes information only in phase. DBPSK and DQPSK is used in the 1 and 2 Mbps DSSS mode of 802.11 (Fig. 2.1).

Representation of MPAM on an I-Q diagram is possible and results in all constellation points lying on a straight line, hence one dimensional. Quadrature Amplitude Modulation (QAM) is a combination of PSK and ASK. Encoding in QAM uses two degrees of freedom, amplitude and phase, versus one in MPSK and MPAM. MQAM, such as 4QAM, 16QAM, 64QAM and 256QAM are popular because of their spectrum efficiency (i.e. more bits for the same energy). 802.11g uses both 16QAM and 64QAM.

Frequency Shift Keying (FSK) is nonlinear modulation, whereas both MPSK, MPAM, MQAM are linear modulations.

Gaussian FSK (GFSK) is FSK where the baseband 1 and 0 are smoothed or shaped with a Gaussian filter, which results in reduced spectral width compared to the step function modulation. GFSK is used in the 1 and 2 Mbps 802.11 FHSS mode. The modulation for 1 and 2 Mbps are 2GFSK and 4GFSK, respectively. The specified minimum deviation from the carrier frequency is 150 kHz for 2GFSK (2-level) and 62.5 kHz for 4GFSK (4-level).

Another type of modulation is called Adaptive Modulation, where the modulation parameters are adapted to the fading condition of the channel. Some of the parameters that are adapted are constellation size, transmit power, Bit Error Rate (BER), symbol period, coding rate, and coding scheme.

Spreading

Two widely used spreading techniques are frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). In DSSS, a higher frequency wideband spreading signal multiplies the modulated signal. The spreading signal is also known as chip and can be many times higher than the baseband signal. The rate of the spreading signal is known as chip rate. DSSS provide protection against narrowband interference and multipath.

To retrieve the signal at the receiver, the spread signal is multiplied by the spreading signal. This multiplication has the property of spreading any signal, not part of the original transmitted baseband signal hence, effectively lowering the noise or interference. A multipath signal is out of phase with respect to the other signal such that the multiplication will reduce the signal at the receiver.

802.11b uses DSSS and the chip code used is a bit Barker code.

Orthogonal Frequency Division Multiplexing

Multi-carrier modulation divides the transmitted data into many different substreams and sending those over many subchannels. The subchannels are chosen to be orthogonal so that the subchannels can be separated out with Discrete Fourier Transform (DFT) techniques. DFT are Fourier Transforms (FT) with discrete time and frequency. Discretization introduces three types of errors—aliasing, leakage or spreading, and Picket-Fence effect. Aliasing results in spectrum overlap and can be avoided by using higher sampling frequency. Leakage or spreading comes from the necessity to limit the duration of sample which spreads the spectrum. Picket-Fence effect results from the discreteness of DFT versus continuousness of FT, and

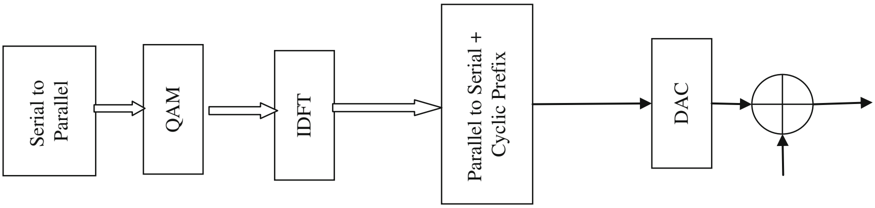


Fig. 2.2 Major operations used in generating OFDM signal

can result in not observing a frequency in between the integral multiple of the base frequency. Usually, DFT are implemented in FFT, FFT are very efficient algorithms to do DFT. The number of subchannels is chosen such that each channel's bandwidth is less than the coherence bandwidth of the medium (i.e. inverse of mean excess delay—described in detail elsewhere in this chapter) thus resulting in flat fading and small ISI. The following equation shows the FT and DFT in mathematical form.

Fourier Transform, Inverse Fourier Transform, DFT and Inverse DFT

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft}\mathrm{d}t,\ x(t) = \int_{-\infty}^{+\infty} X(f)e^{+j2\pi ft}\mathrm{df}$$
$$X(mf_o) = \sum_n x(nt_o)e^{-j2\pi nmf_o t_o}, x(nt_o) = \frac{1}{N}\sum_m X(mt_o)e^{+j2\pi nmf_o t_o} \tag{2.2}$$

OFDM is a form of multi-carrier modulation technique. The subcarriers are separated enough in frequency space so that they are orthogonal. Orthogonality refers to the fact that the integral multiplication of two sinusoidal subcarriers over a time period is zero. The input stream of digital signal is serial to parallel converted into the number of subcarriers. Then each of the parallel streams is QAM (or PSK) modulated. Then, each of the subcarriers is passed through an IFFT block. The signal then passes through a block that adds the cyclic prefix once. The cyclic prefix is needed as the multiplication of two DFTs is a circular convolution (or cyclic convolution), and the prefix makes it so. Then, the signal is converted into analog form by a DAC. Finally the analog signal is multiplied into a carrier wave. Figure 2.2 shows the transmit side.

OFDM's performance supposedly nears that of a single carrier performance for delay spread on the order of ISI. OFDM is able to handle frequency selective fading well by not transmitting on the subcarriers that are experiencing fading. A drawback of OFDM is higher peak-average power ratio, which occurs when the peaks of all the subcarriers aligns, which in turn can cause severe nonlinearity issues with power amplifiers. Please refer to [8] for more details on OFDM.

