Receiver Signal Processing

- transmitting a sequence $\{b[0], b[1], \ldots, b[M-1]\}$
- $(b[i] = \pm 1)$ or a finite alphabet of complex numbers
- linear modulation using a signaling waveform

$$x(t) = \sum_{i=0}^{M-1} b[i] w_i(t)$$

$w_i(\cdot)$ modulation waveform associated with the i^{th} symbol , for example

$$w_i(t) = Ap(t - iT)e^{j(w_c + \phi)}$$

$A > 0 \; \phi \in (- = pi, \pi)$ and $p(\cdot)$ baseband pulse shape

$$p(t) = p_T(t) \triangleq \begin{cases} \frac{1}{\sqrt{T}} & 0 \leq t < T \\ 0 & \text{otherwise} \end{cases}$$

or spreading waveform for DSSP system

$$p(t) = \sum_{j=0}^{N-1} c_j \psi(t - jT_c)$$

N is the spreading gain and $c_0, c_1, \ldots, c_{N-1}$ is a pseudorandom spreading code ($c_j \in \{+1, -1\}$), $\psi(\cdot)$ chip waveform and $T_c \triangleq T/N$ chip interval

- chip waveform may be a unit-energy rectangular pulse of duration T_c: $\psi(t) = p_{T_c}(t)$
- repeat the same spreading code in every symbol interval
- system with long spreading codes, the periodicity is much longer than a single symbol interval and varies spreading code from symbol to symbol

$$p_i(t) = \sum_{j=0}^{N-1} c_j^i \psi(t - jT_c)$$

- spread spectrum modulation can take the form of frequency hopping
- carrier frequency is changed over time according to a pseudorandom pattern
- carrier frequency changes at a rate much slower than the symbol rate - slow frequency hopping
- fast hopping - the carrier changes within a symbol interval
- multicarrier system by choosing $\{w_i(\cdot)\}$ with different frequencies

$$w_i(t) = Ap(t)e^{j(w_i t + \phi_i)}$$

- individual carrier can also be direct-spread - multicarrier CDMA
- OFDM: baseband pulse shape is a unit pulse p_T, intercarrier spacing is $1/T$ cycles per second, and the phases are orthogonal at this spacing

Multiple-Access Techniques

- radio resources shared among multiple users
- FDMA - frequency band available is divided into subbands and allocated to individual user, users do not transmit signals within other subbands
- TDMA - time is divided into equal-length intervals, each user is allowed to transmit throughout the entire allocated frequency band during a given slot
- FDMA allows each user to use part of the spectrum all of the time, TDMA allows each user to use all of the spectrum part of the time
- FDMA and TDMA systems are intended to assign orthogonal channels to all active users by giving each, for exclusive use, a slice of the available frequency band or transmission time
- channels are said to be orthogonal because interference between user does not

- Code-division multiple access (CDMA) assigns channels in a way that allows all users to use all of the available time and frequency resources simultaneously, through the assignment of a pattern or code to each user that specifies the way in which these resources will be used by that user
- spread spectrum modulation - pattern is the pseudorandom code that determines the spreading sequence in the case of direct sequence or the hopping pattern in the case of frequency hopping
- channel is defined by a particular pseudorandom code, and each user is assigned a channel by being assigned a pseudorandom code
- for a system of K users

$$x_k(t) = \sum_{i=0}^{M-1} b_k[i] w_{i,k}(t) \qquad k = 1, 2, \ldots, K$$

$w_{i,k}(\cdot)$ represents ith modulation waveform of user k

- each user in a multiple-access system can be modeled in the same way as in a single-user system
- if the waveforms $\{w_{i,k}(\cdot)\}$ are of the form of sinusoidal with different carrier frequencies $\{w_k\}$ - FDMA
- if they are with time-slotted amplitude pulses $\{p_k(\cdot)\}$ - TDMA
- if they are spread-spectrum signals of this form but with different pseudo-random spreading codes or hopping patterns - CDMA
- Another aspect of wireless network
  - ambient noise, propagation losses, multipath, interference
  - properties arising from the use of multiple antennas
- ambient noise - thermal motion of electrons on the antenna and the receiver electronics and from background radiation sources
- modeled as a very wide bandwidth and no particular deterministic structure (e.g. AWGN)

