Introduction to Spread Spectrum

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Seminar Topics

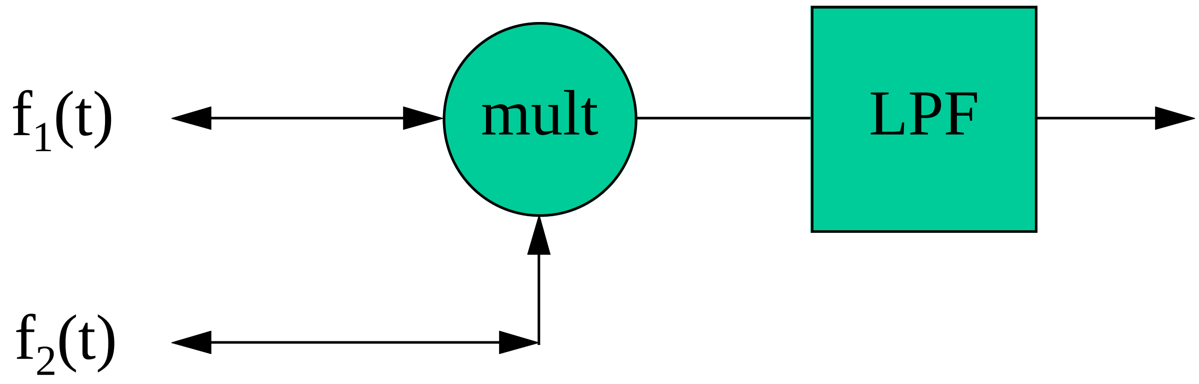
- Spread Spectrum Theory
  - Phil Karn, KA9Q
- Designing a Spread Spectrum Modem for Amateur Use
  - Tom McDermott, N5EG
- Spread Spectrum Regulatory Issues
  - Dewayne Hendricks, WA8DZP

Some Basic Concepts

- Correlation
- Orthogonality
- Although seemingly new with SS, these concepts are widely used in ordinary narrow band analog communications

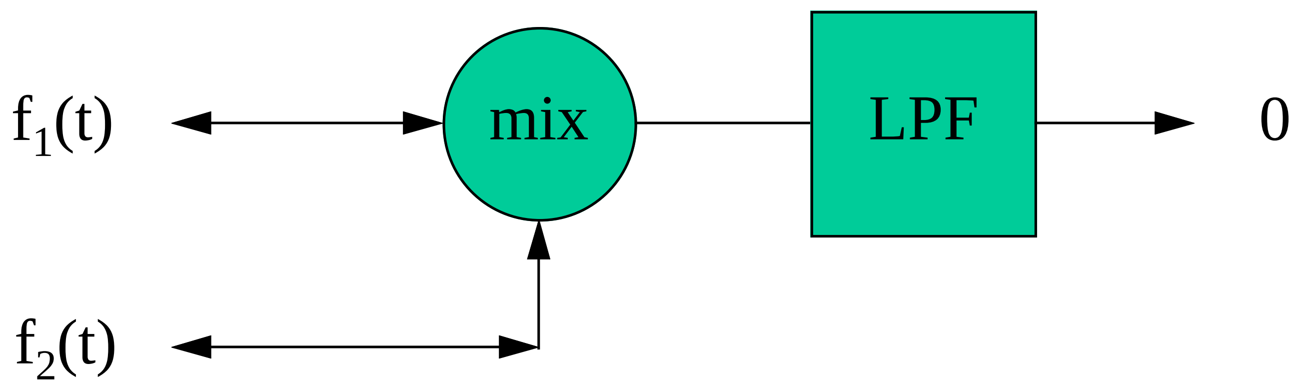
Correlation

- *Correlation* is a time-averaged product of two input functions
- Mixers and product detectors are analog correlators



Orthogonality

- Two functions are *orthogonal* if, when multiplied together and averaged over time, the result is zero:



Orthogonality in Communications

- If two communication signals are orthogonal, then it is (theoretically) possible to build a receiver that responds to one while completely rejecting the other
- If the two signals are not orthogonal, then this is not possible, *even in theory*

Some Orthogonal Functions

- Sine waves of different frequency, or in phase quadrature (0 & 90 deg): FDMA
- Non-overlapping pulses: TDMA
- Walsh functions, e.g., the rows of H_4 :

```
-1 -1 -1 -1
-1 +1 -1 +1
-1 -1 +1 +1
-1 +1 +1 -1
```

Why Sacrifice Orthogonality?

