CDMA receiver algorithms

S-72.4210 Postgraduate course in Radio Communications

14.2.2006

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Outline

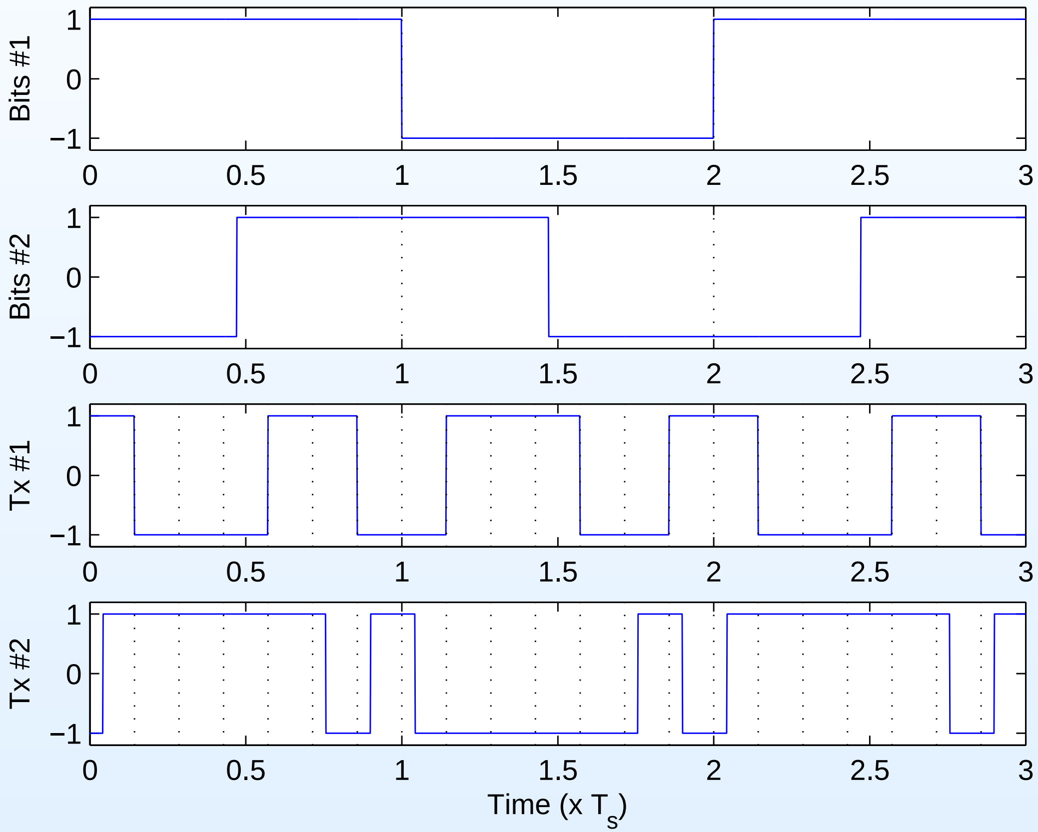
- Introduction
- CDMA signaling
- Receiver design considerations
- Synchronization
- RAKE receiver
- Multi-user detection
- Summary
- References
- Homework

Introduction

- CDMA is currently the dominating air interface technique used in wireless communications.
- CDMA is used e.g. in WCDMA, IS-95 and cdma2000 systems.
- As higher data rates are required, receiver design becomes a more and more important factor regarding the performance of the system.
- In CDMA receivers, tasks such as PN code synchronization, channel estimation and equalization need to be performed.
- Conventional CDMA receivers (RAKE) do not take into account the multiple access interference (MAI) caused by other users.
- This performance degradation caused by MAI can be overcome using multi-user detection where information about the other users is used in detection.

