Code Division Multiple Access (CDMA)

Spread Spectrum Modulation

- *Informal definition of spread spectrum signal* (Viterbi [1]): A spread spectrum information bearing signal is one whose bandwidth is much larger than what is needed to transmit data reliably.

- *Precise definition* (Massey [2]): A spread spectrum signal is one for which the (essential) Fourier bandwidth is much larger than the Shannon bandwidth, where Shannon bandwidth refers to half the number of dimensions in signal space occupied by the signal per second.

- *Spreading versus Coding* (VVV [3]): Spreading is a linear mapping in signal space that is energy and distance preserving. Spreading provides no coding gain against AWGN; it is hence akin to repitition coding. Coding is necessarily a nonlinear mapping in signal space. Every bandwidth expansion scheme can be written as coding followed by spreading.

- Why spread spectrum?

    ◇ Military applications
    - immunity to narrowband jammers
    - low probability of intercept (LPI)

    ◇ Commercial applications
    - multiaccess capability
    - randomization of interference
    - diversity gain against fading

Direct sequence spread spectrum (DS/SS)

Consider the complex baseband signal

$$s(t) = \sum_n s_{m_n}(t - nT_s) \tag{1}$$

where $m_k \in \{0, 1, \ldots, M-1\}$. The signal $s(t)$ occupies a bandwidth W that depends on the modulation scheme used. To spread spectrum, we simply multiply $s(t)$ by a high frequency chip waveform $c(t)$ that has bandwidth NW, where N is said to be the *processing gain*.

DS/SS Linear Modulation

- Without spreading

$$s(t) = \sqrt{\mathcal{E}_\mathrm{s}} \sum_n z^{(n)} \, g_{T_s}(t - nT_s) \tag{2}$$

where $z^{(n)} \in \{a_0 \, e^{j\theta_0}, \ldots, a_{M-1} \, e^{j\theta_{M-1}}\}$ is the complex symbol that is transmitted during the n-th symbol interval (with $\sum a_m^2 = 1$), and $g_{T_s}(\cdot)$ is a unit energy pulse shaping function that satisfies the zero ISI

(Nyquist) condition

$$\langle g_{T_s}(t - iT_s)\; g_{T_s}(t - jT_s)\rangle \approx \delta[i - j] \tag{3}$$

- Examples of $g_{T_s}(\cdot)$ (two extreme cases)

  ◦ *Sinc pulse:*

  $$g_{T_s}(t) = \frac{1}{\sqrt{T_s}} \,\mathrm{sinc}\left(\frac{t}{T_s} - 0.5\right) . \tag{4}$$

  This is the pulse with smallest bandwidth satisfying the Nyquist condition of (3). The Fourier transform of this pulse is given by

  $$G_{T_s}(f) = \sqrt{T_s}\,\mathrm{rect}(fT_s)\, e^{-j\pi T_s f} \tag{5}$$

  where

  $$\mathrm{rect}(x) = \begin{cases} 1 & \text{if } |x| \le \frac{1}{2} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

  ◦ *Rectangular pulse:*

  $$g_{T_s}(t) = \frac{1}{\sqrt{T_s}} \,\mathrm{rect}\left(\frac{t}{T_s} - 0.5\right) . \tag{7}$$

  and $G_{T_s}(f) = \sqrt{T_s}\,\mathrm{sinc}(fT_s)\, e^{-j\pi T_s f}$.
  This pulse is convenient for analysis since the waveforms do not overlap from symbol to symbol, and the pulse autocorrelation function has a convenient triangular form. However, it has poor bandwidth properties and has been shown to result in poor performance in CDMA systems [4]

  ◦ In practice, since sinc pulses cannot be used due to their infinite time extent, pulses that are approximately bandlimited and are time limited to a few symbol periods are used.