- If orthogonality allows ideal (in theory) receivers to be built, what's wrong with it?
- Orthogonal function sets are limited
  - I.e., spectrum is limited
  - usage is often intermittent and unpredictable
- Time shifts of most orthogonal functions are not self-orthogonal
  - I.e., multipath interference is a problem

The Case for Non-Orthogonality (I.e., the case for SS)

- Very large sets of “nearly” orthogonal functions (codes) exist. Every user can have one without reallocation
- These functions are also “nearly” orthogonal with time-shifted versions of themselves
  - Multipath becomes easy to reject
  - Ranging & tracking become possible

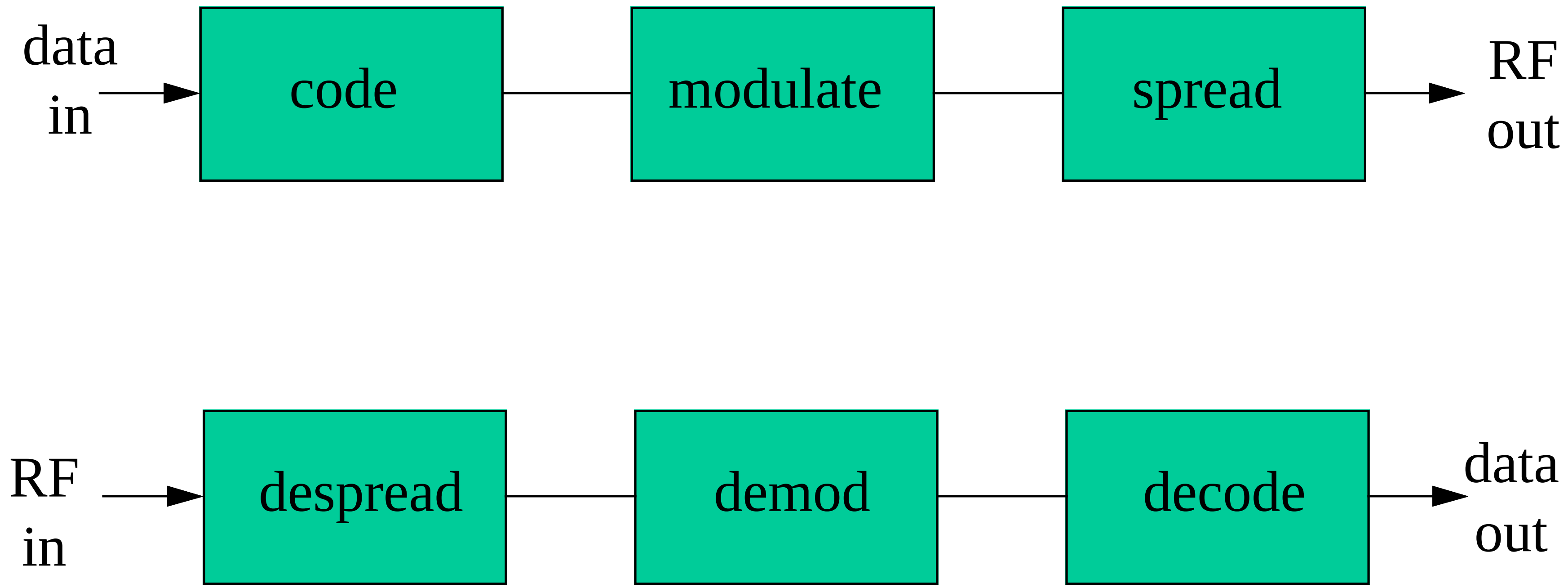
Pseudo-Noise (PN) Codes

- Spread spectrum uses sequences that, while predictable, have noise-like properties:
- Linear Feedback Shift Registers (LFSRs)
- Gold Codes (multiple LFSRs combined with XOR)
- Cryptographically generated sequences for anti-jam/spoof (e.g., GPS Y-code)
- Each bit of a code sequence is a *chip*

The Costs of Non-Orthogonality

- Because spreading sequences (codes) are not perfectly orthogonal, some co-channel interference remains
  - this is the famous "near-far problem"
- The interference is suppressed by the *process gain*: BW{RF} / data rate
- Power control is needed to minimize interference and maximize capacity

Spread Spectrum - the traditional view



Coding

- Convolutional
  - soft decision, usually with Viterbi decoding
  - burst correction requires interleaving
- Block
  - Reed Solomon - excellent at burst correction
  - Hamming
  - Golay, etc
- See my earlier TAPR tutorial on coding