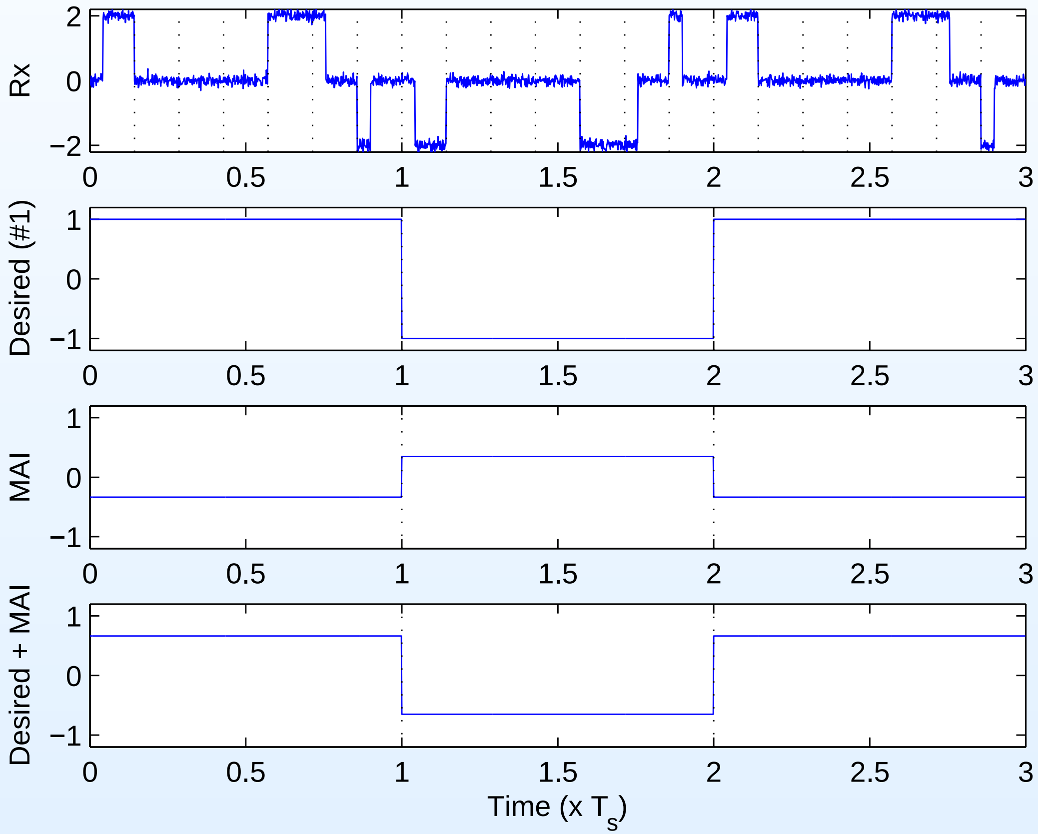
Asynchronous CDMA

The signals are multiplied with a spreading sequence before transmission (as seen as receiver, delay added to signal #2):



Asynchronous CDMA

At the receiver, the signals are summed and noise added. Signal #1 is despread:



Design considerations

- Single user vs. multi-user system: In single user systems (i.e. where a single user transmits at a time, e.g. WLAN), there is no multiple access interference and optimal receiver is much more simple.
- Asynchronous vs. synchronous multi-user system:
  - In asynchronous systems the users cause multiple access interference which may degrade the overall performance severely. WCDMA and actually most CDMA systems are asynchronous.
  - The system can be made synchronous in which case (if orthogonal codes are used) the only interference is caused by multipath propagation. But in this case the system has to be synchronized for example using GPS as in the IS-95 system which makes the systems more complex.

