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Space-Time Processing

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19.1 Introduction

Mobile radio signal processing includes modulation and demodulation, channel coding and decoding, equalization and diversity. Current cellular modems mainly use temporal signal processing. Use of spatio-temporal signal processing can improve average signal power, mitigate fading, and reduce cochannel and intersymbol interference. This can significantly improve the capacity, coverage, and quality of wireless networks.

A space-time processing radio operates simultaneously on multiple antennas by processing signal samples both in space and time. In receive, space-time (ST) processing can increase array gain, spatial and temporal diversity and reduce cochannel interference and intersymbol interference. In transmit, the spatial dimension can enhance array gain, improve diversity, reduce generation of cochannel and inter-symbol interference.

19.2 The Space-Time Wireless Channel

19.2.1 Multipath Propagation

Multipath scattering gives rise to a number of propagation effects described below.

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Scatterers Local to Mobile

Scattering local to the mobile is caused by buildings/other scatterers in the vicinity of the mobile (a few tens of meters). Mobile motion and local scattering give rise to Doppler spread which causes time-selective fading. For a mobile traveling at 65 mph, the Doppler spread is about 200 Hz in the 1900 MHz band. While local scatterers contribute to Doppler spread, the delay spread they contribute is usually insignificant because of the small scattering radius. Likewise, the angle spread induced at the base station is also small.

Remote Scatterers

The emerging wavefront from the local scatterers may then travel directly to the base or may be scattered toward the base by remote dominant scatterers, giving rise to specular multipaths. These remote scatterers can be either terrain features or high-rise building complexes. Remote scattering can cause significant delay and angle spreads.

Scatterers Local to Base

Once these multiple wavefronts reach the base station, they may be scattered further by local structures such as buildings or other structures in the vicinity of the base. Such scattering will be more pronounced for low elevation and below roof-top antennas. Scattering local to the base can cause severe angle spread which in turn causes space-selective fading. See Figure 19.1 for a depiction of different types of scattering.

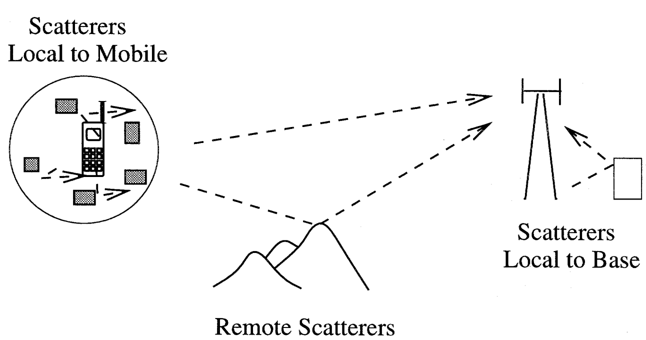

FIGURE 19.1: Multipath propagation in macrocells.

The forward link channel is affected in similar ways by these scatterers, but in a reverse order.

19.2.2 Space-Time Channel Model

The effect of delay, Doppler and angle spreads makes the channel selective in frequency, time, and space. Figure 19.2 shows plots of the frequency response at each branch of a four-antenna receiver operating with a 200 Khz bandwidth. We can see that the channel is highly frequency-selective since the delay spread reaches 10 to 15 μs. Also, an angle spread of 30° causes variations in the channel from antenna to antenna. The channel variation in time depends upon the Doppler spread. As expected, the plots show negligible channel variation between adjacent time slots, despite the high velocity of the mobile (100 kph). Use of longer time slots such as in IS-136 will result in significant

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channel variations over the slot period. Therefore, space-time processing should address the effect of the three spreads on the signal.