- Propagation losses: diffusive losses and shadow fading
- diffusive losses due to open nature of wireless channel, energy decreases with the square of the distance between antenna and source
- shadow fading results from the presence of objects, modeled by an attenuation in signal amplitude that follows a log-normal distribution
- multipath - multiple copies of a transmitted signal are received at the receiver
- multipath is manifested in several ways
  - degree of path difference relative to the wavelength of propagation
  - degree of path difference relative to the signaling rate
  - relative motion between the transmitter and receiver
  - results into Rayleigh fading or frequency-selective fading or time-selective fading

- multipath from scatterers that are spaced very close together will cause a random change in the amplitude of the received signal
- resulting received amplitude is often modeled as being a complex Gaussian random variable
- random amplitude whose envelope has a Rayleigh distribution - termed as Rayleigh fading
- When the scatterers are spaced so that the difference in their corresponding path lengths are significant relative to a wavelength of the carrier and add constructively or destructively
- this is a fading depends on the wavelength of radiation - frequency-selective fading
- when there is relative motion between the transmitter and receiver, this fading depends on time - time-selective fading
- when the difference in path lengths in such that time delay of arrival along different paths is significant relative to a symbol interval, results in dispersion of the transmitted signal and causes ISI

- wideband signaling methods such as spread spectrum - a countermeasure to frequency-selective fading
- dividing a high-rate signal into many parallel lower-rate signal - OFDM mitigates channel dispersion on high-rate signals
- multiple access interference - arising from other signals in the same network as the signal of interest (if signals received are not orthogonal to one another)
- co-channel interference - due to signals different networks but operating in same frequency band
- the above phenomena can be incorporated into a general analytical model for a wireless multiple-access channel

$$r(t) = \sum_{k=0}^{K} \sum_{i=0}^{M-1} b_k[i] \int_{-\infty}^{\infty} g_k(t,u) w_{i,k}(u) du + i(t) + n(t)$$

- $g_k(t,u)$ impulse response of a linear filter representing the channel between the kth transmitter and the receiver
- $i(\cdot)$ co-channel interference and $n(\cdot)$ ambient noise, in general, all are random processes
- co-channel interference and channel impulse responses are structured and can be parameterized
- pure multipath channel

$$g_k(t,u) = \sum_{l=1}^{L_k} \alpha_{l,k}\delta(t - u - \tau_{l,k})$$

L_k number of paths between user k and the receiver, α and τ gain and delay (lth path of kth user)

- model includes frequency-selective fading; relative delays will cause constructive and destructive interference at the receiver, depending on the wavelength of propagation and Rayleigh fading also using path gains

- composite modulation waveform associated with $b_k[i]$:

$$f_{i,k}(t) = \int_{-\infty}^{\infty} g_k(t,u) w_{i,k}(u) du$$

- if these waveforms are not orthogonal for different values of i, ISI will result
- higher-rate transmission are more likely to encounter ISI than are lower-rate transmission
- if the composite waveform for different values of k are not orthogonal, MAI will result
- this can happen in CDMA when pseudorandom code sequences used by different users are not orthogonal, this happens in FDMA and TMDA due to the effects of multipath or asynchronous transmission
- model can be generalized for multiple antennas at the receiver

$$\mathbf{r}(t) = \sum_{k=1}^{K} b_k[i] \int_{-\infty}^{\infty} \mathbf{g}_k(t,u) w_{i,k}(u) du + \mathbf{i}(t) + \mathbf{n}(t)$$

- pth component of $\mathbf{g}_k(t,u)$ is the impulse response of the channel between user k and the pth element of the receiving array

$$\mathbf{g}_k(t,u) = \sum_{l=1}^{L_k} \alpha_{l,k}\delta(t-u-\tau_{l,k})$$

- multiple antennas at both the transmitter and receiver called multiple-input/multiple-output (MIMO) systems
- channel transfer functions are matrices with the number of rows equal to the number of receiving antennas and the number of columns equal to the number of transmitting antennas at each source