Multiple Access

As the communication channel in wireless is a scarce and precious resource, it is necessary to be able to share it. This in other words is Multiple Access [8, 9]. Four widely used multiple access technologies are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), and Space Division Multiple Access (SDMA). In TDMA, one channel (or a band of frequency) is time sliced among a number of transmitters and receivers. One pair of receivers and transmitters is allocated a slice of time. In FDMA, a band of frequencies is allocated to a set of transmitters and receivers. A distinct band can be allocated for each direction. If only a single band is allocated for each direction, then the band is time multiplexed for each direction.

In CDMA, the whole frequency band is shared by all the transmitters and receivers at all times. The communication between a transmitter and receiver is isolated by means of appropriate coding. CDMA and its sibling Frequency Hopped Multiple Access (FHMA) is commonly known as Spread Spectrum Access (SSMA).

The basic idea of CDMA is to multiply the signal by high bit-rate code or chip. In CDMA, the whole frequency band is shared by all the transmitters and receivers at all times. The communication between a transmitter and receiver is isolated by means of appropriate coding. This code appears as pseudorandom number. Each transmitter uses a different code, and the codes between different transmitters are de-correlatedd as much as possible; however, it is not practical to have orthogonal codes. Because of the built-in de-correlation, signals received at a receiver from multiple transmitters can be separated out. There are a number of significant differences between CDMA and TDMA/FDMA. First, power control at the receiver (usually the base station) is important as the noise floor is determined by the summation of the non-correlated signals. Thus, if the power from the transmitters is not equal, then the signal-to-noise ratio at the receiver decreases. There is no absolute limit in the number of users in the system. The noise floor rises linearly with the number of users, and hence, degrades everyone's performance.

In SDMA, directed beams are used between the transmitter and receiver. This can be accomplished by using directional antennas or MIMO. MIMO is a new technology that has been used in both 802.11n and LTE.

Multiple Input Multiple Output

MIMO systems leverage multipath to provide more capacity [8, 10, 11]. With multipath propagation, multiple antennas at both transmitter and receiver can establish essentially multiple parallel channels that operate simultaneously, on the same frequency band at the same total radiated power.

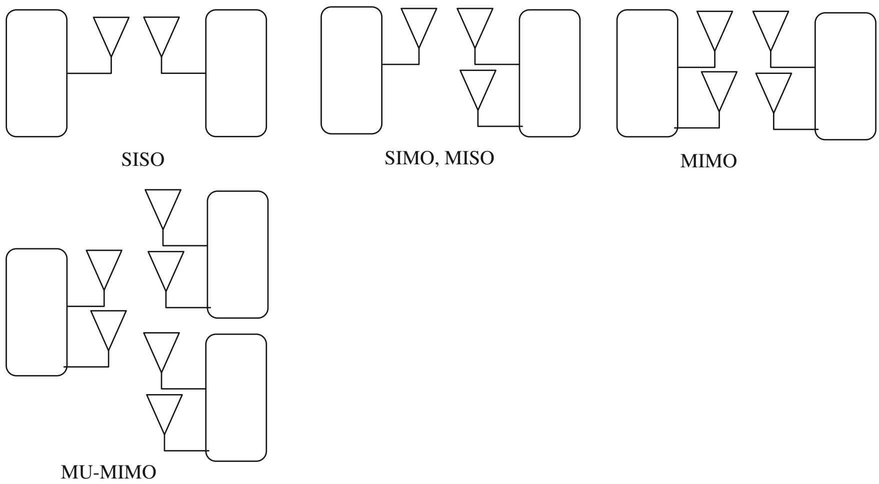


Fig. 2.3 Various MIMO configurations

When there are multiple antennas at the transmitter and a single antenna at the receiver, the configuration is called Multiple Input Single Output system, see Fig. 2.3. In this configuration, it is either possible to transmit the same signal or two different signals over the two transmit antennas. The latter situation increases the spectral efficiency, and hence, data rate of the system, and is considered true MIMO (more on that later). When the same signal is mapped into the transmitter, we can have either transmit diversity or beam-forming. beamforming requires the signals mapped to the antennas to be coherent or have a phase relationship. Transmit diversity does not require phase coherence. Phase coherence is usually achieved by adding a complex gain element between the signal source and the antenna. Transmit beamforming requires feedback from the receiver to the transmitter. When there are multiple antennas at the receiver and only a single transmit antenna, it is only possible to have diversity or beamforming but not MIMO. In this case, beamforming has the ability to amplify a source by N times, where N is the number of receiver antennas.

Multi-antenna equation

$$\boldsymbol{y} = \boldsymbol{H}x + \boldsymbol{n}$$
$$\boldsymbol{H} = \boldsymbol{U}\sum \boldsymbol{V}$$
$$\begin{bmatrix} y_1 \\ \cdots \\ y_r \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1t} \\ h_{21} & h_{22} & \cdots & h_{2t} \\ \cdots & \cdots & \cdots & \cdots \\ h_{r1} & h_{r2} & \cdots & h_{rt} \end{bmatrix} \begin{bmatrix} x_1 \\ \cdots \\ x_t \end{bmatrix} + \begin{bmatrix} n_1 \\ \cdots \\ n_r \end{bmatrix} \tag{2.3}$$