DS/SS Linear Modulation

- *Spreading Spectrum*

The transmitted signal for DS/SS linear modulation is given by:

$$s(t) = \sqrt{\mathcal{E}_\mathrm{s}} \sum_n z^{(n)}\, c^{(n)}(t - nT_s) \tag{8}$$

where $c^{(n)}(\cdot)$ is a unit energy waveform that replaces $g_{T_s}(\cdot)$ in (2), and is given by:

$$c^{(n)}(t) = \sum_{j=0}^{N-1} c_j^{(n)} g_{T_c}(t - jT_c) . \tag{9}$$

The sequence $\{c_j^{(n)}\}_{j=0}^{N-1}$ is the *chip sequence* for the n-th symbol interval, and can be written compactly using the vector notation

$$\mathbf{c}^{(n)} = [c_0^{(n)}\; c_1^{(n)}\; \cdots\; c_{N-1}^{(n)}]^\top \tag{10}$$

with $\mathbf{c}^{(n)}$ normalized such that $\mathbf{c}^{(n)\dagger}\,\mathbf{c}^{(n)} = 1$. There are two special cases that we can consider:

∘ *Short sequences:* $\mathbf{c}^{(n)} = \mathbf{c}$ for all n.

∘ *Long sequences:* $\mathbf{c}^{(n)}$ is different for each n, and the sequence may repeat after a long period that spans several symbols. Such sequences are generated using pseudorandom number generators and are also called *random* sequences.

The chip sequences are typically binary valued, i.e., $c_j^{(n)} \in \{+\frac{1}{\sqrt{N}}, -\frac{1}{\sqrt{N}}\}$, but in general they can be complex valued and satisfy $\mathbf{c}^{(n)\dagger}\, \mathbf{c}^{(n)} = 1$

The chip pulse $g_{T_c}(\cdot)$ is a unit energy function that satisfies the zero ICI (Nyquist) condition

$$\langle g_{T_c}(t - iT_c), g_{T_c}(t - jT_c) \rangle \approx \delta[i - j] \tag{11}$$

and just as with $g_{T_s}(\cdot)$, there is a range of choices for $g_{T_c}(\cdot)$, with the sinc pulse and the rectangular pulse being extreme cases. Since $g_{T_c}(\cdot)$ has unit energy and $\mathbf{c}^{(n)\dagger}\, \mathbf{c}^{(n)} = 1$, it follows that $c^{(n)}(\cdot)$ is a unit energy waveform. It is also clear from (11) that $c^{(n)}(\cdot)$ satisfies the zero ISI condition given in (3).

Single User Communications with DS/SS Linear Modulation

- Consider single user communications over an AWGN channel with DS/SS linear modulation. The received signal is given by:

$$y(t) = e^{j\phi}\, \sqrt{\mathcal{E}_{\rm s}}\, \sum_n z^{(n)}\, c^{(n)}(t - nT_s) + w(t) \tag{12}$$

where ϕ is the phase offset introduced by the channel.

- Assuming zero ISI, symbol-by-symbol detection is optimum, and the sufficient statistic for detecting the symbol corresponding to interval $[0, T_s]$ (say) is given by

$$y = \langle y(t), e^{j\phi} c(t) \rangle = \sqrt{\mathcal{E}_{\rm s}}\, z + w \tag{13}$$

where we have dropped the superscript "(0)" for convenience, and where $w \sim \mathcal{CN}(0, N_0)$. Note that we need to know the sequence $\mathbf{c} = [c_0\; c_1\; \cdots\; c_{N-1}]^\top$ in addition to ϕ to compute the above correlation.

- For soft decision decoding, we send y to the decoder. The performance metric for soft decisions is the signal-to-noise ratio in the statistic y, which is given by:

$$\text{SNR} = \frac{\mathsf{E}[|\mathsf{E}[y|z]|^2]}{\text{var}(y|z)} = \frac{\mathcal{E}_{\rm s}}{N_0}\,. \tag{14}$$

- For hard decision decoding, the MPE decision rule is given by:

$$\hat{z}_{\text{MPE}} = \arg\max_{z \in \mathcal{S}} p(y|z) = \arg\min_{z \in \mathcal{S}} |y - \sqrt{\mathcal{E}_{\rm s}}\, z|^2 \tag{15}$$

where $\mathcal{S} = \{a_0 e^{j\theta_0}, \ldots, a_{M-1} e^{j\theta_{M-1}}\}$.

For binary signaling

$$\hat{z}_{\text{MPE}} = \text{sgn}(y_I)\,, \tag{16}$$

and the bit-error rate (BER) is given by

$$\mathrm{P_b} = Q\left(\sqrt{\frac{2\mathcal{E}_\mathrm{b}}{N_0}}\right) . \tag{17}$$

Note that the performance is the same as without spreading – spreading results in zero coding gain in AWGN, i.e., it is akin to repitition coding with soft decision decoding.