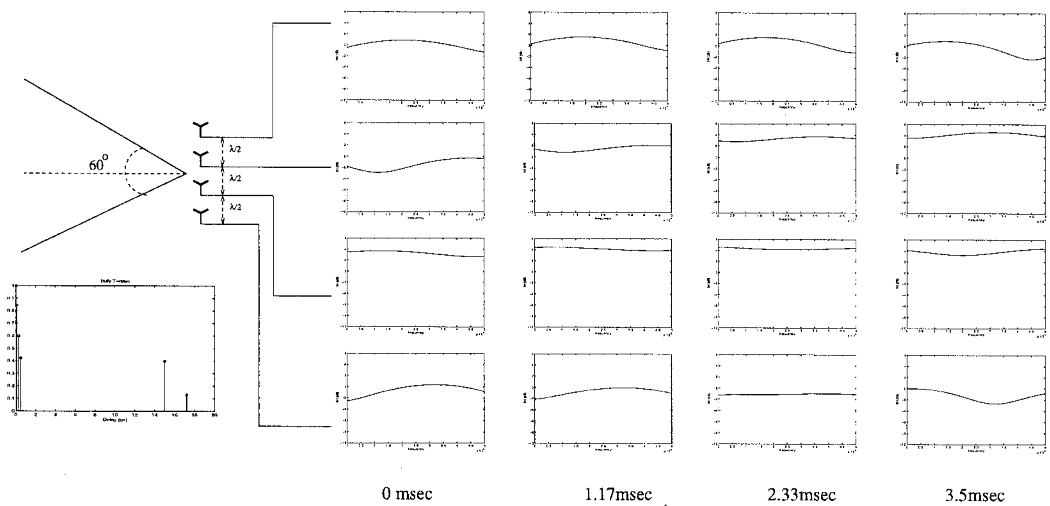

FIGURE 19.2: ST channel.

19.3 Signal Models

We develop signal models for nonspread modulation used in time division multiple access (TDMA) systems.

19.3.1 Signal Model at Base Station (Reverse Link)

We assume that antenna arrays are used at the base station only and that the mobile has a single omni antenna. The mobile transmits a channel coded and modulated signal which does not incorporate any spatial (or indeed any special temporal) processing. See Figure 19.3.

The baseband signal $x_i(t)$ received by the base station at the ith element of an m element antenna array is given by

$$x_i(t) = \sum_{l=1}^{L} a_i\left(\theta_l\right) \alpha_l^R(t) u\left(t-\tau_l\right) + n_i(t) \tag{19.1}$$

where L is the number of multipaths, $a_i(\theta_l)$ is the response of the ith element for the lth path from direction θ_l, $\alpha_l^R(t)$ is the complex path fading, τ_l is the path delay, $n_i(t)$ is the additive noise and $u(\cdot)$ is the transmitted signal that depends on the modulation waveform and the information data stream.

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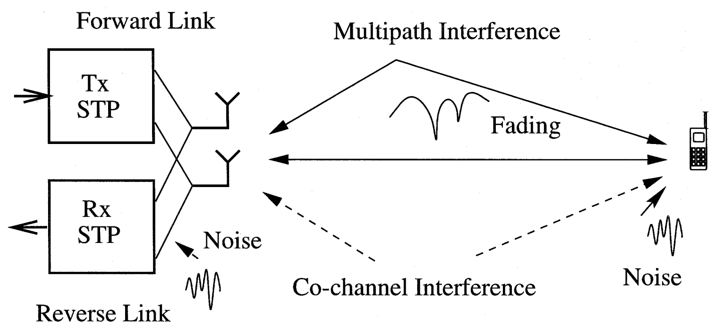

FIGURE 19.3: ST Processing Model.

For a linear modulation, the baseband transmitted signal is given by

$$u(t) = \sum_k g(t - kT)s(k) \tag{19.2}$$

where $g(\cdot)$ is the pulse shaping waveform and $s(k)$ represents the information bits.

In the above model we have assumed that the inverse signal bandwidth is large compared to the travel time across the array. Therefore, the complex envelopes of the signals received by different antennas from a given path are identical except for phase and amplitude differences that depend on the path angle-of-arrival, array geometry and the element pattern. This angle-of-arrival dependent phase and amplitude response at the ith element is $a_i(\theta_l)$.

We collect all the element responses to a path arriving from angle θ_l into an m-dimensional vector, called the *array response vector* defined as

$$\begin{aligned} \mathbf{a}(\theta_l) &= [a_1(\theta_l)\, a_2(\theta_l) \ldots a_m(\theta_l)]^T \\ \mathbf{x}(t) &= \sum_{l=1}^{L} \mathbf{a}(\theta_l)\, \alpha_l^R(t) u(t - \tau_l) + \mathbf{n}(t) \end{aligned} \tag{19.3}$$

where $\mathbf{x}(t)$ and $\mathbf{n}(t)$ are m-dimensional complex vectors. The fading $|\alpha^R(t)|$ is Rayleigh or Rician distributed depending on the propagation model.