The components of $\boldsymbol{H}$ can be determined from a knowledge of Channel Side Information at Transmitter/Receiver (CSIT/R). The receiver side channel information is obtained by sending a known pilot. If a feedback channel from receiver to transmitter is available, then the transmitter side channel information can be obtained. Singular value decomposition of $\boldsymbol{H}$ is also shown in the above equation. When, both CSIT and CSIR are available then the signal can be precoded (e.g., multiplication by $\boldsymbol{V}^H$) at the transmitter and shaped at the receiver (e.g., multiplication by $\boldsymbol{U}^H$). This transforms the channels into a number of parallel SISO channels. This is because Σ is a diagonal matrix with singular values of $\boldsymbol{H}$. The number of parallel SISO channels is equal to the rank of $\boldsymbol{H}$. Beamforming or coherent combining occurs when the precoding and shaping matrices become column vectors—when only one signal is picked and multiplied by a unique weight for each antenna before transmission and similarly at the receiver. Beamforming hence requires knowledge of the channel at the transmitter. Beamforming provides diversity gain and requires simpler implementation. Maximum Ratio Combining (MRC) is a simpler combining technique that can be used both at the transmitter or the receiver, but is popular on the receiver side. Supposing there is one transmitter and multiple receivers, then MRC is obtained by multiplying the signal with an equalizing vector of the channel gain vector, see Eq. 2.4 below. MRC essentially weighs signals at the receiver in proportion to their strength.

Maximum Ratio Combining at the receiver

$$
\begin{aligned}
\boldsymbol{y} &= \boldsymbol{h}x + \boldsymbol{n} \\
\boldsymbol{h} &= [h_1, h_2, \ \ldots\ h_{M_r}]^{\boldsymbol{T}}, \quad \boldsymbol{y} = [y_1, y_2, \ \ldots\ y_{M_r}]^{\boldsymbol{T}}, \quad \boldsymbol{n} = [n_1, n_2, \ \ldots\ n_{M_r}]^{\boldsymbol{T}} \\
\frac{\boldsymbol{h^H Y}}{\boldsymbol{h^H h}} &= x + \frac{\boldsymbol{h^H n}}{\boldsymbol{h^H h}} \\
\boldsymbol{SNR} &= \frac{x\bar{x}}{\left(\frac{\boldsymbol{h^H n}}{\boldsymbol{h^H h}}\right)\left(\overline{\frac{\boldsymbol{h^H n}}{\boldsymbol{h^H n}}}\right)} = \boldsymbol{M_r}\frac{x\bar{x}}{n_i\bar{n}_i}
\end{aligned}
\tag{2.4}
$$

Other combining techniques for Diversity Gain are Selection Combining, Switched Combining, and Equal gain Combining. Selection combining selects the strongest signal, typically at the receiver. Switched Combining maintains the signal above a threshold by switching to a higher signal. In Equal Gain combining, the signals are summed coherently with the idea that sum of the signals will have higher Signal-to-Noise Ratio (SNR) than any single signal. Also, note that Beamforming and Phased-array Antennas described elsewhere in this book are applications of similar techniques to problems.

STBC mentioned previously is commonly used for MIMO systems. Almouti code is full data rate and full diversity STBC for two transmit antennas. The following equation shows the Almouti derivation. By having knowledge of h_i at the receiver it is possible to arrive as the transmitted signals.

Almouti equations

$$
\begin{aligned}
[y_1\ y_2]^T &= \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \\
[y_1\ y_2^*]^T &= \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \\
\boldsymbol{y} &= \boldsymbol{H}x + \boldsymbol{n} \\
\left(\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H}\right)^{-1} &= \left(\frac{1}{|h_1|^2+|h_2|^2}\right) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\
\boldsymbol{x} &= \left(\left(\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H}\right)^{-1}\boldsymbol{H}^{\boldsymbol{H}}\right)\boldsymbol{y} - \left(\left(\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H}\right)^{-1}\boldsymbol{H}^{\boldsymbol{H}}\right)\boldsymbol{n}
\end{aligned}
\tag{2.5}
$$

The time dimensions are the rows and the spatial dimensions are the columns, where x_1 and x_2 are transmitted over antennas 1 and 2 at time slot 1. In time slot 2, $-x_2^*$ and $-x_2^*$ are transmitted over antennas 1 and 2, respectively. Alamouti code assumes flat fading over the two time slots.

Electromagnetic Radiation Propagation

In the simplest case of free space propagation, electromagnetic waves radiate out of an antenna isotropically in all directions without being perturbed in any manner. The received power, any point in space, for such a case is provided by Friis equation as follows [12]:

Electromagnetic propagation in free space

$$P_\mathrm{r} = P_\mathrm{t} G_\mathrm{t} G_\mathrm{r} \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2.6}$$

P_r and P_t are the receiver and transmitter power

G_r and G_t are the receiver and transmitter gains

λ and d are the wavelength and seperation, respectively.

The gain factors come from the directionality and losses of real antenna. The frequency-dependent part of the above equation comes from the receiver's aperture. The aperture of an antenna is expressed as follows:

Antenna aperture

$$A_e = G_r \left(\frac{\lambda^2}{4\pi}\right)^1 \tag{2.7}$$

For an isotropic antenna, the gain is 1. The aperture is the effective area of the antenna that the antenna is able use to collect power..