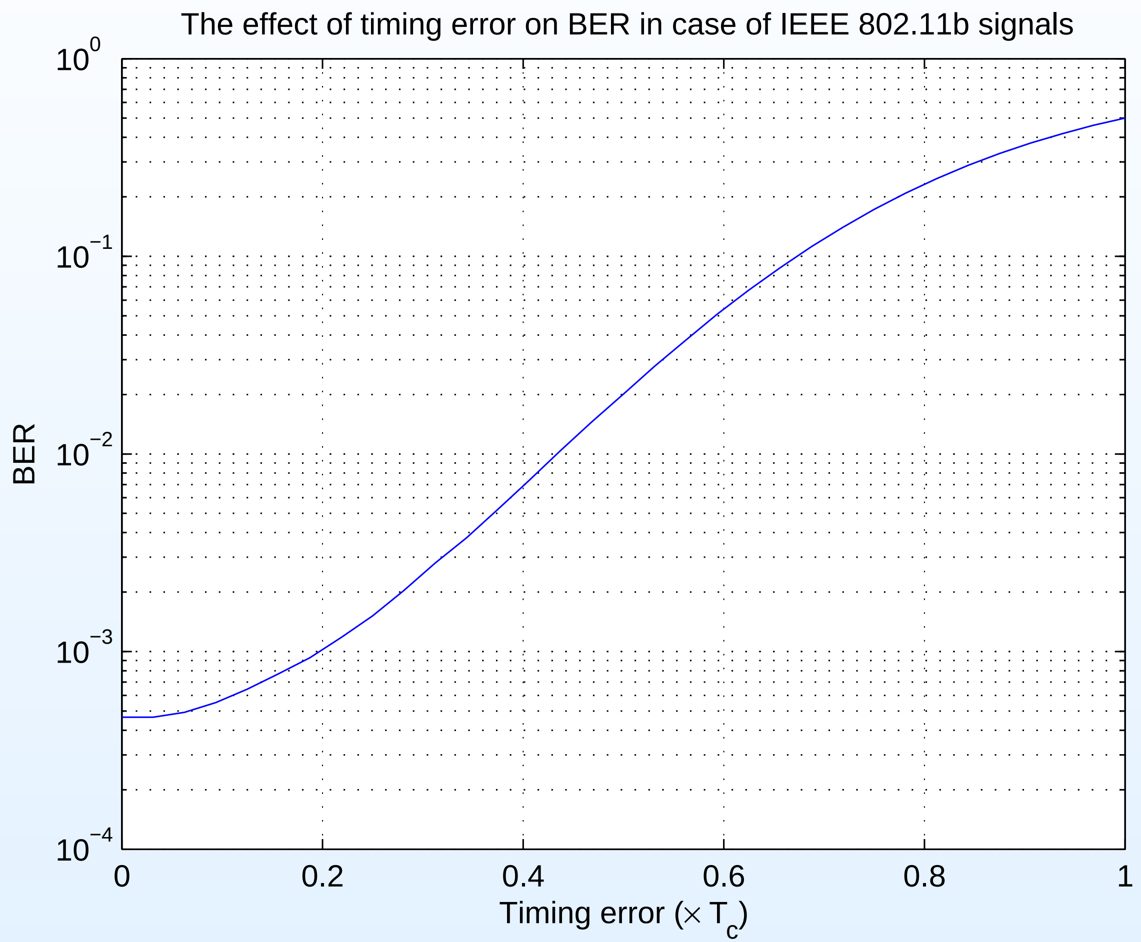
Design considerations

- Near-far effect: A terminal transmitting at a higher power (as received at the base station) than others may cause so much multiple access interference that the signals from other terminals can not be heard.
  - Power control is usually used to alleviate this problem.
  - On the other hand, also power control complicates system and receiver design, so in some cases it might be useful to have algorithms that tolerate near-far effect as well as possible.
  - Also, power control might have failures in which case it is desirable to have near-far tolerant receivers.