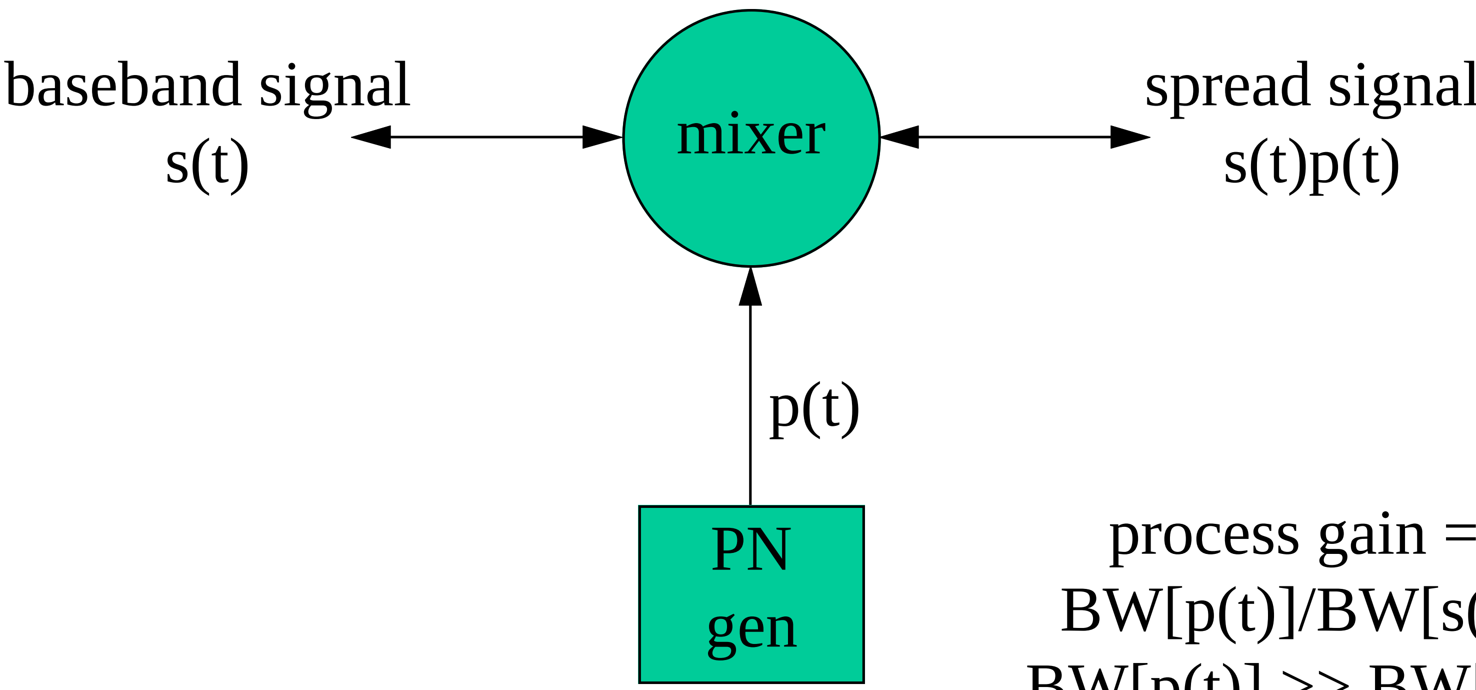
Modulation

- Coherent PSK
- Differentially coherent PSK
- M-ary orthogonal
  - M-ary FSK (including binary FSK)
  - Walsh coded PSK
    - can be seen as a block code
- Non-orthogonal modes not generally used
  - these are for band-limited channels

Spreading

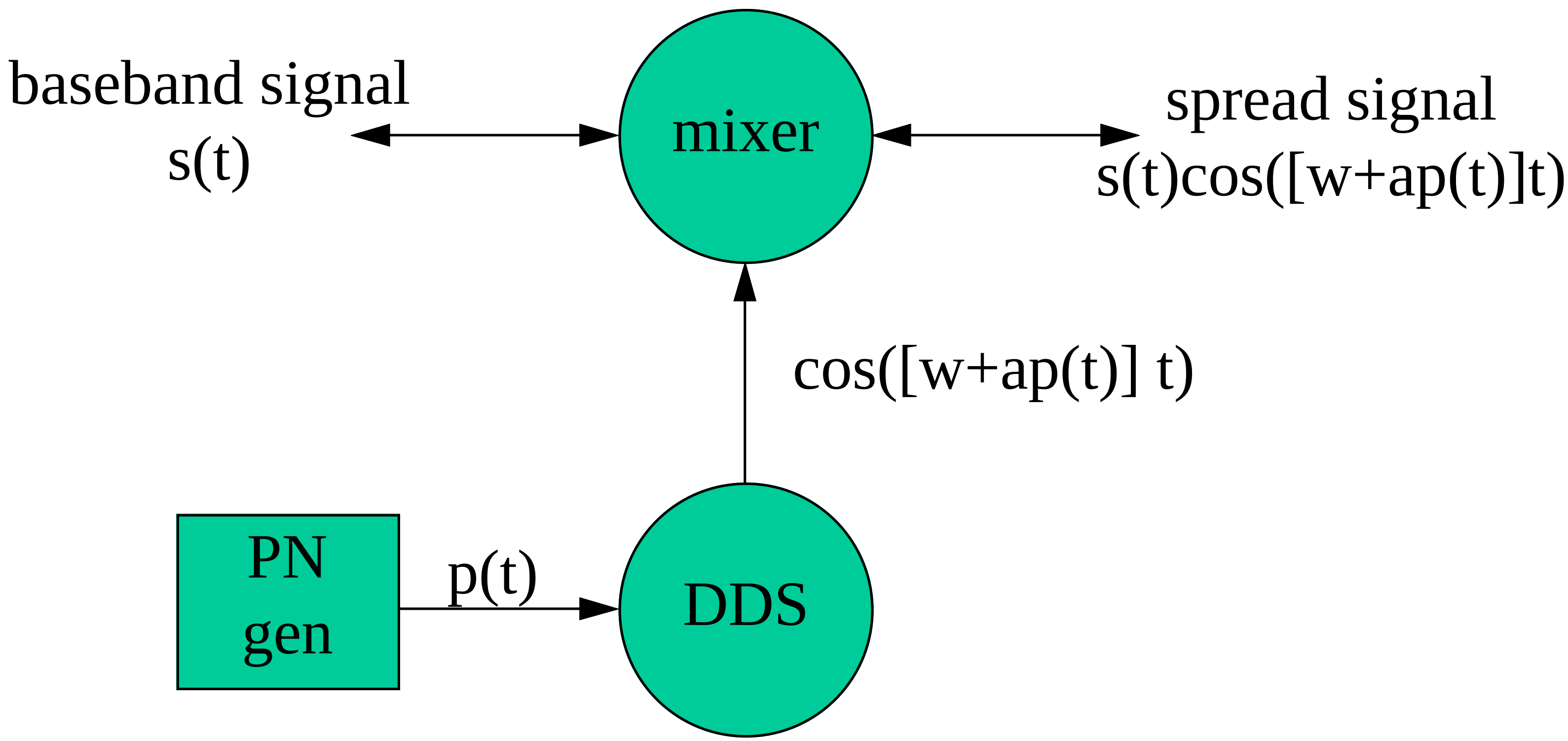
- Direct Sequence
- Frequency Hopping
- Time Hopping
- Hybrid combinations