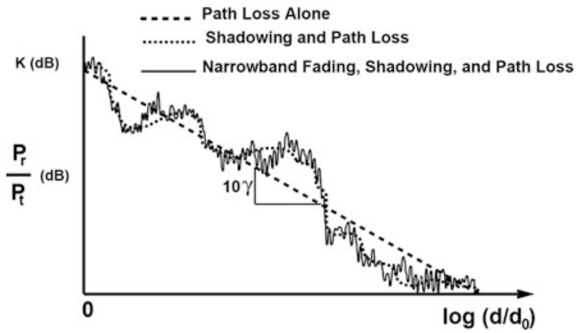


Fig. 2.4 Received signal with combined path loss, large-scale and small-scale fading [8]

The Multipath Effect

In earthly situations, free space conditions are compromised by primarily three electromagnetic phenomena [13]. The first is reflection, which happens when the electromagnetic radiation encounters smooth surface with much larger dimension than the wavelength. The second mechanism is diffraction when the wave is obstructed by objects larger than the wavelength, which results in secondary wave formation behind the object. Diffraction is also known as *shadowing*. Diffraction allows electromagnetic signals to propagate around large objects. The third phenomenon is scattering. Scattering occurs when the waves encounter a rough surface whose dimensions are of the same order as the wavelength.

As the wireless signal radiates out of the antenna, it may encounter reflective surfaces, which may reflect the signal just like a mirror reflects a beam of light. The reflected signal may then reach the receiver's antenna. So, the receiver ends up receiving signals from the same transmitter that traveled through different paths. The reflected signal may be out of phase with the line-of-sight (LOS) signal which can result in destructive interference, and hence, fading the signal at the receiver.

In [13] Sklar categorizes fading into large-scale and small-scale fading. Large-scale fading is due to obstructions such as billboards, buildings etc. Small-scale fading occurs due to subtle changes, such as half a wavelength separation change between the receiver and the transmitter results in drastic phase and or amplitude change. Small-scale effects are also called *Rayleigh fading* when there is no LOS signal component present at the receiver. Here, the envelope of the received signal is described by a Rayleigh probability density function (pdf). When a line-of-sight component is present, then a *Rician* pdf describes the envelope of the received signal. The combined effect of large-scale and small-scale fading together with the LOS signal results in deep variations of received signals. Figure 2.4 taken from [8], shows how the received signal is affected by the different components. In the figure, the Path Loss includes Free Space Loss and attenuation due to other artifacts. The Shadow Loss includes the variation around the mean due to blockage from objects, changes in reflecting surfaces and scattering objects.

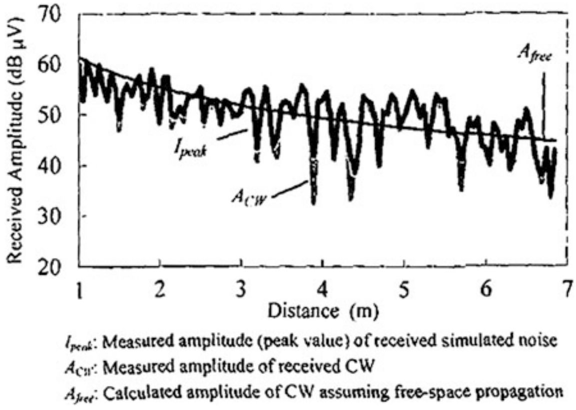


Fig. 2.5 Large-scale and small-scale fading over distance [14]

Figure 2.5 depicts the effect on received power in an indoor environment when is receiver is moved over a short distance [14]. Both the small-scale and large-scale fading is evident. The rapid changes in received power over short distances are due to small-scale fading. The gradual change is due to the large-scale fading.

Figure 2.6 depicts the time varying nature of the fading at one stationary spot [15].

Multipath is an extensively researched areas, and the reader should consult the references mentioned earlier [13–15]. A few additional references are provided for the interested readers [16, 17–25].

The Large-Scale Fading Effect

The average power at the receiver is generally found to logarithmically decrease with distance from the transmitter. The following equation expresses this relationship [26].

Antenna aperture

$$\overline{L(d)} = \overline{L(d_o)} + 10n\log(d) \tag{2.8}$$

In the above equation, the average loss at any distance d, $L(d)$, is log-normally related to distance. The factor $L(d_0)$ is the path loss at a reference distance, d_0. The path loss exponent, n, is usually calculated from measured data. The value of n can vary from 1.6 in-building LOS to six in obstructed in-building situations [9]. The value of n in free space is 2. The observed power at the same distance can vary a great deal depending on the environment due to different obstructions and reflecting surfaces. The observed power has been found to be randomly distributed around the average when considered across various environments. The Gaussian nature of the path loss is expressed by the following equation, where $p(l)$ stands for the probability of loss l [8].

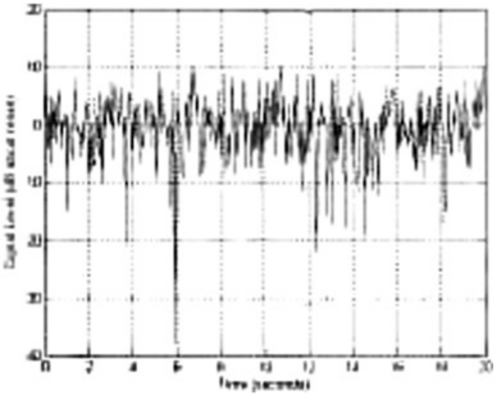


Fig. 2.6 Fading over time at a stationary point [15]

Gaussian path loss

$$p(l) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{1}{2}\left(\frac{l - \overline{L(d)}}{\sigma}\right)^2\right) \quad (2.9)$$

The value of σ, the standard deviation, also called dB spread in this case is between 6 and 13 [8, 26, 27].