19.3.2 Signal Model at Mobile (Forward Link)

In this model, the base station transmits different signals from each antenna with a defined relationship between them. In the case of a two element array, some examples of transmitted signals $u_i(t)$, $i = 1, 2$ can be: (a) delay diversity: $u_2(t) = u_1(t - T)$ where T is the symbol period; (b) Doppler diversity: $u_2(t) = u_1(t)e^{j\omega t}$ where ω is differential carrier offset; (c) beamforming: $u_2(t) = w_2 u_1(t)$ where w_2 is complex scalar; and (d) space-time coding: $u_1(t) = \sum_k g(t - kT)s^1(k)$, $u_2(t) = \sum_k g(t - kT)s^2(k)$ where $s^1(k)$ and $s^2(k)$ are related to the symbol sequence $s(k)$ through coding.

The received signal at the mobile is then given by

$$x(t) = \sum_{i=1}^{m} \sum_{l=1}^{L} a_i(\theta_l)\, \alpha_l^F(t) u_i(t - \tau_l) + n(t) \tag{19.4}$$

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where the path delay τ_l and angle parameters θ_l are the same as those of the reverse link. $\alpha_l^F(t)$ is the complex fading on the forward link. In (fast) **TDD** systems $\alpha_l^F(t)$ will be identical to the reverse link complex fading $\alpha_l^R(t)$. In a **FDD** system $\alpha_l^F(t)$ and $\alpha_l^R(t)$ will usually have the same statistics but will in general be uncorrelated with each other. We assume $a_i(\theta_l)$ is the same for both links. This is only approximately true in FDD systems.

If simple beamforming alone is used in transmit, the signals radiated from the antennas are related by a complex scalar and result in a directional transmit beam which may selectively couple into the multipath environment and differentially scale the power in each path.

The signal received by the mobile in this case can be written as

$$x(t) = \sum_{l=1}^{L} \mathbf{w}^H \mathbf{a}(\theta_l)\, \alpha_l^F(t) u(t-\tau_l) + n(t) \tag{19.5}$$

where $\mathbf{w}$ is the beamforming vector.

19.3.3 Discrete Time Signal Model

The channel model described above uses physical path parameters such as path gain, delay, and angle of arrival. In practice these are not known and the discrete time received signal uses a more convenient discretized "symbol response" channel model.

We derive a discrete-time signal model at the base station antenna array. Let the continuous-time output from the receive antenna array $\mathbf{x}(t)$ be sampled at the symbol rate at instants $t = t_o + kT$. Then the vector array output may be written as

$$\mathbf{x}(k) = \mathbf{H}^R \mathbf{s}(k) + n(k) \tag{19.6}$$

where $\mathbf{H}^R$ is the reverse link symbol response channel (a $m \times N$ matrix) that captures the effects of the array response, symbol waveform and path fading. m is the number of antennas, N is the channel length in symbol periods and $\mathbf{n}(k)$ the sampled vector of additive noise. Note that $\mathbf{n}(k)$ may be colored in space and time, as discussed later. $\mathbf{H}^R$ is assumed to be time invariant. $\mathbf{s}(k)$ is a vector of N consecutive elements of the data sequence and is defined as

$$\mathbf{s}(k) = \begin{bmatrix} s(k) \\ \vdots \\ s(k-N+1) \end{bmatrix} \tag{19.7}$$

Note that we have assumed a sampling rate of one sample per symbol. Higher sampling rates may be used. Also, $\mathbf{H}^R$ is given by

$$\mathbf{H}^R = \sum_{l=1}^{L} \mathbf{a}(\theta_l)\, \alpha_l^R \mathbf{g}^T(\tau_l) \tag{19.8}$$

where $\mathbf{g}(\tau_l)$ is a vector defined by T spaced sampling of the pulse shaping function $g(\cdot)$ with an offset of τ_l.

Likewise the forward discrete signal model at the mobile is given by

$$x(k) = \sum_{i=1}^{m} \mathbf{h}_i^F \mathbf{s}(k) + n(k) \tag{19.9}$$

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where $\mathbf{h}_i^F$ is a $1 \times N$ composite channel from the symbol sequence via the ith antenna to the mobile receiver which includes the effect transmit ST processing at the base station.