Mulitiuser Communications

- Users are indexed by $k = 1, 2, \ldots, K$, with K being the total number of users.

- The signal of user k (for linear modulation) is given by

$$s_k(t) = \sqrt{\mathcal{E}_{\mathrm{s},k}} \sum_n z_k^{(n)} \; c_k^{(n)}(t - nT_s) . \tag{18}$$

  where $\mathcal{E}_{\mathrm{s},k}$ is the average symbol energy of user k, $z_k^{(n)}$ is the n-th symbol of user k, T_s is the symbol period, and $c_k^{(n)}(\cdot)$ is the signaling waveform for the n-th symbol of user k. Note that $c_k^{(n)}(\cdot)$ is not necessarily a spreading waveform.

- *Signal separation*

  ◦ For FDMA, $\{s_k(t)\}_{k=1}^K$ occupy orthogonal frequency slots (possibly separated by guard bands).
  ◦ For TDMA, $\{s_k(t)\}_{k=1}^K$ occupy orthogonal time slots (possibly separated by guard times).
  ◦ For CDMA, $\{s_k(t)\}_{k=1}^K$ have their energy spread out roughly uniformly over time and frequency. The signals are not necessarily orthogonal, and they may not even be linearly independent.

DS/SS CDMA

- For DS/CDMA, the signaling waveform for n-th symbol of user k is the spreading waveform given by

$$c_k^{(n)}(t) = \sum_{j=0}^{N-1} c_{k,j}^{(n)} \; g_{T_c}(t - jTc) \tag{19}$$

  with $T_s = NT_c$. The corresponding chip sequence can be written compactly as

$$\mathbf{c}_k^{(n)} = [c_{k,0}^{(n)} \; c_{k,1}^{(n)} \; \cdots \; c_{k,N-1}^{(n)}]^\top \tag{20}$$

  and $\mathbf{c}_k^{(n)\dagger}\mathbf{c}_k^{(n)} = 1$.

- *Synchronous versus asynchronous users*
  - In general, the received signal in AWGN is given by

$$y(t) = \sum_{k=1}^{K} A_k \sum_n z_k^{(n)} c_k^{(n)}(t - nT_s - \tau_k) e^{j\phi_k} + w(t) \tag{21}$$

    where $A_k = \sqrt{\mathcal{E}_{s,k}}$.
  - Without loss of generality, we may assume that $\tau_k \in [0, T_s]$.
  - For synchronous users, $\tau_k = 0$ and $\phi_k = 0$ for all k.
  - For asynchronous users, one-shot (symbol-by-symbol) detection is not optimum. We hence need to consider a frame of length μT_s, $\mu > 1$, for detection. The asynchronous user problem over μT_s can be converted to an equivalent "synchronous-user" problem with $\mu + 2(K-1)(\mu+1)$ users.
  - For long (random) sequence CDMA, the performance for asynchronous users with multishot detection can be approximated by the performance for synchronous users with one-shot detection.

Synchronous user model

$$y(t) = \sum_{k=1}^{K} A_k \sum_n z_k^{(n)} c_k^{(n)}(t - nT_s) + w(t) . \tag{22}$$

- Sufficient statistics for detection are given by:

$$y_k^{(n)} = \langle y(t), c_k^{(n)}(t - nT_s) \rangle \tag{23}$$

- Using the zero-ICI condition satisfied by $g_{T_c}(\cdot)$ it is easy to show that

$$y_k^{(n)} = \sum_{\ell=1}^{K} A_\ell z_\ell^{(n)} \langle c_\ell^{(n)}(t - nT_s), c_k^{(n)}(t - nT_s) \rangle + w_k^{(n)} . \tag{24}$$

- Note that $y_k^{(n)}$ is a function of only $\{z_\ell^{(n)}\}_{\ell=1}^K$, but not a function of $\{z_\ell^{(n')}\}_{\ell=1}^K$ for any $n' \neq n$. Also, $\{w_\ell^{(n')}\}_{\ell=1}^K$ and $\{w_\ell^{(n)}\}_{\ell=1}^K$ are independent for $n' \neq n$. Thus, one-shot multiuser processing is optimum, i.e., the symbol decisions for the users can be made one symbol interval at time without loss of optimality.