Indoor environments have tremendous variations in materials used for construction and furnishing. The path loss varies for floors and partition types, with concrete and metal obstructions having the greatest attenuation effects. The loss per floor is about 10 db, the loss per drywall is about 3.4 db, the loss per concrete wall is about 13 db, and loss through metal wall is about 26 dB [8, 28, 29, 30].

The Small-Scale Fading or Multipath Effect

With small-scale fading present, a single signal pulse appears as a train of pulses at the receiver appearing at various delays and phase offsets. Sklar further divided small-scale fading into time-spreading and time-variant. In time-spreading fading the response of the channel is such that there is a delay between the first and the last of the signal, called the maximum excess delay time (T_m). Two references are used to characterize T_m, one based on the LOS delay and the other based on the mean delay. The LOS delay is equal or less than the mean delay. Moreover, T_m can also be characterized as average delay or root mean square delay. The typical values for T_m can range from 10 ns indoors for LANs to 30 ms outdoors for WANs [8]. If T_m is much smaller than symbol time (T_s), then the fading is called *flat fading* or *narrow fading*, otherwise it is called *frequency-selective fading* or *wideband fading*. Multipath symbols are resolvable in wideband fading which results in intersymbol interference (ISI). Intuitively, ISI occurs for wideband fading due to multipath signal being delayed sufficiently enough to arrive at the

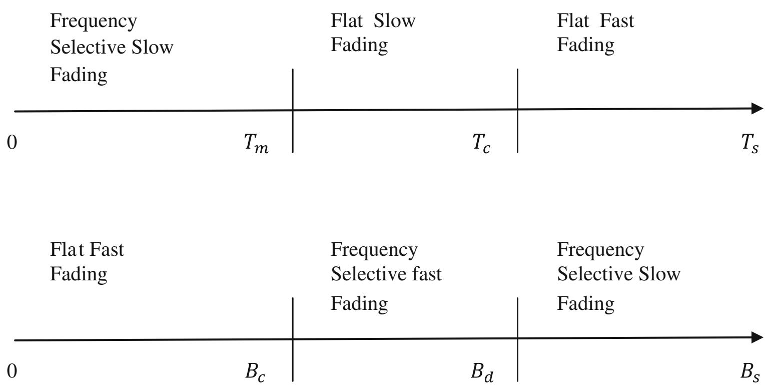


Fig. 2.7 Small-scale fading

receiver at the same time as a later signal. In narrowband fading, the primary impact is severe reduction in the signal power which adversely affects the data rate. Several techniques such as equalization, multi-carrier modulation, and spread spectrum are used for mitigation. In time-variant fading, the phase and frequency of the signal changes over time. In a multipath environment, the received signal arrives from several reflected paths with different path distances and different angles of arrival, and the Doppler shift of each arriving path is generally different for each path. The effect on the received signal is seen as a Doppler spreading or spectral broadening of the transmitted signal frequency, rather than a shift in the frequency. *Coherence Time* (T_c) is the period over which the channel maintains coherence, or remains unchanged due to Doppler effect caused by velocities of transmitter, reflectors, and the receiver. If T_c is larger than T_s, then the fading is called *slow fading* else it is called *fast fading*. For an unmitigated channel, T_m and T_c set the upper and lower bandwidths of the channel, respectively.

Fast and slow fading

$$
\begin{aligned}
&T_m < T_s < T_c \\
&B_c > W, B_s > B_d \\
&B_c \oplus 1/T_m \text{ and } B_d \oplus 1/T_c
\end{aligned}
\tag{2.10}
$$

In the last expression above, B_c and B_d are called the *Coherence Bandwidth* and spread or fading bandwidth or Doppler Spread of the channel, respectively. Coherence Bandwidth is the range of frequencies over which amplitude of two sinusoidal waves have high correlation. The different types of small-scale fading are depicted in Fig. 2.7.

The Signal-to-Noise Ratio and BER behavior can change dramatically in the presence of fading. When only flat-fading and slow-fading are present, Rayleigh limit can be approached. However, in the presence of unmitigated frequency-selective fading or fast-fading the BER can be limited to 0.5 or can be unusable.

The received signal, $r(t)$, and sent signal, $r(t)$, can be represented by the following sets of equations [8, 31].

Multipath signals

$$\begin{aligned} s(t) &= R\left(u(t)e^{j2\pi t f_c}\right) \\ r(t) &= R\left(v(t)e^{j2\pi t f_c}\right) \\ v(t) &= \sum_{n=0}^{N(t)} \alpha_n(t)u(t-\tau_n(t))\ e^{(-j2\pi f_c \tau_n(t)+\phi_{Dn}(t))} \\ \phi_{Dn}(t) &= \int_0^t 2\pi f_{Dn}(l)dl \\ f_{Dn}(t) &= \frac{v(t)}{\lambda}\cos\theta_n(t) \end{aligned} \tag{2.11}$$

The received signal is composed of n multipath components. The number of multipath components, $N(t)$, arriving at the receiver can be time-variant also. The path delay $\tau_n(t)$, is dependent on the path length traversed by the signal, which can also be time-variant. The Doppler phase shift, $\phi_{Dn}(t)$, is dependent on the relative velocities of the transmitter, receiver and the scattering/reflecting surface and can be time-variant. The multipath signal amplitude, $\alpha_n(t)$, is based on the free space path loss and shadowing and can also be time-variant.