In the case of two antenna delay diversity, $\mathbf{h}_i^F$ is given by

$$\mathbf{h}_1^F = \sum_{l=1}^{L} a_1(\theta_l)\, \alpha_l^F\, \mathbf{g}(\tau_l) \tag{19.10}$$

and

$$\mathbf{h}_2^F = \sum_{l=1}^{L} a_2(\theta_l)\, \alpha_l^F\, \mathbf{g}(\tau_l - T) \tag{19.11}$$

If spatial beamforming alone is used, the signal model becomes

$$x(k) = \sum_{l=1}^{L} \mathbf{w}^H \mathbf{H}^F \mathbf{s}(k) + n(k) \tag{19.12}$$

where $\mathbf{H}^F$ is the *intrinsic* forward (F) channel given by

$$\mathbf{H}^F = \begin{bmatrix} \mathbf{h}_1^F \\ \mathbf{h}_2^F \end{bmatrix} = \sum_{l=1}^{L} \mathbf{a}(\theta_l)\, \alpha_l^F\, \mathbf{g}^T(\tau_l) \tag{19.13}$$

19.3.4 Signal-Plus-Interference Model

The overall received signal-plus-interference-and-noise model at the base station antenna array can be written as

$$\mathbf{x}(k) = \mathbf{H}_s^R \mathbf{s}_s(k) + \sum_{q=1}^{Q-1} \mathbf{H}_q^R \mathbf{s}_q(k) + \mathbf{n}(k) \tag{19.14}$$

where $\mathbf{H}_s^R$ and $\mathbf{H}_q^R$ are channels for signal and **CCI**, respectively, while $\mathbf{s}_s$ and $\mathbf{s}_q$ are the corresponding data sequences. Note that Eq. (19.14) appears to suggest that the signal and interference are baud synchronous. However, this can be relaxed and the time offsets can be absorbed into the channel $\mathbf{H}_q^R$.

Similarly, the signal at the mobile can also be extended to include CCI. Note that in this case, the source of interference is from other base stations (in TDMA) and the channel is between the interfering base station and the desired mobile. It is often convenient to handle signals in blocks. Therefore, we may collect M consecutive snapshots of $\mathbf{x}(\cdot)$ corresponding to time instants $k, \ldots, k + M - 1$, (and dropping subscripts for a moment), we get

$$\mathbf{X}(k) = \mathbf{H}^R \mathbf{S}(k) + \mathbf{N}(k) \tag{19.15}$$

where $\mathbf{X}(k)$, $\mathbf{S}(k)$ and $\mathbf{N}(k)$ are defined appropriately. Similarly the received signal at the mobile in the forward link has a block representation using a row vector.

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19.4 ST Receive Processing (Base)

The base station receiver receives the signals from the array antenna which consist of the signals from the desired mobile and the cochannel signals along with associated intersymbol interference and fading. The task of the receiver is to maximize signal power and mitigate fading, CCI and **ISI**. There are two broad approaches for doing this—one is multiuser detection wherein we demodulate both the cochannel and desired signals jointly, the other is to cancel CCI. The structure of the receiver depends on the nature of the channel estimates available and the tolerable receiver complexity. There are a number of options and we discuss only a few salient cases. Before discussing the receiver processing, we discuss how receiver channel is estimated.

19.4.1 Receive Channel Estimation (Base)

In many mobile communications standards, such as GSM and IS-54, explicit training signals are inserted inside the TDMA data bursts.

Let $\mathbf{T}$ be the training sequence arranged in a matrix form ($\mathbf{T}$ is arranged to be a Toeplitz matrix). Then, during the training burst, the received data is given by

$$\mathbf{X} = \mathbf{H}^R\mathbf{T} + \mathbf{N} \tag{19.16}$$

Clearly $\mathbf{H}^R$ can be estimated using least squares as

$$\mathbf{H}^R = \mathbf{X}\mathbf{T}^\dagger \tag{19.17}$$

where $\mathbf{T}^\dagger = \mathbf{T}^H\left(\mathbf{T}\mathbf{T}^H\right)^{-1}$.

The use of training consumes spectrum resource. In GSM, for example, about 20% of the bits are dedicated to training. Moreover, in rapidly varying mobile channels, we may have to retrain frequently, resulting in even poorer spectral efficiency. There is, therefore, increased interest in blind methods that can estimate a channel without an explicit training signal.