- Without loss of generality, consider symbol interval $[0, T_s]$, i.e., $n = 0$, and drop the superscript "0" for convenience. Then

$$y_k = \sum_{\ell=1}^{K} A_\ell z_\ell \langle c_\ell(t), c_k(t) \rangle + w_k . \tag{25}$$

  with $w_k = \langle w(t), c_k(t) \rangle$.

$$y_k = A_k z_k + \sum_{\ell \neq k} A_\ell z_\ell \rho_{\ell,k} + w_k \tag{26}$$

where

$$\rho_{\ell,k} = \langle c_\ell(t), c_k(t)\rangle = \sum_{i=0}^{N-1} c_{\ell,i}\, c_{k,i}^\star = \mathbf{c}_k^\dagger\, \mathbf{c}_\ell \tag{27}$$

and $w_k \sim \mathcal{CN}(0, N_0)$. The noise components are not independent; in particular, $\mathsf{E}[w_k w_\ell^\star] = N_0 \rho_{\ell,k}$.

- If $K \leq N$, the chip sequences can be made orthogonal, i.e., $\rho_{\ell,k} = \delta[k-\ell]$, and hence

$$y_k = A_k z_k + w_k \tag{28}$$

which is the same as the expression for the MF output for a single user in AWGN. Thus single-user detection is optimum in this case, and the performance obtained is the same as that without the multiple-access interference (MAI) from other users. An example of an orthogonal sequence set is the set of Walsh-Hadamard sequences, which are used in the forward link of IS-95 based CDMA systems.

Single user detection

- In general when the sequences are not necessarily orthogonal

$$y_k = A_k z_k + I_k + w_k \tag{29}$$

where

$$I_k = \sum_{\ell \neq k} A_\ell\, z_\ell\, \rho_{\ell,k}\ . \tag{30}$$

If we approximate I_k by a zero mean, PCG random variable, then the conditional pdf of Y_k given z_k is PCG with mean $A_k z_k$.

- A single user (SU) detector treats I_k as a CCG random variable and makes a decision on z_k based purely on y_k, i.e., ignoring $\{y_\ell\}_{\ell \neq k}$.

- For SU hard decision making, the ML decision for z_k based on y_k is given by:

$$\hat{z}_{k,\text{SU-MF}} \approx \arg\min_{z_k \in \mathcal{S}} |y_k - A_k z_k|^2\ . \tag{31}$$

For binary signaling, $z_k \in \{+1, -1\}$, and we obtain:

$$\hat{z}_{k,\text{SU-MF}} \approx \text{sgn}\,[Y_{kI}]\ . \tag{32}$$

- For SU soft decision making, we send y_k to the decoder and the decoder may use knowledge of A_k in decoding.

- For hard decisions, the performance metric of interest is of course the probability of error $\mathsf{P}_{\text{e},k} = \mathsf{P}\{\hat{z}_k \neq z_k\}$.

- For soft decisions, a useful performance metric is the signal-to-intereference ratio (SIR) in the soft decision statistic, defined by:

$$\text{SIR}_k = \frac{\mathsf{E}\left[|\mathsf{E}[y_k|z_k]|^2\right]}{\text{Var}(y_k|z_k)}\ . \tag{33}$$

Single User Detection – Performance Analysis

- *Binary signaling assumption*: For the analysis in this section we make the simplifying assumption that symbols and spreading sequences are binary, i.e.,

$$z_k \in \{+1, -1\} \ , \ \text{and} \ \ c_{k,i} \in \{+\frac{1}{\sqrt{N}}, -\frac{1}{\sqrt{N}}\} \ . \tag{34}$$

- *Case 1: Orthogonal users* $(K \leq N)$

  ◦ Since $\rho_{\ell,k} = 0$ for $\ell \neq k$,

$$y_k = A_k \, z_k + w_k \ . \tag{35}$$

  ◦ The SIR for user k is given by:

$$\text{SIR}_k = \frac{\mathsf{E}\left[|\mathsf{E}[y_k|z_k]|^2\right]}{\text{Var}(y_k|z_k)} = \frac{\mathsf{E}\left[(A_k z_k)^2\right]}{N_0} = \frac{\mathcal{E}_{\text{b},k}}{N_0} \ . \tag{36}$$

  ◦ The BER for user k for the MPE SU decision rule of (32) is given by:

$$\text{P}_{\text{b},k} = \mathsf{P}\left(\{\hat{z}_k = 1\}|\{z_k = -1\}\right) = \mathsf{P}\left(\{y_{kI} > 0\}|\{z_k = -1\}\right) = Q\left(\sqrt{\frac{2\mathcal{E}_{\text{b},k}}{N_0}}\right) = Q(\sqrt{2\text{SIR}_k}\,) \ . \tag{37}$$

  As expected since the interference is completely cancelled out.