Narrowband fading is characterized by $T_{\mathrm{m}} \ll T_{\mathrm{s}}$. In this situation, $u(t-\tau_n(t))$, can be approximated by $u(t)$ for all n. Moreover, we can assume that the other three factors also change slowly enough to approximate them as constant. Then the received signal becomes as follows:

Received signal under narrow band fading

$$v(t) \approx \sum_{n=0}^{N(t)} \alpha_n u(t)\ e^{(-j2\pi f_c \tau_n+\phi_{Dn})} = u(t) \sum_{n=0}^{N(t)} \alpha_n\ e^{(-j2\pi f_c \tau_n + j2\pi t f_{Dn})} \tag{2.12}$$

If we further assume an unmodulated carrier, then $u(t)=1$ and negligible Doppler effect (i.e. very low velocity), then we get the following expression for the received signal.

Unmodulated eceived signal under narrow band fading with no Doppler efect

$$r(t) = R\left(\sum_{n=0}^{N(t)} \alpha_n\ e^{j2\pi f_c(t-\tau_n)}\right) = \sum_{n=0}^{N(t)} \alpha_n\ \cos(2\pi f_c(t-\tau_n)) \tag{2.13}$$

It is evident from the above equation that for $\tau_n \approx \frac{1}{2f_c}$ (i.e. 0.208 ns at 2.4 GHz), the multipath components interfere destructively, whereas, for $\tau_n \approx \frac{1}{f_c}$ (i.e. 0.416 ns at 2.4 GHz), they interfere constructively. In terms of distance, these correspond to 6.25 and 12.5 cm, respectively at 2.4 GHz—thus the received signal power can change rapidly over a very short distance.

When $T_m > T_s$, the received power has different characteristics for wideband and narrowband signals. The wideband signal is a narrow pulse with repetition period much greater than T_m. Intuitively, wideband signals are all resolvable at the receiver, hence received power remains relatively constant over an area. However, for the narrowband signal, the phase delay for the different multipaths interfere destructively or constructively resulting in rapid change of received power (see Sect. 5.2.1 in [9]).

Multipath Mitigation Techniques

Negating multipath is the most significant problem that was solved to make modern radio communication feasible. As we have seen previously fading can dramatically influence the received signal within a very short distance and span of time. Over the years, a number of multipath solutions have been evolved. Broadly, there are two approaches to tackle the effect of multipath, one is to use multipath to advantage and other is to minimize its effect. In the first camp, there are methods like MIMO. In the second camp, there are methods like OFDM, GPS Choke Ring Antenna, MEDLL, etc. There is also problem space differentiation on what a good mitigation for multipath is. The criteria for good solutions for communications, positioning, RADAR are different.

In DSSS, higher frequency chip code is used for spreading. Usually, the chip code chosen has the property that there is zero to low correlation for signals delayed by more than one chip period. Hence, multipath signals are attenuated at the receivers. The DSSS chip codes used in 802.11b and GPS, Barker and Gold code, respectively have this property.

One of the earliest techniques to counter multipath is diversity reception and transmission. Diversity can be in frequency, in space (e.g., multiple antennas), in polarization (e.g., vertical or horizontal or elliptical), and in time. The basic idea behind using diversity is that the diverse elements receive signals along different paths. Hence, by using a combination of these signals, better estimation of the received signal is possible.

Equalization [32] is a proven technique for multipath mitigation. The goal of equalization is to devise a filter such that the combined impulse response of the radio channel and the filter result is zero ISI and distortion. The filter parameters are primarily extracted by one of two methods. The first is called automatic synthesis, where known training signals are sent over the channel. The receiver knows the transmitted signal and compares that with the received signal to determine the filter parameters. The disadvantage of this method is the overhead of the training signals. GSM uses this technique to mitigate multipath. GSM defines 8 training sequences of 26 bits, and can compensate for delay spread to 16 μs. In a second method called the Adaptation, the system first estimates the signal through some form of a decision component. The adaptation system then tries to keep difference between the estimated signal and the received signal to a minimum.

The adaptation system works well because of discrete levels used for digital signals. For slow moving vehicles, adaptive equalization is a good method to mitigate time invariant multipath. One disadvantage of equalizer is that at high data rates they become too costly.

OFDM, described previously, is a modern approach to handle multipath. It uses relatively simple DSP algorithms to mitigate multipath. In OFDM, multiple streams of narrowband signals are transmitted, hence the symbol period is longer. Longer symbol period, results in a period more than the multipath delay. In the frequency domain this translates into fading being constant over the narrow band. This reduces the ISI significantly. Any residual ISI is removed by using cyclic prefix.

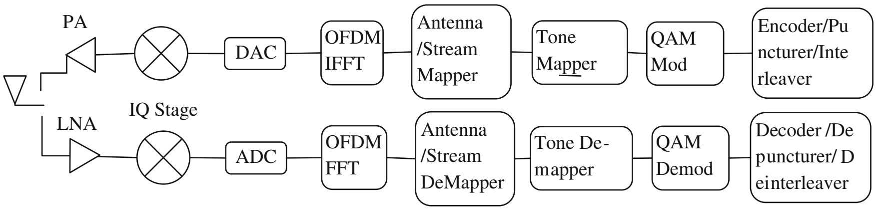
RAKE receiver [33] is another technique used to combat multipath. The receiver has a number of fingers, and each of these fingers is tuned to a particular path in the multipath environment. All the fingers are correlators, where the received signal is multiplied by a timeshifted version of a locally generated signal. The signals from each of the fingers are weighted and combined according to maximal ratio combining. RAKE receivers are widely used in CDMA and W-CDMA. Both the CDMA receiver and the transmitter have RAKE receivers. The receivers on the base station have more fingers but use noncoherent combining of signals. The receivers on the handset side use less number of fingers but use coherent combining. Pilot signals in CDMA enable channel estimation of the delay used in each finger.