Synchronization

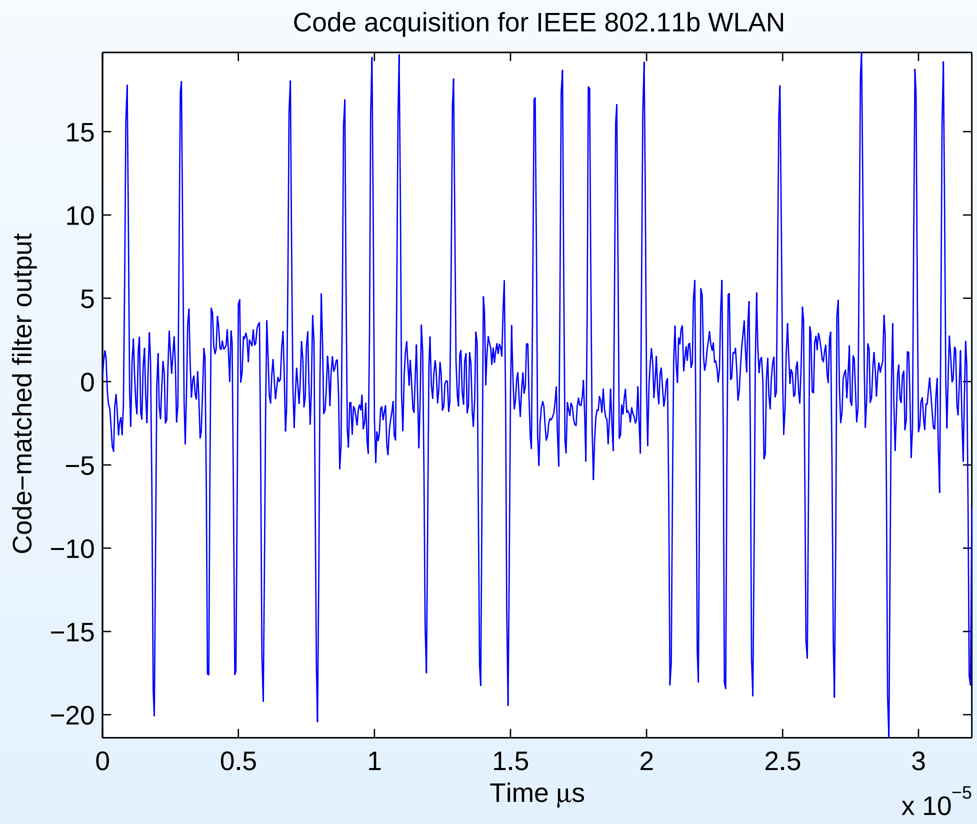
- Precise code synchronization is crucial to the performance of a CDMA receiver.
- In code synchronization, the received signal is synchronized with the local PN code generator.
- Code synchronization can be divided into two phases:
  - Acquisition (coarse synchronization) where a code-matched filter (correlator) is used. The peaks of the correlator output are used for synchronization.