- *Case 2: Synchronous users with non-orthogonal short spreading sequences*

  ◦ Assuming that the bits of the users are i.i.d. Bernouilli$(\pm 1, 0.5)$

$$\mathsf{E}[y_k|z_k] = A_k z_k \quad \Longrightarrow \quad \mathsf{E}\left[|\mathsf{E}[y_k|z_k]|^2\right] = A_k^2 \tag{38}$$

  and

$$\text{Var}(y_k|z_k) = \text{Var}\left(\sum_{\ell \neq k} A_\ell z_\ell \rho_{\ell,k} + w_k\right) = \sum_{\ell \neq k} A_\ell^2 \rho_{\ell,k}^2 + N_0 \ . \tag{39}$$

  Thus

$$\text{SIR}_k = \frac{A_k^2}{\sum_{\ell \neq k} A_\ell^2 \rho_{\ell,k}^2 + N_0} = \frac{\frac{\mathcal{E}_{\text{b},k}}{N_0}}{1 + \sum_{\ell \neq k} \frac{\mathcal{E}_{\text{b},\ell}}{N_0} \rho_{\ell,k}^2} \tag{40}$$

  ◦ The BER for user k for the MPE decision rule of (32) is to be computed by averaging over the distribution of the bits of the other users. We do this by first computing $\text{P}_{\text{b},k}$ conditioned on the bits of the others users, and then average over the distribution of these bits.

$$
\begin{aligned}
\mathrm{P}_{\mathrm{b},k} &= \mathsf{P}\left(\{\hat{z}_k = -1\}|\{z_k = +1\}\right) = \mathsf{E}\left[\mathsf{P}\left(\{\hat{z}_k = -1\} \,\middle|\, \{z_k = +1\}, \{z_\ell\}_{\ell \neq k}\right)\right] \\
&= \mathsf{E}\left[\mathsf{P}\left(\{y_{k,I} < 0\} \,\middle|\, \{z_k = +1\}, \{z_\ell\}_{\ell \neq k}\right)\right] = \mathsf{E}\left[Q\left(\frac{A_k + \sum_{\ell \neq k} A_\ell z_\ell \rho_{\ell,k}}{\sqrt{N_0/2}}\right)\right] \\
&= \mathsf{E}\left[Q\left(\sqrt{\frac{2\mathcal{E}_{\mathrm{b},k}}{N_0}} + \sum_{\ell \neq k} \sqrt{\frac{2\mathcal{E}_{\mathrm{b},\ell}}{N_0}}\, z_\ell\, \rho_{\ell,k}\right)\right] \\
&= \sum_{\tilde{\mathbf{z}} \in \{+1,-1\}^{K-1}} Q\left(\sqrt{\frac{2\mathcal{E}_{\mathrm{b},k}}{N_0}} + \sum_{\ell \neq k} \sqrt{\frac{2\mathcal{E}_{\mathrm{b},\ell}}{N_0}}\, z_\ell\, \rho_{\ell,k}\right)
\end{aligned}
\tag{41}
$$

where $\tilde{\mathbf{z}} = [z_0 \ \cdots \ z_{k-1} \ z_{k+1} \ \cdots \ z_K]$. Note that from the above equation we can immediately conclude that

$$
\mathrm{P}_{\mathrm{b},k} \geq Q\left(\sqrt{\frac{2\mathcal{E}_{\mathrm{b},k}}{N_0}}\right) = \mathrm{P}_{\mathrm{b},k}(\text{orthogonal signaling}) \quad \text{[Why?]} \tag{42}
$$

Also note that the number of terms in the sum grows exponentially with K, and hence it is difficult to compute $\mathrm{P}_{\mathrm{b},k}$ exactly when the K is large.