MIMO on the other hand leverages the multipath propagation to increase bandwidth. In the MIMO system, the multiple paths taken by the signal form the transmitter to the receiver are separated out as independent channels. The bandwidth of each of these independent channels can be maximum, and in that case the total bandwidth will be a multiple of the channel bandwidth without MIMO.

802.11N And 802.15.4 System On Chip

Let us take a look at how all the above-mentioned technologies are used in a modern 802.11n system, or for our purpose in the silicon/chip. Figure 2.8 shows an 802.11n transmitter at a block diagram level. There are several components used to make a complete transceiver. There are usually two pipelines, one to receive and the other to transmit. In a MIMO/OFDM system like 802.11n, the in/out data stream is parallelized and mapped into multiple tones of the OFDM and multiple paths of MIMO. The PA and LNA are the analog components that connect directly to the antenna. Their purpose is to amplify the signal going to or received from the antenna. For further details please refer to [34–37].

The block diagram for a 802.15.4. based Zigbee system is significantly simpler [38, 39] as it does not use OFDM and MIMO, see Fig. 2.9. Zigbee uses DSSS instead, which is used in the 11 Mbps 802.11b version. As 802.15.4 is targeted for low bandwidth and low power applications, the complexities of MIMO and OFMD are not required—this also makes the silicon significantly less expensive. In the



PA – Power Amplifier

LNA – Low Noise Amplifier

IQ : Quadrature

DAC – Digital to Analog Converter

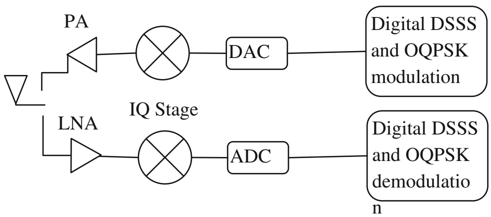
ADC – Analog to Digital Converter

FFT – Fast FourierTransform

IFFT – Inverse FFT

QAM – Quadrature Amplitude Modulator

Fig. 2.8 802.11n PHY/MAC



PA – Power Amplifier

LNA – Low Noise Amplifier

IQ : Quadrature

DAC – Digital to Analog Converter

ADC – Analog to Digital Converter

DSSS – Direct Sequence Spread Spectrum

OQPSK - Offset Quadrature Phase Shift Keyeing

Fig. 2.9 802.15.4 PHY/MAC

transmit chain, the spreading and OQPSK are done in the digital domain and then converted into analog domain by DAC.

There has been some debate over which technology, Zigbee or Wifi, is appropriate for certain applications. A quick comparison of the two technologies is tabulated in Table 2.1.

The power consumption is not exactly comparable as 802.11g has multiple modes, and in the table the highest throughput rate (e.g., 54 Mbps) is considered. There are also multiple idle modes both for 802.15.4 and 802.11; hence, a direct comparison is not feasible. From the table it is apparent that although the die size of Zigbee SOC is significantly smaller, it is not very efficient spectrally and power wise at comparable bit rates. Zigbee is also limited by the maximum 250 kbps throughput.

Table 2.1 Comparison of Zigbee and WiFi

	Zigbee	Wifi (802.11g)	Comments
Frequency band	2.4 GHz ISM	2.4 GHz ISM	
Peak power (mW)	30	100	
Energy per bit (nJ/bit)	119	15	[40]
Spectral efficiency (bit/s/Hz)	0.0125	2.7	7.22 for 802.11n (see [41])
Maximum data rate	250 kbps	54 Mbps	
Modulation/coding	DSSS	OFDM/64-QAM	Spreads the signal by applying a higher frequency chirp—not spectrally efficient
Typical die size (mm^2 at 130 nm)	~5	~100	See [25, 26, 29]
Typical power consumption (mW)	104/86/~0	523/155/~0	Tx/Rx/Idle [42, 43]

References

1. Wilson SG (1995) Digital modulation and coding. Prentice Hall, Englewood Cliffs
2. Heegard C, Wicker SB (2010) Turbo coding. Springer, Heidelberg
3. Barke RH (1953) Group synchronizing of binary digital sequences. Communication theory. Butterworth, London, pp 273–287
4. Golay MJE (1961) Complementary series. IRE Trans Inf Theory 7(2):82–87
5. Sivaswamy R Multiphase complementary codes. IEEE Trans Inf Theory IT-24(5)
6. Öberg T (2002) Modulation, detection and coding. Wiley, New York
7. Lacoste R (2009) Digital modulation demystified. Circuit Celler :54–63
8. Goldsmith A (2005) Wireless communications. Cambridge University Press, Cambridge
9. Rappaport TS (2002) Wireless communications principles and practice, 2nd edn. Prentice Hall, Upper Saddle River
10. Paulraj AJ, Gore D, Nabar RU, B̈olcskei H (2004) An overview of MIMO communications—a key to Gigabit Wireless. Proc IEEE 92(2):198–218
11. Gesbert D, Shafi M, Shiu D, Smith P (2003) From theory to practice: an overview of space-time coded MIMO wireless systems. IEEE J Sel Areas Commun. Special Issue on MIMO Systems, pt. I,vol21. pp. 281–302, April 2003
12. Balanis CA (2003) Antenna theory. Wiley, New York
13. Sklar B (1997) Rayleigh fading channels in mobile digital communication systems: characterization and mitigation. IEEE Commun Mag 35(7):90–109
14. Carroll M, Wysocki TA (2003) Fading characteristics for indoor wireless channels at 5 GHz unlicensed bands. Mobile Future Symp Trends Commun :102–105
15. Murakami T, Matsumoto Y, Fujii K, Sugiura A, Yamanaka Y (2003) Propagation characteristics of the microwave oven noise interfering with wireless systems in the 2.4 GHz band. Pers Indoor Mobile Radio Commun 3(7–10):2726–2729
16. Rigling BD (2008) Urban RF multipath mitigation. Radar Sonar Navig IET 2(6):419–425
17. Johannesson R Fundamentals of convolutional coding. IEEE Series Digit Mobile Commun. http://www.amazon.com/Fundamentals-Convolutional-Coding-Digital-Communication/dp/0780334833
18. Wilson S, Carlson B (1999) Radar detection in multipath. IEE Proc Radar Sonar Navig 146(1):45–54
19. Van Nee RDJ (1993) Spread-spectrum code and carrier synchronization errors caused by multipath and interference. IEEE Trans Aerosp Electron Syst 29(4):1359–1365