Direct Sequence



process gain ==
BW[p(t)]/BW[s(t)];
BW[p(t)] >> BW[s(t)]

Frequency Hopping



Synchronization

- SS receivers must acquire *code phase* as well as symbol timing, carrier frequency and carrier phase (if applicable)
- This creates a multi-dimensional search space that can be impracticably large if the system is not carefully designed

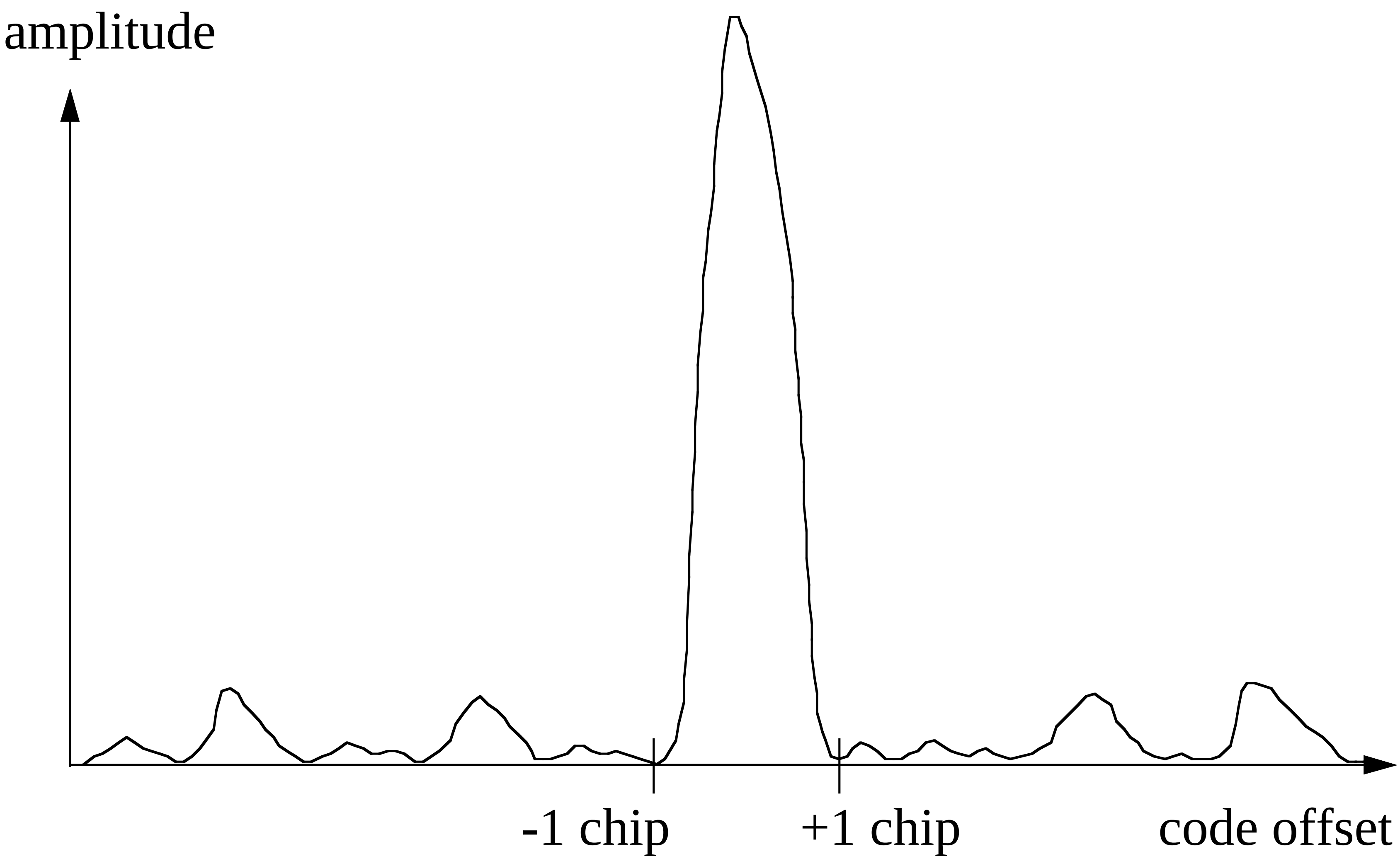
Multi-Step Acquisition

- Acquire code phase
  - in most systems, symbol timing is locked to code phase, so this also provides symbol timing
- Acquire carrier frequency
  - frequency tracking loop, etc
- Acquire carrier phase (if necessary)
  - Costas loop, filtered pilot, etc

Code Acquisition