- Gaussian approximation for $\mathrm{P}_{\mathrm{b},k}$: For large K

$$
\sum_{\ell \neq k} A_\ell z_\ell \rho_{\ell,k} + w_{k,I} \ \approx \ \sim \mathcal{N}(0, \sigma_1^2) \tag{43}
$$

where

$$
\sigma_1^2 = \mathrm{Var}(y_{k,I}|z_k) = \sum_{\ell \neq k} A_\ell^2 \rho_{\ell,k}^2 + \frac{N_0}{2}\,. \tag{44}
$$

Thus we can approximate $\mathrm{P}_{\mathrm{b},k}$ as

$$
\mathrm{P}_{\mathrm{b},k} = \mathsf{P}\left(\{\hat{z}_k = -1\}|\{z_k = +1\}\right) \approx Q\left(\frac{A_k}{\sigma_1}\right)\,. \tag{45}
$$

- *Case 3: Synchronous users with long (random) spreading sequences*

  - Assuming that the bits of the users are i.i.d. Bernouilli$(\pm 1, 0.5)$, and the chips of the users are i.i.d. Bernouilli$(\pm \frac{1}{\sqrt{N}}, 0.5)$, we can show that (see HW#6)

$$
\mathrm{SIR}_k = \frac{A_k^2}{\frac{1}{N}\sum_{\ell \neq k} A_\ell^2 + N_0} = \frac{\frac{\mathcal{E}_{\mathrm{b},k}}{N_0}}{1 + \frac{1}{N}\sum_{\ell \neq k} \frac{\mathcal{E}_{\mathrm{b},\ell}}{N_0}} \tag{46}
$$

For equal power users, $\mathcal{E}_{\mathrm{b},\ell} = \mathcal{E}_{\mathrm{b}}$ for all ℓ, and we obtain

$$
\mathrm{SIR}_k = \frac{\frac{\mathcal{E}_{\mathrm{b}}}{N_0}}{1 + \frac{K-1}{N}\frac{\mathcal{E}_{\mathrm{b}}}{N_0}} \approx \frac{N}{K-1} \ \text{ for large } K \text{ or large } \mathcal{E}_{\mathrm{b}}/N_0 \tag{47}
$$