20. Weill LR (1995) Achieving theoretical accuracy limits for pseudoranging in presence of multipath. Proceedings of ION GPS/GNSS 1995, Palm Springs, CA, 1995, pp 1521–1530
21. Irsigler M, Eissfeller B (2003) Comparison of multipath mitigation techniques with consideration of future signal structures. Proceedings of ION GPS/GNSS 2003, Portland, OR, Sept 2003
22. Van Nee RDJ, Siereveld J, Fenton PC, Townsend BR (1994) The multipath estimating delay lock loop: approaching theoretical accuracy limits. Proceedings of position location and navigation symposium, April 1994, pp 246–251
23. Closas P, Fernandez-Prades C, Fernandez-Rubio JAA (2009) Approach to multipath mitigation in GNSS receivers. IEEE J Sel Top Signal Process 3(4):695–706
24. Puccinelli D, Haenggi M (2006) Multipath fading in wireless sensor networks: measurements and interpretation. Proceedings of the IEEE/ACM international wireless communications and mobile computing conference (IWCMC'06), Vancouver, Canada, July 2006, pp 1039–1044
25. Akl R, Tummala D, Li X (2006) Indoor propagation modeling at 2.4 GHz for IEEE 802.11 networks. Proceedings of the conference on wireless networks and emerging technologies, Alberta, Canada, July 2006
26. Cox DC, Murray RR, Noms AW (1984) 800-MHz attenuation measured in and around suburban houses. Bell Syst Tech J 63(6):921–954
27. Bernhardt R (1987) Macroscopic diversity. Freq Reuse Radio Syst 5(5):862–870
28. De Toledo AF, Turkmani AMD, Parsons JD (1998) Estimating coverage of radio transmission into and within buildings at 900, 1800, and 2300 MHz. IEEE Pers Commun 5(2):40–47
29. Durgin GD, Rappaport TS, Xu Hao (1998) Partition-based path loss analysis for in-home and residential areas at 5.85 GHz. Global telecommunications conference. The bridge to global integration, IEEE, vol 2, 8–12 Nov 1998, pp 904–909
30. Phaiboon S (2002) An empirically based path loss model for indoor wireless channels in laboratory building. 2002 IEEE region 10 conference on computers, communications, control and power engineering, vol 2, 28–31 Oct 2002, pp 1020–1023
31. Gallager R (2006) Course materials for 6.450 principles of digital communications I, Fall 2006. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology
32. Smalley D (1996) Equalization concepts: a tutorial. Texas Instruments. http://www.ti.com/sc/docs/psheets/abstract/apps/spra140.htm
33. Hasan A, Gan K-C, Ahmed I (2003) W-CDMA RAKE receiver comes to life in DSP. CommsDesign.com
34. Su D et al (2009) Design and implementation of a CMOS 802.11n SoC. IEEE Commun Mag 47(4):134–143
35. Trachewsky J et al (2008) A low-power single-weight-combiner 802.11abg SoC in 0.13 μm CMOS for embedded applications utilizing an area and power efficient cartesian phase shifter and mixer circuit. IEEE J Solid-State Circuits 43(5):1101–1118
36. Trachewsky J et al (2007) A 2x2 MIMO baseband for high-throughput wireless local-area networking (802.11n). HotChips. http://hotchips.org/uploads/hc19/3_Tues/HC19.06/HC19.06.02.pdf
37. Trachewsky J (2010) Wireless LAN global standardization and R&D trends. Short range wireless communications, IEICE, 23 August 2010, Tokyo
38. Bernier C et al (2008) An ultra low power SoC for 2.4 GHz IEEE802.15.4 wireless communications. 34th European solid-state circuits conference, 2008. ESSCIRC 2008
39. Le KT (2005) ZigBee SoCs provide cost-effective solutions. EETimes. http://www.eetimes.com/design/industrial-control/4012593/ZigBee-SoCs-provide-cost-effectivesolutions
40. Freeman D, Narayanan S (2011) Power constraints of wireless sensor nodes. EDN Magazine. http://www.edn.com/article/512371-Advances_in_energy_storage_technology_power_wireless_devices.php
41. http://en.wikipedia.org/wiki/Spectral
42. A true system-on-chip solution for 2.4-GHz IEEE 802.15.4 and ZigBee applications (CC2530F32, CC2530F64, CC2530F128, CC2530F256), Texas Instruments (2011)
43. AR 6103 Datasheet, Atheros Communications (2011)

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