19.4.2 Multiuser ST Receive Algorithms

In multiuser (MU) algorithms, we address the problem of jointly demodulating the multiple signals. Recall the received signal is given by

$$\mathbf{X} = \mathbf{H}^R\mathbf{S} + \mathbf{N} \tag{19.18}$$

where $\mathbf{H}^R$ and $\mathbf{S}$ are suitably defined to include multiple users and are of dimensions $m \times NQ$ and $NQ \times M$, respectively.

If the channels for all the arriving signals are known, then we jointly demodulate all the user data sequences using multiuser **maximum likelihood sequence estimation** (MLSE). Starting with the data model in Eq. (19.18), we can then search for multiple user data sequences that minimize the ML cost function

$$\min_{\mathbf{S}} \left\|\mathbf{X} - \mathbf{H}^R\mathbf{S}\right\|_F^2 \tag{19.19}$$

The multiuser MLSE will have a large number of states in the trellis. Efficient techniques for implementing this complex receiver are needed. Multiuser MLSE detection schemes outperform all other receivers.

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19.4.3 Single-User ST Receive Algorithms

In this scheme we only demodulate the desired user and cancel the CCI. Therefore, after CCI cancellation we can use MLSE receivers to handle diversity and ISI. In this method there is potential conflict between CCI mitigation and diversity maximization. We are forced to allocate the available degrees of freedom (antennas) to the competing requirements.

One approach is to cancel CCI by a space-time filter followed by an MLSE receiver to handle ISI. We do this by reformulating the MLSE criterion to arrive at a joint solution for the ST-MMSE filter and the effective channel for the scalar MLSE.

Another approach is to use a ST-MMSE receiver to handle both CCI and ISI. In a space-time filter (equalizer-beamformer), $\mathbf{W}$ has the following form

$$\mathbf{W}(k) = \begin{bmatrix} w_{11}(k) & \cdots & w_{1M}(k) \\ \vdots & \dots & \vdots \\ w_{m1}(k) & \cdots & w_{mM}(k) \end{bmatrix} \tag{19.20}$$

In order to obtain a convenient formulation for the space-time filter output, we introduce the quantities $W(k)$ and $X(k)$ as follows

$$\begin{array}{ll} X(k) = vec\,(\mathbf{X}(k)) & (mM \times 1) \\ W(k) = vec\,(\mathbf{W}(k)) & (mM \times 1) \end{array} \tag{19.21}$$

where the operator $vec(\cdot)$ is defined as:

$$vec\,([\mathbf{v}_1 \cdots \mathbf{v}_M]) = \begin{bmatrix} \mathbf{v}_1 \\ \vdots \\ \mathbf{v}_M \end{bmatrix}$$

The ST-MMSE filter chooses the filter weights to achieve the minimum mean square error. The ST-MMSE filter takes the familiar form

$$W = \mathbf{R}_{XX}^{-1}\overline{H^R} \tag{19.22}$$

where $\overline{H^R}$ is one column of $vec\ (\mathbf{H}^R)$. In ST-MMSE the CCI and spatial diversity conflict for the spatial degrees of freedom. Likewise, temporal diversity and ISI cancellation conflict for the temporal degrees of freedom.

19.5 ST Transmit Processing (Base)

The goal in ST transmit processing is to maximize the average signal power and diversity at the receiver as well as minimize cochannel generation to other mobiles. Note that the base station transmission cannot directly affect the CCI seen by its intended mobile. In transmit the space-time processing needs channel knowledge, but since it is carried out prior to transmission and, therefore, before the signal encounters the channel, this is different from the reverse link where the space-time processing is carried out after the channel has affected the signal. Note that the mobile receiver will, of course, need to know the channel for signal demodulation, but since it sees the signal after transmission through the channel, it can estimate the forward link channel using training signals transmitted from the individual transmitter antennas.

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19.5.1 Transmit Channel Estimation (Base)

The transmit channel estimation at the base of the vector forward channel can be done via feedback by use of reciprocity principles. In a TDD system, if the duplexing time is small compared to the coherence time of the channel, both channels are the same and the base-station can use its estimate of the reverse channel as the forward channel; i.e., $\mathbf{H}^F = \mathbf{H}^R$, where $\mathbf{H}^R$ is the reverse channel (we have added superscript R to emphasize the receive channel). In FDD systems, the forward and reverse channels can potentially be very different. This arises from differences in instantaneous complex path gains $\alpha^R \neq \alpha^F$. The other channel components $\mathbf{a}(\theta_l)$ and $\mathbf{g}(\tau_l)$ are very nearly equal.