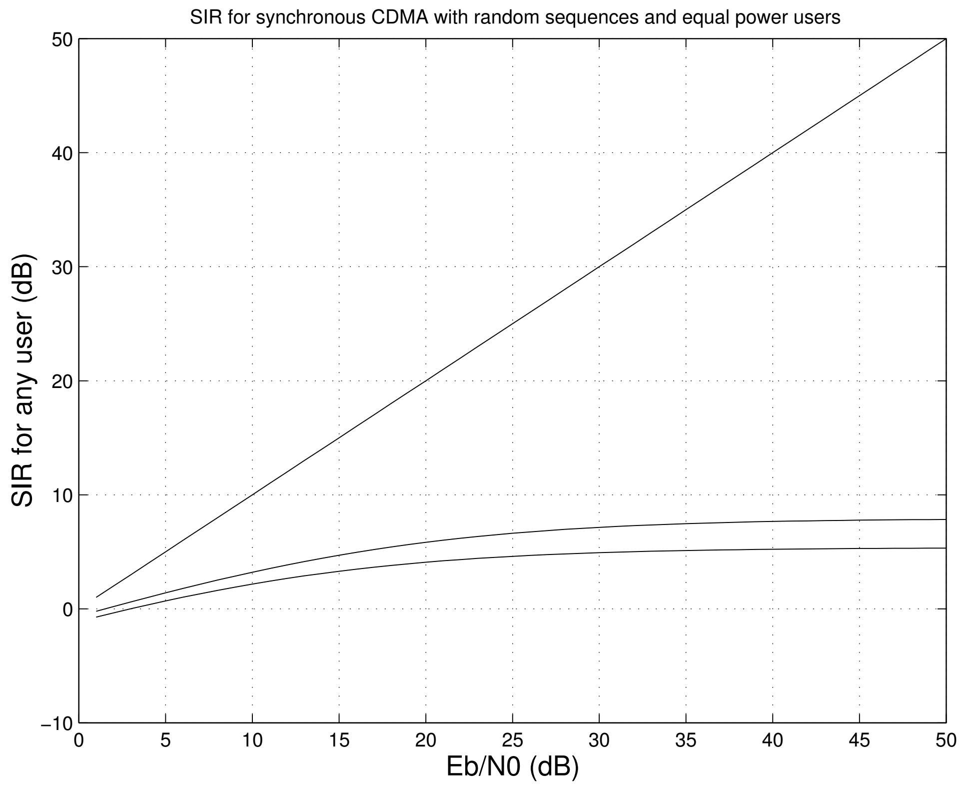

Figure 1: SIR for synchronous CDMA with $N = 31$

- The BER for user k for the MPE decision rule of (32) is to be computed by averaging over the distribution of the bits as well as the chips. The procedure is similar to that used for Case 2.

$$\mathrm{P}_{\mathrm{b},k} = \mathsf{E}\left[Q\left(\sqrt{\frac{2\mathcal{E}_{\mathrm{b},k}}{N_0}} + \sum_{\ell \neq k} \sqrt{\frac{2\mathcal{E}_{\mathrm{b},\ell}}{N_0}}\, z_\ell\, \rho_{\ell,k} \right) \right] \tag{48}$$

  where the expectation is taken over the distribution of the bits and the chips. It is clear that computing this expectation is even more cumbersome than in Case 2.

- Gaussian approximation for $\mathrm{P}_{\mathrm{b},k}$: For large K, and equal powers, using steps similar to those used in Case 2, we can approximate $\mathrm{P}_{\mathrm{b},k}$ as

$$\mathrm{P}_{\mathrm{b},k} \approx Q\left(\sqrt{\frac{K-1}{N}} \right) \approx Q\left(\sqrt{\mathrm{SIR}_k} \right) \ . \tag{49}$$

- See Figures 1 and 2 for typical numerical results.

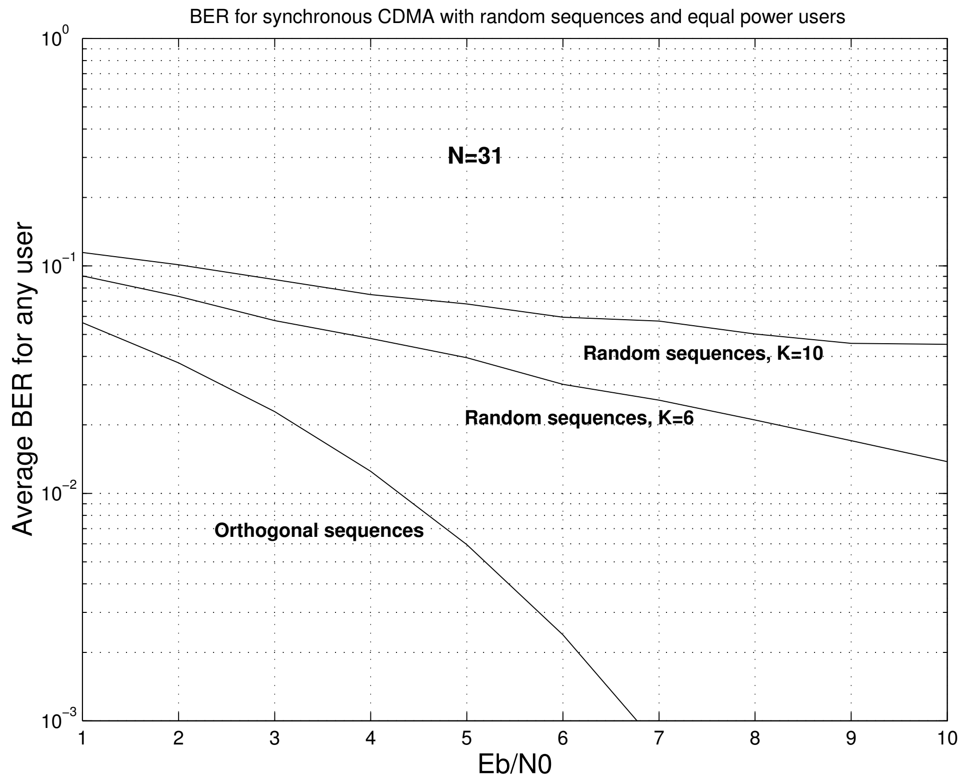

Figure 2: BER for synchronous CDMA with $N = 31$

References

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