- Step through all possible code offsets, looking for narrow band signal energy
  - keep PN sequence short to make this practical
- Post-despread filter must be wide enough for max doppler/osc drift, or be stepped as well (creating 2-D search space)
- Search rate depends on SNR

Correlator Output vs Offset



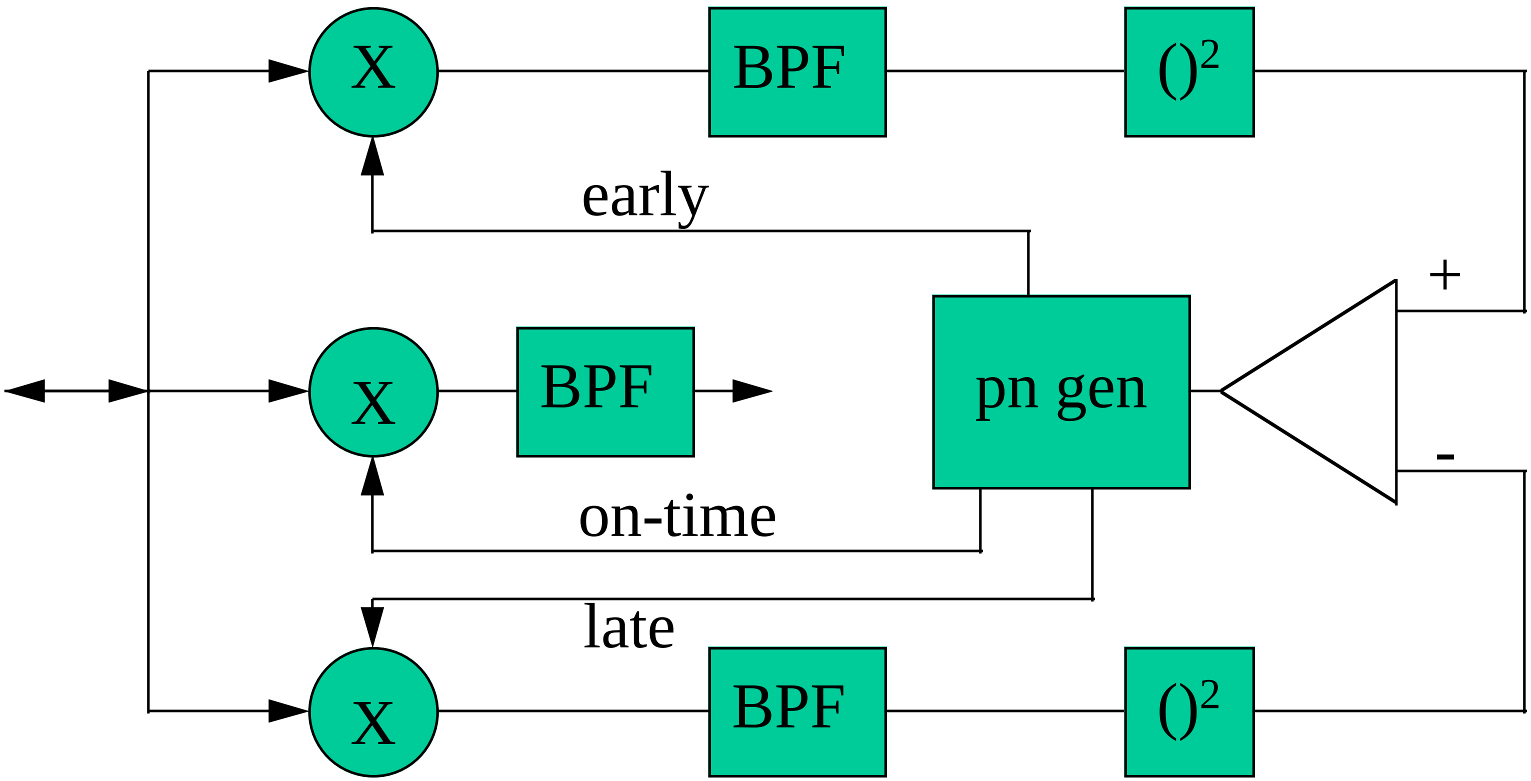
Short & Long Codes

- Several systems aid acquisition by using a short code for quick acquisition and a long code for ambiguity resolution, etc
  - reference component spread only by short code
- IS-95 CDMA (2^{15} chip "short" code, 2^{42}-1 chip "long" code, both at 1.2288 Mc/s)
- GPS (2^{10} chip C/A code at 1.023 Mc/s, week-long P code at 10.23 Mc/s)