  - Tracking (fine synchronization) in which the coarse delay estimate obtained in the acquisition phase is refined and then tracked (delay is time-varying).

BER vs. synchronization error



Acquisition

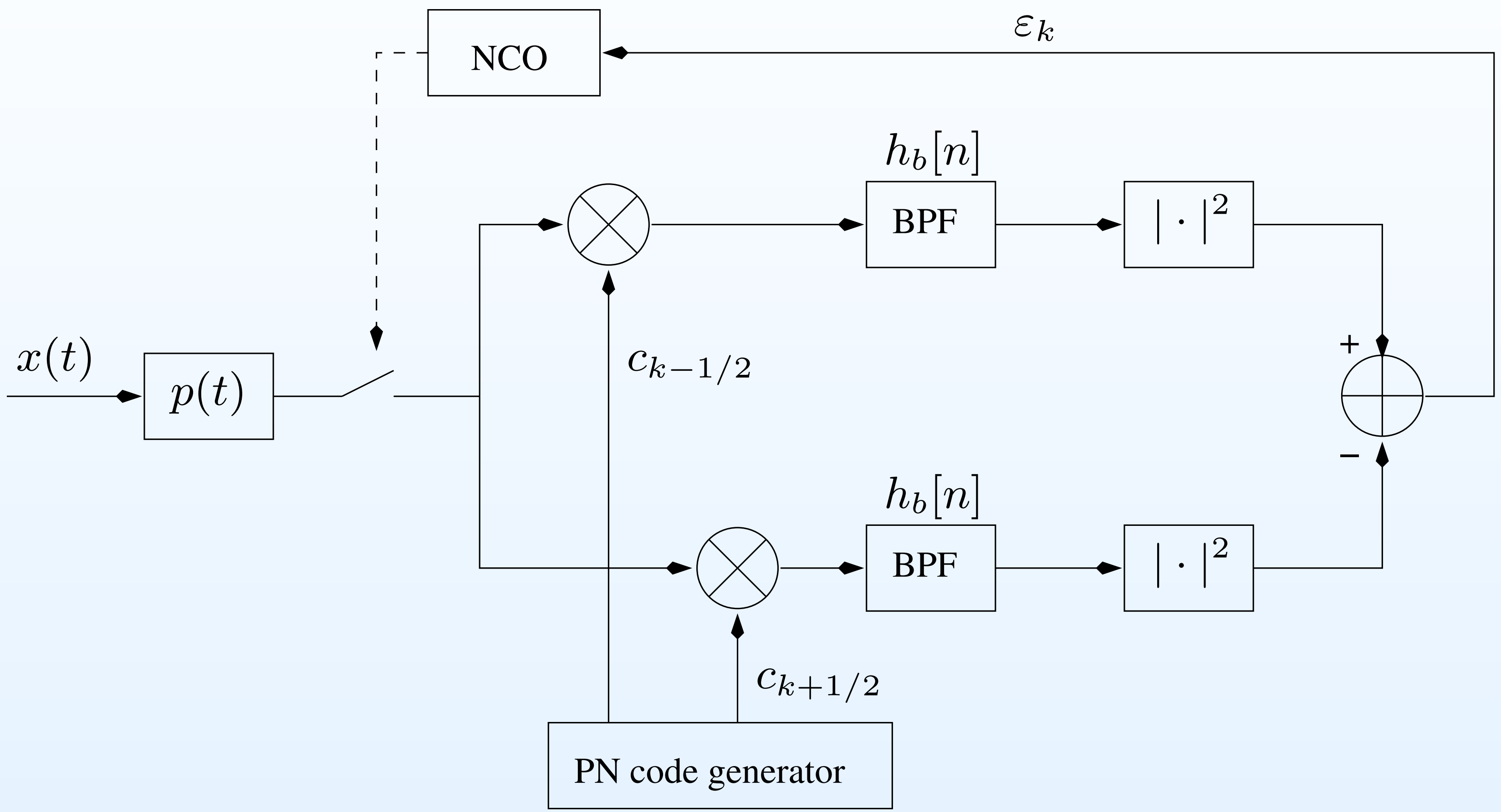
- Coarse synchronization (accuracy up to half a chip period) is achieved using a correlator (code-matched filter):