A direct approach to estimating the forward channel is to feed back the signal from the mobile unit and then estimate the channel. We can do this by transmitting orthogonal training signals through each base station antenna. We can feed back from the mobile to the base the received signal for each transmitted signal and thus estimate the channel.

19.5.2 ST Transmit Processing

The primary goals at the transmitter are to maximize diversity in the link and to reduce CCI generation to other mobiles. The diversity maximization depends on the inherent diversity at the antenna array and cannot be created at the transmitter. The role of ST processing is limited to maximizing the exploitability of this diversity at the receiver. This usually leads to use of orthogonal or near orthogonal signalling at each antenna: $\int u_1(t)\ u_2(t)\ dt \approx\ 0$. Orthogonality ensures that the transmitted signals are separable at the mobile which can now combine these signals after appropriate weighting to attain maximum diversity.

In order to minimize CCI, our goal is to use the beamforming vector $\mathbf{w}$ to steer the radiated energy and therefore minimize the interference at the other mobiles while maximizing the signal level at one's own mobile. Note that the CCI at the reference mobile is not controlled by its own base station but is generated by other base stations. Reducing CCI at one's own mobile requires the cooperation of the other base stations.

Therefore we choose $\mathbf{w}$ such that

$$\max_{\mathbf{w}} \frac{E(\mathbf{w}^H \mathbf{H}^F \mathbf{s}(k)\mathbf{s}(k)^H \mathbf{H}^{FH} \mathbf{w})}{\sum_{q=1}^{Q-1} \mathbf{w}^H \mathbf{H}_q^F \mathbf{H}_q^{FH} \mathbf{w}} \tag{19.23}$$

where $Q-1$ is the number of susceptible outer cell mobiles. $\mathbf{H}_q^F$ is the channel from the base station to the qth outer cell mobile. In order to solve the above equation, we need to know the forward link channel $\mathbf{H}^F$ to the reference mobile and $\mathbf{H}_q^F$ to cochannel mobiles. In general, such complete channel knowledge may not be available and suboptimum receivers must be designed. Furthermore, we need to find a receiver that harmonizes maximization of diversity and reduction of CCI. Use of transmit ST processing affects $\mathbf{H}^F$ and thus can be incorporated.

19.5.3 Forward Link Processing at the Mobile

The mobile will receive the composite signal from all the base station transmit antennas and will need to demodulate the signal to estimate the symbol sequence. In doing so it usually needs to estimate the individual channels from each base station antenna to itself. This is usually done via the use of training signals on each transmit antenna. Note that as the number of transmit antennas increases,

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there is a greater burden of training requirements. The use of transmit ST processing reduces the CCI power observed by the mobile as well enhances the diversity available.

19.6 Summary

Use of space-time processing can significantly improve average signal power, mitigate fading, and reduce cochannel and intersymbol interference in wireless networks. This can in turn result in significantly improved capacity, coverage, and quality of wireless networks.

In this chapter we have discussed applications of ST processing to TDMA systems. The applications to CDMA systems follow similar principles, but differences arise due to the nature of the signal and interference models.

Defining Terms

ISI: Intersymbol intereference is caused by multipath propagation where one symbol interferes with other symbols.

CCI: Cochannel interference arises from neighboring cells where the frequency channel is reused.

Maximum Likelihood Sequence Estimation: A technique for channel equalization based on determining the best symbol sequence that matches the received signal.

References

[1] Lindskog, E. and Paulraj, A., A taxonomy of space-time signal processing, *IEE Trans. Radar and Sonar*, 25–31, Feb. 1998.

[2] Ng, B.C. and Paulraj, A., Space-time processing for PCS, *IEEE PCS Magazine*, 5(1), 36–48, Feb. 1998.

[3] Paulraj, A. and Papadias, C.B., Space-time processing for wireless communications, *IEEE Signal Processing Magazine*, 14(5), 49–83, Nov. 1997.

[4] Paulraj, A., Papadias, C., Reddy, V.U., and Van der Veen, A., *A Review of Space-Time Signal Processing for Wireless Communications*, in *Signal Processing for Wireless Communications*, V. Poor, Ed., Prentice Hall, 179–210, Dec. 1997.

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