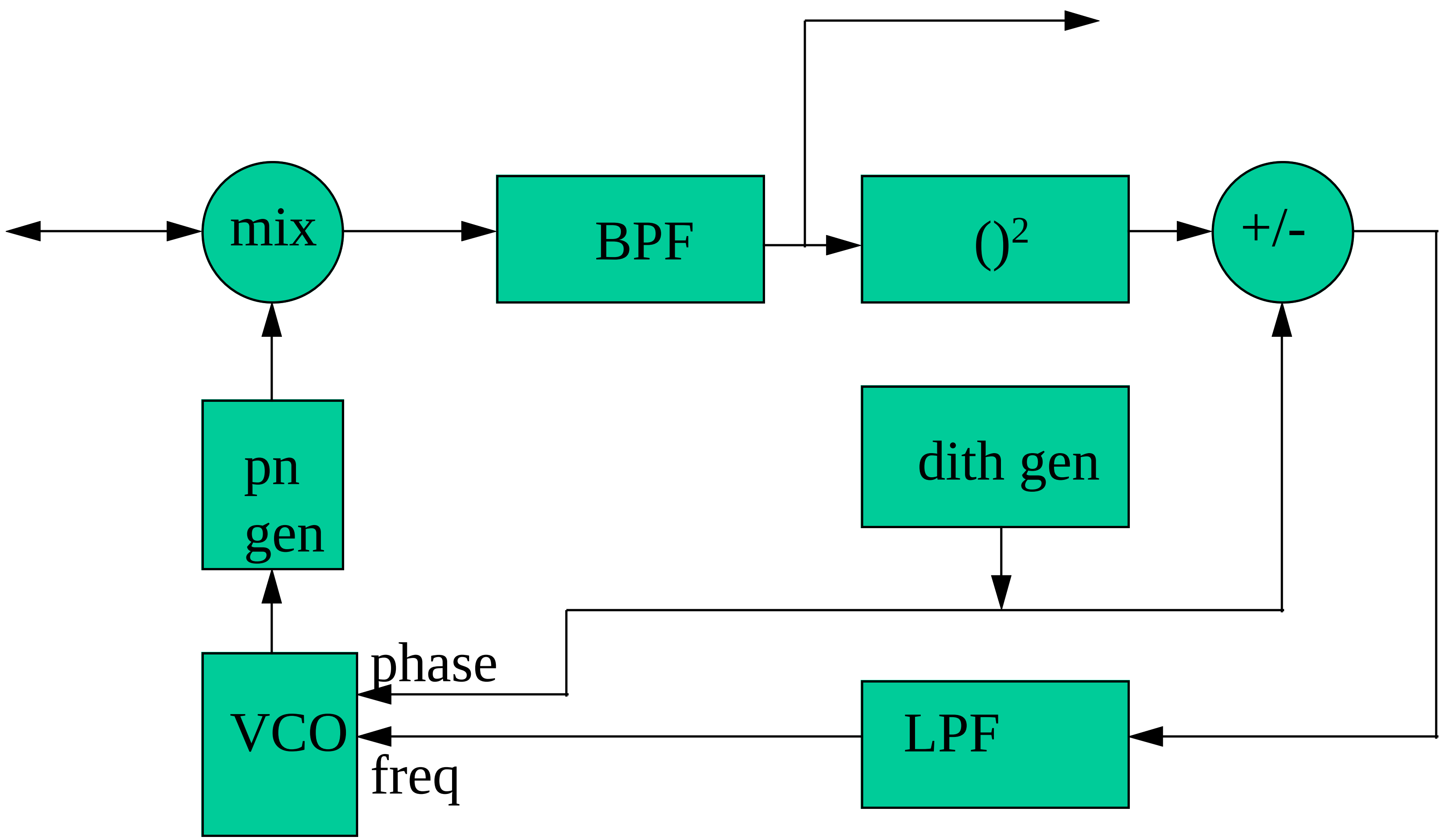
Code Tracking

- Once code phase has been found, it must be continually tracked
- Time-tracking loops analogous to phase locked loops are used
- These exist in several forms, but they all compare early/late versions of the signal

Parallel Tracking Loop



Tau-dither Tracking Loop



SS System Design

- Coding, modulation and spreading must be selected and matched on a system basis
- Each can be seen as a special case of the other, e.g.,
  - FEC “spreads” by increasing bandwidth with redundant info
  - M-ary modulation is a form of block coding; it is also a form of spreading
  - Even BPSK “spreads” by 2x