Tracking

- After the acquisition phase, the delay estimate needs to be refined and tracked.
- This is usually done using a special loop called delay-locked loop (DLL) which is very similar to the early-late gate used in symbol synchronization in digital communications [1].
- Delay-locked loop correlates the received signal with "early" and "late" replicas of the PN code sequence and calculates an error signal from the outputs.
- The error signal is then used to drive a VCO that controls the sampling instants (or in fully digital implementation, an NCO that controls an interpolator).
- Some alternatives to DLL are e.g. tau-dither loop and extended Kalman filter (EKF).

Digital delay-locked loop



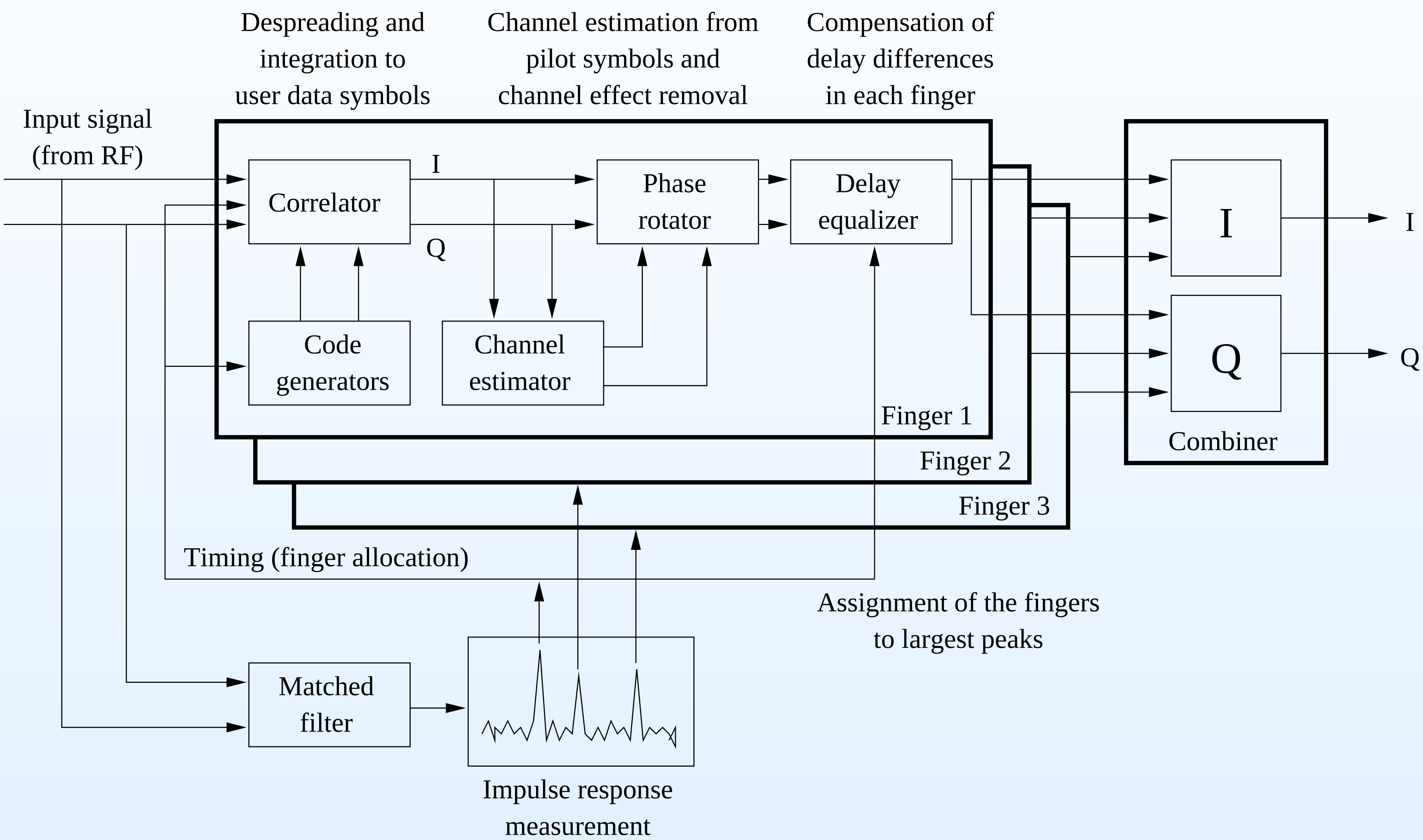
RAKE receiver

- The most common receiver used in most CDMA receivers is RAKE receiver.
- RAKE receiver is basically a maximum ratio combiner that combines differently propagated signal replicas in an optimal manner.
- RAKE receiver consists of several baseband correlators (fingers) that each process a single multipath component independently.
- The outputs of the correlators are then combined to form an improved symbol estimate.
- Thus, RAKE takes advantage of multipath diversity where the diversity order is equal to the number of combined multipath components.
- Obviously, RAKE receiver needs good channel estimation.

RAKE receiver

- It can be shown that the RAKE receiver is (in maximum-likelihood sense or equivalently, in terms of minimizing BER) the optimal receiver in single-user case.
- However, in multi-user systems the performance of RAKE receiver is actually quite poor compared to some alternatives (due to multiple access interference).
- Still it is used widely e.g. in WCDMA base stations due to simple implementation.

RAKE receiver



Multi-user detection

- The performance of the RAKE receiver degrades severely in a multi-user environment, especially if higher data rates are needed and lower spreading factors have to be used (low spreading factor => small processing gain).
- Multi-user detectors take advantange of the information about the other users and hence provide better performance.
- Verdú derived the optimal (maximum-likelihood) multi-user detector in [3]. However, the optimal receiver is too complex to be implemented as its complexity grows exponentially with the number of users and number of detected symbols.
- Suboptimal receivers trade some of this optimality to much lower complexity.
- Some of the most common multi-user detection techniques are decorrelating detector, successive interference cancellation and parallel interference cancellation.

Signal model

- Consider synchronous multi-user DS-CDMA for simplicity.
- Received continuous-time signal can be written as

$$r(t) = \sum_{k=1}^{K} A_k(t)c_k(t)b_k(t) + n(t) \tag{1}$$

where K is the number of users, $A_k(t)$ is the amplitude of user k, $c_k(t)$ is the code sequence and $b_k(t)$ is the bit sequence of user k and $n(t)$ is noise.