Properties of Direct Sequence

- Looks like high speed PSK (in fact, it is)
  - can be band limited just like PSK
- Maintains phase coherence through chips
  - useful for ranging & tracking
- Looks like continuous wide band noise to co-channel narrow band signals, and vice versa

Properties of Frequency Hopping

- Looks like M-ary FSK (in fact, it is)
- Does *not* stay phase coherent through hops
  - even if the DDS did, the channel is probably dispersive
- Looks like occasional strong interference to a co-channel narrow band signal, and vice versa

DS vs FH

- Need tracking and ranging?
  - DS is definitely the way to go (GPS, TDRSS)
- Need maximum capacity, i.e, by minimizing required E_b/N_0?
  - DS somewhat superior because it permits coherent PSK, at least on satellite
  - but large-alphabet orthogonal modulation with FH is almost as good

FH vs DS

- Maximum resistance to narrow band jammers, accidental or intentional?
  - Inherently easier with FH and burst-error-correcting codes (e.g., Reed-Solomon)
  - FH can cut “holes” in hop sequence
  - DS can use notch filters, but this is harder
- Maximum process gain?
  - Easier with FH and DDS chips
  - DS/FH hybrids common (e.g, Omnitracs)

Fast vs Slow Hopping

- Slow hopping: hop rate < symbol rate
  - Easier to implement
  - Carrier phase jumps less frequent, allowing longer symbol integration times
- Fast hopping: hop rate > symbol rate
  - Serious noncoherent combining losses due to frequent carrier phase jumps
  - Highly effective against intelligent jammers when hop rate > speed-of-light delay

Some Examples of DSSS

- Global Positioning System (GPS)
- IS-95 CDMA for Digital Cellular
  - Forward Link
  - Reverse Link

Global Positioning System (GPS)

- (30,24) Hamming (block) code
- BPSK modulation (50 sps)
- Direct sequence BPSK spreading (1.023 Mc/s) on C/A channel
- Direct sequence BPSK spreading (10.23 Mc/s) on P channel
  - P channel in quadrature with C/A on L1
  - P channel also on L2

IS-95 Features

- 1:1 Frequency reuse pattern; higher capacity
  - vs 7:1 or higher for AMPS (FM)
- Mobile assisted (soft) handoff
- Variable rate vocoder
  - lowers average data rate, increases capacity 9.6/ 4.8/2.4/1.2 kb/s (Rate Set 1)
  - 14.4/7.2/3.6/1.8 kb/s (Rate Set 2)

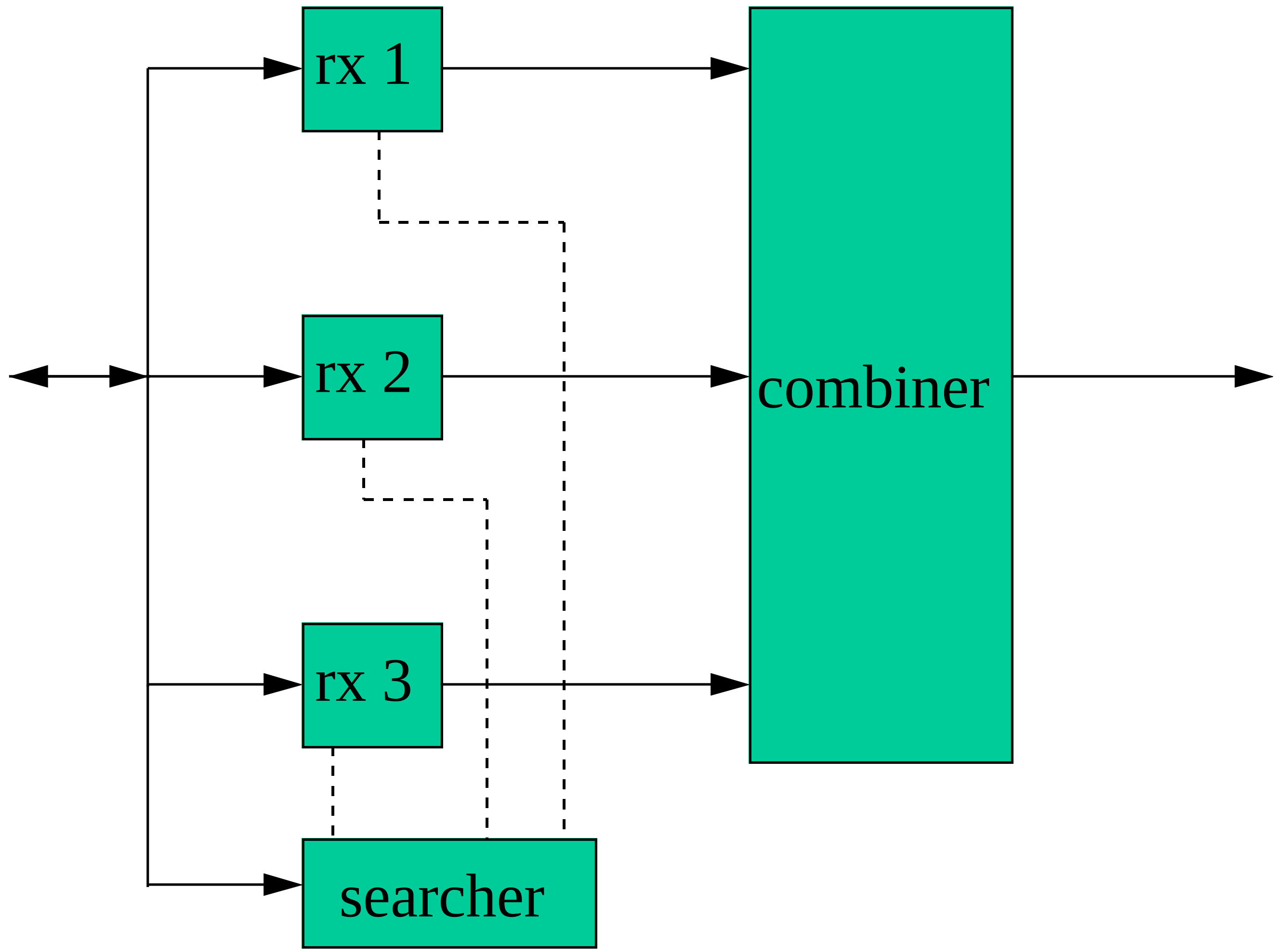
IS-95 CDMA Forward Link

- r=1/2 K=9 convolutional coding (rate set 1)
  - rate 1/4, 1/8, 1/16 for lower data rates
- 20 ms interleaving
  - tradeoff between delay and fade tolerance
- BPSK modulation (19.2 ks/s)
- Walsh code channelization (64-ary)
  - channel 0 reserved for common pilot ref
- QPSK spreading (1.2288 Mc/s)

IS-95 Fwd Link

- Pilot spread only with short code common to all cells
  - cost shared by all mobiles
  - fast acquisition (several sec)
  - handy carrier phase reference for coherent demod in presence of fading
- Traffic channels muxed with Walsh code
  - think of Walsh codes as “subcarriers”

CDMA RAKE Receiver



Soft Handoff

- Special case of multipath resolution and combining where call is routed simultaneously to two or more sectors and components are combined in mobile's RAKE receiver
- Forward link only; reverse link uses simple voting scheme

IS-95 CDMA Reverse Link

- r =1/3 K=9 convolutional outer code (set 1)
  - rate 1/6, 1/12, 1/24 for lower data rates
- 20 ms interleaving
- 64-ary orthogonal (Walsh) inner code
  - equivalent to (64,6) block code
- BPSK modulation (307.2 ks/s)
- QPSK spreading (1.2288 Mc/s)
- Open & 800 Hz closed loop power control

IS-95 Rev Link

- No pilot
  - considered inefficient, but being revisited for next generation CDMA
- 64-ary orthogonal modulation provides good noncoherent E_b/N_0 performance
  - actually "coherent" over each codeword representing 64 symbols or 6 bits
- Frame puncturing at lower data rates maintains constant E_b/N_0

Soft Decision Decoding

- Soft-decision decoding performed with per-bit likelihoods from demodulator
  - better than “winner take all” scheme where each group of 6 bits has the same metric
  - same technique applicable to convolutional decoding and M-ary FSK on HF

IS-95 Rate Set 2

- All data rates increased by 50% by "puncturing" convolutional code
- Rate 1/2 becomes rate 3/4
- Rate 1/3 becomes rate 1/2
- All other symbol and chip rates remain the same
- Cost is increased E_b/N_0 *and* fewer users

FHSS Examples

- Military anti-jam and some commercial Part 15 modems; details hard to obtain
- R-S or dual-k convolutional coding & interleaving
- 8-ary FSK; E_b/N_0 better than coherent PSK
- Frequency hopping
  - pick a set of 8 frequencies on each hop
  - hop as fast as 8-ary symbol rate

FEC for Spread Spectrum

- FEC is essential to efficient SS
- FEC does *not* decrease process gain!
- By reducing E_b/N_0 requirements, FEC reduces SS QRM to other users and makes SS more QRM-tolerant
  - system capacity inversely proportional to E_b/N_0

FEC for DSSS

- Convolutional coding is a natural for DSSS
  - good coding gains, esp with soft decisions
  - modulation is typically binary, a good match
- Convolutional or block (RS) for FHSS
  - FH typically uses M-ary FSK modulation, requiring higher-order code alphabet, a natural for RS
  - error bursts can last as long as a hop

Adaptive Frequency Hopping

- Receiver reports error burst patterns to transmitter indicating narrow band QRM
- Transmitter simply mutes instead of transmitting on QRMed channels
  - avoids resynchronizing on new sequence
- FEC “rides through” the erasures as long as there aren’t too many

Conclusions

- Frequency Hopping is probably more suitable than DS for general amateur use
  - Better narrow band QRM tolerance/avoidance capabilities
- Most appropriate amateur use of Direct Sequence is probably on satellite
  - ranging & tracking
  - near/far problem less acute