- Output of the correlator of user k yields ($\rho_{i,k}$ is correlation between codes c_i and c_k)

$$y_k = \frac{1}{T_b}\int_{T_b} r(t)c_k(t)dt = A_k b_k + \underbrace{\sum_{i=1,i\neq k}^{K} \rho_{i,k}A_i b_i}_{MAI} + n_k(t) \tag{2}$$

Signal model

- Outputs of the correlators can be stacked into a vector $\mathbf{y} = [y_1, \ldots, y_K]^T$, which can be expressed in matrix form as [5]

$$\mathbf{y} = \mathbf{CAb} + \mathbf{n} \tag{3}$$

where $\mathbf{C}$ is a matrix that contains code correlations, $\mathbf{A}$ is a diagonal matrix consisting of amplitudes and $\mathbf{b} = [b_1, \ldots, b_K]^T$.

Decorrelating detector

- Decorrelating detector completely eliminates MAI (similar to zero-forcing equalizer in eliminating ISI).
- This is done by multiplying the correlator outputs by the inverse of the code correlation matrix:

$$\mathbf{z}_{DD} = \mathbf{C}^{-1}\mathbf{y} = \mathbf{A}\mathbf{b} + \mathbf{C}^{-1}\mathbf{n} \tag{4}$$

- Hence, decorrelating detector successfully decouples all users.
- Detector is thus near-far resistant.
- Disadvantage is noise enhancement, since elements of $\mathbf{C}^{-1}\mathbf{n}$ are always greater than or equal to elements of $\mathbf{n}$.
- Another disadvantage is the computation of the inverse of the matrix. Still, the complexity is much lower than that of the ML receiver.

Successive interference cancellation

- SIC takes a serial approach to canceling out interference.
- Each stage of the detector makes bit decisions, regenerates the signal and cancels it out so that it does not appear at the input of the next stage. i:th stage calculates

$$r^{(i+1)}(t) = r^{(i)}(t) - \hat{A}_k(t)\hat{b}_k(t)c_k(t) \tag{5}$$

- Amplitude estimates (in asynchronous systems also timing estimates) are required and hard decisions are performed for the symbols $\hat{b}_k$.
- The canceller typically starts from the strongest signal because the probability of error is then smallest.
- Drawback is that each stage imposes additional detection delay.
- Also, the detector suffers from error propagation — an error in the first stages causes erroneus symbol decisions also in later stages.

Parallel interference cancellation

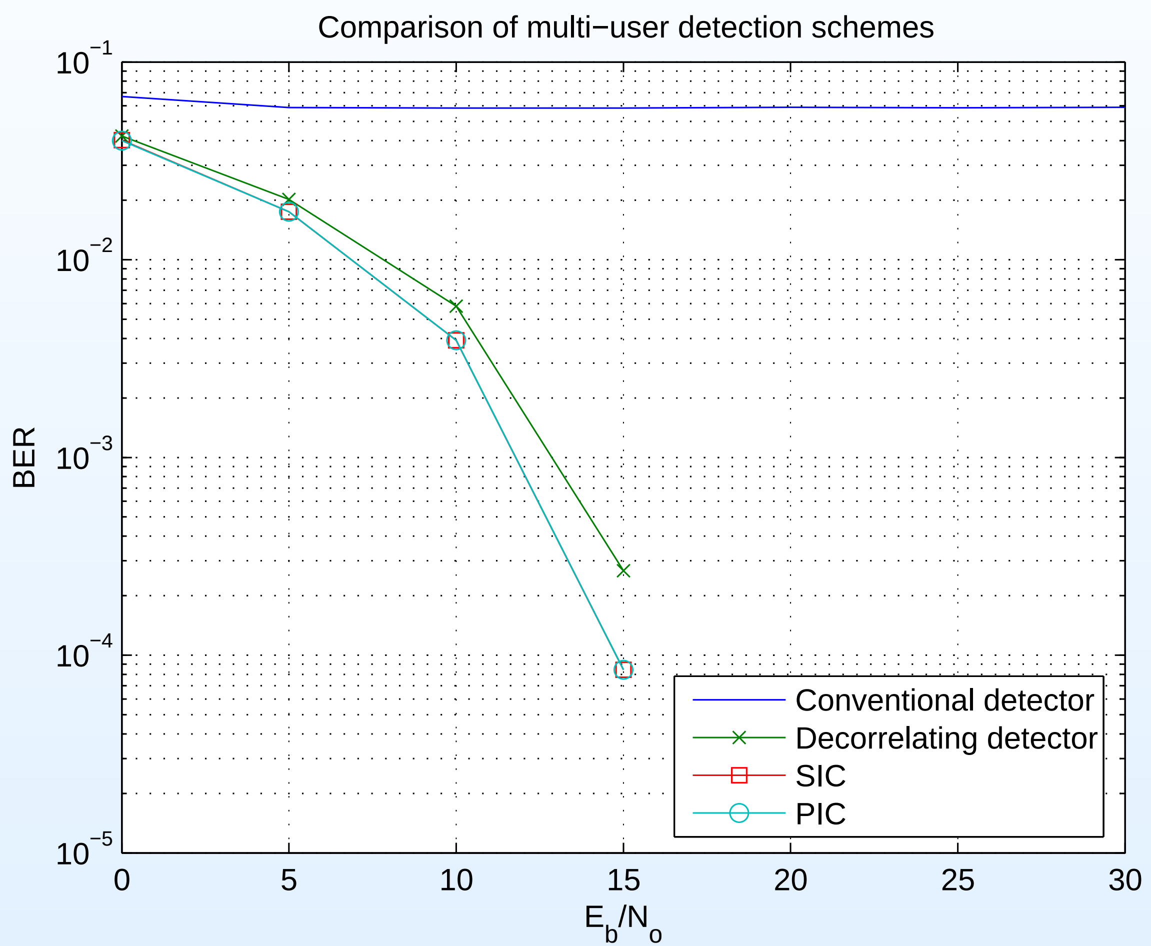
- In PIC, initial bit estimates are used to estimate MAI for each user. The estimated MAI is then removed and the resulting signal is fed to matched filter.
- The bits are estimated from the outputs of the matched filters and then fed to the input of the next stage (MAI estimation).
- Output of stage m is

$$\hat{\mathbf{b}}(m) = \mathbf{y} - \mathbf{QA}\hat{\mathbf{b}}(m-1) \qquad (6)$$

  where $\mathbf{Q} = \mathbf{C} - \mathbf{I}$.
- This process is repeated for multiple stages.
- The performance depends heavily on the initial estimates. So, to improve performance, for example decorrelating detector can be used at the first stage.

Simulation

Spreading factor 31 (Gold codes), BPSK, AWGN channel, 10 users:



Summary

- With higher data rates, CDMA receiver design becomes more important.
- Code synchronization is very crucial to the performance of the receiver.
- Synchronization is divided into acquisition and tracking phases.
- RAKE receiver combines different multipath components and thus takes advantage of multipath diversity. It is the optimal receiver in single user case.
- Multi-user detection improves the performance in multi-user systems by taking advantage of information about all users.

References

[1] J.G. Proakis, "Digital Communications", Fourth Edition, New York: McGraw-Hill, 2001, 1002 pages.

[2] R. De Gaudenzi, M. Luise and R. Viola, "A digital chip timing recovery loop for band-limited direct-sequence spread-spectrum signals", IEEE Transactions on Communications, vol. 41, no. 11, November 1993, pages 1760-1769.

[3] S. Verdú, "Minimum probability of error for asynchronous multiple access communication systems", IEEE Transactions on Information Theory, vol. IT-32, n0. 1, January 1986, pages 85-96.

[4] S. Verdú, "Multiuser detection", First Edition, Cambridge University Press, 1998, 451 pages.

[5] S. Moshavi, "Multi-user detection for DS-CDMA communications", IEEE Communication Magazine, October 1996, pages 124-136.

Homework

Explain briefly the pros and cons of the following multi-user detection techniques (e.g. [4],[5] are good references):

- Decorrelating detector
- Successive interference cancellation
- Parallel interference cancellation